.INTEGRATING HYDROLOGICAL AND SOCIO-ECONOMIC ASPECTS FOR SUSTAINABLE CATCHMENT MANAGEMENT: NEEDS AND OPPORTUNITIES

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Abstract

Sustainable catchment management requires the integration of the hydrologic, environmental and socio-economic components that occur within the catchment. Most existing models deal individually with each component. Modeling of the components alone may not simulate the complete system effectively as physical/environmental and socio-economic systems have emergent properties which relate to the whole, and not merely to the sum of the parts. A realistic framework that integrates a range of models (hydrologic and socio-economic) and datasets will therefore provide the necessary platform for assessing the impacts of proposed policy and management strategies on livelihoods.

This paper introduces a framework for the coupling of hydrologic and socio-economic models. The model framework will account for the interactions between water availability, farmer behavior, agricultural productivity, and will estimate the socio-economic gains from improvement in the allocation and efficiency of water use. The paper further suggests ways in which such models can be developed and used. The integration model will test and evaluate a given policy on the farmer income and the quality of livelihood outcomes. The approach aims to explore, rather than predict, the future and is not oriented towards optimization. By exploring alternative scenarios the user exercises choice of the best bet solutions of proposed policy and management practices. The model framework will be applied in the Olifants River Basin, South Africa at quaternary level (lowest water management area) as a case study for an in-depth investigation.

Key words: livelihood outcomes; model framework; impacts; socio-economic; sustainable catchment management

1. INTRODUCTION

There is need for water to be managed prudently and holistically as concerns mount over food security and water availability in river basins. Numerical research studies combining climate model outputs, water budgets and socio-economic information along digitized river networks demonstrate that a large fraction of the world's population is currently experiencing water stress (defined as the ratio of water withdrawal or water use to discharge) of which the Olifants catchment is one such example (Vörösmarty *et al.*, 2000). It is widely accepted that integrated approaches can lead to sustainability. Hence, there seems to be a wide consensus on the need for multidisciplinary or multidimensional water resources management, but the

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necessary methodologies and ideas for actually doing it are not available (van Delden *et al*., 2004; Prasad, 2004; Ringler, 2001).

The conviction that IWRM realm can provide sustainable water security for every citizen into the twenty-first century has forced water professionals and IWRM to become more responsible to world citizens, especially towards the poor. Janssen and Goosen (2005) argues that water management problems are no longer predominantly addressed as technical issues; but have become part of a complex policy process in which different stakeholders and institutions are involved. Sustainable growth is only conceivable if accompanied by the satisfaction of those cultural and material needs that are indispensable for all individuals to live with the self-esteem to which every individual is entitled.

The current research seeks to contribute to a better understanding of the available water in the catchment in terms of blue water and green water, and further develop a decision support system which can be used to decide on alternative water management strategies. The model will also link rainfall and/or moisture in the soil to the crop yield and socio-economic aspects in a catchment to assess the associated livelihood outcomes. The interaction between climate and land-surface hydrology and socio-economic facets is extremely important in relation to long-term water resources planning. This is especially so in the presence of global warming and massive land use changes, issues which seem likely to have a disproportionate impact on developing countries. Rockström and Falkenmark (2001) indicated that there seems to be no hydrological limitations (see Fig. 3), even in semi-arid, to attain a maximum climax 5-10 times higher than the yields experienced at present (0.5-1 ton/ha yields) by producing more crop per drop.

The integration of socio-economic and water resources considerations in a process that has traditionally been concerned with mainly technical and economic issues represents a warm welcome and interesting paradigm. Research on integration of socio-economic aspects for sustainable management of water resources and the development of Decision Support Systems (DSS) is peculiarly new. Practically no developmental problem is free from the influence of the human socio-economic system. Sustainable social, environmental and water management strategies must therefore coherently address at least the physical, biological or ecological, legal, economic, and social dimensions of the system. To reduce the environmental and water management strategy to one dimension, e.g. a technology or a regulation, will lead to approaches that work only for circumscribed amounts of time with often obsolete and unintended outcomes.

It is against this background that an integrated water management approach has been of extensive interest in the Olifants sub-basin and B72A quaternary catchment. Water demand management and water re-allocation, especially in the agricultural sector, which is the biggest user, are some of the possible management options being considered by the South African Department of Water Affairs and Forestry (DWAF). However, the socio-economic and hydrological responses to related policy changes are unknown. In order to quickly assess alternative water allocation scenarios at basin level, hydrologists, water managers, decision makers and policy makers will need practical and user-friendly tools, hence the current research thrust to develop and test an **integrative modelling framework** for the Olifants sub-basin. It intends to bring together Land, Water, Food, and People in the B72A quaternary catchment.

