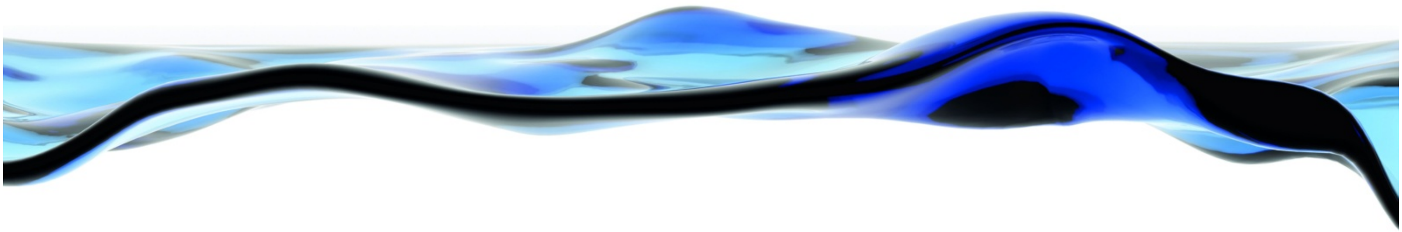
Development of Decision Support Frameworks for Water Resource Management in the South East



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Executive Summary

This report forms part of the Goyder Institute for Water Research priority project to support the sustainable management of water in the South East (SE) of South Australia. Specifically, the outcomes from the first milestone of the decision support task are presented. The objective for this milestone is to scope the structure of a decision support framework, relevant to assist decision making in the SE - for both operational and policy decisions, with the flexibility to incorporate new data and models as they become available, and the uncertainty inherent in such information.

There are two main water resource management questions in the SE. The first, mainly focused in the Lower SE, is the sustainable long term management of the groundwater resources, used for agriculture, industry, town water supply, stock and domestic use as well as supporting a significant proportion of the ecosystems and streamflow in the region. How to balance these consumptive uses, along with ensuring enough water remains to sustain the environment, is a difficult and ongoing question. The second water resource management question in the SE is mainly focused in the Upper SE, where there is an extensive drainage network that can be used to divert water across the landscape. The volume of water available of suitable quality is often not sufficient to support all of the (mostly) environmental demands for this water, and as such decisions must be made as to which assets will have water diverted toward them each year.

The purpose of this report is to outline a number of decision support frameworks to assist the planning process in sustainably allocating the water resources in the SE in the context of the competing objectives of preserving environmental assets, economic development and social values. To begin with, the requirements and objectives for a system to assist with water management in the SE were reviewed, including the relevant policy and legislation instruments and intentions to determine what can or should be achieved through such a system. Recommendations from previous studies for systems to assist with water planning in the SE were also reviewed.

In order to consider water management scenarios that are not represented in the historic data record, or to fill in gaps in available data, models of each component of the water resource (groundwater, surface water, and the interaction between the two), and the different demands on the resource (including environmental, agricultural and industrial), are required. An extensive review of currently available models for the south east has been undertaken. Given the range of specific questions models have been developed to support, and the general uncoordinated approaches across these different modelling projects, no models were identified that are currently in a format to be directly applicable in the context of an integrated Decision Support System (DSS). A number of valuable studies have been undertaken to provide a foundation for future studies that are required to develop models that are fit for this purpose.

A review of recent literature on the definition, characteristics and best practices for the development of DSSs for policy support was then undertaken. These studies generally consider DSSs that represent software that is based around integrating (the results from) a number of models, and allowing for the feedbacks between them, to assess long term policy options. This approach is generally necessary for these types of questions, as 1) models are required to simulate untested possible future scenarios (as opposed to interrogating past datasets) and 2) it is unlikely that one model can represent all salient factors that are of interest for a region. Based on international experiences in developing and assessing the uptake of DSSs over the past one to two decades, a

number of best practice guidelines and methods have been identified. These have been based on experiences in what has and has not worked to 1) produce a DSS relevant to the policy questions posed, and 2) maximise the likelihood that the system produced is actually adopted by the authorities responsible for decision making in the region considered. A number of DSSs that have been developed to answer water resource management questions in Australia and internationally were also reviewed, to inform the development of a similar system for water management in the SE.

The best practice methodology identified in the literature review was implemented to design decision support frameworks for the two main water resource management questions, the short term drain management, and long term groundwater resource management. These frameworks identify models that are required to provide a whole of catchment approach to water management and enable transparent assessment of management scenarios against the competing criteria and demands for the water resource. These frameworks provide guidance on where future projects should be focused to ensure that the outputs are applicable to the overarching questions of sustainable water management in the SE. A number of software packages were identified that are likely to be suitable to implement the frameworks designed, each with very different objectives and requirements. It is recommended that a suitable DSS software package is re-evaluated once the necessary underlying models are developed, to ensure the framework can accommodate these models and their interactions.

Acknowledgements

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- Hedwig van Delden, Research Institute for Knowledge Systems and University of Adelaide
- Carmel Pollino, CSIRO
- Qifeng Ye, SARDI
- Jason Nicol, SARDI
- Glenn Harrington, CSIRO
- Megan Lewis, University of Adelaide

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1 Introduction

The water resources of the South East (SE) region are important for South Australia as a whole. They support primary industries including wine, wool, meat, dairy, forestry and timber, fishing and aquaculture, vegetables and seed production. Given the absence of reliable surface water in the region, groundwater is the dominant source of water for agriculture and industry. Furthermore, groundwater is the primary water source for town supply, stock and domestic use in the SE (Brookes 2010).

Along with significant agricultural development, the SE region contains a number of high value ecosystems and wetlands, including Ramsar listed wetlands of the Coorong and Bool Lagoon. Wetlands originally covered much of the SE, but as a result of drainage in particular, the extent of wetlands has declined to 6% of their original area, and of these, only 10% are regarded as being intact (Harding 2007, 2009). The majority of wetlands (77% of wetlands and 96% of wetland area) in the region are highly likely to be dependent on groundwater (SKM 2009).

The quality and quantity of both streamflow and recharge to groundwater are the result of a complex interaction between rainfall, climate, soils, geology and land cover. All these factors must be considered to assess possible effects of changes in water affecting activities. It is also important that social, environmental and economic implications are considered so that impacts, if any, on other water resource users can be weighed against the socio-economic benefits (Dillon et al. 2001, Keenan et al. 2004, Benyon et al. 2007, Daniell 2010). While there have been extensive studies in the SE on different aspects of the water resources, the balancing of these competing objectives is a difficult and open question. All decision-making regarding individual water resource development proposals must be placed in a total catchment context, and take consideration of existing levels of development, existing aquatic environment assets and the water requirements of those assets (Harding 2009).

There are two main water resource management questions in the SE. The first, mainly focused in the Lower SE, is the sustainable long term management of the groundwater resources, used for agriculture, industry, town water supply, stock and domestic use as well as supporting a significant proportion of the ecosystems and streamflow in the region. How to balance these consumptive uses, along with ensuring enough water remains to sustain the environment, is a difficult and ongoing question. The second water resource management question in the SE is mainly focused in the Upper SE, where there is an extensive drainage network that can be used to divert water across the landscape. The volume of water available of suitable quality is generally not sufficient to support all of the (mostly) environmental demands for this water, and as such decisions must be made as to which assets will have water diverted toward them each year. Again, this is a difficult balancing act, to minimise the likelihood of degradation of the remnant ecosystems over the long term. A map of the region, including a delineation between the Upper and Lower SE is provided in Figure 1.

A number of decision support systems are already in use in the SE, including the Water Dependent Ecosystem Risk Assessment Tool (WaterRAT), and the Flows Management Decision Support System for the drainage network. These two tools provide a substantial basis for the development of a system to assist assessment and water allocation planning decisions and drainage network operational decisions. Both systems would benefit from incorporating model outputs to assist "if-then" analysis of scenarios, as well as integration of data analysis techniques to make maximum use of the existing data on the water resources available.

This work forms part of the Goyder Institute priority project for sustainable management of water in the South East. The purpose of this report is to outline a number of frameworks to assist the planning process in sustainably allocating the water resources in the SE in the context of the competing objectives of preserving environmental assets, economic development and social values. This project will provide a (a) conceptual model of how the hydrology, water use, land use and ecology interact, based on recent research undertaken in this region and (b) use best practice decision science to demonstrate how a knowledge management system can be used to inform policy development. A key requirement for adaptive management of water resources in the SE is an ability to predict the implications of water policy on the ecosystems in this region of high biodiversity. For this requirement to be met, a framework for organising and storing knowledge on the ecological responses to water regime and water quality is required (Harding 2009).

The following section outlines the policy objectives that drive the requirement for a Decision Support System (DSS) in the SE. This is followed by a review of existing modelling studies that may be of use to be integrated into a decision making platform. A review of current DSS literature and best practices for developing such systems is then provided, before the methods identified are applied to scope Decision Support Frameworks for the SE.

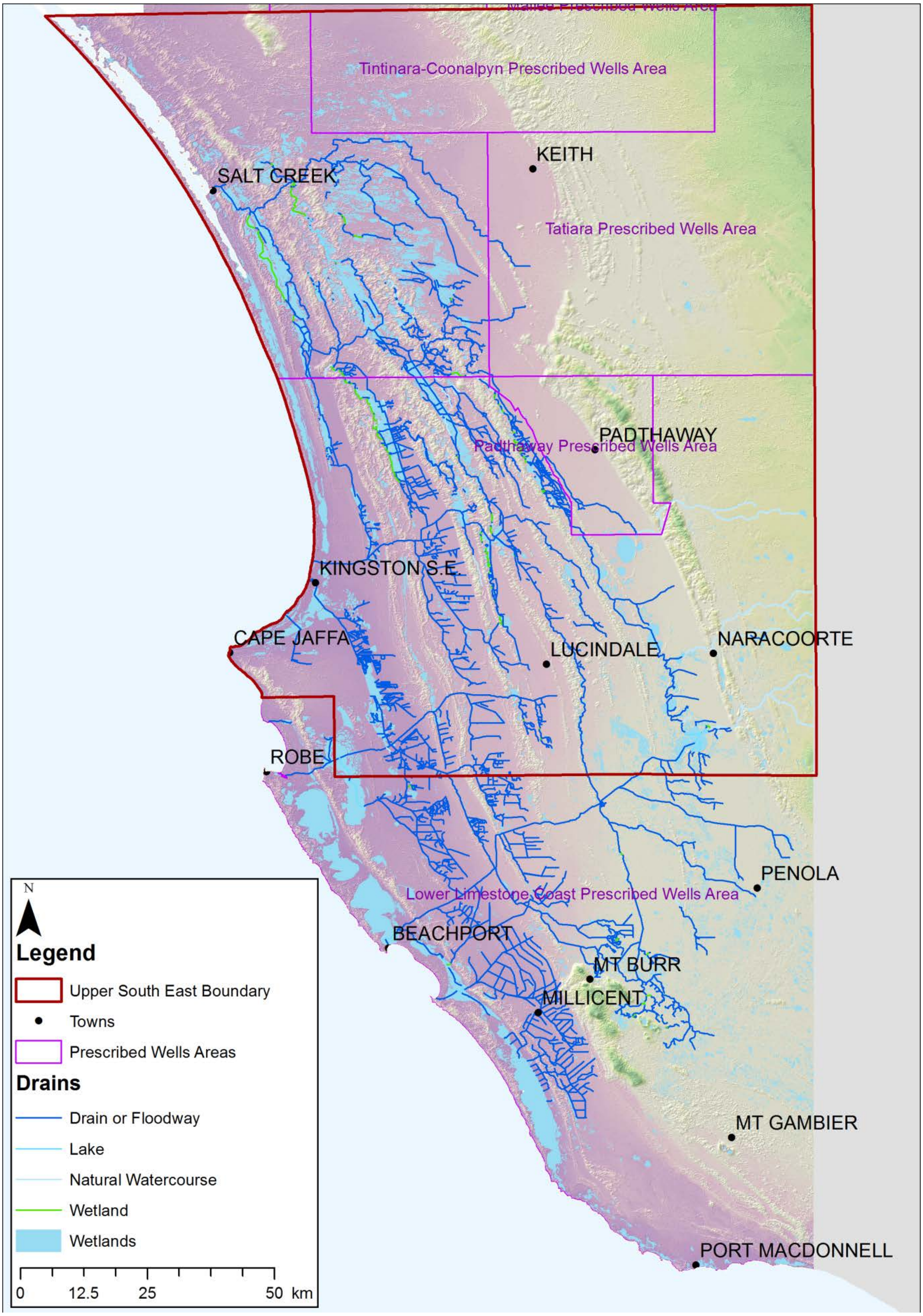

Figure 1 Map of the South East region of South Australia, showing the location and function of the drains in the region, Upper South East boundary, and the prescribed groundwater well areas.

2 Requirements of Decision Support Systems

The requirements and objectives for a DSS to assist with water management in the South East are reviewed in this section. The relevant policy and legislation instruments and intentions are outlined to guide what can or should be achieved through such a system. Recommendations from previous studies for systems to assist with water planning are reported in this section.

2.1 Policy Directions

Harding (2009) provides a valuable overview of the key policies, plans and legislation instruments that statutory authorities are required to work within in the context of natural and water resource management. Further details are provided in Appendix A, adopted from Harding (2009). The State Natural Resource Management (NRM) Plan (2006) states “Natural resources management will be most effective when using an ecosystem approach that recognises and integrates all the components and processes of ecosystems and their use; and manages these at the appropriate temporal and spatial scales” and “The use of our natural resources in response to social and economic pressures must work within ecologically sustainable limits to maintain their life supporting capacity”. The State Water Plan (SA) 2000 states that “Water allocations and management decisions must take a precautionary approach by first ensuring environmental benefit outcomes, including natural ecological processes and biodiversity of water dependent ecosystems, are maintained”. It follows that further allocation of water for new consumptive uses, and any other new water resource developments, must ensure ecological values are protected (Harding 2009). The Plan requires that there be recognition of wetland values and their management and protection in all relevant statutory and non-statutory planning processes.

Objectives stated in the SA NRM Act (2004) include that decision-making processes should be guided by the need to evaluate carefully the risks of any situation or proposal that may adversely affect the environment and to avoid wherever practicable causing any serious or irreversible damage to the environment. Hence, decision-making processes should effectively integrate both long-term and short-term economic, environmental, social and equity considerations.

A goal stated in the State NRM Plan (2006) is to ensure planning policy addresses the importance and value of Water Dependent Ecosystems, particularly watercourses, floodplains and wetlands, and prevents development that would impact upon ecosystem function or habitat value, while the South East Catchment Water Management Plan (2003-2008) has a goal to identify, protect and enhance ecosystems and their associated biodiversity that depend on water.

Water Allocation Plans in the SE for Prescribed Groundwater Resources should include:

- An assessment of the quantity and quality of water needed by the ecosystems that depend on the water resource and the times at which, or the periods during which, those ecosystems will need that water;
- An assessment as to whether the taking or use of water from the resource will have a detrimental effect on the quantity and quality of water that is available from any other water resource; and

- Provide for the allocation and use of water so that an equitable balance is achieved between environmental, social and economic needs for the water.

The SE Water strategy is a Ministerial approved strategy that develops a broad vision and coordinated policy approach for the long term management of water resources of the South East ensuring optimisation of environmental, social and economic benefit within a climate change context. The Lower Limestone Coast Water allocation plan discussion paper (2012) states that sound policy development should be evidence-based and underpinned by a commitment to adaptive management, and that any changes in allocations should be in response to an assessment of the risk to a resource, and be implemented in a way that adaptively manages the risk while achieving a specified outcome. This Policy Position paper also states that surface water and groundwater are intrinsically linked and should be managed in an integrated fashion. It was stated as one of the objectives of the South East Water Science Review that it should consider the most appropriate mechanisms in accordance with National Water Initiative (NWI) requirements for managing the sustainable use of linked water resources (surface and groundwater), based on the concepts of appropriateness, efficiency and equity.

In summary, these policy objectives highlight a number of requirements of a decision support system to assist in the implementation of each policy. Important factors include:

- A risk based approach to water planning.
    - A risk framework is required.
- Decision-making processes should effectively integrate both long-term and short-term economic, environmental, social and equity considerations, and an equitable balance should be achieved.
    - The system should be capable of both short and long term assessments.
    - Each of the competing needs should be represented: economic, environmental, social and equity.
    - Each of these needs should be able to be balanced, for example using optimisation.
- Development should be prevented that would impact upon ecosystem function or habitat value.
    - The current state of the ecosystem should be known, as well as the water requirements, and the expected impacts that might occur due to a failure to meet these water requirements.
- Adaptive management is a key process in the decision making process.
    - The system should adapt to the current state of the resource, learn from the outcomes from previous actions, and not be proscriptive.
- Surface water and groundwater resources are linked and should be managed using an integrated approach.
    - Each resource cannot be considered separately and interactions between resources should be well-understood.

2.2 Recommendations from Previous Studies

Sustainable allocation of the water resources in the South East is not a new problem, and there have been many studies that have made suggestions on how to approach, and improve the approach, to the problem. For the Lower South East Water Balance Project, Harrington et al. (2011) consulted with the Policy Division of the Department for Water and the South East Natural Resources Management Board to identify the main issues facing water planning. Based on the consultations undertaken, the following issues were identified:

- Validation of resource condition triggers, for example rates of decline of groundwater levels, or rates of increase in salinity.
- The risk of double accounting of surface water and groundwater and unconfined and confined groundwater.
- Accurately accounting for forestry impacts.
- Quantifying available water and identifying location of available water.
- Quantifying groundwater inflows from Victoria and outflows at the coast.
- Water balances for current individual management areas and also for possible hydrogeology-based management areas.
- Appropriateness of management area boundaries with respect to hydrogeological boundaries and how future unconfined and confined aquifers and surface water management area boundaries could line up.
- Identification of areas of high recharge or interaction between the confined and unconfined aquifers, possibly to assist with revising management area boundaries.
- Validating estimates of recharge under different land uses and different soil types and methods used to scale up these estimates.
- Having a regional tool that can be used to assess issues in non-hotspot areas in the future.
- Future management of sub-units of the confined and unconfined aquifers.

Paydar et al. (2009) also summarised key NRM issues in the region as follows:

- Salinity increase due to land clearing in the upper South East (resulting in rising groundwater levels) and irrigation recycling in some irrigation developments.
- Unsustainable groundwater extraction and use in some areas and new developments, including land use change. Uncontrolled developments of land use systems that reduce recharge and affect the availability of groundwater in the region (e.g. expansion of plantation forestry).

- The impact of climate on existing and new developments with prediction of an annual decline in rainfall and hence decline in recharge and uncertainty in available water resources.
- Irrigation practice and irrigation efficiency as the key areas for improvements in water resource management of the region.
- Environmental impact of water management - groundwater dependent ecosystems, wetland vegetation health, and biodiversity (e.g. on-going drainage which reduces wetland habitat and changes the quantity, duration and frequency of flows; blockages caused by weed infestation).
- Groundwater contamination - from point sources (e.g. wastewater disposal to sinkholes and drainage bores) and diffuse sources (e.g. nitrate and pesticides from agricultural areas).

Similarly, as part of the Padthaway Prescribed Wells Water Allocation Plan (SENRMB 2009), the current knowledge gaps with respect to the needs of water dependent ecosystems were outlined. A number of the gaps identified are not specific to the definition of water requirements of ecosystems, but they will affect water availability for all users of the results. The knowledge gaps identified included (SENRMB 2009):

1. Intrinsic knowledge of underground water/surface water interaction and dependency of water dependent ecosystems, including:
    a) water level and quality thresholds; and
    b) long term implications of climate change.
2. A regional integrated approach for the collection and interpretation of monitoring data, including:
    a) defining roles and responsibilities; and
    b) establishing reporting mechanisms.
3. Definition of the threatening processes, the risks they pose and the consequences of not addressing them, including:
    a) development of shallow and deep drains; and
    b) land use change (including cross-border issues).
4. Intrinsic knowledge of cause and effect relationships and the development of effective management tools to address the following issues:
    a) declining underground water discharge due to interception of recharge in inland areas by high water use crops and timber plantations; and
    b) declining underground water discharge due to lowering of the water table as a result of climatic trends.
5. Contamination of the aquifer, particularly with nitrates.

Clearly, a set of key questions in the management of the water resources at the management zone scale are to identify: 1) the capacity of the resource in each zone 2) the environmental water requirements and user requirements and 3) what is the consumptive pool, i.e. how much (if any) of the resource is still available to be allocated. Provided the required input information is available, these questions could potentially be answered using a spatially distributed water balance, calculated at regular intervals (possibly annually). While a number of attempts have been made to quantify the water balance of the whole region (Paydar et al. 2009, Smerdon 2009, Wood 2010, Harrington et al. 2011), they all recommend consideration of spatial variability in the water balance, as well as the development of a fully dynamic model of the surface and groundwater system in the South East. Smerdon (2009) stated that “while there has been a preliminary attempt to develop a steady-state water balance of annual water budget components for the entire Lower Limestone Coast, this approach lacked (representation of) the complete groundwater basin, which extends to recharge regions in Victoria, and the spatial and temporal distribution of key processes. A truly integrated water budget would not just consider the entire groundwater flow system as single unit, but rather the spatial distribution of land cover properties, soils, and geology”.

The challenge for the region is to develop an integrated water management regime at the system level that allows a balanced use of water resources taking into account the needs of all groundwater users within sustainable limits. While the irrigation industry and plantation forestry sector will continue to prosper from the water resources (Paydar et al. 2009), the management regime must consider the needs of the environment and groundwater dependent ecosystem for the sustainable management of regional water resources (Paydar et al. 2009). This integrated water budget, accounting for the spatial as well as temporal variability across the region, is necessary to assist management of the water resource at the scale of interest, typically the management zone scale.

Daniell (2010) and Smerdon (2009) suggested a systems based approach is necessary to adequately address the competing needs of water resources uses in the South East. A model that can be used to assess the sustainability of a system or of sustainable system development (Foley et al. 2003) is shown in Figure 2, outlining the flow of resources within a system. The model identifies infrastructure and other human-made resources (I) as a key element of sustainability. Infrastructure for urban development includes buildings, and the water supply system, as well as systems for waste, transport and energy. Such a systems approach provides a good platform for assessing development and sustainability, where infrastructure and resource flow are principal considerations (Daniell 2010). Each subsystem within the larger development system can be modelled. The flow of resources such as water, energy and finance to and from the system can also be included in a more holistic way than in many other currently available tools (Dandy et al. 2007). More specifically to the South East, the conceptual flowpath water budget suggested by Smerdon (2009) can be seen in Figure 3, where each component of the water balance could be quantified at the management zone scale, to identify zones that are over extracted, or zones that have available water resources.

Smerdon (2009) identified that there is uncertainty when utilising scientific findings to define resource management and policy. Currently, scientific assessments of hydrogeologic processes typically focus on point-scale measurement, and then undergo an upscaling procedure for application at a scale more practical for resource management. Considering that there are currently large uncertainties about the different components of the water budget and environmental water requirements, a precautionary approach should be used until the uncertainty can be adequately addressed or reduced (Smerdon 2009). A precautionary approach is where the onus of proof is on ensuring that no harm will be caused by use of a water resource, as opposed to requiring proof that negative effects are likely to occur if that use was to proceed.

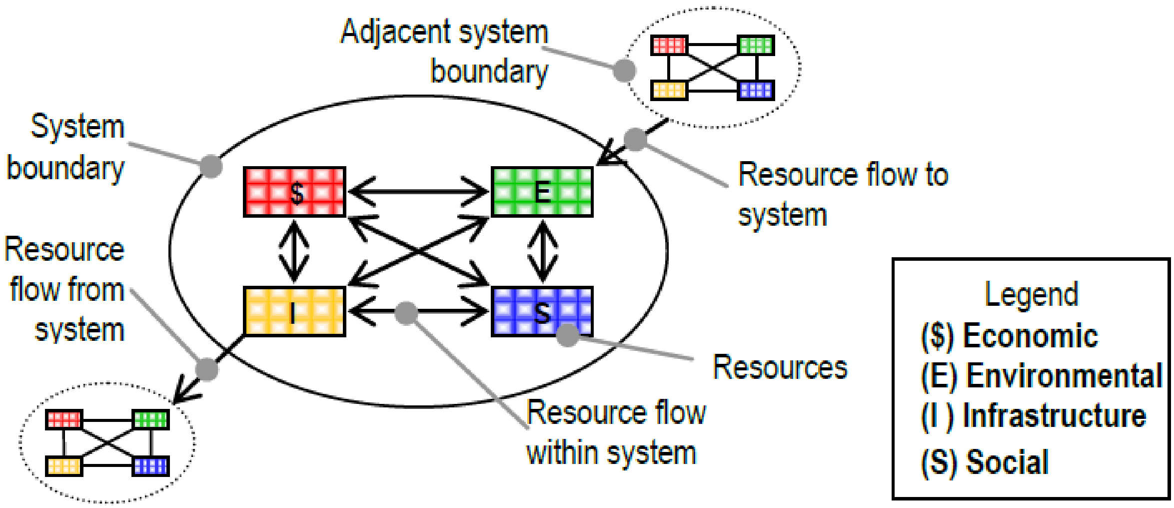

Figure 2 Systems Approach Representation (Daniell (2010) adapted from Foley et al. (2003))

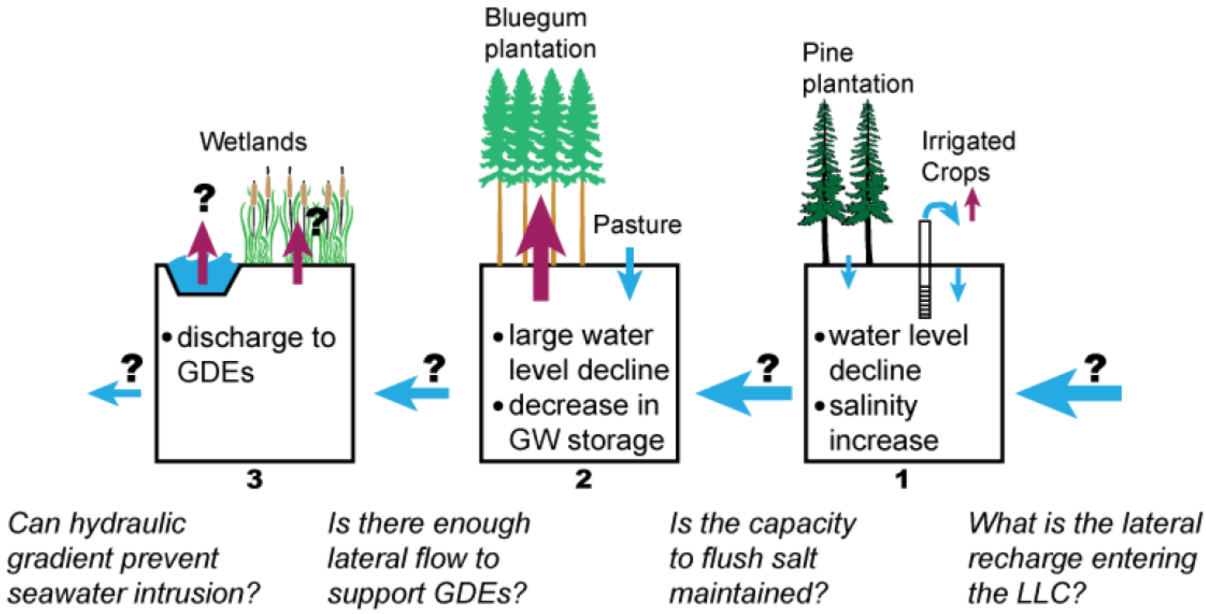

Figure 3 Conceptualised water budget components for areas and Groundwater Dependent Ecosystems (GDEs) in the Lower Limestone Coast (LLC) (Smerdon 2009)

2.3 Summary

Water resource planning requires the integration of many complex physical processes, as well as the interaction of many stakeholders, to ensure the sustainable use of surface and groundwater resources. This planning is intrinsically multidisciplinary, including hydrologic, hydrogeologic, ecological, economic, agricultural and social disciplines. Due to this wide range of information involved, and that this information is always changing, it is extremely difficult to identify equitable, sustainable outcomes. Decision support systems can be of use to document and consolidate the vast range of information required, into a system that can be used to assist with quantifying the available water resource, and identifying interactions, tradeoffs and balances between the competing demands, to ensure sustainable use of the water resource while maintaining economic growth in the region.

