Modelling for Managing the Complex Issue of Catchment-Scale Surface and Groundwater Allocation

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Abstract. The management of surface and groundwater can be regarded as presenting resource dilemmas. These are situations where multiple users share a common resource pool, and make contested claims about their rights to access the resource, and the best use and distribution of the resource among competing needs. Overshadowed by uncertainties caused by limited data and lack of scientific knowledge, resource dilemmas are challenging to manage, often leading to controversies and disputes about policy issues and outcomes. In the case of surface and groundwater management, the design of collective policies needs to be informed by a holistic understanding of different water uses and outcomes under different water availability and sharing scenarios. In this paper, we present an integrated modelling framework for assessing the combined impacts of changes in climate conditions and water allocation policies on surface and groundwater-dependent economic and ecological systems. We are implementing the framework in the Namoi catchment, Australia. However, the framework can be transferred and adapted for uses, including water planning, in other agricultural catchments.

Keywords: Integrated Modelling, Surface and Groundwater Management, Resource Dilemmas, Water Allocation.

1 Introduction

Water resource management issues are often described as: wicked [1] persistent [2] and dilemmas [3]. The main features of such issues include:

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- ill-defined, multiple and conflicting goals leading to disputes and controversies
- interdependency among stakeholder activities, and their effects on the resource
- highly complex and interconnected social, technological, and biophysical processes
- uncertainty about system processes, and how they respond to change

Resource dilemmas cannot be solved in a sense of finding a final and risk-free solution that satisfies all preferences. However, they need to be managed by continually developing and adapting resource sharing policies that can best accommodate various present and future needs under different water availability scenarios. The design for collective and adaptive policies calls for *integration* among:

- policy issues to develop systemic and long term policies rather than short term and piecemeal decisions
- scientific disciplines in order to develop a multi-perspective stance about coupled socio-ecological processes that cannot be derived from isolated mono-disciplinary stances, and
- science-policy-stakeholders throughout the policy making lifecycle.

Models and modelling can play a key role in establishing and supporting these integration dimensions. They can be used as tools for synthesising and communicating our understanding of complex social-ecological systems. Modellers can help integrate methods and findings from different scientific fields (e.g. ecology, hydrology, economics and other social sciences) to present relevant policy and decision-making information. Participatory modes of modelling provide support for framing the issues of concern from multiple viewpoints, clarifying decision options, identifying and engaging with stakeholder groups, and sharing the knowledge generated.

This paper presents a project where modelling has been designed to help deal with over-allocation of surface and groundwater, a key policy issue in Australia and worldwide. The modelling project brings together a collaborative multi-disciplinary research team (i.e. social, economic, ecological, hydrological, legal and institutional disciplines) with the aim of developing an integrated modelling framework to identify the social, economic and environmental trade-offs under various water policy decisions and climate variations. The model allows the exploration of adaptation mechanisms, identified by our social science team, that water users are likely to accept in order to minimise the impacts of climate change and reductions in their water allocation. The modelling framework is implemented in the Namoi catchment, Australia. However, the framework can be transferred and adapted for use in other agricultural catchments.

The paper is structured as follows: in Section 2, we discuss the challenge of over-allocation in water planning in Australia, and briefly introduce the concept of integrated modelling. Section 3 presents water allocation in the Namoi catchment as the case study. The modelling framework is described in Section 4. We wrap up with the discussion and conclusion in Sections 5 and 6.

2 Background

2.1 Over-Allocation and Trade-Offs in Australia

In Australia, returning over-allocated surface and groundwater systems to sustainable levels is a key challenge for water planning. According to a recent national assessment [4] major catchments and aquifers are at or approaching the risk of being ecologically stressed as a result of flow regulation and/or consumptive water use. This may be exacerbated by predicted long term declines in rainfall, increases in temperature and in evapotranspiration, and variability in stream flows and aquifer recharge rates. [5] The National Water Initiative (NWI), the principal blueprint for water reform, stresses the need for water planners to make "trade-offs", or decisions that balance water requirements for the environment with the water demands of consumptive users. The requirements as well as challenges for designing trade-offs include [6]:

