Integrated Science Support for Managing Australia's Tropical Rivers: A Case Study in the Daly River Catchment

Francis Pantus[1], Cathie Barton[2], Lindsay Bradford[1]
and Martin Stroet[1]

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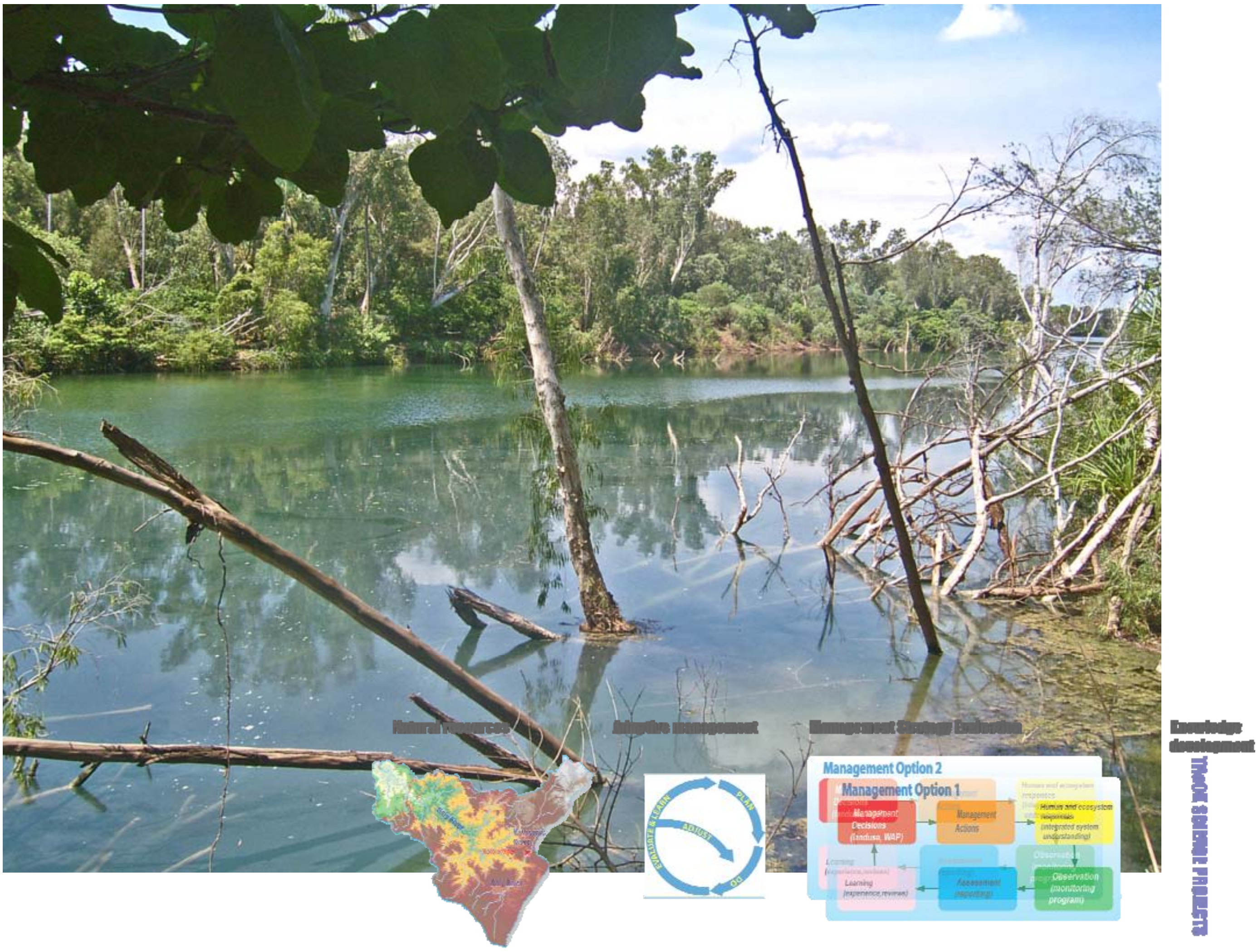
[1] Australian Rivers Institute, Griffith University
[2] Research Institute for the Environment and Livelihoods, Charles Darwin University



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For further information about this publication:
Assoc. Prof. Francis Pantus, Griffith University
f.pantus@griffith.edu.au

Or to find out more about TRaCK
Visit: http://www.track.gov.au/
Email: track@cdu.edu.au
Phone: 08 8946 7444

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Integrated Science Support for Managing Australia's Tropical Rivers:
A Case Study in the Daly River Catchment

Final Report for
The Tropical Rivers and Coastal Knowledge Research Consortium

September 2011

Francis Pantus, Cathie Barton, Lindsay Bradford and Martin Stroet

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MSE RESULTS CAUTION

The Daly River Catchment MSE application described in this report is a prototype only. Its purpose is to function as a demonstration-of-principles and to present an example of the form and content of a MSE application software package to decision-makers and stakeholders in the natural resource management process.

The brief of Project 1.4 first and foremost is about integration and delivery, not so much about developing new models. This means that the prototype MSE application depends heavily on the models developed in other TRaCK projects. The assumptions and constraints of those models can be found in the respective reports and documentation for those models.

The one core model that was developed by Project 1.4 is the Daly River catchment water model. Even though major efforts have been made to calibrate the model with the data available for such a large catchment, the results have not been validated independently.

Uncertainty is one of the key issues in natural resource management. This report will deal with uncertainty in some detail. However, many of the epistemic uncertainties that are used in this report are based on a 'what-if' approach. The presence of these uncertainties serves to raise awareness and to progress discussions on how to assess, express and effectively manage the various forms of uncertainty. When the MSE application is not in demonstration mode, these epistemic uncertainties need to be set to the appropriate levels.

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EXECUTIVE SUMMARY

Project 1.4 is part of TRaCK (Tropical Rivers and Coastal Knowledge) and is entitled "Knowledge Integration and Science Delivery". Project 1.4 has two main aims:

1. To integrate the knowledge that is being developed across the TRaCK program.
2. To use that integrated knowledge to deliver science into the management domain.

Assisted by consultation with both internal and external stakeholders, Project 1.4 has developed concepts, methods and tools that deliver such knowledge in the form of scenario evaluation capacity to a range of stakeholders, particularly in support of natural resource management. The approach adopted is based on a conceptual framework known as Management Strategy Evaluation (MSE).

Management Strategy Evaluation (MSE)

The structure and behaviour of the MSE application described in this report is based on an MSE conceptual framework. Founded on the principals of adaptive management, the framework consists of six functional areas, representing a classification of typical activities that are part of (adaptive) resource management. The MSE application implements the framework as a model-based computational tool that allows managers, policy makers and other stakeholders to assess the potential trade-offs of particular management procedures. An application of MSE to a resource management case makes no attempt to find an optimal management strategy, instead it provides a means by which managers and policy makers can inform their decisions with 'best available science'. This is achieved by dealing explicitly with uncertainties and systematically presenting a clear set of trade-offs between various management options.

MSE and the Daly River Catchment

The Daly River catchment is located in the Northern Territory and is one of Australia's largest tropical river catchments with an area of about 53,000km^2. Being located in the wet-dry tropical region, the catchment experiences high rainfall volumes in the wet season and very little in the dry season. However, despite the dry season, the Daly River is a perennial river that continues to flow throughout the year. Dry season flow is due to groundwater discharge, the source of which is two major limestone aquifer systems. Within the Daly River catchment, all species of flora and fauna (including humans) depend upon water to sustain life. This dependence upon water is particularly critical in the dry season when demand for water is high. Consumptive demand (e.g. for agricultural production, human consumption, industry and stock needs) is competing against non-consumptive demand (e.g. ecosystem, cultural and recreational needs). Consumptive demands in the catchment are growing rapidly and are typically met by pumping groundwater from extraction bores. The Northern Territory Government is in the process of developing, implementing and managing Water Allocation Plans (WAPs). These Plans seek to control the volume of water extracted from the Daly aquifer systems.

In order to demonstrate the potential of the MSE application, an MSE prototype application for the Daly River catchment has been developed. The MSE application is comprised of six main models (conforming to the six functional areas of the MSE framework) configured with sub-models and data pertinent to the Daly river catchment. The sub-models include a catchment water model, groundwater model, economics model, habitat model, WAP decision model, and relationship learning model.

The Daly River MSE application provides resource managers with a powerful tool in which to compose and simulate potential management strategies with great flexibility in development and analysis. Management strategies can include (but are not limited to) reducing/increasing groundwater extraction and facilitating economic growth trajectories. The Daly MSE application presents trade-offs between economic, social and environmental (triple bottom line) performance indicators and associated uncertainties. Resource managers are able to weigh these trade-offs (and uncertainties) and make decisions accordingly as they strive to achieve a balance between ecosystem/cultural needs and economic/ human needs.

Results

Results from projects that have a methodological purpose, such as the one reported in this document, differ from the more conventional science reports in that the results are not so much expressed in tables and graphs but more in terms of capability. The results of the *Knowledge Integration and Science Delivery* project can be grouped around the level of science integration achieved for the TRaCK program and the capability and tools to deliver that integrated science effectively into natural resource management in the form of management scenario evaluation.

The project achieved its goal in demonstrating MSE utility in terms of triple bottom line performance indicators. These management scenario evaluations can be based on integrated knowledge from various TRaCK science projects, notably economics, fish habitat, fish stocks, surface and groundwater hydrology and indigenous harvest. The project also achieved its goals in integrating the science knowledge domain with the management knowledge domain resulting in models for water licensing, groundwater water allocation rules, and groundwater extractions being applied to the models mentioned in the previous sentence. This has been achieved in close collaboration with Government. Currently a trial is underway where NT water managers are examining the MSE tools and their application within their organisation.

In terms of delivering management scenario evaluation capability: the software tools that were developed and configured around the Daly catchment allow a high level of flexibility. The detailed user interface brings this capability to a much broader range of potential users, albeit with appropriate training. The main objective of the MSE is to examine a broad range of management options in relatively short time. The software application achieves that goal, including the assessment of a range of uncertainties.

Conclusions

The potential of MSE concepts and their implementation to help structure the integration between the domains of natural resource management and science has been demonstrated in this report. The broad MSE concepts have been translated into structured processes and tangible tools to support the complex task of natural resource management with the best available science. The results of this project provide a firm start on the road to a stronger synthesis-oriented approach in collaboration between science and management.

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1 TRACK PROGRAM AND PROJECT OVERVIEW

1.1 TROPICAL RIVERS AND COASTAL KNOWLEDGE (TRACK)

TRaCK (Tropical Rivers and Coastal Knowledge) is a research hub under the Australian Commonwealth Environmental Research Facilities scheme, managed by the Department of Environment, Water, Heritage and the Arts.

The objective of the TRaCK program is to:

"Provide the science and knowledge that governments, communities and industries need for the sustainable management of Australia's tropical rivers and estuaries"

TRaCK draws together more than 70 of Australia's leading social, cultural, environmental and economic researchers from 18 organisations. TRaCK research focuses on the tropical north of Australia from Cape York to Broome. The main body of TRaCK projects focus on three catchments in Northern Australia: the Fitzroy, the Daly and the Mitchell River catchments, as shown in Figure 1-1[1].

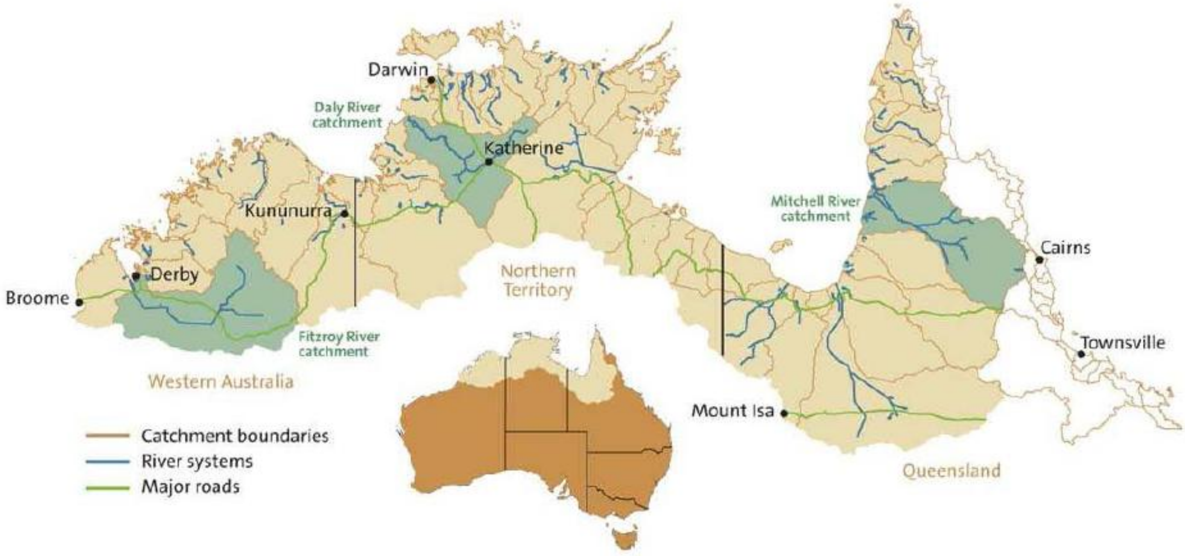

Figure 1-1 Location of the TRaCK focal catchments

The TRaCK program encompasses 27 Projects in seven Themes, of which 12 are in the Daly Catchment. More information is available at the TRaCK program website: http://www.track.gov.au.

1.2 TRACK PROJECT 1.4

Project 1.4 follows on from TRaCK Project 1.1 and started in early-2009. The project is part of Theme 1, Scenario Evaluation.

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[1] All mapping figures in this report are Geographic Information System (GIS) maps.

1.2.1 PROJECT OBJECTIVES

Project 1.4 aims to improve our understanding of the functioning and management of tropical rivers and coasts by integrating the knowledge that is being developed across the TRaCK program. Secondly, Project 1.4 aims to use that integrated knowledge to deliver scenario-evaluation capability. To that end, we have developed concepts, methods and tools that deliver such knowledge to a range of stakeholders, particularly in support of natural resource management.

The approach to knowledge integration is based on a conceptual framework known as Management Strategy Evaluation (MSE). This framework recognises the various functional areas of an adaptive management approach, including (i) management decisions, (ii) management actions, (iii) our knowledge of the natural system and how it responds to management, (iv) our capability for observation, (v) the assessment process and (vi) our 'learning by doing'.

The first level of integration achieved by Project 1.4 is bringing together and connecting scientific knowledge from across TRaCK science projects to improve our system understanding. This integrated knowledge forms the basis of a second level of integration: integration between the science domain and the resource management domain.

To meet these objectives, the project's task areas are to:

- Integrate models and knowledge from other TRaCK projects into the broader MSE framework to explore scenarios for management and development of our natural resources.
- Further develop the broad conceptual frameworks and implement software tools to support decision-making based on best available knowledge.
- Engage external and internal stakeholders at a range of levels to identify realistic scenarios for the future management of key rivers and coasts
- Identify gaps that, when filled, will improve model reliability and predictive capacity

1.2.2 SCIENCE INTEGRATION & INTERNAL STAKEHOLDER ENAGAGEMENT

Integration within the science domain involved bringing together knowledge from across the TRaCK projects. This knowledge encompassed ecologic, socio-economic and cultural research. To facilitate this integration, a range of TRaCK workshops and presentations were held with TRaCK staff. TRaCK staff were an important group of (internal) stakeholders. These workshops and presentations enabled Project 1.4 to communicate the MSE approach and to get a better understanding of the science within TRaCK and how to integrate it. Table 1-1 provides a summary of workshops with the details presented in Appendix A.

1.2.3 EXTERNAL STAKEHOLDER ENGAGEMENT

In this project, selected external stakeholders such as the Northern Territory Department of Natural Resources, Environment, the Arts and Sport (NRETAS) and the Daly River Management Advisory Committee (DRMAC) have been engaged at various levels to develop and evaluate likely scenarios for the future of tropical rivers and coasts. A range of presentations and workshops were organised over the running of the project to introduce the MSE concepts, receive feedback on direction and focus and disseminate progress and results (see Table 1-1).The stakeholders were also invited to explore a range of consequences of selected management scenarios based on the developed tools and capabilities.

Table 1-1 Workshops/Presentations Organised by Project 1.4

Audience	Communication Title and type	Place and date
TRaCK Program Management Committee	Integrated modelling and scenario evaluation, presentation	Darwin, April 2009
TRaCK Consortium Members	Science integration workshop	Brisbane, April 2009
NRETAS	Introducing MSE, presentation	Darwin, August 2009
NRETAS	Daly MSE, presentation	Darwin, October 2009
Australian Rivers Institute forum	TRaCK P1.4, Knowledge Integration and Science Delivery	Brisbane, December 2009
NRETAS and TRaCK scientists	Water budgets (flows) workshop	Darwin, Dec 2009
TRaCK scientists	Aquatic ecology workshop	Brisbane , Dec 2009
DRMAC	Project 1.4 and introduction to MSE, presentation	Palmerston, February 2010
TRaCK and external scientists	Socio-economics workshop	Darwin, April 2009
DRMAC	MSE tools, software demonstration	Katherine, May 2010
NRETAS, TRaCK and invited scientists	Groundwater workshop	Darwin, November 2010
TRACK research executive committee	MSE and Tindall WAP presentations	Brisbane, February, 2011
NRETAS Staff	MSE and Tindall WAP workshop	Palmerston, February, 2011
Griffith University	Part I: MSE concepts and Daly River, seminar	Brisbane, March 2011
Griffith University	Part II: MSE implementation and early results, seminar	Brisbane, April 2011
NRETAS Staff	Introduction to using MSE application	Darwin, May 17, 2011

1.2.4 MSE FRAMEWORK AND TOOLS

This document reports on the MSE framework, the software application development and configuration. This document also reports a range of results to demonstrate its capability.

1.2.5 IDENTIFY GAPS

To effectively identify gaps, we need to be clear on the objective. The objective for the prototype Daly River MSE is to provide a demonstration of the capabilities of MSE to integrate science and provide 'what-if' scenario evaluation capability. We show in this report that the current implementation and configuration achieve this objective, and in that sense there are no gaps.