There are two main water resource management questions in the SE. The first, mainly focused in the Lower SE, is the sustainable long term management of the groundwater resources, used for agriculture, industry, town water supply, stock and domestic use as well as supporting a significant proportion of the ecosystems and streamflow in the region. How to balance these consumptive uses, along with ensuring enough water remains to sustain the environment, is a difficult and ongoing question. The second water resource management question in the SE is mainly focused in the Upper SE, where there is an extensive drainage network that can be used to divert water across the landscape. The volume of water available of suitable quality is generally not sufficient to support all of the (mostly) environmental demands for this water, and as such decisions must be made as to which assets will have water diverted toward them each year. Again, this is a difficult balancing act, to minimise the likelihood of degradation of the remnant ecosystems over the long term.

In this section the policy objectives for water management in South Australia have been reviewed, as well as the current recommendations for implementing these objectives. It is proposed that to assist with the complex, multidisciplinary questions involved in water management, decision support systems can be useful tools to assist with identifying optimal trade-off positions. In order to do this, water availability must be quantified (comprised of the groundwater, surface water and the interaction between the two) as well as quality of these water sources. Then, it is desirable to evaluate the impact of any development to changes in this availability on the ecological and hydro-ecological function of the environment, as well as any social and economic implications. It is clear from previous studies that a temporally and spatially explicit representation of these different factors, integrated into a systems planning framework, is necessary to adequately assist in the planning process.

In order to consider scenarios that are not represented in the historic record, or to fill in gaps in available data, models of these components of the water resource, and the different demands on the resource, are required. In the following section previous studies are reviewed to identify models that are currently available to support decision making. If suitable models for a certain discipline are not identified, the current state of existing models, and how they could be improved to be suitable for this purpose, is outlined.

3 Review of Existing Modelling and DSS Studies in the South East

This section outlines a number of the modelling studies that have been undertaken in the South East, with the objective of identifying existing models that may be useful to assist management and planning through an integrated modelling based DSS, along with purpose built models to address any gaps. This section does not consider the many field based or data review studies that have produced valuable insights into the understanding and processes occurring in the region, but do not provide the ability to simulate scenarios of interest. The section is broken into the different disciplines of interest for the region.

3.1 Groundwater

Groundwater is the main water resource used in the South East, and the majority of groundwater extraction for irrigation, stock and domestic use in the region is from the unconfined tertiary limestone aquifer (TLA). The total annual extractions for these purposes was estimated to be 434 GL/year (Wood 2010). Hence, it is the TLA that is the major consideration for decision making in the South East.

3.1.1 Existing Modelling

Harrington et al. (2011) provided an up-to-date and comprehensive review of the current state of knowledge and modelling of the groundwater resource in the Lower South East. The report:

1) outlined the policy issues, policy context and framework into which a (ground)water balance model should provide input,
2) reviewed the available data and knowledge of the hydrologic system in the Lower South East, and
3) considered modelling approaches to address the management needs of the region.

Four existing groundwater models are outlined as available by Harrington et al. (2011). All models were developed using the MODFLOW code, however different interfaces have been implemented (e.g. GWVistas or Visual MODFLOW). The extent of each model can be seen in Figure 4, and further details can be found in Harrington et al. (2011) and the reports cited therein. A brief outline of each model is provided below:

- Wattle Range Model is a flow model of the management areas of Coles and Short, developed to assess forestry impacts in the region. The model was originally developed as a model of the Bakers Range by the Department for Water (then DWLBC) and extended as part of the South East Water Science Review (Aquaterra 2010b).
- Coonawarra Model represents the border zones 3A and 3B, including parts of zones 2A, 2B, 4A and 4B. The model was developed to model groundwater flows in the unconfined aquifer, assess forestry impacts, consider land-use planning, and ultimately assess nitrate pathways. However, the initial model produced poor calibration statistics.
- Border Zone 1A Model was also developed to simulate nitrate transport in the region south of Mt Gambier for impact assessment to assist with water allocation planning. However, the model did not adequately simulate transient groundwater level trends, possibly due to a number of factors, including complex and poorly understood geology, errors or oversimplification of the conceptual model, or misrepresentation of the impacts of recharge and groundwater extraction in annual time steps (Harrington et al. 2011).

- South of Mt Gambier Model was developed to assess the potential use of the groundwater resources from the unconfined aquifer in the area south of Mount Gambier, to provide technical input for the water allocation plans being developed for the Comaum – Caroline and Lacepede – Kongorong Prescribed Wells Areas (PWA) (Stadter & Yan 2000).

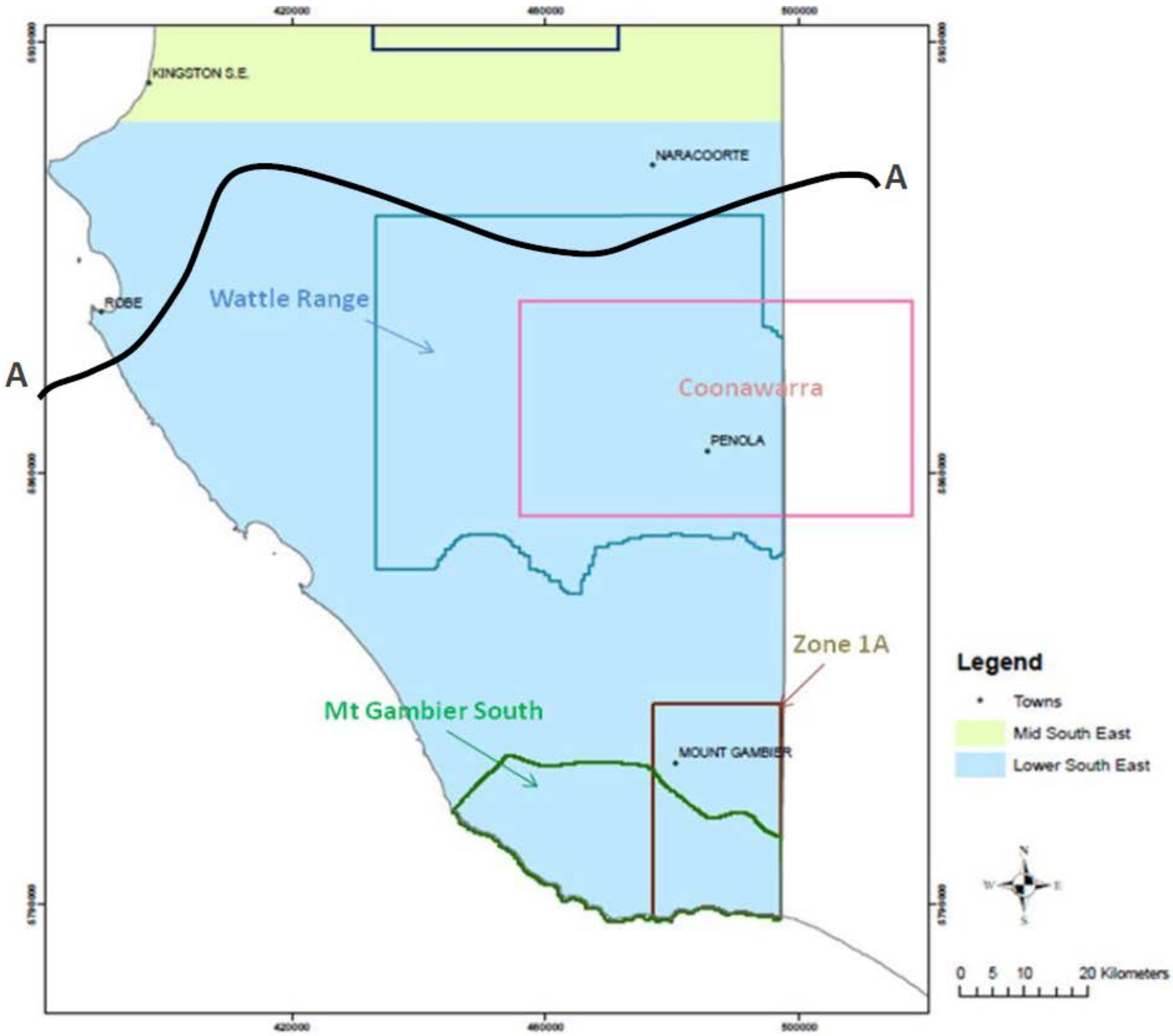

Figure 4 Model domains for existing LSE numerical groundwater flow models (Groundwater model warehouse, cited by Harrington et al., 2011)

Models rated as not available by Harrington et al. (2011) include a Tertiary Confined Sands Model and Compartmental Mixing Cell model. The Tertiary Confined Sands model represented the whole Lower South East region (Figure 4) and extended into the Upper South East and Victoria. The model was developed as a conceptual model of the region with the aim of assessing the impacts of extraction from the confined aquifer. Results indicated that the head contours, as well as seasonal and long term trends, of the confined aquifer were well represented. However the unconfined aquifer, where most of the extraction occurs in the Lower South East, was not modelled accurately (Harrington et al. 2011). Also, Harrington et al. (1999) constructed a compartment mixing cell model along a transect from Naracoorte to Robe, shown as Transect A-A in Figure 4. The model was developed to estimate aquifer properties, including recharge to the confined aquifer, via leakage from the unconfined aquifer. Leakage from the unconfined aquifer was estimated to be 2 – 9 mm/yr, with greater confidence than previous estimates.

Along with the Lower South East groundwater models summarised by Harrington et al. (2011), there are four models that have been developed in the Upper South East region. Again, further details can be found in the cited reports, and the models are summarised here:

- Tintinara – Coonalpyn Prescribed Wells Area (PWA) model was developed to assess the groundwater resource capacity of the area, completed in 2002 (Yan & Barnett 2002). The model was used to simulate groundwater level changes caused by historic and current demands for groundwater from the confined aquifer, and estimate impacts on groundwater levels due to the likely future demands from the confined aquifer.
- Tintinara Highlands model developed for the assessment of long term groundwater salinisation in the south east, to assist in formulating management strategies to minimise increases in salinity (Osei-bonsu et al. 2004). The model domain extended 200 km from North to South as well as 200 km East to West, from above Murray Bridge to below Bordertown.
- Padthaway PWA model was developed to assist with water allocation planning for the Padthaway area and completed in 2009. The model was based on comprehensive field based salt accessions studies, with investigations covering the local geology, soil cover, hydrogeology, hydrology and geochemistry, from 2002 to 2005. The model was developed to quantify groundwater flow and salinity fluxes in the Padthaway study area, and provide a tool for evaluating future management options for the groundwater resource in the Padthaway region, particularly relating to the impacts on groundwater salinity of changing land and water use (Aquaterra 2008). The model was updated to consider further abstraction scenarios by Wohling (2008).
- Tatiara PWA model, representing a section of the PWA located around Keith and Willalooka, was developed to assess the influence of proposed allocation cuts on groundwater level and performance against pilot Resource Condition Limits, for use in future Water Allocation Planning. The model was designed to act as a decision support tool for the Adaptive Management component of the Integrated Water Resource Management project, and assist in developing trial adaptive management scenarios. The groundwater model was used to run a number of scenarios to see how different extraction regimes would perform against the resource condition limits based on groundwater levels under various climate conditions (Wood 2011).

The models have been developed to fulfil a range of objectives, including: investigating the applicability of modelling methodologies, testing conceptual model of groundwater flow systems, assessing the capacity of the groundwater resource to meet demands, simulating the accession of salt in the soil profile, modelling pathways of diffuse source contaminants, assessing the impacts of plantation forestry, and determining permissible annual volumes of extraction and impacts of proposed management scenarios. These previous approaches to groundwater modelling have focused on specific issues and have not been coordinated in any way (Harrington et al. 2011). As a result, a number of models exist in various stages of development, with varied objectives and hence varied input data and underpinning conceptual models. The outputs of such models are not necessarily comparable or relevant for addressing the salient management questions in the South East (Harrington et al. 2011).

3.1.2 Future Directions

The existing groundwater models represent the current understanding of the groundwater system in the areas that they cover, and are a collation of all of the relevant information, providing a large knowledge base for a regional-scale model. The models developed for the smaller PWAs in the Upper South East (Tintinara – Coonalpyn, Tatiara and Padthaway) were developed, in part at least, for Water Allocation Planning purposes and are likely to provide valuable inputs to assist the decision making and planning process in the future. However, as with any model, they will require ongoing maintenance to reflect the current state of the region considered, and ensure that the assumptions made are still valid. The Lower South East has a number of challenges in supporting Water Allocation Planning, and as part of the consultation and review process undertaken for the Lower South East Water Balance Project (Harrington et al. 2011), the following general issues and needs for a future modelling strategy for the South East were highlighted:

- Three-dimensional numerical groundwater flow models are essential to underpin the management of groundwater resources in the Lower South East through testing of our understanding of the resource and simulation of outcomes of proposed management scenarios.
- A suite of numerical models is required, with consistent conceptual models and input data, designed to address at both regional and local scales specific management questions / issues important to the water allocation planning process. Such a suite should be able to identify emerging and likely risks through simulation of specific climate and management scenarios.
- There is a preference amongst a number of stakeholders to move towards a fully-coupled surface water – groundwater modelling approach. However, the specific objectives and the data / knowledge requirements, and hence feasibility (cost/benefit), of such an exercise have not been explored.

The level of detail required in a groundwater model for integration into a decision support system will depend on the questions asked and scale of interest. It is likely that at least a three-dimensional regional groundwater model is required to support water planning decisions in the Lower South East, as well as potentially local scale models if questions on specific drawdown rates and surface water – groundwater interactions are important.

3.2 Surface Water

Natural watercourses in the Lower South East are generally impeded by the low slope of the land surface and the transverse dune system, resulting in the occurrence of numerous swamps and wetlands, lakes and sinkholes in inter-dunal corridors. Since the 1860s, over 2000 km of drains have been constructed throughout the South East for a number of purposes, including to drain land and make it more agriculturally viable, mitigate flooding in high rainfall years, and manage dryland salinity (Harrington et al. 2011). The introduction of drainage to the South East, and subsequent changes in land use, is thought to have reduced the original extent of wetlands by 93% (Harding, 2009). In the Upper South East, Love et al. (1993) describe a system where flow in the unconfined aquifer is dominated by local recharge and discharge, rather than recharge in one end of the basin and lateral flow through the rest of the basin (Wood 2010).

3.2.1 Existing Modelling

The Department for Water Regional Flow Management Strategy project (Wood & Way 2010) was funded under the National Water Initiative (NWI) program under the NWI objective of integrating the management of water for environmental and other public benefit outcomes. As part of the project, the WaterCRESS platform (Cresswell 2002) was used to develop a series of lumped conceptual rainfall – runoff models (using AWBM, Boughton 2004) for a range of catchments in the Upper South East. The catchments modelled are shown in Figure 5, with the gauges used for calibration represented as the Hydstra sites. Average rainfall runoff factors were also derived for the South East Regional NRM Plan, where the runoff factors (percentage of rainfall that is observed as runoff) ranged from less than 0.5% for the north eastern catchments from Keith to Naracoorte, to almost 3% for Mosquito Creek flowing into Bool Lagoon, and 4% for the rest of the South East. Other outputs from the project included a 2m LiDAR derived digital elevation model which has been used for a number of purposes, including identifying catchment boundaries, drain and watercourse flow paths, and wetland depth – area – volume relationships. An initial assessment of wetland environmental water requirements was undertaken, as well as a regional assessment of the likely regions of surface water – groundwater connectivity (SKM 2009).

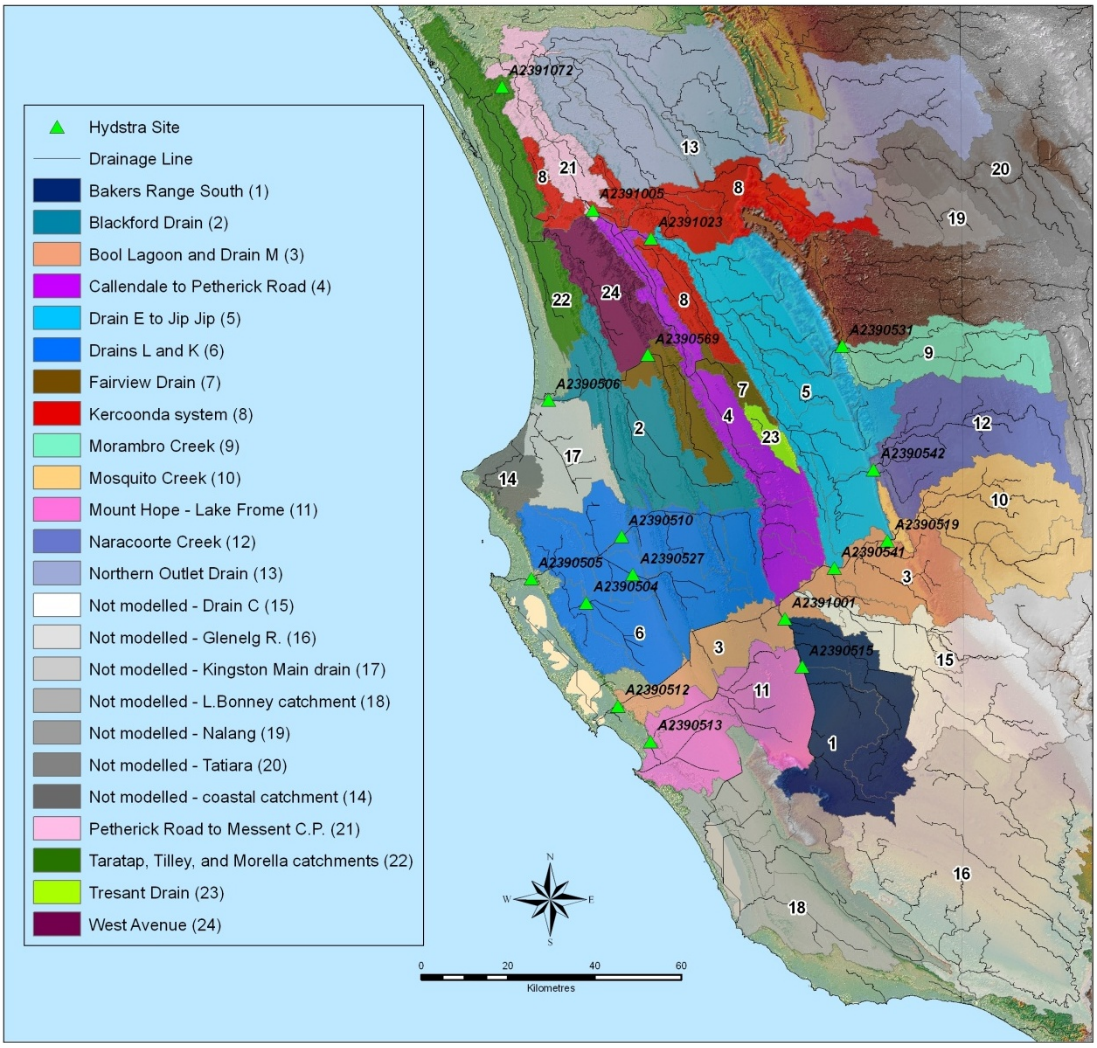

Figure 5 Catchments modelled as part the Regional Flow Management Strategy project (from Wood & Way 2010)

The majority of the catchments modelled by Wood and Way (2010) were also considered in an ARC Linkage Project between the University of Adelaide and Department for Water. Continuous Soil Moisture Accounting models in the HEC-HMS package were used to simulate the Upper South East drainage network, including the major wetland storages and regulating structures. An approach to determining the model parameters based on the soil type and depth to groundwater was developed (Gibbs et al. 2012), and overland flow parameters were derived from the DEM directly (Gibbs et al. 2010). A simple salt transport model based on CATSALT (Tuteja et al. 2003) was also developed, and used to assess the volumes likely to be deliverable to key wetlands based on the winter rainfall experienced (Gibbs et al. 2011).

Through these studies, a number of catchment models representing the runoff processes occurring in the upper south east at the regional scale have been developed. Gibbs et al. (2012) identified that careful consideration to recharge, as well as streamflow, was important for development of the runoff models. To date this has not been undertaken. Also, the reaches representing drains in both studies adopted a constant percolation loss, however, in reality, interaction with the nearby groundwater table will be very influential in this process. While these are limitations of the existing studies, each has contributed to the understanding and ability to simulate volumes available for water resource management in the Upper South East.

There have been a number of studies undertaken to assess the feasibility of works to divert drain flow from the Lower South East to the Upper South East to improve environmental outcomes. Initially, Heneker (Heneker 2006a, b) considered the volume available for diversion from Bool Lagoon to the Marcollat watercourse, as well as from Bool Lagoon releases to Drain M diverted to the Bakers Range watercourse. Way and Heneker (2007) also quantified the volumes of water available to divert from the Lower to the Upper South East on an annual basis, including a discussion on the water quality considerations. KBR (2009) provided an engineering investigation into creating feasible flow-path options for further diversions between the Blackford drain and Drain M, collecting Drain L and Wilmot drain catchments toward the upper south east and eventually the Coorong South Lagoon. AWE (2009b) produced a more detailed analysis of the diversion volumes available from these catchments, and disaggregated the annual runoff volumes to consider transmission losses to groundwater on a daily basis, as well as considering the impact of climate change scenarios for 2030. Based on the daily timestep rainfall – runoff models developed by Wood and Way (2010), Montazeri et al. (2011) developed daily time-step hydrological models of the South East catchments. These included hydraulic modelling to determine water levels in the drains, and groundwater losses from the drains based on analytical equations proposed by Morgan et al. (2011). This study has been extended by Peters et al. (2011) to consider a number of flow path variations and address some of the assumptions regarding the groundwater interactions. One of the main contributions of the recent studies is the consideration of transmission losses based on the groundwater level, and is discussed further in the following section.

3.2.2 Future directions

Groundwater recharge has been identified as the main water source for the region, and allocations are often based on the amount of recharge in the PWAs. However, to date there has been little consideration of the interaction between the groundwater and surface water processes. Due to the flat topography and slow response of streams to rainfall, Stace and Murdoch (2003) estimated up to 75% of streamflow may be derived from baseflow, or discharge from groundwater to the stream. As a simple example and considering the flow record for the Reedy Creek - Mt Hope drain, the average annual runoff for the period 1972 – 2010 was 21.3 GL/year, and based on a catchment area of 466 km^2, this equates to 45.7 mm/year of runoff from the catchment. Baseflow recession analysis suggests that approximately half of this runoff was derived from baseflow, but it could be up to 75% of total flow (Stace & Murdoch 2003). Hence, it is expected that 22 – 34 mm/year of the observed runoff was produced from groundwater discharge.

For the same region, Brown et al. (2006) estimated the recharge to the TLA to be 100-110 mm/yr (the management areas of Rivoli Bay and Mount Muirhead). In the South East up to 90% of the expected recharge can be allocated for extractions, with the remaining 10% allocated to environmental water requirements and assumed to be available for flushing of salt in the soil profile. However, based on this simple analysis, approximately 20-30% of the expected recharge to the unconfined aquifer may subsequently discharge to the drain, and be observed again as baseflow, which is not accounted for. It should be noted that interflow paths and perched layers may intercept rainfall and delay the delivery of the flow to the drain and hence represent baseflow. In this case, the water observed as baseflow is unlikely to also be observed as an increase in the level of the unconfined aquifer, and hence recharge using the water table fluctuation approach (Brown et al. 2006). Nonetheless, this simple calculation highlights the risk of double accounting of the water resource in the region, once as recharge, and again as baseflow in the creeks or drains if recharge and surface water processes are treated separately.

For the operation of the drainage network in Upper South East, improved surface water modelling is highly desirable to assist with quantifying volumes available to be used for a wide range of environmental objectives across the region. There are long term (since the 1970s) records of flow for the major cross-border catchments contributing flow to the region to assist with this planning. However, changes in the land use and catchment processes, particularly in Mosquito Creek and around the southern Bakers Range, have resulted in significant reductions in the flows expected from these catchments compared to the historic record. Improved runoff modelling to represent these changes as well as different climate scenarios, along with water balance modelling to represent conveyance through the drains and storage in the wetlands, would be extremely beneficial to assist with assessing the competing objectives for the limited environmental water available, to support from Lake George at Beachport in the South, to Bool Lagoon in the East, and the Coorong South Lagoon at Salt Creek in the North, as well as numerous wetlands in the watercourses in between.

3.3 Surface Water – Groundwater Interaction

The previous analysis is one way of highlighting the importance of surface water – groundwater (SW-GW) interaction in assessing the water availability in the south east. SW-GW interactions also have a significant influence on the performance of the many drain reaches in the South East, as well as many of the remaining wetlands in the region that are considered to be dependent on a connection to the groundwater table for support.