1. robustness: taking into consideration the possible impacts of climate variations (including climate change and variability) on environmental outcomes and consumptive use,
2. transparency: all information used to set up priorities and assess outcomes are clear and publicly accessible
3. risk-based: assessing consequences, associated risks and benefits under different water sharing scenarios
4. science-informed: assessments to be based on best available scientific knowledge and data, including socio-economic and ecological analysis

To meet these requirements, the design and implementation of trade-offs need to be informed by a holistic assessment of different water uses and how they may change under different climate and policy scenarios. This requires mechanisms for integrating knowledge, methods and tools from different scientific disciplines in order to analyse system elements and synthesise information that is useful and relevant to planners and managers. One of these mechanisms is integrated modelling.

2.2 Integrated Modelling

Integrated assessment and modelling is becomingly increasingly accepted as a way forward to address complex policy issues [7]. Many of the earlier concepts drew upon the integration of different types of models, or different types of data sources [8]. Models have been developed to integrate across more than one discipline. For example Pulido-Velazquez et al. [9] integrated across two disciplines (surface water and groundwater hydrology and economics), and Kragt et al. [10] integrated the hydrologic, economic and ecologic aspects of the management of a river basin in Tasmania. Barth et al. [11] included some social aspects of people's choices and responses to various water-related scenarios. However, only a few examples exist where more than three disciplines have been included, particularly social science disciplines considering behaviour, social impacts, law and institutions. One such example is Mongruel et al. [12] who accounted for governance by implementing

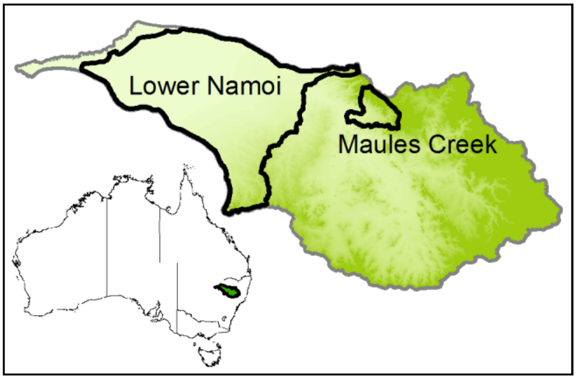


Fig. 1. The Namoi catchment and study locations

various policies, rules, laws and agreements, and social implications (e.g. recreational fishing and oyster growing), linked by hydrological and ecological consequences. To account for all major aspects in the management of surface and groundwater, an integrative approach would need to account for governance, economic, ecological, hydrological and social components of the system, and their relevant linkages.

3 Case Study

The Namoi Catchment is located in northern New South Wales in Australia (Fig. 1). The catchment is about 42,000 sq. km in size and extends from the Great Dividing Range in the east, with elevations of 1000m down to the flat plans in the west at only 250m. The average annual rainfall over the catchment varies accordingly, from over 1100mm to 470mm, and falls mainly in the summer in high intensity events. [13] This makes the catchment hydrologically complex, with many of the streams and drainage channels being ephemeral. The population in the catchment is over 100,000 people residing both in towns (mainly Tamworth and Narrabri) and rural settlements. The regional output is over AUS$1 billion, half of which comes from agriculture. Agricultural land uses include grazing on the steeper elevations, and cropping, both dryland and irrigated, on the flatter country. The cotton industry is a highly lucrative irrigated industry in the area. The latest national assessment by NWC [4] has rated the catchment as “highly” stressed, and over-allocated.

The Namoi has been well studied in the past. Kelly et al. [14] present an extensive list of studies of groundwater alone, including both modelling and data analysis in the Namoi catchment, yet still concluded that more than 15 other projects could be conducted to further our scientific understanding of the groundwater in that catchment. In addition there have been social studies, [15] economic studies, [16] hydrological studies [17] and ecological studies[18]; and a recent report by Hartley et al. [19] demonstrates the complexity of the governance issues surrounding groundwater across the Namoi catchment, with variation in the scale and governing bodies at different locations.

