Combining simulation and optimisation models for catchment management analysis

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Abstract This paper outlines a multi-model framework for exploring catchment management issues. Land and water degradation issues such as dryland salinisation, which is the focal issue in the Liverpool Plains catchment in Northern New South Wales, are of a highly complex nature, including bio-physical, economic and other aspects and compounded by risk factors. Traditionally, (single-) disciplinary models have been employed to analyse specific aspects of a problem. While providing valuable insights into these specific parts of the system, it does require a holistic modelling framework to capture systems complexities and inter-relationships and identify long-term solutions to a problem. This paper presents a point soil-plant-water simulation model, a catchment optimisation model and a catchment hydrology model, all of which have been applied in the Liverpool Plains catchment. After discussing their potentials and limitations, the paper develops the concept of a holistic modelling framework by combining these models to gain synergy effects in analytical ability as well as applicability and implementation of results.

1. INTRODUCTION

The major rationale behind land-use decisions is to generate farm income. However, these activities cannot been seen in isolation from a given geographical, ecological, hydrological, technical, social, economic, legal and political context. In addition, land managers face challenges arising from uncertainty, risk, and conflicting interests. Given this complexity, land management systems can be regarded as complex systems.

Conceptually, complex systems are groups of interacting, interdependent parts linked together by exchanges of energy, matter, and information. They are specifically characterised by strong interactions between the parts, complex feedback loops that make it difficult to distinguish cause from effect, and significant time and space lags, discontinuities, thresholds, and limits [Costanza *et al.* 1993].

Managing a complex system requires an intimate understanding of its dynamics and (potential) control variables. One way of approaching this challenge is by analysing the system and then capturing its essential factors, variables and interrelationships in a holistic systems framework. Holistic systems frameworks are based on multi-disciplinary research, merging ecological, bio-physical, sociological, economic and policy aspects of the problem [Ikerd 1993].

Computer modelling using these frameworks has proven to be valuable in getting to understand regional-scale land and water management systems. The framework must include the constituent elements of the system under investigation, their interactions, prevailing and alternative activities, competing objectives of decision makers, and land-use decision rules in a comprehensive manner. To translate this systems framework into an adequate model that is endogenously consistent and supported by data availability and available resources, the model needs to be clearly defined and adequate in scale, scope and model type. It must also take into consideration the external variables that are essential to explaining system behaviour. In addition, it is critical that the model reflects the perspective of stakeholders if it is to secure acceptance and implementation of the research results.

A series of models have been developed and applied to problems of land and water management in the Liverpool Plains catchment. They are characterised by different scope, scale and resolutions, and follow different paradigms. This paper addresses some of the questions and difficulties associated with sensibly linking these models within a complex systems framework.

2. CATCHMENT MANAGEMENT FOR SALINITY CONTROL: A COMPLEX SYSTEM

2.1 Description of a complex system

The hydrogeology of a catchment determines whether it is predisposed to rising groundwater tables. These can result in soil salinisation through mobilising historic salt and translocating it into the root zone of soils where it modifies soil characteristics and impedes plant growth.

European-type crops are particularly salt sensitive. Hydrogeology determines whether an area may develop salinity. The sufficient condition for salinity to emerge is that recharge to the groundwater system is increasing. This means that more water percolates through the root zone of the soils (diffuse recharge) and/or higher point recharge where surface water joins the groundwater system. Increased recharge can result from increased rainfall, the introduction of irrigation, and/or tree clearing and changes in agricultural practices.

Rising groundwater tables and subsequent soil salinisation are characterised by spatial effects and time lags due to the hydrological processes involved. There is a time lag between when water is being recharged and when this recharge translates into groundwater table rise. For the Liverpool Plains catchment, time lags are thought to be between one year for local ground water systems and more than 20 years for regional groundwater systems [Broughton, A. 1995, Hydrologist, NSW DWR, personal communication].