3.3.1 Existing Modelling

As outlined in the previous section, a number of studies have considered the interaction between the water level in drains and the nearby groundwater table to estimate transmission losses along proposed drain alignments for restoration of flows to the Coorong South Lagoon. Three versions of analytical equations for estimating losses from the drainage network were proposed by Morgan et al. (2011). The first two cases were based on the Dupuit equation, with the difference between the cases determined from how the averaged hydraulic conductivity is derived from the soil or aquifer properties. The Dupuit equation assumes horizontal flow, and for channel seepage this assumption is valid when the depth to the watertable from the water level in the channel is less than approximately twice the width of the channel (Bouwer 2002). The third case proposed by Morgan et al. (2011) considered the scenario when this assumption was not valid, which was based on Darcy's Law to represent when the water in a drain is disconnected from a deeper watertable. Montazeri et al. (2011) assumed one loss case as representative of the connection status for proposed drain alignments, and attempted to determine the relevant hydraulic conductivity from field study values (AWE 2009a) to determine the transmission loss for proposed drain alignments. However, due to the large range in observed values and the upscaling of point measurements to the drain reach scale, this was found to provide a significant challenge, and instead typical values based on the soil types were adopted. Peters et al. (2011) extended the approach to consider variable cases representing the losses from the drains, and also determined the distance of influence to be based on the soil type, where previous studies had considered a constant distance of 250 m.

Similar analytical equations have recently been implemented in the Groundwater Surface Water Interaction Tool (GSWIT) in the Source IMS platform to represent groundwater interactions with the reach. While a full numerical groundwater model will provide a more accurate representation of the groundwater interactions, simple analytical equations may be suitable to represent the groundwater interactions in the drainage network at the reach scale (tens of kilometres). As the existing studies have been undertaken to support the Coorong South Lagoon Flow Restoration Project, the drain alignments that have been considered are proposed new drains, or drains that have limited streamflow measurements for calibration of the drain losses, such as the Taratap – Tilley Swamp sections of drain. Recently, a number of monitoring stations have been installed in the South East that would enable the calibration of such an approach to observed streamflows, and hence the groundwater interactions, which would be valuable in assessing suitability of this approach in representing drain – groundwater interactions at the regional scale.

Also as noted above, as part of the Regional Flow Management Strategy project, SKM (2009) classified the over 16,000 wetlands mapped in the South East using a hierarchical tiered system considering: 1) the potential for groundwater – surface water interaction, 2) the likelihood for connection with the tertiary limestone aquifer, 3) the groundwater flow regime (gaining or losing) and 4) the form of any interaction (i.e. permanent or seasonal). The relationship between the surface elevation of surveyed water bodies (determined from a high resolution DEM) and seasonal watertable elevations was used to assess the degree of interaction. Fifty percent of wetlands are regarded as having a 'likely' dependence on groundwater, however weighted by surface area these wetlands represent 89% of the total wetland area. The majority of wetlands (77% of wetlands and 96% of wetland area) in the region are classified as having a 'high likelihood' of TLA connection, as the wetlands occurred within 5m of the watertable. Those wetlands which are regarded as having a 'low' to 'no likelihood of connection' with the TLA are mostly associated with the elevated topography of the ranges. The classifications developed provided a regional-scale assessment of groundwater dependence among ecosystems, however the approach was too coarse to enable a thorough understanding of processes actually occurring at each individual wetland, which may be required for some management decisions. However, the results have provided a basis for targeted studies determining particular management strategies for regional water resources or specific wetlands based on field studies and monitoring over time. An attempt to quantify the volume of loss or gain between groundwater dependent wetlands and the groundwater system was beyond the scope of the study.

Groundwater interactions in wetlands have been investigated by Cook et al. (2008b), considering wetlands located in Honan Native Forest Reserve, approximately 16 km west-northwest of Mount Gambier. Radon-222 concentrations were measured in the wetland on multiple occasions, and used to construct a steady state and a transient model of groundwater discharge to the wetland, which was estimated to vary between 12 – 18 m^3/day. Cook et al. (2008a) continued to investigate the groundwater dependence of the wetlands, and considering the same location, developed methods for rapid assessment of groundwater dependence. The approach could be used to quantify the rate of groundwater discharge to gaining wetlands and distinguish between losing connected and losing disconnected wetlands. A methodology was developed to identify if a wetland was connected or disconnected to the watertable based on water levels in nearby observation wells. This work established that the watertable depth below which wetlands become disconnected depends upon the depth of water in the wetland, the thickness and hydraulic conductivity of the low permeability sediments that immediately underlie the wetland, the thickness and hydraulic conductivity of the aquifer, the radius of the wetland, and the distance that the observation bore is away from the wetland. This method could potentially be used to assess the groundwater dependence of any wetland, provided there is an observation bore within a relatively short distance of the wetland and the relevant soil properties are known.

3.3.2 Future Directions

Simulating SW-GW interactions at the scale of interest is a complex question and ongoing area of research. Heneker (2006b) reiterated that losses in the stream and drainage systems should be revised when more details about these processes are known. As part of the South East Water Science Review, Daniell (2010) stated that this study on losses should be undertaken as a matter of urgency so that a true appreciation of the various sub-catchment flows can be identified. These SW-GW interactions often occur at the local scale and are highly variable, however, for management purposes, regional scale information is generally required. A greater understanding and representation of SW-GW interactions is highly desirable, as it is this interaction that supports the many Groundwater Dependent Ecosystems (GDEs), as well as presenting a risk of double accounting of the water resource (as noted in the previous section). There are a number of alternatives for modelling SW-GW interactions, including:

- Analytical models, such as the Dupuit equation, as proposed by Morgan et al. (2011) and applied by Montezari et al. (2011), and the GSWIT developed for Source IMS. These approaches adopt considerable simplifications of the processes occurring, and it is unclear if approaches such as this can provide an acceptable representation of SW-GW interaction at the drain reach scale. The groundwater level is a required input to this method, and while observations can be used if available, a groundwater model is required to provide this input where observations are unavailable or to consider future scenarios.

- Numerical groundwater models are necessary to address many of the simplifications and assumptions made by the analytical models, and are expected to provide more accurate estimates of stream fluxes based groundwater levels and stream stages. Harrington et al. (2011) noted that MODFLOW incorporates surface water interactions through the drain, river and stream-routing packages in a way that may be adequate for most needs based on likely objectives and available data. A regional scale groundwater model may not be of a spatial or temporal resolution necessary to simulate SW-GW interactions, however local-scale models may be able to be developed to represent the processes occurring at targeted wetlands or reaches of drains that are expected to have significant SW-GW interaction. There are a number of other challenges in adopting this approach, such as how to represent the recharge input to the groundwater model, as interaction with ephemeral streamflows will be driven by the seasonal variation in groundwater level (in turn driven by the rainfall pattern). A second consideration is how to incorporate losing reaches of drain or streams.
- The most detailed representation of the processes occurring between SW-GW interactions is achieved by adopting coupled SW-GW models, such as Mike-SHE or HydroGeoSphere. Coupled approaches require much more detailed data to implement compared to the above approaches, as well as significantly greater computational requirements due more complex representation of the SW-GW dynamics, and a refined simulation grid to represent these processes. Brunner et al. (2010) noted a number of limitations in the representation of SW-GW interactions used in MODFLOW compared to the coupled model HydroGeoSphere, however it is unclear how important these limitations are in the context of limited data and the high variability and limited knowledge of local soil properties.

The choice between the different levels of modelling will ultimately depend upon the importance of surface water – groundwater interaction to the regional water balance, and hence the need to provide accurate estimates of the exchange flux. Options for modelling surface water – groundwater interactions in the southeast region will be more fully evaluated in future Goyder Institute projects.

3.4 Water Quality

For water resource management, water quality can be just as important variable as the water quantity. The majority of studies have used salinity as the major indicator of water quality, however nutrients, such as nitrates, and pesticides are also an important water resource management consideration.

3.4.1 Existing Modelling

As outlined above, a number of groundwater models have been developed to simulate salt (Padthaway) and nitrate (Border Zone models) transport along with simulating flows. Calibration of nitrate models to observations for the Border Zones 1A or 3A and 3B has proven difficult (Harrington et al. 2011). Solute transport was not considered by Wood (2011) due to limited data, however it was noted that changes in salinity are of great interest in the Tatiara area. Salinity was simulated in the Padthaway model (Aquaterra 2008), where a significant knowledge and data base for the region was available following the Padthaway Salt Accession Project.

Gibbs et al. (2011) developed a salt transport model for the drainage network, based on the simple CATSALT equation (Tuteja et al. 2003) to calculate the expected salinity of catchment runoff, and assuming complete mixing in the drains. The simple CATSALT equations were found to be able to be calibrated to observed salt loads with suitable accuracy. However, the following challenges in simulating salt concentrations were identified:

- Accurate simulation of water sources. The majority of rainfall – runoff modelling has focused on representing the total gauged streamflow accurately. However, to model salt transport the source of the water, e.g. direct runoff, shallow interflow or baseflow, must also be simulated accurately.
- Representative values for the input groundwater salinity. Observation wells and anecdotal evidence indicates that groundwater salinity can vary significantly over very small spatial scales, and one section of drain may contribute to a large increase in the salt load.
- The behaviour of salt in wetlands as they dry out. While salt is a conservative constituent, the representation of the quantity of salt that remains at the soil surface to redissolve during a following wetting up event, and the quantity that is leached or flushed through to the unconfined aquifer, is largely unknown.

3.4.2 Future Directions

As water quality can be as important as the water available for water resource management, the limited water quality modelling available to inform a decision support system is of concern. The amount of water, as well as the source of that water, is an input to any water quality model, and hence the current limitations in the groundwater or surface water modelling outlined above directly influence the ability to simulate water quality accurately.

Monitoring changes in water quality based on observations is likely to provide the best information in the short to medium term. This approach is the basis for water management currently, for example salinity trigger levels in Water Allocation Plans, or using salinity probes or monitoring stations to assist drain management. As the behaviour of the relevant constituents (salt or nitrates for example) is relatively well understood, future water quality models may be able to provide information about the changes that could be expected from a particular management action, however accurate simulation of concentration values is dependent on 1) accurate surface or groundwater modelling, and 2) knowledge of the sources of a constituent, which are both ongoing challenges themselves.

3.5 Ecological and Hydro – ecological Response

Many wetlands in the South East are recognised as having a high dependency on the regional unconfined aquifer and are at risk from increasing competition for water resources and groundwater level decline (Harding 2009). As noted at the start of this section, the many field – based studies that have contributed to the understanding of the processes and assets in the South East have not been included in this review, as the focus is on models that may be available to simulate various future scenarios that are of interest to inform a decision support system. The majority of work in the South East has been focused on detailed mapping of wetland ecosystems completed for wetland inventories, which has resulted in over 16,000 mapped wetlands in the South Australian Wetland Inventory Database (SAWID) for the SE region (Taylor 2006, Harding 2007). The database includes biological, physical and chemical attributes for inventoried wetlands (Harding 2009). A prioritisation framework incorporated into SAWID ranks wetlands on parameters that were identified as useful surrogates for determining ecological value (Harding 2007). As part of the South East Water Science Review SAWID polygons representing wetland boundaries were compared to locations with water detected using LANDSAT imagery and generally found to be accurate representations of wetland features (Miles et al. 2010). In addition, the review included an investigation of 83 wetlands within forest plantations (Billows et al. 2010), where 88% of the polygons considered were found to meet at least one assessment criterion as exhibiting wetland characteristics. As such, it was concluded that SAWID data are the best available source of information for wetland ecosystems in the South East.

3.5.1 Existing Modelling

A method for estimating the target hydrograph and target salinity for the maintenance of the existing ecological status of wetlands in the South East region of South Australia was developed by Ecological Associates (2009). This approach used the Wetland Vegetation Components (WVC) known to occur at a wetland to prescribe the required hydrology and salinity, in terms of water depths for a number of months of the year, and target and tolerable ranges of salinity. The requirements for different events were also considered, with annual and 1 in 3 year requirements specified, as well as the maximum length of inundation or dry phases outlined for each WVC. The approach involved untested assumptions regarding the arrangement of WVCs across the elevation gradient, and did not account for the presence of other components of the ecosystem, such as fish, birds and macroinvertebrates, which are likely to have implications for hydrology and water quality targets and connectivity requirements that are not adequately reflected in the requirements for WVCs (Cooling et al. 2010).

As part of the South East Water Science Review, Cooling et al. (2010) tested the assumptions made in the original definitions of the WVCs by collecting field data, revised the target hydrographs for the WVCs to consider wider elevation bands occupied by the different WVCs, a 3 in 5 year events, as well as the annual and 1 in 3 year events, and considered the hydrological requirements of fish species. The study then went on to assess the impact of reductions in groundwater level on the WVCs found in the 63 focus wetlands considered. The results suggested that a 30 cm drop in groundwater level would result in all 63 wetlands suffering a loss in the extent of at least one WVC. A 60 cm drop in water level would result in 23 wetlands losing all of their WVCs, and at a drop of 90 cm, 31 wetlands would suffer a complete loss of aquatic habitat. A 120 cm drop in water level would lead to the loss of all WVCs in 41 wetlands, and with a drop of 150 cm, all of the 63 focus wetlands suffer the complete loss of aquatic habitat (Cooling et al. 2010).

The response of key aquatic plant species (representative of a number of the WVCs) to pulses of saline water was investigated as part of an ARC Linkage Project between the Department for Water and The University of Adelaide. Both laboratory studies and field sampling were used to investigate germination of the seed bank under different regimes (Goodman et al. 2011) and determine response curves representing the preferred conditions of the different species considered

(Goodman et al. 2010). Goodman et al. (2010) found that adult specimens of aquatic species could safely tolerate 8 000 mg/L (approximately 13 500 EC), much higher than the specified target salinities for many wetlands as determined from the WVCs, suggesting that more saline water in the drains may be able to be diverted to wetlands for environmental purposes. However, growth rates were reduced at these salinities and lifecycle aspects, such as germination and seed setting, were not investigated. Also, there is a risk that salt will accumulate in the wetland if fresher water is not available to flush out an initial saltier diversion. As part of the South East Water Science Review, Goodman (2010) provided a concise description of the salinity requirements of aquatic plants which are surviving in the wetlands of the South East, and how the species diversity has changed considering sampling undertaken before and after the year 2000. Interestingly, the study found that the surface water salinities in ground water dependent wetlands were higher than that in the surrounding groundwater, suggesting that salt accumulation in wetland sediments is having a significant impact.

3.5.2 Future Directions

Groundwater Dependent Ecosystems, by definition, are dependent on the groundwater table, and hence the SW-GW interactions occurring locally around the ecosystem. Hence, the understanding of these interactions is critical to the management of the ecosystems, and the issues outlined above for SW-GW interactions, as well as water quality simulation, are all relevant to assist our understanding and modelling of GDEs. For Water Allocation Planning, environmental water requirements were nominally set to 10% of the available groundwater recharge (SENRMB 2009), based on an assumption that this will maintain lateral groundwater flow and thereby supporting GDEs without adverse effects from water resource development. However, the actual water requirements of GDEs have yet to be quantified.

The WVC requirements derived provide a simple to interpret approach to capturing the current understanding of the requirements of different groups of aquatic species. An evidence based approach based on testing in the field would provide greater confidence in the values currently implemented, which are generally derived from expert knowledge. For each WVC, the number of months per year of desirable wetland water levels are specified, however the timing of these events is not. It is unlikely that a number of months of elevated water levels in late summer will provide the same ecological benefit if the same volume was available over the spring growing period, which may be able to be incorporated in WVC requirements.

Thus far, the focus of definition of ecological water requirements has been on vegetation requirements. Flow regimes (magnitude, timing, frequency and duration) are also critical for the sustainability of other aquatic biota (e.g. influencing aquatic habitats, connectivity and population dynamics of fish populations), and these aspects and currently not factored into the wetland requirements, as described by the wetland vegetation components (WVCs). Also ecological requirements for the water resource are not limited to GDE, for example refugia in drains and summer baseflows are recognised as important habitat for a number of species, such as the southern Pygmy Perch. Definition of the water requirements of the important ecosystems in the region, not just the vegetation located in GDEs, is necessary to ensure these requirements are maintained.

3.6 Agriculture and Economy

The South East of SA is one of the state's most productive regions, and, as such, water planning and management activities must consider the impact on productivity, as well as the impact of the development on the water resources. The South East has some of the most productive land in South Australia with three quarters of South Australia's forests and one third of its improved pastures. The irrigation industry is the most significant user of groundwater in the South East, with approximately 80 000 hectares of land irrigated with over 2 000 licensees, though plantation forestry is considered as a large water user with more than 140 000 ha of plantations (Paydar et al. 2009). It is not surprising then, that the majority of the modelling effort has been focused on the impact of plantation forestry on water availability.

3.6.1 Existing Modelling

Daniell (2010) provides a detailed overview of the recent studies, and reviews of studies, undertaken on expected changes in the water cycle due to plantation forestry. The most significant study in the South East region was undertaken by Benyon and Doody (2004), where groundwater use of plantations was studied in research plots on sandy soils over watertables of low salinity in the South East on closed canopy plantations. For the eight study plots which used groundwater, the mean annual groundwater uptake was 435 mm/ year, which represented 35% of their total water use, and the annual extraction values ranged from 107 to 671 mm/year. Site factors that influenced water use of the plantations with closed canopies included rainfall, soil depth and depth to groundwater (Paydar et al. 2009). Based on these results and some simplifying assumptions, Brown et al. (2006) estimated the mean annual extraction rates of hardwood (230mm/year) and softwood (260mm/year) plantations from shallow groundwater, averaged over the whole forest life cycle. Brown et al. (2006) also determined values of 83% average recharge reduction underneath softwood plantations and 77% reduction underneath hardwood plantations. These values are in line with that outlined in the Policy Framework for Managing the water resource impacts of Plantation Forestry (2009), which states that there is strong evidence that the runoff reduction (including groundwater recharge) due to plantation forests is in the order of 70-100%, and that plantation forests, regardless of species, can be assumed to reduce runoff (including groundwater recharge) by 85% and access groundwater through direct extraction when the depth to the groundwater table is less than six metres. These results have been used as inputs to a number of studies including the Water Range groundwater model and assumptions used in the South East Water Science Review (Aquaterra 2010a).

The extinction depth of six metres, where plantation forestry will cease to access the groundwater, is an assumption under question in recent studies. The basis for this depth appears to be based on Benyon et al. (2006), who stated that:

> *We have suggested that groundwater uptake in the Green Triangle is partly a function of depth-to-the watertable. For trees to use groundwater, their roots must have penetrated to the depth of the capillary fringe above the watertable. Tree roots soon after planting are very shallow (<0.3 m). Clearly, it must take time for the root system to develop as individual trees grow in size and for roots to extend deep enough to access groundwater. Roots might continue to penetrate to greater depths as the trees*

age. This raises the question of whether there is a maximum depth for significant groundwater uptake. The results from the Green Triangle suggest this depth is somewhere between 6 and 8m. Whether this is an indication of species maximum rooting depth, or resistance to water movement through the soil–root–tree–atmosphere pathway is not known.

As part of the South East Water Science Review, extinction depths of 6 m and 9 m were tested using the Wattle Range Groundwater model (Aquaterra 2010a). The results indicated that limiting forestry extraction to 6 m below the surface indicated that the effect of such a conceptualisation is not sufficient to explain observed water levels in some observation bores, and by applying an increased depth of influence of 9 m the match between modelled and observed water levels improved, however it was still insufficient in some bores (Aquaterra 2010a). The effect of an extinction depth will have a significant influence on the final cone of depression produced around plantation forestry, and given that Cooling et al. (2010) found that all wetlands considered in their study would be nonexistent for a groundwater drop of 1.5m, the difference between the 6 m, 9 m or greater extension depth has the potential to have a significant impact on GDEs and water availability.

There is similar uncertainty around buffer zones required to reduce the impact of plantation forestry on the surrounding water system. The Policy Framework for Managing the water resource impacts of Plantation Forestry (2009) recommends that "in the absence of detailed scientific information, generalised buffer widths can be used for surface water systems as a guide to informing management decisions. For surface water systems, buffers of 20 metres width to the edge of streams and wetlands are justified on grounds of water quality, erosion control and ecology, along with providing hydrological benefits". Daniell (2010) notes that the 20 m buffer may no longer be supported by recent scientific findings. Gippel and Watson (2006) have stated that "using data from fully forested catchments is not applicable to the case of a planned forestry operation where appropriate runoff producing buffers have been left on the sensitive areas. It is quite possible that in some areas the proposed 50 m buffer is inadequate to protect the main runoff producing zones." These distances are significantly lower than those derived by Harding (2009) in the risk assessment process of the Water-RAT project, where the lowest distances were in the order of hundreds of metres (as noted in the following section). Hence, Daniell (2010) states that it would seem from this that the policy of requiring a 20m buffer should be reviewed.

As part of a study collating the understanding of the water cycle in the Limestone Coast region, Paydar et al. (2009) undertook one dimensional modelling of the root zone to estimate recharge in the South East. Given climate, soil and crop data inputs, a GIS version of the crop model SWAGMAN-Destiny (Khan et al. 2003) was used to simulate infiltration, drainage, evapotranspiration and crop growth to describe the principal processes that determine the fluxes of water and salt into and through a soil profile under forests and irrigation (Paydar et al. 2009). However, the simulated values of recharge were generally higher than that reported by Brown et al. (2006), and given the robustness of the water table fluctuation method in estimating recharge, the latter values were adopted over the simulated values in the subsequent water balance analysis.

3.6.2 Future Directions

Initial economic modelling was undertaken as part of the South East Water Science Review (Brookes 2010), however the results of this economic modelling were still under review at the time of writing.

A significant modelling component likely to be required to assess the economic impacts of water planning decision making is a land use and crop growth model. A model such as this would provide two necessary inputs for an integrated modelling decision support framework, firstly to establish the demands on the water resource from agricultural and some industrial activities, and secondly to convert that water demand into a yield for different crops (for example). Therefore, a crop growth model is likely to be required to assess the impacts of water planning on the economic considerations of the region. The modelling undertaken by Paydar et al. (2009) provides an initial step along this path, although the authors did not use the results from this modelling in their water balance assessment, and as such the approach is likely to require further improvement.

A component of such a crop model, or a completely separate model, may be required to improve the representation of the water requirements and resulting economic benefits of forestry water use in the region. As outlined in this section, many of the current assumed values appear to be contested, and further investigation may be warranted.

3.7 Existing Decision Support Systems

Two DSSs are already in use in the South East region, the Water-RAT for assessing the impact of groundwater development applications, and the Flows Management DSS to assist with the adaptive management of the Upper South East drainage network. An overview of both systems is provided in the remainder of this section.

3.7.1 Water Dependent Ecosystem Risk Assessment Tool

The original Water Dependent Ecosystem Risk Assessment Tool (Water-RAT) was developed by DFW (then DWLBC) for the Mount Lofty Ranges region (Scholz 2007), and has been adapted for the South East of South Australia (Harding 2009). The tool enables the linking of environmental assets and an assessment of their present and future demands on the groundwater resource. Water-RAT was developed as a means to provide baseline information that would identify significant water dependent ecosystem assets and processes, and incorporates spatial distribution and connectivity issues and associated development threats and risks. The GIS based tool has been used to inform and improve water management decisions across the region, as well as improve referral processes, the effective administration of policies and improved interagency knowledge exchange. Water-RAT implements a risk assessment approach, and has been used to identify high risk zones for potential impacts to high value groundwater dependent ecological assets from water affecting activities and developments (Harding 2009), and as such is an integral part of any future water planning in the South East region of South Australia.

In the South East, aquatic ecosystem, water licensing and allocation, and surface water flow information have traditionally been the responsibilities of DENR, DFW and the SEWCDB, respectively. Information on surface water catchments, groundwater resources and conditions, wetlands, aquatic biota and water resource development were fragmented, where data have been generated and managed amongst various departments and agencies, and not always made readily available (Harding 2009).

The risk assessment was undertaken using an analytical equation (Glover-Balmer method) to determine the high risk zone for potential impact to high value wetlands that have a high likelihood of groundwater dependence (SKM 2009) for pumping scenarios over a 50 year timeline. Spatial layers representing the 10%, 5% and 1% impact zones were developed to assist with the assessment of development applications, with the 10% zones ranging from 738 m to 5 km around the high value wetlands.

The Water-RAT tool provides an excellent resource for the locations of water dependent ecosystems and the locations of users of the water resource. These data are traditionally held across multiple agencies and organisations, and are difficult to piece together to produce the complete picture of water requirements and effects over the region. A number of the recommendations from the project should be recognised as potential avenues to build upon the existing tool:

- The analytical approach used was sufficient for the scope and purpose of the Water-RAT project, but more realistic simulations could be achieved using other available methods (for example numerical groundwater modelling).
- The accuracy and spatial coverage of aquifer property data in the South East were also noted as a limitation of the risk assessment method.
- Due to a lack of data, the approach did not distinguish between the effects of drawdown on different wetlands, and used a uniform method. This is unlikely to represent reality, for example a shallow seasonal groundwater dependent marsh could be significantly impacted by a 10 cm drawdown, whereas a deep coastal lagoon may be less so (Harding 2009). It was recommended that limits of acceptable change in groundwater level be identified for wetland typologies in the South East.
- Climate change scenarios should be investigated in terms of identifying high value wetlands at risk.
- Identification of surface water and groundwater catchments contributing to high value GDEs to enable management of catchment scale water development issues.
- Ground truthing and extension of the current understanding of the degree of wetland groundwater dependence, as reported by SKM (2009).
- The forestry intensity layer should be reviewed in light of future Water Allocation Plan policy and updated, if required.
- Identification of permanently pooling high value habitat provided by artificial drains in the South East.
- The responsibility for managing uploads, data updates and procedures should be defined within DFW for the Water-RAT application. In order to keep the application relevant, a system for on-going responsibility for maintenance and update of the layers needs to be in place.

The requirement for the regular update and maintenance of layers within Water-RAT exposes the stand-alone versions of this program to risk of use of out-of-date information, or un-authorised editing and use (Harding 2009). The development of web-based delivery of Water-RAT is therefore integral to the continued development and relevance of the application (Harding 2009). Groundwater levels were used to determine the rate of decline in the groundwater resource over the five year period 2003-2008, as the average drawdown over a five year period is a resource condition trigger. Groundwater levels were also implicitly used in the assessment of wetlands that are highly likely to be dependent on groundwater, based on the results of SKM (2009). However, incorporation of time series water data, rainfall, groundwater levels and streamflow volumes is a way that the existing tool can be improved, and allow the water balance at each management area to be assessed.

3.7.2 Flow Management Decision Support System

As part of the Upper South East Dryland Salinity and Flood Management Program (USEDSFMP), a decision support system was developed to meet the objectives of the project, namely:

- Reverse trends of land degradation and consequent economic decline caused by salinity and flooding.
- Coordinate drainage and flood management.
- Manage and reinstate wetlands to provide habitat and drought refuge for waterbirds.
- Provide for community needs, in particular the needs for a sustainable agriculture base.

