Water Resour Manage (2010) 24:1161–1194
DOI 10.1007/s11269-009-9490-6

An Operational Model for Support of Integrated Watershed Management

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Received: 13 August 2008 / Accepted: 20 July 2009 /

Abstract This paper presents a computer simulation-based methodology for operational support of integrated water resources management. The methodology is based on the systems approach, and use of feedback to capture physical and socio-economic processes occurring within a watershed. The approach integrates well established simulation models of physical processes with simulation models that describe socio-economic processes. The proposed methodology is illustrated by the evaluation of risk and vulnerability to changing climatic and socio-economic conditions in the Upper Thames watershed (south-western Ontario, Canada).The model results indicate that flooding in the watershed will be more severe as a result of climate change, while low flows are expected to remain at their current level. The most significant socio-economic factor in the Upper Thames watershed is water availability, shown to become under climate change a limiting factor for future growth and development.

Keywords Integrated water resources management · Continuous hydrologic modeling · Climate change impact on hydrologic regime · Flood and low flow frequency analysis · Socio-economic modeling with system dynamics

1 Introduction

Rapidly growing population and associated socio-economic development are placing increasing stress on the water resources in the region. Demand for water, in all sectors of the economy, is increasing, while adequate supply is constantly diminishing.

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Exacerbating the water stress further are increased concerns with anthropogenic carbon dioxide emissions, associated global warming and climatic change that leads to the intensification of the hydrologic cycle (IPCC 2007). Such intensification is expected to change both frequency, and magnitude of extreme events (such as floods, droughts, heat waves, snow and ice storms, etc.), and will therefore have serious implications on future management of water resources systems.

Growing complexity of water resources systems and its management challenges led the international community to introduce the concept of integrated water resources management (IWRM). The concept emerged after a realization that an integrated approach can provide more efficient ways of addressing complex water resources management problems. Although there are many definitions of the IWRM (Cardwell et al. 2006), this paper adopts the definition provided by the Global Water Partnership (GWP 2000):

> "Integrated water resources management is a process which promotes the coordinated development and management of water, land and its related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (p. 22)."

The guiding principles of the IWRM process are systems view, integration, partnerships, participation, uncertainty, adaptation and reliance on strong science and reliable data (Simonovic 2008). *Systems view*—there is a natural need in water resources management to view a broad set of variables related to water and land resources and their interrelationships as a system. Water can have significant implications for terrestrial systems, through its capacity to cause flooding, contribute to erosion and salinity, and support wildlife. An examination of water and terrestrial systems through an integrated approach provides one way to address the dynamics of interrelated systems, ensuring that critical relationships are recognized and managed. *Integration*—water resources management suffers from fragmented responsibilities, from one level of government to another (local, to provincial/state, national, or international). The first role of IWRM is to provide for *vertical integration* of various levels of government in consideration of water resources problems. The water resources management is often dealing with the problem of horizontal fragmentation—within one level of government—among different agencies of a government, such as agriculture, forestry, fisheries, water, mining, municipal affairs, or economic development. IWRM provides a strong support for *horizontal integration* as a way to reach solutions through coordination and collaboration. *Partnerships*—integrated water resources management requires use of the engineering, social, natural, ecological, and economic sciences. Common goals for water and land resources must be developed among people of diverse social backgrounds and values. *Participation*—water is a subject in which everyone is a stakeholder. Participation requires that stakeholders at all levels of the social structure have an impact on decisions at different levels of water management. A participatory approach is the only means for achieving long-lasting consensus and common agreement. *Uncertainty*—human modifications of waters and related lands directly alter the delivery of water, sediments, and nutrients, and thus fundamentally alter aquatic systems. Alterations are using imperfect information about many processes involved, therefore bringing into the IWRM decision making process multiple objective uncertainties. *Adaptation*—high degree of uncertainty associated with water management highlights the need for *adaptive IWRM,* by which the relationships between planning and outcomes are explicit and within a feedback loop. Through the many interactions between the hydrology, land use, ecology, institutions, policies and social interactions within a basin, it is possible to implement an integrated approach to the management of water. At the same time, by building an understanding (within stakeholders) of the feedbacks and interaction taking place, adaptive decisions can be made, reinforcing support for actions as needed. *Science and data*—IWRM requires science of hydrology, hydraulics, geology, meteorology, oceanography, environmental science, engineering, law, economics, etc.

Examples provided in the Global Water Partnership Toolbox document (GWP 2003) document initial successes of IWRM in many countries. *Journal of Contemporary Water Research & Education* provides international perspective of IWRM, and offers examples from the United States, Netherlands, South Africa, Australia, New Zealand, United Kingdom, Canada and the European Union in their December 2006 special issue. Papers by Mitchell (2005, 2006) outline Canadian experience with integrated water resources management. Most notable examples include a linked management system for the Fraser River Estuary in British Columbia, and a multi-barrier approach to drinking water safety in Ontario.

It is acknowledged that the implementation of IWRM principles is often difficult, slow and costly due to shared responsibility of multiple stakeholders and/or agencies. Difficulties are also encountered when transforming qualitative ideas into quantitative plans of action that must guide decision makers. Therefore, development of analytical support and/or modeling approaches that will assist decision makers and stakeholders in the implementation of IWRM principles is needed.

A number of existing and newly-developed modeling tools have been developed that can provide support for IWRM. Most of them combine physical based management of water resources (using hydrologic water balance models or exogenous inputs) with analytical tools (mathematical optimization techniques) that quantify regional socio-economic conditions. These models also explore interconnections between socio-economic policy options and hydrologic basin response, and thus have the potential to be of practical value for integrated water resources management. For example, Cai et al. (2002) focus on the use of “specific sustainability criteria” that are incorporated into a long-term optimization model of a river basin, taking into account water supply risk minimization, environmental integrity, spatial and temporal equity of water allocation, and economic efficiency of infrastructure development. Long-term decisions, based on sustainability criteria, are used to guide the short-term decisions in an attempt to achieve optimal water resources management decisions. Cai et al. (2003) use (a) endogenous demand functions for individual sites; and (b) central authority-based decision-making framework to direct the search for optimal water allocations to demand sites and crops. Ward et al. (2006) are integrating physical and economic total water-related benefits in a quadratic objective function for derivation of optimal consumptive water use. Mainuddin et al. (2007) describe coupled hydrologic-economic spreadsheet model that allows analyses of water allocation and use by different sectors including agriculture and environment under alternative policy scenarios. The model is simple, lumped optimization model that relies on a reach by reach water balance of the river system, irrigation demand and revenue generation. The model is used to optimize profit, diversions and flow subject to hydrological and economic constraints determined by the policy scenario.

The main difference between these models and the approach presented in this paper is in explicit modeling of feedback between physical and socio-economic processes occurring within a watershed.

Shared Vision Modeling (Palmer 1998; Werick and Whipple 1994) provides support for the stakeholder driven processes in modeling with public participation. Shared Vision Models are "computer simulation models of water systems built, reviewed, and tested collaboratively with all stakeholders" (Werick and Whipple 1994). This approach provides for direct participation of stakeholders in model building, which is one of the main principles of integrated water resources management as defined in this paper. The active participation of stakeholders in model development increases the trust in the model and enhances acceptance of its results. Some work in this area has been done by Vennix (1997), although not under the same name. Other recent applications of the IWRM principles are provided by work of Molina et al. (2009) and Koch and Grünewald (2007), among others.

The methodology developed in this paper provides the support for IWRM through system simulation. The emphasis is placed on explicit modeling and simulation of key characteristics of complex water resources systems including:

- Feedback based system structure,
- Integral representation of physical and socio-economic processes (and their linkages),
- Proper consideration of complex spatial and temporal scales, and
- Provision of support for multiple stakeholder participation and involvement.

The rest of this paper is organized as follows. Section 2 presents the methodology proposed to operationalize implementation of IWRM principles through simulation. The main advantage of the proposed methodology is in explicit modeling of feedback relationships between physical and socio-economic processes occurring within a watershed. Section 3 illustrates the methodology with a case study, and shows behavior of physical and socio-economic variables in response to different climate signals and watershed management strategies. Concluding remarks are given in Section 4.

2 Methodology

Integrated water resources management is rooted in the systems approach (Maass et al. 1962; Hufschmidt and Fiering 1966; Loucks et al. 1981; Loucks and van Beek 2005; Simonovic 2008), and affects many natural systems, from the water cycle to the productivity of natural and agricultural systems, and the abundance and survival of plant and animal species. Therefore, integrated water resources management is influencing human welfare through changes in supply of, and demand for water, food and energy, and impacts of water-caused disasters on loss of life and property damage. These effects on natural and human systems mean that the integrated water resources management is directly related to the sustainability of the current socio-economic and environmental systems.

Most of the existing water resources systems modeling approaches offer the best way to understanding the physical water system. They make clear that feedbacks exist both within system components—atmosphere, oceans, surface water, land surface, groundwater and biosphere—and between them. Recognition of the importance of feedbacks between separate water sectors has driven the development of complex simulation and optimization models. However, most of these models consider socio-economic processes as exogenous. From a scientific perspective, the dangers of a failure to represent the entire system are clear. Various water models show that the Earth-system functions as a whole, characterized by nonlinear behavior and feedback processes. Socio-economic systems exhibit complex behavior in the same way as physical systems. And yet, the most common approach to combining socio-economic and water systems involves applying projected long-term trends (socio-economic scenarios) as inputs in the physical water systems models.

In other words, the current approach to understanding connections between physical and socio-economic systems requires their artificial separation. Such an approach explicitly breaks critical feedback relationships that are the defining reach dynamic interactions (integrated system behavior) between the physical (water) and socio-economic processes within the water resources systems. By excluding the feedbacks that operate between physical and socio-economic systems, several assumptions are made about the predictability, nature, and independence of these systems (Simonovic and Davies 2006). It is assumed that: (a) the character of all interactions between the two systems can be predicted, despite their nonlinear nature, (b) the interconnections between the systems do not fundamentally determine the future state of the water resources (in other words, the interactions between these systems are largely irrelevant to the behavior of each), (c) the physical and socio-economic systems are essentially separate, so that feedbacks between the systems are external to both, and (d) the human impacts on the water resources are separate from natural internal physical processes.

Simply stated, natural and socio-economic systems exhibit complex, nonlinear behavior, and that each certainly affects the other, but each system is still essentially treated as independent. Feedback-free representations of water resources management problems are continually made in providing scientifically-sound projections to policy-makers, hoping that actions based on such information, or on collections of such information, will ensure future well-being. Another option is needed, both scientifically and politically. Because human welfare and ecological well-being are interdependent, and the concerns of both present and future generations are equally important, an approach based on explicit modeling of feedback relationships between the physical and socio-economic systems is developed in this paper using system dynamics simulation.

