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Modelling Interactions between Land Use, Climate, and Hydrology along with Stakeholders' Negotiation for Water Resources Management

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Abstract: This paper describes the main functionalities of an integrated framework to model the interactions between land use, climate, and hydrology along with stakeholders' negotiation. Its novelty lies in the combination of individual-based and spatially distributed models within the Socio-Hydrology paradigm to capture the complexity and uncertainty inherent to these systems. It encompasses a land-use/land-cover cellular automata model, an agent-based model used for automated stakeholders' negotiation, and the hydrological MIKE SHE/MIKE 11 model, which are linked and can be accessed through a web-based interface. It enables users to run simulations to explore a wide range of scenarios related to land development and water resource management while considering the reciprocal influence of human and natural systems. This framework was developed with the involvement of key stakeholders from the initial design stage to the final demonstration and validation.

Keywords: river basin management; integrated modelling system; land-use change; climate change; watershed modelling; hydrological modelling; socio-hydrology

1. Introduction

Environmental resource management not only requires accurate observations of natural phenomena but also demands the development of models to help answer policy questions [1]. Investigating the complex nature of environmental problems, which include ecological, social and economic aspects, requires the integration of scientific approaches with those of decision and policy makers. The increasing dissatisfaction resulting from disjoined and narrowly focused environmental management approaches has recently encouraged the employment of integrated environmental modelling approaches [2].

Integrated environmental modelling attempts at providing solutions to complex problems facing human and natural systems by integrating the knowledge from the multi-disciplinary scientific community and the expertise of stakeholders and decision makers to explore and predict the response of environmental systems to human-nature interactions [3]. It is the product of moving from local management exercises towards regional and global issues such as urbanization, climate change, and water availability. The integrated nature of such modelling is motivated by the notion that no single model is capable of representing the complexity of large-scale problems and no single group owns the comprehensive expertise to make decisions in this regard. Rather such problems need to be tackled in a collaborative and integrated manner.

Water resource management is a good illustration of a human and natural system in which numerous stakeholders as social actors interact with a natural landscape. It is a good example of a system that reflects pre-existent biophysical factors such as land cover, geomorphology, hydrology, climate and other natural elements and at the same time mirrors the decisions made by human agents who interact in economic markets and public institutions [4]. The complexity of such interactions due to the non-linear relationships among the system components, along with the influence of human decisions, necessitates the integration of multiple disciplines and understanding the human-nature integrations using an appropriate modelling framework. It therefore requires an integrated environmental modelling approach that considers the mutual interconnections of human-water, human-land, and water-land systems.

Studies have been conducted to understand the impact of land-use/land-cover (LULC) and climate change on hydrological processes using an integrated modelling approach. Chu et al. [5] employed an empirical land-use change allocation model (CLUE-s) coupled to a distributed hydrological model (DHSVM) to examine the influence of various land-use change scenarios in the Wu-Tu watershed in northern Taiwan. Nikolic et al. [6] developed an integrated water resource management tool that includes GIS, system dynamics, agent-based modelling (ABM), and hydrologic simulation while considering socio-economic and administrative and institutional systems. Akhtar et al. [7] employed a system dynamics simulation approach to investigate the mutual impacts of society, biosphere, climate and energy systems. Wijesekara et al. [8] coupled a cellular automata (CA) model with a distributed physically based catchment and channel flow model (MIKE SHE/MIKE 11) to investigate the impact of LULC change scenarios on the hydrology of the Elbow River watershed in southern Alberta, Canada. Farjad et al. [9] pursued this initial research to understand the influence of climate and LULC change on the hydrology of the same watershed in the 2020s and 2050s using GCM scenarios. Their study highlights the importance of employing an integrated modelling approach to explore both the independent and combined impact of climate and LULC change to improve the understanding of the watershed hydrological responses. However, these studies do not take into account the feedbacks and interrelations between social actors and hydrology [10].

Despite the numerous efforts of the last decade, constructing integrated models that incorporates the interrelations between the social and physical components of a system still remains a challenging task largely due to the traditional separation of ecological and social sciences [11]. For long, social scientists have solely focused on human interactions, considering the environmental influences to be constant while ecologists have concentrated on environmental aspects in which humans are considered external [12], therefore neglecting or underestimating their influence. Social scientists and researchers in natural sciences employ different scientific approaches [13]; even the notion of model varies across disciplines [14]. Moreover, scientists and decision makers have maintained different interests, methodologies and perspectives, which resulted into a huge knowledge gap between science and decision-making [15]. Developing novel approaches to fill the gaps between social sciences and other disciplines is crucial.

In recent years, the importance of including social components in hydrological modelling has been advocated by several scientists. The concept of Integrated Water Resources Management emerged from the first Dublin principle, which recommends that water problems be considered in relation to land-use planning, socioeconomic development, and the protection of other natural resources [15]. Carey et al. [16] proposed a holistic hydro-social framework that identifies five major human variables critical to hydrological modelling, including political agendas and economic development, governance, land and resource use, and societal responses. Hong et al. [17] created a combined socio-economic/ecological modelling toolbox, running on the ArcGIS platform, to analyse the impacts of urbanization in response to socio-economic conditions on streamflow and nutrient exports. Baldassarre et al. [18] developed a dynamic model to represent the interactions and feedback loops between hydrological and social processes. The model was designed based on a set of differential equations to conceptualise the dynamics of human-flood systems and external factors such as technological development. Viglione et al. [19] explored the relationship of community risk-taking culture and flooding damages and investigated different risk taking scenarios among people to find solutions that result from a trade-off between risk taking attitudes and economic reasonability of decisions.

The perspective put forward by these scientists and others has resulted in the notions of coupled human-water systems and Socio-Hydrology as an interdisciplinary science of people and water, which focuses on understanding the impact of hydrology on societal changes and the influence of social changes on water cycle dynamics [20–23]. In this regard, the International Association of Hydrological Sciences (IAHS) introduced the hydrological decade of 2013–2022 with the theme of "Panta Rhei" (Change in Hydrology and Society)—in attempt to better understand and forecast the interactions of society and water under a change in environmental conditions in order to support sustainable water resources [24]. The introduction of this new paradigm received the support of numerous experts in the field [25–29] who reached a common conclusion that the inclusion of social and hydrological components and their interactions is necessary in a modelling system [10].

An aspect that has been rarely considered so far while modelling the mutual impacts of land, hydrology, climate, and social systems is the fact that humans employ various strategies in decision making that go beyond the aim of optimization, maximization of profits, or minimization of risk [30]. Policy and decision makers need to constantly negotiate with different parties and consider a wide range of perspectives that are often not included in the legal framework of decision making to come up with a decision that does not affect the environment adversely and satisfies a wide range of stakeholders. However the complexity of coupled human and natural systems and the non-linear interactions of their elements make it difficult to estimate the outcome of decisions.

Such interactions can be captured using bottom-up, individual-based modelling approaches such as ABM and CA. ABM is a well-suited approach to simulate the role of human actors at different levels of land management, from individual choices to enforced policy decisions [31]. A key advantage of ABM is its ability to represent the behaviour of human actors, accounting for bounded rationality, interactions, communication and learning, combined with a dynamic representation of the spatial environment that affects and is affected by human decisions [32]. A recent promising research trend consists of incorporating automated negotiation and machine learning techniques within an ABM to mimic human behaviour when evaluating alternative scenarios and resolving conflicts in social interactions in order to reach an agreement in the context of environmental resource management. CA are largely employed to capture LULC patterns as they evolve in space and time [33–35]. Their application to evaluate the possible occurrence of alternative scenarios based on an understanding of the factors (physical and socio-economic) that drive the evolution of LULC makes them an appealing exploratory tool for scientists, stakeholders, and decision makers [36,37]. When combined to environmental models, these modelling tools provide a powerful integrated framework to consider the interactions and feedbacks between the human and natural components of a system. For example, Murphy et al. [38] integrated a global-scale water balance model coupled with an ABM to explore the impacts of social values on hydrological dynamics. In this study, the ABM provides a means of incorporating human decisions that drive the hydrological processes while the physically based hydrological model simulates the impacts of such decisions on the hydrology.