The Decision Support System was designed to help managers decide which of the options to use for diverting the available water to the highest priority wetlands. Through a series of forms and connection to databases and online services, the DSS performs the following functions:

- Allow for planning of the allocation of water resources to wetland assets.
- Document the current water management plan for the USE region.
- Present information relevant to making planning and operational decisions.
- Document the operational decisions made.
- Allow the review of relevant information to facilitate learning for future planning.
- Provide a consolidated and secure reference data repository.
- Monitor current conditions and alert decision makers when conditions are such that action is required.

The system provides a detailed resource on the location and function of the USE drainage network, including regulators, functions of the regulators, wetlands and drain locations and requirements. The system allows for planning of operations for the upcoming season based on targeted environmental objectives and a record of wetlands assets that have received water recently, or are in need of water diversions to meet the Wetland Vegetation Component requirements. The system then monitors the telemetered stations in the drainage network over the flow season, and sends out email and SMS alerts to alert operators that a trigger has occurred that was set in the planning phase, and requires intervention. Any changes to the regulators in the network are documented to facilitate review processes in the future. Finally, the DSS supports a review phase that is used to assess the performance of the operations of the drainage network against the objectives set at the start of the year, with the goal to assist adaptive management in the future.

The existing DSS provides an extensive database of the assets and functionality of all aspects of the drainage network, encompassing over 700 km of drains constructed as part of the USDSFMP, as well as many more existing and private drains. The system has been set up also enable documentation of operations and outcomes, with the objective to assist adaptive management of the network for future years. The main area for development in the existing DSS is to include water balance and forecasting abilities supported by modelling, to provide an indication of the likelihood of meeting management objectives, to assist the planning phase by enabling if-then type scenario analysis, and to fill in information about expected water availability or delivery in untested areas where monitoring is not available.

3.8 Summary

This section has provided a review of existing modelling studies considering different aspects and regions of the South East, with the aim to identify suitable tools for assisting the decision making process. It should be noted that field studies and data analysis studies have not been included, as although they provide value knowledge and understanding, and are a sound basis for further modelling studies, they in-themselves generally do not provide the predictive capacity to assist with assessing the impacts of “if-then” type scenarios.

The review provided in this section has identified that there are no suitable models to integrate into a DSS in their existing form. The Wetland Vegetation Components are most likely to be the most suitable, where the water quality and quantity requirements of different groups of vegetation species has been loosely quantified. There is scope for improvement here with an evidence based approach to support the existing definitions, based on expert knowledge of the region, to extend the vegetation components to include other important biota such as fish and macroinvertebrates, as well as developing response curves to provide a representation of the likely ecosystem response to a partial supply of the defined requirements. Substantial testing of the current WVCs is required to ensure the intended recomposes for a given water availability are actually achieved. Also, simulation of the necessary inputs, i.e. water quality and periods of inundation, are generally not available at the current time.

For the prescribed groundwater resources, a groundwater model is required to assist with the assessment of the impact of various scenarios, such as different scenarios of various rainfall driven recharge, allocation of different proportions of recharge for proportions of recharge, different trigger levels, etc. Water quality, most notably salinity but also nutrients and pH is in many aspects as big a component of the decision making processes as water quantity. However, as water quality modelling is based on accurate simulation of the water quantity first (which is itself a significant challenge) water quality simulation is a notable oversight from existing studies.

As part of the Lower South Easter Water Balance Project, the current knowledge and gaps in different aspects of the water balance were determined. Key priority knowledge gaps identified were (Harrington et al. 2011):

- Good representations of spatial and temporal variations in:
    - Land use,
    - Recharge,

    - Evapotranspiration,
    - Groundwater interaction with drains, and
    - Forestry impacts.
- An understanding of, and monitoring data to inform, the feasibility of modelling SW-GW interactions.
- A quantitative knowledge of the salt balance.

From the Lower South East Water Balance project, it was also clear that a co-ordinated approach to the collation of the historical data described above would be of great benefit to all stakeholders. This would build a chronological history of the South East and may involve a combination of desktop studies of historical reports, digitising aerial photos and modelling. Having this available as a central resource would be of great benefit to the region (Harrington et al. 2011).

It is clear that there is a large amount of work that could be undertaken to improve the conceptual understanding and simulation ability in the region. Through the consultation process undertaken for the Lower South East Water Balance Project, Harrington et al. (2011) found that there is an urgent need for a tool to assist with identifying and prioritising the research / data needs that are critical to water resources management in the (Lower) South East and to provide a link between current and proposed management scenarios and observed / modelled ecosystem responses. In any case, this improved knowledge and modelling will continue to develop over the coming years and decades, and a DSS must be constructed in a way that can incorporate improved knowledge as it becomes available.

For drain management in the USE, the existing DSS provides a valuable tool for planning and review of operations, and to provide alerts for when planned regulator operations should be acted out. The system could benefit from the ability to simulate water movement around the region, but the lack of consideration to groundwater influences in the drainage network limits the usefulness of existing surface water modelling. Given the ongoing research and modelling in the South East region, it is clear that any system is going to have to be adaptable to incorporate the most up to date information and models.

4 Introduction to Decision Support Systems

For regions with limited natural resources, management of the resources for the competing environmental, economic, industrial and social objectives often requires the assessment of trade-offs of these objectives to identify equitable outcomes for all stakeholders. These trade-offs are characterised by interactions at many scales and often by scarcity of good observed data. Thus natural resource managers often have to trade uncertain outcomes to achieve equitable results for various social groups, across spatial and temporal scales and across disciplinary boundaries (Jakeman et al. 2006). The need to formulate new policy objectives and implementation options, and to change the way in which we manage our environment and resource-using activities on the basis of robust analysis and evidence, has become well accepted (McIntosh et al. 2011). Integrated Decision Support Systems (DSSs) are rapidly gaining attraction in the planning and policy-making community, as these systems can create high added value by bringing scientific knowledge to the decision makers' table (Van Delden et al. 2011a). In this role, a DSS is used as one tool to support the decision making process, as opposed to a system to replace the decision making process. The development of a DSS can also assist with elucidating each stakeholder's interests, facilitating analysis, learning and communication to allow for a more informed discussion when all involved are aware of the information available.

Two recent papers provide valuable overviews of the current state of knowledge, best practice and challenges for the development of DSS for integrated modelling addressing environmental applications and policy support (McIntosh et al. 2011, Van Delden et al. 2011a). The key points from these two studies, and works cited within, are summarised here to provide background to the current state of knowledge and best practice when developing such systems. The key points are presented in separate sections as definitions, components and characteristics, development processes and challenges, and finally examples of applications.

4.1 Definitions

A concept of a DSS was developed by Gorry and Morton (1989), who distinguished between structured, semi-structured, and unstructured decision contexts, and then went on to defined DSSs as computer-aided systems that help to deal with decision-making in semi – or unstructured problems. Pidd (2003) provided simple examples of the difference between the different categories of problems, as a range from structured to unstructured problems going from puzzles (with agreeable formulations and solutions) through problems (with agreeable formulations and arguable solutions) to messes (with arguable formulations and solutions) (McIntosh et al. 2005, McIntosh et al. 2011). The distinction between categories makes explicit the fact that decisions involve problem formulation as well as solution generation and selection, and that both the questions to ask and the proposed solutions to each question may be contested (McIntosh et al. 2011). In this context, DSSs were originally intended to be computer aided systems to support one or more phases of decision-making where either the decision formulation was agreeable but the solution arguable (semi-structured), or both the problem formulation as well as solutions were arguable (unstructured) (McIntosh et al. 2011). For example, Rutledge et al. (2008) define sustainability as an unstructured problem, as it is characterised by (Rittel & Webber 1973, O'Connor 1999):

- multiple actors with differing, legitimate values and opinions,

- high uncertainty,
- aspects of irreversibility,
- no clear solutions,
- being fraught with contradictions, and
- being persistent and unsolvable.

A number of different definitions and terminologies have been proposed to assist with the development of decision support systems. In a recent position paper on the development and best practices for environmental DSS development, McIntosh et al. (2011) summarised a number of definitions including:

- a system that integrates models, or databases, or other decision aids, and packages them in a way that decision makers can use (Rizzoli & Young 1997),
- an intelligent information system that ameliorates the time in which decisions can be made as well as the consistency and the quality of decisions, expressed in characteristic quantities of the field of application which can help to reduce the risks resulting from the interaction of human societies and their natural environments (Cortes et al. 2000),
- an intelligent analysis and information system that pulls together in a structured but easy-to-understand platform the different key aspects of the problem and system: hydrological, hydraulic, environmental, socio-economic, financial-economic, institutional and political-strategic (Elmahdi & McFarlane 2009), and
- tools for recording, storing, processing and dissemination of information to support group or individual decision making (Volk et al. 2010).

A number of commonalities can be drawn from the different definitions that have been proposed. Obviously, there is a focus on decision making, both that a DSS is applicable to the current processes in place to make decisions, and that the system will improve the process in some way, either through the use of a transparent and repeatable approach, or by providing scientific knowledge or modelling results in a way that improves the transition of this information into the decision making process. An integrated approach is acknowledged, where many of the aspects that influence the decision in question, such as water resources, economics, and development, are considered together. A DSS is described as an intelligent computer based system, which implies a DSS includes algorithms and methods to combine and process the multiple sources of information in a way that is logical and reduces the workload in assessing the suitability of different management options. The components that may be involved, such as databases or models, are listed, and these aspects are considered in more detail in the following section.

4.2 Components and Characteristics

Volk et al. (2010) state that the basic concept of a DSS has been derived from management and reporting tools, where data and information are manipulated, aggregated, transformed and presented so that decisions are supported. This can be seen in Figure 6, where an increasing level of aggregation can be observed from raw monitored data, to its usage in tools and models and finally to the simulation of scenarios or of the effect of management options or policy alternatives. From the user's perspective, the level of aggregation increases from the transformation of data to information and knowledge (Volk et al. 2010).

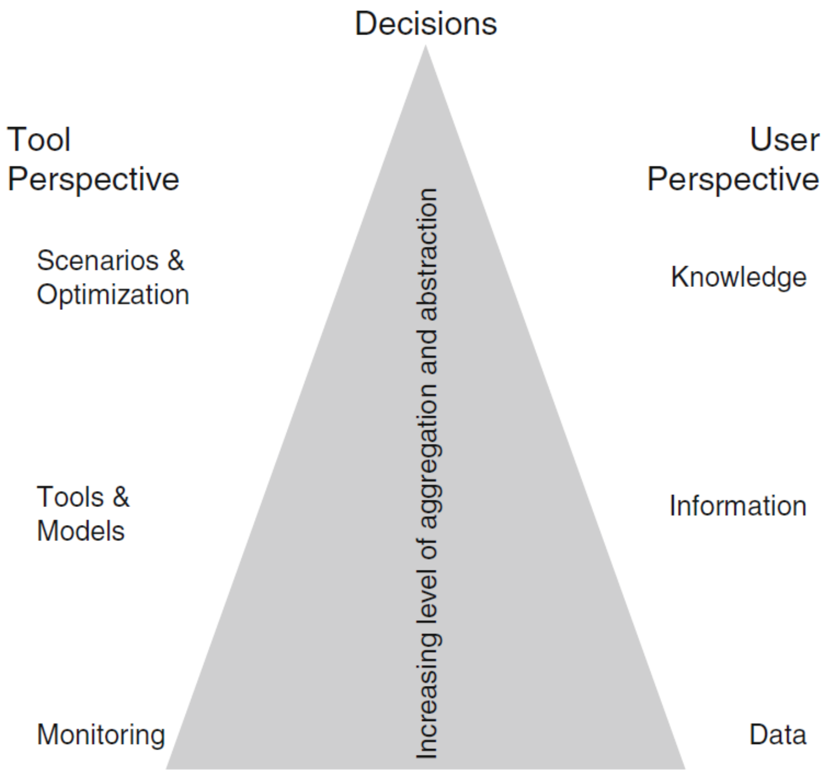

Figure 6 Conceptual diagram of the different levels of aggregation within a DSS from both the tools used and users' perspective (from Volk et al. 2010).

The majority of DSSs that have been reported in the literature focus on long term policy questions, where integrated modelling is one of the most appropriate methods available to investigate and compare different proposed options. With this in mind, van Delden et al. (2011a) summarised a number of common characteristics to DSSs:

- are able to support policy-relevant questions (Parker et al. 2002, Geertman & Stillwell 2003, Van Delden et al. 2007)
- pay particular attention to long-term problems and strategic issues (Geertman & Stillwell 2003, Van Delden et al. 2007),
- aim to explicitly facilitate group interaction and discussion (Geertman & Stillwell 2003),
- apply in complex and unstructured or wicked decision domains, characterised through a large number of actors, factors and relations, a high level of uncertainty, and conflicting interests of the actors involved (Rittel & Webber 1973, McIntosh et al. 2007),
- are user friendly in entering input, viewing output and analysing results (Volk et al. 2007, Volk et al. 2008),
- incorporate actual data and process knowledge from different disciplines (Van Delden et al. 2007),

- operate on different scales and resolutions where required (Van Delden et al. 2007, Volk et al. 2010),
- may be fully dynamic with feedback loops between individual models (Van Delden et al. 2007), and
- are built as a flexible component-based system that can be extended with additional modules over time (Argent 2004, Van Delden et al. 2009).

In addition to helping the process of structuring and identifying potential actions to take when knowledge about the nature and impact of problems are uncertain and contested, one of the main contributions a DSS can provide in the decision making context is to improve communication and the transparency of decision formulation and solution. This transparency comes from the rational basis that can be provided to support decisions, and that user or stakeholder groups can reproduce the decision procedure, play with the weightings applied to different objectives, and perform sensitivity analysis to assess decision strength and robustness (McIntosh et al. 2011).

In order to develop a system that possesses these characteristics, Denzer (2005) suggested that there are four main technological components that can be found in a DSS:

1. numerical calculations (e.g. models),
2. geographical representations (e.g GIS),
3. artificial intelligence (e.g. optimisation and decision analysis), and
4. data management and networking (e.g. databases).

All four technologies may not be applicable for all cases, however the need for data management and a geographical representation of the results are likely to be necessary components. Artificial intelligence is a very broad topic, and while optimisation as such may or may not be applicable in a given application, sophisticated algorithms to integrate the different information sources and process the results in a way that is meaningful and interpretable is likely to be necessary (as highlighted by the different definitions in the previous section). Finally, Jakeman et al. (2006) outline a number of reasons to undertake or include modelling in the context of natural resource management, including:

- gaining a better qualitative understanding of the system,
- knowledge elicitation and review,
- data assessment, discovering coverage, limitations, inconsistencies and gaps,
- concise summarising of data (data reduction),
- providing a focus for discussion of a problem,
- hypothesis generation and testing,
- prediction, both extrapolation from the past and ‘‘what if’’ exploration,
- control-system design: monitoring, diagnosis, decision making and action-taking (an adaptive management procedure),
- short-term forecasting (with a much narrower focus compared to longer term prediction),
- interpolation to estimate variables which cannot be measured directly,

- filling gaps in data, and
- providing guidance for management and decision-making.

So far, each DSS component or characteristic presented has been included in the majority of DSSs that have been developed, and is generally agreed upon in the literature. However, there is some dispute in relation to the extent to which the inclusion of uncertainty in DSS inputs, processing and outputs is necessary (McIntosh et al. 2011). Evidence from integrated assessment modelling workshops suggests that decision-makers are not particularly interested in an accurate representation of uncertainty in its own right, rather there is most interest in identifying decision strategies that are robust across a range of possible scenarios (UNECE 2002). Amann et al. (2011) interpreted this finding by assessing options against the worst case, most conservative conditions, rather than against a range of conditions, and McIntosh et al. (2011) suggested that incorporating uncertainty in the DSS process did not improve the likelihood that DSS outputs would be accepted by users, and adopted in the decision making process. Accurate estimation of uncertainties involved in model outputs may be less important in comparative studies, where gaining an understanding of changes in model outputs and interactions for different scenarios are of interest, as opposed to attempting to predict the exact outcome.

While the extent to which detailed model and DSS uncertainty representations are necessary is unclear, Voinov and Bousquet (2010) argued that understanding scientific uncertainty is important and may play a role in engendering trust across science-stakeholder boundaries. Volk et al. (2010) found that improvements are needed in DSSs regarding the treatment of uncertainty due to sparse data availability, the coupling of different models and tools, the spatial heterogeneity in variables and parameters, and calibration procedures. Refsgaard et al. (2007) considered uncertainty representation a central component of environmental modelling activities, and something that should be focussed on from the outset.

One reason for the lack of consideration to uncertainty in the development of existing DSSs is that quantifying uncertainty in any models that represent components of the DSS can be difficult, and extremely time consuming. This is because each scenario is generally simulated many times with the range of inputs and parameters to represent the uncertainty, as opposed to only one simulation with the 'best case' inputs and calibrated parameters. This is already a challenge with an individual model, and is likely to grow exponentially when models are coupled in a DSS as part of an integrated assessment. Suitable approaches to deal with this problem are largely unknown and the subject of further research. Another challenging in quantifying and incorporating how uncertainty progresses through an integrated DSS is how to handle qualitative and categorical data, where it is difficult to apply traditional methods that apply to numerical data and models.

Voinov and Bousquet (2010) suggest that an appreciation of model uncertainty is best achieved through stakeholder and DSS user participation in modelling activities, to understand model limitations and accuracy. It is easy for a poorly informed non-modeller to remain unaware of limitations, uncertainties, omissions and subjective choices in models. The risk is then that too much is read into the outputs and/or predictions of the model, or that a model is used for purposes different from those intended, making it very likely that invalid conclusions will be drawn (Jakeman et al. 2006). Jakeman et al. (2006) go on to suggest that the only way to mitigate these risks is to generate wider awareness of what the whole modelling process entails, what choices are made, what constitutes good practice for testing and applying models, how the results of using models should be viewed, and what sorts of questions users should be asking of modellers.

While quantifying uncertainty in model inputs and outputs is a significant challenge, this is not to say that it is not important, as from a risk perspective an appreciation of the likelihood of failure or adverse impacts is of interest, as a significant interest of decision makers is to identify robust solutions, rather than optimal solutions (UNECE 2002), as noted above. A reliable estimate of this robustness is unlikely to be adequately represented without considering the uncertainty in the models used to evaluate the scenarios.

4.3 DSS Development and Challenges

Based on the synthesis of knowledge and experience gained over the last 15 – 20 years from developing a number of DSSs for different users in different geographical contexts worldwide, van Delden et al. (2011a) outlined a methodology for the design and development of DSSs using integrated models for policy support and to inform policy making. Previously, Jakeman et al. (2006) produced ten iterative steps for the development of environmental models to inform and support natural resource management, which also covers a subset of the tasks proposed by van Delden et al. (2011a). The resulting methodology from van Delden *et al.* (2011a) can be seen in Figure 7, and Jakeman et al. (2006) in Figure 8.

4.3.1 Defining the Scope

The first step in both procedures is to define the scope of the DSS, where the three steps in Figure 8 could be considered as part of this task by the definition provided by van Delden et al. (2011a) in Figure 7. This involves determining the main functions of the DSS as well as to where and how in the policy process the system can provide support. Examples of where support could be provided include problem recognition, identification of alternatives, assessment of the impact of alternatives, consultation, communication, deliberation and/or implementation. Amongst others, possible functions include knowledge management, what-if analysis, structuring the policy process, finding optimal solutions given a set of constraints, communication to people involved in the decision-making process and communication to the broader public. Many DSSs fulfil several functions, but these need to be made explicit so that potential conflicts can be discussed and overcome (Van Delden et al. 2011a).

In defining the scope of a DSS, van Delden et al. (2011a) suggest a key process of identifying the themes, drivers and indicators that a DSS will be developed to assist with. This should be undertaken with the interest groups, including the clients or end-users of the DSS to ensure that the system is relevant from the beginning. Policy themes are defined as broader problem concepts that will remain important for policy analysis over the coming years. By identifying themes in the first instance, van Delden et al. (2011a) suggest that the resulting DSS will be more flexible and produce efficiencies by being driven by overarching themes that are likely to be important factors for the foreseeable future. Within these themes fit several policy issues or problems of which some are important at the moment, but may also include others are less significant currently, but have been identified as having the potential to become an issue in the near future.

The next step is to find drivers that have an impact on the defined themes and issues. Drivers can be split into external factors, which the policy maker(s) cannot influence (for example changes in climate, global markets and policies, technological developments) and policy measures they can implement or influence (for example subsidies, construction of infrastructure, zoning and other land use or water regulations). These drivers need to be explicitly or implicitly represented in the modelling system to enable scenarios of interest to be tested. The final step in this defining the scope task is to define indicators that follow the main developments over time and provide some quantitative and/or qualitative measure of change in outcomes relative to benchmark situations. The recent past is a commonly used benchmark (Van Delden et al. 2011a), and outcomes may be related to the state of the environment, the water resource and/or socioeconomic outcomes, such as income levels, employment or cultural criteria.

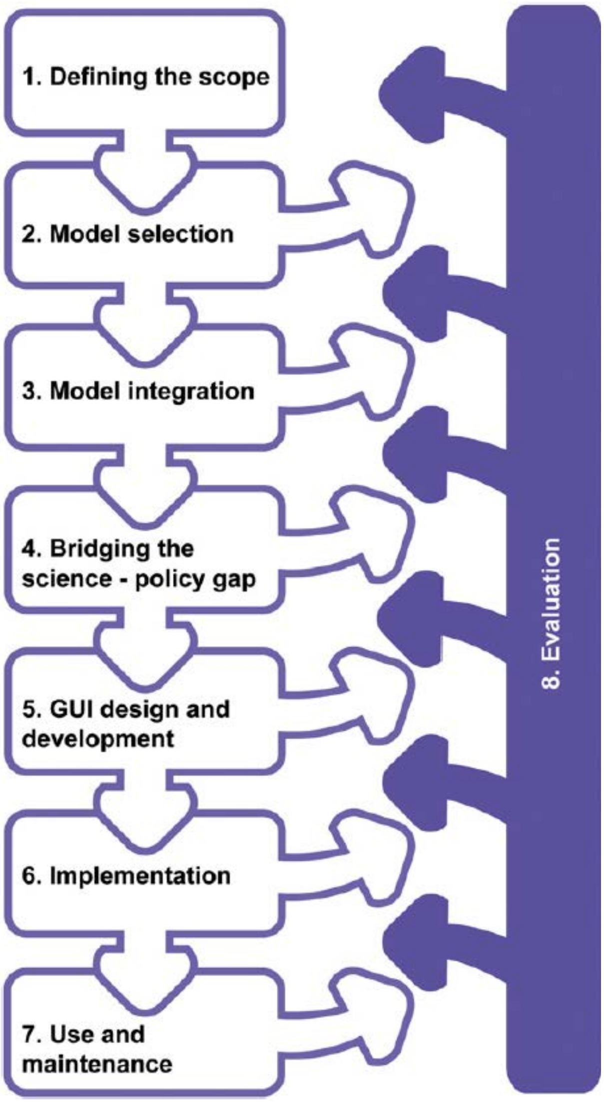

Figure 7 Tasks that need to be carried out during the design and development process (van Delden et al. 2011a).

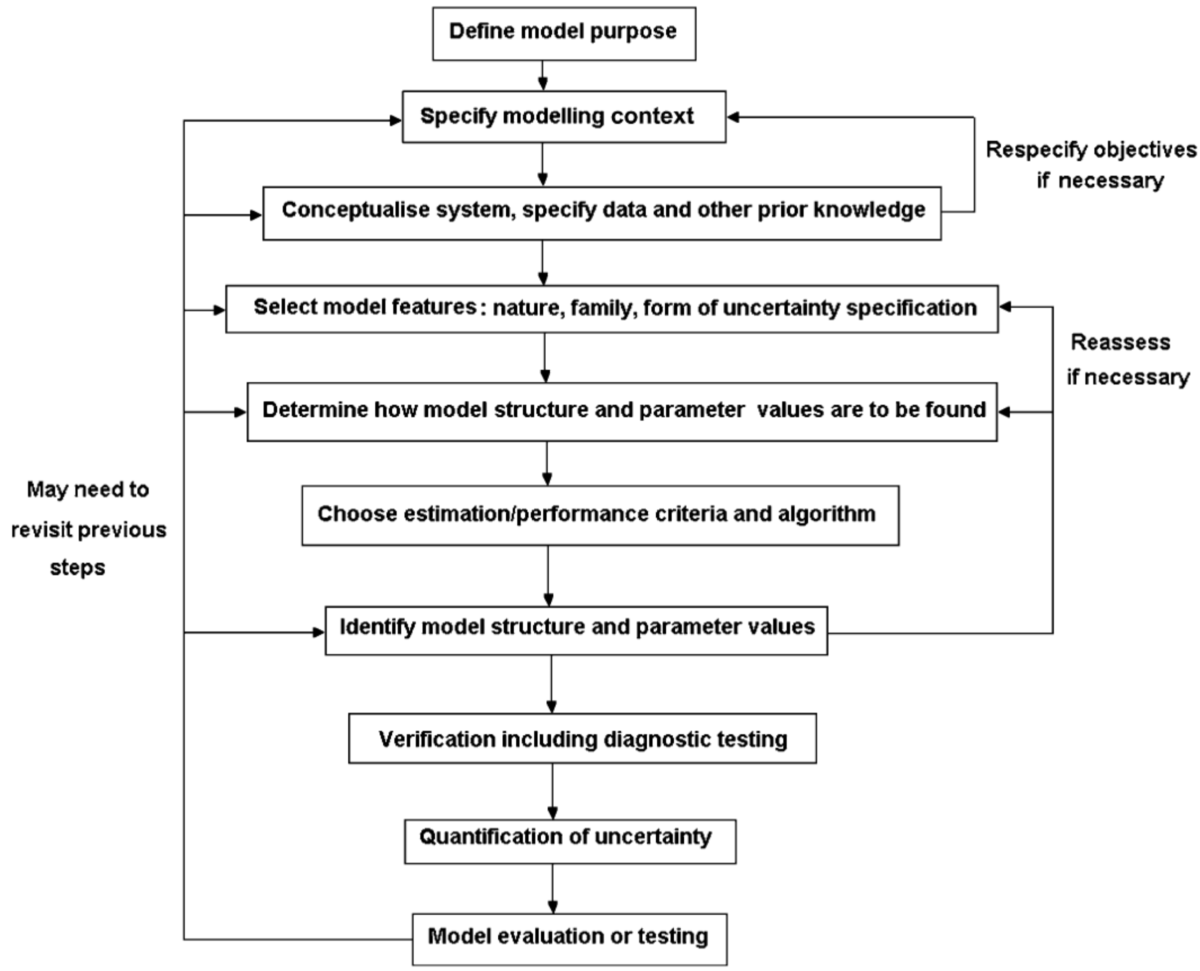

Figure 8 Iterative relationship between model building steps (Jakeman et al. 2006)

4.3.2 DSS Model Selection

After defining the specific questions and issues and extent that the model is to address in the scope definition step, the model selection step can be undertaken. The necessary outputs from models are determined by the identified indicators, and inputs based on the identified forcing variables (drivers). As part of model selection, Jakeman et al. (2006) state that the specification of the modelling context includes:

- the accuracy expected or hoped for,
- temporal and spatial scope, scale and resolution,
- the time frame to complete the model as fixed, for example, by when it must be ready to help a decision,
- the effort and resources available for modelling and operating the model, and
- flexibility, for example, can the model be quickly reconfigured to explore a new scenario proposed by a management group?

van Delden et al. (2011a) also note that it is important to decide on the scale and resolution that is desired by the user and supported by the science, as the request for information at a certain level of detail has large implications for the selection of models. Conceptualisation to decide what to include and what not to incorporate in the modelling activity should be addressed explicitly. Model features include the type of model (for example process based or empirical, lumped or distributed, stochastic or deterministic), and what type of outputs are required, for example, quantitative predictions, time series, spatial maps or more broad indicators of status (Jakeman et al. 2006).

