

1. Introduction

Entire natural ecosystem and human society essentially depend on the presence of water. However, available water resources are limited. Dynamic human population growth, social and economic development of human society, change of land use and urbanization, and high levels of contamination are imposing additional pressure on limited resources. They are also affected by alterations of the hydrological cycle caused by climate change. Food production, human health and wellbeing, industrial development and natural ecosystems are highly endangered, requiring a more efficient water resources management. Considering the complexity and scale of the problem, the Global Water Partnership (GWP) has introduced the concept of Integrated Water Resources Management (IWRM) as a process promoting 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).

Simonovic (2009) elaborates on seven guiding principles of the IWRM: systems view, integration, partnership, participation, uncertainty, adaptation, and reliance on strong science and reliable data. In order to completely satisfy the comprehensive definition and presented principles, IWRM implementation process requires:

- i. Establishment of feedback system structure to capture dynamics of water resources system behavior;
- ii. Integral representation of physical and socio-economic systems;
- iii. Proper consideration of complex spatial and temporal scales; and,
- iv. Partnership provision.

Dynamic complexity of natural and water resources systems is a result of a system structure and the interaction between system elements in time. The main properties of natural systems particularly important for IWRM are (Simonovic 2009):

- Complexity of a system structure and interactions between system elements;
- Variability of system structure and interactions between system elements with time and location in space.

Numerous tools developed and applied to IWRM process primarily concentrate either on spatial or temporal variability of the system, rarely on both. In general, they combine physical components of the system (i.e. hydrology) with analytical tools (i.e. optimization techniques). For instance, Ximing et al. (2002) examine the use of specific sustainability criteria incorporated into a long-term optimization model of river basin. This model takes into account water supply risk minimization, spatial and temporal equity of water allocation, and economic efficiency of infrastructure development. In order to achieve the optimal water resources management practice, short-term decisions are guided by long-term plans based on sustainability criteria. On the other hand, Ward et al. (2006) directly integrate physical components with economic water related benefits in a quadratic objective function to define the optimal water use. Mainuddin et al. (2007) develop a coupled

hydrologic-economic spreadsheet model that analyzes the water allocation between different sectors under alternative policy scenarios. Developed model optimizes the profit and water allocation subject to hydrological and economic constraints defined by the policy scenarios. Raymond et al. (2012) recognize accurate prediction of pollutant loadings crucial for determining operative water management strategies and use artificial neural networks as predictors of the nutrient load in a watershed. Moreover, Clavel et al. (2012) use integrated models and information systems to assess the land-use visions of various stakeholders using their own evaluation criteria, while Coelho, Labadie and Fontane (2012) develop a tool to support IWRM which integrates three components (GIS, Fuzzy set theory, and dynamic programming algorithm) to delineate homogeneous regions in terms of hydrography, physical environment, socio-economy, policy and administration.

As a conclusion, consideration of spatial and temporal scales varies from one approach to another, as well as their ability to address all specific requirements of the IWRM process.

This paper discusses the initial development stage of an analytical tool to support the IWRM process. Proposed methodology aims at describing dynamic behavior, in time and space, resulting from the complexity of water resources system structure and characters of the relationships between the system elements. Moreover, proposed methodology addresses all four previously defined requirements of the IWRM process.

Section 2 of the paper presents the system architecture. Section 3 describes the practical system application to the Upper Thames river basin, Southern Ontario, Canada. Section 4 lays down the directions for future work and presents the conclusions of the work completed up to now.

2. Integrated analytical tool for support of the IWRM process

Recognized challenges of IWRM and its implementation principles necessitate a systemic approach. Systems approach provides a framework for water resources problem analysis and decision making by using the set of rigorous methods to determine preferred designs, plans and operation strategies for complex water resources systems (Simonovic 2009). Those methods can be classified in three major groups: simulation, optimization and multi-objective analysis. The systems approach offers a support for “bottom-up” planning by including the interactions between various bio-physical, socio-economic and institutional sectors, for the purpose of generating the capacity needed for effective and integrated water resources management. Water resources management system can be perceived as a result of interaction of three sub-systems:

- i. River basin sub-system in which physical, chemical and biological processes take place;
- ii. Socio-economic sub-system which includes human activities related to the exploitation of natural system; and
- iii. Administrative and institutional sub-system where decisions and planning processes take place.

