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Computer Based Decision Aids for Sustainable Use of Natural Resources

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Abstract: Sustainability concern and advances in science and technology has led to development and use of simulation models for natural resources management. This paper presents modern concepts and advances in science and technology, which have provided additional impetus to the development of simulation models. It also illustrates the experiences in the development of simulation models for use in the Upper Ewaso Ngiro North Basin in Kenya and highlights main lessons learnt. Finally, challenges in simulation model development and use are discussed.

Key words: Simulation models, natural resources management, Kenya, Ewaso Ngiro North Basin

In the semi-arid and arid tropics, natural resources (soil, water and vegetation) form the back-bone of the livelihood of millions of people who irk their living from this ecosystem. Literature is replete with reports on resource degradation and concerns over trends in land use conversions, conflicts over resources use and increasing poverty. Sustainability of the resource base on which they depend to meet their basic and vital needs is threatened and so is their survival. Fortunately, there are various initiatives determined to reverse this trend and hopefully achieve sustainability. Sustainable development and utilization of these resources depends on a clear understanding of the available resources, their distribution in space and time and the impact of their utilization. In making living sustainably our goal, knowledge systems are going to play a key role in changing the resource users' perceptions and management practices, in ensuring that all other stakeholders play their part in an efficient and effective manner.

This paper reviews the current concepts and advances in science and technology, illustrates the use of computer simulation models using the Upper Ewaso Ngiro North Basin case study and finally identifies future challenges and research priorities in simulation models for sustainable use of natural resources in semi-arid areas.

Current concepts and advances in science and technology

A system is an integrated whole with different sub-systems designed to accomplish certain objectives. The main parts of a system are input, structure or process and output (Dent and Anderson, 1971). In a system many and complex factors are interrelated and interact in ways that influence the system behaviour. This implies that a conceptual boundary can be erected around the system to define the system boundaries. The system boundaries could be natural or artificial (fixed by the investigator).

System research

Systems research encompasses all activities involving the detailed study of the system with a view to improve the understanding of the system, predict the behavior of the system, to improve control over existing system or to design new systems (Wright, 1971). Systems research involves systems analysis and synthesis, and is generally carried out in the following sequence:

- problem specification aimed at qualitatively defining the system and its component and associated problems;
- system analysis aimed at providing quantitative specification of the system processes and relationships between inputs and outputs; and
- system synthesis aimed at offering solutions to the problem.

Systems research offers the following advantages (ICID, 1980):

- holistic approach to problem solving whereby the interrelationship of each part of the problem to every other is considered as well as the interrelations among objectives and the means of their realization;
- permits the combination of strictly scientific approaches with common sense, subjective opinions, evaluations, intuitions and experience for establishing decisions under conditions of uncertainty and risk;
- makes it possible to achieve maximum effectiveness of the overall system, preventing the reduction of the general results as a consequence of the specific objectives, tasks and interest of sub-systems, particularly where the objectives pursued by certain sub-systems are conflicting and incompatible with those of the system; and
- aids decision makers to choose a course of action through a systematic study of the real objectives and quantitative comparison of costs, efficiency, and risks which are associated with each alternative courses of action.

Although there is no fixed sequence of stages in systems analysis various authors have provided guidelines of the stages (Dent and Anderson, 1971 and ICID, 1980). The following stages can be used in natural resources management studies:

- analysis and definition of the problem and diagnosis of the existing system;
- analysis of the system structure (sub-systems, components, key processes);
- formulation of the goals and objectives and identification of conflict and complementary objectives;
- prediction and analysis of future conditions; and
- assessment of objectives, methods and alternatives.

Simulation models

Simulation can be defined as the use of mathematical models describing the phenomenon, process and/or behavior of complex system in ways approaching real world conditions to perform experiments in order to predict the likely behaviur of a given set of input, initial and boundary conditions (Wright, 1971). Simulation, therefore, involves two-phases involving modelling and experimentation.

The modelling phase of the simulation process consists of developing or selecting and validating a mathematical model for the system to be studies. A mathematical model is a representation of reality constructed to help understand, describe, or predict how things work in the real world by exploring a simplified version of system features or phenomena.

The experimentation phase involves the use of the model to study management-oriented issues such as:

- to compare alternative courses of action,
- to estimate the response of the system to changes in level of input,
- to explore the response surface, generated for different combination of input levels, and
- to estimate the input combination required for an optimal or near optimal level of output (Wright, 1971).

Scenarios are important instruments in simulation experimentation. They describe future conditions of a system, possible logical sequence of its state and probable events of interest. Scenarios contain objectives, likely alternative means of attainment and a qualitative and if possible a quantitative assessment of alternatives. Simulation therefore offers tools for studying decision problems in relation to the full complexity and uncertainty of reality.

Decision support systems

Optimal management of the existing and proposed natural resource use projects is a complex undertaking, with complications arising from the system multi-objective and uncertain nature. For example, a river and its water reservoirs may support a plethora of water uses, including agricultural water supply, municipal and industrial water supply, energy generation, flood and drought protection, fisheries, and a rich diversity of animal and plant life. The construction of reservoirs and use of water resources affects (beneficially or adversely) many water users and hence the best decisions are not obvious, but depend on the value of the short- and long-term gains and consequences to water users. There are, therefore, no absolutely best decision but rather more preferable ones, depending on the collective rational adopted by the stakeholders. Consequently, a decision support system merely quantifies the impacts and tradeoffs of several strategies that could potentially interest the stakeholders. The stakeholders then study the associated tradeoffs to arrive at equitable water use agreements.