If models are available that fit the purpose or can easily be adapted to fit the purpose, this is preferred from the point of view of reusability. However, since individual models are often developed for a different purpose this might be a comprehensive task, making it easier sometimes to develop new components (Oxley et al. 2004). Also, when no models are available to simulate crucial processes, components will have to be developed (Van Delden et al. 2011a).

Much of the data required for the development of integrated systems are scarce. In general, the need for a DSS implies that knowledge derived from available data is not sufficient, or that gaps need to be filled. If limited data are available, selection of simpler process representations may be preferred to avoid problems in setting up the model, calibration and validation (Van Delden et al. 2009). The quality and detail of the data available has a direct impact on the quality and accuracy of the results. With limited data or data of poor quality, results will have a higher uncertainty and this should be taken into account in their interpretation. Depending on the policy question, the level of detail in the data will be more or less important (Van Delden et al. 2011a).

As part of the synthesis of the MODULUS DSS, Engelen et al. (2000) provided a list of key end user requirement guidelines for the selection of components and models for integration in DSSs. This list provides valuable insight into model characteristics that are likely to successfully contribute to an integrated decision framework for South East water planning decision making. The requirements included (Engelen et al. 2000):

- *All processes.* The model should adequately represent all the important processes necessary to provide the required policy outputs.
- *Scientifically proven.* The process descriptions within the model should be well understood and scientifically proven. A well understood, proven, but crude process description may be preferred above an innovative but poorly documented and less proven one. The model results should be as robust, reliable and accurate as possible.
- *Level of sophistication.* The models selected for integration were often simplified versions of 'the ultimate' or 'the best available' models. In order to fit the integrated scheme, and to work at the right level of abstraction, models needed to be simplified and stripped of details that are not directly relevant in the process represented, the regions considered and the problems studied. The value of the integrated model is as good as the weakest element in the web of linked models. Hence, improved outcomes are achieved by improving this weakest element in this web, rather than to add details to the more complex sub-models.
- *Compatibility of scientific paradigms.* The basic assumptions and constraints on which the models are developed should be assessed to reduce the likelihood of a clash between scientific paradigms leading to a conceptual incompatibility between model inputs and outputs.

- *Scale.* The model should be spatial and operate at a regional scale. It should provide information at a sufficient level of spatial resolution to reflect the scale of variation in the most important physical, environmental and socio-economic variables.
- *Time horizon.* The model should be dynamic and operate at time scales and temporal resolutions representing realistically the autonomous dynamics of the system modelled. A time horizon which is also relevant for policy design, implementation and assessment should be adopted.
- *Routine data.* The model should be sufficiently simple to run as much as possible from routinely measured data. Routinely available data may include data collected by government agencies or the Bureau of Meteorology.
- *Scenario based.* The model should provide easy to understand scenarios that the user can be taken through. These may be for environmental changes, anthropogenic impacts, and management options.
- *Output centred.* The model should be output centred. It will be judged mostly upon the quality of its output and less upon its scientific or technical innovative character. It should provide appropriate results using indicators or variables that directly interface with the policy implementation process rather than more abstract scientific or technical variables.
- *Interactive.* The model should be fast, responsive and interactive and should cater for a very short attention span. A response time of 15-60 minutes per simulation-run covering a period of 20-30 years should be aimed for. Clever models, fast algorithms, and efficient code are required to achieve this.

The desire for relatively short run time may be a challenge for this decision support framework, especially if three – dimensional numerical groundwater models, and nested regional and local groundwater models, are included. However, this may be achieved by implementing certain model results offline, rather than online. Online means the models are run dynamically, which may lead to very long simulation times, and not suitable for workshop type investigations. Also it may be difficult to integrate each model's nuances in a large framework in a dynamic fashion. Offline involves pre-running a large number of scenarios from each model, or to pre-run whole scenarios across all models, to establish a database of results that can be interrogated when considered in an integrated framework. This has the danger of not including necessary scenarios, as well as not capturing important feedback mechanisms and involving interpolation between scenarios. However, in some cases, this simplification to allow many scenarios to be considered in a short amount of time can be more advantageous than taking long simulation times (in the order of days or more) to accurately simulate a scenario before being able to consider another. The ability to consider many scenarios may then narrow the solution space to be considered down to a smaller subspace, resulting in a smaller number of detailed model simulations to be undertaken as a follow – on step.

4.3.3 DSS Model Integration

While the term "integrated model" is widespread in the scientific literature, and the use of integrated models is strongly advocated in disciplines such as Integrated Assessment (for example Gough et al. 1998), very few guidelines or procedures for model integration are available from the literature. It is likely that a reasonable appreciation for the DSS scope is known to begin with, as there is a problem to cause interest in the first place. Generally existing modelling software and methods provide an indication of the change in indicators expected for different scenarios in drivers, but these models may or may not have been developed and calibrated for the region of interest. However, how to link these models in an integrated method is not a trivial question, and is beginning to become a focus of research efforts.

There are a number of considerations when integrating models from different disciplines and time scales. The first is the method of integration, including a one directional “waterfall” approach, where each model is run independently, and feeds into following models, or dynamic approaches, where models are run simultaneously to permit two directional feedbacks between models. Van Delden et al. (2011a) suggested that the inclusion of dynamic feedback loops between model components is crucial in order to capture how systems might adapt when subject to change, or how the simulation progresses for future time steps. As an example in the South East, it could be conceived that a scenario leading to reduced recharge or over extraction (and hence a lowering of the groundwater table), could lead to possible loss of some groundwater dependent ecosystems, and hence a change in land use, with either increased or reduced demand on the groundwater resource, in turn affecting the original recharge or extraction rates. This interaction between models representing the groundwater and surface water hydrology and ecology is necessary to adequately represent the scenario for long term planning.

van Delden et al. (2011b) have found that scaling issues in model integration typically involve trade-offs among four factors:

1. the scale at which end users or policy makers require information,
2. the scale at which processes take place and the representation of those processes in a single model,
3. the way to integrate model components representing processes occurring at different scales, and
4. the limitations posed by practical restrictions such as data limitations and computation speed.

Van Delden et al. (2011b) suggested that factors 1 and 2 are often very different, where information is often desired over longer periods at a regional scale, however important processes are occurring at a much smaller scales, for example individual wetlands, plots or hill slope spatial scales, and often daily or seasonal scales for water resources models are required.

The most appropriate method to integrate models of different scales will depend on the application. For example, for aspects that contribute to or limit the growth of plants during certain periods of the year (e.g. the soil moisture during important growing stages or the temperature in the blossoming period) the average is taken over these important periods, however for aspects that influence the current condition of the location, such as the fertile soil depth or the salinity, the latest values may be more appropriate (Van Delden et al. 2011b). Which method is most appropriate will also depend on the detail and heterogeneity in the processes represented. For example, if an output or indicator doesn’t vary much, a simple average is likely to be suitable, however if there are large variations in space (or time), critical thresholds or important information may be overlooked by only simple metrics.

The appropriate representation of a process is not always obvious, and it is not always the case that more detail produces better results. Using more land-use classes, more complex process representations, or smaller grid cells does not imply that the underlying processes are represented more accurately and can even give a false impression of accuracy (Van Delden et al. 2011b). Similarly, in many cases more complicated, spatially distributed runoff modelling produce less accurate simulation of end of catchment flows compared to lumped conceptual runoff models (Reed et al. 2004), even though they typically use more complex representations of catchment processes, and the spatial distribution allows the heterogeneity in catchment characteristics and rainfall patterns to be incorporated.

van Delden et al. (2011b) suggest that the complexity of the model components and the spatial and temporal resolutions required in models is generally related to the size of the study area. Besides the computational advantage, this also hints that after a threshold is passed the representation of a process can be upscaled. For example, at a national level the behaviour of farmers can be approximated by their aggregate behaviour, while on a small-scale application, actors need to be represented individually (Van Delden et al. 2011b).

However, not all processes can be modelled correctly with a simpler representation and the implications of upscaling processes should be investigated carefully before including them in integrated models. Therefore, in integrating complex models into a DSS, it is beneficial to test the same model at different resolutions or trying out more or less complex models representing the same process, to investigate if more detail contributes to better decisions on the representation of processes in the context of the DSS (Van Delden et al. 2011b). A point often raised is that integrated models should not be too complex, especially when they have the aim to be used in a policy context. For integrated models similar principles are true as for individual models: reduction of complexity without omitting crucial components is in many cases the best solution (Van Delden et al. 2011a).

Often the biggest challenges in model integration is not the different spatial or temporal scales of the desired models, but when the different models adopt conflicting underlying assumptions (Van Delden et al. 2011b). Many disciplines have their own specific way to construct a model and linking them is not evident. Coupling these models is often technically possible but conceptually not sound (Van Delden & McDonald 2010). In developing coupled human-natural systems van Delden *et al.* (2011a) state that there are often discrepancies between (economic) models that are developed to compute an equilibrium state and (bio-physical) simulation models that simulate future development in subsequent time steps based on a number of drivers, never reaching equilibrium. When this is the case, assumptions may need to be made that minimise the conceptual challenges involved to enable the models to be integrated in a way that does not violate the original premise of each model. Similar problems arise when attempting to integrate models that are qualitative and quantitative by nature, and when different values fall into different quantitative categories. If not handled correctly, the coupling of models adopting different paradigms can lead to conceptual incompatibilities or undesirable step changes produced as an artefact of the integration approach (Van Delden et al. 2007).

4.3.4 Design and Implementation

According to the tasks proposed by van Delden *et al.* (2011a) in Figure 7, model integration is only the third of seven steps for the successful design and development process for a DSS. The final steps involve transferring the modelling outputs into useful metrics for the end users to bridge the science to policy gap, software interface development, implementation, and use and maintenance of a prototype system.

The science to policy interface is one of the crucial elements in any DSS design and development process and creates the link between scoping the project in task 1 and model development and integration in tasks 2 and 3. Often research models are not directly suitable for incorporation in DSSs (Oxley et al. 2004). To move beyond a research model and contribute to decision and policy-making, a model needs to connect to the policy context and process and, moreover, provide added value to those working with it (Van Delden et al. 2011a). This can include clarifying terminology used, pre and/or post processing of model inputs and outputs to ensure that scenarios of interest can be simulated, and that the outputs are presented in a way that provides information on policy relevant indicators. This may require further simplified modelling or processing. On this point, van Delden *et al.* (2007) provide the example of a scientific model that can provide information about the dry matter biomass of lemons, while a policy maker is interested in the yield, or moreover the profit, of the lemon sector.

An important task for the developer of a DSS is to bridge the gap from scientific tools to user friendly systems, by creating a graphical user interface (GUI) that is easy to use, provides access to different policy options and external factors and visualises model output and indicators (Van Delden et al. 2011a). Because the types of DSSs described in this methodology encompass complex integrated models and aim to provide policy support, the GUI should be able to provide access to two different types of users: the policy makers or their resource people who use the system as part of their policy process and who carry out impact assessment studies with the model; and the scientists or modellers who can update the underlying data and parameters and possibly even the model structure. The first group benefits from a GUI that follows the steps of a scenario or impact assessment process. The second prefers to look at the system components and values easy access to individual disciplinary models (Van Delden et al. 2011a).

Implementation is a significant challenge in DSS development. Often DSS projects are produced from research projects or modelling, however without full engagement and ongoing commitment from the organisations and staff that are responsible for the decisions supported by the system, there is little chance the integrated models underlying a DSS will be used in a decision making context. This may partially be because by nature the integrated modelling involves a number of disciplines, and many organisations are still organised in a very sectoral way and integration often takes place at a rather high political level. For example, for the models reviews in the previous section, the responsible government agencies could include DFW, SE NRM Board, PIRSA and DENR.

In scoping the challenges and best practices in DSS development, McIntosh *et al.* (2011) identified four main areas that can lead to limited adoption of a DSS, and that should be the focus of DSS development:

- Engagement challenges related to the quantity, quality, and appropriateness of end user involvement in the development of the DSS, resulting in a product that is unwanted or does not address the salient questions.

- Adoption challenges stemming from a failure to take up and use the DSS as a consequence of a range of factors from lack of capacity to the characteristics of the system.
- Business, cost and technology challenges related to making the DSS sustainable in the long-term through understanding costs and using appropriate software technology.
- Evaluation challenges concerned with defining and measuring how the success of DSS can be assessed.

McIntosh *et al.* (2011) also identified a number of success criteria that can be used to maximise the likelihood that a DSS will be adopted for decision making purposes, and for assessing the success of the system once adopted, as shown in Table 1.

Table 1 Summary of success criteria for different DSSs (McIntosh et al. 2011).

DSS capacity	Success criteria	
To support policy and management decision-making	Analysis	1. Ability to produce understandable results 2. Ability to support the analyst to produce such results 3. Ability to produce results addressing end user questions
	Application	1. Tool used by the intended end users for the intended purpose 2. Tool used at all 3. Number of users 4. Number of organisations using the tool
	Outcome	1. Impact of the tool in changing attitudes, behaviours and on-the-ground outcomes
To support science and engineering analysis		1. Validation of model result against data 2. Representation of uncertainty in results
Underlying software capacities		1. Transferability and extendibility 2. Ease of system maintenance (fix and update)

van Delden et al. (2011a) note that throughout the entire design and development process, user interaction is of crucial importance; not only to ensure that their input is included in the further development, but also because including them enables social learning on the side of the users as well as on the developers' side. It is unrealistic to demand from users a detailed specification document at the beginning of the design and development process, simply because they are not aware of what can be expected and what limitations have to be taken into account (Van Delden et al. 2011a).

A final critical point that has not been highlighted thus far is the importance of rapid prototyping and evaluation and review of a DSS system. It should be noted evaluation and review feed into all DSS development tasks in Figure 7, and that any stage the development process can move back up the chain. It is unlikely that an acceptable DSS that considers all important facets of an unstructured problem will be adequately covered in a first attempt at a DSS framework, where the scoping, modelling, model integration, policy interpretation, interface design and implementation are all perfect. As such, rapid prototyping can be used to allow testing of a system that is not final, but suitable feedback can be obtained before time is lost on misinterpretations along the way. While this to and fro process could be perceived as inefficient and an unnecessary cost, an approach such as this allows for the evaluation process to occur in more of an ongoing fashion, as opposed to only at the end of the project, where often there is very little time or budget remaining to address any recommendations that are made by end users.

The iterative development of a DSS features special requirements that are not shared by all other software development (Hurkens et al. 2008). In particular, involving users in the design process can easily lead to user expectations that cannot be fulfilled (Diez & McIntosh 2009), since the relevant processes that need to be modelled are typically complex and we cannot be certain about the outcome. This can be mitigated by open communication and presenting users with a working prototype from the start, such that end users can immediately form an idea of what is possible (Van Delden et al. 2011a). For example, when the first prototype already incorporates results that depict conflicting objectives and a measure of uncertainty, users will be less likely to expect a piece of software that will tell them the best course of action to solve a given problem or achieve a certain goal (Hurkens et al. 2008).

This section has provided a short overview of a methodology for the design and development of integrated models for policy support. The reader is directed to the original article for further details on each step (Figure 7) of the DSS design and development process (Van Delden et al. 2011a).

4.4 Applications

Finally, a number of examples of DSSs that have been implemented are outlined. The list of examples presented is not intended to be exhaustive, but have particular relevance to the questions raised in regard to water management in the South East. The Research Institute for Knowledge Systems has been developing DSSs using integrated modelling since the early 1990s, and a number of the systems developed are used in similar water resource planning contexts. DSSs have been developed by different groups to assist groundwater resource management , as well as DSS for environmental water management in NSW. Each case is presented in more detail in the remainder of this section.

4.4.1 Research Institute for Knowledge Systems

For the last 20 years the Research Institute for Knowledge Systems (RIKS) has been producing software tools to support planners by allowing them to test and analyse the impact of policy alternatives on their city, region or country (RIKS 2012). DSSs have been developed by RIKS for a number of regions, including Spain, the European Union and in New Zealand. Many of these systems have been developed to assist with similar questions as those raised in the South East, identifying policy options and trade-offs with limited water and natural resources in a semi-arid or Mediterranean climate.

The MODULUS DSS, and follow on MedAction DSS, were developed to capitalise on a large amount of new knowledge and research material that has been obtained from projects carried out under a European Environment and Climate Programme and produce a generic spatial DSS for integrated environmental policy-making at the regional level. The aim of the systems was to support policy impact assessment studies in the field of regional development and desertification in Mediterranean regions, integrating climate change, hydrology, aquifers, irrigation, crop choice and land use. A series of models were linked into a single systems model simulating the linked bio-physical and socio-economic developments in a region up to 30 years into the future. Models were integrated representing the climate and weather, hydrology, sedimentation, salinisation, water use, water resource, land use, profit, plant growth, land management and dynamic suitability of a location for a given land use (Van Delden et al. 2007).

The MedAction DSS provides an example of an application of the DSS development methodology outlined in the previous section (Van Delden et al. 2011a). Broad themes for the system were sustainable farming, water resources and land degradation. The current issues related to these themes include the availability of water, how to price the water, and how to preserve existing forests (Van Delden et al. 2007). While the models developed are specific to the regions considered, the linking between policy themes, measures and indicators developed for the project can be seen in Table 2, many of which are relevant to water resource management around the world, including the South East of South Australia.

The MODULUS and MedAction DSS had a strong focus on finding scientifically correct methods for integrating models with different temporal resolutions and modelling paradigms. The DeSurvey Integrated Assessment Model (IAM) built upon these points to focus on comparing and evaluating model complexity and spatial resolution. Furthermore, the DeSurvey IAM has evolved into a modelling framework, which allows the users to create a Policy Support System for a specific location and a specific resolution by using the components that are included in the framework, as well as by adding new components to the model library of the framework (Van Delden et al. 2009). While this does not add directly to the capability of the DSS from a users' perspective, the methods developed and learnings from the project are extremely useful for developing a DSS and dealing with the questions of scale and conceptual incompatibilities when integrating models from different domains and disciplines.

Another application by RIKS of interest to South East water planning is the WISE DSS long-term integrated planning DSS, integrating models of the biodiversity, economics, demography, land use change, water quality and water resources for Waikato regional council in New Zealand**.** In New Zealand local councils must develop long term community plans that must (Rutledge et al. 2008):

1. identify, prioritize and integrate economic, social, cultural and environmental outcomes that the community wants to achieve in the long term,
2. describe council actions to achieve those outcomes,
3. must be for at least 10 consecutive years, and
4. provide "integrated decision-making and co-ordination" of council resources.

This requirement has a number of parallels with the requirements of Natural Resource Management boards for water allocation and planning. The WISE DSS integrates models at four spatial scales (global, regional, district and local). The tools developed through the project were used to identify links and trade-offs between economic, environmental and social/cultural outcomes, including cumulative effects over space and time (Rutledge et al. 2008). The DSS is currently used to inform the council planning process by highlighting the potential changes and consequences, either positive or negative, to the region and that informs the council and community about what actions to take to avoid adverse effects or achieve beneficial outcomes (Rutledge et al. 2008).

Table 2 Linking themes, policy measures and indicators in the MedAction Policy Support System (Van Delden et al. 2007)

Themes	Policy Measures	Indicators
Sustainable farming		
Long term profits	Subsidies, taxes	Profit
Sustainable land use	Water price	Crop type
	Water availability	Number and location of abandoned cells
		Dynamic suitability maps
		Irrigation Water used from different sources
		Amount and cost of irrigation water
Water resources		
Availability and price of water	Water availability and price	Change in aquifer and reservoir budget
	Amount of Water from outside the region	Natural Water input (runoff and recharge)
	Construction of desalinisation plants	Costs and Amount of water used
Land degradation & desertification		
Erosion	Afforestation	Fertile soil depth
	Grazing regulations	Erosion rates
	Construction of check dams	Change in storage capacity of reservoir
	Dredging	Total cost of Dredging
Preservation of nature and forests	Afforestation	Forested area
	Zoning	Changes in Natural vegetation type groups
		Dynamic suitability maps
Salinisation	Maximum amount of water available from aquifer and desalinised water	Soil salinity
		Salt concentration in the aquifer
	Maximum allowable percentage of salt in desalinised water	Restricted factor for plant growth (yes/no)
Sustainable land use in region	Zoning	Land use map
	Construction of infrastructure (dams, roads, channels)	Dynamic suitability maps

The LUMOCAP Policy Support System (PSS) (http://agrienv.jrc.ec.europa.eu/indexlm.htm) was developed to assess the impact of the Common Agricultural Policy (CAP) on the land use and landscapes of the 27 countries of the European Union (Van Delden et al. 2010). The system incorporates models for agricultural economics, national and regional interaction of population and jobs, land-use allocation, crop choice and suitability. It uses scenarios for climate change, socio-economic developments and policy alternatives as external drivers. It encompasses processes operating on four spatial scales: all 27 European countries, national, regional and local scales. The LUMOCAP PSS models processes at the local level at two different spatial resolutions: a 1km resolution for the entire European Union and a 200m resolution for specific case regions. The temporal resolution of all models is one year and the time horizon of the system is 2030 (Van Delden et al. 2011b). The scale of this system, covering approximately 4.3 million km^2, indicates that large scale DSSs can be developed to support the analysis of policy alternatives when this is the focus of the models underlying the systems, and the scale and level of detail has been selected appropriately. At the same time, the system also shows that it is possible to embed more detailed modelling for selected areas in the DSS, for example for hot spot areas.

All applications outlined in this section adopt a temporal extent of 25–50 years, which was selected due to their relevance for policy support. Through these studies a number of valuable learnings are available, both technically on approaches to dynamically link models of different conceptual bases with different temporal and spatial scales, as well as outcomes for long term policy planning in a water resources context for temperate to semi-arid regions. The DSSs were developed in the RIKS Geonamica® framework, designed for the development and application of DSSs to support policy and planning (Hurkens et al. 2008). This system, amongst others, is outlined in more detail in later in this report.

4.4.2 Gnangara Sustainability Strategy

Similar water resource demands to those in the South East are experienced near Perth, where the combination of lower rainfall since 1975, maturing pine plantations over a shallow aquifer, and increased water extraction has resulted in falling groundwater levels in the Gnangara groundwater system. The Gnangara Mound is a large unconfined surface aquifer and in many locations the watertable is close to the surface. As a result, many significant environmental features, especially wetlands, are dependent on accessing the watertable for their existence. A DSS has been developed for the region adopting innovative modelling approaches to assist in better decision making by modelling the feedback loops inherent in the system and to analyse the impact of alternative land use and water policy in order to better understand the trade offs (Elmahdi & McFarlane 2009). These options included future land use changes, new water allocations, post pine land use options, establishing GDE requirements and bush burning regimes (Elmahdi & McFarlane 2009).

The need to develop a DSS was identified, that considered the key aspects of the region, such as hydrological, hydraulic, environmental, socio-economic, finance-economic, institutional-legislative and political-strategic factors (Elmahdi & McFarlane 2009). The DSS was developed to predict and assess the effects of any actions by performing an integrated analysis of environmental and socio-economic aspects. Scenario analysis, as opposed to formal optimisation, was implemented for two reasons: 1) there was a need to comply with vast numbers of rules and regulations that are related to water resources planning and management but often are not provided in an integrated, harmonised and rational framework, and 2) the preference for community participation in decision-making processes. However, these reasons do not preclude the use of appropriate optimisation frameworks, and such frameworks may be beneficial when the number of options to consider is large.

Elmahdi and McFarlane (2009) outlined a number of criteria for the potential use, development and future updates of a DSS for the Gnangara groundwater system. Many of the criteria identified for this particular DSS closely correspond to those already summarized in this section in a more general context, such as:

- The DSS should be able to assess land and water management options to provide quantitative assessment (with acceptable technical level).
- It can address several scenarios (climate, land uses, land management, water allocations).
- It can incorporate available economic, social and environmental data and values.
- It should be able to communicate scenarios (climatic/water and land) to managers and informed community members.
- Spatially distributed information can be included (but not dynamically linked to GIS at this stage) and should not highly lumped.
- It should be able to incorporate a regional groundwater model.
- It should be able to assess different scenarios using different time horizons (for example 2030 and 2050).
- It should be able to include monthly time-steps (to align with climate, PRAMS, groundwater monitoring, seasonal water use).
- The structure should be able to be adapted to incorporate more detail as required for specific areas/sub-area/ landuse as it becomes available.
- It should be well documented and clear so that it can be used and modified by many people for building capacity (i.e. not dependent on a single user).

A system analysis modelling approach was utilized, and an approach such as this has been recommended for the South East previously (Daniell 2010), as seen in Figure 2. System analysis modelling offers an efficient approach to most effectively utilize available data and understanding of the processes, based on four basic building blocks; stock, flow, connector and converter. Stocks (levels) are used to represent anything that accumulates (e.g. water storage), flows (rates) represent activities that fill and drain stocks (e.g. releases or inflows). Connectors (arrows) are used to establish the relationship among variables in the model, and carry information from one element to another element in the model. Converters transform input into output (Elmahdi & McFarlane 2010). The interactions between processes presented by Elmahdi and McFarlane (2009) in Figure 9 adopt similar concepts to the general DSS methodology later proposed by van Delden et al. (2011a), where external drivers and policy measures influence indicators, or impacts in this case. As with the MedAction DSS, the criteria, drivers and indicators and modelling approach taken provide valuable input to a DSS for the South East of SA.