System dynamics simulation is one of the system analysis tools that provide effective support for the implementation of IWRM principles. The system dynamics simulation (SD) is defined as a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior (Forrester 1961). The main advantage of system dynamics simulation lies in utilization of the feedback structure and control, and, therefore, it presents a powerful approach for describing temporal variability of system behavior (Simonovic 2009). In addition, this approach allows direct description of the complex structure of water resources systems that includes physical and socio-economic sub-systems.

System dynamics simulation has been applied to a variety of WRM problems, for instance: drought management studies by Keyes and Palmer (1993); management of scarce water resources by Fletcher (1998); reservoir operation for flood control by Ahmad and Simonovic (2000); hydrologic studies under climate change by Simonovic and Li (2003) and other.

In general, system dynamics simulation models represent a mathematical simplification of a complex reality. The main premise of SD simulation is that system structure, represented as a set of system elements connected by feedback loops, determines the system behavior, and therefore, it contains a set of equations describing dynamic change of observed variable (Sterman 2000). This enables computation of the preferred system state variable at any point in time.

The main shortcoming of system dynamics simulation for support of the IWRM process is its inability to capture spatial dynamics of the water resources problems. This paper presents a new approach that integrates system dynamics simulation with agent-based model in the Integrated Multi-Agent System (IMAS) capable of capturing temporal and spatial dynamics of complex water resources systems. The same methodology may be implemented in various domains, such as ecosystem modeling, natural resources management, climate change impact assessment or disaster management. The focus of this paper is on (a) the introduction of the methodology; (b) initial implementation to a water resources problem; and (c) the illustration of how the IMAS fits the IWRM process.

2.1. IMAS architecture

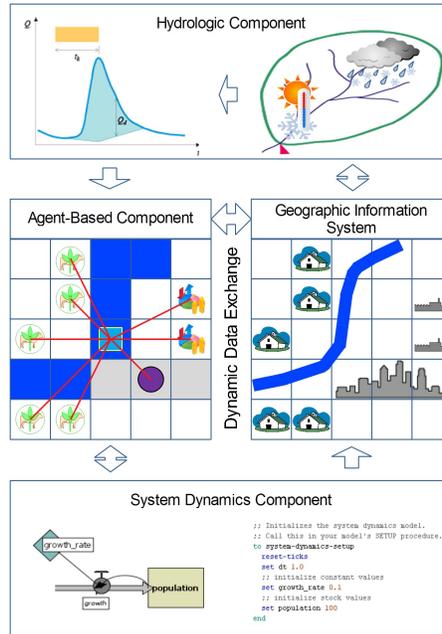


Figure 1. The Integrated Multi-Agent System (IMAS) Architecture

IMAS consists of four loosely coupled components:

- i. GIS;
- ii. Hydrologic simulation model;
- iii. Multi-agent model; and
- iv. System dynamics simulation model.

Primary requirement of the IWRM process - integrated consideration of spatial and temporal variability - is addressed through dynamic data exchange between system components. Physical and GIS IMAS components provide physical (in this case - hydrologic) and spatial information to multi-agent and system dynamics components, which are able to identify alterations in spatial structure over time, and then communicate this information back to GIS. Figure 1 presents the generic IMAS architecture, data and information flows between the system components.

Theory suggests three strategies for integration of multiple computational components: *embedded coupling*, *tight coupling*, and *loose coupling* (Ahmad 2002). The initial version of IMAS presented in this paper uses a loose coupling strategy where all components are developed independently and their interaction is achieved through a set of input/output ASCII files. A tight coupling strategy is being currently investigated.

2.2. IMAS components

Figure 2 shows a detailed schematic representation of the system components with their modules and identifies key operational variables. Following section of the paper describes the IMAS structure, details system components, and presents the functionalities of each component.

