TOWARDS ADAPTIVE WATER RESOURCES MANAGEMENT: SIMULATING THE COMPLETE SOCIO-TECHNICAL SYSTEM THROUGH COMPUTATIONAL INTELLIGENCE

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EXTENDED ABSTRACT

The interactions between individuals, institutions, society and the environment that influence water resources management, particularly at the catchment scale, are complex, challenging to represent and increase the uncertainty, surrounding the system's reactions to both human decisions and natural events. The Water Framework Directive aims to co-ordinate water management strategies and policies thus promoting Integrated Water Resources Management (IWRM). However, there is a growing criticism of IWRM due to its inability to effectively support policy makers. Adaptive water resources management is now emerging as a means to take IWRM one step further, by focusing on the integration between the social and technical system and by integrating learning outcomes.

Adaptive water resources management requires the development of comprehensive decision support systems that are able to simulate the effect of alternative decisions (in policy, pricing, societal values, governance etc) in the future water system, compare them and integrate the feedback from this "learning outcome" into current decision making. In order to create such decision support systems it is necessary to integrate hydroinformatic tools (i.e. hydrological modelling, GIS etc) with social simulation tools, able to enhance our understanding of the socio-economic element of the complete (socio-technical) water resources system.

These social simulation tools, based on computational intelligence are an emerging component of the hydroinformatics toolkit and are geared towards understanding the dynamics of human group processes on the physical system. These dynamics are complex, nonlinear, path dependent and self-organizing. In this work, the most promising Computational Intelligence tools, including Agent Based Modelling, Artificial Neural Networks, Bayesian Belief Networks and System Dynamics, are reviewed. The characteristics of these Computational Intelligence tools are assessed based on their ability to effectively support the simulation of the socio-economic parameters of the complete water resources system and their strengths and weaknesses are discussed with examples from the state-of-art literature. Based on this critical review, the paper proposes a specific research agenda, as a roadmap for both hydroinformatics and adaptive water management.

Keywords: adaptive water resources management, decision support systems, social simulation, agent based modelling, computational intelligence.

1. FROM INTEGRATED TO ADAPTIVE WATER RESOURCES MANAGEMENT

Integrated Water Resources Management (IWRM) is “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2000). The Water Framework Directive (WFD, 2000) through the coordination of all strategies and policies relevant to water supports IWRM.

Even so, there is a growing criticism of IWRM suggesting that it may be inapplicable (Pahl-Wostl, 2007a) and ultimately unable to really support decision making (Biswas, 2004). Even so, researchers recognise IWRM’s strength in providing a good theoretical basis for identifying the major water management issues and their conflicting interests (Pahl-Wostl, 2007a; Butterworth *et al.*, 2010). To assist IWRM to progress to the next level, it has been proposed that IWRM can be upgraded by recognising uncertainty (Gregory, 2006), by taking into account learning outcomes (Pahl-Wöstl and Sendzimir 2005) and by exercising a more practical, adaptive management model (Lankford *et al.*, 2007).

More specifically, adaptive management is a natural resources management approach that can be traced back to 1978 in B. Holling’s publication on “Adaptive Environmental Assessment and Management” (Holling, 1978) where he defined adaptive resources management as a method for implementing policies as *experiments*. A more recent review undertaken by the United States Department of Agriculture in 2005 concluded that adaptive management is a systematic “learn by doing” method that proposes feedback loops, based on learning outcomes, that change management approaches accordingly (Stankey *et al.*, 2005).

The European Water Framework Directive (2000/60/EC) proposes a cyclical review management process, arguably consistent with the notion of adaptive management (CIS, 2009). However, applying adaptive water resources management (AWRM) in decision making is challenging since it requires well-defined management goals and assessment of the anticipated system’s response to decisions (Loucks *et al.*, 2005). Current research on Decision Support Systems (DSS) for water resources management aims to explore and exploit this cyclical approach to planning by using hydroinformatic tools that integrate models, analytical engines, GIS as well as communicate results to stakeholders (Makropoulos *et al.*, 2008). Such component-based DSS tools are becoming more possible through the emergence of software linking protocols and standards such as OpenMI (Makropoulos *et al.*, 2010).