This paper presents an integrated modelling framework that combines an ABM used for automated stakeholders' negotiation and a LULC CA, both developed in house, with a distributed hydrological model (MIKE SHE/MIKE 11), linked through a web-based interface. This study is among the first to integrate the components of land, climate, and hydrology while allowing stakeholders' negotiation in the context of land development and water resource management. An innovative aspect of this study is to employ spatially distributed, individual-based and bottom-up models within the Socio-Hydrology paradigm to capture the complexity of society-hydrology-land-climate systems. The proposed integrated modelling framework can aid the communities of scientists, stakeholders, and decision-makers to understand the dynamics and interactions of these systems through the simulation of various scenarios. While some aspects of the research presented in this paper have been previously published (i.e., design, calibration and simulation results obtained with a particular model), it is the first time that the architecture of the three components of the modelling system and their interconnections through a web-based interface are presented and their functionalities illustrated using a common scenario.

2. Materials and Methods

The components of the integrated modelling system developed in this project and their interactions are illustrated in Figure 1. Each model can be run separately or in combination according to a particular order that a user finds useful. For instance, the system can be run starting from a land development scenario being submitted by a user through the web interface. Using the ABM, agents representing stakeholders negotiate over the location and inner configuration of the proposed land development to find an agreement. The result of the negotiation can be transferred as input to the LULC CA model to simulate the impact of the selected land development in the watershed over time (i.e., current and future land use maps in the watershed). The LULC maps generated by the CA model can then be used to determine LULC related parameters (such as the roughness coefficient and the leaf area index), to be transferred into the hydrological model to evaluate the influence on the hydrology of the watershed independently or in combination to the effect of climate change scenarios. The outcomes can be further evaluated by the stakeholders represented in the ABM who can decide to maintain or revise their original negotiation agreement.

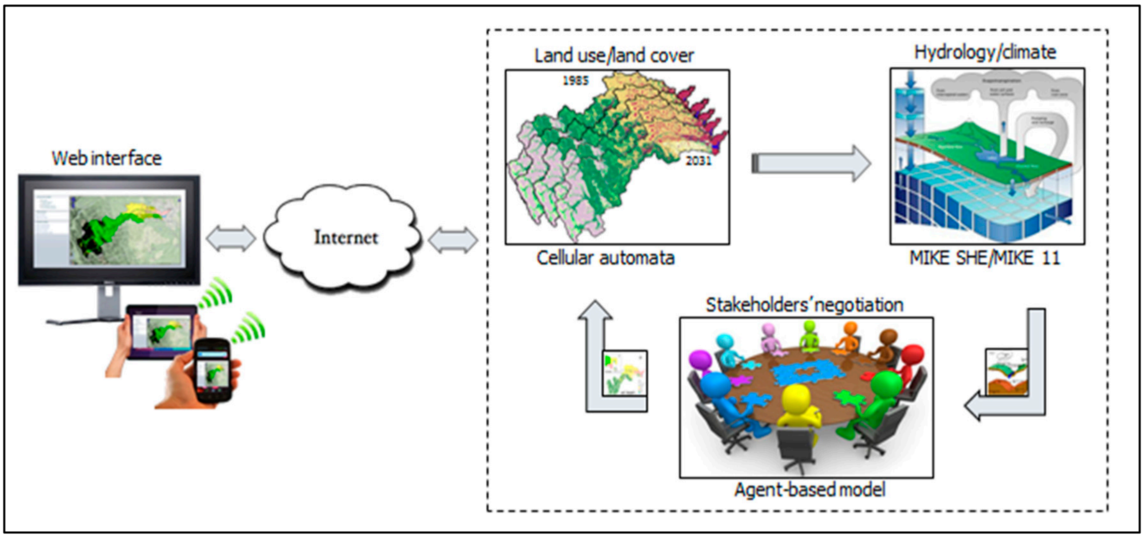

Figure 1. Components and interactions of the proposed integrated modelling system.

The components of the integrated modelling system are described in the next section, followed by a demonstration of their functionalities when applied to the Elbow River watershed, in southern Alberta, Canada.

2.1. Components of the Integrated Modelling System

2.1.1. LULC Cellular Automata Model

A CA is a spatially explicit model used to simulate dynamic spatial processes occurring in a landscape, such as urbanization, and to reproduce its patterns from a bottom-up perspective. The landscape is typically partitioned using a grid of regular cells. The CA model predicts the evolution of the state of each cell through a number of discrete time steps based on a set of transition rules that consider the states of neighbouring cells, external driving factors (i.e., accessibility to services), and optional constraints (i.e., forbid development in flood plains) [39]. CA models have become a predominant approach for LULC change modelling and an appealing exploratory tool for scientists, stakeholders, and decision makers to understand the factors that drive the LULC evolution and assess the possible occurrence of alternative scenarios [36,37,40,41].

The CA incorporated into the proposed modelling system has been extensively tested to predict future LULC changes in the Elbow River watershed [8,9,36]. It was calibrated using a set of historical LULC maps generated for the years 1985, 1992, 1996, 2001, and 2006 from Landsat Thematic Mapper images acquired at 30 m spatial resolution and resampled at 60 m. These maps include nine dominant classes: agricultural land, deciduous forest, evergreen forest, rangeland/parkland, rock, roads, water, urban areas, and clear-cut areas. A sensitivity analysis conducted to identify the best configuration of the model revealed that a cell size of 60 m, a neighborhood consisting of three concentric rings of 5, 9, and 17 cells (corresponding to 300, 540, and 1020 m respectively), and four external driving factors (distance to the Calgary City center, distance to a main road, distance to a main river, and slope) were the most appropriate to capture the LULC dynamics in the watershed. The neighbourhood structure takes into account the local and extended influence on the central cell while reducing the bias from distant cells. Transition rules are built using information about the conditions that prevailed around each cell that has changed state as revealed by the historical maps. This information is displayed via a graphical interface in the form of frequency histograms that can be interpreted by the user of the model. At each time step of the simulation, the neighborhood composition of every cell is read and the level of correspondence with the parameters of the transition rules is computed. The cells having the highest level of correspondence are subjected to change state according to the transition rules. A complete description of the calibration and simulation methods can be found in Marceau et al. [36]. The quality of the simulation outcomes was assessed using a set of landscape metrics to compare the simulated and observed LULC maps of the year 2010. A correspondence of 91% between the simulated map and the reference map was obtained. This high correspondence reflects the fact that LULC changes mostly occur in the eastern portion of the watershed [36].

2.1.2. Hydrological MIKE SHE/MIKE 11 Model

MIKE SHE is a distributed physically-based hydrological model that simulates the major components of the hydrological cycle that occur at the surface and subsurface of a watershed including snowmelt, infiltration, baseflow, actual evapotranspiration (AET), groundwater recharge, overland flow, and streamflow. MIKE SHE represents the spatial variations of a watershed by an orthogonal grid network horizontally, and a vertical column at each horizontal grid square to describe watershed properties and capture the interactions of hydrological components. It includes a water movement (WM) module that simulates overland flow using diffusive wave approximation of the two-dimensional Saint Venant equations solved using finite difference method, actual evapotranspiration (AET) using the Kristensen and Jensen's model , unsaturated zone flow using the one-dimensional Richards' equation, and the two-layer water balance approach and saturated zone flow using the three-dimensional Boussinesq's equation. MIKE 11 simulates the river/channel flow based on a fully dynamic and one-dimensional diffusive wave hydraulic approach. MIKE SHE and MIKE 11 are coupled to address the interactions between streamflow and groundwater [42–44].