System dynamics is a perspective and set of conceptual tools that enable understanding the structure and dynamics of complex systems (Forrester 1961; Sterman 2000). It is also a rigorous modeling method that enables building formal computer simulations of complex systems. System dynamics is grounded in control theory of nonlinear dynamics (Forrester 1961). Over time, system dynamics has evolved into a powerful tool for analysis of complex social, economic, physical, chemical, biologic and ecologic systems. System dynamics is a simulation technique used to learn and generate understanding regarding how systems change and adapt with time. One of its main premises is that system structure (represented through feedback) determines system behavior. System dynamics simulation therefore provides means by which the behavior of the system is linked to its underlying structure. It also relies on understanding complex inter-relationships existing between different system components, and recognizes that these relationships in turn regulate behavior. Advances made during the last decade in computer software provide considerable simplification in the development of system dynamics simulation models. Software tools like STELLA (High Performance Systems 1992), DYNAMO (Lyneis et al. 1994), VENSIM (Ventana 1996) and POWERSIM (Powersim Corporation 1996), use the principles of object-oriented programming for the development of system dynamics simulation programs. They provide a set of graphical objects with their mathematical functions for easy representation of the system structure and the development of computer code. Simulation models can be easily and quickly developed using these software tools. The resulting models are easy to modify, easy to understand, and present results clearly to a wide audience of users. They are able to address water management problems with highly nonlinear relationships.

Classical simulation as a system approach has a long tradition in water resources management (Simonovic 2008). Simulation models describe how a system operates, and are used to predict what changes will result from a specific course of action. Such models are sometimes referred to as cause-and-effect models. They describe the state of the system in response to various inputs, but give no direct measure of what decisions should be taken to improve the performance of the system. The essence of simulation is modeling and experimentation. Simulation does not directly produce the answer to a given problem.

Classical simulation includes a wide variety of procedures. In order to choose among them, and use them effectively, the potential user must know how they operate, how they can be expected to perform, and how this performance relates to the problem under investigation. The classical simulation procedure involves decomposition of the problem in order to aid in the system description. When the main elements of the system are identified, the proper mathematical description is provided for each. The procedure continues with computer coding of the mathematical description of the model. Each model parameter is then calibrated, and the model performance is verified using data that has not been seen during the calibration process. The completed model is then simulated using a set of input data. Detailed analysis of the resulting output is the final step in the simulation procedure.

System dynamics simulation offers many advantages over the classical simulation. (a) The power and simplicity of use of system dynamics simulation applications is not comparable with those developed in functional algorithmic computer languages. In a very short period of time, the users of the system dynamics simulation models can experience the main advantages of this approach. The power of simulation is the ease of constructing what if scenarios and tackling big, messy, real-world problems. (b) General principles upon which the system dynamics simulation tools are developed apply equally to social, natural, and physical systems. Using these tools in water resources systems management allows enhancement of models by explicitly adding social, economic, and ecological sectors into the model structure. (c) The structure–behavior link of system dynamics models allows the analyses of how structural changes in one part of a system might affect the behavior of the system as a whole. Perturbing a system allows one to test how the system will respond under different conditions. (d) For well defined systems with sufficient and good data the system dynamics simulation offers predictive functionality—determining the behavior of a system under a particular input conditions. However, ability to use system dynamics simulation models and extend water resources simulation models to include social, ecological, economic and other non-physical system components offers learning functionality—discovery of unexpected system behavior under a particular input conditions. This is one of the main advantages of system dynamics over traditional simulation. (e) In addition to relating system structure to system behavior and providing users with a tool for testing the sensitivity of a system to structural changes, system dynamics requires a person to take active part in the rigorous process of modeling system structure. Since the use of system dynamics software is very simple, modeling process can be directly done by the most experienced stakeholders. System dynamics simulation can very easily become a group exercise providing for active involvement of all stakeholders and an interactive platform for resolution of conflicts among them.

With systems dynamics modeling, it is possible to link physical, environmental and socio-economic aspects of water resources management in a single unified modeling approach. Flexibility of using scenarios, together with an ability to check sensitivity to different management strategies, offers added practical benefits (Simonovic and Li 2003). Recent times have seen system dynamics simulation applied to a variety of water resources management problems. Some of these include work of Maxwell and Costanza (1994), Simonovic and Fahmy (1999), Ford (1999), Saysel et al. (2002), Stave (2003), Fernández and Selma (2004), Ahmad and Simonovic (2004), Sehlke and Jacobson (2005), among others.

The modeling approach developed in this study allows internalization of socio-economic processes into water resources management problem description. It uses system dynamics simulation to model, in an integrated way, physical and socio-economic systems occurring in a watershed. A combined framework is depicted in general form by the following system of equations:

$$dx/dt = a(x, y, t) \tag{1}$$

$$dy/dt = b(y, x, t) \tag{2}$$

describing dynamics of the general water resources management problem. Equation 1 represents a system of generic equations describing physical processes (hydrologic, hydraulic, water quality, sediment, erosion, etc), while Eq. 2 shows the general form of the socio-economic model component. The state variables x and y describing the problem appear in both equations, indicating that physical and socio-economic variables of the problem are explicitly linked. Vectors a and b represent relationships which describe the system structure, while the variable t denotes time.

2.1 Integrated Simulation Example

A simple example problem (Fig. 1) is formulated here to assist the introduction of the proposed methodology . Consider a flood protection of a small community under high development pressures located near a reservoir. The physical process selected for the illustration of general relationship 1 is the process of reservoir flood attenuation (Chow 1964), described using the following differential equation:

$$dS/dt = I - O \quad S(t_0) = S_0 \tag{3}$$

where S is the reservoir storage (m^3), and I and O represent inflow and outflow vectors (m^3/s), respectively. The initial reservoir storage is specified as S_0. In

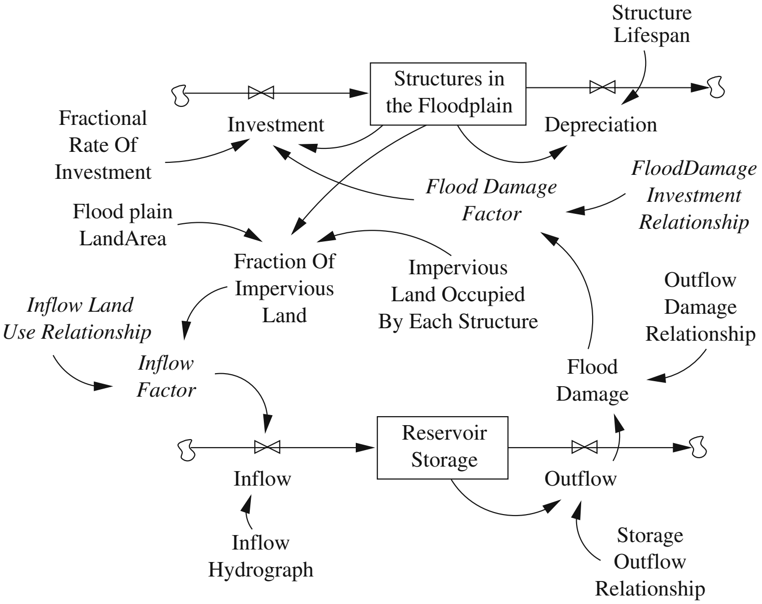


Fig. 1 Example problem

reservoir flood attenuation the outflow can be computed using the storage outflow relationship, represented by h:

$$O = h(S) \tag{4}$$

The relationship h can be developed by hydraulic simulation of steady state water surface profiles calculation (Hoggan 1996). As an alternative, function h can also be formulated from detailed reservoir operating rules employed by the agency responsible for its operation. Next, assume that the inflow hydrograph is known I_k(t) [m^3/s], and is obtained from a detailed hydrologic analysis, modulated (i.e., increased/decreased) by an inflow factor ${}^{i}f[-]$, described later:

$$I = I_h(t) \cdot i_f \tag{5}$$

The quantification of flooding is done using a function that relates outflow to flood damage, denoted by F_D [\$]. An assumption is made that flood damage (both up and downstream) is quantified by using the reservoir outflow. The function g combines the two step process where the reservoir outflow is converted to water elevation, which is combined with stage-damage relationship to estimate flood damage:

$$F_D = g(O) \tag{6}$$

The socio-economic process selected to illustrate the relationship 2 in this example describes the dynamics of floodplain development measured by the number of structures in the floodplain, F_S [units]. This is assumed to be an aggregate measure of floodplain development, representing the change of land use and replacement of natural vegetation with residential and commerical land use. The differential equation representing the land development dynamics is postulated as:

$$dF_S/dt = I_V - D_P \quad F_S(t_0) = F_{S0} \tag{7}$$

where I_V represents the rate of investment and D_P the rate of depreciation of structures located in the floodplain, both in (units/year). F_{S0} (units) is the initial number of structures. To determine the investment rate, the following relationship is used:

$$I_V = d_f \cdot p \cdot F_S \tag{8}$$

where p is constant representing normal rate of investment, in (1/year) and d_f is a flood damage factor (−), defined by the following relationship:

$$d_f = m(F_D) \tag{9}$$

where the function m relates flood damage and effect of investment to future development. The value d_f greater than unity implies that investment is favourable, while values less than unity discourage further investment. The structures in the floodplain depreciate according to:

$$D_P = F_S/k \tag{10}$$

where k represents an aggregate lifespan of structures in the floodplain [yrs]. Based on the number of structures in the floodplain F_S, an average impervious land area occupied by each structure q (km^2/unit), and the total floodplain area A (km^2), a fraction of urbanized land area f_u (−) is computed as:

$$f_u = qF_S/A \tag{11}$$

Lastly, based on the fraction of urbanized land area f_u, a relationship can be formulated to determine the impact of urbanization on the reservoir inflow factor, $^i f$:

$$i_f = n(f_u) \tag{12}$$

The schematic of the example is shown in Fig. 1. The mathematical presentation of the example can be rewritten in terms of state variables alone:

$$dS/dt = I_h(t) \cdot n(qF_S/A) - h(O) \tag{13}$$

$$dF_S/dt = m\left[g(O)\right] \cdot p \cdot F_S - F_S/k \tag{14}$$

The practical implementation of the outlined methodology requires explicit description of the relationships between physical and soci-economic systems occuring within the watershed. In the previous example, they are captured through relationships n and m.

The relationship n can be obtained with the assistance of the hydrologic modeling tools that can simulate the reservoir inflow response for a wide range of land use scenarios. The relationship m can be obtained through economic simulations that will relate the flood damage to the level of invetsment in the floodplain development. Both sets of simulations will be driven by the existing conditions that determine the range of feasible values for the functional relationships n and m. The process of obtaining realistic relationships would benefit from the active participation of all stakeholders.