Salinisation is also characterised by benchmark functions. While groundwater tables may decline quickly, reversing salinity requires the leaching of salts out of the plant root zone. This is a very slow process. For long periods of time, land that is severely salt-affected may only be suitable for low-productivity saltland agronomy use.

In any large catchment there are a multitude of stakeholders, including the farmers who make a livelihood in the area. More than 2000 farms operate in the Liverpool Plains catchment. Understanding the motivations that govern land-use decision which, in turn, influence catchment hydrology, requires a socio-economic layer to be added to the bio-physical problem description. This should include institutional arrangements which are a key factor in determining who benefits from current arrangements and who bears the costs associated with rising groundwater tables and salinisation [Greiner 1993].

All these factors need to be considered when devising a methodological framework for land-use systems analysis and translating it into a systems model.

2.2 Scale, resolution and scope

For many problems, identifying the bio-physical and socio-economic processes operating within the system is not enough. It is equally necessary to identify the scales and range of magnitudes involved [Judge and Takayama 1973].

Analytical frameworks tend to become more complex as their scope is increased (ie. more issues are included into the analysis). Increasing scale, (ie. the geographical and temporal boundaries) can have the same effect. Scale is a key criteria in modelling complex systems along with scope, generality, realism, precision and resolution, [Costanza *et al.* 1993, O'Neill *et al.* 1989]. For an integrated land and water management modelling exercise, scale is pivotal both in a spatial and in a temporal sense because it determines how well system interrelationships can be depicted.

Models require scaling if they are applied at a scale other than the one they were designed. Scaling is directly tied to the problem of aggregation [Costanza *et al.* 1993]. Aggregation leads to a condensation of information and incurs a loss of detailed insight, but it can significantly enhance the understanding of complex phenomena by structuring the data in a way which focuses the attention on important system features. Aggregation becomes problematic when models operating at different aggregation scales are combined [Braat and Lierup 1987].

Equally important is a clear delineation of scope which defines the conceptual boundaries of the model with respect to the conditions under which the model operates. Any extrapolation of results beyond a model's domain requires careful consideration of the specific conditions and general assumptions within which the model operates.

2.3 Methodology

Generally, quantitative models can be divided into statistical and process-based models. The choice of methodology reflects the objective of the modelling exercise and information availability. Statistical approaches determine relationships between historical data sets and have the purpose of forecasting. Process-based models require a description of underlying functional relationships. Predicting the future can be one purpose, however, increasing emphasis of modelling exercises, not only in natural resources management, is being placed on understanding and learning systems behaviour.

Relatively new in the area of natural resource modelling are artificial neural networks. Neural networks are classified as data-driven approaches whereby the system is trained to produce outcomes on the basis of strategically chosen model inputs. They are particularly suited to complex problems, where the relationships between the variables being modelled are not well understood. Maier and Dandy [1996] have successfully applied the technique to predicting the salinity content of the Murray River water.

Process-based models are differentiated by model type into simulation and optimisation models. They can be static or dynamic, deterministic or stochastic, spatially explicit or abstract. Simulation is concerned with exploring the implications of management strategies or the influence of external factors on systems behaviour. It does so by defining variables, describing processes and introducing decision rules. Simulation models can be descriptive, enhancing the understanding of a complex system, or prognostic, anticipating the outcomes of decisions or events.

Optimisation or programming models are concerned with finding a best possible strategy and combination of activities for maximising a defined goal or finding the best solution to a trade-off relationship within a set of constraints. Optimisation models apply values and are therefore normative. Dynamic optimisation models can be truly dynamic (ie. optimising over a planning period) or iterative (ie. optimising in time steps and taking the output of one optimisation period as input for the next). Spatial optimisation models are usually applied for analysing markets within regions and economies. The methodology has been successfully applied in natural resources analysis for identifying ways in which a range of stakeholders can optimise the use of a resource which is common to them [Salerian 1991].