To set-up the MIKE SHE/MIKE 11 model, several datasets were collected including climate data, land-use/cover, geology, soil, and topography. Observed temperature and precipitation data were obtained from Alberta Environment and Parks for three and six climate stations, respectively. Potential evapotranspiration (PET) was calculated using the Hargreaves and Samani's temperature-based model [45], which was selected based on a rigorous comparison procedure [42,43].

The performance of the hydrological model was tested at different grid sizes (e.g., 100, 200, 300 m). The model was set-up at a spatial resolution of 200 m as the best compromise between running the simulation of hydrological processes within a reasonable time period and capturing the effect of LULC change while the model performance indicated a satisfactory agreement between the simulated and observed hydrological processes. Six LULC parameters such as detention storage, paved runoff coefficient, leaf area index (LAI), root depth (RD), Manning's, and leakage coefficient were associated to the LULC observed on the maps of 1985, 1992, 1996, 2001, and 2006. A soil layer was defined based on soil data obtained from the Agricultural Region of Alberta Soil Inventory Database and the Canadian Soil Information Service Data sources. Built-up areas were overlaid on the soil map to identify areas where infiltration had to be limited in the model. The topography map was created from the 80 m spatial resolution DEM (digital elevation model) from GeoBase and resampled at 200 m. Three geological layers along with their corresponding hydraulic parameters such as horizontal and vertical hydraulic conductivity, specific storage, and specific yield were defined in the model based on the geological data acquired from Alberta Environment and Parks [42–44].

The setup of the model was conducted based on a rigorous sensitivity analysis along with different calibration and validation procedures including split-sample, multi-criteria, and multi-point to fully capture surface and sub-surface hydrological interactions. The calibration was done for the period of 1981–1991 with the LULC map of 1985 whereas four time periods (1991–1995, 1995–2000, 2000–2005, and 2005–2008) were used for validation with their corresponding LULC maps (1992, 1996, 2001, and 2006, respectively). The goodness-of-fit was assessed by comparing simulated and observed data of total snow storage and groundwater level using the Pearson's correlation coefficient and mean absolute error (MAE), respectively, and streamflow using the Nash and Sutcliffe coefficient of efficiency (NSE), relative NSE, Ln NSE, and coefficient of determination. The model output indicated a good agreement between the simulated and observed data [44].

2.1.3. Agent-Based Model of Stakeholders' Negotiation

An ABM is a computational model designed to represent the characteristics and behaviours of the main entities of a system, referred to as agents, along with their interactions. An agent corresponds to any entity of the real world such as an individual, a social group or a biological entity that is situated in some environment and is capable of its own action to satisfy its design objectives. An agent can perform human-like intelligent actions such as reasoning, communication, and learning [46].

A first step in designing an ABM is to identify the stakeholders that are the key social actors in the system being simulated. Stakeholders were invited to participate in this project from the very early stages of defining the objectives and the model design. A workshop with an initial group of 15 representatives of NGOs and government agencies at the provincial and municipal level was organized to gather feedback on the overall goal and expected outcomes of the modelling exercise and to confirm their availability and interest in being involved. Five stakeholders were interviewed to gather their perspectives, preferences, and values regarding land development and water resource management in the watershed. These data were used to respectively define five agents in the model, namely the *Developer* agent, the *Planner* agent, the *Citizen* agent, the *AgricultureConcerned* agent, and the *WaterConcerned* agent. A fuzzy approach was employed to translate the stakeholders' perspectives into the model to take into account the uncertainty associated with such perspectives [47].

Agent-based automated negotiation refers to negotiation conducted with computer agents using artificial intelligence techniques in which two or more agents bargain for mutual intended gain [48]. Suitable approaches from the literature were examined and compared; Bayesian learning was selected and adapted to fit the negotiation problem in the context of land development. According to this well-established learning approach, a hypothesis is updated based on evidence of acquired new data [49]. It has been demonstrated that it reduces the number of negotiation rounds in comparison with automated negotiation in which no learning is allowed [47,50].

In this study, the negotiation process enables the agents to perform intelligent human-like behaviours, such as generating meaningful offers, exchanging information, modifying their behaviours throughout the negotiation, and learning based on previous experiences. The negotiation starts with a land development plan submitted by the *Developer* agent who generates offers by changing the location and/or inner configuration of the land development in the watershed. The other agents receive each offer and either accept or return it based on their values and preferences. During the negotiation process, the *Developer* agent attempts to learn the evaluation functions of his opponents in order to make educated guesses for its future proposals. A solution is sought that satisfies all the stakeholders that are involved in the negotiation at a pre-defined minimum level. A detailed description of the implementation of the automated negotiation process can be found in Pooyandeh and Marceau [50].

2.1.4. The Web Interface

To link the models and facilitate the communication between users and these models, a web-based interface was developed to meet the following requirements (Figure 2):

- work with three models having a different architecture, format, and programming language (CA, MIKE SHE, and ABM) in a unified way;
- submit a specific request for simulation and retrieve the results without dealing with the underlying complexity of the software that are involved;
- use the system with a minimum software and hardware requirements; and
- enable the system to be used on portable devices such as tablets and smart phones.

The user interface was designed and implemented following the SOA (Service Oriented Architecture) that treats each model as a service. This architecture allows extending the number of models being used with minimum changes required. The interface consists of several sub-components that are interconnected to deliver the required services to the end user. To ensure a consistent user experience across all browsers, the interface was developed according to Responsive Web Design (RWD). RWD is a web design approach that aims at crafting sites to provide an optimal viewing experience, i.e., easy reading and navigation with a minimum of resizing, panning, and scrolling, across a wide range of devices (from mobile phones to desktop computer monitors). The Twitter Bootstrap library was used to implement RWD in this system. Consequently, the end user can employ any of the available modern web browsers that support HTML 5 on various platforms from desktop computers to mobile phones and tablets.

In our system, the Web Application is the central component that manages and interconnects all the other components. The main tasks of the web application include:

- creating the user interface (web pages);
- authenticating and authorizing the user; authentication examines if the user is registered and provides the valid credentials (user name and password) while authorization determines what information can be accessed or what can be done by the user;
- managing the information submitted by the user and storing it in the database to be further retrieved by the appropriate service;
- triggering the appropriate service in order to process a simulation request; and
- providing the user with the status of a simulation process. Four status are possible:
    - queued: the request is not processed yet; it is waiting for the appropriate service to be picked up and processed;
    - in progress: the simulation process is running and is not finished yet;
    - failed: an error occurred while processing most likely related to an issue with the underlying external applications; it can be resolved by reprocessing the request;
    - finished: the simulation is completed and the user can view the results.

Microsoft ASP.NET MVC was selected as the framework to create the Web Application. It is a framework for building scalable, standards-based web applications using well-established MVC design patterns and the power of ASP.NET and the .NET Framework. A Message Queue mechanism was implemented to maintain an ordered list of messages and dispatch them to the appropriate services.