The model framework reported here will be developed from existing hydrologic, crop yield and socio-economic models. The theoretical premise for this modeling framework is driven by a conceptual framework able to address the socio-economic aspects of a community and its livelihood outcomes.
The conceptual framework will also incorporate social enquiry techniques through role play games for eliciting information from the local actors such as the rural community (farmers, NGO) and institutions responsible for water management and regulation. It is important to identify problems and have a common representation of overarching issues, identify possible solutions, test them and implement the best solutions with available knowledge.

1.1 Water Resources Management and Socio-economic issues
The consideration of socio-economic issues in water resources management is one of the most important prerequisites for sustainable water use and to provide answers to water policy questions (McKinney *et al*., 1999). Social harmony and economic efficiency are the fundamental socio-economic targets at local, national and international levels.

The development of policy support system is difficult and time consuming and it is more than just developing an integrated model. The system needs to be able to support policy questions and provide relevant policy information (van Delden *et al*., 2004; Ray and Gul, 2000). Van Delden *et al*., (2004) realized that by discussing the policy themes, options and indicators with the intended end-users as a starting point provides for successful link between science and policy making. However, it is important to recall that the actual use of a policy support tool depends not only on the contents of the tool but also on the perceptions of the intended end-users regarding its practical implementation as well as their willingness to use the tool.

Several studies on integrated models have been done (Donaldson *et al*., 1995; Matthews, 2000; Njogu, 2000; Oxley *et al*., 2002, 2003; Jakeman and Letcher, 2003; Schieder, 2004**;** Castelletti and Soncini-Sessa, in press). Med Action Policy Support System (PSS) provided a policy support system tool that addresses land degradation and desertification in Mediterranean watersheds. This (PSS) is generic for Mediterranean regions. Previous version of the system has been applied to the Marina Baixa (Spain), Guadalentin river basin (Spain), and Argolidas (Greece). The results are promising.

Another project, MODULUS for integrated environmental decision-making, also consists of a number of sub-models, integrated into a single model (www.rinks.nl/projects/modulus).
Even though both the MODULUS and Med Action projects involved potential end-users, there have not been sufficient answers to the placement of the tool in the organization and its credibility. The end-users' willingness to adopt and adjust their decision-making process were not evaluated.

Under sustainable management and quality of water, (Freshwater Integrated Resource Management with Agents) FIRMA project applied modeling tools to integrate the hydrological, social and economic aspects of water resource management (Krywkow *et al*., 2002). The resulting model improve the current assessment methods by representing customers, suppliers and policy-makers concerned with issues such as waste water, water scarcity and integrated catchment planning.

The Sureuro project adopted an integrated modeling towards testing and implementing new concepts for sustainable transformation of existing housing areas. One of the main novelties is the care taken to involve tenant participation in the renovation management process and to ensure that normal and affordable costs for tenants are not exceeded. This innovative integration of socio-economic aspects in processes which have traditionally been concerned with mainly technical and economic issues represents an interesting trend (URL:http://www.epa.gov/ORD/NRMRL/std/seb/basic.htm).

1.2 Integration approaches in water resources management and planning

Model integrations are important because conclusions from studying individual water related sector aspects, such as agriculture, fisheries, tourism, and wildlife, municipal and industrial water supply could be brought together in a framework allowing an integrated analysis within a common and unified framework to handle any emergent attributes which relate to the whole, and not merely to the sum of the parts. In terms of model formulation and solution approaches, integrated hydrologic-economic models can be classified into models with a compartment modeling approach and models with a holistic approach (Braat and Lierop 1987). Under the compartment approach there is a loose connection between the economic and hydrologic components, and only output data is usually transferred between the components for example, Lefkoff and Gorelick (1990a, b). The integration of stand alone models and their results often proves to be costly and time consuming making their application inefficient and unpractical as a decision support tool since managers only require results that integrate the specific effects into general conclusions. On the other hand a combination of models sharing a common platform for data pre- and post processing will provide an efficient toolbox in relation to river basin planning and management.