3. THE ROLE OF SELECTED MODELS FOR ANALYSING CATCHMENT MANAGEMENT FOR SALINITY CONTROL

The number of models available for analysing various aspects of land and water management, farm economics, and catchment hydrology is large. A selection of these have been applied in the Liverpool Plains catchment which is one of five focus catchments for dryland salinity research in Australia. This section of the paper discusses the models individually and shows existing linkages in applications. The models are summarised with respect to major characteristics in Table 1. Section 4 will then develop a vision of a framework which formalises the linkages between these models to explore the various implications of land-use decisions and analytical aspects simultaneously.

3.1 Soil-plant-water models at point/paddock scale

Two of the most widely used bio-physical models for analysing agricultural systems in the Australian environment are the soil-plant-erosion models PERFECT [Littleboy et al. 1989] and APSIM.

Keating et al. [1995] describe APSIM as a software environment which consists of a series of modules each representing a different aspect of soil-water-plant and a communications system that allows modules to share information. For a particular point in the landscape, APSIM simulates plant growth and soil processes and estimates crop yield, soil erosion, and components of the point water balance. The inputs are soil data, time series of daily rainfall and temperature, plant characteristics and land management rules which apply to the agronomic system. Land management activities are the major variable under investigation for any specified location. The results are displayed as annual aggregates over the chosen time horizon and are particularly useful for comparing the benefits and effects of selected land-use regimes. Employing this sort of model is particularly useful for exploring the causal side of the salinity problem, which is the percolation of water through the soils' root zone and consequent recharge to the groundwater system. It must be noted that recharge (which is referred to as 'deep percolation' in APSIM) is the residual component in the calculated point water balance specified in these modules and is therefore potentially subject to larger error than other components of the point water balance. At the same time, APSIM must be considered a highly sophisticated and precise tool for exploring the implications of land-use decisions and land management strategies on the recharge to groundwater.

Some limitations of using PERFECT and APSIM are that the present array of land management options is restricted to a limited series of crops and cropping regimes, that there is no direct link of salt-concentration in soils to crop yields, that the effects of water logging on plant growth cannot be explored and that the methodology has been validated for cracking black soils only. With further development, the potential of these models is immense. Also, their design is such that they can be customised to report in other than annual time steps and the outputs can be analysed in relation to single input variables [Keating et al. 1995].

3.2 Economic models at farm and catchment scale

3.2.1 Farm-level programming model

There is a suite of farm management models available for different purposes and different applications. MoFEDS is a farm-level optimisation model [Greiner 1996a] which specifically looks into the management options which farmers have to address (the threat of) soil salinisation on their land. MoFEDS analyses land and water management options in a farm context and is parameterised for salinity-affected locations in the Liverpool Plains. The normative model paradigm seeks to explore best possible land and financial management strategies in a medium-term context. In addition to the traditional farm area, capital and labour constraints, the salinity status of the land is included as a resource. The objective function maximises total net present value of after-tax income. This reflects the fact that cash-flow, investment and taxation aspects play a critical role in land management decision making.

MoFEDS acknowledges the catchment context of an individual farm by including the implications of catchment hydrology through the farm-external variable 'lateral groundwater flow'. On-farm recharge is the other critical influence variable on the farm water balance and one that is endogenously determined. The farm water balance determines change in depth of groundwater table which determines the area of land affected by soil salinisation which, in turn, has repercussions for future land productivity.

Table 1: Summary of model features

MODELS descriptors	APSIM	SMAC	CSIRO CLW Model
scope	soil-water-plant interactions	land-use, farm incomes and catchment hydrology	macro-scale hydrological model
model type	simulation	optimisation	simulation
modelling approach	empirical/conceptual process-based	conceptual process-based	empirical/conceptual process-based
scale - spatial	point/paddock	(sub)catchment	(sub)catchment
scale - temporal	time series as long as rainfall records	30-year period (arbitrary)	arbitrary, as long as measured or hypothetical data available
resolution - spatial	point	unique mapping areas or arbitrary grid	arbitrary, user-defined grid
resolution - temporal	day	season	arbitrary, user-defined time steps (at present annual)
inputs	soil parameters, daily rainfall, temperature, topography, crop characteristics, agronomic specifications	crop yields, runoff and recharge for all land-use options, farm structures and finances, prices, policies, hydrological linkages	runoff, recharge, physical dimensions and properties of aquifer
outputs	crop yields, runoff, soil erosion, recharge	optimal land-use across catchment, extent of soil salinisation, farm incomes	groundwater levels, surface and stream discharge fluxes