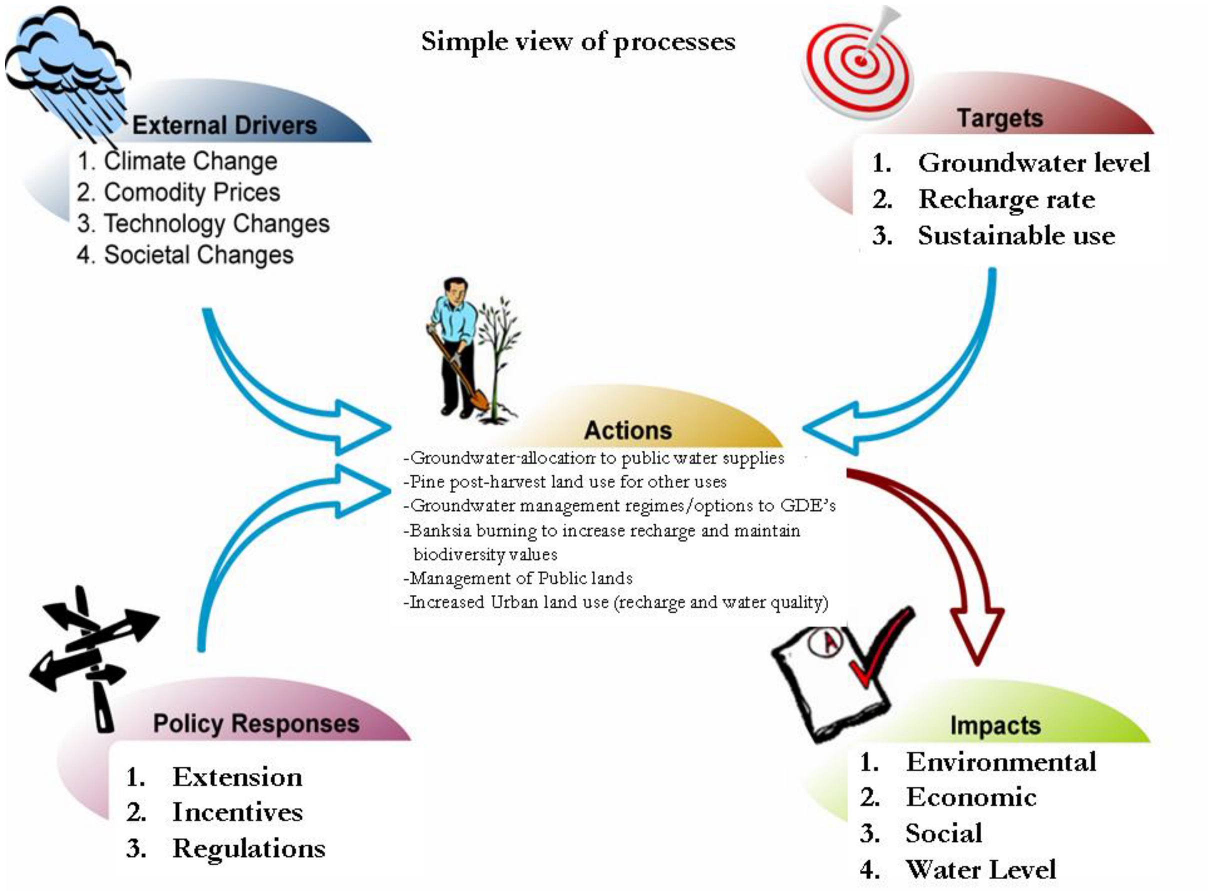

Figure 9 Interaction between processes for the Gnangara Groundwater DSS (Elmahdi & McFarlane 2009)

4.4.3 Decision Support System for the Macquarie Marshes

Another DSS application relevant to a slightly different aspect of water resource management in the South East is the DSS developed by Merritt et al. (2009). The IBIS DSS was developed to explore the likely outcomes of catchment water planning scenarios on the ecological characteristics of the inland wetland systems in NSW. The aim of the DSS was to improve the capacity of organisations (mainly the NSW Department of Environment, Climate Change and Water, DECCW) to plan and manage environmental flows at valley and wetland scales. Using similar methods, the VegBN DSS was developed to assess the effectiveness of NRM interventions on native vegetation quality on private land in northern Victoria (Merritt et al. 2010). The underlying model base of each DSS is comprised of Bayesian Network (BN) models linked with other BN or component models, such as IQQM hydrological models. Bayesian networks have proved to be a flexible and highly valuable approach to modelling such highly complex and uncertain environmental systems, as they can add rigour and transparency to decision-making processes (Merritt et al. 2010).

The capacity of BNs to use different types and sources of data from diverse disciplines (e.g. social science and ecology), and explicitly represent uncertainty has the potential to support NRM by describing realistic outcomes and adding flexibility to the decision-making process (Merritt et al. 2009). Major challenges to the use of BNs in modelling complex environmental systems include the elicitation of expert knowledge and updating of beliefs in large networks, incomplete data sets with which to train the network, and the difficulty of incorporating feedback loops (Lerner et al. 2011a). BNs were selected for the IBIS and VegBN DSSs because they can be used to integrate across complex systems and scientific disciplines, communicate predictions effectively, and thus assist catchment managers make informed management decisions (Ticehurst & Pollino 2007).

The purpose of the IBIS DSS is to enable the primary user of the DSS (DECCW) to compare scenarios relating water delivery (volume and timing) to ecological outcomes in order to provide a consistent, transparent and scientifically rigorous decision-making process. To do this, the DSS links outputs from hydrological models (producing daily time series of inundation area, flow, and volume), to Ecological Response Models (ERM). The ERM are Bayesian networks representing important ecological function, vegetation species and communities, and waterbird and fish species in the wetland system (Merritt et al. 2009). The DSS contains models and data from DECCW and other research programs and is being developed to allow updates over time as information and knowledge improve.

A major criticism of BNs in the scientific literature has been the inability to incorporate temporal dynamics or feedbacks in the network (Lerner et al. 2011b). Given that most complex environmental systems (e.g. wetlands, estuaries) are highly dynamic in their behaviour – further complicating the task of the managers of these systems – greater emphasis is starting to be placed on developing dynamic BNs (Shihab 2008). This was overcome in the IBIS DSS by firstly processing time-series outputs from the hydrology model into ecologically important events: flood duration (number of months), flood timing (month), flood area index and the inter-flood dry period (number of months). Then the outcomes of the environmental response models for a previous event were used to inform the modelled ecological response for the next event to represent the feedback loops from one event to the next (Merritt et al. 2010).

This management question, of assessing scenarios of water delivery to benefit ecological outcomes, is extremely relevant to the operation of the Upper South East drainage network, where water volumes can be manipulated and delivered over a large proportion of the region for different ecological outcomes. Currently these decisions are made through a planning phase at the start of each year, based on wetland complexes or watercourse that have not received water recently, or that require water most years. The plan is then adapted over the flow season based on how the rainfall and flow events unfold. However, the process could be improved by including environmental response models to evaluate the likely benefits from different levels, or timing, of inundation. For example, a similar benefit may be able to be obtained from a much smaller diversion volume, which then allows some of that water to improve the outcomes in another wetland complex. The use of hydrological models to estimate volumes, timing and levels of inundation, to provide input to an ecological response model, in the form of Bayesian Networks or otherwise, has been demonstrated to be a successful framework for a DSS in the Macquarie Marshes. A DSS based on a framework such as this is likely to also provide valuable assistance to the operation of drains in the Upper South East, where the existing Wetland Vegetation Component rules could be extended to include other biota and encompass probability tables of responses to the different components of inundation, the building blocks of BNs, and hydrological models extended to provide estimates of the necessary inputs, such as inundation duration, depth and timing, as well as length of dry periods.

4.4.4 Water Allocation Decision Support System

A Decision Support System was developed to assist with water allocation (called WADSS) in NSW for two large sub-basins of the Murray – Darling system, the Gwydir (42 000 km^2) and Namoi

(25 900 km^2) (Letcher et al. 2003, Letcher et al. 2004, Letcher 2005, Croke et al. 2007). The system considered scenarios of changes to water access, allocation and pricing across three water systems (unregulated, regulated and groundwater) evaluated tradeoffs between socioeconomic (agricultural production) and environmental (flow indicators) factors. The project was a collaborative undertaking with input from NSW Agriculture, the NSW Department of Infrastructure, Planning and Natural Resources, the Australian Cotton Cooperative Research Centre and irrigator groups.

The evaluation of these socioeconomic and environmental factors is achieved using a coupled model approach, including hydrological, policy, economic and extraction sub – models. The models operate by simulating the daily streamflow in a region for a particular climatic condition before being fed into the policy model. This gives the total volume of water available for irrigation in each month, which is used in the economic model to determine farmers' decisions on water management, irrigation practices and crop planting (areas and types). The total water extracted from the stream is then calculated and the remaining water flow is available for input into the downstream region (Croke et al. 2007).

The WADSS has been developed in a modelling platform, ICMS, developed by CSIRO Land and Water. This platform allows for development of a model and data base which can be overlaid by custom built Graphical User Interfaces (GUI). This approach allows for rapid development and testing of both models and interfaces. Model development in ICMS uses a semi-object oriented paradigm, with classes of objects being defined which can be associated with numerous procedural models. An instance of a class (or object) is then associated with a specific model code and a set of data. The WADSS consists of a generic DSS structure and concept, which is encapsulated in a set of classes and a generic interface, consisting of the code and standard content files; and, specific applications of this generic structure and concept. These applications are defined by an object configuration, a data base and object specific model choice, and a set of application specific files which tailor the interface to the catchment. In this way the DSS concept, structure and interface is able to be reapplied to new catchment situations (Letcher 2005).

An application of the DSS of interest to the South East was an assessment of the impact of activation of unused water licences, where a significant proportion of allocations are not currently extracted from the aquifer, but potentially could in the future. The tool was run for various percentages of currently unused (or sleeper) licence activation throughout the basin, where it was found that a decrease in downstream landholders' profits occurred after activation of 40% or more of these unused licences, and a reduction in non – zero flows for after 60% or more of the unused licences were activated.

Stakeholder participation was an important component of the model development process. Workshops were held to identify the controls on water use and drivers for on-farm water use, and to refine and test the model (Croke et al. 2007), as well as allowing for analysis of a library of pre-run scenarios, sharing of scenarios between users, and creation of new scenarios live in meetings and workshops. Development of the system also involved substantial stakeholder involvement, aimed at (Letcher 2005):

- giving stakeholders a greater sense of ownership of the models, results and the DSS by incorporating their comments and ideas into the system;

- obtaining feedback on project directions, model assumptions and interface design
- obtaining information and data necessary for groundtruthing or calibrating the models in the system; and,
- increasing the awareness of stakeholder groups of the existence of WADSS, its potential uses and limitations.

4.5 Summary

This section has provided a review of recent literature on the definition, characteristics and best practices for the development of DSSs for policy support. These studies generally consider DSSs that represent software that is based around integrating (the results from) a number of models, and allowing for the feedbacks between them, to assess long term policy options. This approach is generally necessary for these types of questions, as 1) models are required to simulate untested possible future scenarios (as opposed to interrogating past datasets) and 2) it is unlikely that one model can represent all salient factors that are of interest for a region.

However, for short to medium term decision support the value of databases, and sophisticated analysis of such datasets, should not be overlooked. While there will always be errors and uncertainty associated with observed values, these errors are likely to be much smaller than those produced by models in the fields of interest, especially in the hydrology, hydrogeology and ecology of the South East. A data based approach can be used to indentify undesirable trends and assess short term changes based on past conditions. However, the significant limitation is the inability to evaluate new scenarios and the limited (either spatial or temporal) coverage of the monitoring network, both of which may be addressed to some extent using modelling approaches.

Based on international experiences in developing and assessing the uptake of DSSs over the past one to two decades, a number of best practice guidelines and methods have been proposed. These have been based on experiences in what has and has not worked to 1) produce a DSS relevant to the policy questions posed, and 2) maximise the likelihood that the system produced is actually adopted by the authorities responsible for decision making in the region considered. van Delden et al. (2011a) outline a methodology for the design and development of integrated models for policy support to develop DSSs to inform policy making. This report fits in at step one in the process, defining the scope of a suitable system. Consideration to the following steps is also made, however the evaluation process is likely to evolve the requirements in time. Step two is model selection, and from the previous section it can be seen that while a great deal of work has been undertaken for a range of purposes, there are limited existing models that are in a form suitable for integration into a regional scale decision support system. In the following section, a first step to applying these guidelines to the different decision options in the South East is undertaken.

5 Proposed Decision Support Frameworks

Two DSS frameworks already exist in the South East, and a significant investment has already been made in these systems, by people with substantial local knowledge of the South East. It would be foolish to discard these systems in the anticipation of a 'silver bullet' DSS that promises to answer all the questions of the region in one system. These frameworks are the Water-RAT and Flow Management DSSs. These two systems provide a solid foundation toward assisting decision making in the relevant area. In the following sections, each is considered in more detail and suggestions made for further improvements.

Both existing DSSs are focused on short term (season to annual) or one off decision making, planning and operating the drainage network over the course of a flow season, or assessing if a water extraction development application should be approved on a case by case basis. What does not exist is a tool to assist long term (multi-year or decades) planning, to ensure sustainable use of the water resource while maintaining economic growth in the region. Following the methodology for the design and development of integrated models for policy support outlined in the previous section (Van Delden et al. 2011a), a framework for this purpose for the Lower South East is scoped in the remainder of this section. The operational DSS has been termed the Upper South East DSS, and planning tool Lower South East DSS, however this spatial delineation is not necessary, and it is the prominent decisions of interest and time scales involved that define the different tools. Before outlining frameworks for these two DSSs, the ongoing requirements of the existing Water-RAT tool for assessing development applications are provided in the following section.

5.1 Water Dependent Ecosystem Risk Assessment Tool

The Water-RAT has been developed for a specific purpose, to inform water management decisions and development application referrals based on risks and threats to water dependent ecosystem assets and processes in the South East. The collation of relevant datasets from many different agencies responsible for the datasets into one system, as well as the integration of a risk assessment approach to inform water planning, is an extremely valuable tool. Given the problem and relatively short time frames involved in assessing development applications, the Water-RAT is likely to be best suited as a DSS in its existing form, as opposed integrated into a broader DSS that is used to assess a number of different planning and policy questions. However, the information contained in the Water-RAT layers and databases is likely to be a valuable resource to be imported into a larger system such as this.

As noted by Harding (2009), a significant risk to the Water-RAT is the level of resources required for ongoing support of the tool and keeping the data up to date. The layers produced for the Water-RAT project are largely date specific and require regular updates. In order to keep the application relevant, a system for on-going responsibility for maintenance and update of the layers needs to be in place (Harding 2009). Harding (2009) provides a table with recommended update schedules for layers within the South East Water-RAT and the agencies responsible for provision of raw data and/or processing of the outputs. The recommended update period ranged from rarely required at all, for example the location of permanent pools, to a minimum six monthly update, for example the location of significant wetlands, groundwater levels and threatened aquatic flora, fauna and migratory birds, with many layers requiring an annual update.

There is the possibility that much of the necessary updating required could be automated, for example live links to DENR biological data could be used for threatened aquatic flora and fauna and migratory birds datasets (Harding 2009). Similarly, groundwater levels could be updated directly from the Observation Well database, with the processing required to convert the point observations in time to the spatial layers used in Water-RAT undertaken by a simple programming script. Similarly, if the system was extended to include surface water information, this data could also be obtained directly from telemetered systems. Automating as much of the data updates as possible is likely to provide the greatest likelihood of keeping datasets up to date, however this is not a trivial process, and ongoing support for quality assurance testing is still required.

This updating process is a necessary requirement of the existing tool. Harding (2009) also outlined a number of technical advancements that could be implemented to improve the risk assessment and outputs of the Water-RAT. These were summarised in the model review section, and include identifying and including surface water and groundwater catchment areas for significant GDEs in the system, investigation of climate change scenarios, identification of limits of acceptable change in groundwater level and buffer zones for different wetland typologies, and potential improvements in the analytical equations used to model groundwater drawdown for different development applications.

5.2 Upper South East Flow Management DSS

As noted in the modelling section, the existing Flow Management DSS for the USE drainage network provides a detailed database of the location and function of the USE drainage network, including regulators, functions of the regulators, wetlands and drain locations and requirements. The system is currently used for planning of operations for the upcoming season based on targeted environmental objectives and a record of wetlands assets that have received water recently, or are in need of water diversions. The telemetered flow and salinity stations in the drainage network are monitored over the flow season, and notifications alert operators that a trigger that was set in the planning phase has occurred, and requires intervention. Any changes to the regulators in the network are documented to facilitate review processes in the future. Finally, the DSS supports a review phase that is used to assess the performance of the operations of the drainage network against the objectives set at the start of the year, with the goal to assist adaptive management in the future.

The DSS is currently being extended to include infrastructure in the Lower South East, and the platform is likely to be updated based on the outcomes of an ongoing project in DFW for a decision support system as part of the Riverine Recovery project. A significant focus of the DSS has always been on documentation, to provide justification for why decisions on operational management were made, and what the basis was for those decisions. This is an extremely important function, for example in the circumstance that the operating authority is challenged for adverse impacts that occurred due to a management operation that was undertaken. A relevant example for the drainage network is the potential flooding of private land, and potential damage caused by such flooding, which may occur if drain channel capacity is too small for the flows directed along that section of drain.

The main area for development in the existing DSS is to include water balance and forecasting abilities supported by modelling, to provide an indication of the likelihood of meeting management objectives, to assist the planning phase by enabling if-then type scenario analysis, and to fill in information about expected water availability or delivery in areas where monitoring is not available. This water balance information from a hydrological model can also provide input to an ecosystem response model, to allow the expected benefits from a possible inundation event. The IBIS DSS reviewed in the previous section provides an example of a DSS framework such as this that has been successfully used for environmental management decision support in Australia.

5.2.1 Scope Definitions

In terms of the DSS development methodology of identifying policy themes, drivers and indicators, the existing DSS has implicitly identified these important features, through the incremental development of the system. The three, often competing, themes are supporting the ecological status of the existing wetlands in the region, minimising flooding out of the drains and wetlands onto private land, and improving the agricultural pastures along the drain alignments. Through the removal of saline groundwater near the surface along the drains, the evaporation of this water can be reduced, and along this reduction in evaporation a reduction in dryland salinity. Also, through the discharging of groundwater to the drains, it is possible for salt in the soil profile to be leached out, improving the quality of the soil for agricultural purposes. Landholders are required to pay a levy for these benefits of the drainage network and hence operation of the network for this purpose is one of the overarching themes of the DSS.

The two drivers common to each of the three themes for the operation are the external driver of climate, and the manageable driver of the operation of the regulators within the drainage network and wetland sills. The indicators of successful outcomes are then the water quantity and quality available in the network, the periods of inundation experienced around the region (generally a positive outcome in wetlands, and a negative outcome on private land), the ecosystem response to the water quality and periods of inundation, peak flows to assess the suitability of drain capacities, and the interaction between surface water in the drain and shallow groundwater tables under agricultural land to assess the impacts on dryland salinity. The resulting themes, drivers and indicators identified for the operation of the Upper South East drainage network are given in Table 3.

Table 3 Themes, Policies and Indicators for operation of the drainage network in the Upper South East

Themes	Drivers: External	Drivers: Management	Indicators
Ecological Condition	Climate	Drain Operations	Ecosystem response Water quality Surface water availability/Periods of inundation Natural water input (runoff and recharge)
Flooding	Climate	Drain Operations	Peak flows Surface water availability/Periods of inundation
Agriculture	Climate	Drain Operations	SW-GW interaction Water quality

5.2.2 System Framework

Based on the identified drivers and indicators, the models required to assess the impact of different scenarios of the drivers (climate and drain operations) on the important indicators can be specified. The necessary models have been identified as a hydrological model, to convert rainfall to runoff and allow the impact of drain operations on water availability in the landscape to be simulated, a water quality model, specifically salt transport, as this has a significant impact on the suitability of available water for ecological purposes, and an ecosystem response model to assess the likely benefits from different inundation depths, durations and water quality. The proposed linkages of information between the drivers, models and indicators is shown in Figure 10.

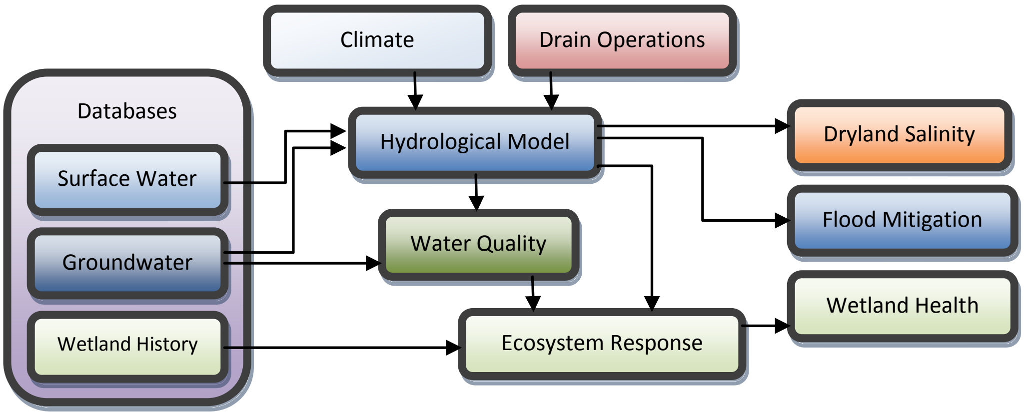

Figure 10 System diagram for the flow of information between models supporting a USE drain operation DSS

From the flow of information, it can be seen that the hydrological model is a key component of an integrated modelling DSS to support drain operations. This model should have the capability to simulate different climate scenarios and drain operations, and simulate the flows expected at numerous points in the drainage network on a daily time step. The hydrological model should consist of three components. The first is the catchment component, converting rainfall and evapotranspiration inputs to the runoff expected from the contributing catchments in the South East. The second component is the routing of these flows through the drainage network, incorporating the drain operations along the way. Given the distances involved in transferring water around the Upper South East, the transmission losses or gains along the open channel drains are an important process to incorporate. As outlined in the model review section, the SourceIMS platform includes the groundwater surface water interaction tool, which uses simple analytical relationships to calculate the flux between the drain and adjacent groundwater table. This flux calculation will provide the direction of flow (gaining to or losing from the drain), and hence may be able to inform the impact of the drain operations on dryland salinity, one of the key indicators of the impact of drain operations on agricultural production in the Upper South East.

The final component of the hydrological model should be to include the storages in the system, representing wetlands and floodplains of interest. This component of the model will provide information of depths, areas and durations of inundation for input to an ecosystem response model, and also identify any potential negative impacts resulting from the flooding of private lands, another important indicator for the operation of the drainage network.

Another equally important model is the ecosystem response model (Figure 10). This model should take the outputs from the hydrological model, in the form of levels, areas and durations of inundation, to provide an indication of the expected response of the ecosystem of the wetland, or wetland complex, subject to the inundation. Depending on the wetland hydrology and species present, different response models are likely to be necessary for different wetland typologies. The current Wetland Vegetation Components provide an indication of the requirements of each wetland based on the dominant vegetation present, however currently they only provide a yes/no outcome if the requirement is met or not. In order to assess different scenarios of trading off delivery volumes to different wetland complexes, the expected response of the wetland ecosystems to different levels of inundation is likely to allow for more detailed analysis. A suitable level of modelling detail should be the subject of further research, such as the Bayesian Network approach of the IBIS DSS has been successfully applied in NSW (Merritt et al. 2009). It is unclear if a suitable level of data or information is available in the South East to support such a model, and a review of existing studies that encompass key indicator biota for the different ecosystems present in the south East (not just vegetation) should be undertaken to determine the extent of further field studies that may be required. However, this lack of data does not preclude the development of the structure of a BN ecosystem response model, with parameters to be derived or updated as more information becomes available.

A water quality model is the final model seen in the framework proposed in Figure 10. In this context, water quality refers to salinity, however nutrients and pH are also becoming a concern in some wetlands in the South East. However, it is salinity that is a regular deciding factor on whether drain water is suitable or will be beneficial to a given wetland complex. As noted in the modelling section above, salt transport modelling remains a challenge for both surface and groundwater modelling in the South East. However, with improved hydrological modelling, including specific concern to the representation of fresher direct flows and saltier base flows, the ability to simulate salt transport through the network may improve. Another important input for salt transport modelling is the spatial variability in the salinity of the groundwater contributing to the drain base flows, which is expected to be highly variable in space and at this point relatively unknown. Nonetheless, the salinity of water available to be diverted into a wetland is likely to be an important input to an ecosystem response model.

As a drain operation DSS is expected to be used to support decisions over a relatively short time period, the current state of the system is an important input to the simulation models. Hence, the databases inputs shown in Figure 10 are an important component of the framework. The groundwater observation well database is expected to provide important inputs on water levels for the interaction with drain water in the hydrological model, as well as groundwater salinity for a water quality model. Groundwater observations are generally taken at a quarterly interval in the South East, and time series models, such as HARTT (Ferdowsian & Pannell 2009) or the improved approach of Peterson and Western (2011) may be useful to interpolate the observation to the daily time step of the hydrological model. It is unclear if a more detailed representation with a numerical model is required to adequately represent the groundwater levels as well as fluxes with the drains, given that Love et al. (1993) describe the USE as a system where flow in the unconfined aquifer is dominated by local recharge and discharge, rather than recharge in one end of the basin and lateral flow through the rest of the basin (Wood 2010).

Given the influence of dry periods on ecosystem responses, a database of historic events of when and to what extent important wetlands and wetland complexes have been inundated is likely to be a valuable input to an ecosystem response model. A database such as this is already part of the existing Flow Management DSS, and is used to identify wetlands that have a high priority when planning the operations for an upcoming winter season. Finally surface water flows are also likely to be a valuable input, to check and correct, or assimilate, with the hydrological model outputs. Given the telemetered sites provide up to date information in the South East, this information can be extremely valuable to update the projections of the models over a flow season, and to provide an indication of the confidence of the model outputs at the telemetered sites, and by inference the points where there are limited data available.

Formal optimisation procedures may be useful to maximise outcomes and consider the tradeoffs between the different themes of the drain management (Table 3). This is especially the case if the number of possible management options becomes large, for example considering the timing of operations throughout the year, multiple wetland complexes across the region, and the degree of opening of different regulators (usually the number of logs placed in the drain, or partial opening of sluice gates). This is a conceivable occurrence, given the REFLOWS drain and if further connecting drains between the lower and upper south east are realised, where drain flow can be diverted anywhere from Lake George to the Coorong South Lagoon, a distance of approximately 200 km, notwithstanding the many significant wetland operations decisions in-between. The timing and volumes available in the drainage network to be managed is largely influenced by the rainfall pattern. As this pattern is unknown months in advance, a feasible forecast horizon is yet to be identified.

