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Multi-method Modeling Framework for Support of Integrated Water Resources Management

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Abstract The contemporary definition of integrated water resources management (IWRM) is introduced to promote a holistic approach in water engineering practices. IWRM deals with planning, design and operation of complex systems in order to control the quantity, quality, temporal and spatial distribution of water with the main objective of meeting human and ecological needs and providing protection from water related disasters. This paper examines the existing decision making support in IWRM practice, analyses the advantages and limitations of existing tools, and, as a result, suggests a generic multi-method modeling framework that has the main goal to capture all structural complexities of, and interactions within, a water resources system. Since the traditional tools do not provide sufficient support, this framework uses multi-method simulation technique to examine the codependence between water resources system and socioeconomic environment. Designed framework consists of (i) a spatial database, (ii) a traditional process-based model to represent the physical environment and changing conditions, and (iii) an agent-based spatially explicit model of socio-economic environment. The multi-agent model provides for building virtual complex systems composed of autonomous entities, which operate on local knowledge, possess limited abilities, affect and are affected by local environment, and thus, enact the desired global system behavior. Agent-based model is used in the presented work to analyze spatial dynamics of complex physical-social-economic-biologic systems. Based on the architecture of the generic multi-method modeling framework, an operational model for the Upper Thames River basin, Southwestern Ontario, Canada, is developed in cooperation with the local conservation authority. Six different experiments are designed by combining three climate and two socio-economic scenarios to analyze spatial dynamics of a complex physical-social-economic system of the Upper Thames River basin. Obtained results show strong dependence between

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changes in hydrologic regime, in this case surface runoff and groundwater recharge rates, and regional socio-economic activities.

1 Introduction

Water resources systems are under mounting pressure due to the rapid growth of the human population, shadowing land-use and land-cover changes, natural variability of the hydrologic cycle and changing climatic conditions. It is apparent that water resources are extremely vulnerable and that sustainable development of human society depends on managing water wisely. The complex character of the problem and its scale call for a holistic approach. The international water community has promoted the Integrated Water Resources Management (IWRM) as a holistic approach to address the inseparable character of social, economic and environmental processes involved in the management of water resources systems. This approach requires coordinated management of water, land and other related resources. The contemporary definition with widest acceptance, formulated by the Global Water Partnership (GWP), states that "IWRM is a process that 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" (Ota 2009). Such a broad definition does not provide practical support to the water management community on how the concept can be used to make the existing water planning, management and decision making more rational, efficient and equitable (Biswas 2004). To bridge the gap between theory and practice, Simonovic (2009) offers seven principles to pragmatically and scientifically guide all water management activities: systems view, integration, partnership, participation, uncertainty, adaptation, and reliance on strong science and reliable data. Each principle is designed to bring additional objectivity to IWRM process, but a single principle that underlies them all is the systems view principle. Since water affects all terrestrial systems, this principle emphasizes the need to account for a broad set of relations among water and land resources. Water resources systems (WRS) interrelate natural, physical and human systems, and can be divided into three main sub-systems Simonovic (2009):

- the natural river sub-system, in which all physical, chemical and biological processes take place;
- the socio-economic sub-system, which includes all human activities related to the use of the natural river and land systems; and
- the administrative and institutional sub-system of administration, legislation, and regulation, where the decision, planning and management processes take place.

In addition, WRSs are subject to numerous sources of complexity continually changing and evolving through space and with time. Analysis of complex WRSs and identification of optimal water resources management policies, together with the magnitude and complexity of the water resources decision making process, require the use of rigorous scientific methods of inquiry found in systems analysis. The systems analysis utilizes three general methods: simulation, optimization, and multi-objective analysis.

This paper focuses on the role of simulation in providing support for practical implementation of IWRM. One of the fundamental challenges of IWRM is the development of simulation models for operational implementation of the concept that dynamically couples both physical and socio-economic components of the system. The literature suggests that a number of models have been developed with the main idea of finding the optimal IWRM management strategies. However, only a small number of models interactively describe how the physical water resources sub-system affects and is affected by the social, economic and environmental sub-systems. The majority of models ignore the interaction between different system components, the non-linearity of a system, the feedback mechanisms, and, most importantly, ignore the explicit representation of spatial characteristics of water resources systems.

The main objectives of this paper are to: (i) analyze the advantages and limitations of available modeling methods applied for support of IWRM; and (ii) define a multi-method modeling framework, able to represent all the structural complexities and interactions within a WRS. The emphasis is placed on explicit modeling and simulation of: (i) integrated physical, environmental and socio-economic sub-systems and their non-linear interactions; (ii) feedback based system structure; (iii) complex spatial and temporal characteristics of water resources systems; and, at the same time, (iv) provide support for direct stakeholder participation and involvement.

Section 2 of the paper briefly analyzes the advantages and limitations of existing modeling methods. Section 3 describes the proposed multi-method modeling framework, while the practical implementation of an operational model for the Upper Thames River basin, Southern Ontario, Canada, is described in Section 4. Finally, Sections 5 and 6 analyze the obtained results, present conclusions, and paper summary.

2 Advantages and Limitations of Models Used for IWRM

System dynamics (SD) simulation is one of the modeling methods extensively used in IWRM due to its capacity to describe complex feedback relations between all three components of water resources management systems. The SD simulation modeling method has been applied to a variety of water resources management problems, as for instance: drought management studies by Keyes and Palmer (1993); management of scarce water resources by Fletcher (1998); reservoir operation for flood control and management by Ahmad and Simonovic (2000a, b, c); hydrologic studies under climate change by Simonovic and Li (2003) and others. Winz et al. (2008) give an effective overview of the use of SD modeling methodology in water resources management, finding that this method has been successfully applied to regional planning and river basin management problems, urban water management, flooding and irrigation. Tidwell et al. (2004) use the method to describe a community-based planning project in the Middle Rio Grande river basin. Stave (2003) applied the method to an urban water management project in Las Vegas, USA. Ford (1996) developed a Snake River Explorer model to simulate the annual flows of the Snake River, USA. Hassanzadeh et al. (2014) used the method to develop an integrated water scenario analysis of the Saskatchewan portion of the transboundary Saskatchewan River Basin.