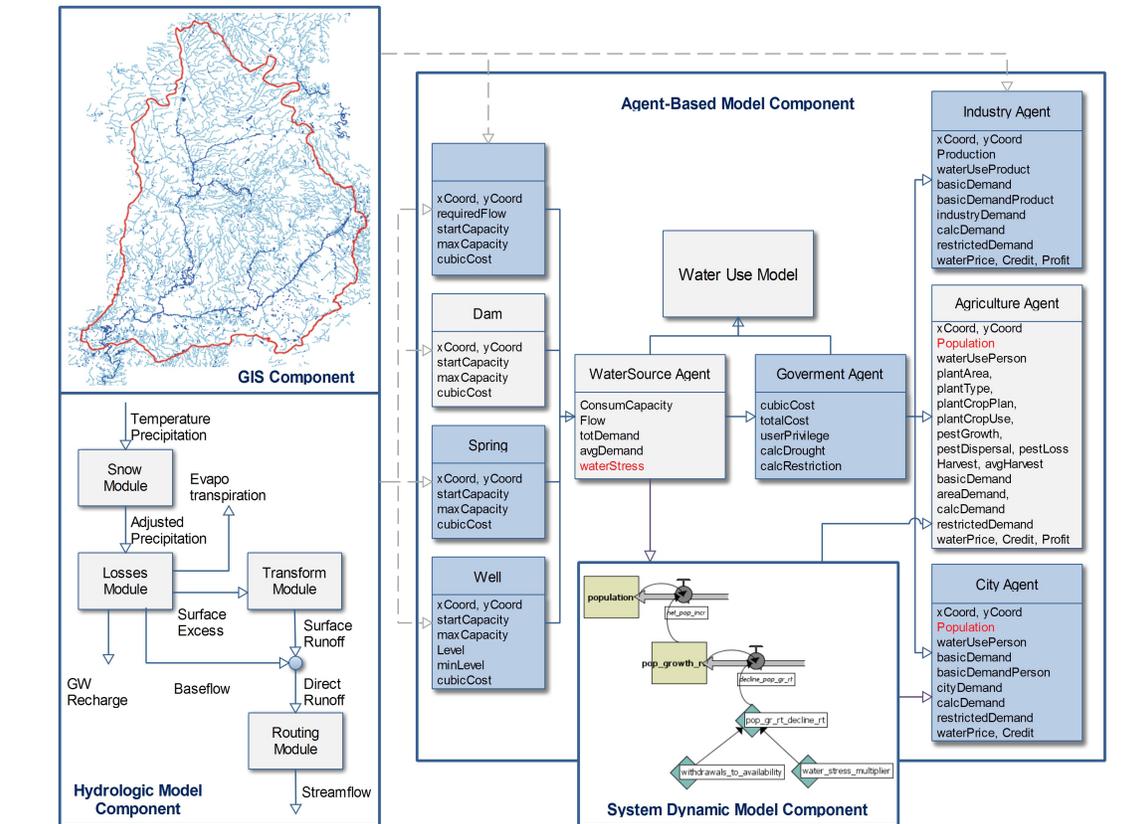


Figure 2. Overview of the IMAS structure (after Gunkel, 2005 and Prodanovic and Simonovic, 2007; 2010)

2.2.1. GIS component

The core of the system is Geographic Information System (GIS) model, which in addition to its primary function of collecting, processing, analyzing and visualizing spatial data, has a role of database and system interface. GIS provides the information on physical properties of the system, in this case – a watershed. GIS model provides information on watershed boundaries, identifies flow paths, determines flow directions, etc. GIS role within the IMAS is to:

- (a) Store the data and manage databases;
- (b) Distribute information to other IMAS components;
- (c) Provide a base for spatial analysis; and
- (d) Present the results.

GIS model within IMAS supports the inventory of available data and mapping of different physical system properties. Inventory includes environmental, social and economic data. For example, a complete inventory includes information on land use, available water resources, water users and polluters, population, agricultural production, ecological information, and economic conditions within the watershed.

2.2.2. Physical component - hydrologic simulation model

The hydrologic model is a mathematical representation of complex hydrologic processes within the watershed. Continuous hydrologic model component developed for this study is based on the HEC-HMS (USACE 2000). Continuous hydrological model has been developed, calibrated and verified in previous studies of the Upper Thames River basin (Cunderlik and Simonovic 2004; 2005; 2007).