However, for the next stage of development where the application is expected to support resource planning and management and stakeholder interactions, there are some improvements that need to be considered. We will discuss three gaps that we will find impeding us in many applications in the Daly River catchment.

Groundwater model: the current groundwater model implemented in the Daly River MSE is not suited to a catchment where groundwater has such a prominent place in the water dynamics, as it has in the Daly River catchment. The model implements a very simple representation of storage, recharge and discharge and has no ability to specify lateral flows and local depletion. Apart from the MSE groundwater model, development of any groundwater model in the Daly River catchment will be severely hampered by the inability to accurately measure low flows during the late-dry season, when they are generally between 0.5 and 5 m^3/s around Katherine. This inability results in an unreliable record of dry-season flows against which to calibrate and validate ANY groundwater model. Closely related is the need for a better spatial and temporal coverage of observation bores in the Tindall and Oolloo basins. On the water use side, the current availability of actual pumpage information was incomplete at the time due to low compliance to reporting requirements. The absence of legal requirements for some industry sectors, primarily mining, stock and domestic use, to report their groundwater usage also impedes the estimation of overall groundwater use in the region. This has subsequent detrimental effects on our ability to simulate groundwater demands under various economic development scenarios.

High-resolution elevation data: some work has been done in the TRaCK program to better simulate fine-scale hydro-physics in a part of the Daly river main channel. This allows the estimation of physical variables such as flow speed and scouring effects and so helps in identifying and locating key ecological processes and effects of flow changes on them. Even though we have now a first-order prediction about the wet-season surface water discharges [m^3/s] in the main channels of the Daly River catchment, turning these discharges into more ecologically relevant measures (e.g. flow speeds [m/s]), we need high-resolution data (e.g. LIDAR and cross-sections) that describe the geometry (and geology where possible) of the main channels in the Daly River catchment. We also need a field program to spot-check the results. Such data would also significantly improve our capabilities to predict effects such as bank erosion and gully forming.

Landuse constituents runoff: even though the current surface water models in the MSE have a module that handles dry and wet-weather transport of constituents (runoffs) such as sediment and nutrients, there is no data available to configure (calibrate, validate) these models for the Daly River catchment. The consequence of the absence of such information is that it is not possible to convert landuse changes to a credible estimation of effects on water quality and in-stream ecology.

In a catchment the size of the Daly River, none of these deficiencies are easily overcome. However, we may need to focus resources to resolve these big-ticket items if we are serious about science-based resource management.

1.3 SUMMARY

TRaCK (Tropical Rivers and Coastal Knowledge) is a research hub under the Australian Commonwealth Environmental Research Facilities scheme, managed by the Department of Sustainability, Environment, Water, Populations and Communities (DSEWPaC), formerly known as DEWHA. Project 1.4 is part of Theme 1 of TRaCK and commenced in early 2009. Entitled "Knowledge Integration and Science Delivery", Project 1.4 has two main aims:

1. To integrate the knowledge that is being developed across the TRaCK program.
2. To use that integrated knowledge to deliver science into the management domain.

To that end, Project 1.4 has developed concepts, methods and tools that deliver such knowledge in the form of scenario evaluation capacity to a range of stakeholders, particularly in support of natural resource management. The approach to knowledge integration is based on a conceptual framework known as Management Strategy Evaluation (MSE).

To achieve the integration required, Project 1.4 hosted and facilitated a number of internal TRaCK workshops and presentations designed to increase understanding of both the individual science projects and relationships between them. In order to deliver relevant science effectively, Project 1.4 also engaged with selected external stakeholders such as NRETAS and DRMAC. Project 1.4 was able to present concepts, progress and results to these organisations. In turn, these stakeholders were able to provide feedback on project direction, focus and selected management scenarios.

During the project, the Project 1.4 team identified a number of areas that would benefit from greater knowledge/data. Filling these knowledge gaps will greatly assist future scientific work within the Daly River Catchment, in particular further development of the Daly Catchment MSE. The gaps include:

1. Groundwater Model – a better model representation of the Daly groundwater system and more reliable calibration data is needed so that the model provides a better validated representation of the natural system. The calibration data include reliable low flow records, more observation bore records and a complete set of actual pumpage records.
2. High Resolution Elevation Data – key ecological processes are dependent upon river flow characteristics, such as flow speed [m/s]. In order to determine flow speeds (given flow rates [m^3/s]) river channel dimensions are needed. At present, channel dimensions are only available in discrete localised areas. A more comprehensive set of channel dimensions is required and can be obtained via the collection of high resolution elevation data.
3. Land-use constituents runoff – measurements of constituents transported by water (such as sediment and nutrients) from various landuses and landcovers are needed in order to validate the transport models and to better simulate the influence of changing landuses.

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2 MSE - CONCEPTUAL FRAMEWORK

2.1 BACKGROUND

In light of continuing pressure on our natural ecosystems (Jackson et al., 2001, Margules and Pressey, 2000), many have called for a change in the status quo of natural resource management (Likens et al., 2009, Sutherland et al., 2004, Pikitch et al., 2004). The adaptive management approach (Walters and Holling, 1990, Holling, 1978) is held up as the benchmark for *best-practice* natural resource management, but has historically proven difficult to implement effectively (Gregory et al., 2006, Mangel, 2010). Adaptive management is an approach to managing natural resources that explicitly acknowledges the complexities and uncertainties inherent in our knowledge of the natural world. Adaptive management deals with the complexity and uncertainty via a *learning by doing* attitude to management (Gregory et al., 2006).

Based on the principals of adaptive management, a management strategy evaluation (MSE) conceptual framework was developed for the management of fisheries (Holland, 2010, Sainsbury et al., 2000, Smith, 1994) and has been adopted to the domain of catchment management (Pantus et al., 2008a, McDonald et al., 2006). An MSE tool uses a computational model (or series of models) to simulate the response of environmental, social and economic performance indicators to a particular set of management procedures. It produces a list of explicit trade-offs with uncertainties, providing managers and policy makers with quantitative and qualitative feedback on the possible effects of particular management strategies (Mangel, 2010, Smith, 1994).

What MSE does not do, is provide an optimal management strategy. Instead, the aim of the MSE framework is to facilitate the implementation of adaptive management by providing a means for managers and policy makers to inform their management decisions with science (Mangel, 2010).

In the face of uncertainty about the effects of both economic and management activities on resources, it is often difficult to enact a precautionary approach (Buschmann et al., 1996) to resource management. Experience has shown that the inclusion of stakeholders in the management process can significantly reduce hostility towards management actions from within affected communities (Butterworth, 2007, Enck et al., 2006). An MSE tool allows managers and policy makers to incorporate stakeholders in the decision making process by providing a mechanism for analysing the possible long and short term impacts (trade-offs) of particular strategies (Mangel, 2010, Butterworth, 2007, Smith, 1994). It is in this context that an MSE tool can fulfil another key objective of *best-practice* resource management; namely the inclusion of managers, stakeholders and scientists in the decision making process.

2.2 THE MSE CONCEPTUAL FRAMEWORK

The MSE conceptual framework outlines a preferred approach to implementing MSE applications. The MSE conceptual framework outlines an approach to delivering science support for natural resource management which allows managers and policy makers to evaluate the possible effects of particular management procedures. The framework includes elements such as management objectives, performance measures, indicators, management scenarios and strategies (see Section 2.3 for detail). Many of its concepts are borrowed from the adaptive management approach, described in Section 2.1 (Holling, 1978, Gilmour et al., 1999, Gregory et al., 2006).

Figure 2-1 The adaptive management cycle is a powerful ally in managing systems that contain many uncertainties (graphics courtesy Dr Keith Sainsbury).

The choice of an adaptive management approach recognises that we need to make decisions in the presence of many uncertain factors, one of them being what effects our management actions will have on our natural resources. It also recognises that our management actions have two objectives:

- One is to steer the managed system *iteratively* in the direction of the objective we have set for it.
- A less visible objective is to *learn* from feedback we get while iterating through the cycle.

It is these characteristics (iteration and adaptive learning) that are brought together into the methodological approach called Management Strategy Evaluation. Figure 2-2 defines a number of elements for the MSE conceptual framework directly related to the adaptive management cycle.

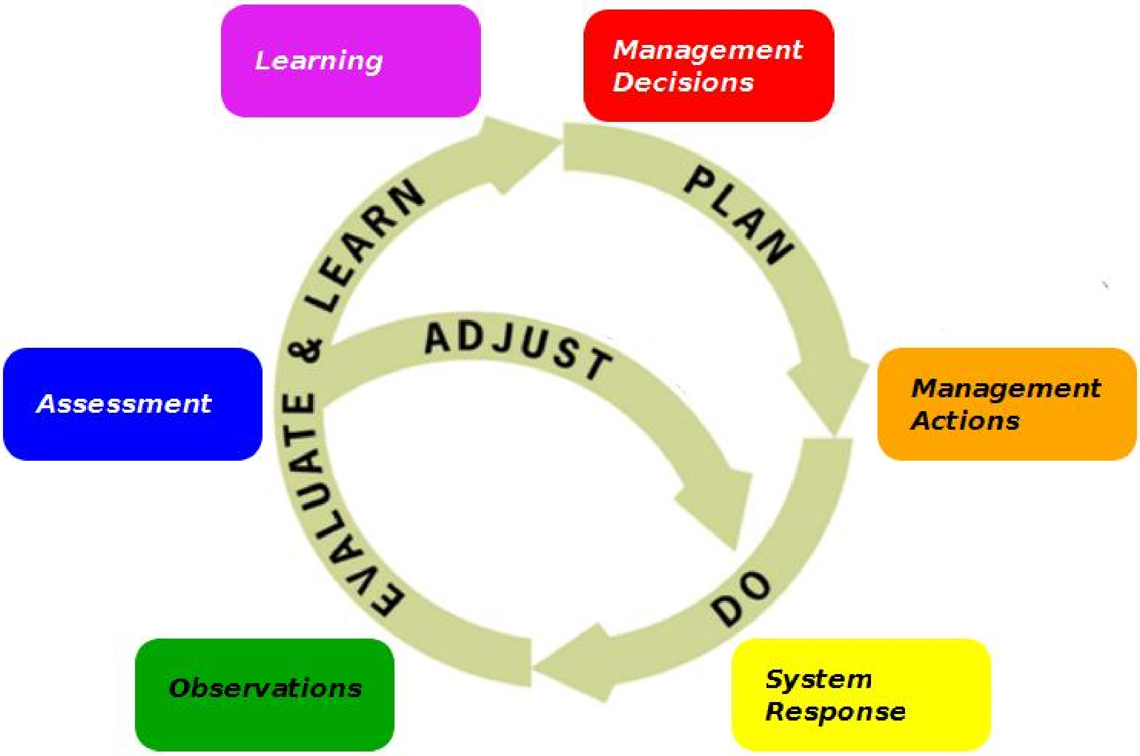

Figure 2-2 MSE Conceptual Elements in Adaptive Management (adapted from graphics courtesy of Dr Keith Sainsbury)

Figure 2-2 demonstrates that the planning phase of adaptive management begins with generating management decisions. Completion of the planning phase involves generating management actions to act as effective levers in supporting the goals of the management decisions. In the "doing" phase, management actions are enacted, which in turn trigger system responses from the resource under management. In the evaluation and learning phase, observations are collated and assessed against measurable objectives defined in the planning phase. Assessments can trigger adjustments to management actions or be fed into a learning activity that triggers a new round of adaptive management, beginning with (possibly revised) management decisions.

Observing the responses of the system under management is necessary in order to allow dynamic feedback and adaptive management to occur. Many traditional modelling approaches do not include the adaptive mechanisms in their approaches.

Aspects of the MSE conceptual model not necessarily catered for in general adaptive management are described below.

2.2.1 MANAGEMENT STRATEGIES

A *management strategy* is a set of rules that transforms the results of an *assessment* into management actions, given some knowledge of the system under management. An explicit management strategy allows us (in principle) to close the adaptive management loop by feeding assessments from the previous iteration of the adaptive loop into a set of strategy rules, which adjust management actions for the next iteration. By choosing contrasting management strategies, we can then evaluate the effectiveness of different sets of management strategies (rules). We call this process, together with a set of standards and deliverables, Management Strategy Evaluation.

2.2.2 MANAGEMENT SCENARIOS

A set of *management actions* (and their level of implementation over time) is referred to as a *management scenario*. Testing such a set of management actions (in the context of a set of given models) is called a *Management Scenario Evaluation*. As the standards and the deliverables are the same for strategy and scenario evaluation, the term MSE will be used in this document to indicate both strategy and scenario evaluation and the particular form will be clear from the context.

2.2.3 DYNAMIC FEEDBACK

The MSE conceptual framework works by putting the adaptive management principle into practical use in order to further strengthen and consolidate the management of a region's waterways. This means that management actions are altered in response to changing circumstances. At the same time, the approach recognises that actions can seldom be postponed until we have "enough" information to fully understand the situation.

Operationally, *adaptive* means that we can change our (management) behaviour based on what we've learned from our previous experience (trial, error AND learn). To be able to learn, we need to be informed of the results of our actions. Allowing the results of our previous actions to assist in shaping the subsequent actions is the essence of *adaptive* management. The management decisions are partly or wholly based on this dynamic feedback of the results from the previous iteration. As a consequence, support for dynamic feedback is a necessary aspect of the MSE conceptual framework.

2.2.4 TRADE-OFF EVALUATION

Managing the multiple uses of resources is often a requirement for resource managers. If a resource is limited, multiple uses can often compete for adequate share of the resource. An MSE framework should allow resource managers to systematically evaluate management strategies/scenarios by presenting a set of performance indicators that allow consideration of trade-offs between those strategies/scenarios.

The *trade-offs* between various management scenarios are often expressed in measures that are used to set (operational, measurable) management objectives. Such measures indicate how well management is performing against the objectives and are referred to as *performance measures*; informing the manager on any discrepancies between a set objective and the actual status of a resource under management.

For example, a performance measure may indicate how well a particular water quality indicator (say, phosphorus concentration in the water) is tracking against some reference value. Other performance measures may inform us of the effects of a given management scenario with respect to overall economic activity.

Reporting in terms of performance measures often condenses a wide range of collected data into an informative, high-level indicator of how a management option is performing. The ability to evaluate these performance measures for a range of different management options allows us to inspect the trade-offs between the different management options. To facilitate decision-making, a systematic evaluation of each performance measure against each management scenario is needed. A table listing performance measures against management scenarios is needed to allow effective trade-off decisions and is referred to as a (management) *decision support table*.

The MSE conceptual framework needs to support tracking of performance measures against scenario evaluations in order to produce such a decision support table which, in turn, allows the resource manager to engage in trade-off evaluation.

2.2.5 EXPLICIT SUPPORT FOR UNCERTAINTY

Monitoring data sets often contain error and variance. Error may be caused by instruments not indicating the precise value of what is being measured, or observers (mis-)reading an instrument with finite precision. Variance is often part of the underlying process that we're trying to measure (e.g. amount of algae in the water is affected by a number of other, non-observed, variables). For instance, if we sample 10 minutes later or 10 metres away from a given time/location, chances are that the value would be different from what we obtain at that location. Such *process variability* is not an error that we can rid ourselves of, but remains an intrinsic aspect of the process we study. We refer to the result of observation error and process variability as *uncertainty*. Managers often need to make decisions based on information that contains a degree of uncertainty. The MSE conceptual framework should be able to explicitly deal with the uncertainty in order to allow managers to understand the impact of error and/or variance.

2.3 FUNCTIONAL AREAS

In this Section we describe each of the six functional areas (the 'boxes') of the MSE conceptual framework (see Figure 2-3), including the nature of activities that are conducted for a given functional area.

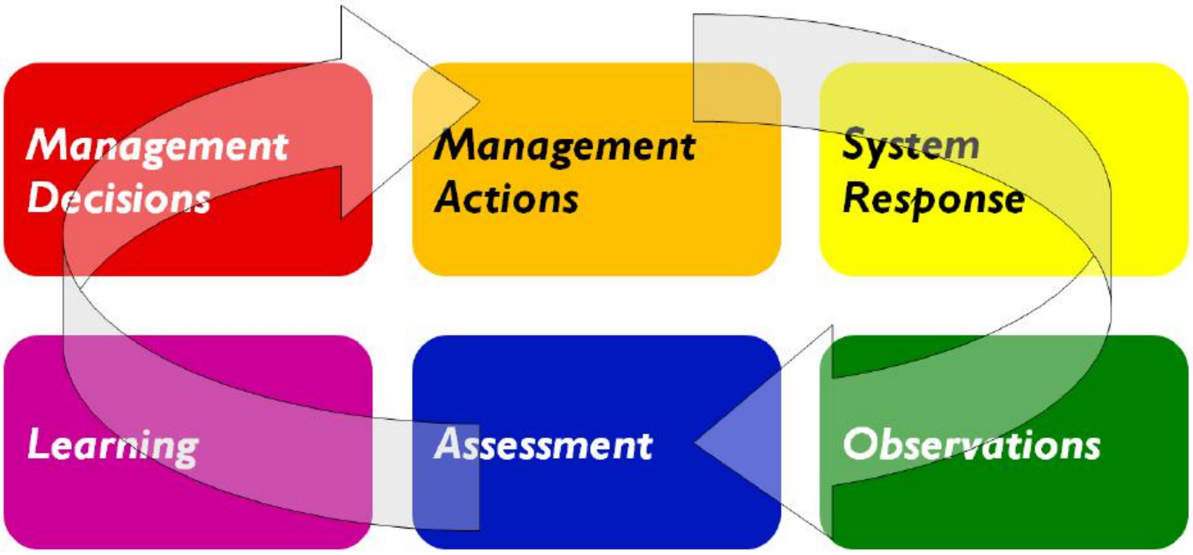

Figure 2-3 The six functional areas of an adaptive MSE system.

2.3.1 MANAGEMENT DECISIONS

The *Management Decisions* functional area of the conceptual framework refers to the general task of setting operationalised (measurable) objectives for managing a set of natural resources. Such objectives are either explicitly stipulated, or implicitly inferred in a management charter outlining how the wellbeing of natural resources under management is to be maintained or enhanced.

