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# CLIMATE CHANGE AND SOCIO-HYDROLOGICAL DYNAMICS: ADAPTATIONS AND FEEDBACKS

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A functioning ecological system results in ecosystem goods and services which are of direct value to human beings. Ecosystem services are the conditions and processes which sustain and fulfil human life, and maintain biodiversity and the production of ecosystem goods. However, human actions affect ecological systems and the services they provide through various activities, such as land use, water use, pollution and climate change.

Climate change is perhaps one of the most important sustainable development challenges that threatens to undo many of the development efforts being made to reach the targets set for the Millennium Development Goals. Understanding the provision of ecosystem services and how they change under different scenarios of climate and biophysical conditions could assist in bringing the issue of ecosystem services into decision making process. Similarly, the impacts of land use change on ecosystems and biodiversity have received considerable attention from ecologists and hydrologists alike. Land use change in a catchment can impact on water supply by altering hydrological processes, such as infiltration, groundwater recharge, base flow and direct runoff. In the past a variety of models were used for predicting land-use changes. Recently, the focus has shifted away from using mathematically oriented models to agent-based modeling (ABM) approach to simulate land use scenarios. The agent-based perspective, with regard to land-use cover change, is centered on the general nature and rules of land-use decision making by individuals. A conceptual framework is developed to investigate the possibility of incorporating the human dimension of land use decision and climate change model into a hydrological model in order to assess the impact of future land use scenario and climate change on the ecological system in general and water resources in particular.

## 1. Introduction

The land use and landscape changes that are being observed today could signal the possibility that extreme events (such as floods, droughts, heat waves, etc.) could occur with higher frequency in any given year. These changes also imply that changes in natural ecosystems and socioeconomic activities are bound to occur. For example, change in climatic conditions could shift the sustainability of natural resources, such as water, air, land, forests, fish and wildlife. This is because these systems cannot adapt as quickly as the climate (Flannery, 2006 and McBean, 2006; cited in Prodanovi'c and Simonovi, 2007). The implications of climate change on the socioeconomic systems are also great. The threats of adequate supply of drinking water, energy and other necessary services in light of changing hydro-climatic conditions are real, and need to be addressed.

Land-use/land-cover change occurs through complex interactions between land users (agents) on one hand and biophysical and socioeconomic factors on the other hand. The complex interaction between environment and social factors could bring emergent changes in land uses. As a consequence of land use change, the water balance of a specific catchment could significantly be affected. The altered hydrological cycle resulting from the land use change may significantly affect a local climate such as the precipitation and temperature of a particular ecology. This may impact the sustainable usage of water resources and ecological balance of an environment.

For a given environment land use change can be predicted by an agent based model (ABM), based on the possible interactions between agents (land users), socio economic and the biophysical factors. An ABM consists of autonomous decision making entities (agents), an environment through which agents interact, rules that define the relationships between agents and their environment, and rules that determine sequence of actions in the model. Agents in ABMs are considered as components that can learn from their environments and change their behaviors accordingly. Purnomo and Guizol[17] described agents as entities with defined goals, actions and domain knowledge which operate and exist in an environment. Adhering to the emerging paradigm shift, decision to change land use would only be obtained after a complex interactions of the socioeconomics and environmental factors which influences the behavior of the farm manager.

ABMs can be useful tools for studying the effects of land-use/cover change processes on the water resources at multiple scales and organizational levels. Bousquet *et al.*[4] recognized ABMs as useful tools in involving stakeholders in a collective design of management plans. Brown (2006) defined ABMs as computer representations of systems that are comprised of multiple, interacting actors (i.e., agents). These models have components for the socioeconomic factors as well as for the biophysical inputs.[2,6] ABMs are also considered useful in capturing emergent phenomena as a result of complex interactions happening in an environment. They are also praised in providing a natural environment for the study of systems composed of real-world entities, and by their flexibility particularly in relation to the development of geospatial models.[7,15] Generally, ABM is a method by which one investigates and describes complex systems and their emergent properties.[3,5,14,18,19]