The precipitation for the time interval Δt is separated into solid (snowfall) or liquid (rainfall) form based on the average air temperature for the time interval Δt . The solid precipitation is then subject to the snow accumulation and melt algorithm. At each time interval Δt , the melted portion of snow, if any, is added to the liquid precipitation amount. Precipitation adjusted by the snow component falls on pervious and impervious surfaces of the river basin. Precipitation from the pervious surface is subject to losses (interception, infiltration and evapotranspiration) modeled by the precipitation loss component. The 5-layer soil-moisture accounting (SMA) model is used to estimate and subtract the losses from precipitation. The SMA model can be used for simulating long sequences of wet and dry weather periods. There are four different types of storage in the SMA model: canopy-interception storage, surface-depression storage, soil-profile storage, and groundwater storage (the model can include either one or two groundwater layers). The movement of water into, out of, and between the storage layers is administered by precipitation (input into the SMA system), evapotranspiration (output), infiltration (movement of water from surface storage to soil storage), percolation (from soil storage to groundwater storage 1), deep percolation (from groundwater storage 1 to groundwater storage 2), surface runoff (output), and groundwater flow (output). For computational details of the SMA model, see USACE (2000,). Precipitation from the impervious surface runs off with no losses, and contributes to direct runoff. The output from the precipitation loss component contributes to direct runoff and to groundwater flow in aquifers. The Clark unit hydrograph is used for modeling direct runoff. In the Clark method, overland flow translation is based on a synthetic time-area histogram and the time of concentration. Runoff attenuation is modeled with a linear reservoir. The groundwater flow is transformed into baseflow by a linear reservoir baseflow model. In this model, outflows from SMA groundwater layers are routed by a system of baseflow linear reservoirs. Both overland flow and baseflow enter the river channel. The translation and attenuation of water flow in the river channel is simulated by the modified Puls method. This method can simulate backwater effects (e.g. caused by dams), can take into account flood-plain storage, and can be applied to a broad range of channel slopes. The modified Puls method is based on a finite difference approximation of the continuity equation, coupled with an empirical representation of the momentum equation. The effect of hydraulic facilities (reservoirs, detention basins) and natural depressions (lakes, ponds, wetlands) is reproduced by the reservoir component of the model. Outflow from the reservoir is computed with the level-pool routing model. The model solves recursively one-dimensional approximation of the continuity equation.

2.2.3. Multi-agent component

Multi-agent methodology presents an innovative approach in software engineering, social, economic, and environmental modeling (North and Macal 2009). It facilitates

direct representation of an individual system actor, description of its behavior and its interaction with other individual system components. Intelligent agent (IA) represents the core of multi-agent models and it is defined as an autonomous entity which is able to perceive the environment, through physical sensors or input data files, and to act on it (Wooldridge 2009). All activities of an intelligent agent are directed toward achieving desired and prescribed goals. Depending on their structure, intelligent agents can be very simple, described by simple rules (for example, a thermostat that has two defined actions on or off, depending on the perception of temperature in environment) or very complex, described by complex behavioral models in domain of cognitive science and artificial intelligence (North and Macal 2009). The main attributes of an intelligent agent include: autonomy, reactivity, communication, adaptation, flexibility, and spatial awareness (Ferber 1999). The full potential of intelligent agents lies in their ability to interact with each other and to work together towards a goal. This interaction is known as “social ability” of intelligent agents. In computer science, intelligent agents are related to software agents, autonomous software programs performing the task given by the user. Hence, intelligent agents can be described as abstract functional systems similar to computer programs. Multi-agent system enables spatial definition of system elements – actors (for example in our case water users). By definition of a location of an element in space and behavior at individual level, we obtain the global system behavior as a result of interaction between many individuals, each following its own goal, living together in some environment and interacting with each other and the environment (Wooldridge 2009).

Multi-agent systems enable empirical description of human-environment interactions. These systems represent actors in more natural way, either as individuals or institutions. Agents can have simple set of goals, beliefs and available actions. This approach is not limited by the amount of data about agents’ behavior and their relationships (Gunkel 2005). Proper design of a multi-agent system necessitates definition of representative system actors – agents, desired goals, critical amount of time for goal achievement, available actions of agents, and uncertainties of environment.

In this research, a multi-agent model is developed to describe socio-economic aspects of water resources allocation between agricultural users in a watershed and it is based on the Bali irrigation system model, presented by Lansing and Kremer (1993). The model is developed in Netlogo multi-agent programmable environment (Wilenskiy 1999).

Figure 3 presents a principal structure of the agent-based model component, and shows graphically the decision making tree as a function of the water use, water source and government agents. Multi-agent model consists of two functionally different components: environment and a set of agents (system actors) living in the environment. Environment has a form of a regular squared grid, while the precise spatial distribution of agents is defined by the GIS component. Multi-agent model contains three classes of agents:

- (a) Water source agents;
- (b) Water user agents; and
- (c) Administrative agents.

Four types of water source agents are introduced: rivers, reservoirs, springs and wells. The information on capacity of each water source is imported from the physical (hydrologic) system component.