For ambiguous or immeasurable objectives, this element of the conceptual framework ensures that such objectives are converted into a set of derived, unambiguously measurable objectives that can be used to assess the effect of management actions on natural resources (below).

Tightly coupled to the concept of operationalised objectives are performance indicators, reference values, performance measures and observed values. *Clear, measurable management objectives and derived performance measures are necessary to give management decisions a goal to work towards.*

Once operationalised objectives have been established, management actions that allow managers appropriate levers with which to influence the wellbeing of the natural resources under management can then be derived.

Explicit vs Implicit Management Decisions

To be able to simulate the decision making process in real-world management, the rules and schemes used to make decisions need to be made explicit. In practice, decisions are often being made with only imperfect data available. Decisions are made based on a mix of many arguments, and only a subset of these arguments is based on the assessment of the feedback data.

There are two ways of using the MSE software: the first use is by modelling *explicit* management decision rules (given a result, what action should be taken). This means that the feedback from the assessment and the learning models can be converted into management actions. However, often these explicit management rules are not available or are under development. In which case, the MSE can be used to model *implicit* management decisions by *manually* substituting the management decision models. It works as follows: a set of management actions (and their level) is chosen as a starting point for a scenario. The scenario is run for a set time (typically one year or so). After inspection of the results, the user chooses to change (or not) the management actions based on the results of the previous evaluation and undertake the simulation for another time interval and so on. This does not only allow a more intuitive approach to management decisions, it also would be a valuable support for developing explicit management rules. Currently, the MSE system does not fully support this mode of working, but changes to the application would be minor in order to achieve this.

2.3.2 MANAGEMENT ACTIONS

The *Management Actions* functional area of the model refers to specific activities that can be undertaken in response to an issue or event. Actions identified in the Management Decisions element of the framework as being appropriate for managing natural resources should be described here, and act as a reminder that these actions are to be implemented and/or enforced. The *Management Actions* element converts management decisions into actions. Two key functions of this element are:

1. Add implementation uncertainty: not all actions will be implemented to exactly conform to planning time lines.

2. To allow the specification of 'fixed' management actions (those management actions that do not take external conditions into consideration). Arguably this element could be dissolved into *Management Decision* and *System Response* functional areas. However,

this element is made explicit to directly address the complications of implementing management actions.

In the case of tropical river management, these management actions may include various spatial restrictions on land-uses (e.g. urban development), the implementation of various urban design standards, simulating the results of behavioural change using targeted incentive schemes or whatever other management levers are available. A resource is often managed through either controlling its exploitation (e.g. water use restrictions) or via remedial actions (e.g. riparian revegetation) or, perhaps more interestingly, various combinations of such actions.

2.3.3 SYSTEM RESPONSES

The *System Responses* functional area of the conceptual model captures how the natural system responds to a combination of a) specific management actions, and b) changes to the natural resources outside of the direct influence of management actions, such as rainfall and/or population growth.

This functional area represents our understanding of the response of the 'real world' to the management action (and its exploitation) based on our best knowledge of the system or resource. They may include models of the ecosystem (biology, environment and their interactions with human use), economy, water quality and quantity etc. This element is typically the most challenging and time-consuming part of the MSE.

In reality, resource managers (and others) do not have a perfect knowledge of the results of our actions. The results of actions in the *System Responses* functional area could (in principle) be fed directly back to the *Management Decision* functional area. In the real world this could be done only if we had perfect information about a system's responses to the actions. Often, we only have a sparse subset of that information.

The design of a monitoring program (spatial and temporal), which is reflected in the *Observations* functional area described next, is critical for the robustness of the system understanding incorporated in the *System Responses* element, and consequently how we track the response to management actions. Simply said, the *Observations* functional area acts as a filter for, or snapshot of, a complete system understanding.

2.3.4 OBSERVATIONS

The *Observations* functional area of the conceptual model includes the design and implementation of an observation network for the natural resource under management that:

a) Supplies raw measurement data to assess whether the system is within acceptable bounds of operationalised objectives for the resource.

b) Supplies sufficient triggers to ensure that management actions can be invoked in a timely manner.

The three questions to ask in considering adequate observation coverage are:

1. What needs to be observed?
2. Where does it need to be observed?
3. How often should it be observed?

The *Observation* model(s) within this element simulate the way we <u>track or monitor</u> the 'real world', typically through field programs. Such programs may be used to extract information about the status of parts of the system under investigation but also to assess efficacy of management. These programs are costly to implement and maintain, and it is important to properly design the spatial and temporal characteristics of such field programs and carefully choose the indicators they collect.

2.3.5 ASSESSMENT

The *Assessment* functional area covers the <u>reporting</u> phase of the conceptual framework and contains (often statistical) methods to convert the data collected data in the *Observations* functional area into management performance measures. This activity may be as simple as drawing some summary statistics from the monitoring data or as complex as expressing an ecosystem's 'health'.

Generally speaking, performance indicators are collected from the *Observations* functional area, and compared to reference values initially set within the *Management Decisions* element to generate performance measures. These performance measures describe the magnitude and direction of the difference of a performance indicator from a reference value. Performance indicators can be as simple as applying some statists to one or a combination of monitoring results. In some cases performance indicators can be based fairly complex models themselves such as ecosystem health indicators (Pantus and Dennison, 2005). As such, performance measures and indicators can be used to learn about the resource system and its management and to drive further management actions that aim to close the gap between the performance measure(s) assessed and desired reference value(s).

2.3.6 LEARNING

The *Learning* functional area looks at the discrepancies between the expected results of management actions and the actual results after they have been applied to the *System Response* model. Management decisions often include some expectation of the efficacy and effects of the management actions (controls, levers). Learning often means updating those expectations. However, learning may also include switching the overall approach for making decisions, for instance from a set of simple heuristics (if this happens, do that) to quite complicated statistical schemes of optimising some cost functions in the presence of uncertainty.

The *Learning* functional area, in theory, focuses on two modes of learning conforming to the adaptive management paradigm (Holling, 1978, Walters, 1986): passive and active learning. In *passive* learning, managers review natural system responses to actions but do not actively change the management decisions. The management actions are solely used to get the system to a set of objectives. In *active* learning, management actions may be altered based on system response and some management activities may be undertaken purely to gain information about the responses of the managed system to management actions.

Besides the two learning modes, there are a range of potential objectives for learning. Examples of such objectives include learning to gain more system understanding, or to check assumptions underlying decisions, or the assess management action efficacy.

2.4 SUMMARY

MSE is a conceptual framework based on the principles of adaptive management. The MSE computational tool allows managers and policy makers to assess the potential trade-offs of particular management procedures. An application of MSE makes no attempt to find an optimal management strategy, instead it provides a means by which managers and policy makers can inform their decisions with science. This is achieved by dealing explicitly with uncertainties and presenting a clear set of trade-offs between various management strategies.

The structure and behaviour of the MSE application described in this report is based on an MSE conceptual framework. The framework consists of a number of functional areas, representing a classification of typical activities that go on in adaptive resource management. Being based on adaptive management, the framework requires compatible applications to support comparison of differing management strategies and scenarios, dynamic feedback, tradeoff-evaluation, and explicit support for uncertainty.

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3 MSE - SOFTWARE APPLICATION

The MSE software application is an implementation of the MSE conceptual framework described in Chapter 2. Each of the major elements presented within the framework is directly supported within the MSE application. This section briefly outlines general aspects of the application and how they support the conceptual framework. Descriptions included in this Chapter are confined to the capability of the system. Further information and worked examples on how a user may utilise these capabilities is provided in Appendix B. In addition, Chapter 5 outlines details specific to the management of the Daly River catchment for each of the individual MSE elements.

This Chapter is divided into the three key activities that users typically undertake with the MSE application. Namely: specification, followed by evaluation, and then analysis.

3.1 SPECIFICATION

The MSE application is a highly flexible system, allowing users to configure (or specify) rich management strategy evaluations. Figure 3-1 exemplifies the various levels of configuration available within the application, and how those levels are composed into a particular instance of a management strategy evaluation.

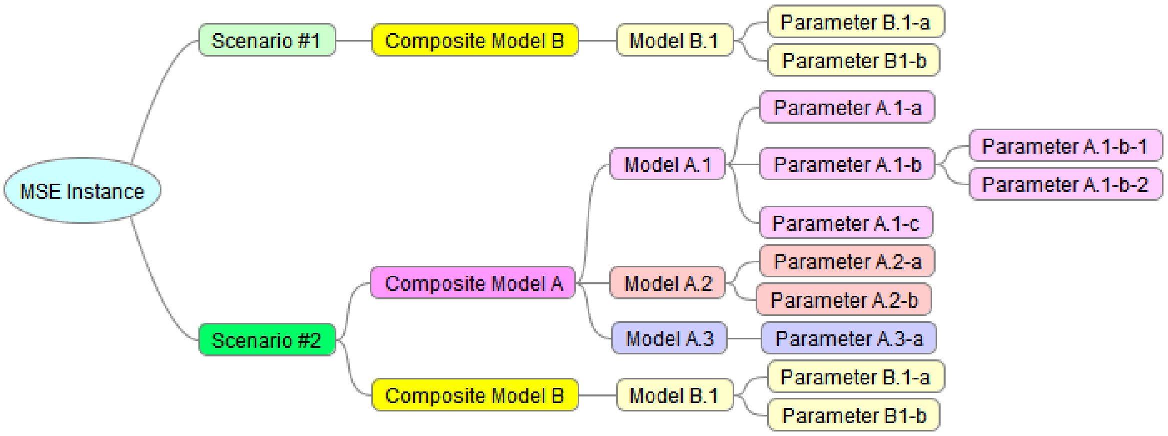
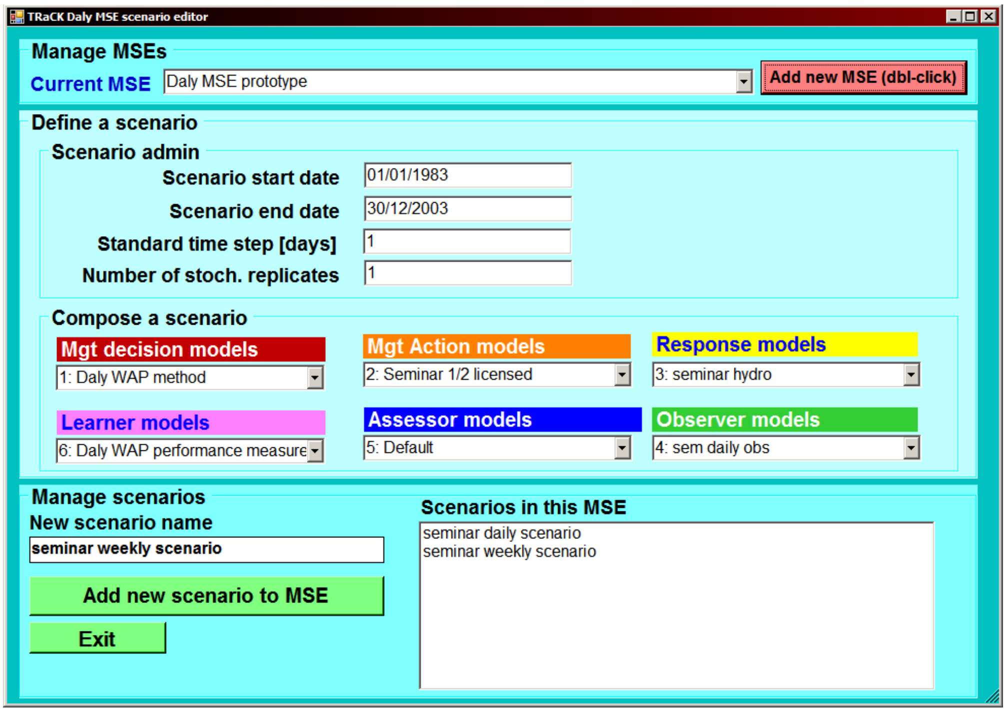


Figure 3-1 Layers of Configuration in an MSE

The TRaCK MSE application is configured to run an MSE instance. An MSE instance is composed of a number of scenarios. For example, one scenario might represent 5% economic growth over a period of time, while another represents no economic growth over the same period. Each scenario is configured to run a set of composite models (one composite model per functional area described in Section 2.3). A composite model is composed of a number of models, and each model has a set of parameters used to configure it. Parameters can be composed of finer-grained parameters. These layers are discussed in more detail as follows.

Figure 3-2 shows the MSE application screen allowing the definition of an MSE instance by adding one composite model per functional area into a scenario, and saving the scenario as a part of the MSE instance.



Current MSE: Daly MSE prototype

Scenario start date: 01/01/1983

Scenario end date: 30/12/2003

Standard time step [days]: 1

Number of stoch. replicates: 1

Mgt decision models: 1: Daly WAP method

Mgt Action models: 2: Seminar 1/2 licensed

Response models: 3: seminar hydro

Learner models: 6: Daly WAP performance measure

Assessor models: 5: Default

Observer models: 4: sem daily obs

New scenario name: seminar weekly scenario

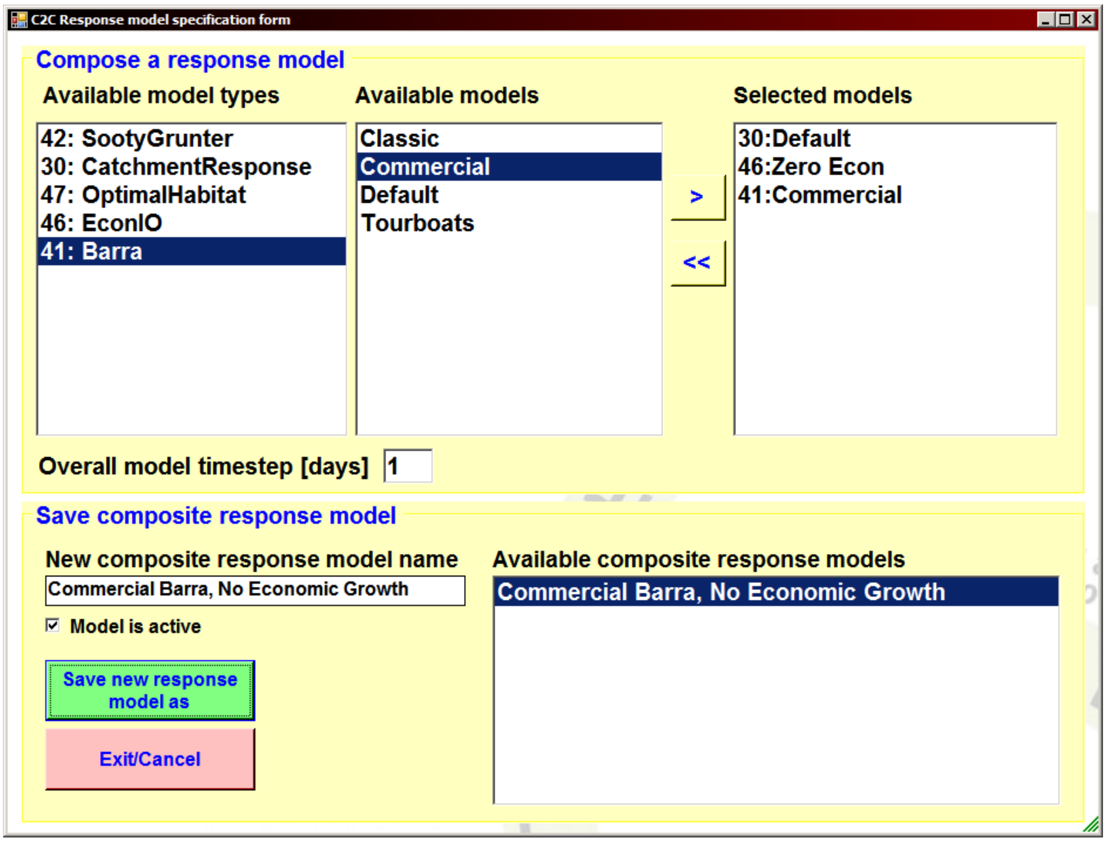
Scenarios in this MSE:
seminar daily scenario
seminar weekly scenario

Figure 3-2 MSE Instance Configuration Screen

A composite model is sharable between scenarios. For example, a Management Action composite model might be equally valid for both economic scenarios described earlier, and thus re-useable by each when considering economic impact on groundwater flow. A composite model has a *Composite Model Type* which is directly synonymous with the MSE functional areas discussed earlier. This type dictates which functional area an application model belongs to. For example, the catchment water model has a *Response* composite model type, which means it belongs to the System Response functional area. A number of models of the same composite model type can be composed together into a single composite model. As mentioned earlier, this single composite model can then be added to one or more scenarios.

Each model has a *Model Type* that dictates the model programming to run, and the set of parameters that governs the model's behaviour. An important concept of MSE models is that parameters governing the behaviour of a model are considered a part of that model. If a user of the application changes parameters to a model, they are in fact, creating a new model.

Figure 3-3 is a screen-shot of the MSE Application form that allows users to compose a number of models into a composite response model.