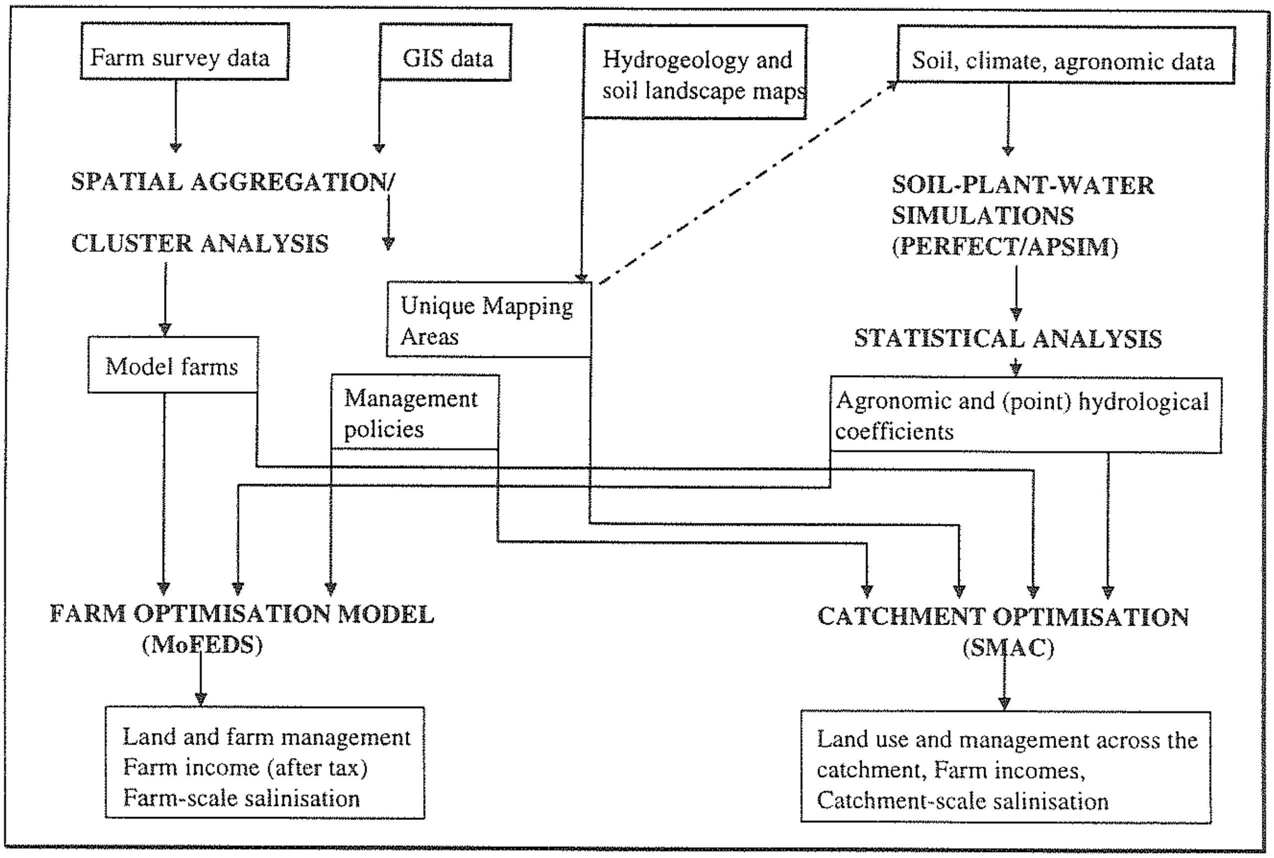

Figure 1: Relationship between farm and catchment optimisation models MoFEDS and SMAC and hierarchical procedure for their parameterisation

MoFEDS has established that soil salinity caused by catchment conditions imposes huge costs on affected farms and may rapidly erode their financial viability. These catchment conditions are influenced by the land-use systems that other landholders in the catchment have implemented. In economic jargon, these relationships describe externalities whereby (1) the decisions of some people (causing agents) influence the well-being of other people (recipients) and (2) there are no mechanisms in place which attribute the costs/benefits for the recipients to the causing agents.