Water user agents are divided into three groups: municipal, industrial and agricultural. Spatial distribution of households and population is not of particular importance for this model. Therefore, the municipal and industrial water demands in the watershed are represented by only two water user agents. On the other side, the agricultural agents represent farms as decision making units. Each agricultural agent is characterized by a portion of arable land (name of the variable in the model: *plantArea*). It involves one or several land parcels owned by a farm. Every year an agricultural agent defines the crop type and spatial crop pattern for the upcoming season (variable: *plantType*). The selected crop consequently defines planting schedule (variable: *plantCropPlan*), seasonal plan of the crop evolution (variable: *plantType*), and plan of seasonal water consumption (variable: *plantCropUse*).

Administrative agents represent the administrative structure that exists within the watershed: local institutions, regional institutions, provincial institutions and/or federal institutions. These agents have legislative and regulatory roles in establishing price of water, allocating water permits, determining prioritization of water rights in extreme conditions, water allocation during dry seasons, and similar.

Simulation time step is one month, while the time interval of study is 50 years. Monthly agent activities determine their monthly water demand:

$$productDemand = productWaterUse * Product \quad (1)$$

$$personDemand = personWaterUse * Population \quad (2)$$

$$plantDemand = (plantCropUse - Rain) * plantArea \quad (3)$$

Irrigation water demand depends on the difference between crop water demand (variable: *plantCropUse*) and precipitation (variable: *Rain*). The overall demand is obtained using Equation (3). Industrial water demand is defined by Equation (1) as a function of the industrial product (variable: *Production*) and the amount of water required by the particular product (variable: *productWaterUse*). Municipal water demand as per Equation (2) depends on the population (variable: *Population*) and the assessed per capita water use (variable: *personWaterUse*).

Based on the defined water demands and available water resources, the model assesses the ability of agents to obtain requested quantities of water (*Water consumption*, Figure 3), introduces the necessary measures of water resources management during dry seasons (*Water supply during drought*) and, finally, initiates the adequate action of the administrative agent. Based on the available quantities of water, the agricultural agents provide: plant growth rate, pest growth rate, and harvest yield. The harvest yield (variable: *Harvest*) is calculated:

$$Harvest = plantStage * yldMax * (1 - Pest * pestSens) * area \quad (4)$$

PlantStage variable represents a fraction of the water demand that is actually met and it ranges between 0 and 1; *yldMax* is the maximum crop yield under optimal climate conditions and water reserves; *pestSens* represents crop losses to pests.

The goal assigned to agricultural agents is to maximize the financial effects of the crop yield while minimizing the water consumption expressed through water stress index. The water stress is defined as the deficiency in water for meeting the municipal demand or agricultural production. For instance, if a crop takes *X* months to grow, each month the crop is assumed to grow by $1/X$. If only a fraction $Y < 1$ of the required water is provided, the crop growth that month is reduced to Y/X . The agents are able to learn, evolve and modify the cropping patterns to achieve higher yield. At the beginning of the season, agents can adapt new cropping patterns, while evaluation of selected cropping patterns is done using *CropYield* variable. The agents are able to imitate the cropping patterns of neighboring agents which resulted in higher yields during the previous year.