AWRM experiments require the integration of such hydroinformatic tools with social simulation tools, able to enhance our understanding of the socio-economic element of the complete (socio-technical) water resources system. This description requires tools that assist the understanding of the dynamics of human group processes which are “complex, nonlinear, path dependent and self-organizing” (Macy *et al.*, 2001).

The aim of this paper is to review computational intelligence (CI) tools, based on their capabilities to address the socio-economic parameter of the water system and to integrate with other hydroinformatic components, to create Decision Support Systems that meet the requirements of AWRM.

2. COMPUTATIONAL TOOLS FOR THE SOCIO-ECONOMIC PARAMETER

The field of Computational Intelligence (CI) has produced applications that vary from applications for logical reasoning to playing chess and diagnosing diseases. The common features of all these applications are that they model and perceive the world within which they act given a specific goal; and they learn based on past experience (Russell *et al.*, 1995). The most relevant sub-fields of Computational intelligence (CI) to hydroinformatics are, among others: Agent Based Modelling; Artificial Neural Networks; Bayesian Belief Networks and Systems Dynamics Modelling (Solomatine, 2008).

Agent Based Modelling (ABM) is based on agents which are "computer systems situated in some environment, capable of autonomous action in this environment in order to meet its design objectives" (Wooldridge, 1999). ABM reduces the complexity of a problem by representing a system using sub-groups, associating an independent intelligent agent to each group and coordinating the activities of the agents (Bousquet *et al.*, 1999). In terms of complexity, agents may be categorised into deliberative and reactive. Deliberative agents are complex mental models that operate based on their “given” belief-desire-intention rules. Reactive agents are used mainly for the simulation of life - and the natural systems - with one main goal, viability, and are based only on simple interactions of agents with their environment (Gandon, 2002).

ABM is slowly gaining ground in the water sciences field. Becu *et al.* (2003), in the CATCHSCAPE project, used an ABM for simulating a catchment in North Thailand integrating modules representing the hydrological system with social dynamics and describing water management according to different control levels (individual, scheme and catchment). In the NeWater project, Schluter *et al.* (2007) developed an ABM, for the Amudarya basin, to explore system characteristics and mechanisms of resilience. Athanasiadis *et al.* (2005), in the DAWN DSS, combined an ABM for simulating the consumers’ behaviour and conventional econometric and social models for estimating water consumption for evaluating water-pricing policies. Barthel *et al.* (2008) developed the DANUBIA DSS consisting of 16 models for the simulation of Global Change in the Upper Danube Catchment (Germany, 77,000 km2) integrating an agent based model for representing the water supply sector and the domestic water users. Janmaat *et al.* (2010) investigated the coupling of MIKE-SHE, for hydrological modelling, with REPAST’s SWARM agent-based modelling toolkit, for land-use change, for investigating the impacts of climate change in the Okanagan River System in British Columbia.

Artificial Neural Networks are inspired by the biological nervous systems imitating the ability of people to learn by example. The main characteristic of ANN is that non-linear elements of the network can be trained to adapt to input-output training pairs of available data (Nillson, 1998). ANNs are capable to gain knowledge by extracting patterns and detecting trends from available data (Barnden, 2003). The main advantages of ANNs are their abilities to derive conclusions from insufficient data; adaptive learning; self organisation, pattern completion and real time operation (Barnden, 2003).

Applications of Artificial Neural Networks in water resources management are mainly about creating Data Driven Models of the water system (Fu *et al.*, 2007; Solomatine, 2008). Such models have been utilised in order to forecast flow (Khalil *et al.*, 2005; Conrads *et al.*, 2007) and water demand (Firat *et al.*, 2008; Msiza *et al.*, 2008).