3.2.2 Catchment-level optimisation model

Catchments are defined on the basis of hydrological boundaries and therefore catchment models tend to be hydrological models. SMAC is a regional optimisation model, based on MoFEDS, which operates at the catchment level [Greiner 1996b]. It answers three questions: what does catchment-optimal land use look like in a spatial and temporal sense?; how do existing farm structures need to respond?; and how can this process be influenced by policy mechanisms? It optimises land management on the assumption that farmers make land use decisions within the context of their land and labour resources and capital structure. However, instead of looking at individual farms in an isolated context, land use decisions between farmers are linked through hydrological formulations, so that the external costs associated with salinisation can be internalised at the catchment scale.

Spatial and temporal dynamics and risk

To capture spatial variability, the spatial parameters in SMAC are linked to an arbitrary grid structure that is superimposed on the catchment map. The resolution of SMAC is based on unique mapping areas (UMAs) which evolved from bio-physical information [Johnston et al. 1995]. Each UMA can be viewed as being homogenous with respect to catchment management because it contains areas of similar contribution to, and relevance and disposition for the development of soil salinity. Hydrological connections define the spatial dynamics between UMAs.

Rainfall is the crucial external factor to the 'catchment-salinity-management' system. Rainfall variability in the region is high. The coefficient of variation for annual rainfall over the past 100 years is 0.27. Rainfall variability adds a significant element of risk to land management and salinity control.

Exploring stochasticity and risk with a programming model involves a large number of model runs [Pannell 1997]. SMAC deals with climatic risk through discrete stochastic programming. In the data base of the model, five conditions for winter and summer seasons are distinguished. These conditions are very dry, dry, average, wet, very wet, and respectively represent the 10, 30, 70, 90 and 100 percentiles of total in season rainfall over a 113 year time period. Over the 30-year planning period, weather conditions for both seasons in each year can be chosen randomly, giving 25 possible combination. Alternatively, discrete stochastic programming allows the deliberate construction of weather conditions for the purpose of investigating the implications of climatic extremes on recharge, water table movement, salinisation, and farm incomes.

Connections to APSIM

In addition to structural features, SMAC requires a large amount of detailed data as model parameters. In the absence of experimental data, estimates of the relationships between soil, topography, land use and management, yield, water recharge and runoff, are obtained from APSIM runs. Land use, farm structural and financial parameters have been obtained from farm surveys data [ABARE 1996, Ockerby 1995]. Estimates of the hydrological connections between UMAs were elicited from expert discussions.

Figure 1 conceptualises the links between APSIM and other parameter sources and SMAC. It also shows the similarities and differences between the farm and catchment optimisation frameworks MoFEDS and SMAC.

To obtain the coefficients necessary to parameterise SMAC for discrete stochastic programming, APSIM was set up to record crop yield, water runoff and recharge in seasonal intervals and the estimates were grouped according to seasonal rainfall into the corresponding categories.

Figure 2 shows examples of the salinisation trajectories obtained from SMAC under random seasonal rainfall distribution using given probabilities. These outcomes provide a realistic picture of the bandwidth of potential developments assuming that land managers are concerned with the management of soil salinisation.