Decision support system (DSS) uses heuristic approaches to problem-solving by blending hard data with semi-structured procedures and common sense expertise (Stuth and Smith, 1993). DSS can, therefore, be viewed as an integrated approach of helping people make better decisions. Decision support systems may be used by individuals or assist group interactions. DSS offers a mechanism for improving objectivity of decision making, especially in complex ecosystems where many processes and interactions are involved.

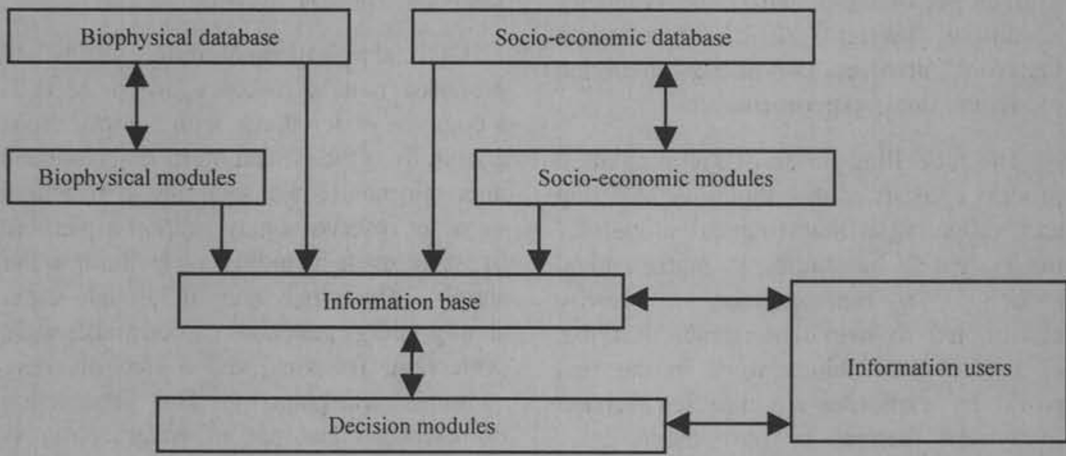

Fig. 1. Interaction of the main components of a decision support system.

The decision system includes an array of models and data bases. DSS encompasses computer models, expert systems, geographical information systems, discussion groups and structured thought processes (Stuth and Smith, 1993). The core of a decision support system are biophysical and socio-economic simulation modules and decision modules together with the associated data bases. The purpose of biophysical modules is to simulate and predict the response of the biophysical sub-systems to various inputs. The socio-economic modules are intended to quantify the value of available resources and human response to different levels of resource availability. The purpose of the decision modules is to derive multi objective tradeoffs that provide integrated impact assessments useful to the stakeholders in making decisions or establishing resource use agreements.

Integrated natural resources management

Integrated natural resources management (INRM) concept, like integrated water resources management, expresses the idea that natural resources should be managed in a holistic way to ensure that all aspects and functions of the key natural resources are well coordinated and integrated so as to bring sustainable and equitable benefit to all (Fig. 1). INRM implies a concerted attempt to moderate between competing or conflicting demands by users and stakeholders. Prerequisites to effective INRM are therefore: improved understanding of the dynamic and interactive process and impacts of different courses of action by all stakeholders, implementation of relevant resource use and conservation programmes, and an appropriate institutional, legal and financial framework.

Within an integrated natural resources management concept, natural resources assessment is now becoming an important tool in promoting sustainable natural resource use. The objectives of resource assessment is to quantify resource availability and its variability in space and time and to predict likely environmental impacts of natural and/or human intervention, find ways of mitigating unacceptable impacts, and present decision makers with the predictions and appropriate mitigation options. Because of the high potential for conflicts arising from perceived or real biases in impact assessment, natural resources assessments (ideally) involve public consultation with interested parties and the affected population. This ensures that the proposed interventions achieve and sustain the predicted benefits with minimal unacceptable environmental consequences. Simulation tools will be expected to play a key role in providing the necessary data and information for wise decision making.

Information systems: Information is important to answer the "who", "what", "where", and "why" questions required to identify the best way forward. A natural resources information system is a system for the collection, storage, analysis and reporting of information related to the status and trends in natural resource use, productivity, threats and sustainability. The information system consists of computers as tools of handling the information, monitoring network and operational and administrative procedures for the collection of data, hardware and software for processing of that data to produce useful information, and a dissemination sub-system geared towards the application of that information to improve productivity and sustainability of natural resources.

Ecoregional research approach: The Consultative Group on International Agricultural Research (CGIAR) started an ecoregional research approach to ensure that research done in a particular area is adequately disseminated in regions having similar characteristics (Rabbinge, 1995). The ecoregional research approach is a holistic, systems-oriented approach which seeks to integrate the contributions of different disciplines, to deal adequately with natural resource management issues, and to identify meaningful recommendation domains for the application of the products of research, thus enhancing the efficiency of the research process. Several ecoregional research programmes have been started and research methodologies developed. However, the benefits of these methodologies have not been integrated in most natural resource use systems.