Despite its wide application to water resources management, the SD modeling method has a number of important limitations; among them, the most important is its inability to deal with the spatial variability of WRSs. Some attempts have been made to introduce space into SD simulation modeling. BenDor and Kaza (2011) use

disaggregated spatial data and relationships in order to understand spatial forms and processes. Choice of spatial representation (zonal, grid or network) completely alters the structure, composition and behavior of spatial models. Zonal models are mainly applied to studies of urban dynamics. However, Anselin (2002) concludes that zonal models present a restricted solution in cases when significant environmental and spatial system heterogeneity determines global system behavior. One recent development is a tessellation of space into regular grids (BenDor and Metcalf 2006). Ford (1999) used a gridded landscape to represent heterogeneity in a drainage basin. The main difficulty of gridded representation is in replicating SD simulation model for each grid cell. As a solution to this problem, Ahmad (2002) suggests Spatial System Dynamics (SSD) that couples the SD simulation model with the Geographic Information System (GIS) through a data exchange link. SSD requires that the area of interest be divided into cells. Each cell contains an SD model which communicates with neighboring cells through a set of feedback links. This interaction initiates a change in the observed parameters at any point in space according to an average of the parameter values in neighboring cells. Neuwirth et al. (2015) take a similar approach that provides for bidirectional interactions of operations between SD and GIS. They find that the results of the spatial model are not only influenced by the initial spatial structure, but also depend on raster resolution. Anselin (2002) and Vionov et al. (2007) show that both processes are greatly exposed to artifacts of grid geometry, which is likely to go undetected in SD modeling.

Alongside the SD simulation, a number of other modeling methods are available for describing the feedback-based processes between different system components in both time and space, in particular, Cellular Automata (CA), temporal GIS, and Agent-Based Models (ABM). In a number of examples, various modeling methods are combined in the so-called multi-method or hybrid models. For instance, Prodanovic and Simonovic (2010) developed an IWRM model in order to test the response of a system to changing climate conditions. The model adequately represents temporal dynamics of a WRS but is unable to describe the changes in the spatial structure of the system. Ghimire et al. (2013) couple one-dimensional hydraulic model and a cellular automata (CA) model to represent two-dimensional space. In order to analyze the effects of contamination of the water distribution system on public health, Zechman (2011) develops a multi-method modeling framework that combines agent-based, mechanistic and dynamic modeling.

The following is a description of the new proposed multi-method modeling framework that (a) provides for explicit consideration of space and time and (b) meets the requirements of IWRM.

3 From the Generic Architecture to an Operational Modeling Framework

The design of methodology is divided into three distinct phases that drive transition from the generic system architecture towards detailed description of all components of an operational model. In the first phase, the generic system architecture is defined so that it can be applied to any water resources system and context in support of integrated water resources management. Second phase describes the preliminary design of an operational model for IWRM support, while the third phase gives the detailed explanation of all components of an operational model.

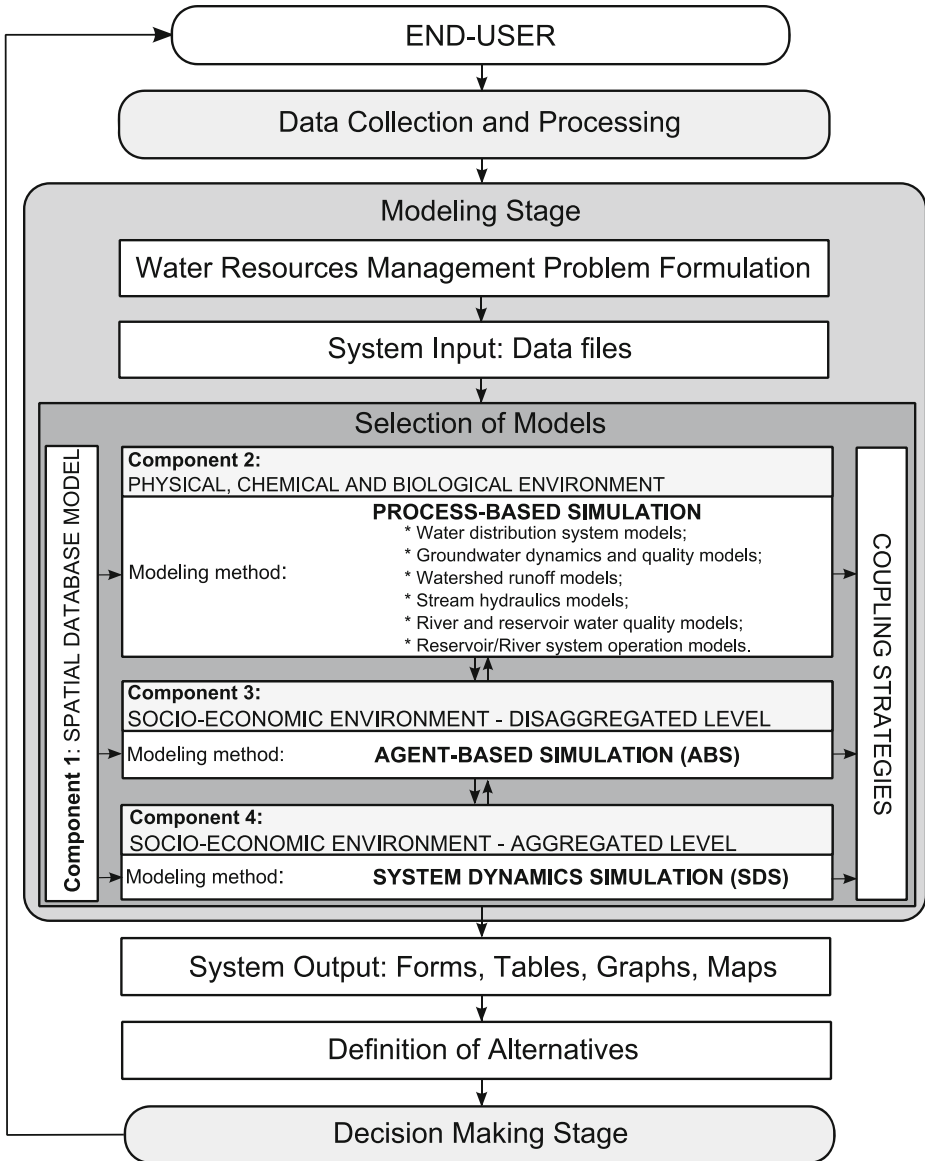## 3.1 Phase One: Generic Architecture of a Multi-Method Modeling Framework

The generic architecture of a multi-method modeling framework is designed to meet the IWRM implementation requirements (Nikolic et al. 2012):

(i)   establishment of feedback system structure to capture dynamics of water resources system behavior;
(ii) integral representation of physical and socio-economic sub-systems;
(iii) proper consideration of complex spatial and temporal scales; and
(iv) partnership provision.