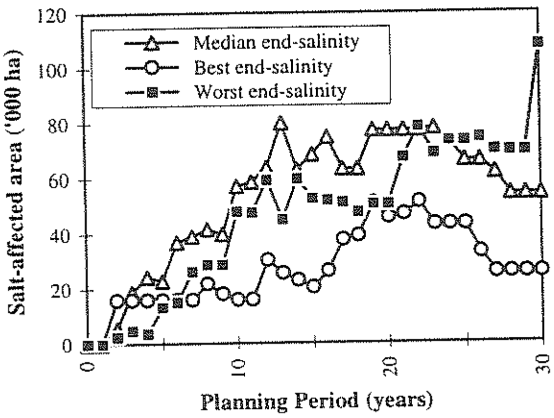

Figure 2: Examples of salinisation estimates under random rainfall conditions

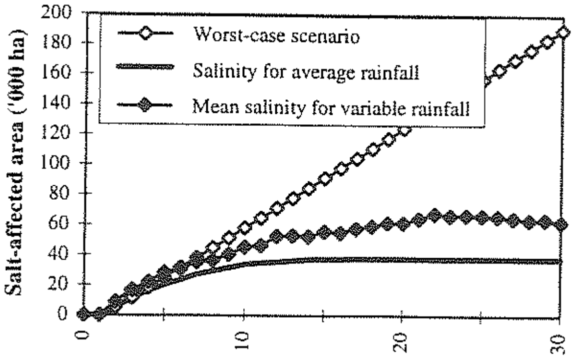

Figure 3: Expected salinisation under variable rainfall conditions in the context of worst-case scenario and catchment-optimum under average rainfall conditions

Figure 3 views these results in comparison to estimates obtained in other scenario runs which assume average rainfall conditions. The top line extrapolates current trends of groundwater level rise and may be referred to as 'worst-case scenario'. The bottom line shows salinity arising from optimal catchment management under average rainfall conditions. It is evident that rainfall variability adds considerable 'noise' to the salinity estimate and leads to a higher level of estimated soil salinisation. At the same time, it does not change the general outcome of the analysis which says that from a catchment perspective, land-use change should optimally be implemented to a level where salinity is contained at a level far below the worst-case scenario.

These results also suggest that in the context of global warming and increasing rainfall variability, salinity control may become increasingly difficult.

3.3 Catchment-scale hydrological model

The continued application of SMAC is part of the AGSO-lead Integrated Catchment Modelling project. This project originally envisaged the application of two strains of catchment-scale hydrological models. Firstly, the MIKE-SHE modelling package would be parameterised for the Liverpool Plains catchment. MIKE-SHE could not yet be operationalised due to insufficient data [Evans 1996]. Secondly, a low-data-requirement model would be specifically developed and applied.

The CSIRO CLW model [Dawes and Walker 1997] provides a framework that requires least data, as far as hydrological models are concerned. It is based on a Multi-FUNNEL principle [Dawes et al. 1997] and constitutes a process-based groundwater flow model that reduces, in principle, to a one-dimensional diffusion equation It is based on a simple conceptual model of a high conductivity zone sandwiched between an impervious basement and a semi-confining layer above. The parameters required for this model can be obtained from drilling to determine the physical boundaries of aquifers. This model is amenable to receiving outside inputs, such as distributed groundwater recharge, and returning model results, such as groundwater levels, to other external or integrated models.

4. VISION OF A FULLY INTEGRATED CATCHMENT MODEL

Two principal approaches to building an integrated systems model can be considered. Existing (mono-disciplinary) models which address different parts of the system may be integrated in a hierarchical or interactive manner. This requires the formulation of linking procedures. If such models do not exist or existing ones are incompatible, a systems model has to be built from scratch. While this is a time consuming procedure, the merit in doing so is that the different modules can be designed specifically to interface each other. Either way is paved with a series of methodological issues and decisions and technical problems.

As shown in Figure 1, MoFEDS and SMAC have gone some of the way to integrating various simulation and optimisation models in a hierarchical manner to maximise their utility for answering questions related to catchment management for salinity control. However, this combination package still displays major weaknesses in accurately estimating the extent and location of salinity development. This is why CSIRO CLW needs to be incorporated to form a consistent, multi-stage modelling system (Figure 4).