Advances in Science and Technology

Many advances have been made in science and technology to make sustainable natural resource use possible. In this paper we highlight advances in mathematics, remote-sensing, modelling and spatial data interpretation which we believe have made a tremendous contribution in improving our understanding of the natural resources systems.

Advances in mathematics

The explosion of the number of models in the last three decades is principally as a result of the advances in numerical methods (e.g., finite difference), a better understanding and conceptualization of the mathematical equations governing various process and increases in computing capacity. Considering that most of the data describing variables in natural resources systems are positively skewed, have outliers, are not normally distributed, have seasonal patterns, have an autocorrelation within certain temporal limits, what we have been able to achieve in terms of interpretation of data would not have been possible without the advances in statistics. Advances in statistical methods are now making it easier to understand the data and apply the most appropriate statistical analysis technique in order to arrive at a conclusive interpretation of the data (Helsel and Hirsch, 1992). Statistical tools such as descriptive statistics, confidence intervals, hypothesis testing, curve fitting, trend analysis and spatial statistics have proved to be invaluable tools in analyzing natural resource use issues.

Advances in remote-sensing: Remote sensing is "the science and art of acquiring information about an object, area or phenomenon by different information gathering systems which are not in contact with the object, area or phenomenon" (Lillesand and Kieffer, 1994). For natural resources management, remotely sensed data can be acquired by aerial photography, pilot balloons, meteorological radars and by satellite and ground receiving stations for satellite imagery. Remote sensing techniques utilizes electromagnetic energy sensors to assess the state of an object or areas under study and records it in the form of image or digital data (Singh, 1996). Over the last 50 year, advances in science has made it possible to perfect the technology of acquiring, storage, processing and use of remote sensing data.

Satellite imagery is one of the most important tools available for collecting spatial data that can be used for planning natural resource use and management. This is the only data source that is received with sufficient regularity and spatial coverage. To date remote sensing data products are being effectively used in appraisal of natural resources, monitoring changes in the status of natural resources, mineral resources exploration, weather forecasting, yield prediction, drought monitoring and land use capability assessments to name a few (Thomas, 1974; Wahome, 1984; Draper and Rao, 1986; Stromquist *et al.*, 1988; Isavwa, 1989; De Jong and Riezebos, 1992). Given the paucity of spatial data, these images should be thoroughly exploited in routine monitoring and assessment of the natural resources.

Advances in model development

In the past, most models were developed along disciplinary lines. However, when dealing with complex natural resource use systems, the causes and consequences of various changes cannot be examined from a single disciplinary perspective. This has led to the development of integrated approaches to link socio-economic and biophysical aspects (Riebsame *et al.*, 1994; Ojima *et al.*, 1994; Shepherd and Soule, 1996).

Spatial modelling: Spatial modelling includes process models, systems analysis models, and other types of models linked in some way to spatial databases or Geographic Information Systems (GIS). In last two decades, tremendous advances have been made in spatial modelling using models of biophysical processes (rainfall, soil erosion, nutrient dynamics, hydrology, plant growth, livestock productivity, human and animal population dynamics) linked to spatial extrapolation and interpolation tools to demonstrate spatial properties. Integration of socio-economic processes have lagged behind because they are less amenable to modelling. Nevertheless, social, cultural and economic processes and spatial attributes are linked into the biophysical modelling and applied in solving natural resource use problems (Turner *et al.*, 1996; Wint, 1996;

Shepherd and Soule, 1996; Chomitz and Gray, 1996; Thornton and Jones, 1997; Stoorvogel, 1995).

Object oriented modelling: Object oriented modeling is a new way of developing simulation models using computer software tools. Computer software tools such as STELLA (High Performance Systems, 1996) and ESRI spatial analyst model builder (ESRI, 2000) make model development easier by letting the modeler focus more on the processes rather than on the computer code required to simulate the processes.

STELLA ModelMaker tool uses stocks, flows, converters and connectors as the building blocks. Stocks represent accumulations and serve as resources and constraints. Flows are linked to stocks. Converters convert inputs into outputs while connectors connect stocks (High Performance Systems, 1996).

ModelBuilder is a tool in the ArcView Spatial Analyst extension that helps you create a spatial model of a geographic area (ESRI, 2000). In ModelBuilder, a spatial model is represented as a diagram that looks like a flow chart. It has nodes representing input data, spatial functions that do the processing, and output data. Arrows connects nodes to show the sequence of processing in the model. The model is reusable and shareable with others who can use it in different geographic areas by simply changing the input data.

The main advantage of object oriented model simulation is the ease of constructing the model and "what if" scenarios to tackle real-world problems. Other advantages of using object oriented modeling tools are:

- Models are built up conceptually using a diagram representing the input data, processes and functions, derived data and final output.
- Equations representing the processes being modeled are easily defined and accessible.
- All calculated values are displayed as graphs and tables.
- No programming skills are required.

