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GENERIC MODELING FRAMEWORK FOR INTEGRATED WATER RESOURCES MANAGEMENT

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ABSTRACT: By definition, integrated water resources management (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 disasters. Complexity is a result of water resources system structure and interaction between system components. This paper presents a generic modeling framework which integrates: (i) geographic information system (GIS); (ii) system dynamics simulation model (SDS); (iii) agent-based model (ABM); and (iv) a set of physical models (hydrologic, hydraulic, water quality, reservoir operation, and river hydrodynamic). Selection of tools is driven by their ability to (a) respond to the main requirements of the IWRM; (b) properly capture the system structure; and (c) explicitly present the system behaviour as function of time and location in space. System dynamics simulation captures temporal dynamics in an integrated feedback model that includes physical and socioeconomic sectors. Management policies established in the participatory decision making environment are easily investigated through the simulation of system behaviour. Agent-based model is used to analyze spatial dynamics of complex physical-social-economic-biologic system. The IWRM modelling framework is tested using data from the Upper Thames River Watershed located in Southwestern Ontario, Canada, in collaboration with the Upper Thames River Conservation Authority.

KEYWORDS: Integrated water resources management; agent-based model; system dynamics simulation

1. INTEGRATED WATER RESOURCES MANAGEMENT

Major challenges of human civilization include water, food, energy and environment. Having water as a common element, the nature of these problems is fundamentally identical and represents a direct consequence of serious pollution of natural resources**.** In addition, temporal and spatial distribution of water resources is significantly altered by the climate change processes caused by the natural cycles and effects of socio-economic development. Recognizing the complexity of the challenges, the Global Water Partnership (GWP) has introduced the concept of Integrated Water Resources Management (IWRM) which is defined as 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). Simonovic (2009) recognizes seven guiding principles to properly address IWRM challenges: 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 between system sectors in order 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.

Adopted definition and guiding principles imply that integrated water resources management 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 to meet the social and environmental needs while preserving natural balance of the entire ecosystem. In general, a system represents a set of structural and non-structural elements that are organized in such a way as to achieve some specific objective through the control and distribution of material resources, energy and information, (Simonovic 2009). On the other hand, water management systems are defined as natural water systems combined with all human-made systems, including guiding legislations, such as policies, acts or regulations. Consequently, the complexity of water resources systems is a result of a system structure and interactions between system elements, and, variability of the system structure and interactions between system elements with time and location in space. Complex structure of water resources systems necessitates a holistic, systems approach**.** Systems view of the IWRM process suggests that water resources systems cannot be analyzed in isolation, but they must also take into consideration all interactions with human and environmental systems. The systems approach represents a framework for water resources analysis and decision making in which assumptions, objectives and criteria are rationally identified. It represents a general problem solving technique in engineering planning and design. To analyze large-scale systems methodically, system analysis uses a combination of rigorous methods in order to identify ‘best’ designs or operational plans (Simonovic 2009). Techniques used for this purpose in water resources management are:

- Simulation;
- Optimization; and
- Multi-objective analysis.

Implementation of water resources management programs is a demanding task because of wide-ranging implications of decisions on not only physical, but also sensitive socio-economic environment. Transformation of qualitative ideas into very concrete plans of action is extremely delicate area of water resources management which requires support of contemporary information technology. Numerous modeling frameworks, which combine not only different techniques of systems analysis, but also different modeling methodologies, have been developed and applied to the IWRM process. However, they primarily concentrate either on spatial or temporal variability of the system, rarely on both. Generally, they combine physical components of the system (i.e. hydrology) with analytical tools (i.e. optimization techniques). For instance, Ward et al. (2006) directly couple two techniques of systems analysis: physical components of the system integrate with economic water related benefits in a quadratic objective function in order to define the optimal water use. Mainuddin et al. (2007) develop an integrated hydrologic-economic spreadsheet model that analyzes the water allocation challenges 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, while Coelho et al. (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.