Available model types: 42: SootyGrunter, 30: CatchmentResponse, 47: OptimalHabitat, 46: EconIO, 41: Barra

Available models: Classic, Commercial, Default, Tourboats

Selected models: 30:Default, 46:Zero Econ, 41:Commercial

Overall model timestep [days]: 1

New composite response model name: Commercial Barra, No Economic Growth

☑ Model is active

Available composite response models: Commercial Barra, No Economic Growth

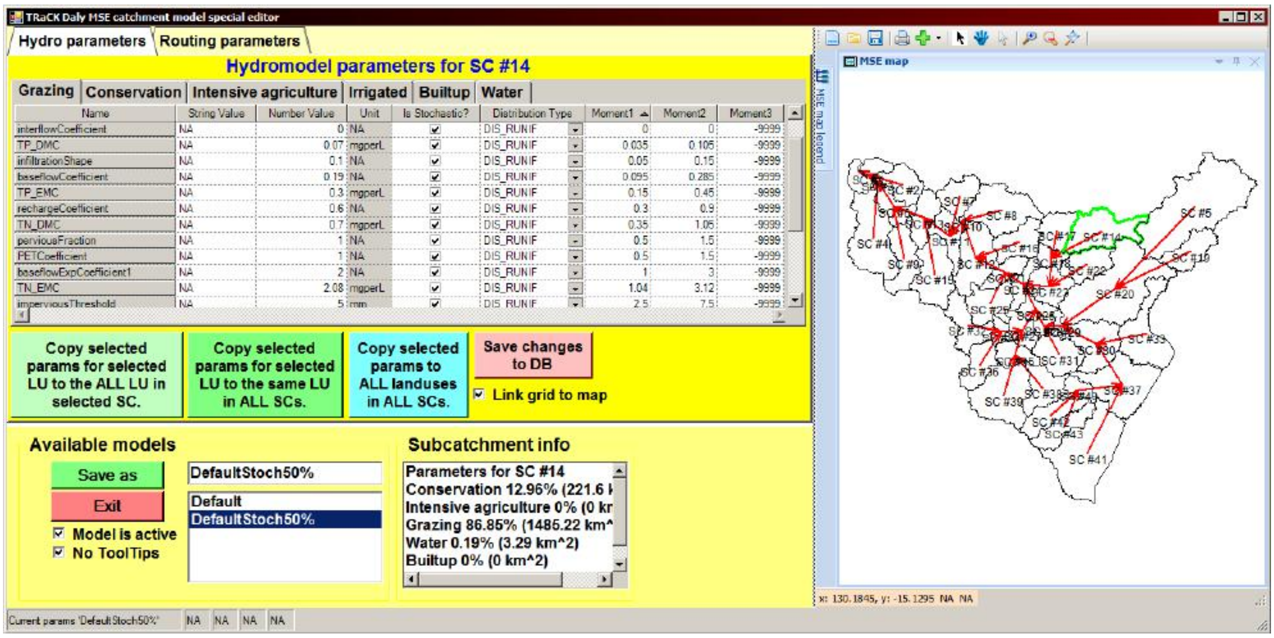
Figure 3-3 Composite Response Model: composed of Catchment, Economy and Barramundi Sub-Models

Each model has a number of parameters that must be configured to allow it to model a particular behaviour. Parameters can be as simple as a string or number. However, potentially very complex models can also be accommodated with support for:

- arbitrary levels of parameter hierarchy,
- ordered arrays of related parameters,
- relationships of parameters to each-other (for example, to describe model inputs that graph how one aspect of a model relates to another).

Parameters can be flagged as being stochastic (that is, explicitly describing uncertainty). To illustrate, a catchment response sub-model requires rainfall interception store capacity (INSC) as a parameter. Marking this parameter as stochastic, we can control the range and distribution of INSC from which a value is extracted for each stochastic realisation. We may choose that the INSC values range from a minimum value of 0mm and maximum value of 5mm and that values within this range exhibit a normal distribution.

Figure 3-4 shows an example model configuration screen for the catchment response model where key model parameters are made stochastic.



Name	String Value	Number Value	Unit	Is Stochastic?	Distribution Type	Moment1	Moment2	Moment3
interflowCoefficient	NA	0	NA	☑	DIS_RUNIF	0	0	-9999
TP_DMC	NA	0.07	mgperL	☑	DIS_RUNIF	0.035	0.105	-9999
infiltrationShape	NA	0.1	NA	☑	DIS_RUNIF	0.05	0.15	-9999
baseflowCoefficient	NA	0.19	NA	☑	DIS_RUNIF	0.095	0.285	-9999
TP_EMC	NA	0.3	mgperL	☑	DIS_RUNIF	0.15	0.45	-9999
rechargeCoefficient	NA	0.6	NA	☑	DIS_RUNIF	0.3	0.9	-9999
TN_DMC	NA	0.7	mgperL	☑	DIS_RUNIF	0.35	1.05	-9999
perviousFraction	NA	1	NA	☑	DIS_RUNIF	0.5	1.5	-9999
PETCoefficient	NA	1	NA	☑	DIS_RUNIF	0.5	1.5	-9999
baseflowExpCoefficient1	NA	2	NA	☑	DIS_RUNIF	1	3	-9999
TN_EMC	NA	2.08	mgperL	☑	DIS_RUNIF	1.04	3.12	-9999
imperviousThreshold	NA	5	mm	☑	DIS_RUNIF	2.5	7.5	-9999

☑ Link grid to map

DefaultStoch50%

Default
DefaultStoch50%

☑ Model is active
☑ No ToolTips

Parameters for SC #14
Conservation 12.96% (221.6 k
Intensive agriculture 0% (0 kr
Grazing 86.85% (1485.22 km^
Water 0.19% (3.29 km^2)
Builtup 0% (0 km^2)

Current params 'DefaultStoch50%' NA NA NA NA

x: 130.1845, y: -15.1295 NA NA

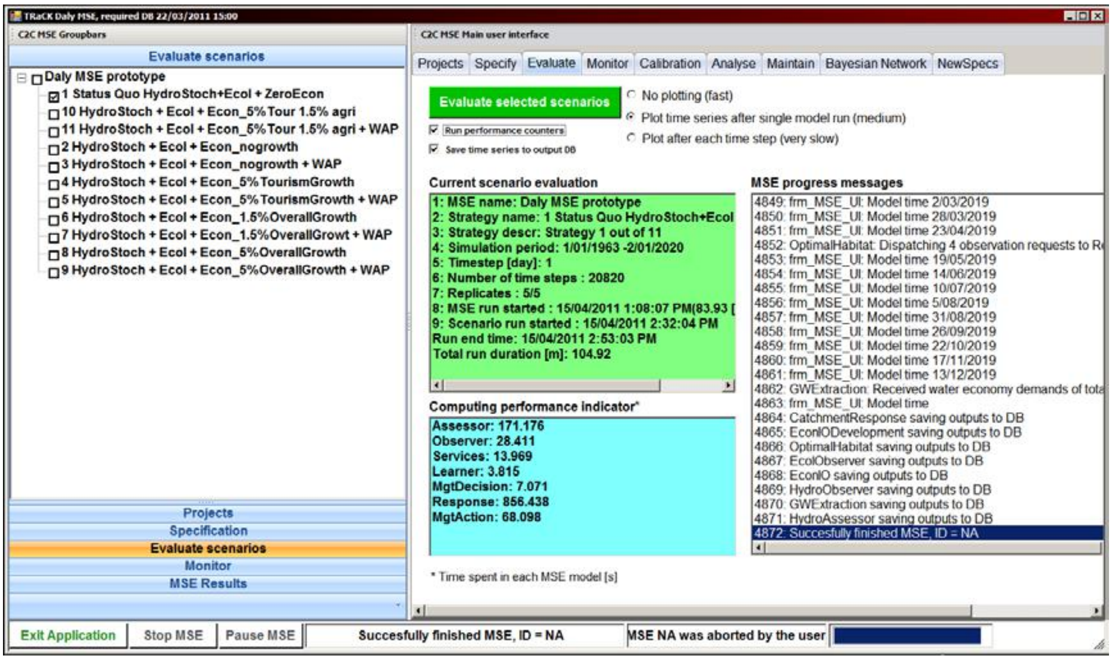
Figure 3-4 Uncertain Parameters in a Catchment Response Model

If a parameter is defined as being stochastic, a manager can configure scenarios to repeat a number of times. Each time a scenario is run/evaluated, a stochastic parameter is "sampled" to give it a certain value that falls within the parameter's uncertainty definition. The cumulative results of re-running a scenario multiple times are brought together at the completion of an evaluation. If a manager is interested in how sensitive a model is to uncertainty in given parameter(s), for instance, they might define two scenarios. One scenario where uncertainty is explicitly defined (stochastic mode) and another with uncertainty removed (deterministic mode). Once the scenarios are evaluated, a manager can observe the effect the uncertain parameter(s) had by analysing scenario results. Demonstrations of MSE results for both deterministic and stochastic modes are provided in Chapter 7.

3.2 EVALUATION

Once an MSE has been adequately specified, users are able to evaluate the MSE either partially or completely by picking scenarios to evaluate. For an MSE to be evaluated, it needs at least one scenario that in turn is composed of at least one model composed of at least one sub-model. The application thus allows MSEs to be incrementally constructed as new scenarios are envisioned and models configured to test these scenarios.

Figure 3-5 shows the Evaluation screen of the MSE application after having a single "stochastic" scenario specified. The MSE was configured as five stochastic realisations of parameters for the selected scenario, and gave five different sets of results for that scenario.



☐ Daly MSE prototype
- ☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon
- ☐ 10 HydroStoch + Ecol + Econ_5%Tour 1.5% agri
- ☐ 11 HydroStoch + Ecol + Econ_5%Tour 1.5% agri + WAP
- ☐ 2 HydroStoch + Ecol + Econ_nogrowth
- ☐ 3 HydroStoch + Ecol + Econ_nogrowth + WAP
- ☐ 4 HydroStoch + Ecol + Econ_5%TourismGrowth
- ☐ 5 HydroStoch + Ecol + Econ_5%TourismGrowth + WAP
- ☐ 6 HydroStoch + Ecol + Econ_1.5%OverallGrowth
- ☐ 7 HydroStoch + Ecol + Econ_1.5%OverallGrowt + WAP
- ☐ 8 HydroStoch + Ecol + Econ_5%OverallGrowth
- ☐ 9 HydroStoch + Ecol + Econ_5%OverallGrowth + WAP

○ No plotting (fast)
● Plot time series after single model run (medium)
○ Plot after each time step (very slow)
☑ Run performance counters
☑ Save time series to output DB

Current scenario evaluation

```
1: MSE name: Daly MSE prototype
2: Strategy name: 1 Status Quo HydroStoch+Ecol
3: Strategy descr: Strategy 1 out of 11
4: Simulation period: 1/01/1963 -2/01/2020
5: Timestep [day]: 1
6: Number of time steps : 20820
7: Replicates : 5/5
8: MSE run started : 15/04/2011 1:08:07 PM(83.93 [
9: Scenario run started : 15/04/2011 2:32:04 PM
Run end time: 15/04/2011 2:53:03 PM
Total run duration [m]: 104.92
```

Computing performance indicator*

```
Assessor: 171.176
Observer: 28.411
Services: 13.969
Learner: 3.815
MgtDecision: 7.071
Response: 856.438
MgtAction: 68.098
```

* Time spent in each MSE model [s]

MSE progress messages

```
4849: frm_MSE_UI: Model time 2/03/2019
4850: frm_MSE_UI: Model time 28/03/2019
4851: frm_MSE_UI: Model time 23/04/2019
4852: OptimalHabitat: Dispatching 4 observation requests to Re
4853: frm_MSE_UI: Model time 19/05/2019
4854: frm_MSE_UI: Model time 14/06/2019
4855: frm_MSE_UI: Model time 10/07/2019
4856: frm_MSE_UI: Model time 5/08/2019
4857: frm_MSE_UI: Model time 31/08/2019
4858: frm_MSE_UI: Model time 26/09/2019
4859: frm_MSE_UI: Model time 22/10/2019
4860: frm_MSE_UI: Model time 17/11/2019
4861: frm_MSE_UI: Model time 13/12/2019
4862: GWExtraction: Received water economy demands of tota
4863: frm_MSE_UI: Model time
4864: CatchmentResponse saving outputs to DB
4865: EconIODevelopment saving outputs to DB
4866: OptimalHabitat saving outputs to DB
4867: EcolObserver saving outputs to DB
4868: EconIO saving outputs to DB
4869: HydroObserver saving outputs to DB
4870: GWExtraction saving outputs to DB
4871: HydroAssessor saving outputs to DB
4872: Succesfully finished MSE, ID = NA
```

Succesfully finished MSE, ID = NA

MSE NA was aborted by the user

Figure 3-5 The MSE Scenario Evaluation Screen

3.3 ANALYSIS

Once evaluation is complete, access to the evaluation model results is available through the MSE *Analyse* tab. The Analyse facilities of MSE allow users a rich environment for composing results into graphs and tables as they interrogate the results of the evaluation. Selected outputs from models can be graphed and tabulated in a variety of ways, allowing the user substantial control and flexibility. A worked example of how the user may take advantage of these facilities is provided in Appendix C.

3.4 SUMMARY

The MSE application implements a number of software models simulating behaviour per functional unit that may be composed together in a highly flexible manner. Scenarios, describing alternatives management approaches may be specified and then evaluated via the models provided. Results from evaluations are then available for analysis, allowing resource managers to consider tradeoffs and uncertainty characteristics of the various scenarios evaluated.

The MSE application is a powerful tool that may be used to support decision-making. It allows users to configure and simulate management strategy evaluations with great flexibility in development and analysis. The capabilities of the MSE application are demonstrated in this Chapter by dividing the key types of activities of an MSE software user into three areas: specification, evaluation and analysis. Appendix C provides screenshots and worked examples designed to complement the descriptions of MSE capabilities contained within this Chapter, and assist a user in utilising key functions of the MSE application.

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4 MSE IN THE DALY RIVER CATCHMENT

4.1 INTRODUCTION

As demonstrated in Chapter 3, the MSE application is a powerful tool that may be used to support decision-making. It allows users to configure and simulate management strategies with great flexibility in development and analysis.

In order to demonstrate the potential of the MSE application, an MSE prototype application has been developed. The prototype application contains models that are applicable to the Daly River catchment. Resource managers in the Northern Territory (NT) are currently developing and evaluating water management strategies for the Daly catchment. These strategies are designed to achieve a balance between ecosystem/cultural needs and economic/ human needs. To achieve this balance, resource managers will be required to weigh trade-offs between conflicting requirements.

A model is an idealised representation of the properties and interactions of a system under study. Before introducing the models that comprise the Daly River catchment prototype MSE application (see Chapter 5), it is first necessary to gain an understanding of the system under study: the Daly River catchment. This Chapter describes the general characteristics of the catchment, the reasons for water demand and the water management strategies employed by the NT government. It also highlights the unique qualities that make the Daly River catchment worthy of well-supported management decisions.

4.2 GENERAL CATCHMENT DESCRIPTION

The Daly River catchment is located in the Northern Territory of Australia and is one of the major tropical river systems being researched by TRaCK. The location of the Daly catchment is shown in Figure 1-1. Lying to the south of Darwin, the Daly River catchment is about 53,000km^2 in area (about 80% of the size of Tasmania). It includes the major tributaries of Katherine, King, Fergusson, Douglas, Edith and Flora Rivers, as shown in Figure 4-1. The Daly River flows in a general westerly direction into the Joseph Bonaparte Gulf. The volume of water discharged into the sea is the second highest of any river in Australia (CSIRO, 2009).

The Daly River is one of the largest perennial river systems in Northern Australia (CSIRO, 2009). Being located in the tropical region of Australia, it experiences a wet season (November to April) and a dry season (May to October). Dry season flow is dominated by groundwater discharge with the baseflow being the highest of any river in the Northern Territory (CSIRO, 2009). This groundwater flows from the two major limestone aquifer systems located within the geological basin known as the Daly Basin (Tickell, 2009). These aquifers store and transmit significant volumes of groundwater and are named the Oolloo Dolostone and the Tindall Limestone. They are separated by an impervious siltstone formation known as the Jinduckin formation, and thus water does not flow between them. In addition to the major Daly Basin aquifers, the Wiso Basin also discharges some groundwater to the Flora River. This basin is separate from the Daly Basin and is located to the south, outside the Daly surface water catchment. However, regional water levels in the aquifer suggest that the *majority* of Flora River baseflow comes from the Wiso Basin (Tickell, 2011). CSIRO (2009) contains an estimate that 50% of Flora River baseflow originates from the Wiso, but Tickell (2011) believes that proportions have not been calculated.

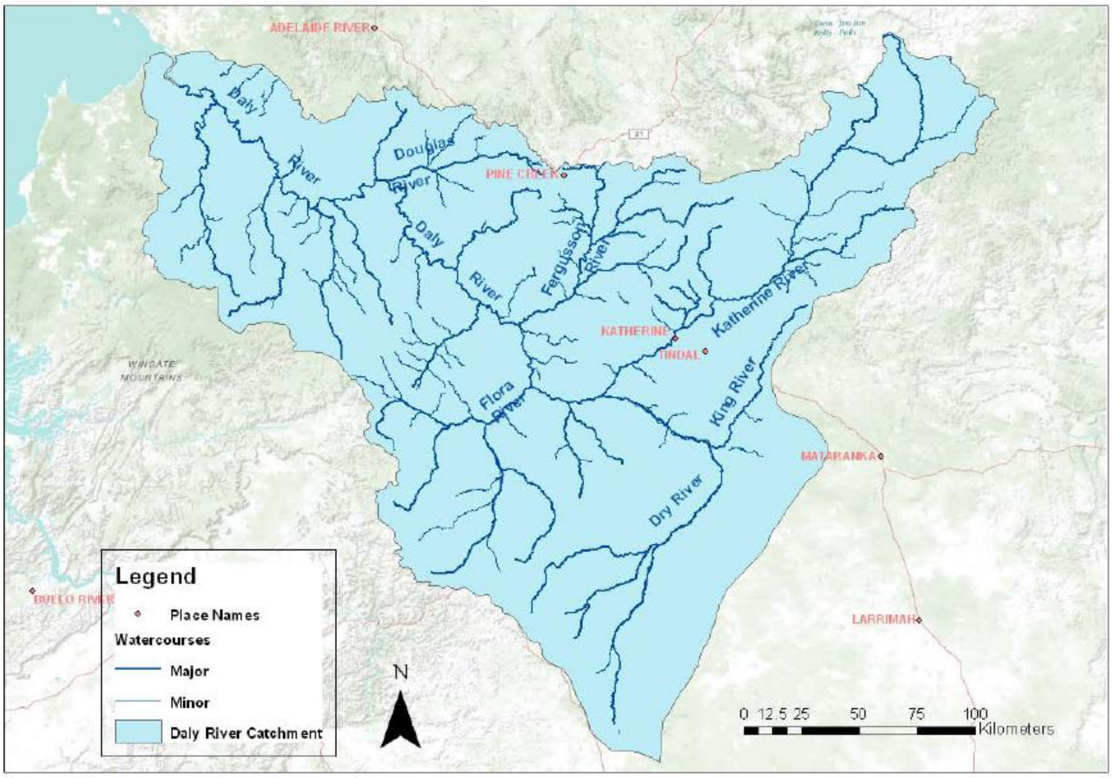


Figure 4-1 Location of Major Rivers within the Daly River Catchment

Groundwater extraction from the aquifers occurs via bores with the extracted water used primarily for agricultural irrigation. These extractions may reduce dry season flows within the Daly River catchment and subsequently may impact upon the ecological and socio-economic systems dependent upon the dry season flows. The Northern Territory government (NRETAS) has developed a Water Allocation Plan for the Tindall Aquifer around the township of Katherine, designed to maintain the dry season flows.