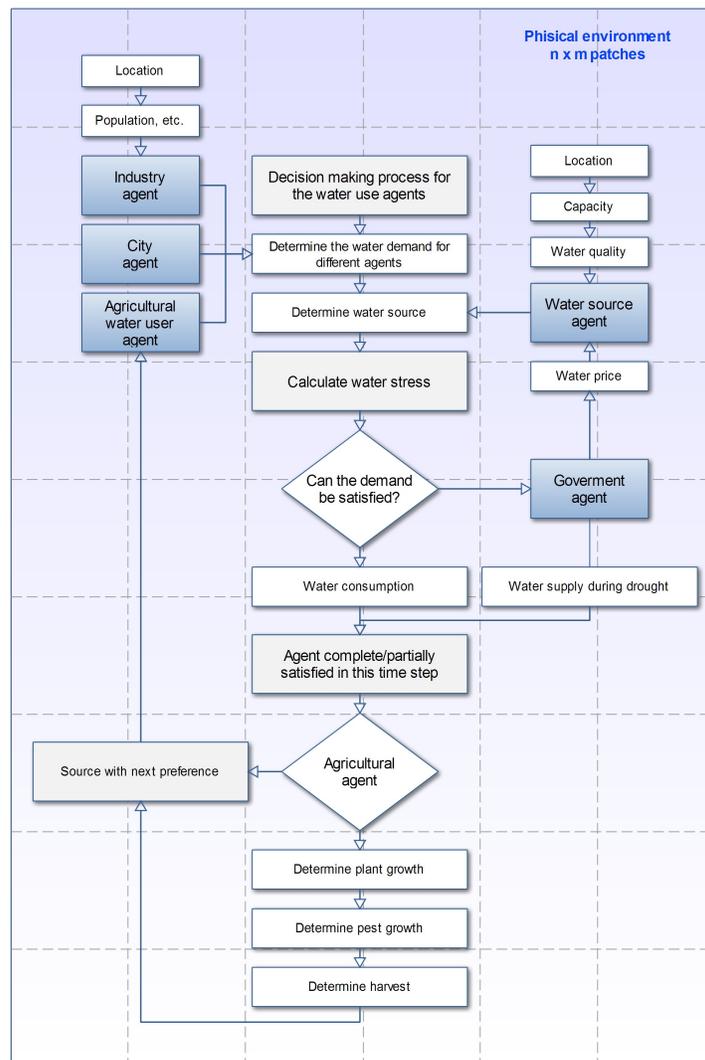


Figure 3. Principal structure of the IMAS agent-based model component

2.2.4. System dynamics simulation component

System dynamics simulation mathematically and graphically describes the structure of the system, its elements and their interactions. In presented system, the system dynamics simulation is utilized to define certain behavioral characteristics of selected agents. Netlogo System Dynamics Modeler (Wilenskiy 1999) is used to capture demographic dynamics as shown in Figure 4. Demographic dynamics functionally depend on the available water resources. Water resources availability coefficient (*WaterStressMultiplier*) is calculated for each water source, and then used with the system dynamics IMAS model component. This model describes the population dynamics of the region under consideration through the change in value of variable *Population*. The growth/decline of population is a function of population growth rate, which is influenced by the water stress and withdrawal to availability ratio.

$$Population(t) = population(t-1) * population_growth_rate \quad (5)$$

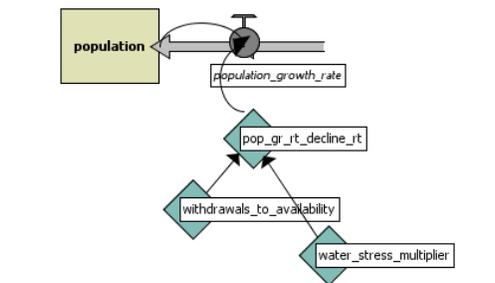


Figure 4. Stock and flow diagram of population dynamics

The system dynamics simulation is also used to describe the crop growth as a function of available water resources and to model the pest growth.

3. The case study

Presented methodology included in the initial version of IMAS is tested on the Upper Thames River basin, Southern Ontario, Canada.

3.1. Water resources management problem definition

Figures 5 and 6 present the Upper Thames river basin with total area of 3,432 km² (UTRCA 2006). Approximately 78% of the total surface is dedicated to agriculture, while urban areas and forests cover 9% and 12%, respectively. Remaining area is categorized as quarries or water bodies (UTRCA 2006). According to the census data (UTRCA 2006), the Upper Thames river basin has population of 485,000 with majority living in the City of London (433,000). Other urban centers are Mitchel, St. Mary's, Stratford, Ingersoll, and Woodstock. Average precipitation depth is 1,000mm/year. Thames River has two main branches. The north branch flows south from the top of the basin, near the municipality of Mitchel. The south branch flows

south-west from the eastern part of the basin. Thames River enters the Lake St. Claire north of Tilbury. Average annual discharge is $35,9\text{m}^3/\text{sec}$. The Upper Thames river basin is divided into 28 sub-basins, Figure 6.