The innovative aspect of the presented methodology is explicit integration of the socio-economic characteristics of the watershed with the physical processes of importance for efficient water resources decision making. System dynamics simulation offers numerous advantages for practical implementation of the methodology. Compatibility of the system dynamics simulation with the main principles of integrated water resources management is represented: (1) through the support for modeling physical and socio-economic processes using the same modeling tool, (2) through easy capturing and modifying system structure with the help of system dynamics computer tools that are proven to support modeling with participation of multiple participants, (3) through explicit linking of water resources system structure to system behaviour, (4) through easy use of system dynamics simulation models for exprimentation with various system design options, system operational strategies and policy decisions, (5) through the easy communication of system dynamics simulation results to the widest range of stakeholders with diversity of backgrounds, and (6) through learning from system dynamics simulation that guides the iterative process of adaptive management through investigation of various scenarios and sensitivity analyses of system behaviour to model structure, various inputs and alternative representations of internal relationships.

3 The Upper Thames Watershed Case Study

The system dynamics simulation methodology for integrated water resources management is *illustrated* in this section using the Upper Thames Watershed case study. An integrated system dynamics simulation model of the Upper Thames Watershed is developed that explicitly couples detailed physical processes (captured with a continuous hydrologic model) with the socio-economic characteristics of the watershed using multiple feedback relationships. The main objectives of the model development were: (a) to illustrate how the principles of integrated water resources management can be made operational on the watershed scale, (b) to introduce the methodology to the local water managers—the Upper Thames River Conservation Authority; and (c) to illustrate the use of model in investigating the changes in magnitude, frequency, timing and variability of hydrologic extremes in response to changed climatic conditions; and (d) to illustrate the use of model in the investigation of socio-economic response to alternative watershed management policies.

The case study area of the Upper Thames River watershed is located in southwestern Ontario, Canada. The majority of the watershed is covered with agricultural land (80%), with forest cover and urban uses taking about 10% each (total watershed area is 3,500 km^2). The population of the watershed is about 420,000, of which 350,000 are residents of the City of London, the largest urban center in the basin. The length of the Thames River is 273 km; its annual discharge is 35.9 m^3/s. The Upper Thames watershed receives 1,000 mm of annual precipitation, 60% of which is lost through evaporation and/or evapotranspiration, stored in ponds and wetlands, and/or recharged as ground water (Wilcox et al. 1998). The slope of the Thames River is 1.9 m/km for most of its upper reaches, while its lower reaches are much flatter with a slope of less than 0.2 m/km.

Growing development pressures of both, urban and rural communities within the Upper Thames watershed, coupled with changing climate have a potential to fundamentally alter both the physical and socio-economic characteristics of the basin. A changed climate signal may shift the magnitude, frequency of occurrence, timing and variability of extreme hydrologic events (such as floods and droughts), which may force watershed managers to adapt regulations, and management strategies to changing conditions. In particular, the water management infrastructure in the Upper Thames watershed (dams, dykes, as well as numerous sewer and drainage systems) may need to be retrofitted and/or completely replaced, as a result of their age and changing conditions. This can have significant socio-economic impact on the region which is currently experiencing intensive development. The main trend observed in the recent past (Nirupama and Simonovic 2007) is the conversion of the forested land into agricultural land and the agricultural land into industrial, institutional and residential land uses. Strong industrial and economic base together with closeness to major urban and industrial centers of Ontario are currently fuelling a high rate of development. Over last three decades (1971 to 2001) the percent of urban land area surrounding the City of London has increased from 10% to 22% (Nirupama and Simonovic 2007).

3.1 Integrated System Dynamics Simulation Model of the Upper Thames Watershed

The integrated water resources management model developed in this work contains two major components describing detailed hydrologic (i.e., physical) and socio-economic processes operating in the Upper Thames watershed. The main components of the Upper Thames system dynamics simulation model are presented in the following sections. The illustrative nature of the modeling effort imposed a limitation on the use of existing physical and socio-economic data in the watershed. Collection of new data was not possible in this study.

3.1.1 Continuous Hydrologic Model Component

The continuous hydrologic component of the Upper Thames system dynamics simulation model uses the computational engine of the model developed by Leavesley et al. (1983), later modified by Bennett (1998) and USACE (2000), currently known as HEC-HMS. Previous hydrologic studies (Cunderlik and Simonovic 2005, 2007) have applied this model to the Upper Thames watershed.

The physical processes considered within the model are captured by the continuous hydrologic model component shown in Fig. 2. Each box in the figure represents a module that mathematically describes one physical process. Precipitation and temperature (obtained from an external weather generator model, described later) are used as inputs into a snow module, where adjustments are made to account for both solid and liquid precipitation. The output of the snow module is adjusted precipitation, used for the computation of losses. The losses module captures the movement of moisture through various conceptual reservoirs within the catchment, such as canopy, surface, soil, and ground water. One of its outputs is evapotranspiration, or moisture that evaporates from the canopy, surface depressions, and/or the soil. Other outputs include baseflow (or flow being returned to the stream from ground water), surface excess (portion of the flow that does not infiltrate into the soil), and

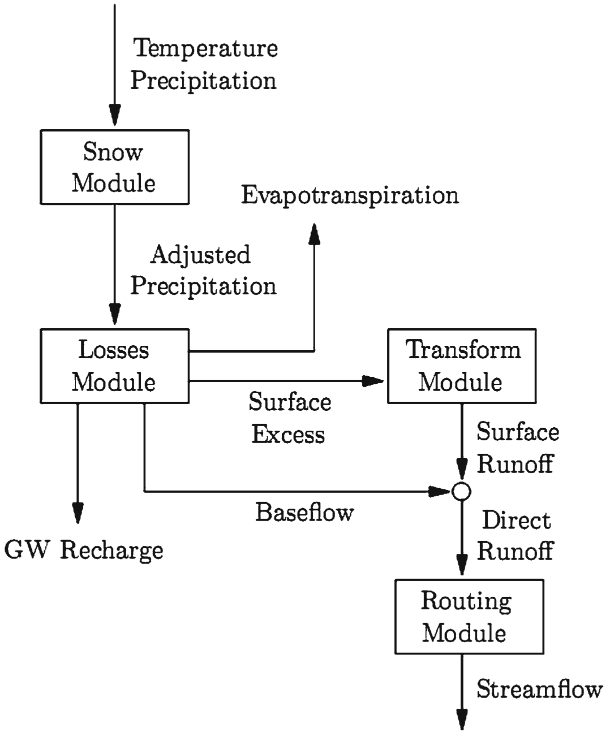


Fig. 2 Hydrologic component of the Upper Thames system dynamics simulation model

ground water recharge (the flow that enters deep aquifers and does not return to the stream). The surface excess is used by a transform module and converted into direct runoff using a unit hydrograph. The output of the transform module is surface runoff, which is combined with baseflow to produce direct runoff. Direct runoff is used as input into a routing module, which eventually produces streamflow.

The most complicated part of the hydrologic model component is the losses module (Fig. 3), with the following set of differential equations representing the dynamics of canopy A, surface B, soil C, and top D and bottom E ground water layers, all in (mm):

$$dA/dt = P(t) - ET_A(t) \tag{15}$$

$$dB/dt = P_B(t) - ET_B(t) - S_E(t) \tag{16}$$

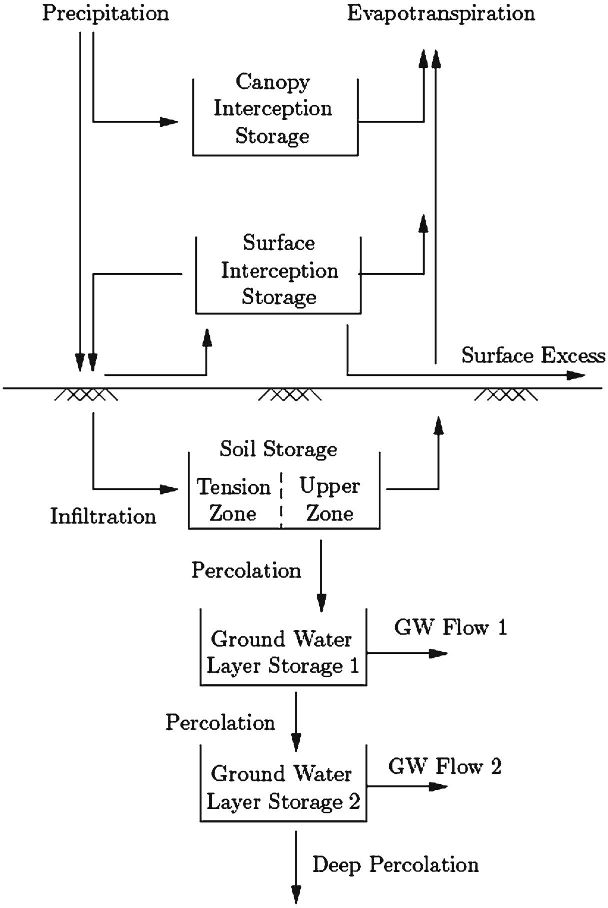
$$dC/dt = I(t) - R_C(t) - ET_C(t) \tag{17}$$

$$dD/dt = R_C(t) - GWF_D(t) - R_D(t) \tag{18}$$

$$dE/dt = R_D(t) - GWF_E(t) - R_E(t) \tag{19}$$

where $P(t)$ represents precipitation, $ET(t)$ evapotranspiration (from canopy ET_A, surface ET_B and soil ET_C storage layers), $P_B(t)$ precipitation going beyond the canopy, $S_E(t)$ surface excess, $I(t)$ infiltration, $R(t)$ percolation (from/to soil R_C,

Fig. 3 Soil moisture accounting losses module



ground water 1 R_D and 2 R_E layers), and $GWF(t)$ lateral ground water flow (from layers 1 GWF_D and 2 GWF_E), all in [mm/hr].

The equation for infiltration, presented here for illustration purposes, takes the following form:

$$I(t) = min\left[I_m - \frac{C(t)}{C_m} I_m, P_B(t) + \frac{B(t)}{dt}\right] \tag{20}$$

where I_m represents maximum soil infiltration (mm/hr), and C_m maximum soil storage (mm). Equation 20 calculates the infiltration rate as the minimum of potential infiltration (first term), and water available for infiltration (second term); that way, infiltration can only occur if water is available, and if soil storage is not completely saturated.

The Upper Thames watershed hydrologic model component consists of thirty two sub-catchments, twenty one river reaches, and three major reservoirs. The computation is performed on a six hour time step. The input data (precipitation and temperature) is obtained from an externally built weather generator model (Sharif and Burn 2004, 2006a) operating on a daily time step. The weather generator uses both locally observed climate data, as well as outputs from the global circulation models to synthetically generate an arbitrary long climate information for the region. Precipitation and temperature data is provided for one hundred years, the time horizon of the integrated watershed systems dynamics simulation model.