The topography of the Daly River catchment is relatively flat with a maximum elevation of around 500m AHD (Australian Height Datum). As shown in Figure 4-2, these maximum elevations are found in the upper reaches of the Katherine River and some areas along the south-west catchment boundary. Consequently, river profiles are also relatively flat as shown in Table 4-1. The Daly River has a mean slope of 0.0002 and the Katherine River a mean slope of 0.0011.

Table 4-1 Major Watercourse Lengths and Slopes

Watercourse	Main Channel Longitudinal Length* (km)	Main Channel Longitudinal Slope (m/km)
Daly River	325	0.2
Katherine River	180	1.1
Flora River	85	0.9
King River	65	0.6
Dry River	125	0.6

*as per available GIS Data

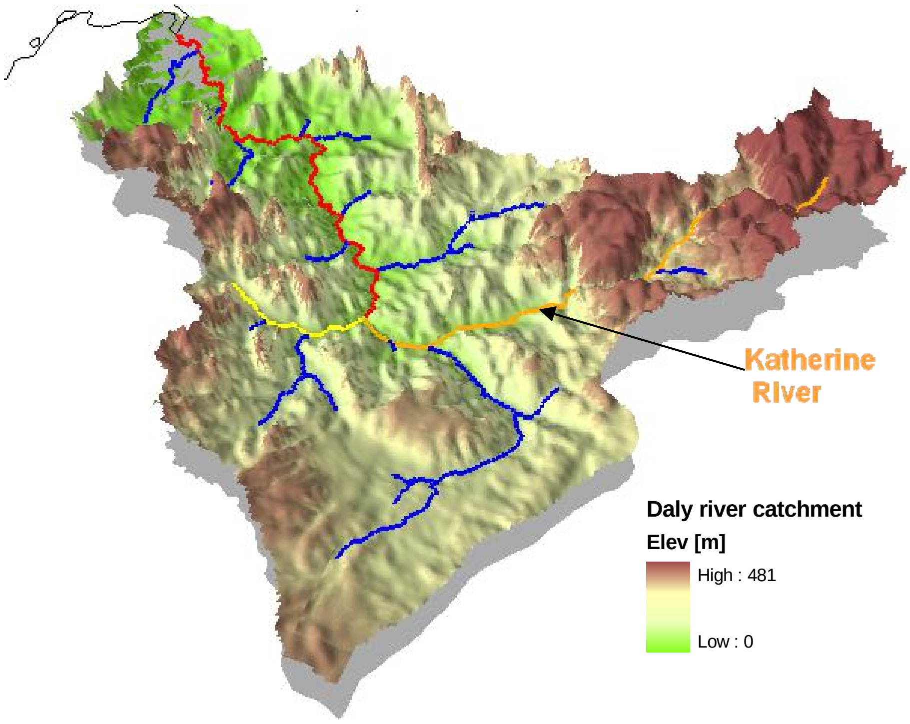


Figure 4-2 Daly River Catchment Elevations

Approximately 10,000 people live within the Daly River catchment, with 27% of these being Aboriginal people. The population density is about 1 person per 5 square kilometres.

Grazing is the most extensive land-use within the Daly River catchment, with the majority of this occurring within natural vegetation. The second largest land-use is for traditional indigenous purpose. Less than 0.4% of the catchment is currently under intensive agriculture, such as peanut and mango farming. The catchment contains Nitmiluk (Katherine Gorge) National Park and Flora River Nature Reserve, as well as a part of Kakadu National Park.

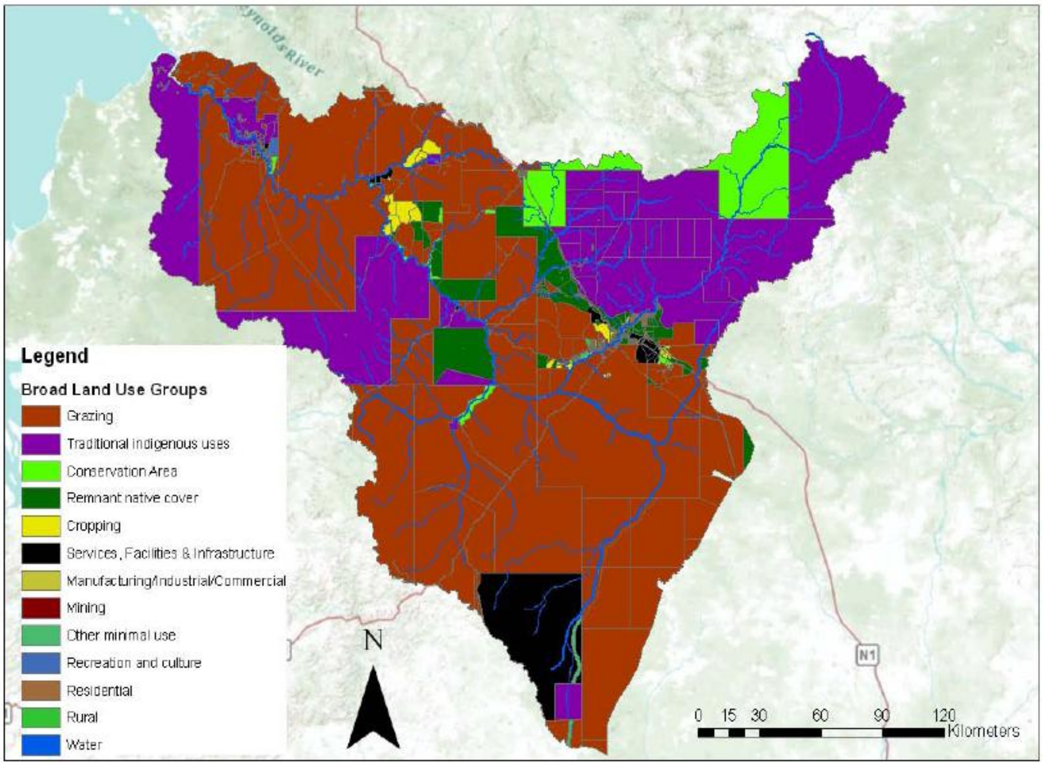


Figure 4-3 Broad Land-Use Categories across the Daly Catchment

Due to the areas of permanent water within the Daly River system, distinctive ecosystems are supported both within the river and along its banks. Notably, the endangered pig-nosed turtle breeds and lives within the middle reaches of the Daly River. Rare species of shark and sawfish are also found within these reaches. The lower reaches and estuary of the Daly River support a significant number of bird breeding sites and an estimated 30,000 birds utilise this area in a single wet season (Blanch et al., 2005). The river and tributaries also form the habitat for many species of freshwater and estuarine fish, including the well-known Barramundi. It is considered the best Barramundi fishing river in Australia (Blanch et al., 2005).

4.3 HYDROLOGIC REGIME

4.3.1 WATER PROCESSES

Within the Daly River catchment, all species of flora and fauna (including humans) depend upon water to sustain life. This dependence upon water is particularly critical in the dry season, where river flows are low and are solely due to groundwater discharge. Demand for water in the dry season is high. In order to understand the natural environment in the Daly River catchment, knowledge of the fate of water is critical. These components for the Daly River catchment are summarised here. Further details are contained within Appendix E.

The major source of water input in the Daly catchment is rainfall (precipitation). Average annual rainfall across the catchment is about 1000mm. However, rainfall within the Daly River catchment varies significantly both temporally and spatially. Due to the strong wet-dry seasonality, about 96% of the rain falls within the wet season (from November to April inclusive). The spatial variation in rainfall across the catchment is also significant, with the north-western areas receiving on average up to 1460mm per year and the southern areas only

700mm per year. The temporal and spatial variation in rainfall is discussed further in Appendix E.

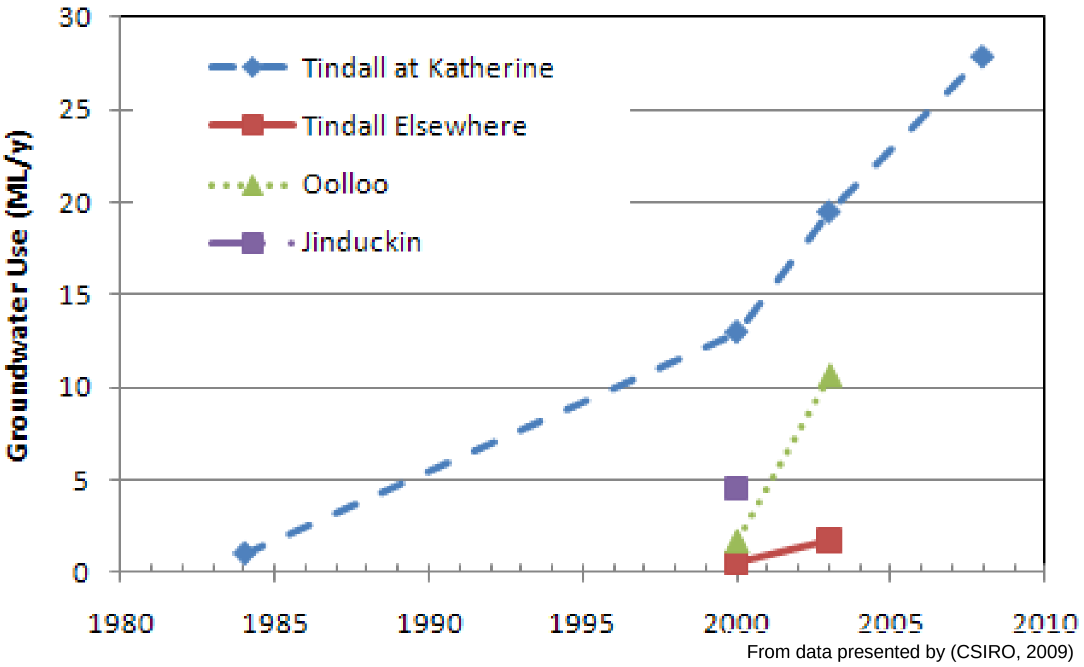
Evapotranspiration is the loss of water to the atmosphere due to *evaporation* from the soil, waterbodies and interception sites and *transpiration* from plants. Potential evapotranspiration (PET) is the theoretical maximum evapotranspiration possible if water available was equal to energy available. Evapotranspiration in the Daly River catchment is significant and represents a relatively large of loss of water to the system. Unlike rainfall, PET does not vary significantly either temporally or spatially. Average annual PET is about 1950mm per year. Appendix E contains further information on PET.

As explained in Section 4.2, the Daly catchment is underlain by a major groundwater system, which is predominately composed of two limestone aquifer systems named the Oolloo and the Tindall. These aquifers fill with water (recharge) in the wet season and discharge water in the dry season. The amount of recharge depends primarily upon the amount of rainfall, losses due to evapotranspiration, soil type and local geology. The amount of discharge over the dry season depends primarily on the amount of recharge that occurred during the wet season. This discharge allows rivers in the Daly catchment to flow year round, making the Daly a perennial system. It is unusual for rivers within the wet-dry tropics to flow all year round as they typically become dry when rain and runoff cease. Thus, the perennial flow supports a unique and diverse ecosystem. Further information is provided in Appendix E.

4.3.2 WATER DEMAND

During the dry season, all river water within the Daly catchment is the result of groundwater discharge. As there are no other sources of water in the dry season, demand for river water and groundwater is high. Consumptive demand for water is often competing against non-consumptive needs, which are typically aligned with the natural behaviour of the perennial system. Drivers of the consumptive demand for water include agricultural production, human consumption, industry and stock needs. At present this demand is satisfied by extraction of water from the natural system via pumping directly from the river or by pumping from groundwater bores, with the latter supplying the greatest volume.

The actual volume of water used is difficult to determine as pumpage volumes have not previously been metered, although this is changing. Estimates of pumpage rates over time (CSIRO, 2009) are summarised in Figure 4-4. Despite the lack of a complete dataset for each aquifer, it is clear from Figure 4-4 that pumpage rates have increased significantly in recent years in both the Tindall and Oolloo aquifers.



From data presented by (CSIRO, 2009)

Figure 4-4 **Estimated Groundwater Use Over Time in the Daly Catchment**

Non-consumptive water users include aquatic and riparian flora and fauna (who need water for breeding areas, habitat, refuge, transpiration), indigenous people (who need water to maintain cultural traditions and beliefs and as a source of food), local people & visitors (who are attracted to the recreational opportunities provided by fishing, camping, swimming, boating along the rivers). These water users rely on natural system behaviour to deliver their needs and opportunities.

It is of interest that non-consumptive users and consumptive demands are not mutually exclusive. For example, visitors to the region who are attracted to the recreational opportunities offered by the natural environment can create consumptive demand as they shower, wash and drink during their stay.

4.3.3 WATER MANAGEMENT

The Northern Territory Government manages its water resources through the *NT Water Act 1992*, the Water Regulations and a series of Water Allocation Plans (CSIRO, 2009). In the Daly catchment, one Water Allocation Plan (WAP) is finalised and one is in preparation. The finalised WAP covers water extraction from the Tindall Limestone Aquifer around the township of Katherine (NRETAS, 2009), which for the purpose of this report will be called the "Tindall WAP at Katherine" or simply "the WAP". The Oolloo Aquifer WAP is currently in preparation with the draft for public comment due for release in 2011.

The Tindall WAP at Katherine will have a lifespan of 10 years (2009 – 2019) and will be reviewed after 5 years. The WAP "has been developed with the vision to ensure that the water contained within the Tindall Limestone Aquifer is managed sustainably and a balance is created between the environment and all other uses." (NRETAS, 2009)

The WAP has provisions to change the amount of water allocated for extraction from the Tindall Aquifer at Katherine depending upon the amount of recharge to the aquifer over the previous wet season. However, rather than looking directly at the "amount of recharge to the aquifer" in determining water allocation, the WAP process looks at a prediction of the 1st November dry season flow at the Katherine River Rail Bridge. This process is based on the assumption that dry season flow has a direct correlation with wet season recharge to the aquifer.

The prediction of 1st November dry season flow in the Katherine River is undertaken by a hydrodynamic model prior to 1 May each year. This specialised model, developed and calibrated for this purpose, is a two-dimensional finite element groundwater model coupled with a one-dimensional surface water model using the FEFLOW and MIKE11 modelling packages respectively (Knapton et al., 2009). For the purpose of this report, the model will be referred to as the "FEFLOW model". Input data sets, required by the FEFLOW model for the purpose of undertaking the 1st November prediction, are the wet season rainfall and an estimate of the corresponding recharge. The WAP process in determining allocations using the 1st November predictions is summarised in the schematic shown in Figure 4-5.

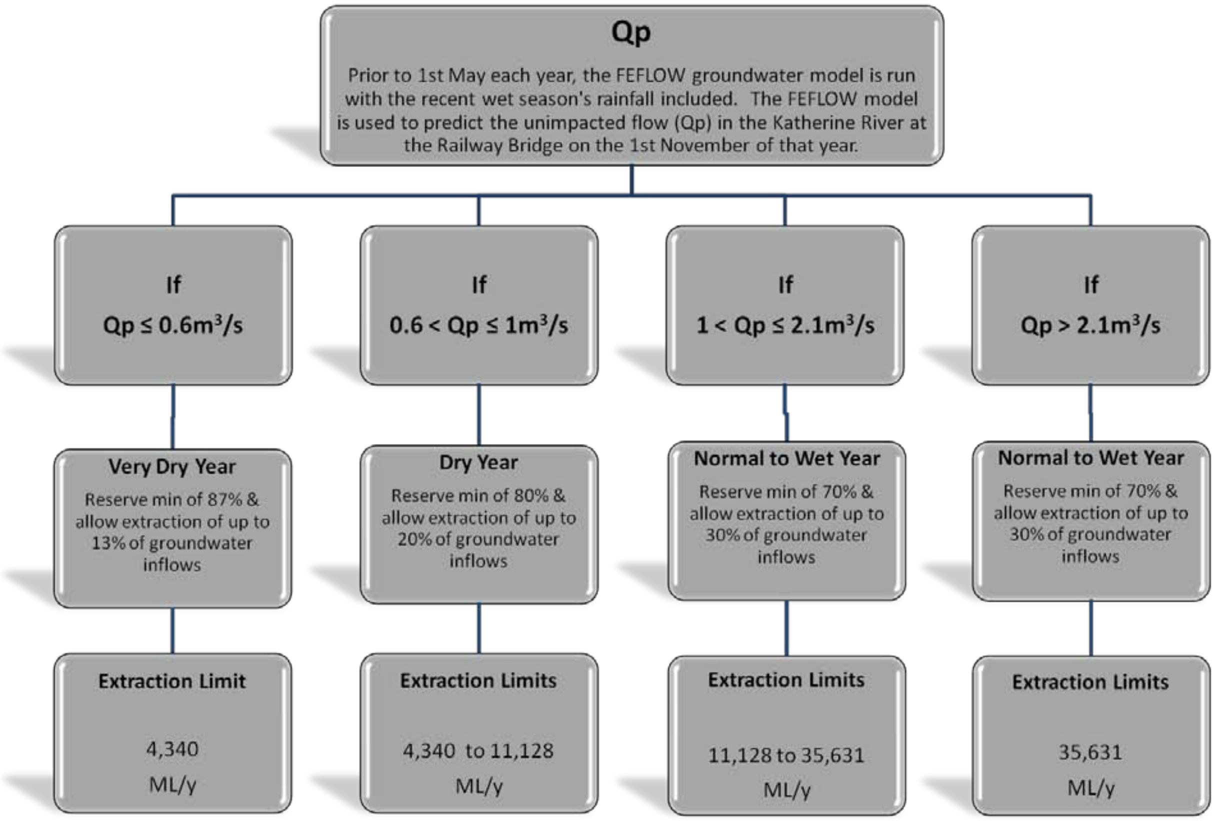


Figure 4-5 Process for Determining Water Allocations: Tindall WAP at Katherine

4.4 SUMMARY

An MSE prototype application has been developed with models that are applicable to the Daly River catchment. The Daly River catchment is located in the Northern Territory and is one of Australia's largest tropical river catchments. Being located in the wet-dry tropical region, the catchment experiences high rainfall volumes in the wet season and very little in the dry season. However, despite the dry season, the Daly River is a perennial river that continues to flow throughout the year. Dry season flow is due to groundwater discharge, the source of which is two major limestone aquifer systems. These aquifers store and transmit significant volumes of groundwater and are named the Oolloo and the Tindall. They fill (recharge) in the wet season and drain (discharge) in the dry season.