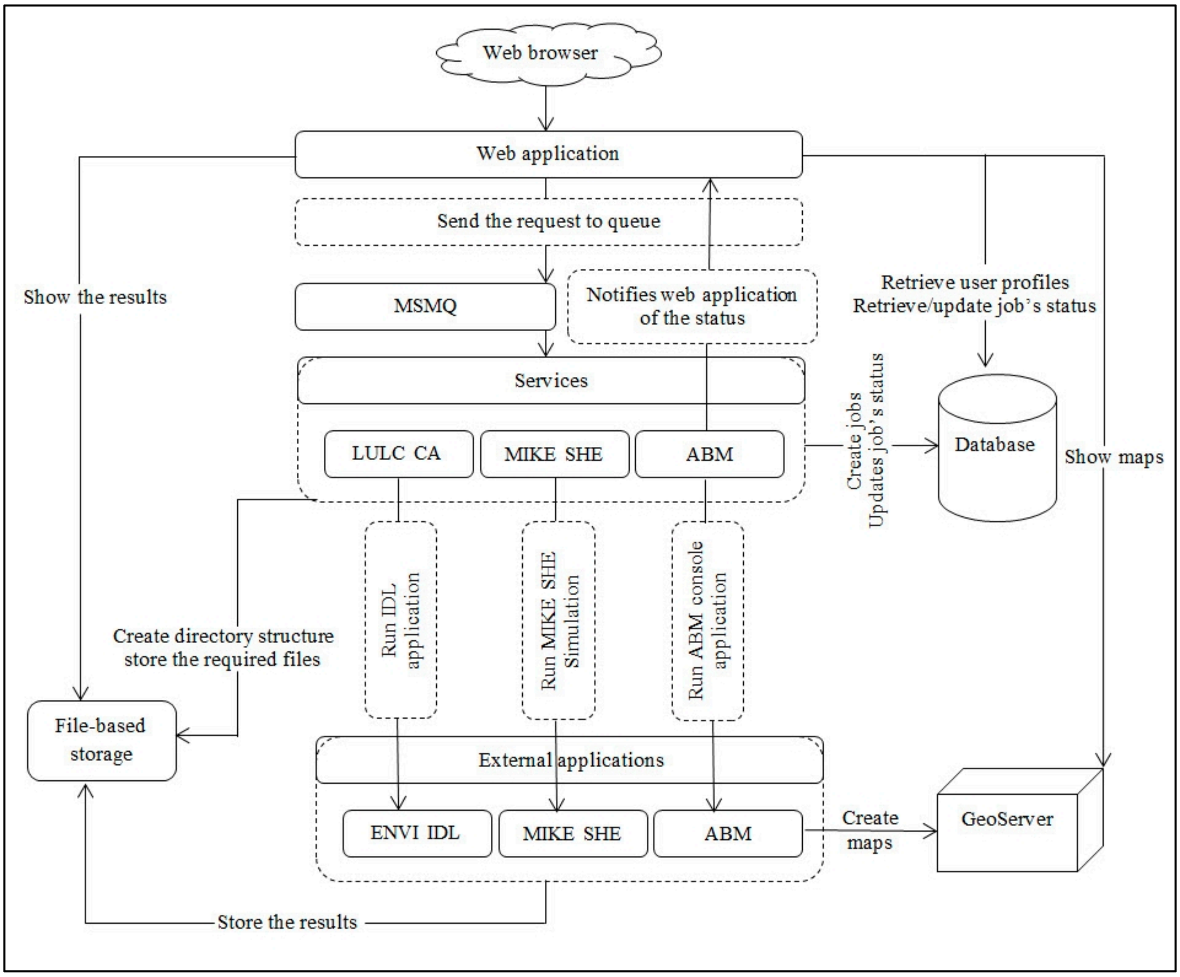

Figure 2. Architecture of the web-based interface and its connection with the components of the integrated modelling system.

2.2. Illustrating the Functionalities of the Modelling System

The functionalities of the integrated modelling system are illustrated according to the following steps. First, a land development scenario located in the Elbow River watershed was submitted as initial input for the automated stakeholders' negotiation. The negotiation outcome was then used as input in the CA model to generate LULC maps for the years 2021 and 2031, for two LULC change scenarios. From these maps, LULC parameter values were determined and transferred to MIKE SHE/MIKE 11 to simulate the combined and independent impact of the two LULC scenarios and one GCM climate scenario (the warmer and drier scenario, CSRNIES-A1FI) on the hydrological response of the watershed. Finally, a detailed demonstration of the functionalities of the modelling system and the simulation outcomes was provided during a one-day workshop that was attended by 65 representatives of industry, government, and NGOs who provided feedback on the modelling approach. These steps are sequentially described in the following section after a brief description of the location and main characteristics of the Elbow River watershed.

2.2.1. The Elbow River Watershed

The Elbow River watershed lies between 50°30′ and 51°20′ North latitude and 114°00′ and 115°00′ West longitude with a drainage area of 1235 km^2. The Elbow River originates in the eastern slopes of the Rocky Mountains, and flows eastward, before entering into the Glenmore reservoir in the City of Calgary. Elevations of the watershed range from a high of over 3000 m above sea level to a low of

1080 m (Figure 3). The watershed supports several uses such as irrigation for crops, supplying drinking water and various recreational activities while experiencing rapid rural and urban areas development. This can induce stress to the water quantity and quality of the watershed. It is predicted that in the near future, human activity along with climate warming, through its effect on glaciers, snow packs and evaporation, and cyclic droughts, will cause a crisis in water availability in this area [42,43,51]. Therefore in recent years, there have been numerous concerns regarding the sustainability of water resources in the watershed.

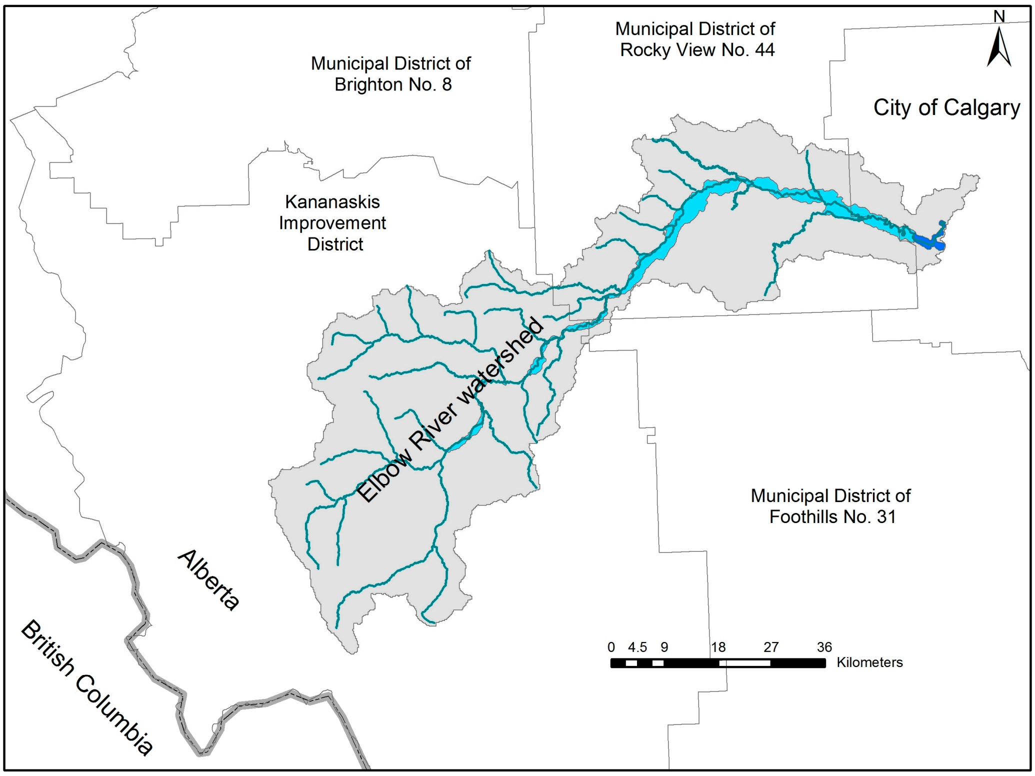

Figure 3. Location of the Elbow River watershed.