This paper presents a modeling framework under development which supports the systems view of IWRM process. Proposed methodology addresses all previously defined requirements of the IWRM process and aims to describe behavior of the system, in time and space, resulting from the complexity of system structure and properties of the relations between the system elements by combining different modeling technologies.

2. ARCHITECTURE AND METHODOLOGY OF GENERIC MODELING FRAMEWORK

The most significant documents that formally regulate main principles of water resources management, such as European Water Framework Directive, suggest that water resources are managed on a level of watershed, independently from international or any other geographical boundaries. Also, Canadian province of Ontario implements protection, management and restoration of rivers, lakes and streams on watershed scale executed by the 36 watershed conservation authorities (UTRCA 2012). Consequently, process of watershed-based management requires sophisticated tools to accompany and support the decision making. To fully support the systems view, these tools should not only represent physical processes independently, but also they need to establish feedback links between socio-economic environment and physical segments of the system. In that sense, a water resources management system can be perceived as a result of interaction of three sub-systems:

i. River basin system in which physical, bio-chemical and environmental processes occur;
ii. Administrative and institutional system where decisions and planning processes take place; and
iii. Socio-economic system which includes human activities related to the use, protection of and protection from water.

The core of water resources system is a *physical system* (PS) which represents all physical features and processes (e.g. physical, chemical, and biological). Physical system is managed by the *operational rules and regulations* (ORR) which define and make operational decisions and manage the physical system (e.g. administrative or institutional). Based on the inputs of *socio-economic sector* (SES) of the system, and after defining the goals and objectives of water resources system, ORR selects appropriate operational rules from the set of available options and implements the decisions. All operational decisions, through the feedback links, affect both physical and socio-economic systems.

Figure 1 presents a generic architecture of the proposed analytical framework which combines different tools to capture the complexity of water resources systems. Suitable selection of suggested modeling methodologies is driven by their ability to (a) respond to the main requirements of the IWRM; (b) authentically represent the system structure; and (c) explicitly present the system behaviour as function of time and location in space. The architecture of proposed modeling framework contains four main components:

1. *Relational database model*;
2. *Physical component of the system*: Hydrologic, Groundwater, Reservoir Operation, Hydrodynamic and Water quality models;
3. *Operational component of the system*: Agent-based model;
4. *Socio-economic component of the system*: System dynamics simulation model; and
5. *Spatial Database Management*: Geographic Information System (GIS).

Integral consideration of spatial and temporal variability, as a primary requirement of the IWRM process, is addressed through data exchange between system components. The physical models provide spatial and temporal qualitative and quantitative information on the state of water resources in the system (Hydrologic, Groundwater, Reservoir Operation, Hydrodynamic, and Water Quality). Operational segment of the system is represented by means of an agent-based model. This model analyzes spatial dynamics of decision-making actors based on the current state of the physical system and requirements of the socio-economic system. System dynamics simulation captures temporal dynamics in an integrated feedback model that includes sectors representing socio-economic system on a watershed level. Management policies defined in the participatory decision making environment are then easily investigated through the simulation of system behaviour.

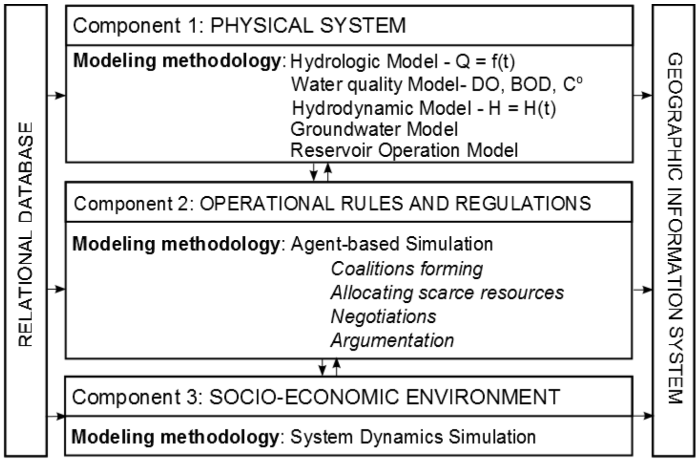

Figure 1. Proposed modeling framework for integrated water resources management.