Within the Daly River catchment, all species of flora and fauna (including humans) depend upon water to sustain life. This dependence upon water is particularly critical in the dry season, where river flows are low and are primarily due to groundwater discharge. Demand for water in the dry season is high. Consumptive demand (e.g. for agricultural production, human consumption, industry and stock needs) is competing against non-consumptive demand (e.g. ecosystem, cultural and recreational needs). Consumptive demands in the catchment are growing rapidly and are typically met by pumping groundwater from extraction bores.

The Northern Territory Government is developing Water Allocation Plans. These Plans seek to control the volume of water extracted from the Daly aquifer systems.

5 MSE-DALY MODELS

5.1 INTRODUCTION

The conceptual MSE framework for the Daly River Catchment divides the resource management process into six functional areas, as described in Chapter 2. In this Chapter we will be looking at the models and capabilities of each of these six functional areas, as implemented in the prototype Daly River Catchment MSE application.

5.2 DECISION MODEL

The *Management Decisions* functional area typically consists of models that implement a set of *if–then* rules. These rules convert information from other functional areas (e.g. assessment or monitoring) into decisions. These decisions are made in terms of what actions to undertake and at what level and scale.

The current decision capability simulates a simplified version of the procedure described by the Water Allocation Plan (WAP) for the Tindall Aquifer, developed by NRETAS (NRETAS, 2009). This plan explicitly states the decision rules that are to be followed to set annual groundwater allocation limits for the Tindall Aquifer at Katherine. The WAP procedure is discussed further in Section 4.3.3 and depicted in Figure 4-5.

A requirement of the WAP is to predict the flow in the Katherine river which emanates from groundwater at the end of the dry season (1st November) based on the rainfall in the previous wet season as a basis for the groundwater extraction allocations set at the beginning of the dry season (1st May). NRETAS undertakes this prediction using the coupled 2D hydrodynamic model FEFLOW, as described in Section 4.3.3. Within the current Daly MSE application it is not practical to use such complex models as the lengthy computation times would prevent the extensive range of MSE simulations being undertaken. This is discussed further in Section 6.1.1 . The Daly MSE application predicts the late-dry-season groundwater flows based on its own 'experience' of the relationship between early-dry groundwater levels and late-dry groundwater discharges. During the first years of MSE simulation all groundwater extraction will be blocked and during that period a table of early-dry groundwater levels and late-dry groundwater discharges is collected. After that period, a range of functions are fitted through that data (experience) and the best fitting function is used to predict late-dry groundwater discharges based on early-dry groundwater levels.

5.3 ACTION MODEL

As described in Section 2.3.2, the *Management Actions* functional area converts management decisions into actions, includes implementation uncertainty and allows specification of *fixed* actions.

Currently, the Daly MSE application allows the following management actions to be specified and run:

- Groundwater extraction allows the specification of licensed monthly extraction amounts per bore. Apart from editing single bores, the application also has basic capabilities to increase/decrease all or parts of the licenses in bulk.

- Economic development trajectories need to be defined as inputs to the economics response model for up to twelve economic sectors (see Section 7.3). These economic development trajectories are interpreted as *planned* development trajectories. If, for instance, water availability is less than what is needed to follow these planned trajectories, the economic model will report on the 'actual' (within the model) economic growth trajectory.

- Remediation actions are designed to simulate the cleanup of polluted water before it reaches the waterway. For instance, sediment runoff could be remediated by maintaining or establishing riparian vegetation. The MSE remediation action allows simulation of the filtering characteristics of such a solution on water quality.

- Landuse changes can also be simulated. The constituent transport model, embedded inside the hydrodynamics model recognises six landuses as placeholders in the prototype MSE application: grazing, conservation, built-up, irrigated landuses, water and agriculture. Each subcatchment comprises one or more landuse areas. The runoff constituents transported by the model as a fraction of the water runoff are total nitrogen, total phosphate, and sediment. Each landuse is characterised by its own level of runoff per m^3 of overland water flow. This Action model allows changes to the landuse composition to be made for each subcatchment, thus simulating landuse planning activities.

The expectation is that the range of management actions will extend when new management actions need to be tested. As this approach aims to adapt to changing management questions, we expect other modules to be implemented over time, either for the Daly River MSE application or future MSE developments in other localities. For example, management actions and corresponding response models pertaining to biodiversity and landscape restoration can be developed and implemented as required.

5.4 RESPONSE MODEL

As described in Section 2.3.3, the *System Response* functional area covers our understanding of the behaviour of the natural system and its response to change. The MSE *Response Models* represent the behaviour and response of the biological, ecological, economic, social and physical environments in the form of numerical models. For the current Daly River MSE, these models include the catchment water model, groundwater model, habitat model, and economics model. Chapter 6 describes each of these response models in more detail.

5.5 OBSERVATION MODEL

As detailed in Section 2.3.4, the *Observation* functional area incorporates the way in which we monitor the 'real world', typically through field programs. The Daly River MSE *Observation Model* allows us to simulate monitoring programs. That is, we are able to specify where, when and what to monitor from the Response Model.

As mentioned in Section 2.3.5, monitoring (field) programs in the physical world are very costly to implement and maintain. The Observation Model can assist with the *design* of monitoring programs. The MSE application supports this process by simulating various monitoring options. The MSE application also helps to assess the option results and determine how these results would be used in the Learning and Decision functional areas.

The Observation Model allows us to make the filtering characteristics of a monitoring program explicit. By monitoring a certain item, say recording the yearly employment figures, the fine-scale dynamics of seasonal changes will not be available when the time comes to make management decisions: that is, the monitoring program *filters* the employment figures. In addition, the Observation Model may simulate observation noise, as would happen in monitoring programs in the physical world.

Currently, there are two monitoring (sub) models implemented in the Daly River MSE application: an observer for the hydrodynamics model and an observer for the ecology model.

5.6 ASSESSMENT MODEL

The *Assessment Model* simulates the reporting phase of a resource management system. It contains (often statistical) methods to convert values 'collected' by the Observation Model into management performance measures. Further information on performance indicators, reference values and performance measures is provided in Section 2.3.5.

Currently in the Daly River MSE application, there is a comprehensive Assessment (sub) Model implemented for the catchment water Response Model with assessment models for economic and ecologic Response models to follow.

5.7 LEARNING MODEL

As described in Section 2.3.6, the *Learning* functional area focuses on two modes of learning: passive and active learning. In *passive* learning mode, the *Learning Models* only collect and process information that is being produced during scenario runs, but do not actively change the management decisions. In *active* learning mode, the Learning Models may request management actions be applied to learn more effectively or faster about efficacy of various management actions.

Effective learning is a key element in making adaptive management pay off the added costs it incurs. It is also a fertile area of scientific research. As such, the *Learning Model* is one area that needs more attention in future developments.

The Daly River MSE Learning Model currently contains one model. This model collects enough information to allow prediction of late-dry season base flows from early-dry season groundwater levels. These levels are produced by the groundwater model. This predictive capability is then passed on to a management decision model that implements the WAP procedure as described in Section 4.3.3. The WAP procedure uses this predictive capability to set the water quota at the beginning of the dry season.

5.8 THE MSE ITERATIONS

To better understand the workings of the MSE application, this Section explains how the six functional areas, as depicted in Figure 2-3, impress a timing element on the underlying model communication, discussed in the previous Section.

To impress the element of time and synchronicity on the models that communicate with each other, each of the functional areas as implemented in the MSE software will be apportioned computing resources on a sequential basis, as indicated by the direction arrow in Figure 2-3.

This process can be pictured as a relay race where the baton (access to computing resources) is passed from model to model. It works like:

1. Suppose the scenario simulation period is between 01/01/1963 and 01/01/2020
2. The global time is set to the start 01/01/1963
3. Control is given to the first model, e.g. the Management Decision model
4. Management Decision model and its sub-models perform the tasks they are instructed to perform up to and including the global time. One of those tasks may be to request information from the observation module. When it is done it sets its internal clock to the global time, and hands back control
5. Control is given to the second model, e.g. the Management Action model
6. Management Action model and its sub-models perform the tasks they are instructed to perform up to and including the global time. One of those tasks may be to instruct the groundwater model to extract water. When it is done it sets its internal clock to the global time, and hands back control

5.9 SUMMARY

The prototype Daly River Catchment MSE application is comprised of six main models representing the six functional areas of the MSE conceptual framework. These models are:

- **Decision Model.** This model represents *if-then* management decisions by converting values obtained from other component models into a decision (e.g ***if*** Value A ***then*** Decision 1*)*. The Decision model component of the Daly River prototype represents the *if-then* rules of the Tindall WAP. The Tindall WAP rules relate predicted late-dry season flow at Katherine (say, Qp) to the groundwater extraction limit (say, Ge) in tabular form. Quite simply, ***if*** Qp A ***then*** Ge 1. The Decision model implements these rules by predicting Qp based on an relationship between early dry season groundwater level and Qp *observed* and *learnt* during its initial simulations.

- **Action Model.** This model represents actions taken by management due to a decision made, including the uncertainty of implementation. It currently includes the ability to simulate the following actions: groundwater extraction, economic development trajectories, riparian remediation and landuse changes. Additional action models are planned for the near future.

- **Response Model**. This model represents our understanding of the systems in the real world and their response to management actions, based on our best knowledge of the system or resource. The response model component often holds most of our scientific knowledge in the form of numerical models. More details on response models are given in Chapter 6.

- **Observation Model.** This model represents monitoring programs and allows us to simulate their spatial and temporal design. In the Daly River MSE application, the observation model allows us to specify where, when and what to monitor from the catchment water and ecologic Response Models.

- **Assessment Model**. This model represents the reporting phase of resource management and contains (often statistical) methods to convert the 'collected' data into management performance measures. The Daly prototype model currently has detailed assessment functionality for the catchment water Response Model.

- **Learning Model.** This model may contain models that learn 'on the fly' about behaviour such as of the reaction of Response Models to management actions or about the validity of assumptions that were used when making decisions in the previous adaptive cycle. The Daly River MSE application currently contains one Learning Model that 'learns' a relationship between late-dry season baseflows and early-dry season groundwater levels. This allows the Management Decision Model to predict late-dry season baseflow and implement the WAP rules.

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6 MSE-DALY RESPONSE MODELS

The Daly River MSE aims to deliver on two levels of integration: integration between science and resource management knowledge areas and integration of various science disciplines such as ecology and economy. The response functional area is the most likely, though not exclusive, area where this knowledge is brought together. In this Chapter the three main response models are discussed. Figure 6-1 shows the overall outline of currently implemented models with the emphasis on the response models (yellow boxes) underpinning the triple-bottom-line focus for the prototype of the Daly MSE application.

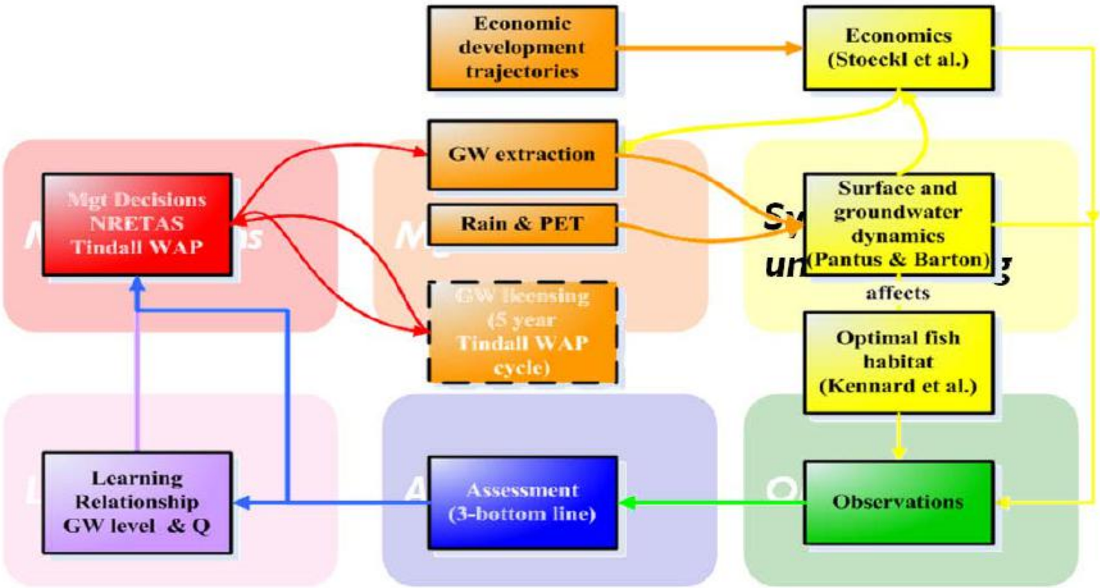


Figure 6-1 Main Models implemented for the Daly River MSE prototype application. The six MSE functional areas (decision, action, response, observation, assessment and learning) can be seen in the background. Implemented models are coloured to conform to the MSE functional areas.

The focus of the Project has been to deliver a prototype of an MSE application (tool + regional information) for the Daly River Catchment. To achieve this, the Project has worked towards an MSE application that allowed us to evaluate a range of water-related management options for the Daly River catchment showing (triple bottom line) trade-offs between social, economic and environmental (physical and ecological) performance indicators.

6.1 CATCHMENT WATER MODEL

The 'central' model in the Daly River catchment MSE is the catchment water model, allowing us to trace water from precipitation to overland and groundwater flows through the catchment. The catchment water model sits at the core of the response model interactions and enables the integration of the other response models. This model was developed, implemented, tested and (preliminarily) calibrated by the P1.4 team.

6.1.1 SELECTION

There are many types of catchment water models ranging from the very simple to the highly complex. It is perhaps obvious but nevertheless important to state, that simple models tend to be less data and time intensive and complex models the converse. With this in mind, consider the following points:

1. The Daly River catchment is a data poor catchment (CSIRO, 2009). That is, the available data is sparse and when available, not always accurate.

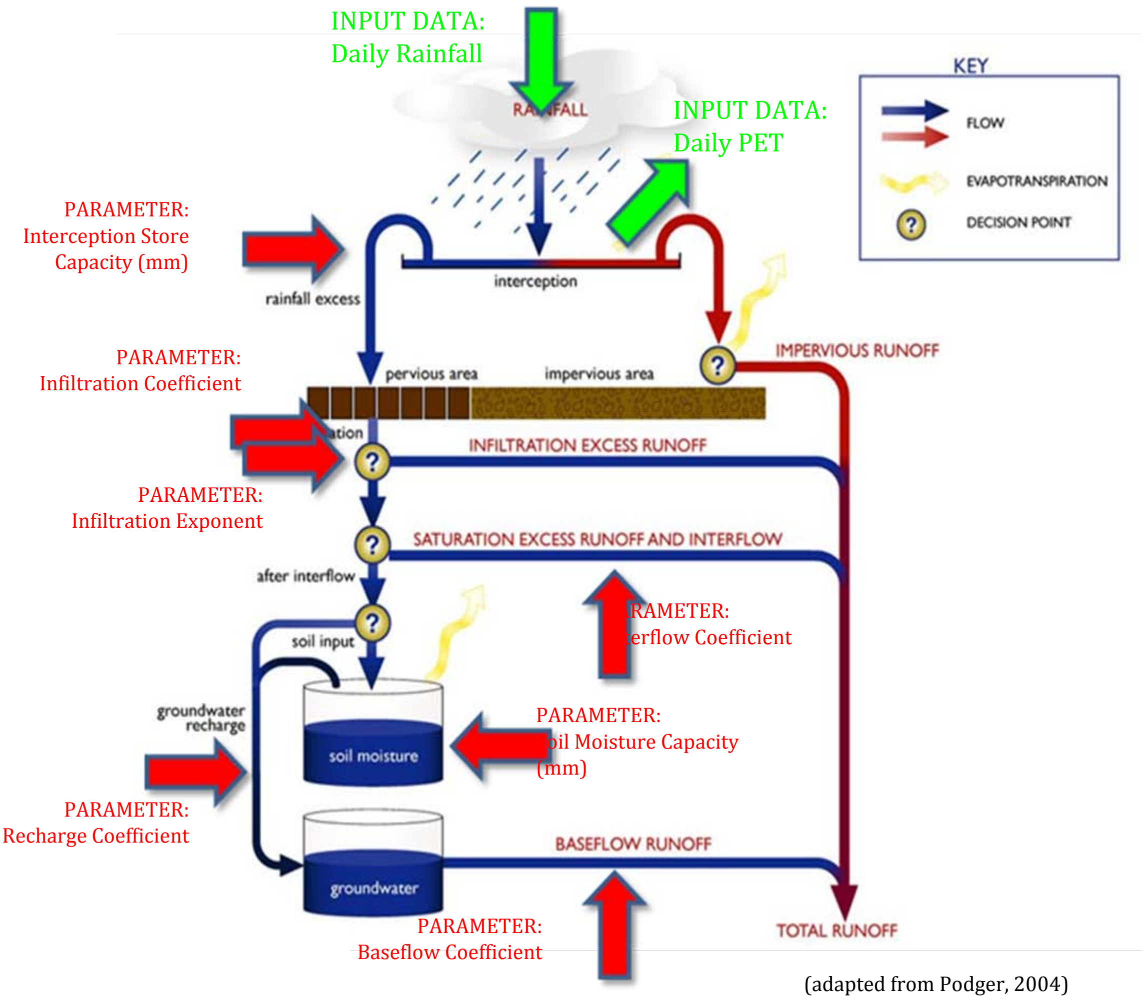
2. The MSE framework requires a model capable of undertaking many simulations in a relatively short period of time to enable a multitude of strategies to be assessed.