Under the holistic approach, there is one single unit with both components embedded in a consistent model. Information transfer between hydrologic, agronomic, and economic components remains a technical obstacle in ‘‘compartment modeling,’’ while in ‘‘holistic modeling,’’ information transfer is conducted endogenously. However, the hydrologic side is often considerably simplified due to model-solving complexities for example, Booker and Young (1994) as cited in Cai *et al.* (2003).

In compartment modeling approach, simulation and optimization techniques can be used, while under the holistic approach, the model must be solved in its entirety. Stochastic dynamic programming (SDP) has often been used to solve those complex holistic models for example, Vedula and Mujumdar (1992); Dudley and Scott (1993). However, SDP is often computationally impractical due to dimensionality problems. Other solution approaches include linear programming (Brooker and Young, 2005) and quadratic programming (Bras and Seo, 1987 as cited in Cai *et al.* (2003); Oxley *et al*. 2002). Basin models integrated with Geographical Information Systems (GIS) makes models accessible to a broad range of users and provides a good fashion for handling, compiling and presenting large amounts of spatial data.

A good example is MIKE suite of models, which includes a database management system for the exchange of information with models describing the physical and biological processes (Larsen *et al.*, 2000). The model uses Graphical User Interface (GUI), which links MIKE models directly with customized Arc View GIS. However, the social aspects of the basin are not included in the models which the current project intends to include for efficient and transparency in basin management.

2. STUDY SITE

Olifants Sub-Basin

The Olifants River originates from the east of Johannesburg and flows through the Kruger National Park, where it is joined by the Letaba River before flowing into Mozambique (DWAF, 2004a). As shown on Fig.1, the Olifants Water Management Area (WMA) corresponds with the South African portion of the Olifants river basin, excluding the Letaba river catchment, which is a tributary sub-basin to the Limpopo Basin shared by South Africa, Botswana, Zimbabwe and Mozambique. The Olifants sub-basin starts in South Africa and ends at the confluence with the Limpopo River in Mozambique. It is one of the largest sub-basins of Limpopo Basin, with total area of 54, 563 km^2 and receives an average rainfall of 630 mm per year but there is considerable spatial and temporal variation (DWAF, 2004a). The Olifants sub-basin is selected under the HELP initiative (Endreny *et al.*, 2003) and is one of IWMI's benchmark river basins, serving as a field laboratory for carrying out research and capacity building in partnership with a range of national collaborators, including ministries of water and agriculture, research organizations, universities, NGOS, and local communities. The Olifants is also a major tributary of the Limpopo, which has been denominated as benchmark river basin of the Challenge Program on Water and Food (CPWF). This offers added chances for synergies and inter-linkages with a wide range of CPWF research projects, both those led by IWMI, World Vision as well as those implemented by their partners.

Overcrowding and insecure land ownership in the communal farming areas (such as the Shingwedzi, Selati, and Middle Olifants sub-catchments in the Olifants basin) is a primary source of land degradation in the basin. This feature is an important critical driver of poverty within the Olifants river basin and is associated closely with declining indices of per capita agricultural production. The Olifants river basin is a closing basin; hence water management is of paramount importance (DWAF, 2004a). There are a number of ecologically important areas within the Olifants Water Management Area (WMA) and various conservation areas have been proclaimed in the WMA. The most well known conservation area is the Kruger National Park (KNP) located in the Lower Olifants sub-area of the Olifants WMA.

The pilot catchment, B72A quaternary catchment located in the lower Olifants river basin was chosen in the current study. The B72A quaternary catchment (an area of 534 km^2 and rural population of 50 000) is in the Sekororo area, shown in Fig. 1. The quaternary catchment is the lowest drainage area for water management in South Africa. They are delineated based of topography and labelled from the top down to the mouth of each particular water management area. The quaternary catchment is characterized by diverse water users and land uses likely to ignite conflicts due to water shortages in the river basin. More than 80% of the population depends on agriculture and partly on government remittances (DWAF, 2004b). An immense disparity in distribution of wealth and standards of living among different parts of the quaternary catchment and sub-basin alike exists, as an aftermath of former government regime development priorities. The majority of the populations, mostly in the former homelands, have derived little or no benefit from the considerable development of water resources in the Olifants river basin. The challenging issues are massive soil conservation work, degrading environment, constant flood threats (see Fig. 2) and increasing water scarcity and inequity between commercial farmers and rural community.