Influence diagram models: Influence diagram models consist of nodes that represent variables, and directed arcs that represent the relationships between variables (Howard and Mathenson, 1984; Schachter, 1988). The nodes may be deterministic nodes (certain quantities given the values of their conditioning variables), probability nodes (uncertain quantities), decision nodes (relationships or quantities under the control of the decision-maker), and value nodes (objective functions). When influence diagrams contain only probability nodes they are called Bayesian belief networks. A Bayesian belief network have been applied in natural resource use to study the relationships between elevation, average annual rainfall, changes in human population densities, area under cultivation, average field size, and cropping systems mix. Bayesian belief networks support both empirical and subjective (i.e., based on expert opinion) inference which, given the uncertainties associated with analysing land-use change processes, makes this approach particularly appealing for modelling these types of phenomena (Edwards, 1995).

Spatial data interpretation: A geographical information system (GIS) is a geo-referenced computer-based database that captures the spatial relationship between data for display and analysis (Konecny, 1992; Loran *et al.*, 1988; Giordano, 1984). What makes a GIS different from a standard database is its ability to perform spatial analysis on the information stored. The spatial relationship between features and their associated attributes can be analysed to reveal underlying patterns. GIS technology can be applied to any situation in which data can be linked to a spatial location. One of the GIS outputs is the thematic map (a map presentation that displays a simple subject (theme) to spatially illustrate a specific situation or condition). Thematic mapping has proven to be a useful presentational and analysis tool for understanding spatial variability in natural resources attributes and has been used to show situations or conditions such as environmental degradation hotspots, areas of resource use conflicts, spatial availability of resources, etc.

Application of Simulation Models: Ewaso Ngiro North Basin Case Study

Description of the study area

Location of the study area: The Upper Ewaso Ngiro North Basin constitutes the upper stream section of the Ewaso Ngiro North drainage area. It is defined by the natural topographic divide, from the source of the river itself and its tributaries to Archers Post river gauging station. This drainage basin covers an area of 15,200 km^2. The Upper Ewaso Ngiro North Basin lies between latitudes 0°15′ South and 1°00′ North and longitudes 36°30′ East and 37°45′East. It traverses the administrative districts of Nyeri, Nyandarua, Laikipia, Meru, Nyambene, Isiolo and Samburu. The Basin has a steep ecological gradient that can be divided into seven major zones, namely: the Alpine, the upper mountain slopes, the lower mountain slopes, the volcanic highland plateau, the highlands on basement complex, the hills and scarps, and the lowlands (Gichuki *et al.*, 1998a).

Biophysical environment: The mean annual rainfall varies from 1500 to 350 mm. The average rainfall over the entire basin is 650 mm per annum and 44% of the areas receive less than 600 mm and only 1% of the areas receive more than 1000 mm per annum. The basin rainfall is divided into four three months seasons, namely: the long rains (mid March-mid June), the continental rains (mid June-mid September), the short rains (mid September-mid December) and dry season (mid December to mid March). The relative importance of each rainfall season varies. Long, continental and short rains are significant in the west part of the basin producing a tri-modal rainfall pattern with one long growing season. For the remaining areas continental rains are insignificant giving rise to a bimodal rainfall pattern with two short growing seasons. An annual water balance shows that most of the area has moisture deficit (Liniger, 1991). The means annual moisture deficit is 1089 mm per year. Approximately 1% of the areas has surplus whereas 33% experiences a moisture deficit of more than 1250 mm per year.

The major land uses are natural and plantation forests in the upper mountain slopes, mixed farming dominated by crop production in the lower mountain slopes, mixed farming dominated by livestock production in the plateau, and the lowland zone is under natural savannah rangelands predominately used by pastoralists livestock and wildlife. Major land use changes are taking place where cultivators are encroach on the forest land and converting grazing land into marginal crop growing areas. Land use systems results in highly diverse natural resource use systems from a biophysical and socio-economic stand-point. This makes blanket recommendations unworkable and calls for site specific recommendations and the need for careful extrapolation and/or interpolation of research findings.

Surface water resources sub-system can be divided into the Ewaso Narok catchment (3380 km^2), the Ewaso Ngiro-Mt Kenya catchment (4640 km^2) and the lower Ewaso Ngiro catchment (7180 km^2). The Ewaso Narok catchment is the main source of water during the months of July-September due to the continental rains. Ewaso Ngiro-Mt Kenya catchment is a major source of water during the dry season due to the contribution of the glacier and the forested catchment. The lower Ewaso Ngiro catchment is characterised by many ephemeral rivers and its main contribution is during the wet seasons (Gichuki *et al.*, 1998b).

Groundwater resources are considered to be very limited due to the assessment of groundwater potential, depth of groundwater (more than 50% of boreholes in high to medium potential zone are more than 100 m deep); high cost of maintaining wells and pumping equipments, difficulty in locating high yielding aquifers, attendant risk of minimising groundwater, and low rate of groundwater recharge. Borehole water yields are reported to be in the range of 2-4 L s^{-1}.

Socio-economic environment: The basin is home to several communities with diverse socio-economic characteristics. The major communities are: the Kikuyus and the Merus who are traditionally cultivators and hence are responsible for the main land use changes in the footslopes and plateau, the European ranchers who own land in the Laikipia plateau and mainly uses it for livestock and game ranching, the pastoralist communities (Maasais, Turkanas, Samburus, Borans and Somalis) who practice communal grazing in the lowlands.