Based on these factors, the most suitable model for the task is a simple model. That is not to say that complex models do not have a place in the Daly River catchment but such models are likely to be highly specialised models. The FEFLOW model developed by NRETAS (and described in Section 4.3.3) is an example of such a specialised model. One model simulation can take around 18 hours (pers. comm. Des Yinfoo, NRETAS 2009) but as the number of simulations is small, the long simulation time is sustainable. Another example of a specialised water model is the complex hydrodynamic and morphological model (using the RMA software) developed for assessing 3D velocities and sediment movement. Two RMA models have been developed with one covering a 10km reach of the Daly River and the other a 130km reach (in-bank only) for TRaCK project 4.4 and 4.2 respectively. These models are data intensive and require an accurate Digital Elevation Model (DEM) and in-bank cross-sections to represent the topography. Again, this is feasible for these relatively small reaches of river. However, these reaches represent less than 0.1% and 1% respectively of the total watercourse length within the Daly River catchment. Thus, they are infeasible to be developed (or evaluated) on a catchment scale within the given means. The model selected must be suited to both the data available and the time required to undertake the necessary simulations.

In consideration of the data limitations and the relatively short run time required for the catchment water response model, a conceptual rainfall-runoff model was chosen to simulate the fate of water in the Daly River catchment.

6.1.2 MODEL COMPONENTS

One of the major physical processes requiring simulation by the catchment water model is the conversion of rainfall to runoff. To represent this process a lumped conceptual rainfall-runoff model called "SIMHYD" has been selected to form the basis of the catchment water model. SIMHYD is one of a suite of conceptual models offered within the eWater rainfall runoff library toolkit (http://www.toolkit.net.au/Tools/RRL)(Podger, 2004). It is relatively simple, with only 7 parameters, and has been used extensively across Australia (e.g. Chiew and Siriwardena, 2005b, Tan et al., 2005, CSIRO, 2009, Post et al., 2007, Post et al., 2008 etc.). A schematic of the SIMHYD model showing inputs, parameters and outputs is shown in Figure 6-2.



(adapted from Podger, 2004)

Figure 6-2 SIMHYD Schematic Showing Inputs and Parameters

The input data required for SIMHYD is daily rainfall and daily PET. Daily flow records are required to allow the model to be calibrated. The catchment area is also required to allow the volume of rainfall to be determined. For this purpose, the Daly River catchment has been divided into a number of sub-catchments. The sub-catchment delineation at this stage of the project is shown in Figure 6-3. Each sub-catchment has been further divided into 6 land-use classes to allow different model parameters to be assigned for each land-use if required.

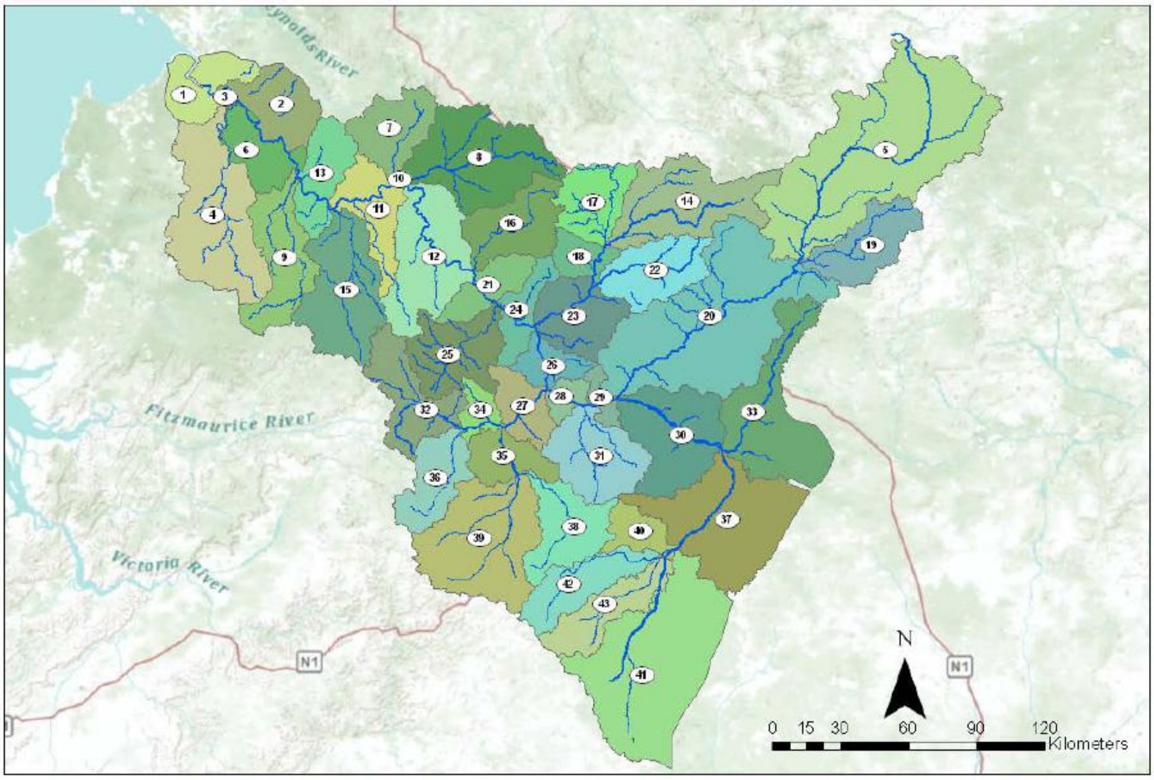


Figure 6-3 Sub-catchment Delineation for the Daly River Catchment SIMHYD Model

ROUTING OF FLOWS

As water flows downstream in creeks and rivers, its hydrograph is delayed and attenuated. Delay to the hydrograph occurs due to the time it takes for the water to move along the river from location A to B, with the amount of delay dependent upon the distance between A and B and the speed of the water. Attenuation is the reduction in amplitude (height) and broadening of the flood wave due to the impacts of storage along the river. An example of delay and attenuation of Daly River flow hydrographs can be seen in Figure 6-4, which shows the flow observed at two gauges in the mid-reaches of the Daly River separated by about 130km of river length.

SIMHYD calculates the amount of rainfall that will become runoff for each of the land-uses within each of the sub-catchments. To simulate the delay and attenuation of flow, sub-catchment flows are routed from one sub-catchment to the next using Muskingum routing (Cunge, 1969, Ponce et al., 1996). In a large catchment like the Daly, delay and attenuation of flows has a significant impact upon the shape and magnitude of the output hydrograph, particularly in downstream areas of the catchment. If routing is not included, calibration of the water model would not be possible on a daily basis. Some studies using lumped conceptual rainfall-runoff models in large catchments, calibrate to monthly flow totals (rather than daily) to avoid routing of daily flows (eg Reichl et al., 2009, Chiew and Siriwardena, 2005a). The linking between sub-catchments not only allows for the passage of water, but also the passage of sediments and nutrients.

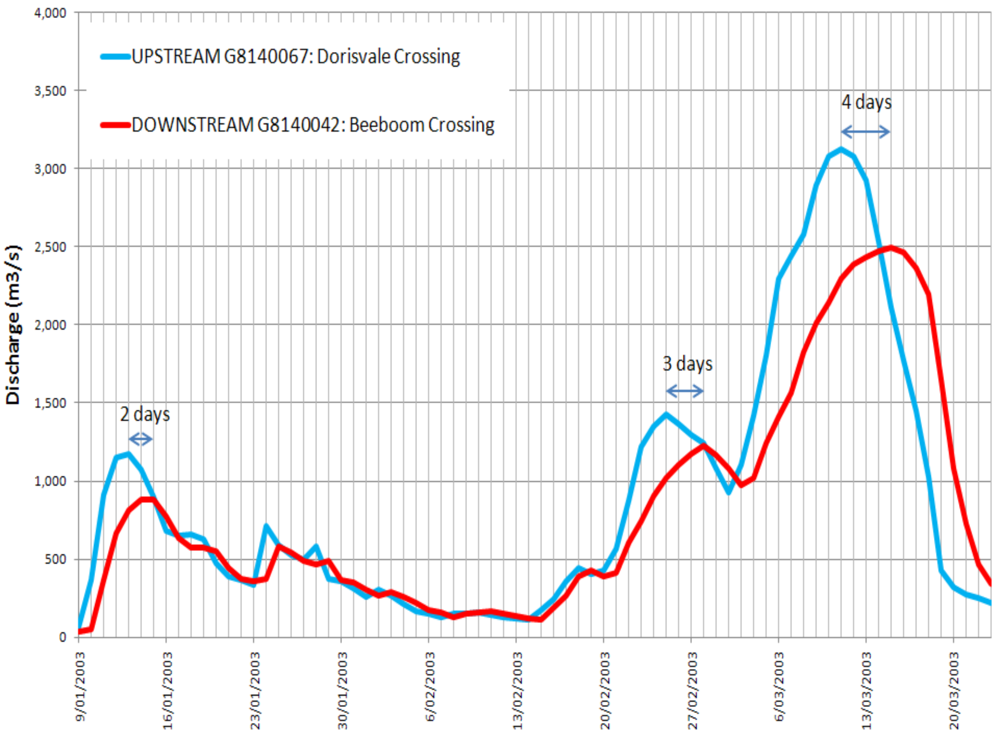


Figure 6-4 **Delay & attenuation of Flow in the Daly River**

6.1.3 MODEL INPUT DATA

RAIN

An historical time-series of daily rainfall is one of the two input datasets required by the catchment water model. The temporal and spatial variability of rainfall within the Daly Catchment is discussed in Section 4.3.1. The rainfall dataset selected for use in the catchment water model is the SILO gridded daily rainfall dataset (Jeffrey et al., 2001, Jeffrey, 2006). This dataset is constructed using spatial and temporal interpolations of measured daily rainfalls, allowing a continuous set of 0.05degree (about a 5km by 5km grid) daily rainfalls from 1895. Prior to undertaking the preliminary calibration, the full SILO daily rainfall set was unavailable to Project 1.4 due to its prohibitive cost. However, CSIRO (Petheram, 2010) was able to supply Project 1.4 with Daly sub-catchment averages of the SILO gridded daily rainfalls over the period 01/01/1895 to 29/07/2008. This data was used by the MSE model for all model simulations, including preliminary calibration, presented in this report. In 2011, the cost of the SILO daily rainfall set was reduced substantially and Project 1.4 is currently sourcing this dataset (updated to 2011) for future use with the MSE Model.

POTENTIAL EVAPOTRANSPIRATION (PET)

Evapotranspiration (ET) is the transfer of water from the landscape to the atmosphere. It is a combination of evaporation and plant transpiration. Potential ET (PET) is the maximum ET possible in an area without limitation of the amount of water available (that is, PET is a theoretical maximum ET). Daily PET is the second dataset needed by the catchment water model. The temporal and spatial variation of PET across the Daly catchment is presented in 4.3.1, based on the SILO gridded daily PET dataset.

6.2 GROUNDWATER MODEL

The original SIMHYD model (refer to Section 6.1) contains a simple groundwater component to simulate recharge and discharge. This is shown conceptually in Figure 6-2. Recharge to the SIMHYD groundwater system is simulated by the equation:

$$R = C_R.SMF.In$$

Where: R = Recharge

SMF = Soil Moisture Fraction

In = Infiltration after Interflow

Discharge from the SIMHYD groundwater system is simulated by the equation:

$$Q_B = K.S_g$$

Where: Q_B = Baseflow

K = Coefficient of Baseflow

S_g = Groundwater Storage

However, the complexity of the Daly River groundwater system means that it is not able to be well-represented by the simplistic SIMHYD groundwater model. An alternative exponential groundwater model component was developed by Project 1.4 to represent the discharge from the groundwater system (baseflow). This introduced two new model parameters, BF_1 & BF_2. The equation for the exponential groundwater discharge is:

$$Q_B = \frac{S_g}{BF_1}.\frac{BF_2}{e^{S_g}}$$

Where: BF_1 = Baseflow Parameter 1

BF_2 = Baseflow Parameter 2

The alternative exponential discharge approach improved the performance of the model in simulating dry season baseflow, but not enough to be considered satisfactory. Appendix F provides details of the preliminary model calibration. In summary, the ability of the model to simulate dry season flows is poor. This is reflected in Figure 6-5, which shows that the modelled flows at Katherine do not follow the behaviour demonstrated by the observed flows. This indicates that the groundwater model component should be revised to better replicate the dry season flows, which are critical in the Daly River catchment.

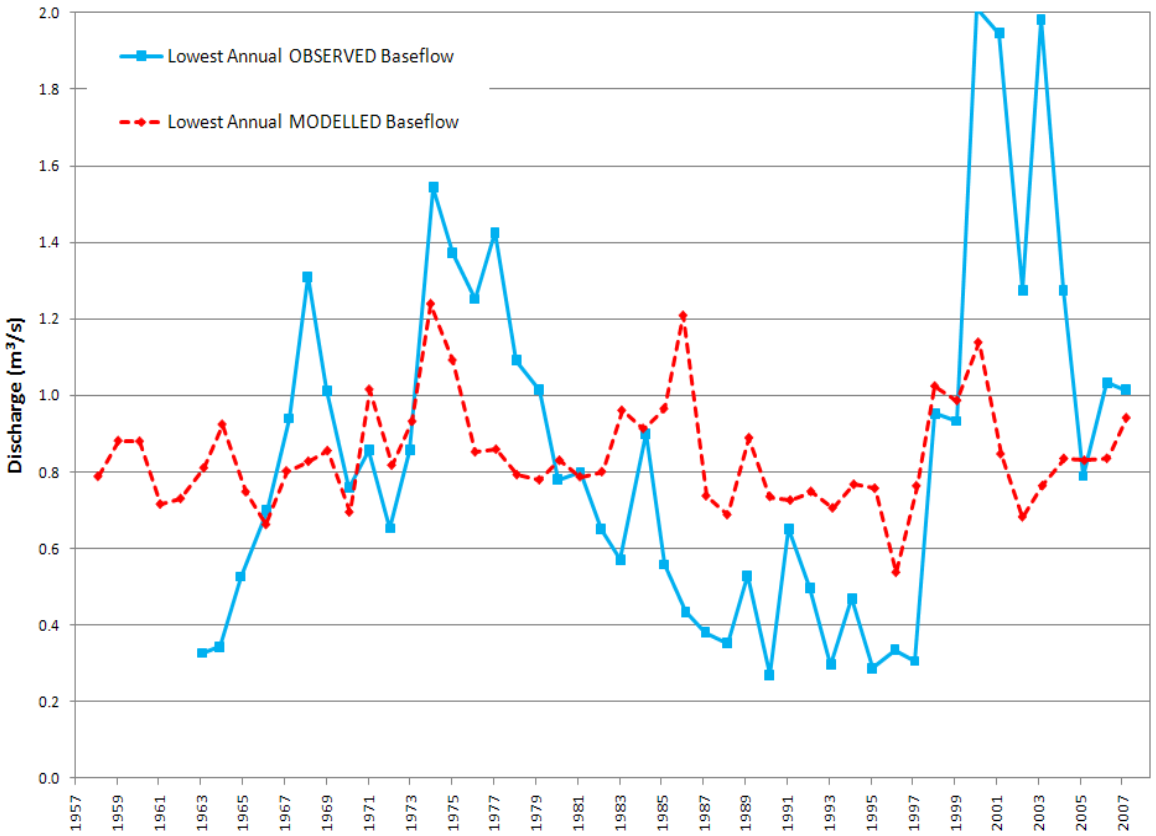


Figure 6-5 Lowest Annual Baseflow at G814001 (Katherine River at Rail Bridge): Modelled and Observed Comparison

6.3 WATER MODEL CALIBRATION

Model calibration is the process of comparing model predictions to measured variables, making adjustments to the model and/or inputs until the model is able to satisfactorily replicate real world behaviour, within the bounds of data uncertainty and model capability.

A preliminary calibration of the Daly catchment water model has been undertaken, using the datasets described in the previous Sections. Functionality has been added to the MSE GUI to allow calibration to be undertaken within the MSE system. Full calibration of this catchment water model will only be possible once groundwater behaviour and floodplain inundation have been successfully modelled. Preliminary calibration results indicate that the model performs well in simulating water behaviour generally in the Daly catchment, but performs poorly in simulating dry season flow specifically. Appendix F provides details on the preliminary calibration of the Daly catchment water model.

6.4 HABITAT MODEL

For the *ecology*-based performance measures, we employ the optimal fish habitat models developed by Project 5.9: "Northern Australia Aquatic Ecological Assets". These models established the relationship between dry season baseflows (mainly groundwater) and optimal habitat for key species such as Sooty Grunter and Barramundi and their life cycles. Linking these models to the catchment water model and accepting 'optimal habitat availability' as a performance measure for the ecological state of the riverine system in the Katherine area is a first step in the adaptive process of discussing and selecting appropriate performance measures for the Daly catchment.

6.5 ECONOMICS MODEL

The model used to represent our *socio-economic* knowledge in the current version of the Daly River catchment MSE was developed by Project 3.1, "Socio-economic activity and water use in the tropical rivers region". This model does not only function as a response model using available or allowed water extraction limits as an input, it also functions as a driver of water demand itself. It allows us to evaluate the efficacy of the WAP under a range of scenarios. The twelve sectors included in the economics model are: Accommodation, Agriculture, Construction, Cultural and Recreational Services, Electricity, Financial, Communication & Property, Govt, Education & Health, Mining & Manufacturing, Trade, Transport, Indigenous households, Non-Indigenous households. The economics I/O model is described in detail by Stoeckl (Stoeckl et al., 2011).