2.2.2. Simulation of the Stakeholders' Negotiation with the ABM

A land development identified as one of the potential growth nodes in the Elbow River watershed (Rocky View Growth Management Strategy) due to its proximity to the City of Calgary and the vicinity of two highways was selected for the purpose of this study (Figure 4). It contains four land uses, namely residential, recreational, open green space, and a waste water management site. Four situations were considered in the negotiation. In the first case, the Developer agent sorts the geographical locations of the development based on its utility function, and proposes them to the other agents in a descending order. In the second case, the Bayesian learning approach is employed by the Developer agent to make a new offer to its opponents. In the two additional cases, the Developer agent has the option of changing both the location and the inner configuration of the proposed land development by choosing different land-use densities and combinations, with and without the learning component. A minimum satisfaction level of 60% of each agent was selected as the threshold to consider an agreement acceptable [52].

When the user submits an ABM process request, an ABM Service is triggered. ABM Service runs ABM java program and updates the status of the request. The ABM java program starts the processing and as a result publishes the map services that represent the negotiation outcome. When the process is completed, ABM Service notifies Web Application, which in turn notifies the user.

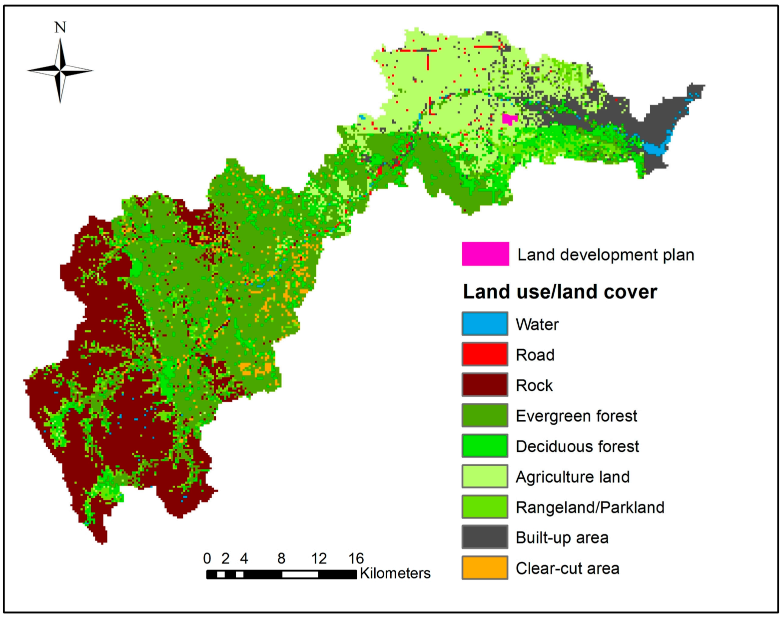

Figure 4. Land use/land cover map of the Elbow River watershed and location of a proposed land development.

2.2.3. Land-Use/Land-Cover Change Simulation with the CA Model

The CA model was run to predict the future LULC maps of 2021 and 2031, for two LULC change scenarios: (i) the ABN (agent-based negotiation) scenario that refers to the simulation of future LULC changes in the watershed based on the result of the stakeholders' negotiation; and (ii) the BAU (business as usual) scenario that refers to the simulation of future LULC changes based on the assumption that they will be similar to the observed historical changes.

The CA model was developed in the ENVI environment and IDL programming language. When the user submits a CA simulation request, it triggers Land-Use CA Service that prepares the files and directories required by the IDL program, and runs it via COM Wrapper Objects. The IDL program completes the simulation. The result of the simulation is a collection of ENVI image files that are further converted to ESRI GRID ASCII format files to be used in the MIKE SHE Service when needed. When Web Application finds out that the request is processed and completed successfully, it allows the user to see the result.

2.2.4. Simulation of Hydrological Processes with MIKE SHE

Hydrological processes were simulated using the water balance (WB) module in the MIKE SHE model in response to LULC and climate change. A base case scenario (BL) was defined that represents the hydrology of the watershed from 1961 to 1990 with its corresponding LULC map of 1985. Then, the WB was estimated in the 2020s (2011–2040) for the following conditions, relative to the base case scenario (Figure 5):

1. Impact of LULC change on hydrology: seasonal and annual variations of hydrological processes were simulated under the ABN and BAU scenarios (predicted by the CA model) when climate was assumed constant.
2. Impact of climate change on hydrology: seasonal and annual variations of hydrological processes were simulated under the warmer and drier scenario, CSRNIES-A1FI, when LULC was assumed constant.
3. Impact of climate change and LULC on hydrology: hydrological processes were simulated under the combined ABN + A1FI and BAU + A1FI scenarios.

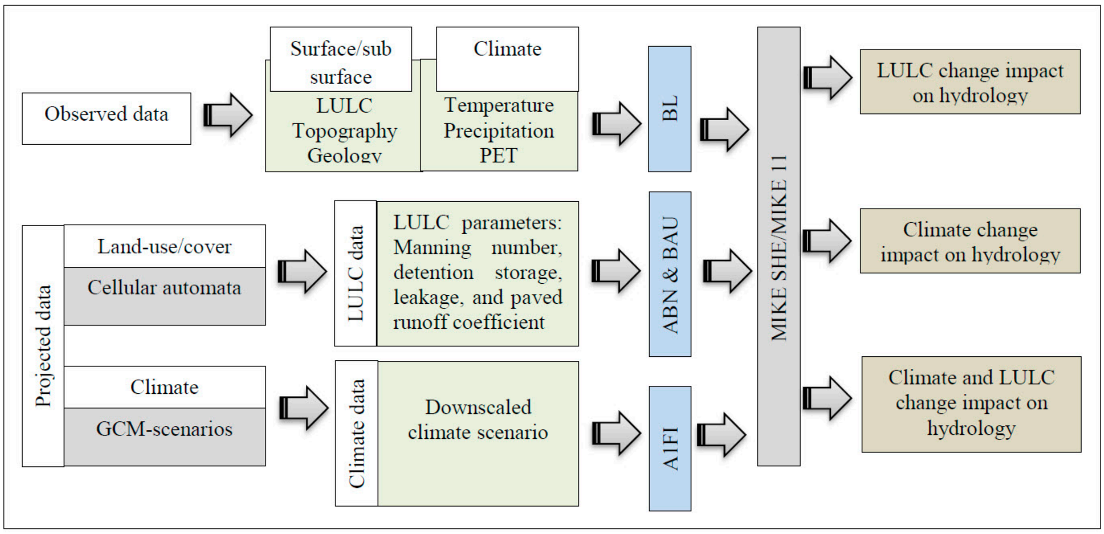

Figure 5. Implemented procedure for assessing the impact of LULC change-only, climate change-only, and combined LULC and climate change on the hydrology of the watershed.

The MIKE SHE model requires different data files, including, the land use files that are generated by Land-Use CA Service in the ESRI GRID ASCII format. In order to be understandable by MIKE SHE, these files must be converted to DFS format files. MIKE SHE provides a .Net framework library that enables to create and modify DFS files. MIKE SHE Service makes use of this library to create the DFS files. When a user submits a MIKE SHE simulation request, MIKE SHE Service retrieves the CA simulation results, generates the corresponding DFS files and runs MIKE SHE. When the simulation is completed, MIKE-SHE Service produces the water balance results and Web Application notifies the user that the simulation results are ready.