ABMs are also used to simulate different scenarios for use in future policy and management preferences. For instance, Polhill *et al.*[16] used an ABM model known as FEARLUS to investigate the effect of different events such as market globalization and global change of climate on land use change. Their long-term goal also encompasses providing advice to policy makers on possible land-use outcomes. For instance, Becu *et al.*[2] integrated a hydrological model in an ABM known as CATCHSCAPE to manage the conflicts arising between upstream and downstream water users and to investigate impacts of upstream irrigation management on downstream agricultural viability in northern Thailand. This ABM is equipped with biophysical modules, which simulate the hydrological system with its distributed water balance, irrigation scheme management and crop and vegetation dynamics.

## 2. Procedure

An integrated conceptual socio-hydrological model for the prediction of the impact of land use and climate change on water resources was developed for the central region of South Africa in the Upper Modder River basin (Fig. 1). The focus of this exercise was on C52A, a quaternary catchment in the Upper Modder River basin of the central region of South Africa. The catchment is characterized by semi-arid climate and dominated by soil type which is susceptible to surface crust formation. The annual mean rainfall is about 588 mm. The maximum mean daily temperature is 29$^o$C while the minimum mean daily temperature is −0.1°C. The catchment is dominated by the slope range of 0–3% which comprises 57% of the catchment area followed by the slope range of 3–8% which covers 34% of the catchment area.