3.1.2 Socio-Economic Model Component

The socio-economic model component structure is built on the basis of available socio-economic data within the watershed. The component consists of three spatial units, representing the main socio-economic characteristics of three counties located in the watershed: Oxford, Perth and Middlesex. Separate model sectors are built to take into account the region's economic output from industrial and agricultural activities. Each spatial unit contains model sectors describing urban and rural population, urban and rural business activities, housing, and land use. The socio-economic model component structure is shown in Fig. 4, where each major sector is depicted by a rectangle and linked to other sectors using variables shown adjacent to the solid lines.

The structure of the population sector is further divided into urban and rural sectors. These sectors contain information that generates dynamics based on current population, birth and death rates, as well as in and out migration. The population sector depends on the availability of water, jobs and housing. Each of these three variables places a limit on the future growth and expansion of an area. For example, the area can not experience population growth if sufficient water supply, jobs or housing are not available.

The business activity sector of the model is also divided into urban and rural categories. Each sub-sector captures dynamics of business and farm activities, respectively, through the investment and depreciation of capital. The business activities depend on a labor force provided by the population sector (only a fraction of the total

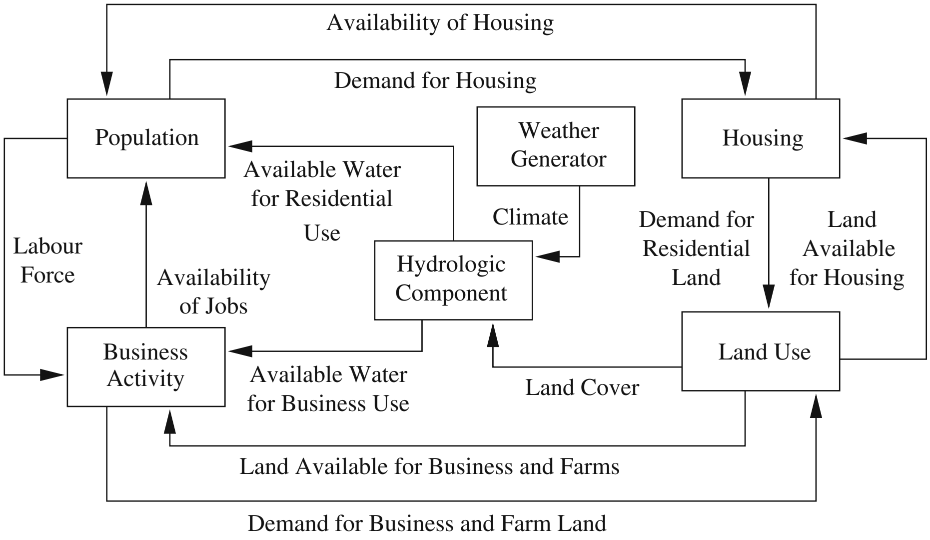


Fig. 4 Socio-economic component of the Upper Thames system dynamics simulation model

population represents labor force), water availability provided by the hydrologic model component, as well as availability of land allocated for business and farm use, obtained from the land use sector. The economic activities are regulated by: available land; labor force; and available water supply. Therefore, each has the potential (independently and in combination) to affect the regional economic growth. Population and business activity sectors are extensions of the system dynamics model originally developed by Alfeld and Graham (1976). The present model structure, however, is adapted to the characteristics of the Upper Thames watershed and available socio-economic data.

The housing sector receives information from the population sector (through demand for housing) and land use sector (through land available for development), and thus simulates dynamics of the housing industry. Housing sector is modeled only in urban settings, as farm units in rural sector are defined to represent places where rural families both, live and work.

The land use sector is the most detailed part of the socio-economic model component as it describes dynamics of change in terrestrial land cover—defined in this study as forest, agricultural, business and residential land use types. The land use sector's structure is based on the model presented in Schroeder et al. (1975). The main dynamics captured in this sector describe the change of land use in order to meet the needs of the residential and business communities. The analyses of the available data in the Upper Thames watershed strongly support the following dynamic hypothesis: with business and population growth the forest land is converted into agricultural land, while agricultural land is used for business and/or residential rezoning. Examination of remotely sensed watershed land use data for the period between 1974 and 2000 provides the support for the above hypothesis (Nirupama and Simonovic 2007; Table 1, page 32). A competition structure between residential and business land development is established to cover cases when further conversion of agricultural land is not allowed and/or not possible (as in fully urbanized areas). In such cases, conversion between residential and business lands alternates.

The final model structure is established using the following available data: (a) population, housing, business activities and agricultural production (STATCAN 2001), (b) land use change (Nirupama and Simonovic 2007; Wilcox et al. 1998), and (c) water availability, water use and water demand (Brown 2001; Kell 2004; Merry 2003; OLWR 2003). The state variables of the socio-economic model component are shown in Fig. 5, and are mathematically described with the following set of differential equations:

$$dBS/dt = BC(t) - BD(t) \tag{21}$$

$$dUH/dt = UHC(t) - UHD(t) \tag{22}$$

$$dUP/dt = UIM(t) + UB(t) - UOM(t) - UD(t) \tag{23}$$

$$dFU/dt = FUI(t) - FUD(t) \tag{24}$$

$$dRP/dt = RIM(t) + RB(t) - ROM(t) - RD(t) \tag{25}$$

$$dFC/dt = -FAR(t) \tag{26}$$

$$dAL/dt = FAR(t) - ABR(t) - ARR(t) \tag{27}$$

$$dRL/dt = ARR(t) - BLR(t) - RLR(t) \tag{28}$$

$$dBL/dt = RLR(t) + ABR(t) - BLR(t) \tag{29}$$

where *BS* represents business structures [business units], *UH* urban houses [housing units], *UP* urban population [people], *FU* farm units [farm units], *RP* rural population [people], *FC* forest cover [km^2], *AL* agricultural land [km^2], *RL* residential land [km^2], and *BL* business land [km^2]. State variables are represented graphically using boxes, while flows are shown by solid lines with valves. Definitions of flow variables can be looked up from Fig. 5, from which short forms are obtained for use in the above equations (for example *RIM* is used for Rural In Migration in Eq. 25). The units of flow variables are those of their respective state variables, divided by time. The socio-economic component of the model operates on a monthly time step. The final structure of the socio-economic model was presented and discussed with the Upper Thames watershed stakeholders (Mortsch et al. 2005).

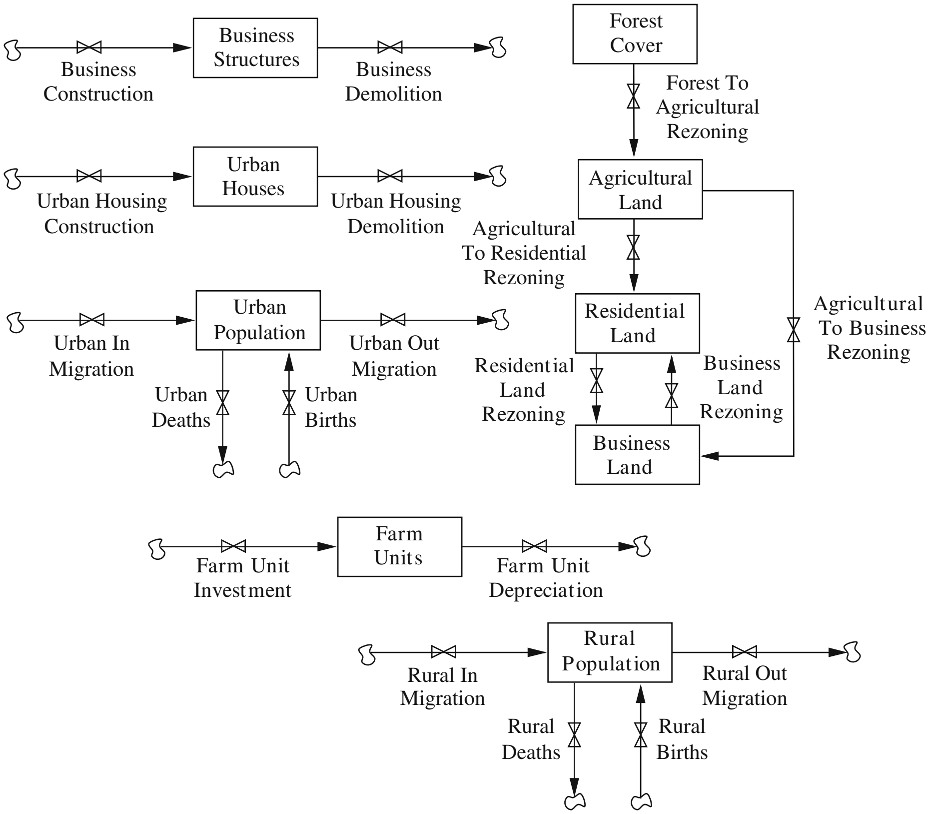


Fig. 5 State variables of the socio-economic model component

A definition of a structure (business, farm or house) embodies occupied space. Space required for a structure (whether part of an office, warehouse, or a farm) requires a considerable investment of capital. In a viable business, an initial investment of capital usually generates more invested capital, thus potentially growing a business. With this definition, a large corporation (such as a manufacturing company or a farm) employing a large number of people and occupying a sizable land area is counted as a number of structures (exactly how many depends on number of employees, and land area occupied). Growth of business activity, as it is defined here, takes place when area creates a demand for investment and construction of new structures. Similarly, an increase in the rate of demolition and depreciation of structures creates an economic down turn by eliminating places of employment, therefore lowering the number of jobs in the area. Under favourable economic conditions, the number of structures will tend to rise even though the available land for new structures may be shrinking. It is possible for the number of structures (i.e., businesses, farms, houses) to grow, even if the available land for new structures may be shrinking. This assumption implies that structures will remain economically viable under higher densities (i.e., a farm structure may operate more efficiently while occupying smaller land area).

3.1.3 Feedback Coupling of Hydrologic and Socio-Economic Model Components

Examples of integration of a well known and widely accepted hydrologic models with socio-economic models using system dynamics simulation are not available in the literature. All examples of system dynamics simulation models adopt a simplified framework for describing physical processes, and thus lose the rigor of models widely accepted in the hydrologic practice. On the other side, the trust of water resources professionals in system dynamics simulation models is not established yet to the full extent. Very common criticism is that the system dynamics simulation models are using socio-economic variables and relationships that are difficult to quantify.

The response to the above criticism is addressed by noting that persons involved in the study of physical, economic, and/or social systems adopt different modeling paradigms. This leads to different groups to apply different criteria for data selection, model building and performance evaluation. Using criteria of one paradigm and applying it to the models produced by another may not be entirely appropriate. For example, in modelling approaches emphasizing precise, short term predictions of state variables (i.e., flood volumes after a storm; performance of the economy after a recession) it is necessary to adapt and accept the main focus of system dynamics simulation—where the discovery of mechanisms responsible for behaviour of complex systems is of interest (how is precipitation transformed into runoff; what are the main economic drivers that affect the performance of economy).