Bayesian Belief Networks (BBN) can simulate physical phenomena under uncertainty, estimating, for example, future river flows under changing climatic conditions (Henriksen *et al.*, 2007). A BBN is a graphical structure of interconnected nodes representing a set of variables and their links represent the relationship between these variables (Van der Belt *et al.*, 2009). Nonetheless, BBNs are acyclic and do not support feedback loops (Jensen, 2001).

Bromley *et al.* (2005), in the MERIT project, developed BBNs in order to investigate water demand and conflicts in different areas (UK, Italy & Spain). Furthermore, BBNs can be combined and produce an Object-Oriented Bayesian Belief Network (OOBBN) which basically links different BBNs together in order to transfer information between them (Koller *et al.*, 1997). Molina *et al.* (2010) developed a Decision Support System (DSS) with the integration of Object-oriented Bayesian Belief Networks for representing a complex water system supplied by four groundwater aquifers in the Altiplano region (Murcia, Southern Spain).

System Dynamics Modelling surfaced in the 1970s when the World3 model was developed in MIT and the Club of Rome's report "Limits to Growth" presented alternative development scenarios and their sustainability (Meadows *et al.*, 1972). System Dynamics Modelling (SDM) is based on the notion that a system's structure simulating the positive and negative relationships between variables, feedback loops, system archetypes, and delays is sufficient in order to observe and predict its behaviour (Winz *et al.*, 2007). SDM is flexible, user-friendly and transparent and can be a valuable tool for analysing complex interdisciplinary problems for decision-making (Winz *et al.*, 2007).

Stave (2003) created a System Dynamics Model for the water demand and supply in Las Vegas and used it in order to inform the public about different water policy scenarios. Simonovic has published on the assessment of global water resources through the WorldWater model and concluded that global models based on system dynamics can provide valuable understanding of the drivers of change in water use (Simonovic, 2009).

The above tools can be included in an integrated decision support system that will allow experimentation with 'what if' scenarios where changes in socio-economic parameters (such as demand elasticity or technology uptake rates) could then feedback to the decision process. These integrated DSSs may be created using modelling frameworks that can link together different components (Rizzoli *et al.*, 2006; Argent *et al.* 2006). These frameworks, however, often require substantial rebuilding of integrated models in order to be included in a common modelling platform (Harou *et al.*, 2010).

3. DISCUSSION

The reviewed tools provide unique traits that could be useful in representing the socio-economic element in AWRM experiments. Table 1 illustrates an analysis of the ability of the different reviewed CI tools to represent the socio-economic element of the water system.

Table 1: Scoreboard of the ability of the different CI tools to represent the characteristics of the socio-economic element of the water system.

CI tools	**Characteristics of the socio-economic element** (Macy *et al.*, 2001) **Complex**	**Non linear and Path-dependent**	**Self-organisation**
ABM	All of the reviewed CI tools are able to represent complex systems and their reactions either by observing available data or through adapting expert knowledge	Agents are complex mental models that operate based on their “given” belief-desire-intention rules	Agents decide how to meet their set belief-desire-intention goal. However, the different agent categories (individual, institution etc) need to be set.
ANN		Having emerged from the effort to mimic the human brain ANNs are by nature capable for non-linear and path-dependent thinking	ANNs can be trained by observing data. However data for the socioeconomic parameter are scarce and mainly qualitative.
BBN		BBNs demonstrate non-linear and path-dependent thinking however they are acyclic and unable to feedback knowledge	Self-organisation is possible depending on the software used
SDM		SDM consists of different variables that demonstrate non-linear and path-dependent thinking	SDM depends on the conceptualisation and design of the system. However, the system’s variables can be dynamic and thus able for self-organisation

Figure 1 presents a qualitative ranking of these CI tools based on their ability to represent the socio-economic element of the water system and their state-of-the-art use in water resources management.