Component 1 of the framework is a spatial database used to store both spatial and non-spatial information, and directly communicate necessary information to other components (see Fig. 1). Component 2 includes a set of processed-based models used to describe the physical, chemical and biological sub-systems. According to the definition of IWRM and in order to support the systems view principle, the most important feature of newly designed modeling framework is an authentic representation of the interactions between natural resources and socio-economic environment. In studies that include diverse social and large spatial scales, social and economic processes can be represented on different levels of abstraction: system (aggregated) level and more specific individual-centric (disaggregated) level. Based on that, System Dynamics (SD) simulation is used for representation of socio-economic processes at the system level, while Agent-Based (AB) simulation represents socio-economic processes at the individual-centric level, Components 3 and/or 4 in Fig. 1. All components are integrated by choosing one of three coupling methods: embedded, tight or loose coupling (Ahmad 2002). The modeling framework supports utilization of simulation scenarios to analyze various "what-if" management questions. Finally, the modeling framework uses a set of output maps, tables and figures to display various results.

3.2 Phase Two: Preliminary Design of Operational Model to Support IWRM

Figure 2 presents the preliminary design of an operational model for support of integrated water resources management. Component 1 is the spatial database that stores and supplies all necessary data relevant to the socio-economic model. According to the basic principles of integrated water resources management, physical and socio-economic systems strongly depend and continuously influence each other through a number of feedback processes. Typically, analysis of interactions between the two sub-systems is built upon the conceptual representation of water balance and water budget models. For this reason, from all available process-based models used in water resources management (watershed runoff, groundwater dynamics, stream hydraulics, river and reservoir water quality, reservoir/systems operation and water distribution system models), the spatially semi-distributed hydrologic model is placed in the center of the operational model for support of IWRM, Component 2 in Fig. 2. Based on the climatic inputs and current physical conditions in a basin, the hydrologic model provides information on stream flows and groundwater recharge rates. After the hydrologic model estimates the hydrologic quantities, they are compared with the water demand. This value, on the other hand, comes from the individual-centric spatially explicit socio-economic model, Component 3. Estimates of water demand come from the socio-economic sub-models that

Fig. 1 Generic architecture of a multi-method modeling framework

include population dynamics, industrial and agricultural production, economic activities, urbanization, reforestation and deforestation. Then, the hydrologic model takes into account temporal and spatial alterations of physical and climate conditions resulting from numerous socio-economic activities, and provides information on how socio-economic activities alter the hydrologic regime in the basin. To achieve this, the main requirement is dynamic data exchange between the system components to provide a feedback structure under a single user interface. The tight coupling strategy is chosen as the most appropriate for the implementation
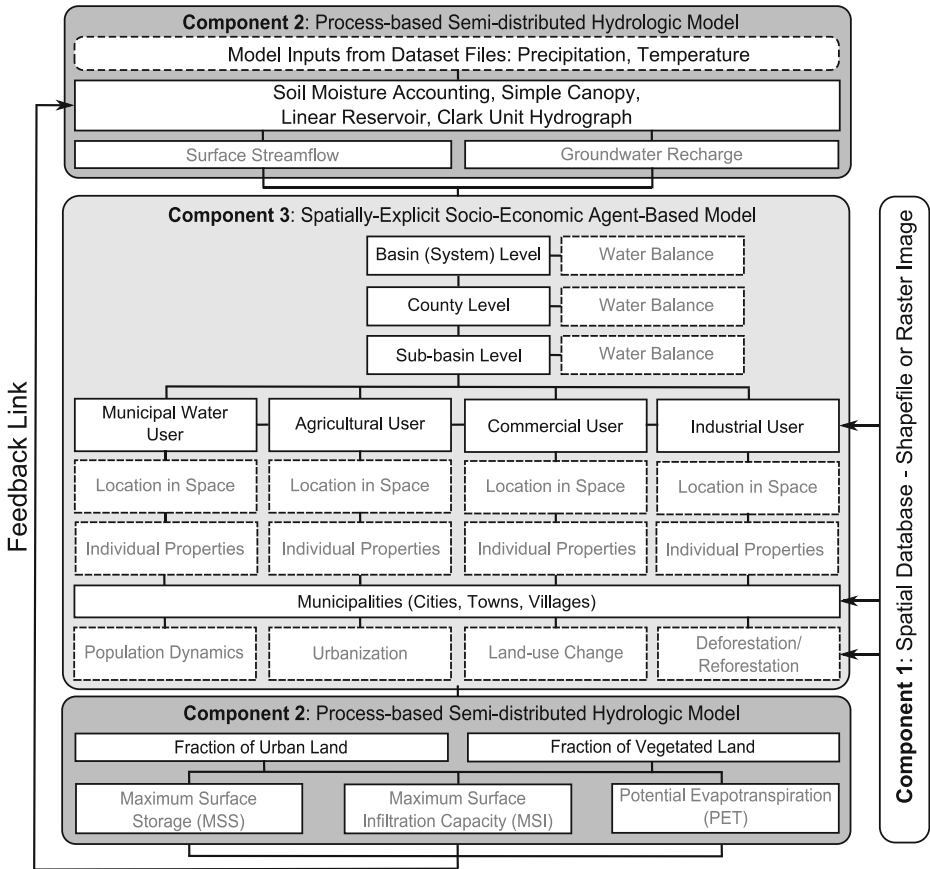
Fig. 2 Preliminary design of an operation model for support of IWRM

in this study. It is also known as integration under a common interface where different components are developed independently containing their own data structure.

3.3 Phase Three: Detailed Architecture of the Operational Model - Individual Components

The final phase gives the more detailed presentation of three components of an operational model for support of IWRM.

3.3.1 Component 1: Spatial Database

Spatial database is designed to store and manage information related to geometric features that are explicitly defined in geographic space. To store all necessary information, two different formats are used: shapefiles and raster images (ESRI 2014). Shapefiles store the geometric location and attributes information of geographic features. A shapefile includes dBASE tables that store a number of attributes that are related to a shapefile's features. On the other side, spatially continuous geographic features are stored as raster datasets.