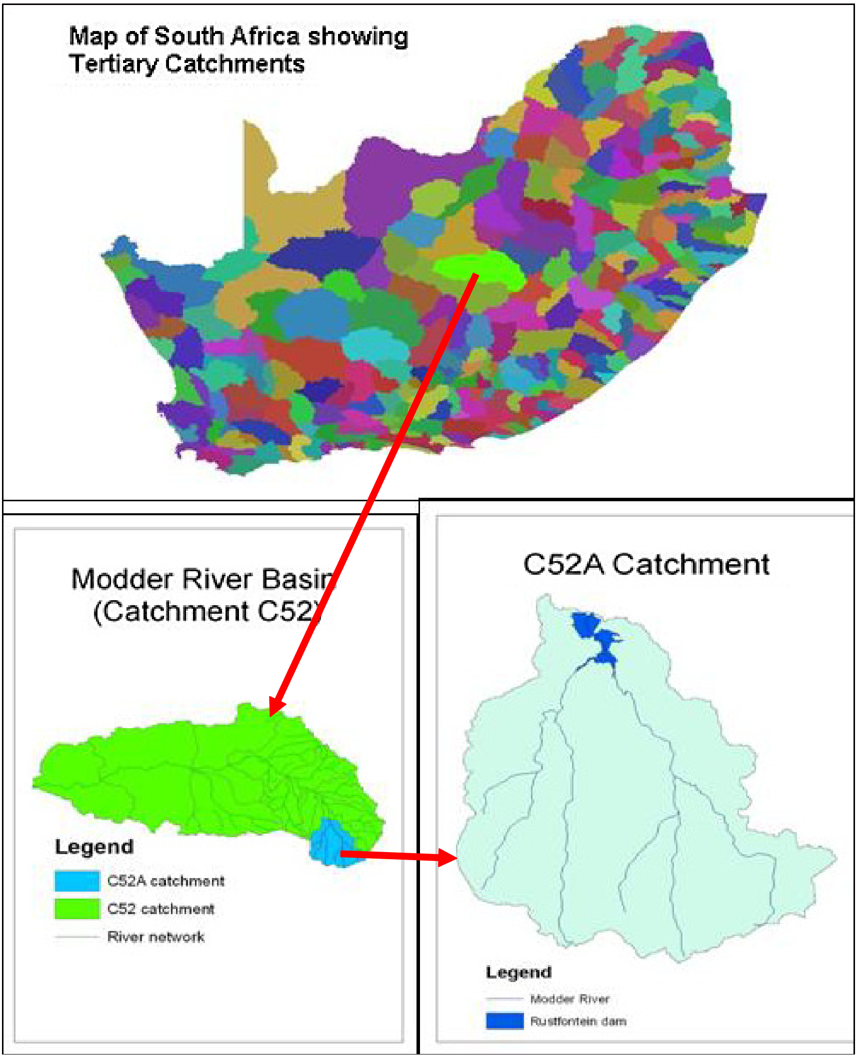


Fig. 1. The study area.

The interactions which was assumed to take place in the catchment was conceptualized rationally through an interactive process with different stakeholders, namely hydrologist, soil scientist, socio-economist and information technologist. Similarly, a climate change scenario was built in using appropriate climate change model that will link up with the climate database.

## 3. Conceptual Socio-Hydrological Model

Figures 2 and 3 present the integrated conceptual model for the quaternary catchment C52A. In Fig. 2, it can be seen that the environment comprises all resources, agents and socioeconomic interactions that are taking place. The environment is assumed to include both external as well as internal agents.

Agents represented by farmers or farm managers, after a complex interaction with similar agents and/or other agents and with the environment, will be assumed to undergo a behavioral change. These agents who may acquire an immense knowledge from the interaction and the environment can react individually or as a group. A reaction may lead to a decision towards change of land use. Land use changes could occur spatially as well as temporally within the environment. The environment may contain spatially different soil types and physiographic features which can be considered static for a considerable period. This, in combination with climatic changes, could contribute to the generation of surface runoffs depending on the land-use, soil type and topography of the explicitly situated land/agricultural land.

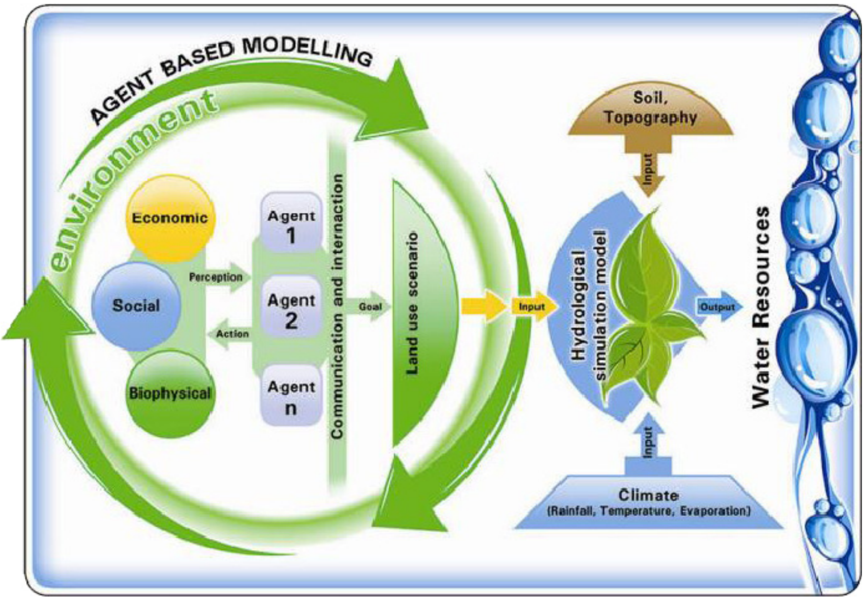


Fig. 2. Socio-hydrological conceptual framework.