A DSS based on integrated modelling, as proposed in the framework presented in Figure 10, will have the ability to add value to the short to medium term planning of drain operations. This is likely to occur through assessing the likely environmental benefits produced, while minimising adverse flooding impacts and maintaining improvements in soil salinity, based on a limited volume of water available, as determined from different climate scenarios. A DSS such as this is likely to provide valuable further inputs to be considered when planning management operations for an upcoming winter season, as well as throughout the season, as events are occurring based on the rainfall patterns experienced.

5.3 Lower South East Planning Decision Support Framework

While there are a number of drains in the Lower South East, currently the abilities or needs to operate these systems for short term environmental, agricultural or flood protection outcomes are limited when compared to the Upper South East. However, this may change in the future, and if this is the case, integration of these additional drains into a system such as that outlined in the previous section is likely to be beneficial. The objective of the DSS described in this section is long – term water resource planning for the region, which is more of a focus in the Lower South East and border zones. The overarching objective of a long term water planning DSS is likely to be to ensure sustainable extractions for development to occur while preserving the ecological and social function of the region.

The main benefit of a long – term planning decision support framework is an integrated approach to enable evaluation of different potential policy or management scenarios. In order to evaluate scenarios, models are required to simulate cases that are not represented in historic datasets. The review of modelling, along with previous studies, has highlighted that generally highly desirable models are currently not in a form to directly inform policy settings and decision making. Groundwater models have been constructed and have provided valuable contributions to the intended purpose of the project and to the conceptual understanding of the region, however currently are not at the scale of interest for policy decisions, most notably water allocation planning (for the Lower Limestone Coast PWA at least). Surface water models have been developed that provide an acceptable representation of gauged catchments, however regionalisation of the models to the majority of the region that is not gauged is questionable, and the conveyance of runoff along the drainage network is not representative of the processes occurring, and hence provides limited confidence when used for decision making purposes. Ecological requirements of many of the wetlands of the South East have been initially described by WVCs, which have scope to be simplified and assigned to each wetland based on the dominant species present (Cooling et al. 2010). While the WVC components propose untested wetland requirements, they still do not provide an indication of the ecosystem response, and what the likely response might be if the requirements are only partially met. Similarly, there has been little work in agricultural productivity and economic modelling, which is a large component required to assess both the impacts and benefits of agricultural and industrial development resulting from different planning scenarios.

In the following section, a process similar to that undertaken for the Upper South East drainage DSS is presented for sustainable water use in the Lower South East, working through the themes, drivers and indicators for the region, and the modelling framework required to support such a system. This is followed by a number of points of consideration for developing a system, such as the need for a database to store relevant information on processed datasets and previous studies, handling of uncertainty, and provenance frameworks. Finally, a number of software frameworks available to implement such a DSS based on integrated modelling are outlined.

5.3.1 Scope Definition

The DSS development methodology (Van Delden et al. 2011a) begins with a description of policy themes, drivers and indicators that have been identified from recent studies and knowledge. The outcomes are outlined in Table 4, organised by theme and then driver. As described in the previous section, drivers in this case are components that are input to the DSS, and that can be altered as part of a scenario, where indicators refer to output of the DSS, which can be used to assess the effect of drivers. Because some drivers influence processes in more than one theme, and because some indicators can express the influence of several drivers, some appear more than once in Table 4. The list provided is not intended to be complete, and provides a starting point for the incremental development and review DSS development process (Figure 7).

5.3.1.1 Themes

The critical themes identified that are unlikely to change in the medium term are largely driven by the need for decision-making processes to integrate both long-term and short-term economic, environmental, social and equity considerations. Obviously the water resource is a critical theme of interest, and preserving or improving the ecological status, social values and agricultural and industrial development in the region are the factors that are largely dependent on and influence the condition of the water resource.

Table 4 Themes, Policies and Indicators for long term water resource planning in the Lower South East

Themes	Drivers		Indicators
	External	Policy	
Water Resources	Climate Demographic development	Water allocation Water pricing Referrals and Approvals Subsidies/levies Infrastructure	Groundwater levels Water quality Abstractions/licensing/ water demand Surface water availability/Periods of inundation Natural water input (runoff and recharge) Change/deficit in water balance
Sustainable Agriculture and Industry	Climate Demographic development Economic factors	Water allocation Water pricing Referrals and Approvals Subsidies/levies Infrastructure	Productivity/Yield per ha Crop type/change in land use Crop price/Profit Groundwater level Water quality (salinity/nutrients) Natural water input (runoff and recharge) Change/deficit in water balance Soil Salinity Abstractions/licensing/water demand
Ecological Status	Climate	Water allocation Zoning Referrals and Approvals Subsidies/levies Infrastructure	Wetland area/change in land use Ecological indicators of ecosystem response Groundwater levels Water quality (salinity/nutrients) Surface water availability/Periods of inundation Natural water input (runoff and recharge) Change/deficit in water balance
Social Values	Climate Demographic development Economic factors	Water allocation Zoning Subsidies/levies Infrastructure	Maintain wetland values Equitable outcomes Fish stocks Natural water input (runoff and recharge) Change/deficit in water balance

5.3.1.2 Drivers

Drivers are divided into external and policy drivers. External drivers are events that are outside of the control of the decision making process for the region, yet will have an influence on the themes identified. A large component of the inputs to the available water for the region is derived from the climate, particularly the rainfall over the winter period, defined from approximately April or May to September or October. An external climate driver will allow scenarios to be assessed for different climate conditions, historical average conditions, extended wet or dry periods, as well as climate change projections for the future.

Larger scale economic and demographic factors are also likely to be external drivers that influence sustainable water use in the region, where demographic factors population scenarios will affect the demand and distribution of this demand on the water resource directly. Economic factors will influence the industrial and agricultural practices in the region, and through changes to these practices the demands on the water resource may also change. For example changes to meat or wool prices may influence decisions by land holders in the region, as well as processing options and final prices for timber produced in the region may influence future planting rotations.

Policy drivers are defined as the factors that can be influenced by policy makers by developing regulations, water allocation plans or economic incentives, for example. These are the levers that policy makers can use to influence society. The obvious policy driver is the water allocation process, to be used to control how much can be extracted from different management areas. Contained within this driver, scenarios for the fraction of recharge allocated or different management boundaries and sizes may be considered. Similarly, the referrals and approvals process is listed, where different scenarios of buffer zones, trigger levels or salinity thresholds may be tested. Water pricing is a possible instrument that could also be used to balance water use, where hypothetical cases may be tested to investigate the impact on key indicators.

Other policy drivers that could be included in the DSS include subsidies, to encourage, or levies, to discourage, certain practices. This approach was used successfully in the Upper South East Dryland Salinity and Flood Management Program, where levies were introduced for landholders who were located near drain alignments, however subsides were offered to offset these levies by entering into agreements to protect existing native vegetation on private land, or to reintroduce corridors of native vegetation. The outcomes produced included protection and extension of ecological habitats and introducing deep rooted vegetation lowered the groundwater table and hence reduced the occurrence or severity of dryland salinity.

Similarly, infrastructure projects may be considered as policy drivers, where further drains may be used to divert flows to improve certain outcomes, or regulators may be used to retain water in the landscape for recharge to the groundwater table. Alternatively aquifer storage and recovery may be considered, in a natural sense as occurs near Bordertown using runaway holes, or in a more managed approach such as that which currently occurs to some extent on Morambro Creek. Finally, zoning regulations are another policy driver which could be used to protect existing land uses (such as native vegetation), or to prevent high water uses occurring in management areas that are already over or close to being over – extracted.

5.3.1.3 Indicators

Indicators are used to assess the impact of different scenarios of combinations of changes to the drivers outlined above. Indicators of the impact on the water resource include changes in groundwater levels, the estimated natural water input (from recharge and runoff), demands on the water resource are an important indicator (including actual and licensed abstractions), and the combined effect of these indicators represented as the change or deficit in the water balance. It is important to present the distribution of these indicators both spatially and temporally, as aggregated metrics, such as average changes or the total regional water balance only are likely to mask any regions where negative impacts are expected.

Any change to the quality of water available is also a necessary indicator, where the feasible indicators will be driven by the models available. As noted in the review of existing modelling studies section, modelling of water quality in the South East has been difficult historically, largely due to a lack of quantitative information, and difficulty in simulating the necessary inputs (groundwater flows or surface and baseflows for drains and watercourses). Currently this limitation reduces the ability to consider changes to salinity or nutrients directly; however the ability to simulate water quality variables may improve in the future. Without these water quality models, indicators may be able to be used as surrogates for water quality, such as maintaining lateral groundwater flows for flushing of salts, or the ratio of direct flow to baseflow for surface water.

Surface water availability and periods of inundation provide critical inputs to assess environmental outcomes. However, the locations and periods of inundation can also provide a valuable indicator of interest, of any flooding occurrences that should be avoided. Useful indicators of the environmental outcomes are likely to be from a model representing ecosystem responses, where the indicators are defined by the change in area or extent of current wetlands, as well as indicated by the species present, especially endangered or protected species. Again, it is important to represent the spatial distribution in the ecological indicators across the region, as maintaining a diverse range of ecosystems across the region is preferable to a similar situation that provides the same average metrics across the region, but results from a much more homogenous landscape, where all the wetlands represent very similar typologies and functions.

Similarly, the change in land uses provides an indicator of interest for an integrated modelling DSS considering time horizons in the order of decades. The impact of the changes in land use will be observed in other indicators, for example an increase or decrease in irrigated areas on the volume extracted from groundwater, and the groundwater levels. However, changes in the spatial extent of different land uses is also an indicator of interest, to ensure certain agriculture or industries have not been adversely affected or driven out of the region by the scenario considered. Other important indicators of the sustainable agriculture and industry theme include the productivity of the different agricultural practices, in yield per unit area or similar, as well as how this yield translates into a profit for the sector.

Finally, further social value indicators overlap with many of those already described. However, there are likely to be further social indicators of interest, such as fish stocks that support commercial and recreational fisheries in the coastal lakes. Also, an indicator of the distribution of the impacts of a given scenario across the different stakeholders represented in the system is necessary, to ensure equitable outcomes are achieved, and that one small sector or region is not significantly worse off than others, even though many of the indicators across the region may have responded in a positive direction.

5.3.2 System Framework

Based on the themes, drivers and indicators identified in the previous section, the models required to convert different driver scenarios into the effects on the indicators, and how results may be passed from one to the next, are outlined in this section. Given that the water resource planning problem is more detailed, and integrates more components, compared to the drain operation DSS, it is not surprising that more models are required to represent all the necessary inputs and outputs. The proposed framework is shown in Figure 11, where each box represents a different model, and arrows represent the flow of outputs and information from one model to the next.

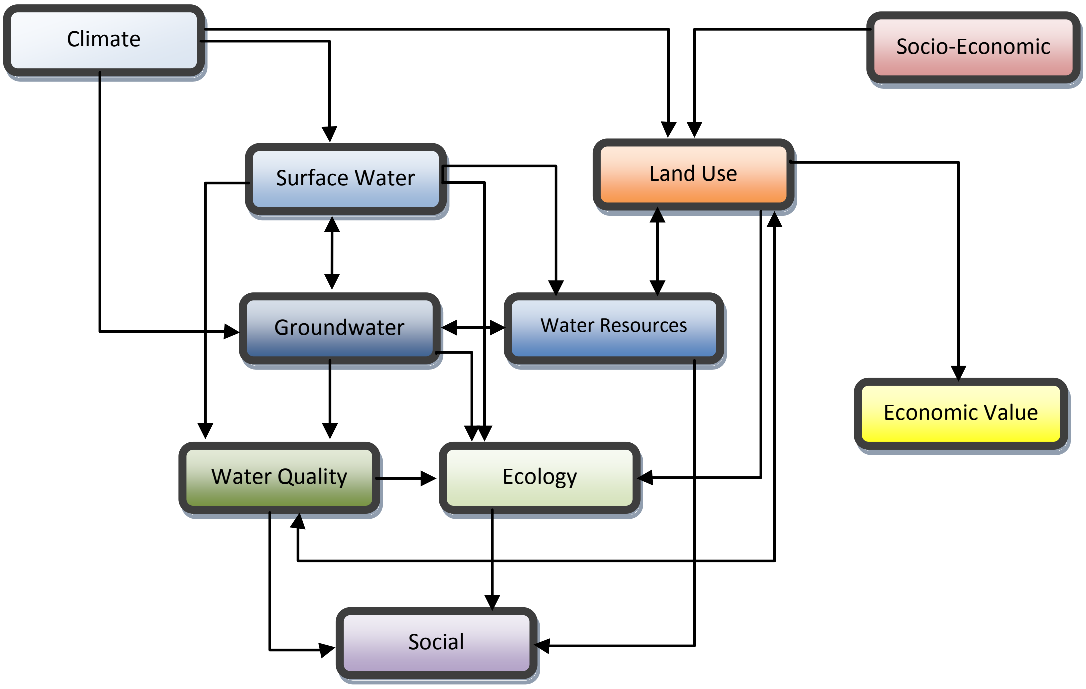

Figure 11 System diagram for the flow of information between models supporting a LSE water planning DSS

The climate represents a large proportion of the available, or at least sustainable, water resource. Hence climate scenarios are a necessary input to the framework. This should include scenarios representing the historic case, as well as the influence of climate change projections for long term planning. The other drivers for the region are contained within the Socio-economic model. These might be the market prices or policy drivers to encourage changes in land use such as subsidies and levies or changes in population. While they may not be strictly socio-economic factors, this box is also used to represent the other policy drivers outlined in the previous section, such as water allocations, trigger levels and infrastructure projects.

As groundwater is a significant proportion of the water used and available in the South East, the groundwater model is a crucial component of the framework. It can be seen that many of the other components in the framework are dependent on groundwater model outputs, the water quality model, surface water availability, ecological response and the state of the water resource. The climate is represented as providing an input to the groundwater model. However, this depends on the form of the groundwater model, as it is most likely that a recharge input is required, rather than rainfall. A straight percentage of recharge based on seasonal rainfall was recommended by Harrington et al. (2011), however this could also come from a dedicated recharge model, a surface water model, or a soil/plant growth model. A regional model was identified as a high priority by Harrington et al. (2011), providing a systematic methodology and boundary conditions for more detailed models. Outputs from these models, such as changes, and rates of change, in groundwater levels are likely to provide important indicators for the assessment of scenarios, as indicated in Table 4.

The surface water model required for a water resource planning DSS may be simpler than that required for drain operation, where the main purpose is to provide frequency of inundation and input of fresh water to a water quality model. The surface water model may become more important if surface water, or the water resource as a whole, is prescribed in the future. The level of complexity required may be dependent on the ability of a groundwater model to represent discharge to drains and stream adequately, and whether a dedicated surface water model is necessary to provide more accurate information on this process. The interaction between surface water and groundwater models is presented in both directions, representing the SW-GW interactions occurring and the exchange of discharge and water levels between the models to represent these processes.

The water resource is represented as a separate model to the surface and groundwater models in Figure 11. This separation is adopted to provide further routines to track changes in the water balance in each management zone, to provide an indication of the presence of regions where there is water available or regions where over – extraction is likely. The flow of data back to the groundwater model is used to represent the extractions from the water resource, largely influenced by the land use model.

As with the total water availability, water quality is also an important issue for the region. Thus far, water quality parameters have proven difficult to model adequately in the South East, as accurate simulation of the corresponding flows transporting the constituents is necessary. As noted above, without these water quality models, indicators may be able to be used as surrogates for water quality, such as maintaining lateral groundwater flows for flushing of salts, or the ratio of direct flow to baseflow for surface water.

Water quality indicators are likely to be an important input to an ecosystem response model, represented by the ecology model box in Figure 11. This model can be seen to also be influenced by groundwater, surface water and land use. Depending on the models available, the land use link may not be necessary, as the impacts of land use practices may be reflected through the water quality and quantity modelling links. However, there is also the possibility that the spatial locations may be influenced, with ecosystems either removed or restored to the region, and hence this link has been retained in the framework presented in Figure 11. Both surface water and groundwater are important inputs, as depth to groundwater below GDEs has been identified as an important indicator, hence groundwater model outputs are important to assess environmental outcomes. Also, the current Wetland Vegetation Components are based on frequencies and depths of inundation, and this information is likely to be derived from surface water models.

Along with the groundwater model, a land use model component plays another large role in the decision support framework. Land use practices have the potential to have a large influence on the quality and quantity of the water resource, and this model provides outputs for one of the main indicators for decision making, the economic value of the region as well as the economic viability of individual plots, which can be an important driver for land abandonment. Land use, including crop growth modelling, will be driven by climatic factors not only represented in the water resource, for example plant growth influenced by temperature, potential or actual evapotranspiration, and atmospheric CO_2 concentrations. There is the potential for a land use model, with 1D soil models such as SWAGMAN-Destiny, LEECH-M or WAVES to also provide recharge inputs to the groundwater model, provided it is adequately calibrated for both plant growth and deep drainage (recharge) objectives.

Landholders' decisions are encompassed within the land use model represented in Figure 11. This model is used to represent changes in land use caused by other factors represented in the framework, such as water resource availability and quality, market prices or subsidies. For modelling requirement such as this, Agent Based or Cellular Automata systems are often used to simulate the actions and interactions of independent agents to assessing their effects on the system as a whole. A site suitability index is also required to ensure unrealistic scenarios do not occur, such as plantations or grape vines in locations where these land uses would not be expected to succeed. This way, large scale policy instruments can be tested, and the long term response of the region can be simulated to assess the possible outcomes.

The important factors that must be considered for short and long term decision-making are represented in the framework, with indicators for economic, ecology and social factors. These indicators allow different potential scenarios to be assessed in an integrated manner. As discussed above, the ecology model is likely to be complex, and based on a number of other model outputs. The economic and social models are likely to be much simpler, as a relatively straight forward conversion of other model outputs to relevant indicators. For example, the ecological model may simulate changes in the fish population in Lake George based on the relevant inputs, which may be summarised or assessed again threshold changes by the social model to indicate social aspects of interest in the region. Similarly, the economic value of the region may be a conversion of market price, crop growth and net present value to provide an indication of the impact of policy options on projected profit in the region. Further input – output models are required to simulate the economic growth of the region, as the impact of changes in one sector on all related sectors must be taken into account.

5.4 Common DSS Components

A number of components are important for all three of the DSS frameworks outlined in this section. From the review of literature, these have been identified to be a database of necessary information, a framework to represent uncertainty and risk, as well as provenance procedures to track and document the flow of information and decision making process.

5.4.1 Centralised Knowledge Database

In Phase One of the Lower South East Water Balance project, Harrington et al. (2011) found that a co-ordinated approach to the collation of the historical data related to the water balance in the South East would be of great benefit to the different stakeholders and agencies involved. This would essentially build a chronological history of the South East and may involve a combination of desktop studies of historical reports, digitising aerial photos and modelling. Having this available as a central resource would be of great benefit to the region (Harrington et al. 2011).

A database such as this serves two purposes. Firstly, to provide a repository or at least documentation of relative studies to ensure interested groups know of any work that has been undertaken. For example, this could include up-to-date recharge estimates, provided in an easy to access format, such as an attribute table for a spatial GIS layer. In this way, any further related studies can be based on consistent data, from the same, up-to-date information. Also, simple models can be included in the database, to undertake repetitive processing of observations as they are updated. For example, interpolating point observations of groundwater levels at observation wells to a spatial map, comparing observations at different time periods to identify trends, accumulation of variables, such as daily to annual rainfall or cumulative deviation curves, and calculating relationships between variables, such as rainfall runoff relationships, or rainfall impacts on groundwater levels.

The database can also be used to flag abnormalities that have occurred in the system, such as significant deviations from the expected streamflow or groundwater level based on the recent climate and historical datasets, or to report when trigger levels have been exceeded. This will at least prompt further investigation to ensure the data source is accurate, and that the instrumentation is functioning correctly, before further investigating the context of the observed deviation.

Data of interest for a South East water balance database include, but are not limited to, variables such as:

- Climate variables, rainfall, PET, temperature,
- Groundwater levels,
- Streamflow volumes,
- Extractions,
- Wetland water levels/storages,
- Land use datasets,
- Drain regulator operations,
- Ecological field surveys, and
- Record of relevant studies and reports.

Currently these data are available in at least some form, and may be able to be extended using additional data sources, such as remotely sensed data. However, displaying and analysing all variables spatially is not a simple process, but is required to provide an overview of any changes in the region. There are likely to be large gaps in different datasets for different periods, which will complicate the process of analysis. These may be able to be infilled with process based models, statistical time series methods, or based on relationships with other nearby sites.

This centralised database is also a necessary foundation for a DSS based on integrated modelling, to provide a basis of information to update the initial states of the models involved, as well as observations to improve the calibration and performance of the models as more data become available. Observed data are likely to have less uncertainty associated with their values compared to the results from any model, and as such the historical record of important variables, and the relationship between them (especially rainfall, streamflow and groundwater levels), can provide valuable insights into current trends, as well as responses to changes or disturbances that have occurred in the past, which may be relevant for proposed or expected scenarios.

5.4.2 Uncertainty and Risk Assessment

Objectives stated in the SA NRM Act (2004) include that decision-making processes should be guided by the need to evaluate carefully the risks of any situation or proposal that may adversely affect the environment and to avoid wherever practicable causing any serious or irreversible damage to the environment. As such, quantifying the risk of a certain outcome occurring is a desirable output from a DSS. From a planning perspective, 'optimal' scenarios may be of less interest than scenarios that are very likely to be beneficial, with a low probability of negative consequences occurring.

Risk is typically defined as the combination of likelihood and consequence. The two inputs to the calculation of risk can be derived from modelling studies, where the consequences are interpreted from the model outputs, and the likelihood of the outputs occurring derived from changing model inputs over a feasible range, or interrogating an extended time series of results to identify how often certain events have occurred.

However, a more detailed appreciation of likelihood can be achieved through quantifying the uncertainty involved in the modelling outputs. This uncertainty in the model outputs can be brought about by uncertainty in the inputs used, in the structure (or conceptualisation) of the model adopted, and in the values used for the parameters of the model structure. As such, an appreciation of model uncertainty, and how that uncertainty progresses through the models in an integrated DSS, provides an improved representation of the likelihood of the consequences simulated, and in turn any risks involved.

The specific uncertainties that can be considered in a DSS framework will depend on the models that are included in the framework, depending on the input data used as well as the model complexity and structure adopted. Conceptually, the approach to transfer uncertainty through integrated models is similar to that of the individual models, where the distribution of outputs from one model is transferred to the inputs of the next model. The largest complexities arise from representing any correlations between the model output values that are used as inputs for a sequential model (potentially from multiple models), as well as the computation requirements involved in running each model many times (e.g. hundreds to thousands), instead of only once.

There is a possibility that by adopting an approach such as this to quantifying the risk, that by the end of the integrated modelling process the results are so uncertain that there is little confidence in them for decision making purposes. Hence, minimising the uncertainties involved in each model, for example in each model's set of parameters, is critical to ensuring useful outputs are produced by an integrated system. This should involved adopting advanced calibration procedures, such as PEST (Doherty & Johnston 2003) or BATEA (Thyer et al. 2009), to quantify and minimise the uncertainties involved. Data assimilation approaches (Henderson et al. 2011) may also be useful to reduce model uncertainty, by correcting model biases using observed data.

However, given the challenges and complexities involved, accurate quantification of the uncertainty of individual model results may not be necessary. If quantifying the risk is of less value due to very wide ranges of likelihood (uncertainty) for different consequences (model outputs), comparative studies can be used to gain an understanding of the impact of different scenarios of interest. Provided the internal models are systematic and not driven by random processes, a comparative approach such as this is likely to be valid. In this case, the outputs from one possible management scenario can be compared to another, and the change in the indicator model outputs can be investigated. In this way, there is less of a requirement for the quantitative values output by each model to be an accurate prediction of the expected results from each scenario. As such, even without an assessment of risk as such, an approach such as this can still be a very useful contribution of a DSS to inform decision making processes. The most suitable approach to take to interrogate and present the results from an integrated modelling DSS should be reassessed as integrated models are developed.

5.4.3 Provenance Procedures

A record of the evidence, data and other sources of information used to decide on a final option or scenario to implement can be just as important as the information itself. This has been a focus of the existing Flow Management Decision Support System for the Upper South East, where a record of information used to change regulator settings are recorded, such as telemetered flow gauges or the upcoming weather forecast. This way, if unforeseen adverse effects occur as a result of that decision, when questioned the evidence to support the action is available. Another name for this trail of documentation is provenance, and provenance systems to document procedures are becoming a focus of research and a component of automated workflow environments.

Groth et al. (2006) state that the provenance of a piece of data is the process that led to that piece of data, where Gil et al. (2010) define of provenance of a resource as a record that describes entities and processes involved in producing and delivering or otherwise influencing that resource. As such, provenance is about the capture and exploitation of information that enables an understanding use of information resources that have been created (Box et al. 2011), and provides a critical foundation for accessing authenticity, enabling trust, and allowing reproducibility. This becomes even more important as increasing volumes of information becoming available, increasingly complex data processing and modelling is undertaken, and often conflicting signals are obtained from different sources.

Provenance information is required for a broad range of uses, both within organizations and by external stakeholders. These include (Box et al. 2011):

- Regulatory/legal – providing an audit trail for external audits to assess compliance with jurisdictional laws and regulations.
- Corporate – enabling assessment of compliance with best practice and corporate policies and responsibilities as government agency.
- Business – providing provenance information to support the interpretation of information products by end users.
- Scientific – information to support exploration, documentation and reproduction of experimental and business information production pipelines.

To meet a range of provenance use cases, provenance management system are required to capture, store, query and represent provenance information. As different users and uses have varied requirements for the granularity or level of detail in provenance information, the representation of provenance information is critical (Box et al. 2011). Making provenance information accessible to specialist users and decision makers not only helps to determine the data's value, accuracy and authorship, but also enables users to determine the trustworthiness of the data product. Two currently available provenance management languages include the Proof Mark-up Language as well as the Open Provenance Model.

It is easy to envisage that all the requirements listed by Box et al. (2011) are applicable to the conceptual decision support frameworks proposed in this section, and as such provenance management systems should be a feature of a DSS used to support any conclusions or decision drawn from the scenarios presented.

5.5 Software Frameworks

Thus far, this section has proposed a number of conceptual frameworks to integrate models from different disciplines to produce a system to add value to the decision making process, in a number of different contexts relevant to the South East. For an integrated modelling DSS such as those proposed above, three major components can be identified:

1. databases to store information used by the system – mostly raster or vector map data, time series data and cross-sectional data,
2. a model base to manage the models that are used, and
3. a user interface to enable the user of the system to interact with it.