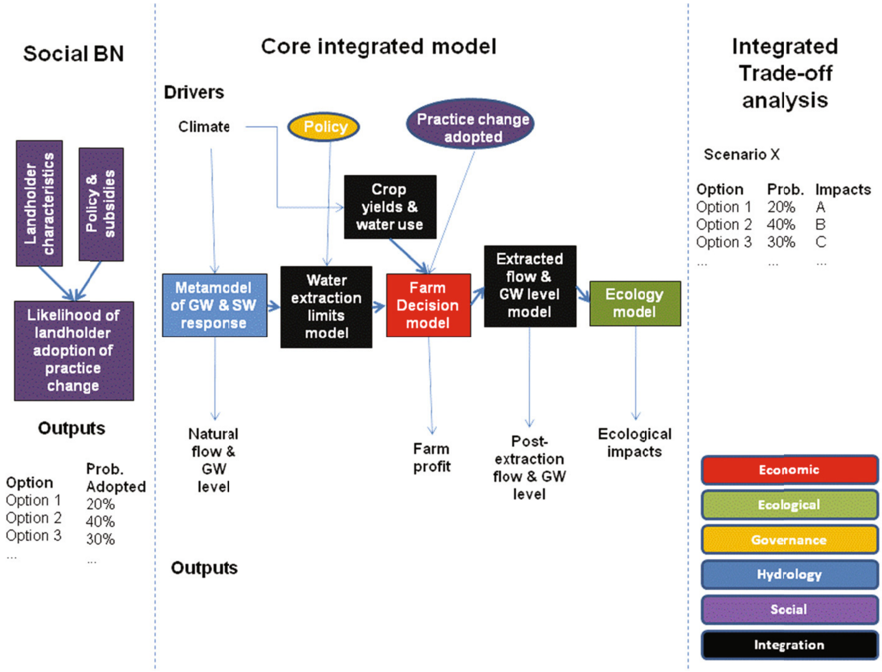


Fig. 2. Conceptual diagram of the integrated model

The work presented here builds upon that of Letcher et al. [20] by utilising the expertise of disciplinary research scientists to: add ecological and social models; improve the hydrological model to include a component for surface-groundwater interactions; update the data and information in the social, economic and crop models; and develop more informed policy (and adaptation and climate) scenarios using the expertise of governance and law researchers.

Within the Namoi catchment we are focusing upon two specific groundwater areas - the Lower Namoi which includes access to regulated surface water, and the smaller Maules Creek catchment which has unregulated surface water access. These case study areas capture the complexity of the social, hydrological and ecological components crucial to the wider area for the management of groundwater.

4 Model Description

The model has several components which are integrated into a single working model shown in Fig. 2. The various model components have been designed to run at various spatial scales (see below), with a temporal horizon of 20 years to allow for irrigation infrastructure investments.

The integrated model:

- Uses prediction of the natural surface and groundwater flow, and the policy scenarios to estimate the water extraction limits

- Determines the water use and crop yields given the climate and various crop types
- Uses the output from the likely behaviours and adoption of various actions by landholders from the social model, the water allocation levels and the crop yields and water use, to input into the farm decision model and determine the farm profit
- Calculates the extracted flow and groundwater levels remaining following farmer decisions, and
- Estimates the ecological impacts of the available surface and groundwater flows on the ecology.

Descriptions of each component of the integrated model now follow.

4.1 Model Components

Hydrological Model

At the core of the integrated model is a hydrological model that predicts the effects of surface and groundwater extraction regimes on surface flows, aquifer storage and discharge. These hydrological impacts are used to assess water availability and the resulting social, economic and ecological outcomes.

A key challenge in developing the hydrological model was identifying an appropriate level of spatial aggregation and parameterisation that provides satisfactory prediction of water storages and fluxes necessary for evaluating options for managing the water resources, given the uncertainties in modelled output and observed data. The social and economic components of the project, as is common with such models, divide the catchment into a number of large regions that are considered homogenous with respect to land use and farm management practices [20]. Hence the performance of the hydrological model only needs to be assessed at this large spatial scale. A second consideration was that the run times of the integrated model needed to be minimised to facilitate assessment of model performance and uncertainty analysis.