Figure 5. The Upper Thames Watershed, Southern Ontario, Canada

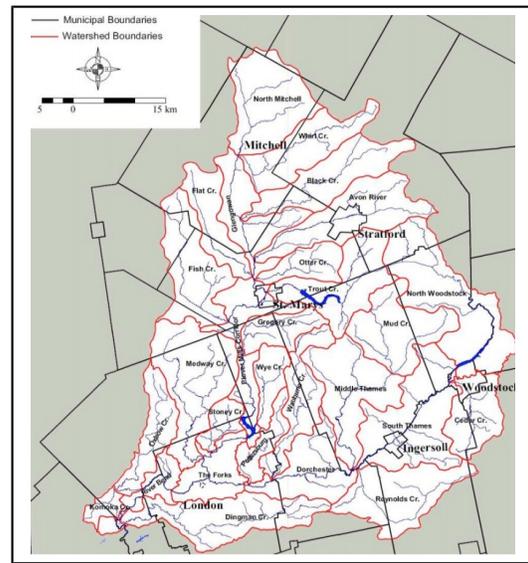


Figure 6. The Upper Thames River Sub-basins

A system of three reservoirs is implemented for the purpose of flood management. Wildwood, Pittock and Fanshawe reservoirs are also important local recreational facilities. Moreover, Wildwood and Pittock augment the river flow during dry seasons. The Wildwood dam offers 24.7 million of cubic meters of storage. The maximum total discharge capacity is $565\text{ m}^3/\text{s}$. The main function of the Pittock reservoir is also flood protection. The reservoir is 10.3 kilometers long. The Fanshawe dam was constructed in the period between 1950 and 1952 with the main function to prevent flooding caused by intensive rainfall events and snowmelt in the upper regions of basin. Typical summer reservoir discharge is $4\text{ m}^3/\text{s}$. The full storage capacity is 48 million cubic meters, while normal operating storage is 12 million cubic meters.

In order to test the presented methodology, the initial version of IMAS focuses mainly on agricultural water demand and allocation of available resources to agricultural users. The initial version consists of 28 sub-basins acting as independent agents. They represent groups of water managers, in this case farmers, responsible for crop pattern selection in each sub-basin. An assumption is introduced that the three watershed reservoirs are the only water sources - points where agents acquire appropriate quantities of water. Unused water returns to the reservoirs. Each sub-basin has certain percent of land area dedicated to agricultural activities. Arable land and selected crops determine the total water demand. The main objective of this initial version is to represent interactions between responsible water managers in order to define the policy which would maximize the potential agricultural benefits subject to available water resources and minimum water consumption.

Physical IMAS environment is represented by the spatial grid of 25 x 30 cells. The resolution of a single cell is 3,000 x 3,000 meters (the smallest rectangular area that covers watershed boundaries). The 28 sub-basins represent agricultural agents responsible for water management. Various crop choices include: barley, corn, oats, spring wheat, winter wheat, canola, and soybeans. They all have their own water demand. Data required for the model setup include: (i) physical watershed information and spatial distribution of water sources and water users; (ii) behavior of agents, available actions, and interactions between agents; (iii) hydrologic information – precipitation and capacity of each water source; and (iv) crop water demand over the season.

Geographical properties of the basin and spatial distribution of agents are defined in the form of GIS database (water courses, water bodies, basin boundaries, sub-basins, municipalities, households, etc.). Spatial information is converted into Netlogo environment, while required additional information on agents and their relations, hydrologic information, and crop information are imported via ASCII files.

3.2. Simulation scenarios and initial results

The initial version of IMAS is developed in the Netlogo environment (Wilensky 1999) that enables the graphical interpretation and control over the model. Figure 7 shows the main control window. A user is provided with the graphical tools for model execution and preparation of different simulation scenarios. The graphical interface allows selection of different techniques for presentation of GIS data, agents and their relations. User can also modify certain parameters during the simulation. Results of the simulation are presented in graphical form. The initial version of the IMAS provides the following results for each spatial unit or particular agent: average harvest per hectare (t/ha); total annual harvest (t/year); population dynamics; and water stress index.

to agriculture. It is assumed that one agent represents one sub-basin. Each agent is responsible to define the crop plan for the next season. Selection of crop plan is done in two ways:

- it can be predefined in the form of an input file;
- or randomly selected by the model.

Based on the selected crop, a water demand is defined as a product of the agricultural land in the sub-basin and a basic crop demand per hectare. Water price is defined by the Administrative agent and is assumed to be 1.60 \$/m³.

Agents are capable to imitate the cropping patterns of neighboring agents which have a higher crop yield in previous year. Consequently, the harvest revenues become constant over the years, while the water stress coefficient is minimized, Figure 8.