The main stakeholders in natural resources of the basin are the main resource users (smallholder farmers, private ranchers, pastoralists, small and large scale irrigators, saw millers, tourist operators), Government and non-governmental organisations. As the population increases the competition for resources use is increasing. The main areas of conflicts are in utilization of forest products particularly timber, deforestation for crop production, overabstraction of surface water resources in the upper reaches, and human-wildlife conflict.

A large percentage of the inhabitants of the Basin are poor and illiterate. They frequently experience food in-security and drive over 60% of the basic need from utilization of soil, water and vegetation resources in these areas. They have limited financial resources and therefore substitute labor for capital in resource use and conservation.

Because of lack of external input, most land users adopt low-input low-output production systems. Such a system in most cases results in unsustainable use of natural resources particularly where the land tenure is not secure and there are options for moving on to other areas. With such production system, adoption of yield enhancing and natural resource conservation technologies is very low.

Following years of irking a living in these environments, the land users have acquired skill and knowledge on how to minimize the adverse effect of their actions. This indigenous knowledge base has not been adequately integrated into the scientific knowledge base.

Development and Application of Simulation Modelling and Decision Support Information

Foundation for sustainable development

The interaction of people, biophysical resources, institutions, economics forces and policies determine how soil, water and vegetation resources are used and managed. Effective management of natural resources requires adequate information upon which decisions can be made and a supportive social, legal and political framework. This calls for an understanding on the following:

- the biophysical system in terms of natural characteristics, resource inventory (availability and quality of resources) and development potential;
- resource use, demand and allocation rules;
- organisation structures, policies, legal and socio-economic aspects; and
- interactions and inter-relationships of physical and socio-economic sub-systems and systems and their impacts on resource conservation and productivity.

Fig. 2 shows how Natural Resources Monitoring, Modeling and Management Project monitoring and modeling initiatives are contributing to sustainable development.

Assessing Data and Information Needs

Land users, planners, development agencies and policy makers require information upon which they can base their decisions. A survey of the data and information needs by various stakeholders was undertaken in 1997 (Gichuki *et al.*, 1998a). The key water management stakeholders identified key areas of where improvements could be made to make water resources information more accessible, thereby ensuring that informed decisions are made. Example applications include:

- ENNDA can use this information in planning water resources development (e.g., The study on streamflow regulation of an upstream and a downstream reservoir provided valuable insights on the merits and demerits of the two reservoirs).
- Water Apportionment Board (WAB) can use this information to determine the nature and extent of efficient, reasonable and beneficial use of water resources in the basin and use this as a basis for future water allocation.
- District Water Office can use the information in planning and designing water projects, giving advice on water allocation and rationing, monitoring illegal water related activities (e.g., pollution, illegal abstractions, etc.).
- Water users associations can get information required in resolving water use conflicts in their river reach and also downstream and upstream.