We recognize two levels of integration in the implementation process of the proposed modeling framework. The first level refers to integration of different modeling components (such as physical process model, system dynamics simulation and agent-based simulation), while the second level refers to the integration of different models within the same component of the framework (for example, hydrodynamic and water quality models within the physical component) or different techniques of systems analysis within the component (for example, simulation and optimization). Following sections give brief information on applied methodologies and justify how particular methodology fits requirements of IWRM system representation.

2.1. First Level of Integration

2.1.1. Spatial Database Management: *Geographic Information System* (GIS)

Geographic Information System (GIS) represents the core of the system. Its primary function is to process, analyze, and visualize spatial information. GIS provides required information on physical properties of the watershed, such as watershed boundaries, flow paths, flow directions, etc. It holds an inventory of available data, such as environmental, social and economic data. For example, a comprehensive inventory contains information on land use patterns, spatial and qualitative information on available water resources, registered water users and potential polluters, distribution of population density, agricultural production and water demands, ecological information, and economic conditions within the system. Therefore, GIS role within the system is to:

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

2.1.2. Physical System: *Hydrologic Simulation Model*

The hydrologic model mathematically represents the complex hydrologic processes within the watershed. Figure 2 presents the structure of hydrologic model. Precipitation and temperature data are used as inputs to the system. In snow module, precipitation data is adjusted for computation of losses. Loss module describes the movement of moisture through various conceptual reservoirs within catchment (canopy, groundwater, etc.). Surface excess is used by transformation module to predict direct runoff using unit hydrograph. Finally, routing module uses direct runoff result calculation to quantify the streamflow regime (Prodanovic and Simonovic 2010).

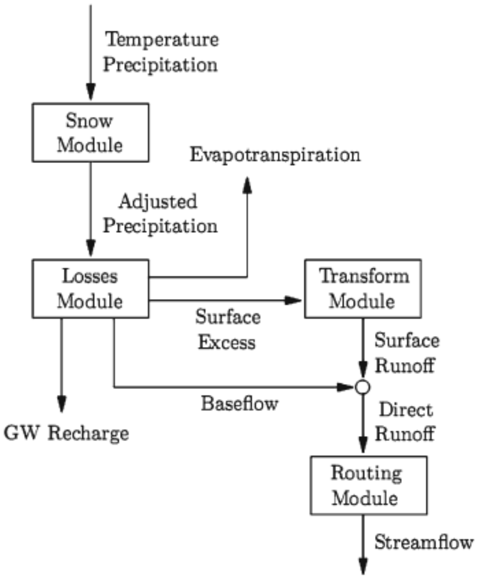

Figure 2. Modules of hydrologic simulations model.

2.1.3. Operational Rules and Regulations**:** *Agent-based Model*

Agent-based modeling methodology presents an innovative approach in software engineering, social, economic, and environmental modeling (North and Macal 2009). This methodology describes individuals or agents as unique and autonomous entities that interact with each other and their environment. Humans, organizations, institutions or any other entities that pursues a certain goal may be represented as agents. Depending on the structure of their goals, intelligent agents can be rather simple, described by simple rules or very complex, described by complex behavioral models in domain of cognitive science and artificial intelligence (North and Macal 2009). All activities of an intelligent agent are directed toward achieving prescribed goals. An intelligent agent is, naturally, the core of agent-based models. 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 in order to achieve a certain goal (Wooldridge 2009). Agent-based models are also known as “across-level” models because they are used to analyse problems of emergence (Railsback and Grimm 2011). Traditional modeling methodologies represent the complex systems using techniques such as differential equations to represent the system. Other methodologies, on the other hand, analyze how elements of the system change due to altered external system conditions. Therefore, agent-based models are used to assess “what happens to the system because of what its individuals do, and also, what happens to the individuals because of what system does” (Railsback and Grimm 2011). The strength 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. The main attributes of an intelligent agent include: autonomy, reactivity, communication, adaptation, flexibility, and spatial awareness (Ferber 1999). Agent-based models enable spatial definition of agents (for example water users or polluters). By spatial definition of an element and behavior at individual level, we obtain the global system behavior as a result of interactions between many individuals, each following its own goal, living together in some environment and interacting with each other and the environment (Wooldridge 2009).