The poor spatial distribution of rainfall and high rates of actual evaporation makes the natural variability of water across the catchment highly uneven (see Fig.3). This has resulted unsustainable low yields under rainfed agriculture which is practiced on a larger scale by rural communities. However, yields can be increased through wise soil (nutrient) and water management supported by well-grounded policies. With low yields comes the low or no income to support their livelihoods, hence rural communities are unable to break the poverty cycle.

2.1 Agricultural production

Water scarcity is clearly the predominant limiting factor for agricultural production and food security in the B72A quaternary catchment, though nutrients are a concern as well. The gist issues of agricultural development include redressing the low productivity of current systems and degradation of available resources; diversification of crop and livestock production systems; improvement of technical and managerial capacities; increased investments in agriculture; all of which need appropriate policies and adapted regulatory frameworks for ameliorated household food security and improved livelihoods.

3. METHODS AND MATERIALS

In the first phase, detailed studies of the key aspects of water and social activities in the quaternary catchment were conducted through interviews. This data will be complimented by land cover, socio-economic and crop production systems databases as the main driving databases. Existing interconnections will be established using available models that will be adapted with minor modifications to serve the respective disciplines. The integrative model is driven by variability of water for crop production, technological and policy management issues which have emerged from the study area.

The sub models will be developed as stand alone modules which will be calibrated and validated in the B72A quaternary catchment (Olifants). Such an approach ensures that each model maintains its specific internal spatial and temporal resolution and at the same time provides access to a shared database through the integration system and user interface.

3.1 Linking of sub models

Loose connection between the different socio-economic and hydrological components is accomplished when only output data is transferred between components usually by a database management system. The main challenge of this approach is the transformation of information between these different and often complex components. The holistic approach will be implemented.

In the holistic approach both components are connected to a consistent model and an integrated analytical framework is provided. Information transfer is done endogenously but results in simplification of the hydrological model. Further research is needed to develop more dynamic connections, through which hydrological components and socio-economic aspects can be solved in an interactive way (McKinney *et al*., 1999; Heinz and Eberle, 2002).

The linkage and interactions of the different models is presented in the Fig 4. The feedbacks are captured as dashed arrows. The hydrology/water is assumed as the driver for improved livelihoods. Hydrology forms the foundation of any water available to be managed and decided upon in the crop-yield and socio-economic systems and modules. For instance if there is enough water for crops combined with high productivity there is increased yield which translates to increased disposable income and food security in the rural community and improved livelihoods. The criteria to assess livelihoods betterment will include economic, social and environmental attributes of sustainability.

The integration of the sub models will be achieved without having to re-code through the use of wrapping technique by Oxley *et al*. (2000; 2004), whereby each sub model is transformed from its native code into an ActiveX Model Building Block (MBB) which is a more or less complete model with a predefined set of inputs and outputs. The wrapping process will be tailored to each component sub model, involving some minor recoding when need arises.

There is also need for the spatial modeling environment simulation engine and platform for integration. The standard interface definitions and the attribute of ActiveX will be used to integrate each MBB with the simulation engine system. Windows shall be the operating system. The development and use of standard interfaces enables models implemented in different languages to exchange information and also facilitates model re-use where different Model Building Blocks (MBBs) can be exchanged without compatibility problems. A standard interface is defined to permit the simulation engine to run models with different time steps at the same time and to control variable computation order. The output of the integrative model is aggregated over a seasonal time step. Another standard interface will be defined to retrieve each MBB's input and output specification thereby allowing the simulation engine to transfer information from one MBB to another MBB (Oxley *et al*., 2000; 2004).

3.2 Role-play game

The conceptual diagram for eliciting the information from local actors and policy makers through role-play games in the catchment is shown in Fig 5. A river basin game has already been implemented in the B72A quaternary catchment to show upstream and downstream water inequity in irrigation schemes and the results are promising. The current game object will be to improve rural livelihoods by implementing sound technological and policy options under agriculture. The role-play game necessitates building a shared representation of the problems in the catchment between policy makers, technical experts and local stakeholders. Reference is made to the environment under the water resources available in the catchment. Through the game play the local context, problems and possible solutions are identified and shared with the community. On the next step the regulator and policymakers' responses to the proposed solutions is assessed and the feedback is discussed with the community. The local community will again give feedback of their reactions to the regulators, and the cycle continues until a consensus is reached on the best and acceptable options to be pursued. The iteration is important because the social response is not linear. It should be validated by the factual behavior from the local community. These steps will be carried through workshops, first with local community and second with policy makers and thirdly with the combined groups of local community and policymakers. By exploring specific solutions with the integrated model, the stakeholders will experiment the monitoring of the option under a range of conditions and possibly reorient their choices to attain sound management options.