This framework is not dis-similar to NELUP, a general systems framework which investigates environmental issues associated with agricultural land-use change in the River Tyne catchment in England. Moxey *et al.* (1995) emphasise the advantages of mathematical programming for economic analysis of regional land use issues. The economic model is one of a series of interrelated quantitative models which are inter-linked (O'Callaghan 1995).

In the case of the Liverpool Plains model framework, advantages from combining existing simulation and optimisation models are obvious. APSIM provides a (partially) validated methodology and a consistent data base for the economic and hydrological catchment models. SMAC provides suggestions of optimal land management from an economic perspective. These can be fed to the CSIRO CLW model which explores the hydrological and salinity implications and shows where, within each UMA, the recommended land use changes would be best implemented for maximum hydrological efficiency. Estimates of groundwater levels and salinisation can be returned to SMAC for fine-tuning of land-use change and farm income estimates. Combining SMAC output with a catchment-scale hydrological modelling procedure would greatly assist the translation of the highly abstract optimisation results into spatially more explicit recommendations. This has the potential to increase the perceived relevance of modelling results for land managers in the Liverpool Plains which may improve adoption rates of land use change for salinity control.

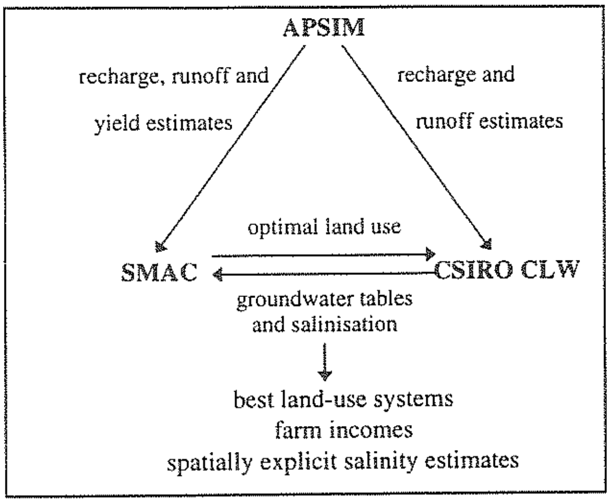

Figure 4: Concept of a composite catchment modelling system

The proposed framework maximises the usefulness of each individual model by complementing their strengths and overcoming their weaknesses. The outcomes can be expected to provide specific recommendations towards catchment management and encourage landholders to participate in a land management strategy for the catchment.

Maximising implementation of the research outcomes is also pursued by encouraging stakeholder involvement in model development and presenting results to the local community on various occasions. In addition, a decision support system can be put on top of the proposed model combination package to provide stakeholders and resource managers with an interface that allows them to explore potential futures themselves.

Given the modular structure of the catchment modelling framework and the individual models, it is easy to envisage widening of scope of the analysis beyond catchment-internal salinity problems. For example, off-site effects of salt exports out of the catchment could be incorporated into the economic analysis. The range of potential land-use options could be enlarged. The range of catchment-internal issues could be expanded to include, for example, habitat and biodiversity considerations or other aspects of resource degradation. In summary, the modular structure enables above catchment modelling framework to develop into a truly holistic approach.

5. CONCLUDING REMARKS

This paper examines a complex natural resources management issue: dryland salinity management in a large catchment. A number of models have been applied to analyse various aspects of the management problem. The characteristics of these models are presented with particular emphasis on spatial and temporal dynamics. Scope and limitations are discussed and existing linkages between models highlighted. The paper argues that an integrated holistic modelling framework is required to capture the complex system characteristics of the problem, increase understanding of its dynamics, and reveal long-term management solutions. It develops a conceptual framework of a hierarchical modelling system that combines a point-scale soil-water-plant model with an economic catchment optimisation model and a hydrological catchment model to maximise the analytical capacity of the models. The goal is to identify long-term management solutions to the problem which have a high chance of being implemented by stakeholders.

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