2.1.4. Socio-Economic Impacts**:** *System Dynamics Simulation*

System dynamics simulation modeling methodology is a powerful tool for comprehensive analysis complex systems, especially for water resources problems. System dynamics simulation, first graphically and then mathematically, defines the system structure by identifying system elements and their interactions. Defined system structure and recognized relationships determine the system behaviour through the simulation.

2.2. Second Level of Integration

Second level of integration refers to coupling of different models or techniques of systems analysis within one component, in this case a water quality model and optimization procedure, Figure 3. Water quality models are particularly important for implementation of integrated water resources management programs, especially in the part of protection of water resources from pollution. These models enable a qualitative estimation of pressures on the water quality status, and detection of reasons of potential status change. Moreover, the models allow analysis of the prospect actions of restoration of aquatic eco-systems and support the selection of most sustainable options.

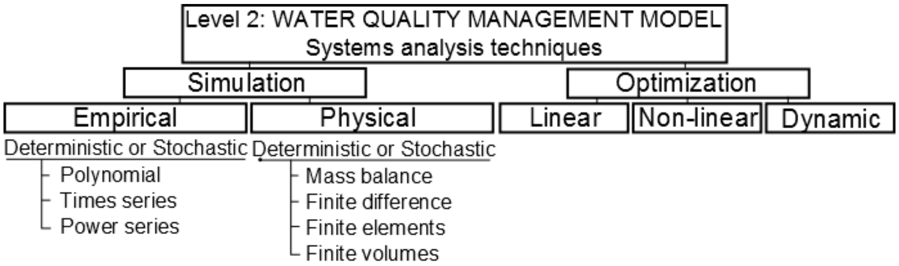

Figure 3. Second level of integration.

3. CASE STUDY: THE UPPER THAMES RIVER BASIN

Due to data availability and assistance of responsible authorities, the Upper Thames watershed is selected for development of a pilot model. The Upper Thames river basin is located in Southwestern Ontario, Canada, and covers the area of 3.432 km^2, Figure 4. 78% of the total area is dedicated to agriculture, while urban areas and forests cover 9% and 12%, respectively (UTRCA 2012). The Upper Thames river basin has population of 485.000 with majority living in the City of London (433.000). Average precipitation depth is 1.000 mm/year. Thames River has two main branches, the North and the South branches. Average annual discharge is 35.9 m^3/s. The Upper Thames river basin is divided into 28 sub-basins.

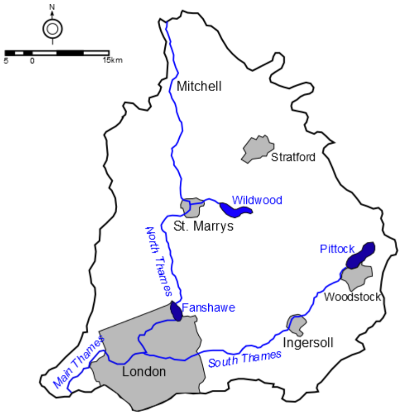

Figure 4. The Upper Thames River Basin.

First level of integration has been successfully completed and presented by Nikolic, Simonovic and Milicevic (2012). First level successfully combined physical simulation (hydrologic), agent-based simulation and system dynamics simulation, while second level integration is still in progress.