3.3.2 Component 2: Spatially Semi-Distributed Continuous Hydrologic Model

Process-based hydrologic models are used to mathematically describe the physics of complex hydrologic cycle occurring within a basin. In contrast to the event-based hydrologic models, continuous models describe the long-term movement of moisture and evaluate the detailed soil moisture balance of dry and wet climate conditions. Since the hydrologic model needs to be integrated, and thus exchange data with other components that represent the socio-economic environment, continuous HEC-HMS model is used as one of the possible choices (USACE 2000). The structure of a typical HEC-HMS hydrologic model is separated into a number of different modules where each module describes a particular physical process (Fig. 3). Temperature and precipitation data serve as inputs into the snow module. Based on the average daily temperature, this module adjusts precipitation, and determines if the state of precipitation is solid or liquid. Snow module produces adjusted precipitation which then is used for computation of the losses module. Losses analyzed by the model are interception, infiltration, surface storage, evaporation and transpiration. The losses module accounts the movement of moisture through a set of conceptual reservoirs within a basin, such as canopy, surface, soil and groundwater. Evapotranspiration represents one of the outputs of the loss module and includes the moisture that evaporates from the canopy, surface depressions, and soil. Second output
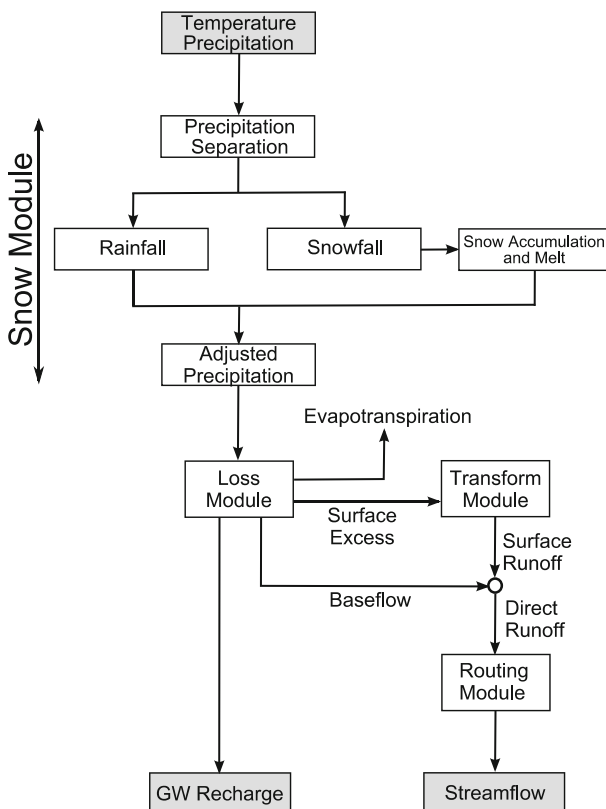
Fig. 3   Modular structure of the spatially semi-distributed continuous model

from the loss module is baseflow that computes the lateral flow returned to the stream from the ground. Also, the surface excess output calculates the volume of water that remains on the surface and does not infiltrate into the soil. Finally, the groundwater recharge represents flow that infiltrates deep aquifers and do not return to the surface. The surface excess is used by a transform module and is converted into direct runoff by convoluting a unit hydrograph. The surface runoff is obtained as an output from the transform module. It is then combined with the baseflow to produce the direct runoff. The direct runoff represents an input to a routing module which calculates the propagation of a flood wave and produces the channel streamflow.

3.3.3 Component 3: Spatially Explicit Agent-Based Model

Agent-based (AB) modeling is used to represent the spatially explicit socio-economic component of a water resources system. According to Railsback and Grimm (2011), AB modeling method is one in which individual system entities, also referred to as agents, are described as unique and autonomous units that interact with each other and their local environment. In agent-based models, the global system behavior emerges as a result of interactions between agents, how they perceive and respond to each other, and interactions between agents and their environment. Even though agents represent the core of agent-based models, researchers have not come to a full agreement on the definition of an agent. Wooldridge (2009) suggests a definition that defines an agent as an autonomous entity that is situated in some environment, is able to perceive it through physical sensors or data files, and is capable of autonomous action in this environment in order to meet prescribed objectives. Schieritz and Milling (2003) identify a set of active features that can characterize an agent: goal directed behavior, situatedness, reactiveness, autonomy, social ability, learning, continuity, mobility and specific purpose.

In case of water resources systems, depending on the purpose of the model, agents can take numerous forms. For example, agents can represent individual ground or surface water users, water polluters, different infrastructural elements (such as dams, water treatment plants, etc.), cities and municipalities, or decision and policy makers on different levels. Each agent can be characterized by their own set of behaviors. Individuality of agents can be exploited to describe their unique features, such as individual water demand, seasonal variation of water demand, spatial location, economic activities, water availability or resilience to water scarcity.

Recently, the agent-based modeling method has found some applications in the analysis of different aspects of water resources management. Saqalli et al. (2010) built a decision support model (MAELIA) to assist decision makers to investigate potential social conflicts related to the water resources management in the Adour-Garonne river basin. In the next example, Cai et al. (2011) use a multi-agent system modeling framework to explore the different management options and their respective effects on irrigators and the downstream ecosystem in the Yellow River basin in China. Yang et al. (2009) observe a basin as a multi-agent system composed of water users and the common environment from which they exploit the resource. Van Oel (2009) uses an agent-based modeling method to analyze the processes related to the distribution of water availability over space and time in Northeast Brazil.

In the presented work, the spatially explicit agent-based model is used to simulate the utilization of common natural resources by various users. Not only that this model analyses the effects of availability of local resources on recognized actors, it also simulates the effects their actions have on the environment, in this case hydrologic regimes. In the model the common resources are ground and surface water and land, used by different economic, agricultural, social and infrastructural entities in the system.

Since the structure of an agent-based model strongly depends on the particular system being modeled, the detailed description of the agent-based model is given in the following section.

4 Implementation of Operational Model

The practical implementation of a newly suggested multi-method modeling framework is developed for the Upper Thames River basin, located in Southwestern Ontario, Canada (Fig. 4).

4.1 The Upper Thames River Basin

The main Thames river course was formed after the retreat of the Wisconsin Glacier from Ontario around 14,000 years ago. Native inhabitants firstly named the river Askunessippi
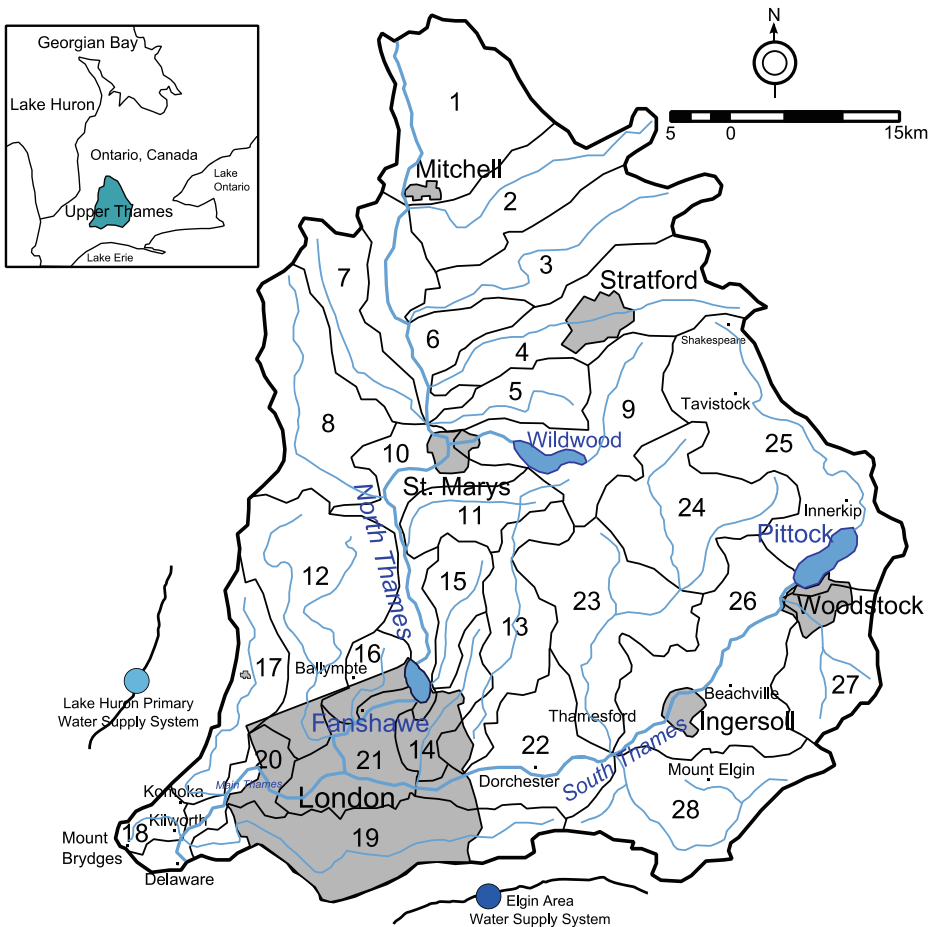