The selected hydrological model is a spatially lumped model that employs a catchment-scale conceptualisation of the key hydrological processes, and includes two groundwater layers: a shallow system that contributes baseflow to the river, and a deeper groundwater system that is used as a water resource. The model consists of three components: a rainfall-streamflow model representing runoff and baseflow from the shallow aquifer system for each subcatchment; a groundwater mass balance model for the deeper aquifer system, and a lag-route routing model [21] capturing the flux of water between nodes. The hydrological model represents the stream network as a series of nodes. Each node represents a sub-catchment and is comprised of two modules. The first is a non-linear loss module that takes rainfall and temperature data and produces ‘effective rainfall’ (rainfall that becomes runoff or recharge), accounting for losses due to evapotranspiration. The second is a linear routing module that converts effective rainfall to stream flow via two parallel transfer functions representing a quick-flow pathway (equated to surface runoff) and a slow-flow pathway (representing discharge from the shallow aquifer system).

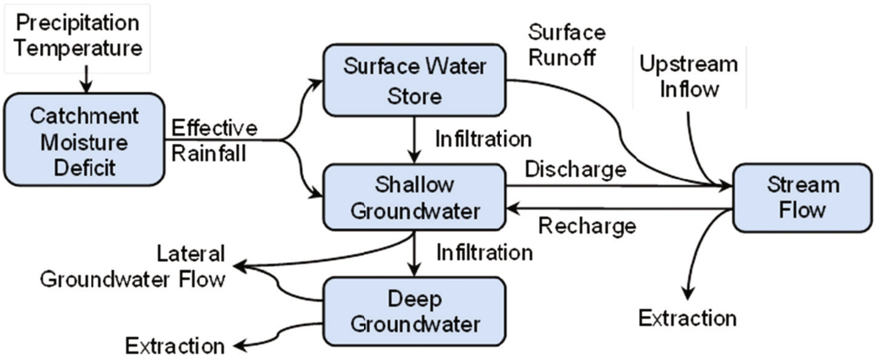


Fig. 3. Structure of the hydrological model for a single subcatchment and connected groundwater aquifers

A preliminary formulation of the model is detailed by Blakers *et al.* [22] and is represented in Fig. 3. The model is based on the IHACRES rainfall-runoff model [23] with the addition of groundwater and surface water interactions from Ivkovic *et al.* [24] and a two layer aquifer system by Herron and Croke [25]. The additional work by Blakers *et al.* [26] allows for better specification of the groundwater aquifers, which do not follow surface catchment boundaries, and improved representation of surface-groundwater interactions and groundwater flow.

The model takes rainfall, temperature and extraction data and other basic catchment information (e.g. catchment area, location of aquifers) to predict on a daily basis:

- surface water flows, including contributions from surface runoff and baseflow
- groundwater levels at selected locations in the catchment, for use in ecological modelling and water availability assessment.

Social Model

A Bayesian network (Bn) has been developed to represent the social model component. Bns capture the conceptual understanding of a system by causal links between variables with multiple states, and the strength of the links is represented by probability distributions. These models are becoming increasingly popular in natural resource management for their ability to incorporate quantitative and qualitative information, their implicit representation of uncertainty and their usefulness as communication tools. See Ticehurst et al. [27] for an example discussion on the advantages and disadvantages of using Bns in natural resource management. Bns have also been successfully used in the analysis of social data [28].

Here the Social Bn has been developed to map the likely behaviours of farmers in terms of compliance, changes in farming systems and water use efficiency depending upon various climate scenarios and policy options. It is based upon the findings of Sharp and Curtis [29].

Ecological Model

The ecological model for the Namoi is directed to healthy river function. This involves:

- a sustained level of base flow, which provides refuges during drought
- regular flushing at various levels of benches and anabranches, in order to increase habitat areas and transport nutrients and carbon to the river system
- regular flooding to sustain the growth of riverine vegetation and support regeneration
- suitable groundwater and salinity levels to allow the access of water by riverine vegetation, particularly during drought.