6.1. First Level of Integration

6.1.1. Physical System: *Hydrologic Simulation Model*

Continuous hydrologic model component developed for this study is based on the HEC-HMS (USACE 2000). This model has been developed, calibrated and verified in previous hydrologic studies of the Upper Thames River basin by Cunderlik and Simonovic (2004; 2005; 2007). Calculated flows present input information to agent-based model.

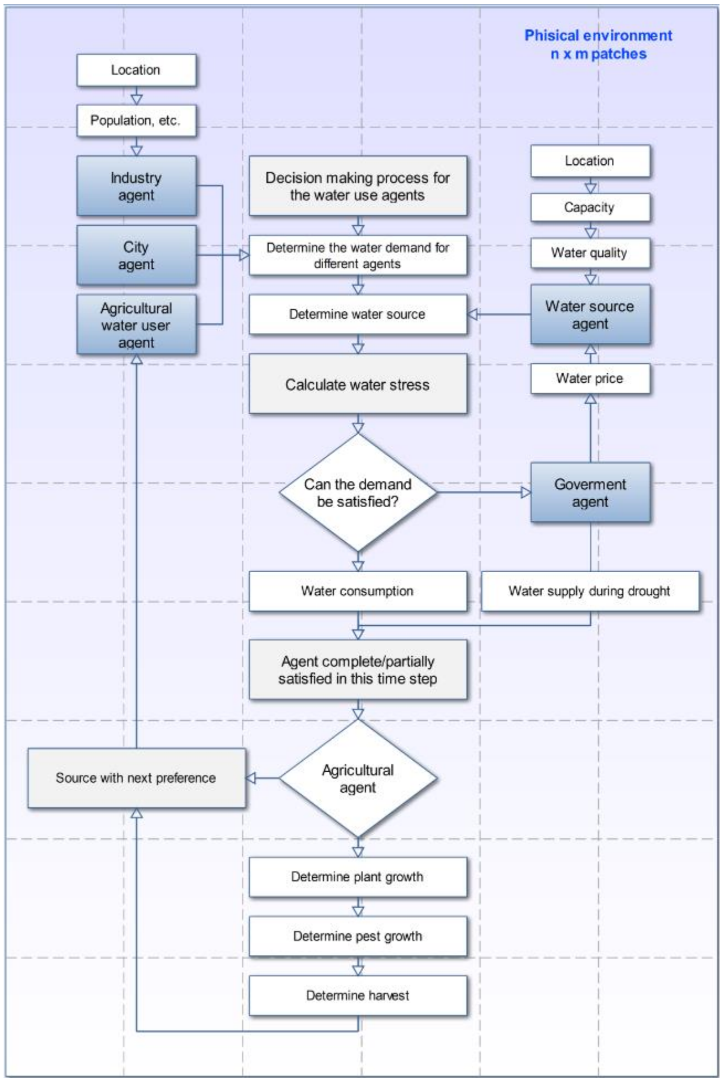

Figure 5. Agent-based model structure.

6.1.2 Operational Rules and Regulations: *Agent-based Model*

Pilot agent-based model describes economic aspects of water resources allocation between agricultural users in the Upper Thames watershed, based on the quantitative inputs from hydrologic model. The model contains three classes of agents: (a) Water sources agents (rivers, reservoirs, springs and wells); (b) Water user agents (municipal, industrial and agricultural) and (c) Administrative agents. Figure 5 shows the decision making tree as a function of the water user, water source and government agents. Therefore, the main goal of agricultural agents is to maximize the revenues of the crop yield while minimizing the water consumption expressed through water stress index. This index defines deficiency in water for meeting the demand. Initial model includes 28 sub-basins within the Upper Thames watershed acting as regulatory agents responsible for agricultural planning. They represent one group of potential stakeholders, in this case farmers, responsible for crop pattern selection. Administrative agents have a regulatory role in allocating water permits and prioritization of water rights, etc. Based on the defined water demand and available water resources, the model analyzes ability of agents to obtain required quantities of water. The intention was to represent interaction between responsible managers which would maximize the potential agricultural benefits subject to available water resources and minimal water consumption.