The system dynamics simulation method emphasizes discovery of relationships within the system structure (represented by feedback loops) that are responsible for the observed patterns of behavior. Revealing logical implications of discovered (or assumed) relationships, as well as formulating alternate simulation options, are at the core of system dynamics modeling and are deemed more valuable than precise, short term predictions. Lack of data is acknowledged as a serious limitation in building models that require integration of physical and socio-economic processes. Proponents of system dynamics simulation recognize this problem, but still believe that it is better to build models based on assumptions (which can be questioned, tested for sensitivity, and changed once additional data becomes available), than to abandon modeling of complex integrated systems. Meadows et al. (1982) claim that: (a) omitting elements (because of lack of knowledge or available data) implies they are not important, which is not true, (b) providing correct signs to feedback loops is ultimately more important than including more accuracy in any relationship or parameter value, because the goal of the analysis is to obtain dynamic character of the system behavior, not to produce precise predictions, and (c) "if one believes an unmeasured psychological, environmental or political factor is important in a system, one should state this belief explicitly and precisely, to encourage observation or experimentation that will increase knowledge of this factor" (Meadows et al. 1982, p. 116).

The model presented here links the detailed description of hydrologic processes with a larger scale socio-economic processes, and therefore provides support for practical implementation of integrated water resources management principles at the watershed scale.

The links between hydrologic and socio-economic model components used in this work are shown in Fig. 6 using a causal loop diagram; they are also listed in Table 1. Causal loop diagram shows a systemic structure of the model by emphasizing feedback loops (Sterman 2000). Variables in a causal loop diagram are linked via arrows with polarity signs (positive or negative) to indicate a direction of change in causal relationships. For example, a positive link means that both variables connected with the arrow change in the same direction (i.e., an increase (decrease) in one produces an increase (decrease) in the other). Similarly, a negative link implies a change in the opposite direction (i.e., an increase (decrease) in one produces a decrease (increase) in the other).

The left part of the Fig. 6 shows the feedback structure of the continuous hydrologic model component, while the right portion points to a select few variables of the socio-economic model component. The hydrologic component of the model provides precipitation and temperature (originally obtained from the weather generator model), alongside with ground water recharge and direct runoff to the socio-economic model component. Temperature, precipitation and direct runoff are used to determine a level of drought (link 1 in Table 1) based on local guidelines (OLWR 2003). The level of drought is assumed to have an influence on total water use. An assumption is made that, as drought conditions deteriorate, residential and business water use decreases basin wide. Using the local drought guidelines and the input obtained from stakeholders (Mortsch et al. 2005), a feedback relationship is derived in the form shown on the left side of Fig. 7.

A feedback relationship between direct runoff and the amount of flood damage (identified as link 2 in Table 1) is also used in the model. It quantifies the amount of flood damage, and its influence on further development. The model takes direct runoff from the hydrologic component, for each stream gauge in the watershed, and converts it to water elevation in the first step. After this, the model takes water elevation and estimates the flood damage based on the stage-damage function obtained from the Upper Thames River Conservation Authority (agency responsible for the management of the basin). The amount of flood damage is then related to future investment in watershed development and population growth. An assumption is made that as flood damage increases, so does the level of investment. This relationship captures the assumption that after flooding, actions are taken to rebuilt,

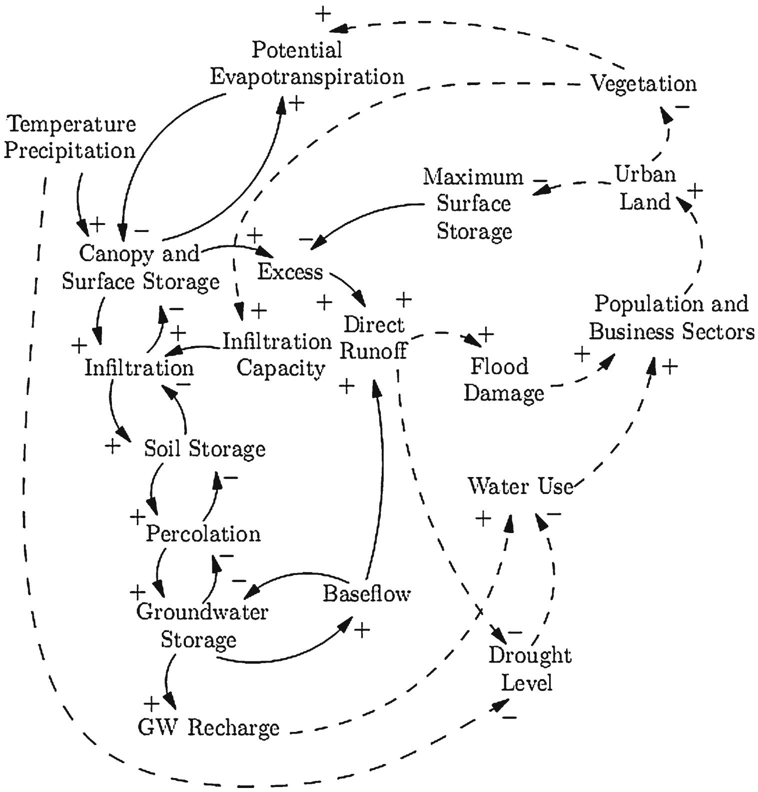


Fig. 6 Causal diagram of the Upper Thames system dynamics simulation model

repair and/or replace the damaged assets. Of course, alternate formulation can easily be tested, simply by changing the character of this relationship.

The feedback link between ground water recharge (i.e., deep percolation in Fig. 3) and water availability (identified as link 3 in Table 1) quantifies the assumption which states that an amount of ground water recharge into the aquifer represents the maximum allowable ground water use in the watershed. Further, the ground water recharge is assumed to represent the available water (for counties that rely on ground

Table 1 Feedbacks of the Upper Thames system dynamics simulation model

Number	Physical→socio-economic
1	(temperature, precipitation and direct runoff)→ drought level
2	Direct runoff→flood damage
3	Ground water recharge→water availability (which places limit on water use)
4	Urban land→maximum surface storage
5	Vegetation→potential evapotranspiration
6	Vegetation→soil infiltration capacity

water). Current management practice of the Upper Thames River Conservation Authority prevents the use of water from the aquifers that exceeds the ground water recharge.

The hydrologic model component receives input from the socio-economic model component. The main input is from the land use sector: vegetation and urban land uses. One feedback relationship associates the amount of urban land to the maximum surface storage of the hydrologic component (link 4 in Table 1). As the urban land use increases, the surface storage capacity decreases (shown on the right side of Fig. 7) and the surface excess runoff increases. Larger runoff reduces the infiltration of water into the soil. This reduces the ground water recharge over the long term, therefore decreasing the available water for future socio-economic development.

A similar feedback relationship is formulated between the vegetation land cover in the watershed (forest and agricultural land) and the potential evapotranspiration in the hydrologic model component (link 5 in Table 1). As vegetation cover increases the total amount of water released into the atmosphere from vegetation (i.e., evapotranspiration) also increases. The same reasoning applies in the opposite direction—if vegetation cover decreases, so does the amount of potential evapotranspiration.

The last feedback relation is between vegetation cover and the infiltration capacity of the soil (link 6 in Table 1). The infiltration capacity of the soil depends on many factors, some of which are the soil type, moisture content, organic matter, vegetative cover, and season (Linsley et al. 1958). The soil type is by far the most important regulator of infiltration capacity, as soil porosity modulates the resistance of flow. More specifically, increasing soil porosity increases infiltration capacity (for example, infiltration is greater in sandy soil than in the soil containing large amounts of clay and silt). Vegetation also increases infiltration capacity of the soil, as it tends to increase soil porosity. Furthermore, Linsley et al. (1958) claim that: "The effect of vegetation on infiltration capacity is difficult to determine, for it also influences [canopy] interception. Nevertheless, vegetation cover does increase infiltration as compared with barren soil because: (1) it retards surface flow, giving the water additional time to enter the soil, (2) the root system make the soil more pervious, and (3) the foliage shields the soil from raindrop impact and reduces packing of the surface soil" (p. 166).

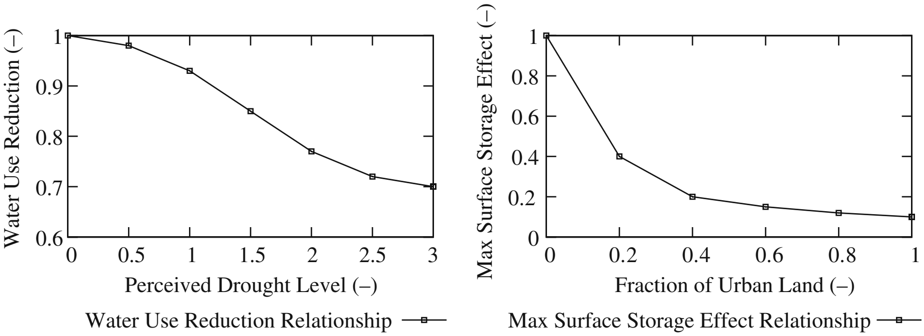


Fig. 7 Selected feedback link relationships of the Upper Thames system dynamics simulation model

The relationship used in the model shows that as vegetation cover increases, so does the maximum soil infiltration. However, the reverse is also true: as the vegetation cover decreases, the infiltration capacity also decreases, thus increasing surface runoff and even further lowering ground water recharge.

Functional forms of two feedback links are illustrated in Fig. 7, and show relationships between a perceived drought level (measured on a scale between zero and three) and reduction of water use, as well as the relationship between the fraction of urban land and its effect on maximum surface storage.

The hydrologic component implemented as part of the integrated model consists of the continuous hydrologic model that operates with a 6-h time step, while the socio-economic component operates with a monthly time interval. The two model components are dynamically coupled (i.e., one influences and is influenced by the other during simulation) within the integrated model. Since mechanisms required to achieve dynamic coupling of this sort currently do not exist within the of-the-shelf hydrologic or system dynamics software packages, great effort was invested in building the component model using the Java object-oriented programming language. Even though schematic diagrams presented in the paper resemble existing software packages, the engine of the integrated model was completely built from scratch. The interested reader is encouraged to look at the reports by Prodanovic and Simonovic (2007) and Prodanovic (2008), where additional information on the modeling effort is provided.