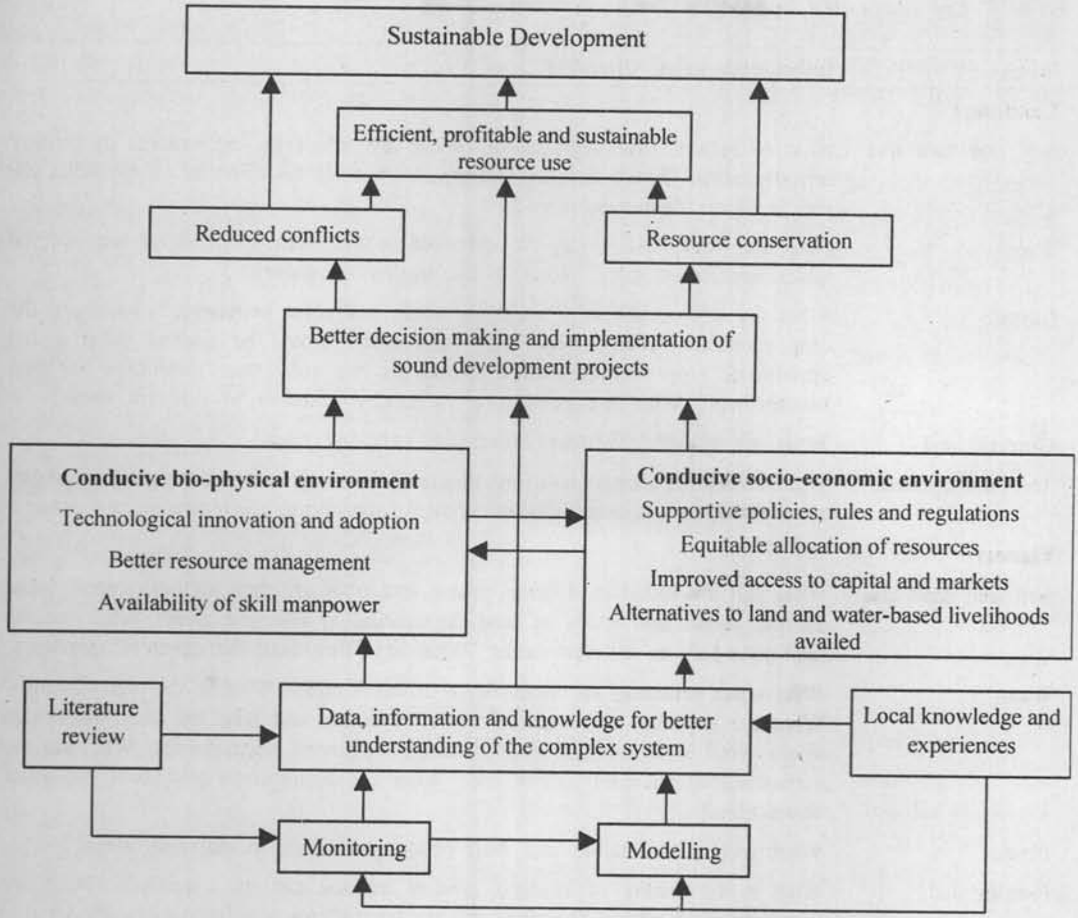

Fig. 2. Contribution of Natural Resources Monitoring, Modeling and Management Project monitoring and modeling initiatives to sustainable development.

The key natural resources information needs identified by land users, planners and policy makers are presented in Table 1.

Long-term monitoring: A basis for model development and calibration

The purpose of Natural Resources Monitoring, Modeling and Management Project research is to contribute to improving natural resources use and management by addressing the problems of a lack of reliable data, poor data management and reporting. An analysis of the natural resources issues identified the absence of natural resources information and inefficient information management systems as the main constraint to wise decision-making on natural resource use.

Natural Resources Monitoring, Modeling and Management Project adopted a strategic approach, involving the

Table 1. Key issues and information needs identified

Issues	Information needs identified
Landusers	
Soil and land use	How to reduce land degradation? What are affordable approaches to fertility improvements? Which farming systems are suitable for different areas? What are the fertilizer recommendations?
Water	How can water availability be improved at the farm level? What are optimal water application rates? What is the quality of water?
Crops	What are appropriate crop varieties, seeds and plant population? What are the crop production risks? What high value crops should be grown? What is the appropriate crop rotation pattern? What are the indigenous techniques for pest management? What are good crop husbandry practices in different areas?
Grazing land	What are suitable livestock breeds and stocking rates?
Tree management	What are superior alternatives to grevillea tree? What supplemental irrigation techniques are available for tree establishment? What are appropriate tree management practices?
Planners	
Soil and land use	What soil are found in different places and what are their fertility status? What are the causes and levels of land degradation in different areas? What are the land potentials in different areas? What are "Best land management" practices?
Water	What water resources are available in different areas? What is the water quality? What are the uses and users of water resources and how are they distributed in the area? What are appropriate water management technologies? What are the economics of different water use? What are appropriate guidelines on water abstractions?
Crops	What crops are suitable and their production levels in different areas?
Grazing land	What is the quality of available pasture and the carrying capacities? What are the appropriate mix of livestock, the grazing patterns and livestock units per unit area?
Tree management	What are suitable tree species in different areas? What are the social and economic values of different trees? What are the main tree products in different areas, what are the production levels? Should we grow indigenous or exotic trees? What are the available tree resources in different areas? What is the rate of deforestation?
Policy Makers	
Soil and land use	What is the role of agricultural subsidies in ASAL areas? How does land tenure affect land productivity and sustainability? What are the impacts of subdivision of ranches in ASAL areas? What are the appropriate land use policies for ASALs? What is the minimum land size for different areas?
Water	What are the temporal and spatial distribution of water balances and their effect on the economy and social status of users? How is the water abstraction pattern and how does it affect community relations? How could equitable water allocations be attained? What are the appropriate mechanisms for enforcing water regulations?

Contd...

Table 1. Key issues and information needs identified

Issues	Information needs identified
Crops	Should we promote export crops or food crops? What are the crop/wild life conflicts and how can they be minimized? What subsidies, marketing and pricing structures would promote crop production?
Grazing land	What are the economic and social impacts of livestock disease and how can these impacts be minimized?
Tree management	What are appropriate policies to promote tree planting? Can the indigenous knowledge on tree management and use be promoted? What tree ownership and utilization strategies are appropriate for ASALs?

introduction of two core elements of an natural resources information system to effectively address the problems of information gaps. These core elements are:

- The collection of natural resources (soil, water, plant and animal) information using an extensive and long-term monitoring network.
- The introduction of appropriate information technology, to improve the management, analysis and reporting of natural resources information. Modelling to fill in data gaps and conduct simulation experiments to complement field experiments.

Maize production simulation tools

Monitoring data improves understanding of crop production risks: Long-term monitoring of maize production at Matanya and Kalalu experimental sites, which are representative of small-scale farming systems in a semi-arid environment, has been going on since 1986 (Liniger *et al.*, 1998). Data from these long-term experiments have been used to analyze maize production risks and improve the understanding of the effect of management and rainfall conditions on yield. The data were also used in calibration and validation of the APSIM model.