3.3 Scenario testing

The scenarios to be tested are new technology and policy options. Each scenario will be run under drought year, normal year and wet year to find the consequences of water variability.

3.4 Treatment of uncertainties in the project

Qualitative uncertainties such as in the analysis and policy formulation will be tackled in a variety of participatory approaches targeted at achieving learning processes and negotiations with agreement despite different perspectives. When possible, statistical analysis of the input data will be performed and the level of confidence of the output specified. A sensitivity analysis of the output to uncertainties in the inputs, parameters and model structure features will be done to ensure that reliable conclusions are drawn from the models.

3.5 Challenges to the project methodology

The challenges to the methodology approach are presented below. Some of the concerns have been addressed in the methodology.

- Finding models that better integrate and visualize the research results.
- Initial data limitations as some basins reside in poor and or remote regions and others cross local government borders and hence experience different levels of monitoring.
- Test and evaluation of the integrated model on actual policy problems in collaboration with the end-users.
- Better integrate models that operate at different temporal, spatial scales and time horizons. Economic models use larger time intervals such as seasonal or annual and longer time horizons while hydrologic models use daily/monthly time step.
- Better exploit the research material in practical policy making. The models will run with the aim of exploring and evaluating possible management alternatives in terms of their level of effectiveness on the path towards sustainability and poverty reduction.
- In basins with large rural populations, the group may not identify itself or its needs, and this does not mean they have relinquished these needs. The implementation of role-play games will address this challenge.
- Guiding of stakeholders to distinguish between problems that coordinated hydrology and socio-economic research can beneficially address from those best left to other social programs.

The representation of the socio-economic and hydrology used in this work have inevitably been simplified, specifically to facilitate the coupling of these different disciplines. However, of importance is to show the direction and magnitude of change in livelihood outcomes in relation to changes in hydrology, technology and policy management options.

4. CONCLUSIONS

The research will provide effective tool for sustainable policies by improving knowledge base required for informed decisions in policy formulation under water scarcity and agriculture management. The study can be used as learning or evaluation tool for catchment management groups and those interested in comparing and contrasting the different policy and management options that need to be dealt with in improving catchment management for improved rural livelihoods. It must be clearly understood that the best approach to improving water resource management, currently affected by population growth, climate variability and regulatory requirements is through involvement of stakeholders in planning and decision-making. Role-playing games have shown to be relevant tools to deal with social issues as they support stakeholders to express their needs and expectancy and can be used to test technical and policy innovations. For instance farmers agree on new bye-laws and infrastructure maintenance schedule for managing water resources.

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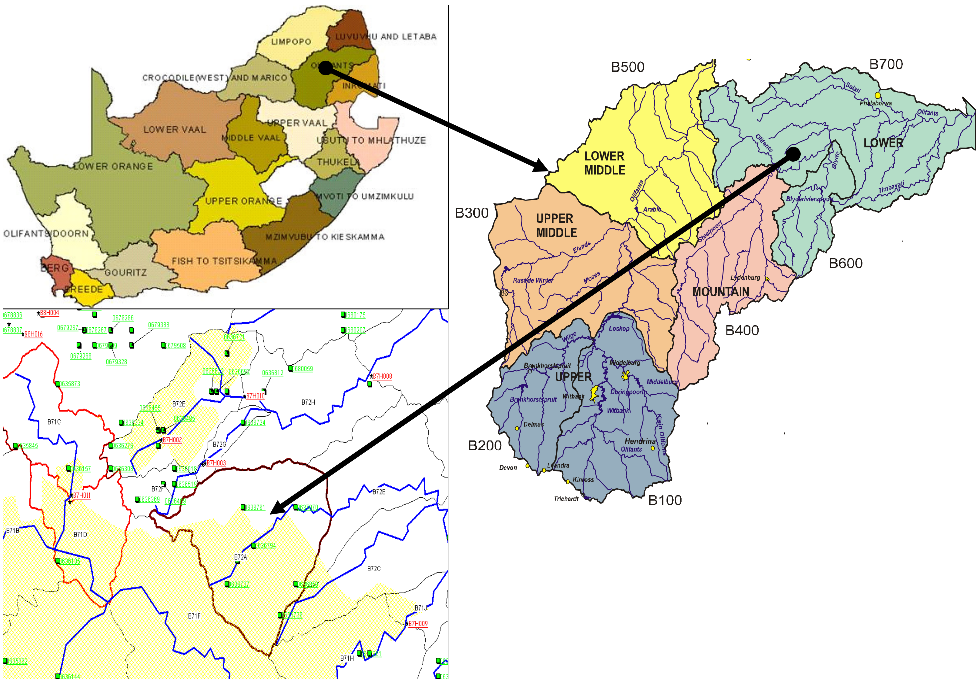