3.2 Model Simulations

A simulation scenario in this work is defined as a combination of climatic input (obtained from the external weather generator and used to drive the hydrologic model component) and a particular management strategy (status quo, reduction of water use, changes to rate of development, etc). In this way, impacts of alternative climatic conditions may be evaluated in combination with different socio-economic policies and management strategies. The simulation scenarios used here have been formulated using available data and discussions with a selected number of stakeholders (Mortsch et al. 2005) to illustrate the benefits of integrated system dynamics simulation modeling. They do not capture the broad scope of the Upper Thames River basin management.

3.2.1 Climatic Input

Three different climate scenarios are used in this study—the historic (or base case), and two scenarios based on the predictions of global circulation models. The historic scenario is obtained by using the weather generator with the observed record of regional climatic conditions for three variables (precipitation, maximum and minimum temperature) for the period between 1964 and 2001. Other two scenarios use the historic data, as well as information from the latest global circulation model simulations. In these two scenarios, the historic data set is perturbed and shuffled (in addition to using information provided by the global circulation model outputs), thus creating meteorological conditions not observed in the past. The scenarios considered in this study (historic, wet and dry) are based on the work of Sharif and Burn (2004, 2006a, b).

Wet and dry climate scenarios use the information provided by CCSRNIES and CSIROM2kb global circulation models for the grid cell where the Upper Thames watershed is located. The wet climate scenario provides a plausible future with more intense rainfall over the next century, while the dry climate scenario illustrates the future with more pronounced dry spells and droughts. The wet scenario has been specifically designed to test the basin's response to increasing incidents of flooding, while the dry scenario is used in examination of drought conditions. By having a historically similar long term record of climate information, together with wet and dry climate scenarios, an attempt is made to capture a range of possible future climate conditions of importance to the Upper Thames watershed. More details on the climate scenarios are provided in Prodanovic (2008).

3.2.2 Socio-Economic Policy Scenarios

A number of water management scenarios based on different socio-economic conditions are considered in this work, of which three are briefly described next. The first scenario is referred to as the base case, and is considered to illustrate the current watershed management practice.

Most of the data used to initialize the socio-economic component of the integrated system dynamics simulation model comes from census data published by Statistics Canada Community Profiles (STATCAN 2001). The socio-economic characteristics of the region are available for a larger aggregated areas (i.e., the spatial units representing counties in the watershed). Three spatial units are used in the model. It should be noted that the hydrologic model component uses 32 subcatchments to describe hydrologic processes in the watershed. State variables of the socio-economic model component are therefore initialized with 2001 census values for population, housing, business, and number of farm units. State variables in the land use sector (forest, agricultural, residential and business land use types) are initialized with values obtained from watershed report cards (UTRCA 2001). Water use data (for ground and surface water) is available for each county, for residential, industrial/commercial water, as well as water used for livestock and irrigation (Brown 2001; Kell 2004; Merry 2003). Water supply data is obtained from local municipalities in the basin. Initial rates of population growth, business and farm investments and land use type conversion are obtained from the historic census data.

A base case scenario is used for comparison of outcomes with other management scenarios. In system dynamics simulation modeling of physical and social systems the goal is usually to estimate behavioral implications of assumptions, decision rules, strategies and policies embedded in the model. In performing scenario analyses, evolution of alternate (and sometimes very different) management polices can be acquired. The utility of a simulation model is therefore derived from testing its different assumptions, policies and management strategies, and comparing such outcomes with a reference, or a base case.

In the base case scenario, economic growth and expansion is assumed to occur at rates similar to what has been historically observed. Given the current strength of the Canadian economy, rapid increase in population growth and immigration, together with wide availability of water, labor force, and land, is not an unreasonable assumption. As expansion of business investments continues, it is postulated that population will continue to grow. Rates of immigration (and possibly birth rates) are assumed to increase, mainly due to attractiveness of social and economic conditions.

During the period of growth, jobs are considered to be plentiful (and sometime may even exceed the actual labor force), thus attracting more people to the area. Due to such attractive economic conditions in both urban and rural sectors, the stock of housing must inevitably rise to be able to support such a rapid pace of growth. Additional stresses related to urbanization include conversion of agricultural land to residential and business uses. The study by Nirupama and Simonovic (2007) shows that some urban areas in the watershed have more than doubled in size during the past three decades. The stock of forested and agricultural lands may start to decline, as the urbanized landscape increases (businesses, shops, malls, parking lots, homes).

The second water management scenario—policy (a) scenario—is identical to the above base case scenario, and assumes that all area residents and businesses (in other words all users of ground and surface water) voluntarily agree to reduce their water use by 30% when compared to the base case. This scenario is aimed to illustrate the behavioral implication of a strict water conservation policy. Within the socio-economic model component, this scenario is set by initially reducing per capita water use rates of urban and rural population, as well as reducing business and farm water use by 30%. The authors are aware that more realistic approach will be based on the improvement in water use efficiency (production of the same economic output with less water). Since the purpose of the model is to illustrate the integrated approach, a simple form of the conservations scenario is sufficient. More detailed studies based on the extensive data collection can be used to develop more realistic conservation scenarios that can be tested using the model developed in this study.

The third water management scenario—policy (b) scenario—combines water use reduction of 30% with a land rezoning policy for forest and agricultural land conservation. The variables describing normal rates of conversion of agricultural land to business and residential uses are reduced by a factor of 10 when compared to the base case scenario. In this case conversion of agricultural land is still possible, although in a more restricted fashion. This scenario is developed to illustrate effects of controlled urbanization caused by favorable socio-economic conditions (abundant land, water, jobs, housing, etc.). Severe restrictions are thereby imposed on conversion of agricultural land to business and residential uses, and water use. Formulation of this scenario illustrates how a different policy option may influence overall behavior modes of the watershed model.

3.3 Simulation Results

The system dynamics simulation model of the Upper Thames watershed provides a variety of output results that are discussed here. The physical component of the model captures hydrologic features of the study area, and provides hydro-climatic information for every hydrographic element (creek/river) of the watershed at a daily time step.

The socio-economic component of the system dynamics simulation model provides the output (in aggregated form) for three spatial units/counties considered: Oxford, Perth and Middlesex. The hydrologic model component provides the information to the socio-economic component at critical locations only (locations near cities, and/or where the damage is most likely to occur). The socio-economic model component (through the distribution of land use in each county) changes the physical properties of each subcatchment within that county. The socio-economic component provides detailed information regarding urban and rural population, business and farm units, land availability and use, water availability and use, as well as numerous other factors affecting social and economic prosperity of each county in the watershed. Simulation time horizon is 100 years.

3.3.1 Hydrologic Output

The simulation output of the physical—hydrologic—model component is synthesized in Table 2 and Fig. 8. The results show relative changes in hydrologic extremes and provide additional insight in possible consequences resulting from changing hydro-climatic conditions. In analyzing change in peak flow magnitude, the flow with a return period of 100 years is selected as a reference indicator, and is obtained by fitting the output flow data for each location using Gumbel (top left plot in Fig. 8) and Log Pearson III statistical distribution (top right plot in Fig. 8). This indicator is selected as majority of water management structures (such as dams, levees, dykes and diversions) in the watershed are designed to withstand the impacts of 100 year events. The 100 year daily peak flow magnitude for the historic climate input at the Byron stream gauge in the City of London is 714 m^3/s, while under the wet climate scenario the flow of the same return period can increase to 885 m^3/s. This is a significant finding, signalling the need for possible revisions of existing flood management guidelines and municipal infrastructure design practices. Dry climatic input on the other hand shows an actual reduction of peak flow, with the magnitude of 602 m^3/s. The variation of flood flow (between 885 and 602 m^3/s) defines the range of climate change impact in the Upper Thames watershed. Obvious focus, in the case of floods is on the high value, while in the case of droughts on low values.

The timing and variability (Cunderlik and Burn 2006) of annual maximum daily peak flows is also affected by the changing climate, and are used to measure changes in the seasonality of flow. Timing is defined as an average day of year on which the annual extreme occurs, and takes values between 1 and 365 (366 for the leap years). Timing value of 50 therefore implies that an annual extreme occurs, on average, on the 50th day of the year. Note that in the calculation of timing the occurrence of the annual maximum flow is recorded and averaged for the entire period of simulated

Table 2 Comparisons of timing and variability of climate change impacts for the Byron stream gauge (Middlesex County)

Scenario	Daily max			Seven day min			Monthly min		
	MDF[a] (day)	R[b] (−)	$1Q_{100}$[c] (m^3/s)	MDD[a] (day)	R[b] (−)	$7Q_{20}$[c] (m^3/s)	MDD[a] (day)	R[b] (−)	$30Q_{20}$[c] (m^3/s)
Historic	36.90	0.56	714.01	213.07	0.69	1.61	217.55	0.73	3.37
Dry	20.68	0.63	601.71	214.94	0.68	1.56	216.83	0.72	3.31
Wet	55.16	0.51	885.21	220.94	0.61	1.85	232.64	0.64	4.10

[a] MDF (MDD) represents a mean day of occurrence of flood (drought) on a Julian calendar with values between 1 and 365 (366 for leap year)

[b] R depicts regularity of extreme flows, with values between 0 (completely irregular) and 1 (completely regular)

[c] $1Q_{100}$ = maximum annual daily flow with a return period of 100 years fitted with a Log Pearson III distribution; $7Q_{20}$ ($30Q_{20}$) = minimum annual 7 day (monthly) flow with a return period of 20 years fitted with a Weibull distribution

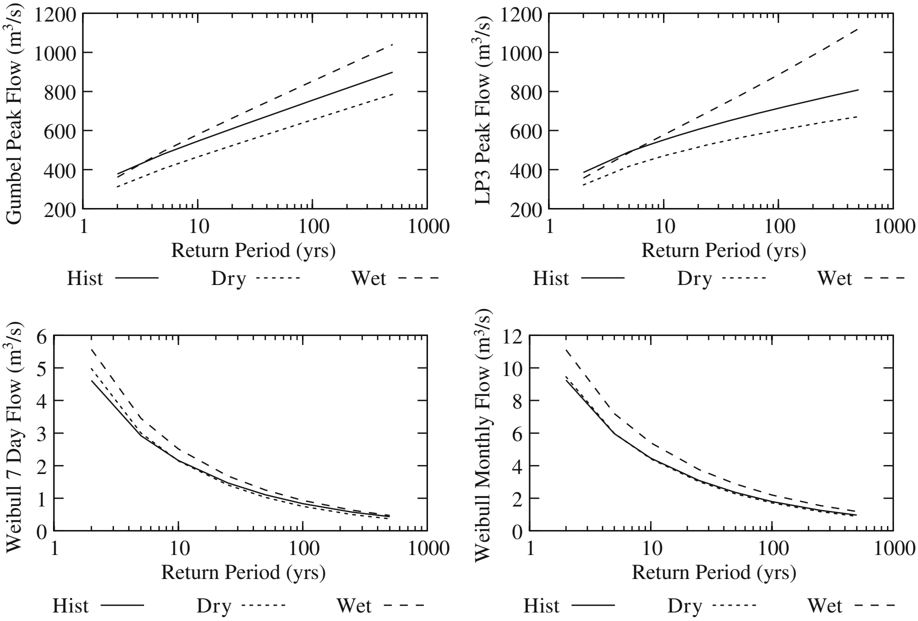


Fig. 8 Effect of changing climate on floods and droughts at the Byron stream gauge (Middlesex County)

record. Variability on the other hand, is defined as a measure of dispersion around the mean, and is measured as an index between zero (completely variable) and one (extreme always occurs on the same day of the year). For example, higher values of variability imply that an average day of occurrence (i.e., timing) of an extreme are tightly grouped around the mean, while low values suggest greater dispersion around the mean.