Maize production simulation experiments: The Agricultural Production Simulation Model APSIM (Muchow and Bellamy, 1991) was selected on the basis of the following: (1) the model is sensitive to the extreme environmental conditions that exist in this area especially rainfall onset, amount and distribution; and (2) the model is able to simulate various crops and management techniques allowing the evaluation of alternative production systems and to simulate systems of crop sequences and mixtures. The model was calibrated and validated using soil moisture regime, crop phenology, maize biomass and yield data obtained from the long-term (1986-99) maize production monitoring experiments (Njeru *et al.*, in preparation). The model was then used to examine maize productivity in relation to (i) the spatial and temporal rainfall variability within the upper Ewaso Ng'iro basin, (ii) maize crop residue management (mulching vs. no-mulch), and (iii) plant population.

Spatial and temporal yield variability: the results of the simulation along the ecological gradient of the upper Ewaso

Ng'iro basin produced data for use in identifying areas in which maize production should not be encouraged due to the high production risk and low yield potential. This was particularly important for the large scale ranches that have been subdivided for smallholder farmers who generally prefer to grow maize even under these marginal conditions.

Maize crop residue management: Methods such as mulching (retaining crop residue at harvest time) and non-mulching (removing crop residue) have been widely tested in the field. Mulching was shown to lead to higher yield. The APSIM modelling study identified the conditions under which mulching is beneficial. Mulching is most beneficial under average rainfall conditions. Under above average rainfall conditions, rainfall provides an adequate amount of crop water and hence there is no yield advantage. With below average rainfall conditions, crop failure is experienced in both mulched and non-mulched fields. The only advantage being that under mulched conditions, high biomass is produced providing livestock feed. Simulation of different levels of crop residue used as mulch provided an insight on how to utilize crop residue when there is competition between using the crop residue as mulch or feeding it to livestock.

Maize plant population: was studied in relationship to in-crop rainfall (amount of rainfall from planting to harvesting) and crop residue management. The model simulation experiments showed that yield increased with plant population as long as there was sufficient soil moisture (from high in-crop rainfall or moisture conservation by the crop residue). This information is particularly useful as most farmers have a tendency to use a high plant population.

Streamflow simulation model

Model development: The model selected for the study (Thomas, 1993) gives weight to model simplicity (in view of data availability and quality), transferability to ungauged catchments (low number of parameters requiring identification by calibration), the need for an explicit soil moisture accounting routine and the ability to represent land use information (MacMillan *et al*., 1999). It is a conceptual, distributed daily catchment water balance model based on the USDA SCS curve number methodology which partitions rainfall into runoff and infiltration, a method widely used in the USA, but as recommended, requiring testing on measured data before its application to a new region. The model uses input data of daily rainfall and pan evaporation time series together with information on soils and land cover from field surveys and areal grid cell GIS data for vegetation cover, soils and elevation. In order to reduce a source of uncertainty in the modelling process, considerable time was invested in examining the time series datasets and removing identifiable errors (i.e., in measurement and processing). Similarly time investment was required for the preparation of the GIS coverages of aerial data. The performance of the model is assessed statistically by comparison of observed and simulated daily and monthly streamflows. The quality of the observed flow series is therefore crucial to the success of the study and the derivation of the flows has been subject to considerable scrutiny.

Three small study catchments representing different climatological and vegetational zones in the Ewaso Ng'iro basin were used to calibrate the model at the small scale. Prior to modelling, the rainfall and runoff data were examined to identify the hydrological processes occurring in the catchments. Sensitivity analysis on six key parameters/variables showed that the highest sensitivity is from the accuracy of the rainfall (amount and density of measuring gauges) and from the land use and cover.

Simulating land use change scenarios: The model has been used to examine the hydrological impact of land use change in the small catchments. Simulation experiments have shown that a deterioration of the grass cover in Mukogodo catchment would result in an increase in the annual flow, whilst intensifying the crop cover in Ngenia would decrease the annual flow.

Application of simulation modelling tools

Natural Resources Monitoring, Modeling and Management Project database for informed decisions: Database containing information on the basin's land resources (physiography, soils, climate, hydrology, cropping system and crop suitability) and socio-economic and demographic factors influencing land use has been developed. The database is geared towards generating readily accessible information on the land resources for use by researchers, extension workers, and decision makers in land and agricultural resources management as well as agricultural planning.

The monitoring database constitutes the foundation for a new effort to develop a comprehensive multiscale GIS-based natural resources and agricultural information system. The system will be updated regularly to better deal with the intricacies of land resources planning under the complex environmental conditions that prevail in this highly diverse ecosystem. The utility of this database has been demonstrated on a small scale and the results were encouraging. It is hypothesized that a decision support information system can facilitate land users, planners and policy makers to make informed decisions for more effective and sustainable use of natural resources, e.g., have better choices for investments in resource conservation and productivity enhancement, which would lead to sustainable resource management and increased value of output per unit resource.

Application in resource use conflicts resolution: Land and water use conflicts in the basin are intensifying and have led to loss of human life and destruction of property. The conflicts are most intense during the dry season due to scarcity of water and grazing resources particularly in the lower areas. The information base developed from long-term monitoring and simulation experiments is being used in conflict resolution. This is achieved through a participatory identification of the nature and extent of conflicts, seeking stakeholders view on how the conflicts can be reduced, seeking conflict resolution strategies with minimal negative impacts on all parties.