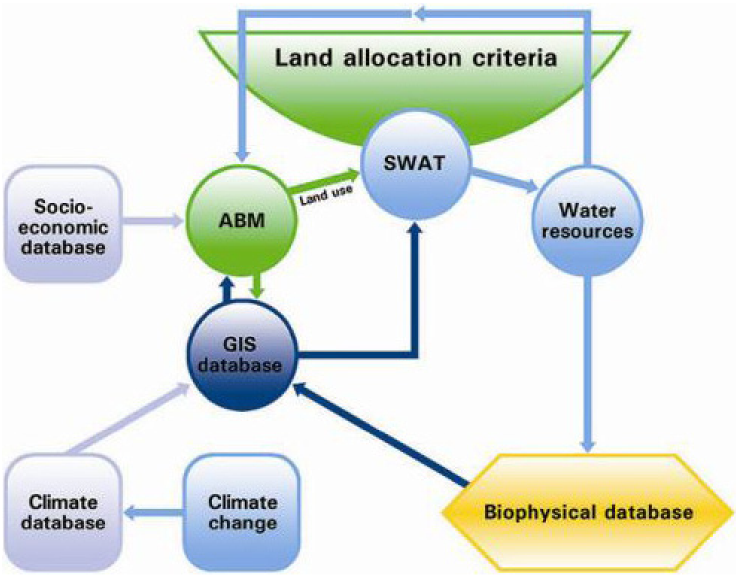


Fig. 3. Integration of land use and climate change model.

Figure 3 shows the conceptual model illustrating the database types and its linkage to the different nodes in the process of the model. The socioeconomic factors and the interaction that lead to decision in land use change would be captured by the ABM module while changes in the stream flow would be dealt by the hydrologic module integrated in the system (SWAT). In this way, all land use changes resulted by the interactions will be simulated by the ABM while climate change scenario is captured and linked to the climate database within the GIS system. The cyclic effect of climate and land use change will be continuously updated in the GIS database module. The GIS database supplies data to both the ABM and hydrological models, creating a means of investigating the impact of one on the other in addition to their combined impact on the water resources.

## 4. Hydrological Simulation

The impact of different land use scenarios on the water balance of C52A (see Fig. 1) was demonstrated using Soil and Water Assessment Tool (SWAT), which was developed by the United States Department of Agriculture (USDA) to simulate the impacts of land-use changes and land management practices on water balance of catchments, especially for ungauged catchments.[1]

SWAT has also proven to be an effective tool for understanding pollutions from fertilizer applications and point sources[1,11] and for wider environmental studies.[12] The model is also used as a decision support tool in land use planning by simulating the impact of different land use scenarios on water resources.[10] The following figures (Figs. 4 and 5)