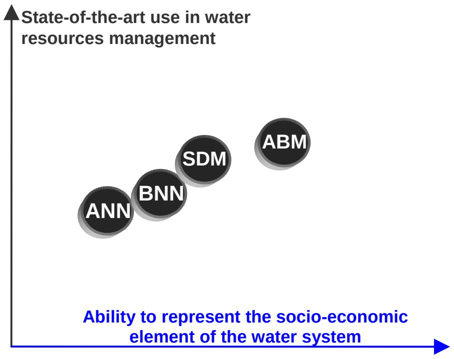

Figure 1: CI tools scoring based on their ability to represent the socio-economic element of the water system and their state-of-the-art use in water resources management.

From the above, it can be concluded that ABM is a most promising tool able to represent the socio-economic element of the water system. This conclusion is also enhanced by the discussion of Wheater *et al.* (2007) who suggest that ABM is able to address the need for dynamic interaction of the socio-economic element with the water system. There are a number of different systems that can support the development of ABM, using different programming languages (Java, Python, Logo and other) and covering a range of open source (Repast), freeware (NetLogo) and proprietary (AnyLogic) systems.

In order to address adaptive water resources management, a generic methodological process was designed (Figure 2).

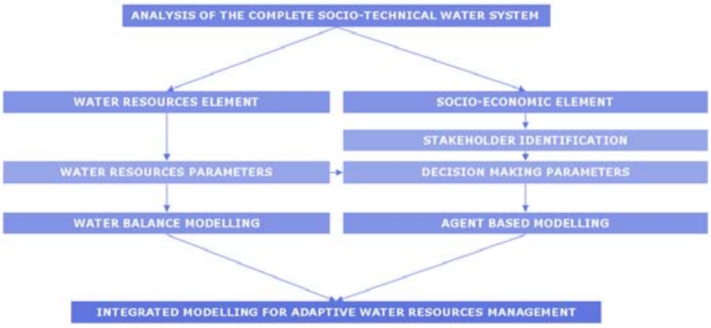

Figure 2: Schematic of a methodology to design adaptive water resources management.

The first step of this methodological process is to identify the parameters of both the water resources and the socio-economic element of the water system. In general, the stakeholders of water resources management, at the RBD level, are: water users (individuals, industries, agricultural cooperatives etc); water suppliers (public water suppliers, reservoir operators, water abstraction licensing authorities etc); regional water, environmental and development policy makers; country water, environmental and development policy makers; and European Union policy makers. These stakeholders base their decisions on different parameters of the water resources system. The second step is to use ABM for the simulation of the socio-economic parameter and a physically-based water balance model, such as WEAP21, MIKE-Basin or SWAT, evaluate the effects of decisions taken and use them to (in)form an integrated decision support system for AWRM.

5. CONCLUSIONS

Water systems evolve through time, changing constantly in an unrepeatable fashion (Koutsogiannis *et al.*, 2008). Changing socio-economic conditions increase even more the uncertainty of the outcome of the water resources management decisions (Pahl-Wostl *et al.*, 2007b). In hydroinformatics, CI tools are slowly gaining ground as means to simulate reasoning and decision making processes of various stakeholders. An “experimental” approach, such as the one proposed by adaptive water resources management, gives the opportunity to better understand the way the system may react to changes and supports incremental adjustments on the management decisions based on these learning outcomes. Water resources management experiments are developed using models that allow investigation of behavioural patterns, linkages and feedback loops to the management and performance of water systems (Van der Belt *et al.*, 2009).

Decision Support Systems for water resources management need to move towards acting as “thinking environments” supporting a variety of issues and linking the socio-economic element with the natural water system (Makropoulos *et al.*, 2008). The above review suggests that great promise in terms of addressing the socio-economic element of the water system and supporting adaptive water resources management lies with Agent Based Modelling. The next step of this work is to identify an appropriate ABM system and physically-based water balance model and link them in order to create an integrated decision support system for supporting adaptive water resources management experiments.

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