Fig. 4 Upper Thames River Basin, Ontario, Canada

(Wilcox et al. 1998). The name was changed to Thames River in 1793 when Governor J. G. Simcoe renamed it after the river in England. But as a result of a political agreement, the Thames River basin is divided and managed by two separate conservation authorities (CA) responsible for supervision of local water and land resources – Upper and Lower Thames River Conservation Authorities. The Upper Thames River Basin is naturally divided into 28 sub-basins.

Annual discharge of the Upper Thames River measured at the Byron station is approximated to 35.9 m^3/s. The Upper Thames River basin receives on average approximately 1000 mm of precipitation annually. Over the years, the Upper Thames River Conservation Authority (UTRCA) has implemented a number of structures to protect the local municipalities from flooding, such as dykes, municipal drainage schemes, flood and fill line regulations. However, the most dominant structures in the Upper Thames River basin are three reservoirs: Wildwood, Pittock, and Fanshawe. Together with other structural measures, the three reservoirs constitute an effective system for flood management and protection. Floods and droughts are still two major natural hazards in the Upper Thames River basin (UTRCA 2012).

The study area covers portions of three counties: Oxford County, Perth County, and Middlesex County. The largest urban centers in the basin are London, Mitchell, St. Marys, Stratford, Ingersoll, Dorchester, and Woodstock, London being the largest, with a population of approximately 366,000. The main economic strength lies in wide-ranging agricultural activities, from specialized crops to various livestock operations. Approximately 76 % of the total basin area (approximately 3430 km^2) is dedicated to agricultural activities (UTRCA 2012). Urban areas take 10 %, forest land 12 %, while the remaining 2 % go to water and queries.

The Upper Thames River basin has initiated a water allocation program in order to regulate surface and groundwater withdrawals. According to the Section 34 of the Ontario Water Resources Act (OWRA), Permit to Take Water (PTTW) database, maintained by the responsible conservation authority, in this case the Upper Thames River Conservation Authority (UTRCA) holds a record of all individual permit holders. According to the provincial Ministry of Environment and Climate Change, all users that pump more than 50,000 L per day require a special permission, except in the case when water is used for agricultural livestock.

4.2 Integrated Hydrologic-Socio-Economic Model of the Upper Thames River Basin (IHSEM-UTRB)

The operational model for support of integrated water resources management in the Upper Thames River basin has been developed using the modeling framework presented in Section3 and includes three components.

4.2.1 Component 1: Spatial Database

The shapefile format is used to store attribute tables with all relevant information about the Upper Thames River basin due to the restrictive features of the agent-based modeling platform used in this study and the requirements of the tight coupling strategy. The shapefiles (10 of them) contain basin boundaries, sub-basins, hydrography, urban centers, gauging stations, individual water users from the permit to take water database (agricultural, industrial, commercial and municipal) and critical infrastructure. In addition to the vector data stored as shapefile datasets, spatially continuous data is stored in raster image format. The spatial data,

both vector and raster, are retrieved from the Ontario Ministry of Environment and Climate Change (Ontario 2014) and Scholars Geo Portal (Scholargeoportal 2014). The raster datasets include:

- *Land use dataset.* This dataset contains information on The Upper Thames River basin land use and contains 39 land use categories for all cells. Each cell contains only one value of current land use category, and this value is updated throughout the simulation.
- *Sub-basins dataset.* The Upper Thames River basin contains 28 sub-basins, and each cell belongs to only one sub-basin.
- *County dataset.* Portion of three counties located in the Upper Thames basin are represented in this dataset. Each cell belongs to only one county.
- *Digital Elevation Model (DEM) dataset.* Each cell contains a value that defines the elevation in meters above sea level.

4.2.2 Component 2: Hydrologic Model

In this case study a spatially semi-distributed continuous hydrologic model is applied to describe long-term hydrologic processes in the Upper Thames River basin based on the HEC-HMS platform. The hydrologic model was initially developed by Cunderlik and Simonovic (2004, 2005), and later rewritten and converted to Java programming language by Prodanovic (2007).

The hydrologic model schematic developed for the Upper Thames River basin is presented in Fig. 5. This model includes twenty-one river reaches and represents all three reservoirs in the system. Since the applied methods can only approximate the reservoir management practices, the representation of reservoir operations is the most important limitation of the model.

The model is calibrated for the daily data in the period between November 1979 and October 1988, while the model verification is done for the period between November 1988 and
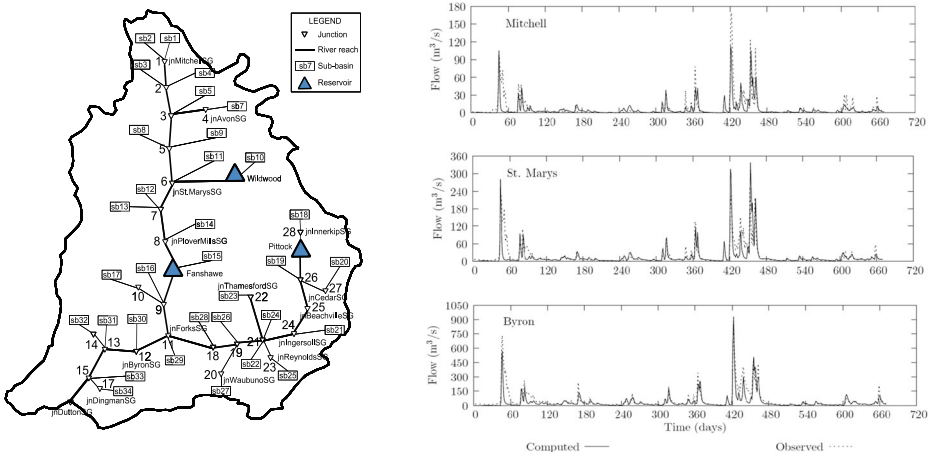
Fig. 5 Upper Thames RB hydrologic model schematics and model calibration results

October 1997. The calibration procedure is based on spatially and temporarily interpolated precipitation. Different sets of parameters are used to characterize seasonal variations between summer and winter months. Figure 5 illustrates the simulation results of the calibrated model for three flow-gauging stations (Mitchell, St. Marys and Byron).