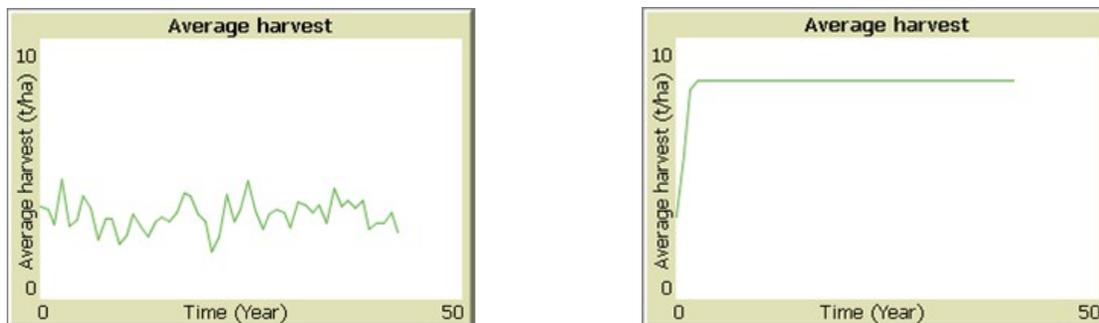


Figure 8. Plant selection scenarios: Random Selection of crops (left), optimized crops selection (right)

The crop yield depends on the available the water resources, level of water stress index, and presence of pests. Pests' dynamics scenarios, their spatial distribution and their impacts on crops are defined by the *pestGrowth* and the *pestDispersal* model variables. Figure 9 compares effects of two different pest dynamics scenarios on crop yield over the whole basin. First scenario defines pest growth rate of 2.0 and pest dispersal rate of 0.60, while second scenario involves slightly higher rates of pest growth and pest dispersal, 2.4 and 1.50, respectively. The average harvest is evidently higher in the case of lower pest growth rates.

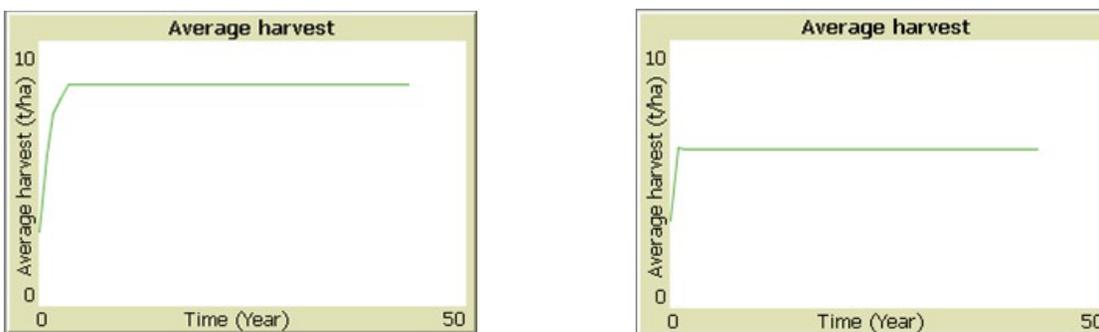


Figure 9. Pest scenarios: Low pest growth scenario (pest growth rate = 2.00, pest dispersal rate = 0.60) (left), and High pest growth scenario (pest growth rate = 2.40, pest dispersal rate = 1.50) (right)

4. Conclusions

The proposed methodology tests the potential of integration of various tools for providing complete support of IWRM within a watershed. Four different components are assembled within IMAS: (i) GIS model; (ii) hydrologic model; (iii) agent-based simulation model; and, (iv) system dynamics simulation model. The initial test of IMAS is conducted using 28 sub-basins of the Upper Thames River as intelligent agents. Each agent has a role of a water manager responsible for defining the agricultural plan for appropriate sub-basin. Therefore, agents define the cropping plan for upcoming year. Agents are given the only one goal in the initial phase - to maximize crop yield revenues while minimizing the water consumption and water stress index. In addition to spatial units, the aggregated water user groups (population and industry) as well as water resources (three reservoirs) have been also represented as agents. Population dynamics variation is described with the SD model components, while reservoirs are provided with information on available water resources from the hydrologic model component.

Initial simulation results demonstrate the potential of IMAS for the application in integrated water resources management. Further IMAS model development continues in two directions. First, the real world model application is being developed (presenting each single water user - households and/or farms) with the introduction of different types of agents with their own behavior, set of actions and goals. Second, the tight integration of IMAS model components is being developed within a single user interface.

However, the proposed methodology requires resolution of existing limitations. First limitation is a standardized communication between agents. It would allow interaction between agents that have been created independently, possibly by different users, and their integration into a single model. This implies resolving the two fundamental issues: the lack of clearly defined methodology for agent's development and absence of extensive and standardized applications for multi-agent systems development. Another important question is the model validation. Standardized techniques of agent-based model validation still have not been fully established (Feulliette et al. 2005; Gunkel and Kulls 2005).

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