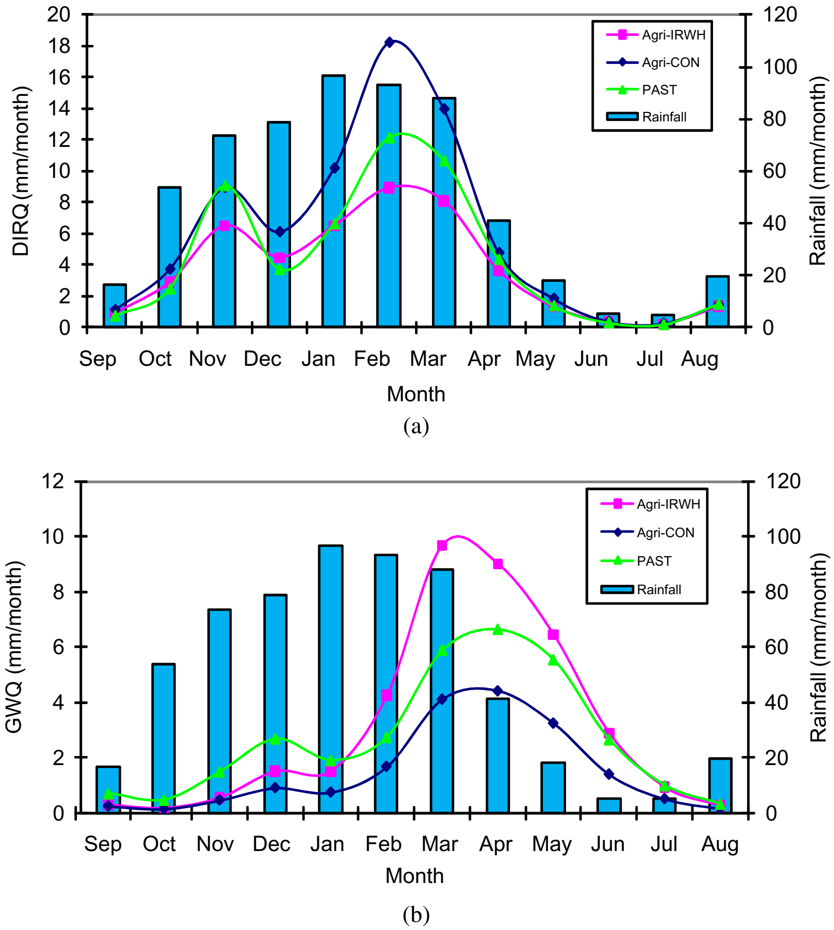


Fig. 4. Simulated streamflow components: (a) Direct flow; (b) Base flow in the quaternary catchment (C52A) under three land use scenarios (PAST = Pasture; Agri-CON = Agriculture using conventional tillage; Agri-IRWH = Agriculture using rainwater harvesting).

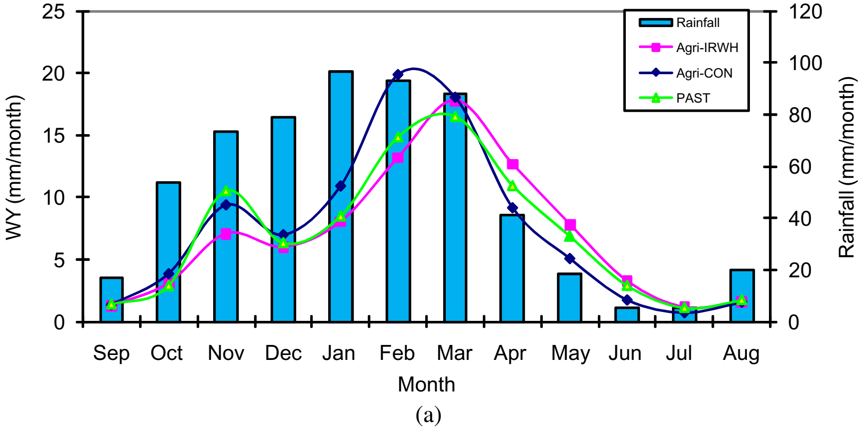


Fig. 5. Simulated water yield (a) and evapotranspiration (b) in the quaternary catchment (C52A) under three land use scenarios.



present hydrological simulation results of three different land use scenarios, namely pasture (PAST), agriculture using conventional tillage (Agri-CON), agriculture using rainwater harvesting technique (Agri-IRWH). The model was able to illustrate the potential impact of different land use types on the water resources of quaternary catchment C52A. The results of the scenario analysis revealed that conventional agricultural land use type generated the highest direct flow compared to the ones dominated by pasture or IRWH land use types.

The use of the ABM in the prediction of land use scenario (see Fig. 2) is still in the process of development. Once this is in place, it will make it possible to have a realistic simulation of land use decision which will serve as input to the SWAT hydrological model for impact analysis.

## 5. Conclusions

Global climatic changes threaten the livelihoods of the farming community in the developing countries and in most of the Sub-Saharan African countries. The cyclic effects of climate and land use change may cause a double fold negative impact on the water resources of the aforementioned countries. As most of the populations of these countries income and food depend on agricultural production, water is the most critical natural resource. To minimize the future crises in water resources resulting from land use and global climatic change and in order to take proactive measures for sustainable water resources utilization, development of an integrated socio-hydrological model could be a step in the right direction for decision support system.



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