### 4.2.3 Component 3: Agent-Based Model

The socio-economic agent-based model is developed to analyze the utilization of natural resources by numerous users within the Upper Thames River basin. On one side, this model simulates the effects of availability of local resources for recognized system actors, while on the other, it examines the effects that actions of system actors have on the environment, in this case – hydrologic regime. The spatially explicit agent-based model is designed to address two main questions:

1. How does the simulated socio-environmental system and its individual entities develop and respond to changing physical and climate conditions, and what model indicators warn of the system vulnerability?
2. How socio-economic activities affect the hydrologic cycle in the Upper Thames River Basin?

The very first task in an agent-based modeling process is definition of entities that are essential for the overall system behavior. The Upper Thames River basin socio-economic agent-based model identifies the following types of entities that influence and are influenced by the natural resources in the basin (Fig. 6): registered water users (from the permits to take water database – industrial, agricultural, commercial, municipal water supply), 8 urban centers in the Upper Thames River Basin (London, Ingersoll, St. Marys, Mitchell, Dorchester, Komoka, Woodstock, and Stratford), primary water supply systems (PWSS), and the decision makers at the sub-basin and the municipal (county) levels.

The model contains $870 \times 752 = 654,240$ cells (patches). However, the spatially explicit model consists of 381,979 patches that represent just the area within the basin. Each cell contains a set of variables that define the current land use, and belongs to one county and one sub-basin. The time horizon of the simulation is 20 years. The simulation starts with data initialization on January 1, 2000 and ends on December 31, 2019, and it is executed on a monthly time step, with 240 time steps in total.

An agent-based model can be seen as a collection of sub-models that subsequently simulate the most important processes from the aspect of system performance. Sub-models are
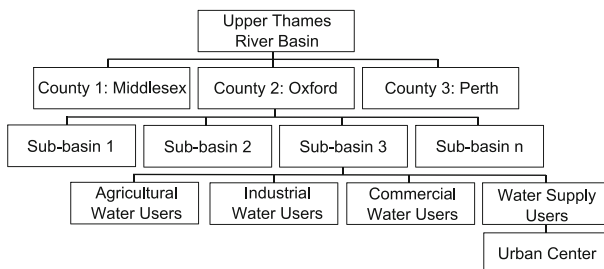
Fig. 6 System actors within the socio-economic model
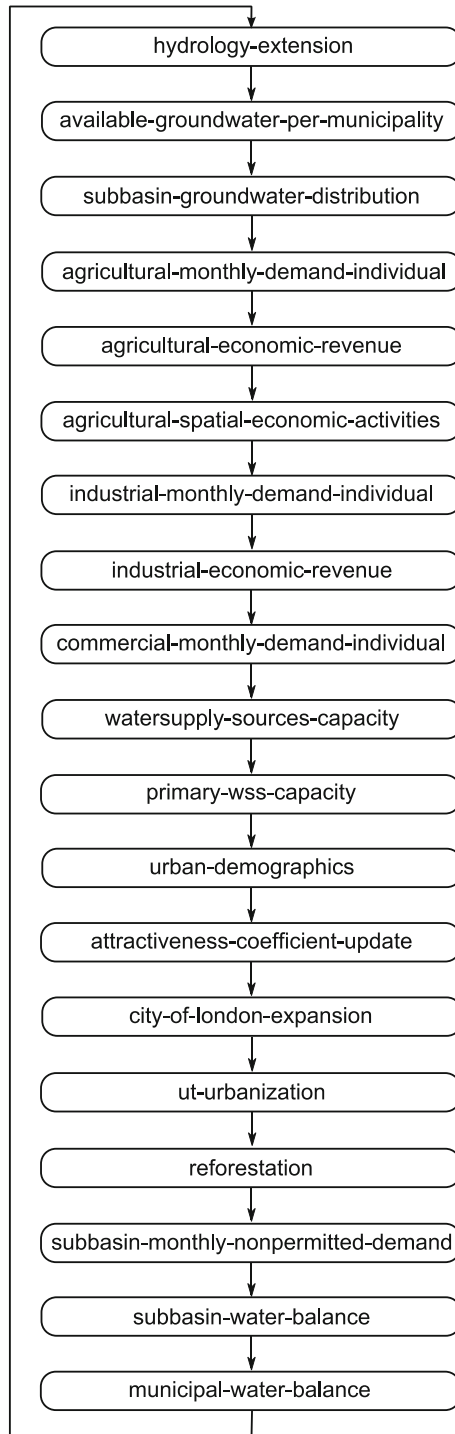
Fig. 7 Sub-models and their order of execution

designed, tested and analyzed independently before the final integration. IHSEM-UTRB model contains 19 sub-models executed in every time step presented in Fig. 7, but the most important one that enables communication with hydrologic sub-model is named *hydrology-extension*.