For the historic climate input, the mean day of flood occurs on the 37th day of the year with a variability index of 0.56 (Table 2), implying that floods are occurring in the spring from snowmelt, and later in the fall from intense precipitation. Under the changing climate scenarios, the mean annual daily peak flow occurs as late as the 55th day of the year (for the wet climate scenario), with variability comparable to the historic scenario. This implies that future flooding conditions are expected to be as variable as in the past, but may occur on average some 20 days later (i.e., floods from intense precipitation are expected to play more of a dominant role than in the past). The shift is attributed to higher peaks occuring in the summer months, thereby shifting the annual averaged timing index.

Note that timing and variability indicators presented here are based on critical annual values (for floods, peak daily flow each year is extracted and used in the calculation; for droughts, annual 7 day minimum and monthly flows are used). Based on this interpretation, critical annual flow values may occur during any season of the year. Some studies looking at impacts of timing and variability of floods due to snowmelt select critical spring peak values only. In this case however, critical peak values are selected regardless of the season.

Drought conditions are also analyzed under the the three climate scenarios. Hydrologic indicators are presented in Table 2 and Fig. 8. The magnitude indicator selected for the study of hydrologic drought conditions is the annual minimum 7 day flow with the return period of 20 years (i.e., $7Q_{20}$). This is the flow defined by Ontario's Ministry of Environment as a limiting condition for sewage treatment and wastewater disposal into a receiving water body. The $7Q_{20}$ flow is therefore used to measure the stream's ability to accept (and dilute) point source discharge like treated sewage effluent, and consequently represents stream's water quality (bottom left in Fig. 8). Monthly minimum flows of the same return period are shown here for completeness, as they might be useful in studying longer term trends (bottom right in Fig. 8).

The $7Q_{20}$ parameter for the Byron stream gauge (Middlesex County) is computed as 1.61 m^3/s for the historic climate scenario. Little variation of this parameter is observed under alternate climatic scenarios (Table 2 and Fig. 8) implying that low flow conditions are not expected to change significantly. Timing and variability of low flows are also not significantly impacted by the changes in climate, as annual minimum low flow is occurring on the 213th day of year (end of July and/or beginning of August) for the historic climate scenario, while the dry climate scenario (designed specifically to study impacts of drought) shows minimum annual low flow occurring on the 215th day. Variability indicator also shows a consistent trend, supporting the conclusion that large changes are not expected in timing of low flows.

Results obtained from model simulation suggest that droughts will be less frequent than those experienced in the past. For example, the flow of 1.61 m^3/s (the bottom left plot in Fig. 8) under historic climate scenario has the return period of about 20 years. Under the wet climate scenario, the same flow has a return period of 30 years, implying that such low flow is expected to occur (on average) less often.This means that the probability of observing an annual minimum 7 day flow of 1.61 m^3/s or less any given year is currently 0.05 (1 in 20), but may be as little as 0.03 (1 in 30) as a result of changed climate. Under the dry climate scenario there is no significant difference in return period.

Although the province of Ontario has a drought management framework that incorporates various long and short term measures, local and/or regional drought management plans are still missing. This is in part because negative drought related impacts in Middlesex County (and the Upper Thames watershed as a whole) are considered to be quite minor. Drought damage related studies in the basin are altogether lacking, in spite the fact that droughts can be severe and will remain that way under changed climate conditions.

3.3.2 Socio-Economic Output

By performing extensive model simulations and analyses, one conclusion is reached that warrants further discussion prior to addressing specific socio-economic model results. The variation in socio-economic scenarios (that illustrate potential watershed management strategies) produces more impact on the watershed than physical consequences of climate change alone. This conclusion is reached by performing the following simulations and analyses: (1) keeping the climate scenarios fixed while varying socio-economic scenarios, and (2) keeping the socio-economic scenarios fixed while changing the climatic scenarios. The first set of simulation results shows a larger variation in socio-economic behavior when compared to the results of the second set of simulations.

Simulation results of the strict water conservation—policy (a), and its comparison with the base case are shown in Figs. 9 and 10. The main state variables of the integrated system dynamics simulation model are presented (urban and rural population, businesses, farm units, agricultural and residential land), along with the key water supply/use variables (ground and surface water use, ground water recharge and the amount of surface water pumped from Lakes Erie and Huron). SW and GW in Fig. 10 stand for surface and ground water, respectively.

The resulting behavior seems at a first glance to be counter-intuitive. Immediately after the implementation of the strict conservation policy, total water use is indeed reduced. However, since the region in this case has a greater water availability (people and businesses are consuming less water), the water availability restriction on future growth is not as severe (more water is available). This converts into higher growth rates of the regional economy and population, thus resulting in more growth compared with the base case scenario. Eventually, the state variables equilibrate with higher levels of population, number of businesses, farm units and houses, thereby increasing the area's overall water use in comparison to the base case. What was thought to be a policy with aim to reduce the total water use, at the end accomplished the opposite.

The results that show the combined water conservation and restricted land development policy, policy (b), are shown in Figs. 11 and 12. A notable reduction is observed in the number of businesses over time, although the level of urban

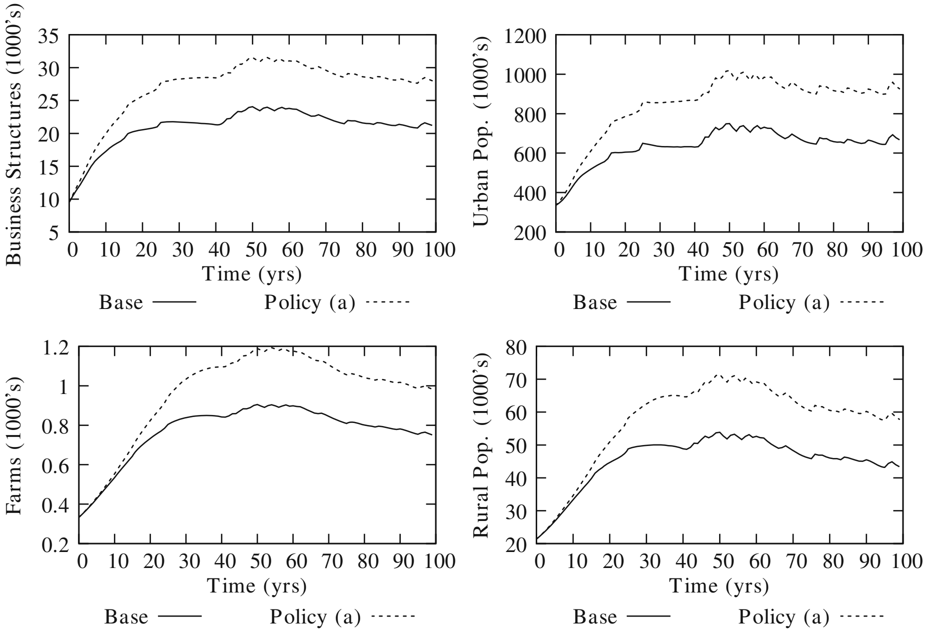


Fig. 9 The Middlesex County urban and rural conditions illustrating the impact of a strict water conservation scenario

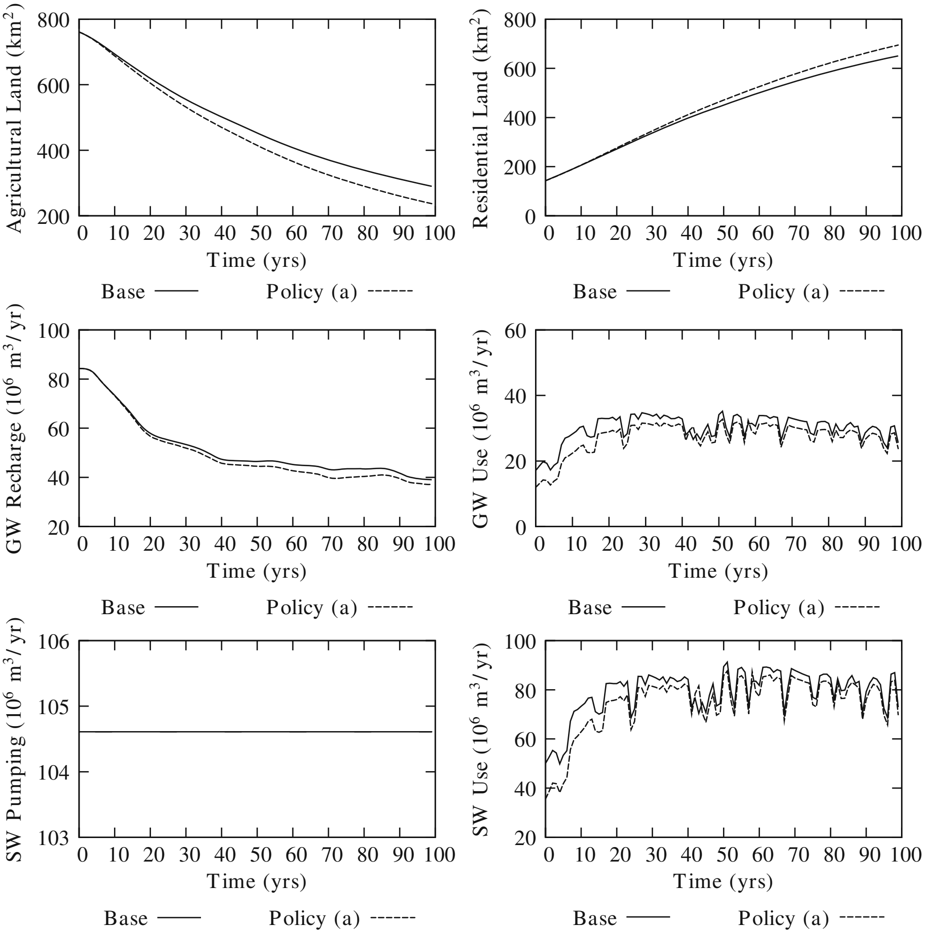


Fig. 10 The Middlesex County land and water conditions illustrating the impact of a strict water conservation scenario

population remains nearly as high as in the base case. The state variables in the rural sector increase, as there is more freedom for those involved with agriculture to expand without pressures of urbanization. The urban communities are facing restricted development opportunities under this policy, as emphasis is placed on the preservation of the environment. The urban population doubles when compared to the population in 2001, while expansion of residential land use occurs at more modest rate.