Figure 1. Location of Olifants catchment and pilot B72A quaternary catchment.
Source: IWMI- SA database.

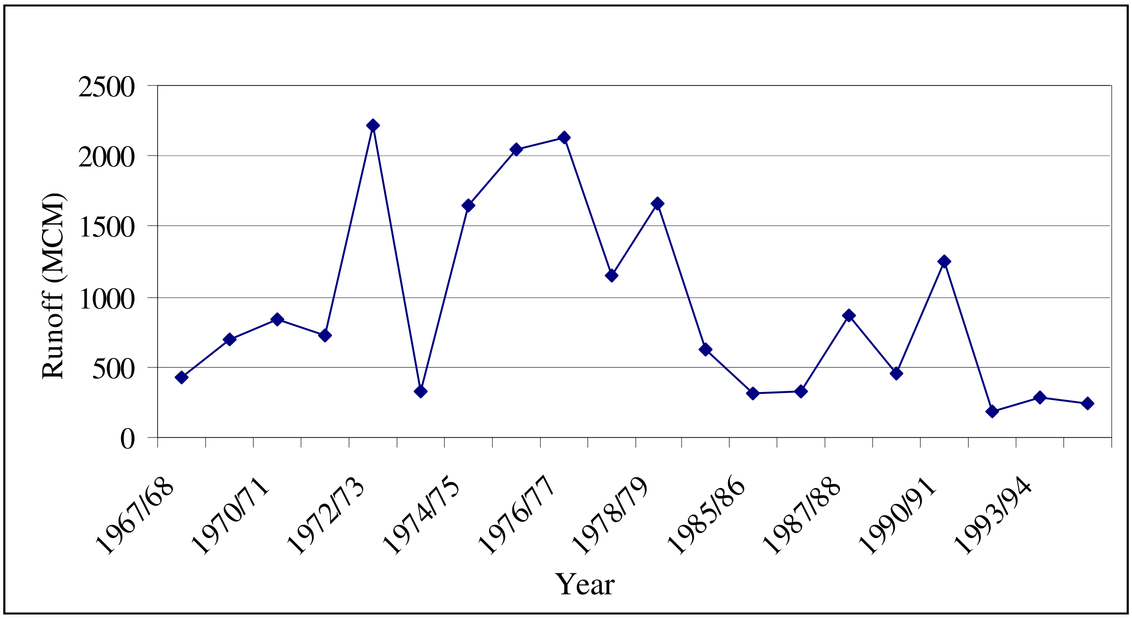

Figure 2. Annual runoff in quaternary catchment near to B72A