6.1.3. Socio-Economic Impacts: *System Dynamics Simulation*

In this case, system dynamics is used to present the demographic dynamics in the system as a function of available water resources. This process is related to specific spatial unit, in this case watershed. Initial model describes the population dynamics within the Upper Thames watershed as a function of calculated water stress.

6.2. Second Level of Integration

River Thames is 273km long. Due to specific physical properties of the basin, the water quality parameters, such as dissolved oxygen concentration, significantly vary in time. The most important reasons for this are the existing flow regimes and mild watershed gradient. For example, the maximum velocity is monitored near Byron (0.75 m^3/s), while near municipality Thamesville the river velocity is only 0.3 m^3/s (UTRCA 2012). In addition to complex network of estuaries and numerous municipalities within the watershed which use septic tanks, this variation of river velocity significantly affects the water quality. Construction of waste water treatment plants (WWTP) began during 1970s. However, a number of WWTPs is currently hydraulically overloaded and requires further capacity extension. Despite the fact that existing WWTPs are efficient, due to occasional breakdowns, 18 spills in average are reported every year in southwestern Ontario (UTRCA 2012). Water quality in the Thames River has radically improved since construction of WWTPs. However, variations of water quality parameters are still noticeable. For example, severe fluctuations of dissolved oxygen have been observed with concentrations lower that 5 mg/l, sometimes even as low as 1.5 mg/l (UTRCA 2012). Therefore, significant fluctuations of flow regimes in the Thames River, occasional WWTP breakdowns, seasonal events of algal proliferations, and excessive situations, such as chemical spills, require a model which would simulate given situations and facilitate finding of the optimal operational plan.

Selection of model to be applied is based on the characteristics of analyzed problem, its data requirements, and model availability. For that reason, QUAL2E model has been selected to create the Upper Thames River water quality model. QUAL2E can analyze up to 15 water quality parameters and it is used as a planning tool for definition of total maximum daily loads (TMDLs). This model solves the advective-dispersive transport and reaction equations using a finite difference method. Therefore, model is used to analyze the impacts of waste loads on in-stream water quality (EPA 1995).

Figure 6 shows a schematic view of the developed model. Existing waste water treatment plants have been defined as potential sources of pollution to examine the effects of waste water treatment plants breakdowns on water quality. However, this model does not include existing Fanshawe reservoir and potential use of the reservoir for water quality management. Figure 7 shows preliminary results of three simulated water quality parameters: temperature, biochemical oxygen demand (BOD) and dissolved oxygen (DO). In this scenario, Greenway water treatment plant has to be bypassed, and waste water needs to be released into the Thames without any treatment (assumed 300mg/l of BOD).

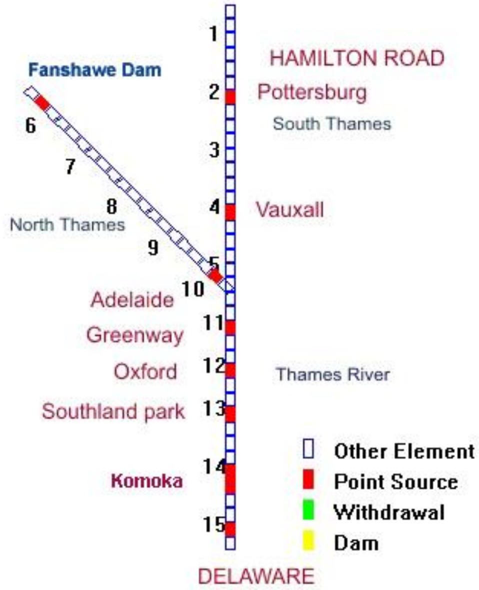

Figure 6. Thames water quality model.