Working with farmers to adapt the modelling tool to their needs: Farmers continue to experiment in an effort to adapt technologies to the changing biophysical and socio-economic production environment that they find themselves in. In working with farmers we sought to develop a method that could be used to improve access and use of farmer- and scientist-based information. Partnerships (farmers, extension officer and researcher) in problem analysis and search for feasible solutions were developed. Open discussions were held to synthesize information gained from different sources and provide answers to farmers' questions.

Lessons learnt

The main lessons learnt are grouped into three categories, data, simulation modelling and utilization of the resulting information.

The main lessons learnt on data are:

1. Due to the inherent spatial and temporal variability of natural resource systems attributes and key processes, a comprehensive and long-term monitoring network is required to collect the data required to improve understanding of the system and for use in developing mathematical relationships of the key processes.
2. Data collection is expensive and those paying for data collection may fail to see the need for some data or for long-term monitoring. Data collected should therefore be put to use to ensure that the value of data is also appreciated.
3. Data management affects the quantity and quality of data and access and utilization of the data. A good data management system consisting of data collection, analysis and reporting is therefore required to ensure that appropriate use of data is made in answering specific questions. Proper documentation on the conditions under which the data was collected is vital for future interpretation of the data.
4. The quality of data is in most cases taken for granted. Poor quality data complicates data analysis and hypothesis testing. High quality of data can only be assured if data are verified at data collection, entry, storage and retrieval to ensure that the data are of as high a quality as possible.
5. Utility of data is limited if the data is not transformed into information and the information transformed into knowledge and used as grounds for actions. For ease of interpretation and use by the decision makers the data and information must be put into the context of the problem at hand. Data should therefore be properly packaged for use in decision-making.

The main lessons learnt in the context of simulation models development are:

1. Natural resources use systems are complex and model development should adopt an open-ended approach that allows additional model components to be added to expand the scope of modelling and cater for a wide range of dynamic scenarios.
2. Model development, calibration and validation should go hand in hand with an elaborated monitoring network to provide the data needed for model development.
3. Some scientists still question the ability of modelers to deal with the complexity and subtlety of the natural resource

systems. These model skeptics make valuable contribution in model development by ensuring that model developers take into consideration their concerns.

4. There is need to apply models cautiously. The modelers should identify if, when, where and how their models should be used, what level of training the users should have and what relationships there should be between modelers and model users. This will ensure that models are used correctly, within the constraints of both the models and the data that are available.

5. Uncertainties in simulating natural resources systems can be classified into four categories, namely: inherent variability of natural systems, data quality uncertainty, model uncertainty and parameter uncertainty. Inherent variability refers to the variability in time and space of natural processes such as evaporation, infiltration, stream flow, plant growth, etc. Data uncertainty is related to the measurements, recording, conversion, handling, computation and human errors. Model uncertainty arises because not all processes are completely and correctly modeled. Parameter uncertainty reflects incomplete models, incomplete information and inadequate parameter estimation techniques. Consequently, there is no model that predicts correctly and repeatedly, over diverse situations and time, the exact values. Model users will therefore have to accept the uncertainties in simulation modeling as they have with uncertainties in life.

If simulation results are to be used to guide managerial decision-making, the following are necessary:

1. Model input should be in line with frequently monitored system data.
2. Simulation output users must have confidence in the model. They should be informed of the limitation of the model.
3. Simulation output should be generated in the form amenable to managerial assessment and must address the specific data and information needs for decision making.
4. Simulation output must be able to be generated and processed quickly, so that it is availed to the decision makers when the issue is still relevant.

Future Challenges

The main challenges in the use of simulation models in natural resources management are:

- Improving the prediction accuracy of the models under different conditions.
- Current trends are indicating stronger future reliance on computer networking, easily accessible databases, decision support systems, object oriented programming, and system dynamics simulation. In dealing with the complex natural resources management problems, model developers will have to develop more and more on sophisticated tools.
- Uncertainty in natural resources phenomenon will continue to make modelling results uncertain. These un-certainties are attributed to (1) inherent temporal and spatial variability,

(2) uncertainty due to lack of knowledge and (3) uncertainty arising from controversy or ambiguity on how to compare and weigh social objectives.

- Systems analysis is particularly promising when scarce resources must be used effectively. Simulation models will be expected to play an important role in natural resources assessment, development, and management. Optimization techniques will have to be incorporated in most models.
- Models should be used to bias natural resource allocation decisions. There is need to ensure that such misuse of models is reduced.
- As more and more young mathematically minded scientists replace field-based researchers, more attention is being given to elegance of model formulation, mathematical treatment of data and improved users interface. This is in some cases coming at the expense of the important first steps of making reliable field measurements that are representative of the natural system. Wagenet 1988 stresses this point by the statement "Even a good model cannot compensate for biased or invalid data". There is need to develop efficient data collection methodology and ensure that data is used to ensure that those asked to pay for data collection will continue supporting data collection initiative.

Conclusions

The current achievements in simulation models are encouraging and investment in the further development of simulation models is expected. Simulation models development has contributed to the improved understanding of the complex system and ability to design experiments and interpret field data. Simulation models are being used as tools to (a) guide the researcher formulate hypothesis about a system behavior, (b) guide management or regulatory decision making process, and (c) educate intelligent, but scientifically less knowledgeable individuals on consequences of various courses of action.

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