3. Results

Figure 6 illustrates the results of the agent-based negotiation model. The numbers on the map depict the location of the land development while the respective utility value (satisfaction level) for each agent is shown in the graph for each round of the negotiation. It can be seen that the utility value for the agents evolves throughout the negotiation. As expected, the negotiation starts with a high value for the Developer agent, which declined gradually with the change in the location and inner configuration of the land development plan to accommodate the perspectives of other agents until the pre-determined minimum satisfaction for all agents is reached.

The same procedure was repeated with the inclusion of a learning component. The results show that adding a learning capability helps the agents to reach an agreement in a fewer rounds of negotiation comparing to the no-learning scenario (Figure 7).

The outcome of the negotiation module is a location and inner configuration of the land development that is preferred by all agents. This result was used in the CA model to simulate LULC changes under the ABN and BAU scenarios for the year 2021 and 2031, relative to the LULC map of 1985. The LULC change simulations reveal a reduction in evergreen forest, deciduous forest, and agricultural land and an expansion in rangeland/parkland and built-up areas in both scenarios in 2021 and 2031 (Figure 8). In 2021, rangeland/parkland extends from 54.6 km^2 to 76.7 km^2 in the BAU scenario and to 76.3 km^2 in the ABN scenario while built-up areas increase from 35.4 km^2 to 97.2 km^2 in the BAU scenario and to 94.8 km^2 in the ABN scenario. The evergreen forest manifests a decline from 470.4 km^2 to 406.2 km^2 in the BAU scenario and to 407.9 km^2 in the ABN scenario. The deciduous forest also shrinks from 186.0 km^2 to 114.8 km^2 in the BAU scenario and to 114.2 km^2, in the ABN scenario while the agricultural land decreases from 216.9 km^2 to 199.4 km^2 in the BAU scenario and to 201.5 km^2 in the ABN scenario.

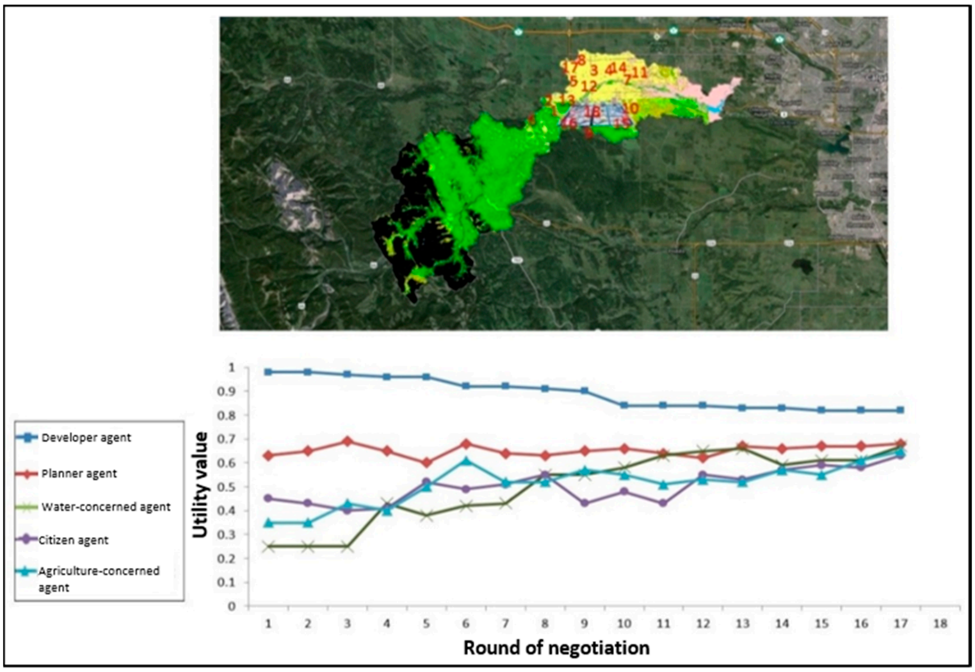

Figure 6. Utility value of the agents through the negotiation process when no learning is employed.

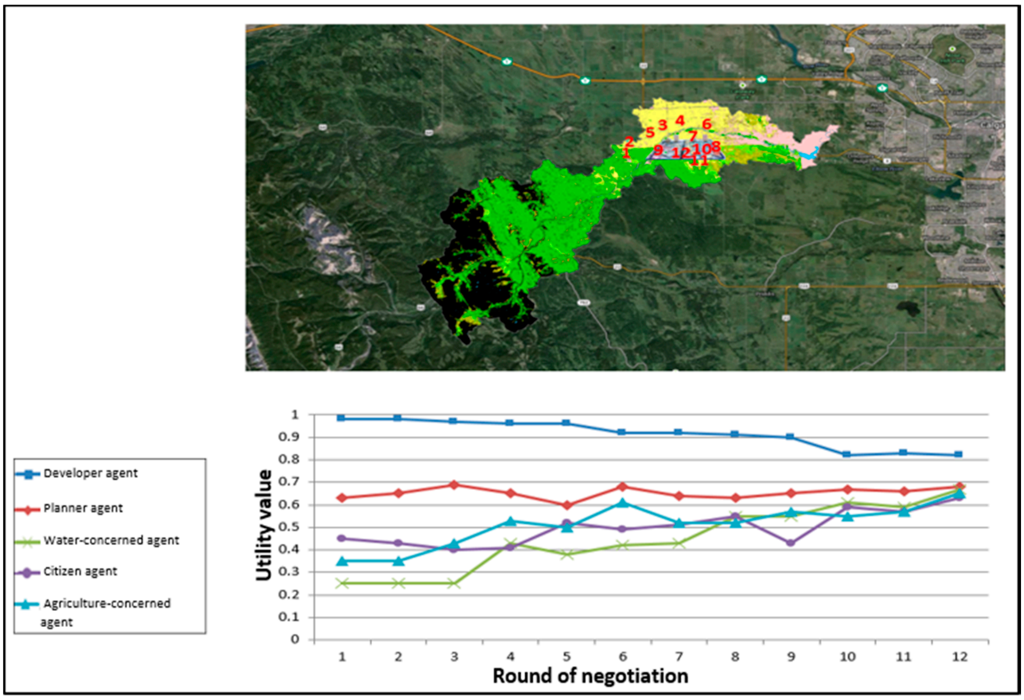

Figure 7. Utility value of the agents during the negotiation process with the inclusion of the learning component.