Hydrology-extension procedure is created to establish the direct data exchange link between spatially semi-distributed hydrologic model and socio-economic agent-based model. Before it is executed, the hydrologic model reads the information that describes the current physical state of the system. Parameters *Fraction of Vegetated Land* and *Fraction of Paved Land* are calculated for 3 counties to describe local physical conditions and then they are passed to the hydrologic model. The hydrologic model updates following parameters: *potential evapotranspiration* (PET), *maximum surface storage* (MSS) and *maximum soil infiltration capacity* (MSI). For the updated hydrologic parameters, the hydrologic model calculates groundwater recharge for all three counties and surface flows for three flow gauging stations at a 6 h time step. At the end of each month, the obtained values are communicated to the socio-economic model. The socio-economic model uses the hydrologic outputs to initiate and execute all scheduled sub-models. The sub-models subsequently calculate the groundwater recharge rates for three counties (*available-groundwater-per-municipality*), obtain groundwater recharge rates at the sub-basin level (*subbasin-groundwater-distribution*), calculate the monthly water demand for agricultural users (*agricultural-monthly-demand-individual*), and calculate the individual gross economic revenue (*agricultural-economic-revenue*). The monthly industrial water demand is calculated based on the allowed permitted takings (*industrial-monthly-demand-individual*), and resulting economic activity based on water demand (*industrial-economic-revenue*). Next sub-model calculates the commercial water demand (*commercial-monthly-demand-individual*). Municipal water demand is then compared with the capacity of water sources (*watersupply-sources-capacity*). The population dynamics is calculated for 8 urban centers (*urban-demographics*) and used for the calculation of the City of London urban expansion (*city-of-london-expansion*) and expansion of other urban centers (*ut-urbanization*) in the basin. *Reforestation* sub-model describes the reforestation process in the basin. Unpermitted domestic and agricultural water withdrawals are also calculated (*subbasin-monthly-non-permitted-demand*). Finally, the current and cumulative water balances are calculated for each sub-basin (*subbasin-water-balance*) and each county (*municipal-water-*
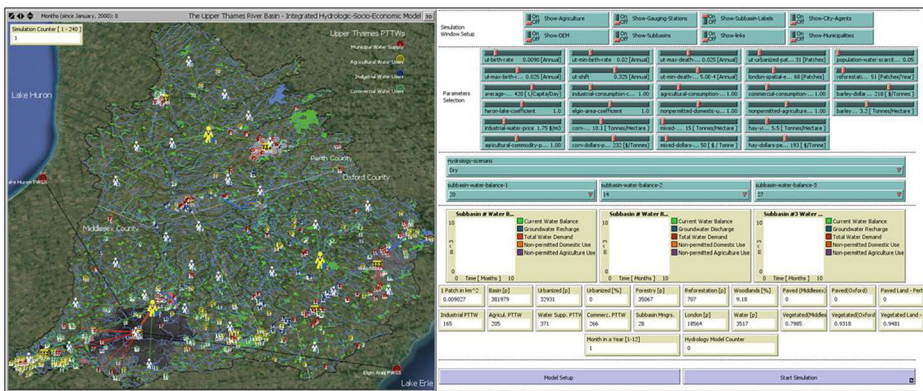

Fig. 8 The main simulation control window

balance). Modified socio-economic conditions after one simulation time step update the physical state of the hydrologic system and simulation proceeds with the next time step.

Tight integration of all components and the agent-based model development are done in Netlogo modeling environment (Wilensky 1999). The designed operational model allows a game-like interactive control of all parameters throughout the simulation, using available options on the user interface (Fig. 8). On the left side, the map shows the spatial manifestation of land-use change

Fig. 9 List of variables of an agent representing an industrial water user

and presents all active water users within the current simulation time step. On the right hand side, a number of sliders, choosers, and switches are used to define the parameters of sub-models (simulation scenario), modify system operational decisions during the simulation and visualize the simulation output. The Model Setup button initializes all model variables and reads the information from databases. The Start Simulation button initializes the simulation. Figure 9 shows a list of variables that characterize an agent, in this case industrial, and its change over time. Figure 10 shows some of the resulting graphs and monitors, such as mean monthly surface flows for three stations, groundwater recharge rates and water demand for three counties and three sub-basins.

4.3 Development of Simulation Scenarios

Two sets of scenarios are created to investigate the two distinct conditions in the Upper Thames River basin: *climate* and *socio-economic* scenarios. Each simulation run is performed using one combination of two groups of scenarios.

4.3.1 Climate Scenarios

Previous research that studied the hydrologic effects of climate variability in the Upper Thames RB applied the weather generator algorithm to produce arbitrary long-time series of climatic input data (temperature and precipitation) (Prodanovic 2007). The weather generator algorithm utilizes

Fig. 10 Resulting graphs and monitors

different shuffling and perturbation mechanisms with a local-climate time series to create a statistically similar and locally applicable set of climate conditions for the future. In this research, the historically observed precipitation and temperature data for the period between 1964 and 2001 are used to condition the weather generator. Therefore, each station contains 100 years of 365 days per year data, giving in total 36,500 days of precipitation for each of the three climate scenarios:

a. *Historical Climate Scenario*: The historical records have not been altered, only extended to the period between January 1st, 2000 and January 1st, 2020, based on the regional hydro-climatic data from the 1964–2001 period;
b. *Wet Climate Scenario*: This scenario represents the wetter future climate that is warmer than normal;
c. *Dry Climate Scenario*: It represents the drier and cooler climate future scenario.

4.3.2 Socio-Economic Scenarios

Two socio-economic scenarios were developed for the purpose of this research: *the baseline* and *infinite natural resources* socio-economic scenarios. The baseline socio-economic scenario (i) studies the system behavior under current socio-economic conditions used in the design of all sub-models. These conditions are derived from the observed historical analysis, and this scenario assumes that identical socio-economic trends will be occurring during the period of simulation (January 1, 2000 - January 1, 2020). In the infinite natural resources scenario (ii), the focus is primarily placed on economic growth and enhancement of living standard, while disregarding the state of natural resources.

Different combinations of three climate and two socio-economic scenarios give a total of six experiments used to simulate the system response. Each experiment should improve the understanding of how different climate conditions can potentially affect the local socio-economic environment in the basin. At the same time, the insight should be provided on how the projected and expected socio-economic trends may affect the local hydrologic regime (Table 1).

5 Simulation Results

The designed operational model provides numerous outputs on different spatial scales (the basin, sub-basin, or individual-actor levels) used to assess the state of the system. Figure 11a shows the seasonal variations of ground water recharge rates and total water demand for the