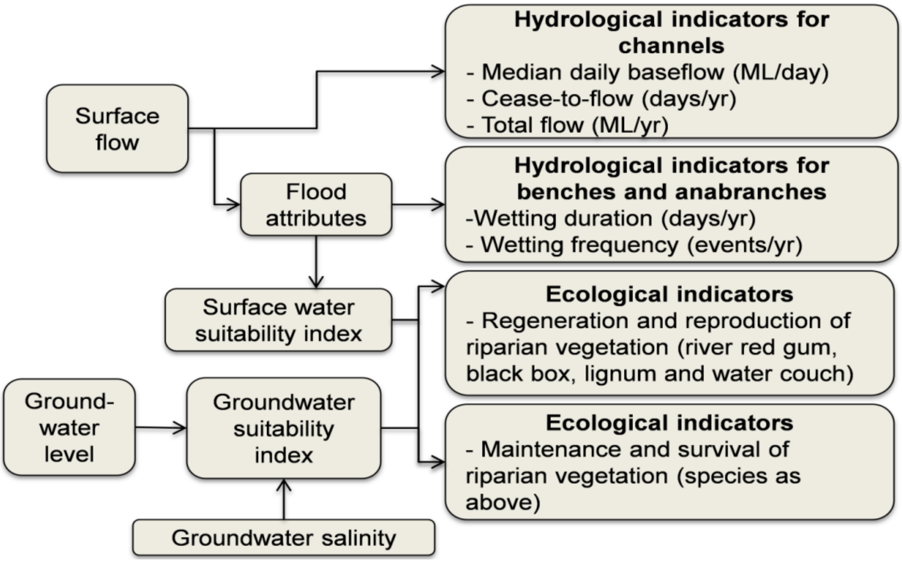


Fig. 4. Structure of the ecological model

The ecological component has been developed by Fu and Merritt [30]. The model, shown conceptually in Fig. 4, uses inputs of surface water flow and groundwater level and salinity to estimate hydrological and ecological indicators for niche ecological assets identified for the Namoi. The hydrological indicators include baseflow level, cease-to-flow days and total flow. Wetting duration and frequency for benches and anabranches are estimated at each asset. The ecological indicators report the water suitability index for the maintenance and regeneration of four riverine vegetation species: *Eucalyptus camaldulensis* (river red gum), *Eucalyptus largiflorens* (black box), *Muehlenbeckia florulenta* (lignum) and *Paspalum distichum* (water couch). The water suitability index is generated from both surface water and groundwater suitability indices. Variables considered for the surface water suitability index are flood duration, timing and interflood dry period. The groundwater suitability index is derived from the groundwater level index and adjusted by groundwater salinity. Groundwater salinity acts as a modifier: if the groundwater salinity level is greater than the salt tolerance threshold for a given species, the groundwater suitability index is reduced to 0; otherwise, the groundwater suitability index is equal to the groundwater level index. Finally, all ecological model outputs in annual time series are converted into exceedance probabilities for use in the integrated model.