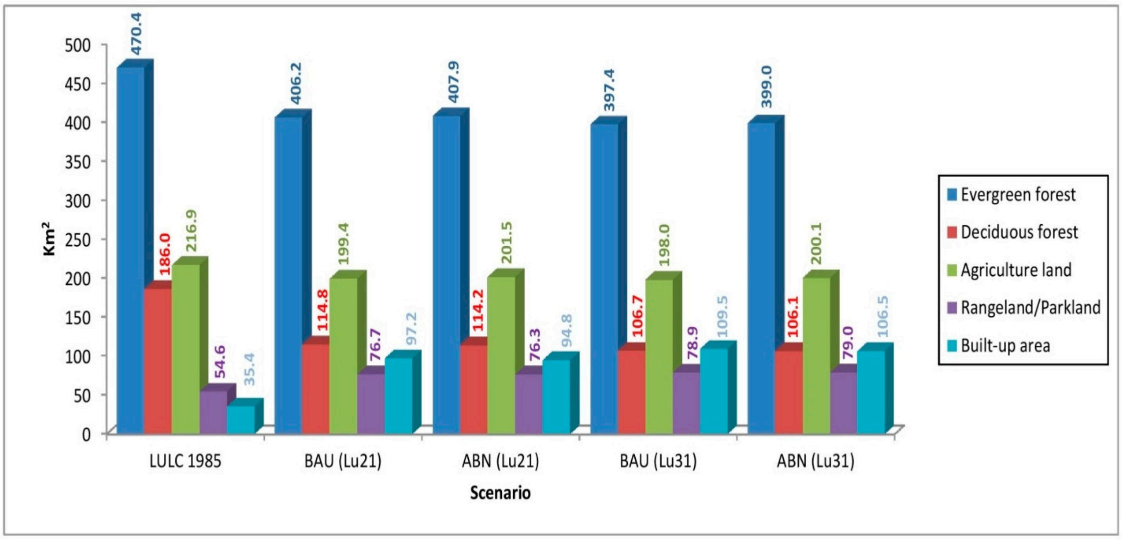

Figure 8. Simulated LULC changes for the year 2021 (Lu21) and 2031 (Lu31) in the Elbow River watershed based on the BAU and ABN scenarios relative to the LULC map of 1985 (Lu85).

In 2031, the growth of rangeland/parkland and built-up area reaches 78.9 and 109.5 km^2 in the BAU scenario and 79.0 and 106.5 km^2 in the ABN scenario, respectively. Evergreen forest, deciduous forest, and agricultural land decrease to 397.4 km^2, 106.7 km^2, and 198.0 km^2 in the BAU scenario and to 399.0 km^2, 106.1 km^2, and 200.1 km^2 in the ABN scenario. The change in area of each LULC class is almost the same in both scenarios in 2021 and 2031 whereas their spatial distributions are different (Figure 9). In the ABN scenario, the new built-up areas are concentrated in the vicinity of the land development that resulted from the stakeholders' negotiation while new built-up areas in the BAU scenario are mostly distributed north of the Elbow River.

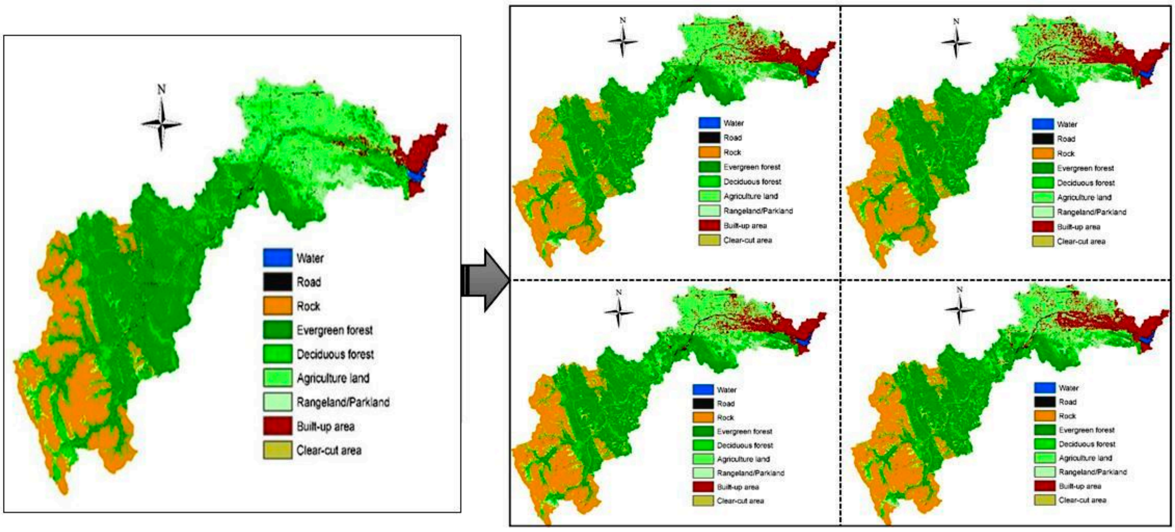

Figure 9. LULC maps for the BAU scenario in 2021 (**b**) and 2031 (**c**); and the ABN scenario in 2021 (**d**) and 2031 (**e**); relative to the LULC map of 1985 (**a**).

When looking at the hydrological response to LULC change, the BAU and ABN scenarios result in a decrease in actual evapotranspiration (−5.3% and −6.8%) and infiltration (−5.3% and −14.0%) and an increase in overland flow (12.4% and 21.6%), respectively (Figure 10). These changes are associated with the conversion from evergreen/deciduous forest to built-up areas that results in a decrease in root density and canopy, and an increase in impervious surface areas, which create the conditions for a decline in actual evapotranspiration and infiltration and a rise in overland flow.

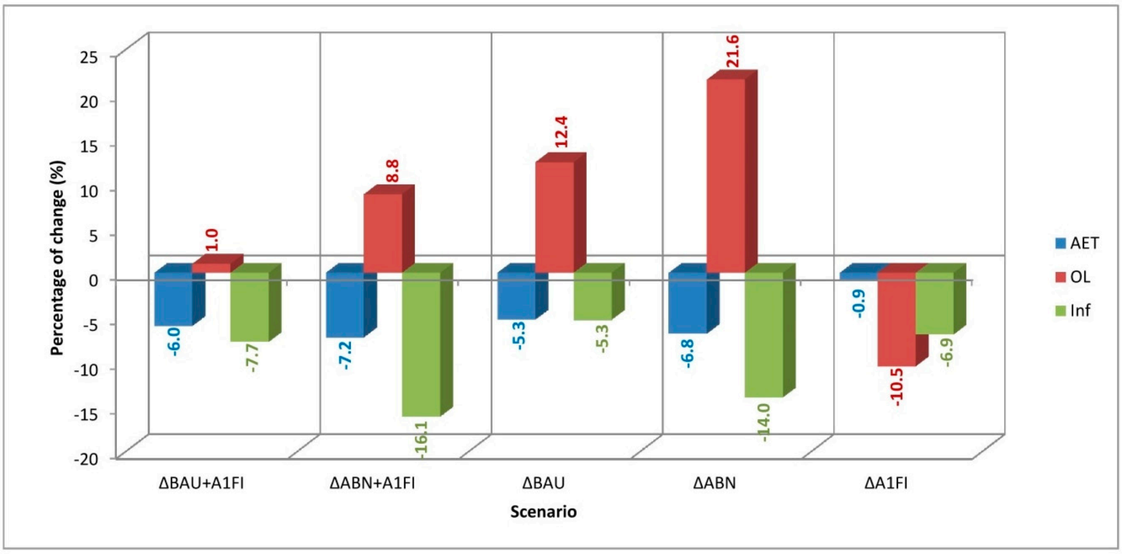

Figure 10. Percentage of changes in actual evapotranspiration (AET), overland flow (OL), and infiltration (Inf), relative to the baseline.

Responses of actual evapotranspiration and infiltration to the climate change scenario (A1FI) occur in the same direction as the LULC change scenarios, resulting in a reduction of 0.9% and 6.9%, respectively. However, overland flow decreases by 10.5% under the A1FI scenario, which is in the opposite direction to the LULC change scenarios. Consequently, under the combined LULC and climate scenarios (BAU + A1FI and ABN + A1FI), overland flow rises by 1.0% and 8.8%, respectively. On the other hand, there is a decline in actual evapotranspiration (−6.0% and −7.2%) and infiltration (−7.7% and −16.1%) for the BAU+A1FI and ABN+A1FI scenarios, respectively.