A software framework is required to set up each of these components and letting them work together.

The initial impulse is often to develop a custom made system that addresses the specific issues of the region and decision context. However, this can be extremely time consuming and difficult to maintain, often reliant on a small number of individuals who are familiar with the development. This long development time can also reduce the time available for review, feedback and improvement of the software framework, which is critical to producing a relevant system that is likely to be adopted in the end. An in-house development approach is also prone to duplicating existing products in a large part, as well as technical difficulties in actually running a number of models and handling the inputs and outputs can be prone to introducing bugs and errors.

As noted previously in this section, there are many similarities between the functions and requirements of existing integrated modelling DSSs and those posed for the South East. A number of systems already support model integration, simulation and/or optimisation, scenario management, displaying and exporting model results, and adjusting model inputs or parameters. None of this functionality is central to the model, but rather is part of the application logic that determines how interaction between user and models – and between different sub-models – is facilitated (Hurkens et al. 2008). Capturing this logic in a generic way can save a lot of time and effort for reinvention (Hahn & Engelen 2000).

Hence, a more streamlined approach is to adopt an existing software application framework, which can be customised and adapted to address the relevant questions. A software application framework is defined as a reusable, semi-complete software application that can be specialised to produce custom applications (Fayad et al. 1999). Since an application framework already offers a working application to which specific functionality can be added, it allows the development of an early prototype that can be iteratively adapted and extended without having to start from scratch whenever requirements change (Hurkens et al. 2008). The benefits of a framework can be summarised in four classes: reuse, modularity, extensibility and inversion of control (Fayad et al. 1999). These classes can be described as (Hurkens et al. 2008):

1. *Reuse* can be in the form of implementation reuse, for example methods and procedures for integrating models that have been implemented and tested previously, and design reuse, which can save development costs and improve overall consistency and scalability by applying a coherent set of patterns that have been developed to support similar solutions (for example in a graphical user interface).
2. *Modularity* means the decomposition of an entire system into interacting parts. Ideally each part has a single, well defined purpose or responsibility, and each part can be updated, improved or replaced without affecting the functionality of the remainder of the system.
3. *Extensibility* means the ability to add or change functionality without affecting existing design or implementation. This makes it possible to adapt the system in accordance with changing demands, for example by adding new models, new user interface features or by extending the functionality of the framework itself without the need to change existing model implementations accordingly. Examples include the addition of scenario support and parallel computation of sub-models or (simulation) runs of the integrated model.
4. *Inversion of control* is a software engineering term, referring to the way that the program performs different operations. Rather than the traditional sequential processing of functions, the software framework represents generic code that then calls the problem specific functions (models), removing the implementation information for the execution stage. As such, this approach facilitates the ability to change functionality or models of a DSS, without affecting the operation of the framework.

An overview of three such software application frameworks is provided in the remainder of this section. No recommendation is made based on this simple overview, as more detailed consideration to the ability to integrate the key models outlined in the conceptual framework (e.g. Figure 11) should be undertaken as these models are developed in the future.

5.5.1 Workflow Management Tools

Workflow management tools have been adopted recently to automate the process of collating and interpreting huge datasets, processing this data as an input to multiple models, consider a number of scenarios and collating the results for interpretation. The benefit of a tool such as this is to automate as much of the process as possible to improve run times, efficient throughput of information, reduce the risk of error through manual processing, and provide documentation of the processing undertaken to so the results can be repeated and reviewed if necessary. Two workflow management frameworks are currently in use in Australia, Delft-FEWS and Microsoft Trident.

Delft-FEWS has also been adopted as the workflow engine for the Australian Water Recourse Assessment (AWRA) system. The AWRA system is a modelling system designed to support water resources assessment and water accounting undertaken by the Bureau of Meteorology. After a review of available systems, Delft-FEWS was selected as the most tested and reliable hydrological workflow control system (Van Dijk et al. 2011). Developed by Deltares, FEWS stands for Flood Early Warning System. However, the system has been used for a number of applications beyond hydrological forecasting and warning systems. The philosophy of the system is to provide a fully scalable, open shell for managing data handling and forecasting processes. This shell incorporates a comprehensive library of general data handling utilities, allowing a wide range of external forecasting models to be integrated in the system through a published open interface (Deltares 2012a). This includes connecting to external data sources, validating, interpolating and transforming data with a focus on modelling and disseminating the results in advanced graphical and map-based displays (Deltares 2012a).

In an application similar to that considered for the Lower South East Planning Decision Support Framework above, Delft-FEWS was used as the basis for a National Groundwater Modelling System (NGMS) in England and Wales. The system was developed to manage interactive scenarios for groundwater management, and to improve and simplify the use of models by the operational staff and in the same time create uniformity in groundwater management with the different regions. This allowed operational staff to ascertain the effect of certain measures on the groundwater and to use the model for regulatory needs, rather than relying on the groundwater modeller, which was often a time consuming practice. However, it is also noted that the NGMS is not a substitute for a good understanding of both the numerical model and the conceptual model behind it (Deltares 2012b).

Another workflow management tool that has been adopted by the AWRA - Water Information Research and Development Alliance (WIRADA) is Microsoft Trident, which has been used to develop the Hydrologist Workbench. Barga et al. (2008) reports on the development of Trident and describes it as a scientific workflow workbench which has been built upon a commercial workflow system, which brings benefits of robustness. The application was originally developed for the oceanographic community and one of the primary goals of this development was the ability to construct a data processing pipeline to convert raw sensor data into derived data products and visualisations. It was initially developed as a collaborative project between the University of Washington and Microsoft research and has now been made available to the community as an open source software project (http://tridentworkflow.codeplex.com/) (Fitch et al. 2011). Trident has been used as the basis of the Hydrologists Workbench developed by CSIRO and BoM, and currently includes interfaces for the eWater Source models, amongst many others.

It should be noted that for these applications, both software packages (Delft-FEWS and Trident) are used as workflow engines, to automate the running and interaction between a number of models in a sequential manner to analyse results and generate reports. This is opposed to a more user centric system for investigating a number of scenarios of interest. However, both workflow tools provide the ability to visualise both time series and spatial data, for interpretation of the model results.

5.5.2 Vensim

Developed by Ventana Systems Inc, Vensim is a System Dynamics modelling platform used for developing, analysing, and packaging high quality dynamic feedback models. Features of the software include dynamic functions, sensitivity analyses, optimization routines, data handling and application interfaces. The Vensim modelling environment is a programming environment for model development and integration, thus providing a tool to solve problems that would be very complex to address otherwise. In line with the four benefits of integrated modelling software frameworks outlined above, the Vensim environment insulates the user from the underlying mathematics and the details of the language specification and provides an interface to help the decision maker to use it and run exploratory scenarios with limited technical experience (Beddek et al. 2005).

The Vensim environment was the basis for the Gnangara Sustainability Strategy Western Australia (Elmahdi & McFarlane 2009) outlined in the previous section. Hence, the software is likely to be applicable for the frameworks proposed in this section, given the similar questions asked in the Western Australian study. Elmahdi and McFarlane also used Vensim to develop an Economic Surface and Groundwater Model (ESGM) to analyse the historical water allocation for part of the Werribee Irrigation district in Victoria within constraints of environmental rules based on economic rationale. This was done by linking Crop distribution mix and water demand under set constraints to groundwater drawdown spatial distribution resulting from MODFLOW simulations scenarios (Beddek et al. 2005). The outputs of the ESGM model are total cost, total yields, total return, irrigation demand, gross margin, losses, surface water used and ground water pumping to match the demand within system constraints (Beddek et al. 2005).

5.5.3 Geonamica

Geonamica® is a software environment developed by the Research Institute for Knowledge Systems, designed to build decision support systems based on spatial modelling and simulation. The framework offers set components for the storage of map data, time series and cross-sectional data. It provides a modelling framework based on the Discrete Event System Specification (DEVS) formalism (Zeigler et al. 2000) and includes a model controller that manages the models, makes sure they interact properly and tells each model when to perform certain, predefined actions. To create a user interface, Geonamica® includes a skeleton structure and a rich class library of user interface components, such as map display and editing tools, list and table views and two-dimensional graph editing components (Rutledge et al. 2008).

Geonamica® also has a focus on the user interfaces, to allow the system to be easily operated by different stakeholders. This is a feature that does not appear in the other software frameworks presented in this section. Two user interfaces are commonly implemented; one a policy interface, to provide access to the settings and scenarios that could or are of interest to be influenced by policy makers, while the sub-models with all their adjustments are accessed by scientific users through a separate modeller interface. This way the different settings can be grouped in an intuitive way for each user, either by each model for the modeller interface, or by each scenario or logical function of the policy interface.

Geonamica® has been developed over the past 20 years and has been used to generate a number of integrated spatial decision support systems (Hurkens et al. 2008). A number of the DSSs that have been developed using Geonamica® were outlined in the Applications section of the Decision Support Systems review provided earlier, such as the MODULUS DSS, MedAction DSS (Van Delden et al. 2007), DeSurvey IAM (Van Delden et al. 2009), WISE DSS (Rutledge et al. 2008) and LUMOCAP PSS (Van Delden et al. 2010).

5.5.4 Integrated Catchment Modelling System

The WADSS and IBIS DSS systems were designed and implemented using the Integrated Catchment Modelling System, developed by CSIRO Land and Water (Cuddy et al. 2002). ICMS provides catchment managers with a tool to develop and investigate a range of 'what if' scenarios for a range of complex issues important in their catchment. ICMS has been used to develop Projects that link (CSIRO 2011):

- simple rainfall/runoff models with instream flow routing models to predict changes in flows in the Upper Murrumbidgee under different climate scenarios
- simple rainfall/runoff models with instream flow routing and regression models to predict changes in flows in the Namoi under different farm dam storage scenarios
- socio-economic models of crop selection with water allocation constraints, to predict effects on flows in the Namoi under different water allocation scenarios
- rainfall, ground and surface water models, with salinity and nutrient transport models to predict potential socio-economic impacts of expansion of dryland salinity in a south-west catchment in Western Australia.

ICMS has been designed for processing of simple representations of catchment behaviour and is not suitable for processing of spatially dense, or computationally intensive applications (CSIRO 2011).

This system allows models to be developed and connected using an object oriented paradigm. ICMS has several main advantages that were utilized in the WADSS design (Letcher 2005):

- the compiled code runs rapidly.
- models are able to be developed, shared, re-used and updated easily in the system. This reduces development time and allows other users to be trained in model development and coding and means that component models developed in WAdss can be exported and used for other purposes.
- custom built Graphical User Interface (GUI) can be built to complement the Model Builder. These GUI are relatively cheap to construct, requiring only weeks rather than years of programmer time. Programmers are able to build the GUI without any knowledge of the working of the underlying models. Additionally modellers are able to write and debug their own model code, rather than relying on iteratively testing code written for them by programmers.
- the system contains a number of in-built visualisation tools and functions. These include a range of charting tools, a raster view and a simplex algorithm function capable of solving linear programming problems.

A 'lean interface' (or GUI) has been designed to open over the top of an ICMS project to allow for DSS features including scenario creation, saving and comparison with base case scenarios. ICMS allows for 'parent' and 'child' layers, such that parent objects can contain numerous child objects with which they communicate. For example, in the WADSS the parent layer was used to capture the spatial structure of the catchment reflected by the nodal network, while each child layer represents the interactions between component models at the node (eg. Rainfall runoff, policy, crop and economic production models) (Letcher 2005).

5.5.5 Summary

An overview of five very different software frameworks for integrating models has been provided in this section. Delft-FEWS and Trident has been used in the water sector for as a workflow tool, to automatically simulate a number of models in a sequential manner to address complex questions. Another significant benefit of these systems is the documentation and provenance of the process undertaken and reproducibility of the results. However, this type of approach can limit the ability of the software to include interactions and feedbacks between the different models included. Conversely Vensim is extremely suited for simulating feedbacks, and can be a good tool for modellers who can create models themselves, without the requirement to write software code. However, Vensim has had limited support for spatial models, and does not include a user friendly interface for policy support. The ICMS software is available to download from the CSIRO Land and Water website (http://www.clw.csiro.au/products/icms/). However, it is unclear how actively the software is currently used or developed, with most publications and tutorials dated in the early 2000s. Geonamica has been developed to integrate spatially explicit models with large datasets and incorporate feedback loops between these models. Almost any model can be included in the software, either through existing methods or by writing C++ wrapping code. Also, the software has a focus on user-friendly interfaces to support both modellers and end users intending to run and evaluate scenarios, and has been in development for this purpose for over 20 years. It is recommended that a suitable DSS software package is re-evaluated once the necessary underlying models are developed, to ensure the framework can accommodate these models and their interactions.

6 Conclusions

This report has scoped the requirements of a DSS to support management decisions related to the water resources of the South East of South Australia. These decisions include the development approvals process, short term management of the drainage network, and long term policy development around sustainably balancing the development and preservation of the water resources of the South East. Computer-based DSSs are proposed to support, not replace, some the phases of the decision-making process. It is expected that the development of a DSS will assist with elucidating each stakeholder's interests, facilitating analysis, learning and communication to allow for a more informed discussion when all involved are aware of the information available.

A review of recent modelling studies in the South East was undertaken, to identify existing work that is likely to provide a valuable foundation for a DSS based on integrated modelling. Given the many different problems to address and general uncoordinated approaches in different modelling projects, limited models were identified that are currently in a format to be directly applicable in this context. However, a number of valuable studies have been undertaken to provide a foundation for future studies that have a focus on the objectives outlined in this report.

A review of the recent literature on DSS development best practices was also undertaken, to learn from previous studies that have tackled similar problems. This review identified the approach of identifying themes, drivers and indicators as an accepted methodology for the design and development of integrated models for policy support. This approach was implemented for both short and long term planning in the Upper and Lower South East, respectively, to propose decision support frameworks for the different problems that were identified.

These frameworks provide one source of information to prioritise future projects, with a focus on how the results can contribute to the management of the region in an integrated manner, as opposed to answering an interesting question with limited contribution to management implications. This was a common theme throughout the consultation process for the Lower South East Water Balance Project (Harrington et al. 2011), where an urgent need for a tool to help identify and prioritise future knowledge and data collection projects was required. Future modelling projects required to provide input to an integrated modelling DSS include (in no particular order), groundwater models, surface water models, land use and crop growth models and ecosystem response models.

A centralised knowledge database was previously identified as a valuable tool for water management in the region. The development of this database should commence immediately, as it is not dependent on suitable models to form an underlying basis. The database should not only hold a record of previous studies and relevant data, but also include data analysis tools to process monitoring data into useful information for management of the region, for example interpolating point observations of groundwater levels at observation wells to a spatial map, comparing observations at different time periods to identify trends, accumulation of variables, such as daily to annual rainfall or cumulative deviation curves, and calculating relationships between variables, such as rainfall runoff relationships, or rainfall to changes in groundwater levels.

A record of the evidence, data and other sources of information used to decide on a final option or scenario to implement can be just as important as the information itself. This record becomes even more important as increasing volumes of information become available, increasingly complex data processing and modelling is undertaken, and often conflicting signals are obtained from different sources. This record of how information or data was produced is termed the provenance of the information. A provenance framework was also identified as an important component of any DSS developed, to provide a repeatable, transparent record of the sources of information used to undertaken an action, should that decision be challenged in the future.

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APPENDIX A. key policy & legislation instruments relevant to water dependent ecosystems in the south east

Reproduced directly from Harding (2009).

Water Allocation Plans (Groundwater & Surfacewater) 2001

NRM Act Chapter 4 Part 2 Division 2, 4a:

i) Must include: an assessment of the quantity and quality of water needed by the ecosystems that depend on the water resource and at the times at which, or the periods during which, those ecosystems will need that water; and

ii)An assessment as to whether the taking or use of water from the resource will have a detrimental effect on the quantity or quality of water that is available from any other water resource;

4b i) provide for the allocation and use of water so that an equitable balance is achieved between environmental, social and economic needs for the water and ii) the rate of water use is sustainable.

SECWMB Plan 2003-08

Goal: To identify, protect and enhance ecosystems and their associated biodiversity that depend on water.

Strategy:Manage ecosystems and biodiversity

Actions:

- Enhance development planning for water quality and ecosystem protection
- Identify major WDE's and identify threats
- Develop management plans for key WDE's
- Investigate and refine EWR's for key WDE's

***Catchment wide provisions – Principles*:**

- Activities should not adversely affect WDE's
- Activities should not adversely affect the capacity for the migration of native aquatic biota or their EWR's
- Activities should not adversely affect the quality, quantity, duration or in any other way the supply of water to WDE's
- Activities should occur in a manner that protects the ecological values of ecosystems and natural features of lakes, wetlands watercourses or floodplains
- Drains should be designed and constructed to enable the preservation and enhancement of ecological functions of ecosystems reliant on groundwater and surfacewater
- Culvert and bridge design and construction shall include provisions to ensure fixed sill levels do not adversely impede the flow of water in a watercourse, across a floodplain or a lake/wetland.
- The placement of a road that spans a watercourse, floodplain, lake, wetland, area subject to inundation should not adversely affect the provision of EWR's of those areas.

Surface water Policy Areas – Principles:

- Dams to be located off-stream
- Capacity of dams in surfacewater policy areas shall not exceed volume – policy area (ha) x max dam capacity factor (0.05-0.07ML/ha) (see policy area runoff and allotment runoff estimates)
- Dams on divided allotments should not exceed 30% median runoff of original allotment
- Infrastructure to enable diversion of water from a watercourse or floodplain shall be constructed to allow no more than 50% of the available flow to be diverted at any time
- Water storage or diversion should not cause unacceptable groundwater mounding or cause adverse impacts to neighbours
- Dams should not be located in ecologically sensitive areas/areas prone to erosion
- Drainage wells should not be constructed in wetlands as mapped in SAWID, or banks of a watercourse
- Construction and siting of wells for drainage purposes should not compromise surfacewater flow to WDE's
- Specific policy area principles apply

State NRM Plan 2006

Goals:

- Adopt policy guidelines for managing rivers and wetlands

- Ensure planning policy addresses the importance and value of WDE's, particularly watercourses, floodplains and wetlands (Ramsar and DIWA) and prevents development that would impact upon ecosystem function or habitat value.
- Develop a robust water accounting system to provide certainty to consumptive users and for the environment
- Review the legislative and institutional arrangements that directly relate to NRM to ensure efficient coordination and that arrangements support effective and sustainable landscape/ecosystem management
- Encourage and remove impediments to cooperation between institutions with responsibilities that effect NRM
- Encourage cooperation between land use, industry and NRM policy bodies

Strategy: Use the state NRM Plan as a guide to provide comment on development applications

Resource Condition Targets:

- By 2011 all ecosystems dependent on prescribed water resources have improved ecosystem health.
- By 2020 all aquatic ecosystems have improved ecosystem health.

Water Allocation and Management Guidelines (*State Water Plan 2000*)

Surface Water:

- Outside prescribed areas until there is additional info, 25% median annual adjusted catchment yield should be used as an indicator of the sustainable limit of the catchment SW and watercourse water use.
- Pumping or diversions from a watercourse must not result in the water in refuge pools falling below critical ecological levels.
- Off-stream dams are preferable.

Groundwater:

- In calculating sustainable yields, a precautionary approach must be taken with sustainable yield being lower where there is limited knowledge, large existing use, higher risks, and less reliable recharge.
- Management controls in WAP's on S&D use of water from groundwater basins should be applied where required to achieve sustainable use. Current and likely future S&D requirements must be included in assessments of resource use.

Water for the environment:

- Water allocations and management decisions must take a precautionary approach by first ensuring environmental benefit outcomes, including natural ecological processes and biodiversity of WDE's are maintained. It follows that further allocation of water for new consumptive uses and any other new water resource developments, must ensure ecological values are protected.
- In systems where there are existing consumptive users, environmental water provisions must be as close as possible to the required EWR's while recognising rights of existing users
- Where environmental water provisions cannot meet EWR's arrangements should be established that will allow for the requirements to be met in the minimum time practicable (considering socio-economic needs).
- The provision of water for the environment is recognised under the NRM Act. Environmental Water Provisions will be legally described and protected through WAP's (through operational/extraction constraints described in WAP's and effected through conditions on permits and licences to take water.
- All water uses must be managed so as to achieve defined environmental outcomes.
- Environmental Water Provisions should be linked to environmental objectives.

Principles for riparian and floodplain management:

- Protection of refuge areas and maintenance of connections along watercourses must be given priority due to the highly variable flow patterns.
- Interactions between surfacewater and groundwater must be maintained so as to sustain ecological function and dependent biodiversity that rely on this hydrological connectivity.

Principles for wetland management:

- The management of natural wetlands should aim to provide adequate water in an ecologically appropriate regime and appropriate quality so as to maintain wetland function and ecological value.
- There should be recognition of wetland values and their management and protection in all relevant statutory and non-statutory planning processes.
- Wetlands of recognised conservation significance should be given special protection and management so as to maintain their ecological values.

NRM Act 2004

Promotes sustainable and integrated management of SA's natural resources and make provision for their protection.

Chapter 2 Part 1 – Objectives: 1c) provides for the protection and management of catchments and the sustainable use of land and water resources 2c) avoid, remedy or mitigate any adverse effects of activities on natural resources 3a) decision-making processes should effectively integrate both long-term and short-term economic, environmental, social and equity considerations 3b) if there are threats of serious or irreversible damage to natural resources, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation. 3c) decision-making processes should be guided by the need to evaluate carefully the risks of any situation or proposal that may adversely affect the environment and to avoid wherever practicable causing any serious or irreversible damage to the environment. ***Chapter 7 Part 2 Division 1 126 – Relevant authorities:*** DWLBC – activities under 127 3 a-c NRMB – activities under 127 3 d 127 3 e-f – either of above ***Permit required to:*** 3a) drill, plug, backfill or seal a well b) Repair, replace or alter the casing, lining or screen of a well c) Drain or discharge water directly/indirectly into a well d) Erect, construct, enlarge, modify, remove a dam, wall or other structure that will collect/divert water flowing in a watercourse. 5b) erect, construct or place any building or structure in a watercourse or lake or on a floodplain c) drain/discharge water directly into watercourse/lake d) deposit or place object/solid material in watercourse/lake (or on floodplain f)) e) obstruct a watercourse or lake in any manner g) destroy vegetation growing in a watercourse or lake or growing on the floodplain h) excavating rock, sand, soil from watercourse, lake, floodplain, banks ***No permit required:*** • Erect, construct, enlarge contour banks to divert surfacewater to prevent soil erosion The Minister is able to issues a notice to a land holder in an non-prescribed water resource area if water taking exceeds a rate considered to adversely affect other users or is likely to cause damage to ecosystems that depend on water from the water resource (Chapter 7 Part 2 Division 2 132). When determining demands on available water the need for water of the ecosystems that depend on water from the water resource concerned must be taken into account. • Permits: Decision of authority must not be inconsistent with the SA NRM Plan • Authority must take into account Regional NRM Plan provisions ***Allocation of water (Chapter 7 Part 3 Division 2 151):*** • Before allocating water the Minister may direct that an assessment of the effect of allocating water be made by an expert (DWLBC) • Water is to be allocated consistent with WAP's and conditions attached to licenses must not seriously vary with the WAP. • Chapter 7 Part 6 170 – effect of water use on ecosystems. Needs of ecosystems that are dependent on water resources must be considered in decisions regarding availability of water.
No Species Loss 2007-2017 ***Goals*** • To build capacity to collect and share info to inform biodiversity management • To provide a contemporary legislative framework for the protection and conservation of SA's biodiversity • To ensure the planning and development assessment system facilitates sustainable development that minimises the impacts of development on biodiversity ***Targets*** • The survey, definition of EWR's and assessment of SA's DIWA wetlands are completed by 2013. • Systems providing relevant and timely information on areas of ecological significance to inform the development planning system are improved. • SA legislation that rationalises policy, reduces admin and compliance costs to business and improves protection of biodiversity is developed by 2010. • Planning policy and development assessment processes are informed by ecological investigation and impact

assessment specific to the affected area and its biodiversity and administered in a manner that identified and protects areas of biological significance.

DEH Corporate Plan 2007-2010

Objectives – Sustainable Growth

- Provide innovative advice and solutions that seek to achieve the best environmental results from the State's major developments
- Influence government policy to secure better environmental results from development, particularly in coastal and other vulnerable areas.

Objectives – Better decisions and partnerships

- Ensure our investments in science, knowledge and information systems support our strategic and operational decision-making
- Strengthen our policy capacity and performance

Clarify and reinforce mutual roles and responsibilities with other Government Organisations (DWLBC, SENRMB, EPA)

Native Vegetation Act 1991

See Schedule 1 – principles of vegetation clearance.

Vegetation should not be cleared if it:

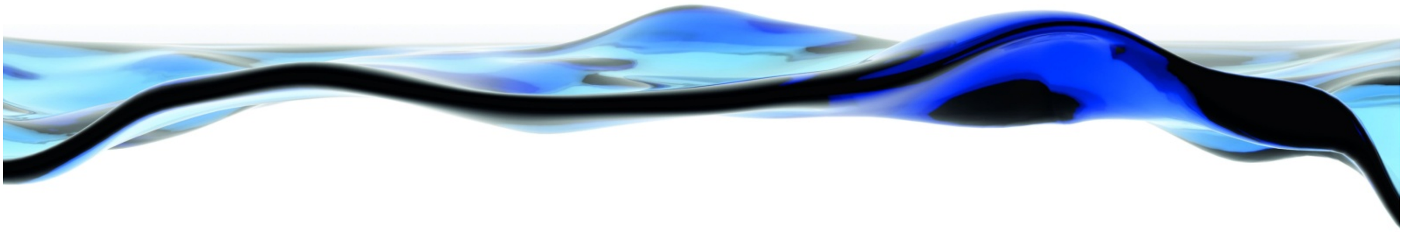
- comprises high level of plant diversity
- comprises threatened species, community
- comprises significant habitat
- comprises a wetland or is associated with a wetland environment
- contributes to significant amenity
- contributes to erosion/salinity
- causes deterioration in water quality (surfacewater or groundwater)
- exacerbates intensity of flooding

Tackling Climate Change 2007-2020

- Incorporate climate change in the sustainable management of water resources and water supply
- Increase the capacity of ecosystems to adapt to climate change

Principle: NRM and water allocation stay within sustainable limits to ensure that the state's natural resources and ecosystems have optimum resilience and capacity to adapt to climate variability and change.

Strategies: Ensure WAP's reflect climate change projections and provide a framework to adjust water allocations if necessary.



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