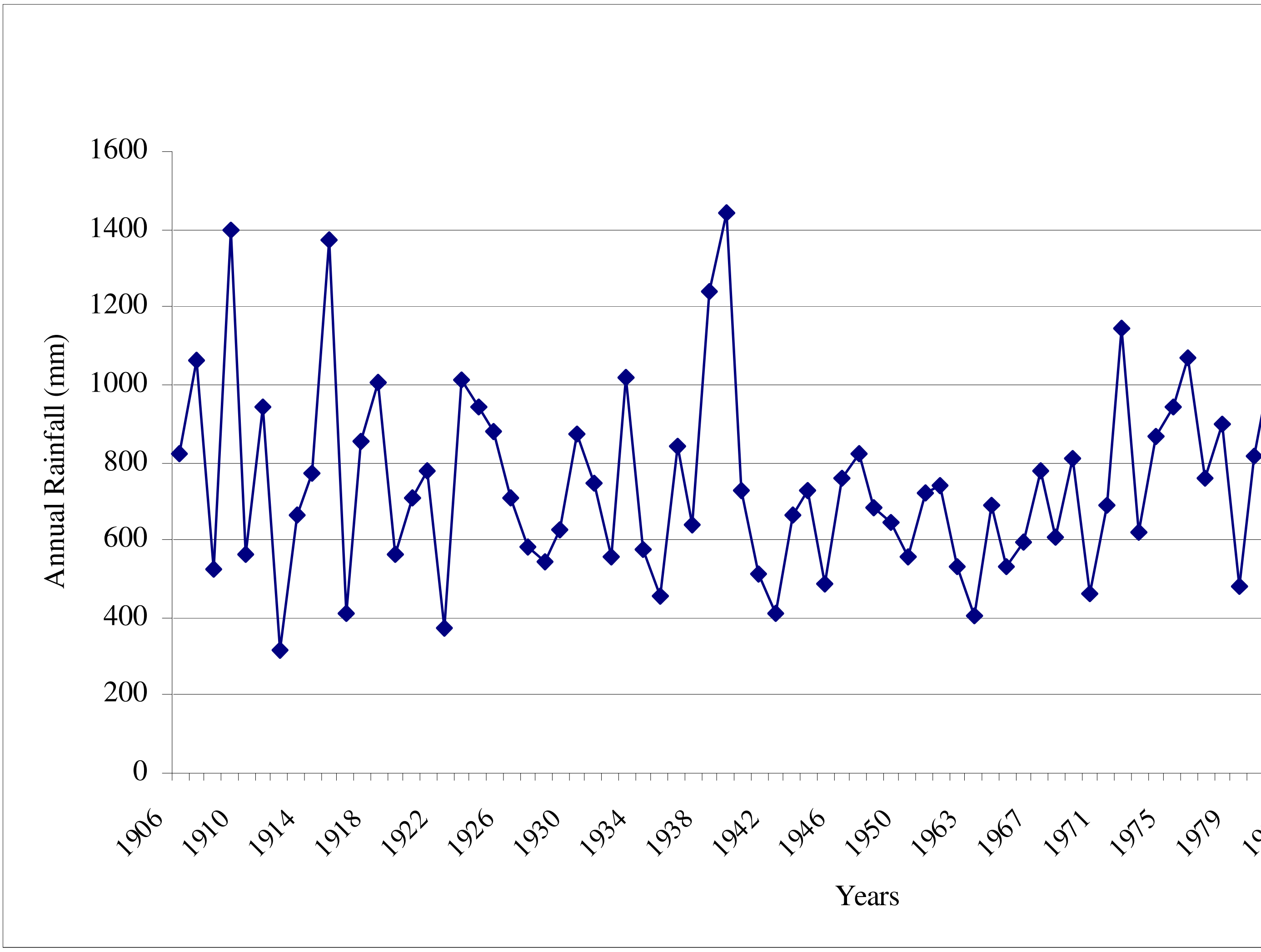

Figure 3. Annual Rainfall in the B72A quaternary catchment in the Olifants river basin (Data extracted from DWAF, 2006 database).