The scenario that has the largest impact on hydrological processes is the ABN scenario. Although the ABN and BAU scenarios generate almost the same quantity of changes for each LULC class, their impacts on the hydrological processes are different due to the varying spatial distributions of the LULC patterns, which may alter the interaction of surface and subsurface hydrology differently, and induce different responses to the same amount of precipitation.

These results clearly indicate that an investigation of hydrological processes based solely on climate change [53,54] or LULC change [8,55] impacts may not provide a reliable conclusion since the hydrological processes are tied to both LULC and climate. The results also highlight the importance of using an integrated modelling system for climate and LULC change impact assessment to avoid underestimating/overestimating the hydrological response of a watershed.

Flow duration curves (FDCs), which represent river flow ranging from low to peak flows, were constructed for the baseline period and each scenario (Figure 11). River flow discharge was identified at Q5 (flows for exceedance percentages 5%) and Q95 (flows for exceedance percentages 95%), which represent peak and low daily flows, respectively. The FDC indicates that discharge increases under the ABN and BAU scenarios and decreases under the A1FI scenario at Q5 and Q95. The largest increase in streamflow occurs under the ABN scenario at Q5 and the BAU scenario at Q95, respectively. This implies that both LULC change scenarios considerably contribute to flood peaks rather than drought, particularly the ABN scenario.

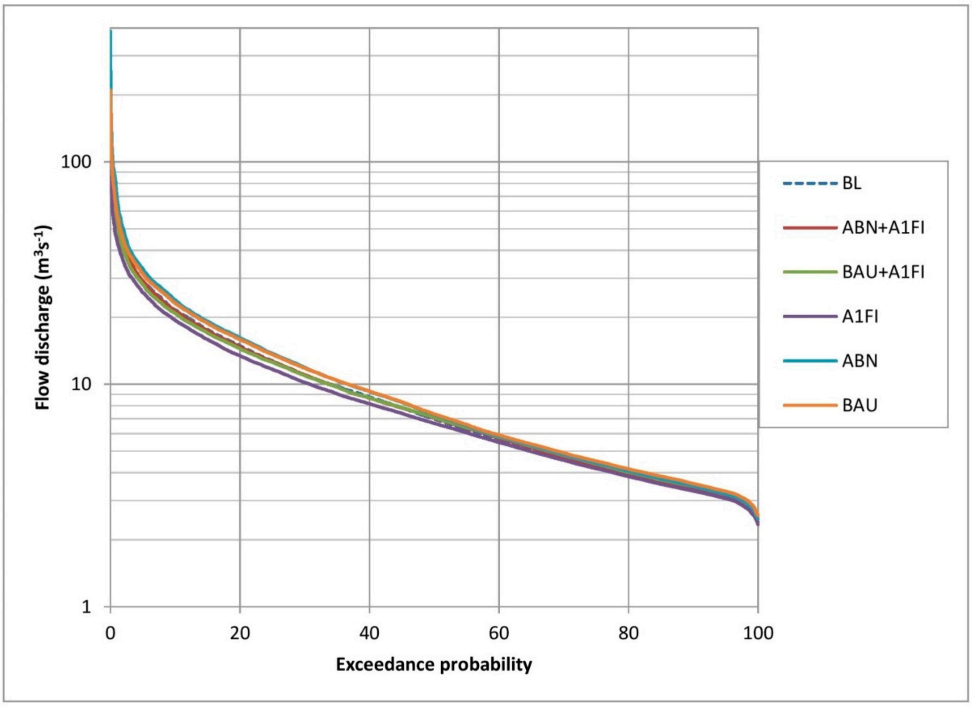

Figure 11. Flow duration curves for each scenario and the baseline.

These results represent a limited set of outcomes that could be achieved with the proposed integrated modelling framework. To complete the study, a one-day workshop was held with 65 representatives of industry, government agency, and non-for-profit organizations where a detailed demonstration of the functionalities of the models was provided. These stakeholders were also offered the opportunity of running simulations with the different models and discuss the specificities of their design and implementation with the scientific team. A discussion with a panel of experts was also organized. The participants confirmed the necessity of using an integrated modelling approach to investigate complex water resource management issues and the importance of engaging stakeholders along with scientists in the crucial phases of model design, implementation, and validation.

4. Conclusions

This paper describes an integrated framework to model the interactions between land use, climate, and hydrology along with stakeholders' negotiation within the Socio-Hydrology paradigm. The framework addresses the implicit uncertainty and complexity involved in the interactions of these systems, using a combination of individual-based and spatially distributed models, namely an agent-based model for automated stakeholders' negotiation, a LULC cellular automata model, and the hydrological MIKE SHE/MIKE 11 model that are linked through a web-based interface. This modelling system was then applied to the Elbow River watershed, in southern Alberta, Canada, to illustrate its functionalities.

Five agents representing the role and values of five key stakeholders were incorporated in the ABM: the Developer agent, the Planner agent, the Citizen agent, the AgricultureConcerned agent, and the WaterConcerned agent. A fuzzy approach to tackle the inherent uncertainties in the way stakeholders expressed their perspectives about land development and water resources management along with artificial intelligence techniques to equip the agents with intelligent behaviors such as learning were implemented. The negotiation results indicate that adding a learning capability allows the agents to reach an agreement about a preferred location and inner configuration of a land development more quickly compared to a no-learning scenario. The outcome of the ABM negotiation presented in the format of a map and referred to as the ABN scenario was used as input into the CA model to predict how it could affect future LULC in the watershed. This scenario was compared to the BAU (business as usual) scenario in which changes in the future are considered as being similar to historical changes. LULC changes corresponding to each scenario were simulated for the years 2021 and 2031. Results indicate that the area of each LULC class remains almost the same for both scenarios but that their spatial distributions vary. The two LULC change scenarios along with a climate change scenario (A1FI) were applied in the MIKE SHE/MIKE 11 model to simulate hydrological processes in response to LULC change-alone, climate change-alone, and combined LUCL and climate change in the watershed. The two LULC change scenarios and the climate change scenario amplified and/or offset each other's influence on hydrological processes according to the direction and magnitude of their impact. This was shown with an amplified magnitude of reduction in the average annual infiltration and evapotranspiration, and an offset rise in overland flow. The flow duration curves indicate an increase in peak flows under the ABN and BAU scenarios and a decrease under A1FI scenario while the largest rise in peak flows occurs under the ABN scenario. Simulation outcomes reveal that the ABN change scenario induces the largest modifications to hydrological processes compared to the two other scenarios. This result illustrates the importance of engaging stakeholders in the evaluation of land development scenarios and their potential consequences on water resources.

This study highlights the necessity of going beyond traditional modeling approaches in order to capture the interactions between society-hydrology-land-climate processes to better cope with water-related issues associated with changes in climate and land use. The models employed in this study offer several advantages. The physically based distributed MIKE SHE/MIKE 11 model provides a detailed description of the processes that occur in the entire land phase of the hydrological cycle, including the interactions between surface and groundwater. The CA, as an individual-based model, captures the evolution of LULC patterns that emerge from the influence of neighboring cells and external driving factors at different time intervals that represent an important data source in a distributed hydrological model. Finally, the ABM allows the incorporation of human negotiation and decisions and the exploration of the potential impact of such decisions on the hydrology of the watershed. The linkage of these three models through a web-based interface offers the user the flexibility of investigating a wide range of scenarios related to water management issues while considering the reciprocal influence of human and natural systems. Involving key stakeholders via a series of workshops, from the initial design phase to the final demonstration of the models, considerably enriched the research through the sharing of knowledge and expert validation, and confirmed the necessity of using an integrated modelling approach to address complex water resource management issues.

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