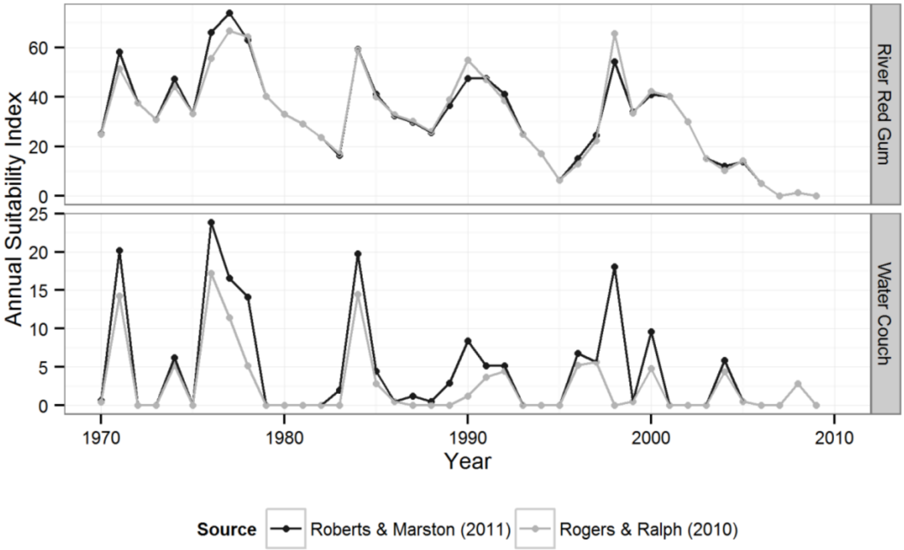


Fig. 5. Estimated annual water suitability index for river red gum and water couch over 1970-2010 at the river corridors between Mollee and Gunidgera (Asset 4), Namoi. Estimation was based on preference curves generated from Rogers and Ralph [34] and Roberts and Marston [35]. Note the overall declining trend for the river red gum, which reflects the decline in groundwater levels.

Preference curves are used to generate the surface water suitability index and groundwater level index. This approach was initially developed for the Murray Flow Assessment Tool [31] and then [32-33]. The key to this approach is to convert flood and groundwater attributes to suitability indices, based on data, literature and/or expert opinions. However, our knowledge of riverine ecosystems is imperfect, which contributes to the uncertainty in the generation of preference curves. Fu and Merritt [31] found that this uncertainty can have impacts on the estimated ecological outcomes. The level of impact varies depending on species and water regime. For example, water requirements of water couch are much less studied than river red gum, which is reflected in the lesser level of consistency in the preference curves and model outcomes (Fig. 5). In terms of water regime, the requirement for flood timing is most uncertain for most species and contributes to the variation in model outcomes. The implications of ecological uncertainty for the modelling will be further assessed through the comparison of model outcomes for different climate and policy scenarios. The integrated model will allow comparison of the impacts of hydrological uncertainties and ecological uncertainties on the same scales. Such analyses will provide valuable insights into the relative significance of ecological knowledge uncertainty in the integrated hydro-ecological model.

Farm Decision (economic) Model

The farm decision model builds on the approach previously developed by Letcher et al. [34] This model uses a multiple-period linear programming approach to capture farmer decisions relating to crop choice, area planted and irrigation water use. Farming system information, gross margin values and crop rotations options have been obtained through interviews with cotton growers, irrigation extension agents and irrigation engineers. Carryover rules and allocations in each of the three water systems (groundwater, and regulated and unregulated surface water) as well as the potential to carry water over in on-farm storages are also accounted for. Long term decisions, such as those relating to decisions to invest in changes in irrigation technology, develop water storages or to permanently sell water are simulated using the social Bn and input to the farm decision model. Representative farms of 940 ha, 4 000 ha and 11 000 ha with differing access to groundwater, regulated and unregulated surface water are used to represent the diversity of farmers in the case study areas.

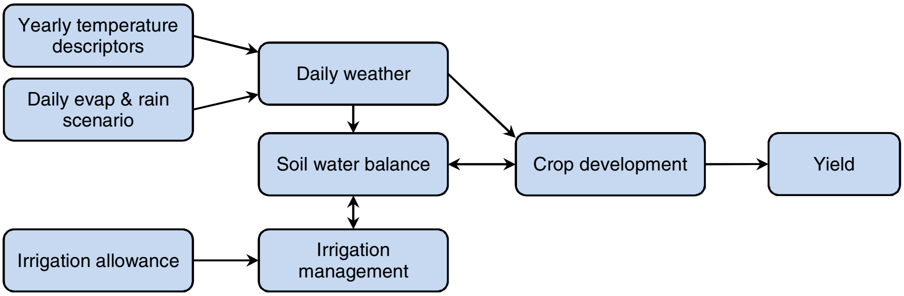


Fig. 6. Conceptual structure of the crop model

Crop Metamodel

A simplified crop metamodel is used to simulate the effects of applied water on crop yield for various commonly used crops in the region (Fig. 6). Cotton, wheat, chickpea and vetch components are used, based on simplified versions of industry standard models used in the APSIM package described by McCown *et al.* [35].