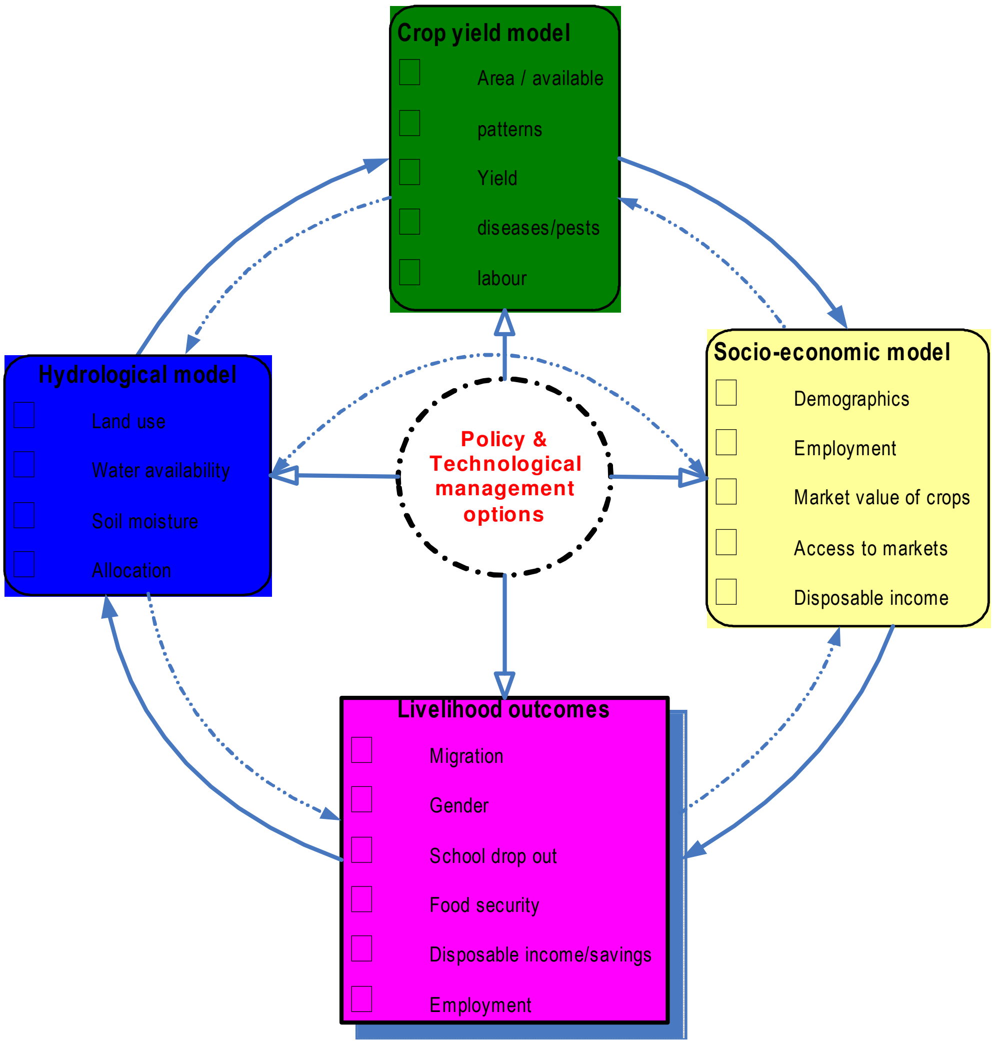

Figure 4. A conceptual representation of the interacting models and the feedback involved in evaluating technology and policy management options for improved livelihood outcomes.

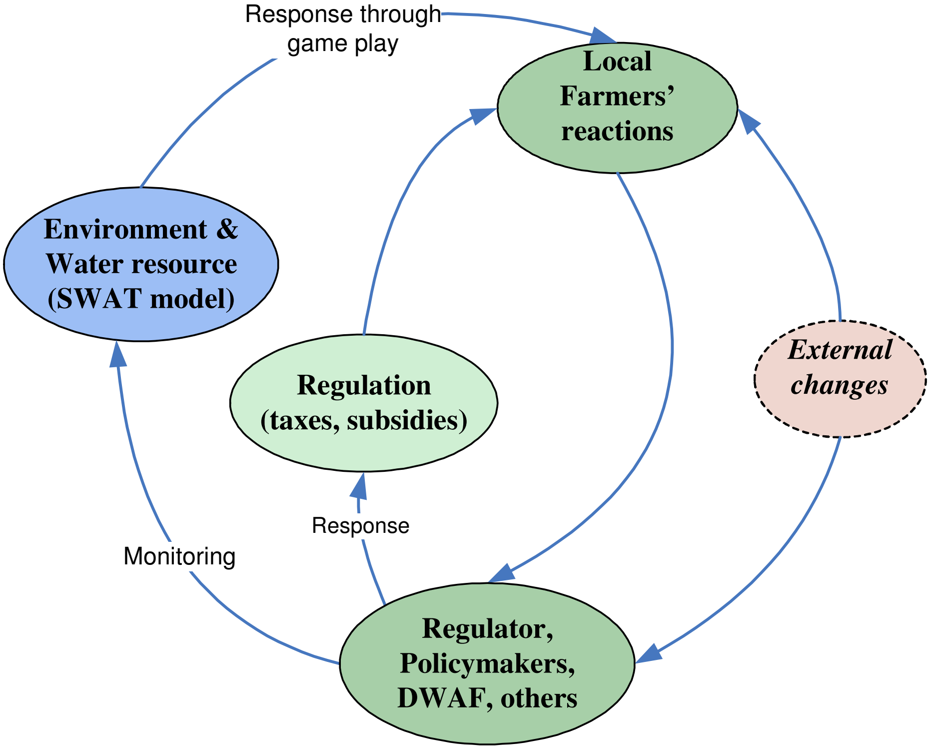

Figure 5. Conceptual diagram for eliciting the information from local actors and policy makers through role-play games in the catchment.