Figure 12 shows an effect of preserving much of the original agricultural land while increasing residential land only by a modest amount. The implication of having more agricultural land available over time increases ground water recharge, resulting in more water available for use than in the base case scenario. Even though more ground water is available, the combination policy (b) successfully achieves a reduction of total water use (both from ground and surface water).

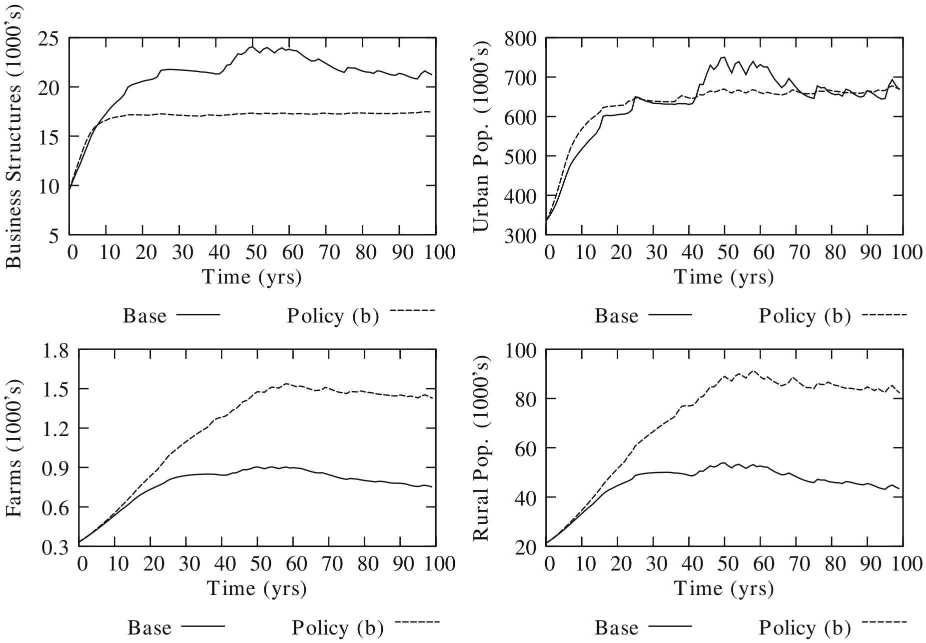


Fig. 11 The Middlesex County urban and rural conditions illustrating the impact of reduced water–limited land development scenario

Socio-economic scenarios discussed here are used for illustration purposes. Modeling and system dynamics simulation of various policy inputs and scenarios provides the model user with additional insight and learning experience of relevance to water resources management in the basin.

3.3.3 Model Calibration and Sensitivity

Report by Cunderlik and Simonovic (2004) describes in detail the calibration and verification procedures applied to the continuous model component of the Upper Thames River basin. Different data sets are used for calibration and verification purposes. The simulation results show that the continuous model component (coupled with the external snow accumulation and melt algorithm) adequately captures regional long term hydrologic characteristics. The model shows no systematic bias for peaks produced during spring or summer flood events, even though it has the tendency to underestimate total streamflow volumes by 10–15%.

In system dynamics simulation studies the emphasis is not placed on replication of historic behaviour, but rather on formulation of systemic structures able to produce behaviour modes consistent with observations, as well as behaviour modes that are possible, but not yet observed. The focus is therefore on dynamic feedback character of interconnections between model components, and not on fitting simulated to observed behaviour. Additional details regarding sensitivity of the socio-economic model component is given in Prodanovic (2008).

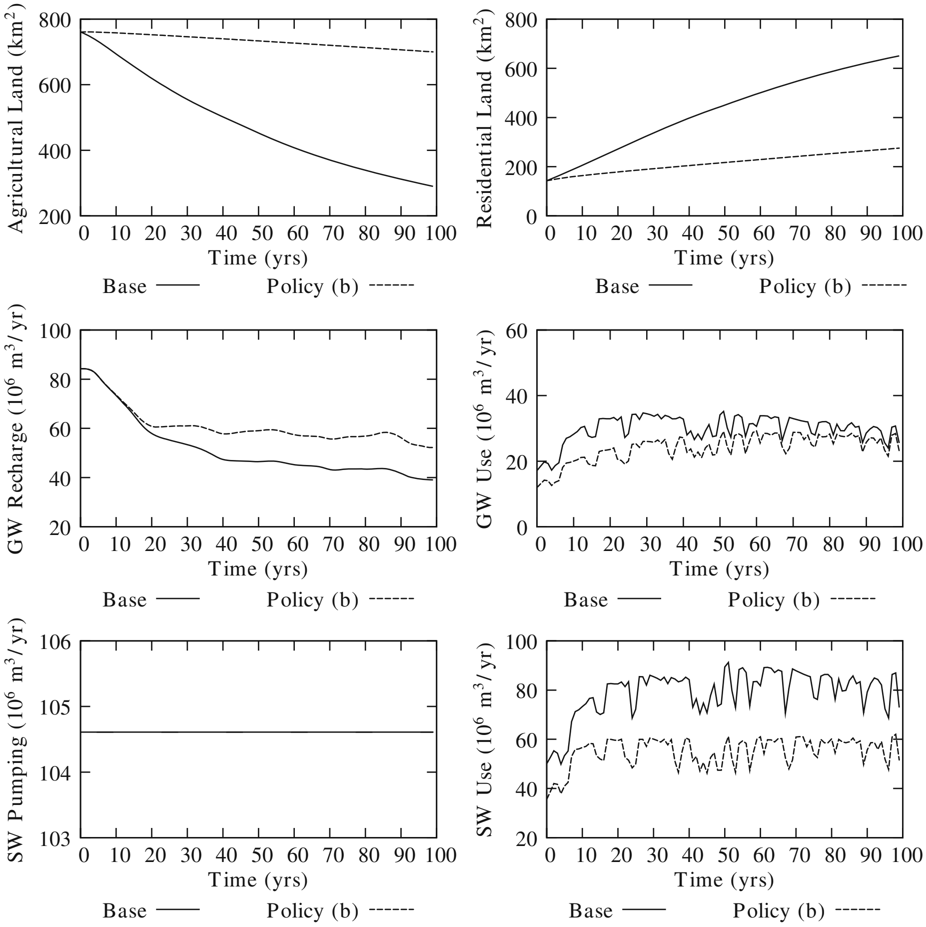


Fig. 12 The Middlesex County land and water conditions illustrating the impact of reduced water—limited land development scenario

4 Conclusions

The system dynamics simulation based methodology for support of integrated water resources management is proposed, with the main premise that physical aspects of water management should be studied within the socio-economic context they are embedded in. The methodology aims to broaden the scope of modeling used in water resources practice by introducing the system dynamics simulation approach. The system dynamics simulation is a tool that aids description of system structure, provides explicit incorporation of feedback relationships among many system components, and supports the participation of stakeholders in the model development process. Combining physical and socio-economic watershed components via feedback gives the model users greater insight into the system structure responsible for the behavior of the entire watershed. Simulation of the model with various system structure representations and/or policy options generates learning experience that can result in better management decisions acceptable to a wider group of watershed stakeholders.

Integrated system dynamics simulation watershed management model developed in this work is used for illustrative purposes. It is applied to the Upper Thames watershed to demonstrate the advantages of the proposed methodology in the (a) analyses of climatic change impacts on the watershed, and (b) examination of impacts that socio-economic policies have on the watershed. The results of model simulations outline how the climatic change, coupled with various water management policies, can alter the physical and socio-economic landscape of the watershed.

Climate change is expected to intensify flooding in the basin, thus bringing flows of higher magnitudes more frequently. Such conditions may demand additional investment in flood management infrastructure and may require complete revisions of budgets for flood management and maintenance of flood protection infrastructure, and engineering design standards. Drought conditions are expected to remain at their current levels, with no appreciable shifts in magnitude, frequency, timing, or variability. In spite of this, droughts in the watershed are already severe enough to warrant serious attention from water resources managers and stakeholders. This is of particular importance, since drought impact assessments in the watershed are altogether lacking.

The socio-economic characteristics of the Upper Thames watershed can be significantly altered as a result of both, climatic change, and watershed management practices. Illustrating the impact of various combinations of climatic and socio-economic policies using the model revealed that the availability of water may become the most important factor for future regional economic development. The results of two illustrative socio-economic scenarios are presented here. Simulation reveals that implementation of strict water conservation—illustrative scenario (a)—actually may have negative long term consequences on the behavior of regional socio-economic systems. This is because the reductions in per capita (and per business/farm) water use lowers the total amount of water used in the short term, while increasing the overall water availability. The higher water availability implies that the region can actually intensify its economic development. Over time, the increased economic activity eventually ends up in using more water.

One way to keep total water use at acceptable levels may be to implement a combined policy—illustrative scenario (b)—where a reduction in per capita water use is required, together with regulations that control further expansion and development. Such a scenario is simulated with the model, and encouraging results are obtained. Total water use can indeed be lowered, while maintaining the current land use. Ground water recharge rates become higher when compared to the base case scenario, while the socio-economic expansion occurs at modest rate without negative impact on the population in the watershed.

4.1 Model Limitations

The model presented in this work is developed to demonstrate how physical and socio-economic characteristics of a watershed may be combined into a single simulation model that can support implementation of integrated water resources management principles. Physical characteristics of the watershed are captured within a very detailed hydrologic model (discussed in the previous section). Social studies investigating impacts of changing socio-economic conditions in the watershed are not available. The structure of this model component is developed by extending system dynamics models developed (Schroeder et al. 1975; Alfeld and Graham 1976), in addition to using socio-economic data available for the watershed. Additional work will be required to strengthen this component before implementing the results of simulation modeling to actual management practice.

An additional recommendation of the work presented here is to explore additional feedback relationships within the model. This can be undertaken by targeted social studies of the watershed (currently being considered by the Upper Thames River Conservation Authority) and the continuation of the dialogue between the watershed stakeholders that has been initiated in 2004 (Mortsch et al. 2005).

Additional work should also address the question of excluded model components. For example, the current model does not include the water quality sector in spite of the fact that the water quality is one of the serious water management problems in the watershed. The simulation model structure is very flexible and could be easily be expanded by the addition of more sectors.

Acknowledgements The work presented here was developed as part of the project Assessment of Risk and Vulnerability to Changing Climatic Conditions, for which Canadian Foundation for Climate and Atmospheric Sciences provided funding. Financial assistance from the Natural Sciences and Engineering Research Council is also acknowledged.

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