The metamodel is a collection of modules that rusn components of the model on a daily basis. The model inputs are yearly temperature descriptors, daily evaporation and rainfall, and seasonal irrigation water allowance.

The metamodel contains a soil water balance module based on CERES-maize, developed by Jones and Kiniry [36] that provides water input for the simulated crops. The module maintains a daily water balance using irrigation, weather and crop growth feedback as inputs. Water balance is outputted for crop development as a soil moisture index for a single depth layer that is defined for each crop.

The irrigation module provides input to the water balance module by supplying water from a yearly allocation pool. Timing and amount of irrigation is automated based on feedback from the water balance module to maintain a soil moisture index above a desired threshold during crop cycles.

The model takes daily evaporation and rainfall data from historic or generated climate scenarios as inputs. Temperature descriptors of average yearly and daily temperature amplitude and average yearly maximum temperature are input to generate daily temperature patterns to correlate with the evaporation and rainfall data. The daily weather and soil balance modules provide input to the crop development module to simulate daily crop development and generate yield estimates for each season.

To fit within the wide scope of the analysis, agronomic decisions are limited to seasonal irrigation quantities. Daily tasks such as sowing, irrigating and harvesting are automated by the metamodel using heuristics utilised by the crop models that it is based on.

4.2 Running the Model

The model can be used to explore the impact of landholder activities, climate and policy scenarios. Landholder scenarios include the maximum change in hydrological and ecological condition if all landholders were to adopt particular water efficiency practices. This information could be used to inform hydrological targets for the region.

The climate scenarios are predetermined predictions based upon the CSIRO predictions for the year 2030 [37]. The likely change in landholder actions and economic situation, and consequent hydrologic and ecological condition are predicted following changes in the climate.

The model can explore a number of governance and policy issues that pertain to the achievement of water extraction limits. These include existing experiences such as collaborative governance, participatory democracy, adaptive management, compliance and enforcement, Sustainable Diversion Limits, Water sharing rules, cease to pump rules, and trading rules as well as potential future/alternative policy approaches, such as self-management and co-regulation. More specifically, three scenarios that the integrated model will be used to test relate to the economic loss incurred as a result of reductions in access entitlements. Two of the scenarios model the loss incurred as a result of government actions, with the third relating to loss incurred from the actions of private water users.

These scenarios calculate the economic loss arising from:

i. climate change induced reductions in water availability leading to reductions in access entitlements;
ii. investments in water use efficiency when facing reductions in entitlements because of over-allocation; and
iii. the cost of water theft, where some licensees have their water access reduced as a result of other users taking water in breach of their licence entitlements.

The primary output of the integrated model is an integrated trade-off matrix for a selected set of scenario options, presented through reports, workshops and other presentations (e.g. Fig. 7). The matrix comprises the likelihood of the adoption of various practices under each scenario, as well as the impacts simulated from each of the integrated model components, which are:

- Natural flow and groundwater level
- Farm profit
- Post extraction flow and groundwater level, and
- Ecological impacts.

The model outputs for each of these are not necessarily numerical. They could also be presented as graphs, pictures, or a qualitative measure of impact compared to a baseline, or base case condition. It is likely that the trade-off matrix will rely on summary indicators from each of the components to explore the multi-disciplinary trade-offs associated with scenario options.