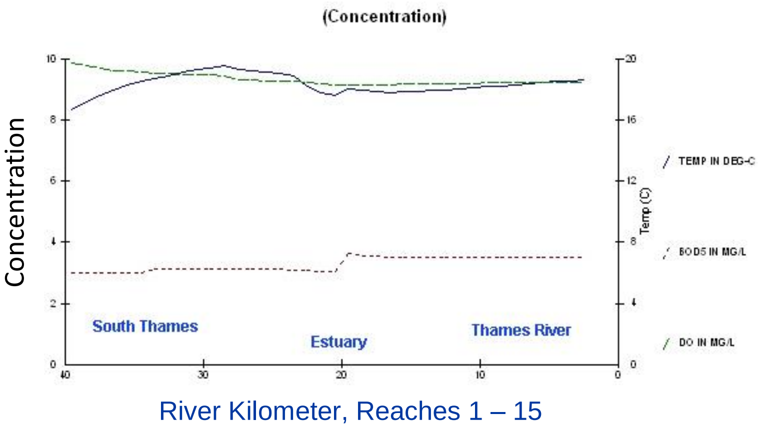

Figure 7. Thames water quality model.

Figure 8 shows BOD levels in case of breakdowns of three waste water treatment plants (Vauxall, Adelaide, and Greenway), while Figure 9 analyzes the effects of augmented release from the Fanshawe reservoir in case of a breakdown downstream.

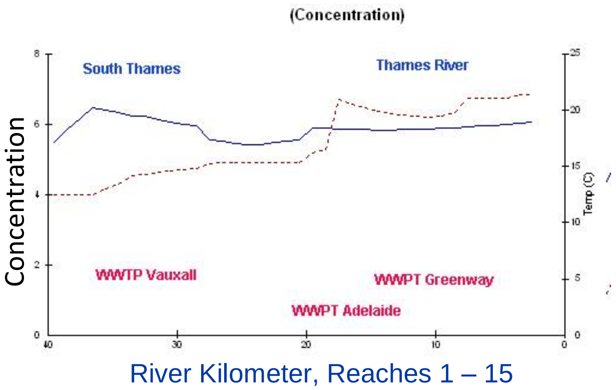

Figure 8. Thames water quality model.

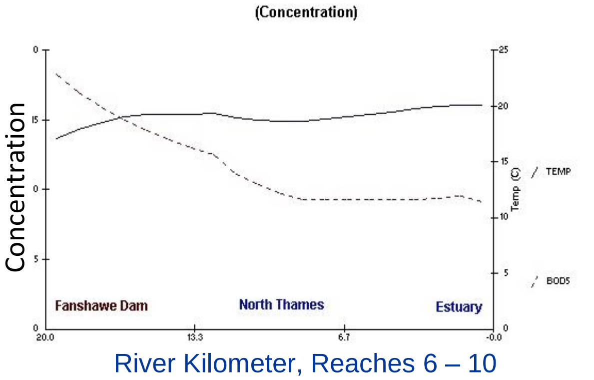

Figure 9. Thames water quality model.

Obtained results are only descriptive, since they haven’t been compared to observed values. However, this model is under further development and will be coupled with an optimization model in the future.

7. CONCLUSION

Systems view is recognized as the primary guiding principle of integrated water resources management. Systems view implies that water resources systems cannot be analyzed in isolation, but they must also take into consideration all interactions with human and environmental systems. This paper presents a modeling framework under development which supports the systems view of IWRM process. Proposed methodology addresses all previously defined requirements of the IWRM process and aims to describe behavior of the system, in time and space, resulting from the complexity of system structure and properties of the relations between the system elements by combining different modeling technologies. Therefore, suggested methodology fully integrates a number of specific models into one comprehensive tool which allows realistic representation of water resources systems. First level of integration process has been completed, and it involved integration of physical process model, system dynamics simulation and agent-based simulation, while integration of water quality model and optimization model presents a work in progress.

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