Table 1 Six combinations of climate and socio-economic scenarios

		Socio-economic scenarios	
		Baseline scenario (i)	Infinite natural resources scenario (ii)
Climate scenarios	Historic climate (a)	Experiment 1	Experiment 4
	Wet climate (b)	Experiment 2	Experiment 5
	Dry climate (c)	Experiment 3	Experiment 6
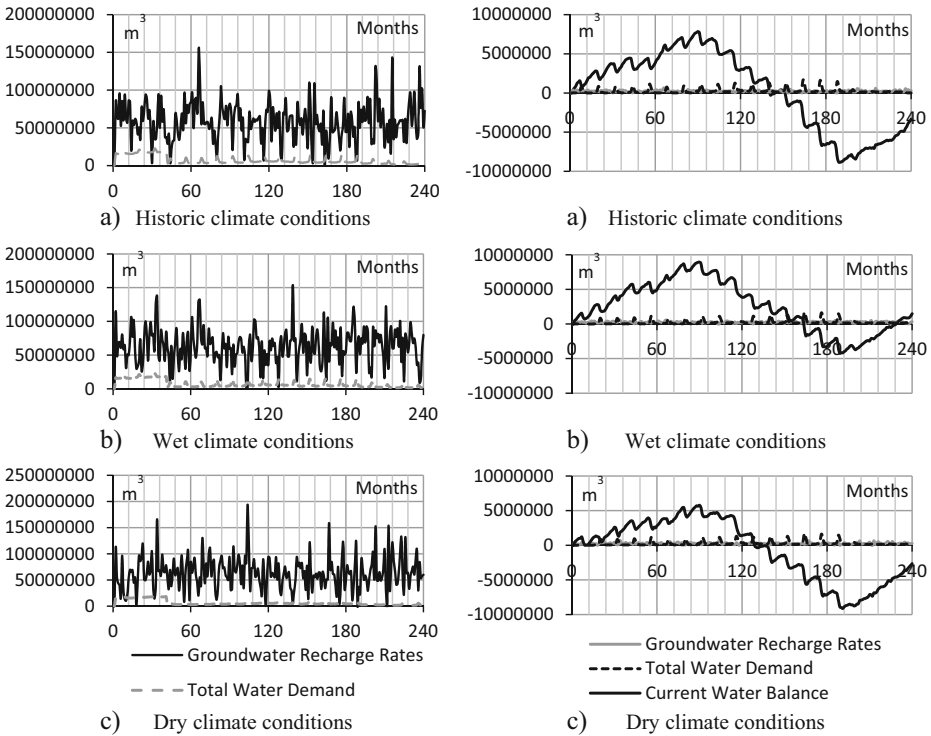
Fig. 11 **a** Middlesex County ground water recharge rates and total water demand for baseline SE scenario. **b** River Bend cumulative water balance for baseline SE scenario

Middlesex County for three climate scenarios and baseline socio-economic scenario. Since the model does not support the assessment of the state of local aquifers, the ground water recharge rates are compared to the water demand. It is preferred that the water demand remains lower than the recharge rates, to avoid additional extraction of reserves from ground water aquifers. At this spatial scale, results do not show any significant disproportion between natural recharge and demand rates for all three climate scenarios. This suggests that ground water aquifers in these three counties are not in danger of overexploitation under the projected socio-economic and climate conditions. However, the situation can be drastically different at the lower spatial scales (the sub-basin level). As a result of intensive local socio-economic activity, mainly

Table 2 Changes in total runoff volumes at Byron [m^3]

Byron station		Baseline SE (i)	Infinite SE (ii)	Change [%]
Historic climate	(a)	1.895E+10	1.985E+10	+4.76 %
Wet climate	(b)	2.099E+10	2.210E+10	+5.32 %
Dry climate	(c)	1.745E+10	1.799E+10	+3.11 %
Change (b) – (a)	[%]	+10.76 %	+11.35 %	
Change (c) – (a)	[%]	− 7.89 %	−9.34 %	

Table 3 Changes in total runoff volumes at Ingersoll [m^3]

Ingersoll station		Baseline SE (i)	Infinite SE (ii)	Change [%]
Historic climate	(a)	7.050E+09	7.605E+09	+7.87 %
Wet climate	(b)	7.605E+09	8.905E+09	+17.09 %
Dry climate	(c)	6.785E+09	7.144E+09	+5.30 %
Change (b) – (a)	[%]	+7.87 %	+17.09 %	
Change (c) – (a)	[%]	−3.76 %	−6.05 %	

intensive agricultural practices, the River Bend sub-basin has issued a significant number of water permits. Long-term cumulative water balance, presented in Fig. 11b, reveals that the local groundwater recharge rates are not sufficient to sustainably replenish groundwater aquifers. It can be concluded that in the future, under all three climate conditions, local aquifers will be exposed to a severe pressure. However, this conclusion should be investigated in more details as the model currently does not account for interactions between the local aquifers and large water bodies, such as the neighboring Great Lakes.

One of the main questions that a spatially explicit agent-based model is designed to address is how changes caused by socio-economic activities affect the hydrologic cycle in the Upper Thames River basin. Tables 2, 3 and 4 show the total runoff volume at three flow gauging stations (Byron, Ingersoll and St. Marys) during the course of simulation (20 years) for three climate conditions and two socio-economic scenarios. The presented results reveal two important insights in the system's hydrologic behavior.

First, the initial assumption is that the higher rates of urbanization are influencing the ground water recharge rates since a larger portion of rainfall ends up in rivers and streams, thus increasing the volumes of surface runoff. As expected, the different climate conditions demonstrate the variability in volumes, but, more importantly, the results show the increased volumes of surface runoff in the case of infinite natural resources scenario. For instance, in the case of historic climate conditions, the Byron station experiences 4.76 % higher runoff volumes as a response to more intensive urbanization process compared to the baseline socio-economic scenario (see Table 2). The same trends are observed for other two stations, Ingersoll and St. Marys (see Tables 3 and 4, respectively).

Second, the presented results do not show a significant variability of mean runoff between different climate scenarios as observed in the previous studies (Prodanovic 2007). The reason for this lies in the choice of initial climate datasets. Datasets used in this research were

Table 4 Changes in total runoff volumes at St. Marys [m^3]

St. Marys station		Baseline SE (i)	Infinite SE (ii)	Change [%]
Historic climate	(a)	2.531E+09	2.676E+09	+5.73 %
Wet climate	(b)	2.891E+09	3.118E+09	+7.86 %
Dry climate	(c)	2.278E+09	2.487E+09	+9.14 %
Change (b) – (a)	[%]	+14.21 %	+16.51 %	
Change (c) – (a)	[%]	−9.97 %	−7.07 %	

originally created to define three different climate conditions in the period between 2000 and 2100. On the other hand, available socio-economic data requested that the socio-economic model is developed for the period between 2000 and 2020 with a monthly time step. The relatively short simulation horizon (only 20 years) is the main reason why significant variability is not present in the hydrologic system response.

6 Summary

The main objective of this research is to provide a simulation method that practically implements the basic ideas and seven guiding principles of IWRM. First, the presented modeling framework supports the systems view principle by recognizing a broad set of critical dependencies among water and land resources on one side, and socio-economic environment on the other. Second, it allows for the representation of the roles of different levels of responsibilities characteristic for water resources systems, both vertical and horizontal. Third, the developed framework requires a multidisciplinary approach to deal with complex water resources systems in a holistic way. By representing each individual actor in the system, this modeling framework ensures active involvement of all stakeholders providing support for their individual contribution to the decision making process. The framework makes the IWRM process more certain by supporting the descriptive assessment of modifications to water and land resources caused by human activities. Adaptation principle is supported by building the feedbacks and interactions that take place in water resources system so that adaptive decisions can be made. Finally, the presented framework benefits from the knowledge of numerous scientific disciplines interacting within the IWRM (hydrology, hydraulics, geology, meteorology, engineering, economics, regional planning, etc.)

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