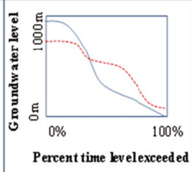
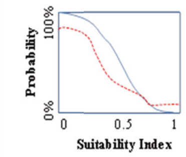
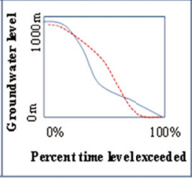
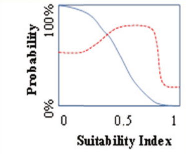
Scenario	Short-term profit (Base case)	Capital costs (Base case)	Government subsidies (Base case)	Groundwater impacts (Full line= Base case Dashed line = Scenario)	Ecological impacts (Full line = Base case Dashed line= Scenario)
1	(350,000) 300,000	(30,000) 25,000	(5,000) 20,000		
2	(350,000) 400,000	(30,000) 35,000	(5,000) 10,000		

Fig. 7. Prototype of example model output showing trade-offs of various outputs

The model outputs from the specific scenarios discussed above will be utilised by the legal team to conceive a viable framework for introducing compensation measures in circumstances when entitlement reductions occur consequential to factors outside a licensee's control.

4.3 Testing Model Uncertainty

It is assumed that decision makers will naturally draw conclusions from the trade-off matrix and model outputs. However, model development involves a number of assumptions and modelling decisions about how uncertain data and knowledge are used, including the choice of parameters and model structures. An investigation will involve working with experts on each model component to identify alternate assumptions and decisions that would also be considered plausible. It will then search for a set of these decisions for which the conclusions drawn by decision makers would be shown to be wrong. This provides an audit of the model. If it fails, sensitivity analysis will help prioritise future improvements to ensure decision makers can draw robust conclusions.

5 Discussion

The novelty of the integrated model described here is its holistic capture of the issues in managing groundwater from five different disciplinary perspectives (i.e. ecology, hydrology, economics, governance and social). Importantly, the model has been developed by integrationists working with research scientists from each of these disciplines, all working concurrently in researching and collecting data to support the development and running of the integrated model. It is envisaged that, although results from scenario runs and the uncertainty testing are not yet available for publication, the outcomes from the scenario results will provide insight and a discussion focus for the local policy staff, government water managers and irrigators.

One trade-off in developing such an inclusive integrated model with a group of research scientists is that it takes a significantly longer period to consolidate the model and its components than if it had been developed in isolation by the integration team. However the additional benefits gained from being able to integrate the collective expertise of such a diverse team are substantial.

Another trade-off is that the model itself is quite complex and is not suitable to be distributed as a decision support tool without intensive training. Consequently scenarios of interest will be identified by the steering committee of the project, and the results of these will be analysed and then delivered in a facilitated workshop in the Namoi catchment during 2013.

Previous work with FARMSCAPE [38] suggests that, despite having spent a large amount of time (several years) running and testing models for local conditions, the end-users still benefit more from running, analysing and discussing the model results with the local researchers and advisors. Our experience also suggests that significant value can be gained in the discussion around the model development and analysis of the results, as opposed to focussing just on the direct model output.

6 Conclusions

This paper describes the development of an integrated model for use in the management of groundwater-surface water systems that are particularly under pressure due to past over-allocation and potential climate change. The model provides the opportunity to explore the socioeconomic, hydrologic and ecological trade-offs of various policy, adaptation and climate scenarios. The model is implemented for the Namoi catchment, but its components can be transferred to other agricultural catchments.

The model developed is the result of a collaborative research project by a team of disciplinary research scientists from ecological, economic, social, hydrological, governance and integrated modelling backgrounds. The team has been working together, with the project steering committee of local catchment water managers, irrigators and advisors since the outset of the project, to generate and share knowledge, research new ideas and collect data to inform the integrated model.

As a consequence of developing such an inclusive model, with such a large team, a considerable amount of time has been spent in the model development phase. Unsurprisingly, the resultant model is quite complex despite its identified components being kept as effectively simple as possible. The model scenario results will be presented as part of a facilitated workshop with the local water managers and irrigators throughout 2013. It is hoped that the findings from such an inclusive integrated model will be well-received by the local water managers as a tool to assist in unravelling the complexities and clarifying their options in groundwater and surface water management.

If identified as advantageous, further work may be completed to develop and modify a meta-model of the integrated model, to be used as a decision support tool at the farm scale. As with any wicked problem there will be no stopping point, the work contributing more to on-going problem resolution rather than the specification of black and white solutions. In this connection the model can be updated as new issues and information become available in order to shed light on appropriate tradeoffs.

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