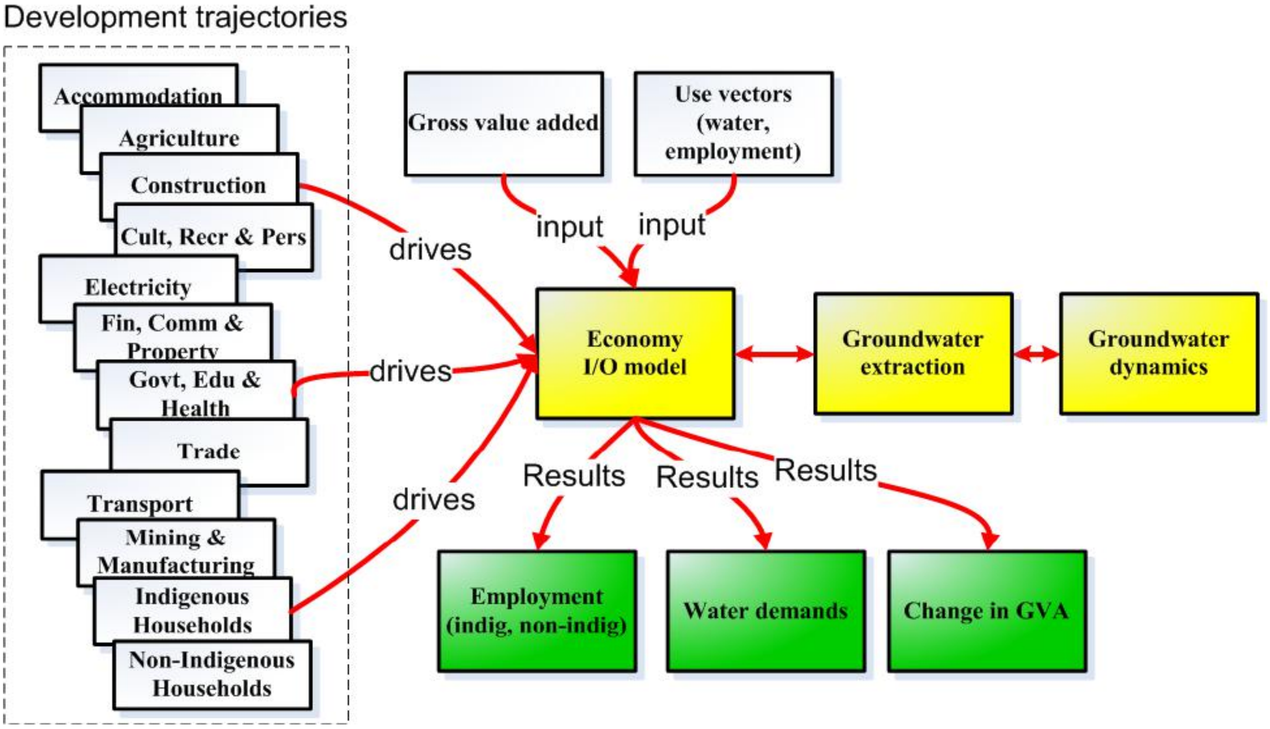


Figure 6-6 The Economic I/O Model: Relationships

6.6 TINDALL WAP MODEL

Although the Tindall WAP model is strictly speaking a management decision model, we will discuss its workings in this section. The third model of importance in the Daly prototype MSE, albeit not developed by a TRaCK project, is the NRETAS Tindall Aquifer Water Allocation Plan (WAP). This plan explicitly states the decision rules followed to set annual water allocation limits for the Tindall Aquifer at Katherine. This is explained further in Section 4.3.3.

These rules have been incorporated (with some simplifications) into the Daly River MSE application. This is of importance as it allows us to examine the effectiveness of the WAP in an adaptive fashion, where the WAP takes the place of the management decision functionality within the MSE framework.

6.7 RESPONSE MODEL INTEGRATION

The MSE approach helps us to integrate various science domains. To give that claim some substance, this Section explains the interactions between a couple of models developed by TRaCK science projects.

The response (sub) models configuration used in the MSE example presented in the next Section are depicted in Figure 6-7 where the flow of information between the sub-models (yellow boxes) is indicated by red arrows. The software architecture at the basis of the MSE application, allows the models to communicate in a network-fashion: any model can communicate with any other model. Appendix B contains more details. To demonstrate this, we'll discuss some interactions as they would arise in the prototype Daly River MSE application.

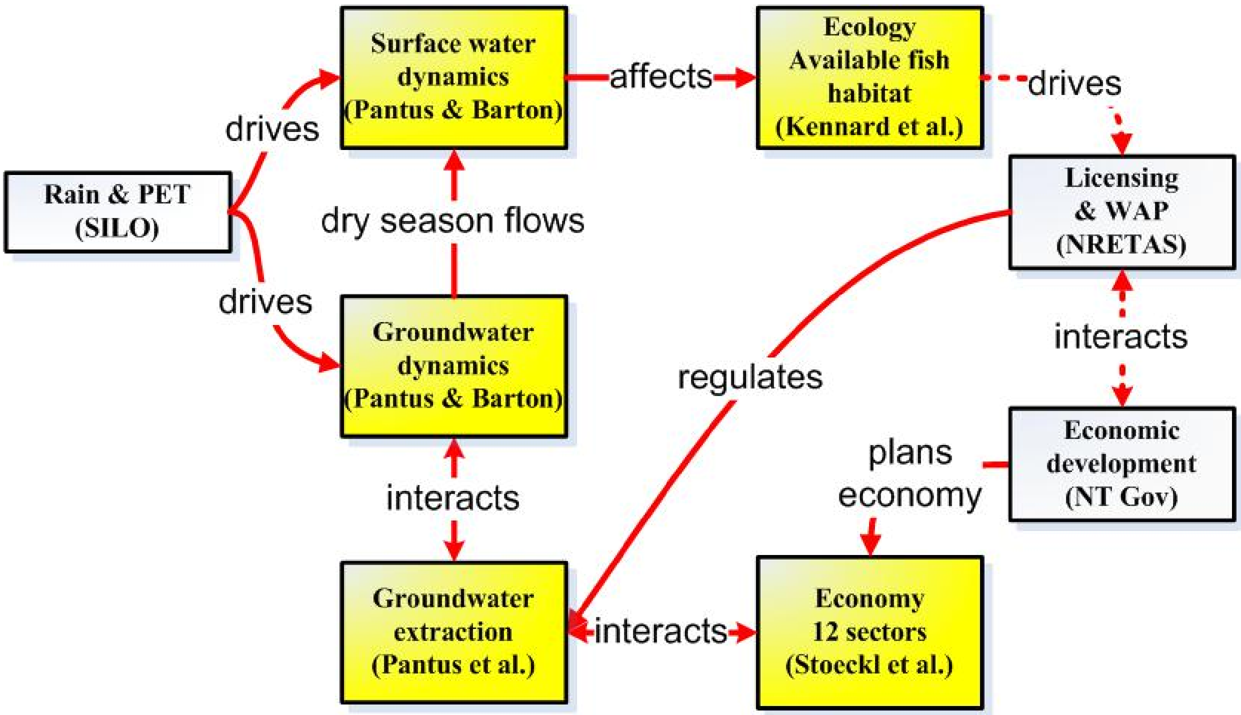


Figure 6-7 The response (sub) models in the Daly River MSE application integrate via interactions and feedbacks based on information flows between them. The dotted lines indicate future links.

The interactions may go along the following lines:

1. The economy model requests a certain amount of water extraction (planned volume) from the groundwater *extraction* model to simulate the needs of a growing economy, as dictated by the economic development plans.
2. The groundwater *extraction* model checks against available licenses and WAP quotas and passes on that request to the groundwater *dynamics* model, scaled by what the result of the licence and WAP examination were.
3. The groundwater *dynamics* model tries to subtract the requested volume of groundwater from its stores over a period of time as per request, but may not always be able to do that if the reserves are too low. It then informs the groundwater *extraction*

model how much it was able to extract (actual volume), which informs the economy model.

4. The economics model adjusts its actual growth accordingly.
5. In the meantime, the groundwater dynamics model does not only keep track of extraction requests and storage, it also keeps track of *recharge* from the surface water dynamics model and *baseflow* into the river
6. The dry-season baseflow in turn drives the available fish optimal habitat model, which reports its status during the dry-season.

The quite complex interaction between the (response) models that is allowed to develop is the basis of the connection and integration between the various science domains; economic communicates with the ecologic via the water models. The other models in the five remaining MSE functional areas (decision, action, observation, assessment and learning) do whatever jobs they have been assigned to do too.

The MSE approach also integrates the resource management and science domains. While the response models are interacting, the *Decision* model is simulating the Tindall WAP procedure every year and so simulates the resource management decisions and actions by regulating the economic growth and ecology via the groundwater extraction, thus integrating the resource management decisions and actions with the integrated science models. The Observation models simulate existing monitoring programs and the assessments simulate regulatory reporting requirements. These are all resource management domain activities and interact (integrate) directly or indirectly with the (science-domain) response models.

6.8 SUMMARY

The MSE Response Model is one of the six 'super' models representing the six functional areas of the MSE Conceptual Framework. The Response Model is the primary area in which integration of the science disciplines occurs. The Daly River MSE Response (sub) models are: the catchment water model, the habitat model, and the economics model.

The **catchment water model** sits at the core of the response model interactions and enables the integration of the other response models. It is based on the SIMHYD rainfall runoff model. SIMHYD was selected for its simplicity (low data requirements and short simulation time). Modelled flow is routed through the catchment using Muskingum routing. Initially, recharge and discharge of the Daly River groundwater reserves were simulated by the SIMHYD **groundwater model**.

A preliminary calibration of the catchment water model (including the groundwater model) was undertaken. Preliminary calibration results indicate that the model performs well in simulating water behaviour generally in the Daly catchment, but performed poorly in simulating dry season flow specifically. The groundwater model was modified to improve the simulation of dry season baseflow. Simulation results for baseflow did show some improvement, but not enough to be considered satisfactory. As such, further work is needed to improve the groundwater model.

Ecological behaviour in the Daly River is represented by the optimal fish **habitat model.** This model was developed by Project 5.1 and established a relationship between dry season baseflow and optimal habitat for key fish species.

Daly River socio-economic knowledge developed by Project 3.1 is represented by the **economics model**. This model not only functions as a 'response' model but also functions as a driver of water demand itself. There are 12 sectors in the economics model for which development trajectories may be set.

The Response (sub) models described here interact with each other to simulate interactions that occur in the real world. Software architecture supports this communication.

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7 MSE PROTOTYPE DEMONSTRATION SCENARIOS - RESULTS

7.1 INTRODUCTION

In this Chapter, we present the results of two demonstration applications of the Daly River Catchment MSE application prototype. The MSE models used in this Chapter are shown in Figure 6-1 and explained in Chapter 5 and 6. This Chapter builds (and relies fairly heavily) on Appendix C, in which we explain the basic statistical terminology, processing, presentation and visualisation of the MSE application in stochastic mode.

The first part of each of the two demonstration application sections discusses the results of the scenarios in *deterministic* (single evaluation) mode. A typical output is a decision support table where the results of each of the scenarios (rows) are reported against a collection of statistics that serve as performance indicators (columns). Where it is of interest, we also discuss the temporal variability (yearly epochs) of results from the deterministic mode. Appendix C contains details on temporal variability. The second part of each of the three demonstration application sections uses the same scenarios and models as the first part, but now evaluated in *stochastic* mode: each scenario is evaluated ten times with sampled values of selected model parameters (stochastic realisations) to assess the influence of the uncertainty in our knowledge (ignorance-based or epistemic uncertainty). The main (but not only) source of uncertainty in the scenario results is the variance in the surface and groundwater model, simulated by a uniform distribution with 50% range around their calibrated values. The resulting decision support table includes the resulting levels of uncertainty.

The (fictitious) management questions for the three demonstration applications are:

Question 1: To examine the effects of varying monitoring intervals: what would be the effect on a response variable such as river discharge under varying monitoring intervals?

Question 2: To examine the effects of economic growth trajectories: what are the triple bottom line trade-offs between a set of given economic trajectories? A short section on the effects of water allocation planning is also included.

Note that all results in this Chapter are based on fictitious scenarios and that the results discussed in this Chapter are for demonstration purposes only.

The current MSE application covers the whole trajectory: it allows us to specify and evaluate scenarios, visualise the results and produce a range of statistical indicators. All the information shown in this Chapter, including graphs and statistics of the results, are produced wholly by the MSE software application. Only formatting the result tables, such as selecting relevant information and converting it to reportage standard is done via a copy and paste into MS Excel and subsequent manual formatting.

7.2 DEMONSTRATION 1: EFFECTS OF MONITORING INTERVAL

7.2.1 DETERMINISTIC MODE

To examine a very basic question on the influence of the monitoring interval on the information gained from it, let us define five scenarios which differ only in their monitoring interval (daily, weekly, fortnightly, monthly and quarterly) settings. The response model consists of the surface and groundwater model only. The variable to be monitored is the river discharge [m^3/s] and the monitoring site is chosen to be in the Katherine River subcatchment (refer to Figure 7-5 for location). We assume no major groundwater extraction or other human disturbances.

The five scenarios are evaluated in *deterministic mode* for 10 years, from 1995 to 2004 inclusive, and the monitoring module will collect river discharge data from the response model conforming to its settings. The time series results of the five scenarios are shown in Figure 7-1.

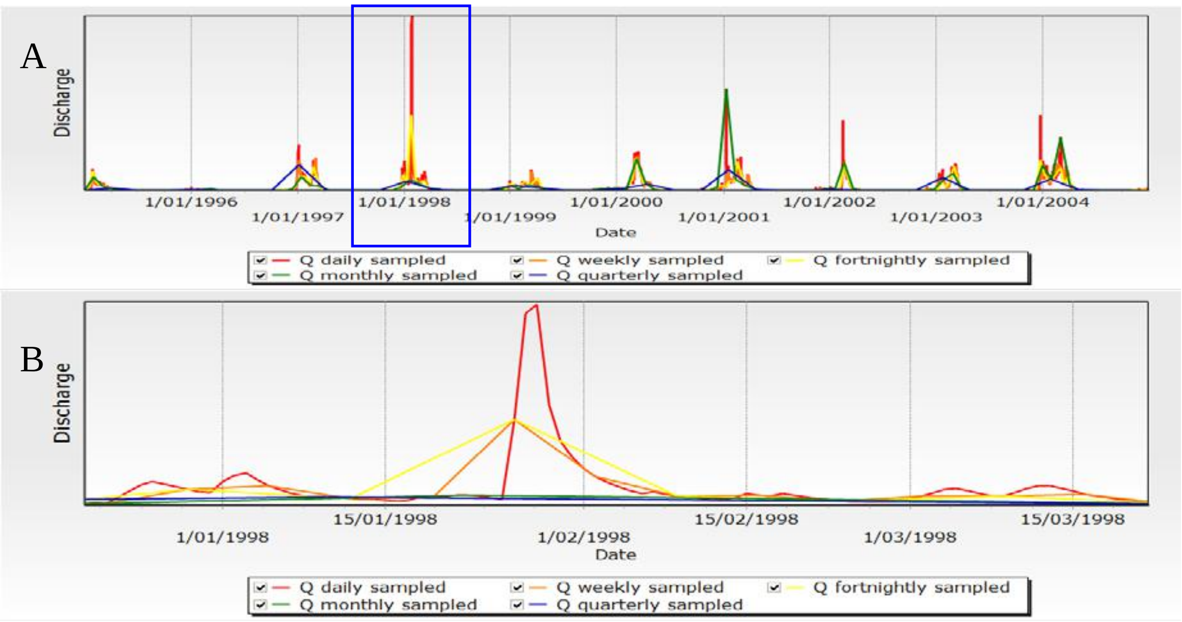


Figure 7-1 The simulated results of monitoring the river discharge over ten years (top graph) using a range of sample intervals. See text for details.

Figure 7-1 A shows a ten year overview of the monitoring results. The effects of the different monitoring intervals on the temporal dynamics of the flow are more easily viewed in Figure 7-1 B, which zooms in on one wet season. The red trace in Figure 7-1 B represents the daily monitoring interval results. The surface and groundwater flow model also operate on a daily time-step. Two qualitative results are immediately evident in Figure 7-1 B. The first is that the peak flows are often underestimated by longer monitoring intervals, as a fixed-interval monitoring program may miss the days on which those peaks occur. The second is that even the weekly sample interval looses a considerable amount of detail in representing the temporal dynamics of the river discharge. Both results agree with our intuition when increasing the monitoring interval.

The next step is to inspect statistical summaries of the results of the five scenarios. Table 7-1 allows us to do this in a more quantitative way.

Table 7-1 Effect of monitoring interval length on discharge [m³/s] estimates: deterministic mode.

Scenario	Mean	StDev	%CV	Min	Max	Q10	Q25	Q50	Q75	Q90
Daily	103	281	273	0	6,337	0.976	1.47	4.87	53.6	340
Weekly	99	239	241	0	2,726	0.975	1.48	5.04	51.1	333
Fortnightly	99	257	260	0	2,726	0.965	1.44	5.01	50.4	308
Monthly	125	413	329	0	3,660	0.949	1.51	4.41	50.8	271
Quarterly	90	202	225	0	935	0.902	1.58	4.87	35.8	332

The first of the qualitative conclusions derived from visually inspecting the temporal flow dynamics of the results is readily verified by the numbers in the Max-column in Table 7-1. The daily monitoring interval provides a maximum simulated river discharge of 6,337 m^3/s, which is considerably larger than the other sample intervals.

Table 7-1 also shows another interesting result: the maximum discharge of the monthly monitoring interval is larger than the weekly or fortnightly. This can be attributed to two factors: the fact that we're looking over the whole time series and that a maximum (like a minimum) is based on a single event, unlike for instance a mean which takes all data into account. So, if there is just one event where the monthly sample date coincides with a high discharge value, the maximum will be high. However, the conclusion for a monitoring program is that it should be less dependent on such coincidences if the maximum discharge is of importance. Practical solutions such as a more adaptive sampling approach may help prevent such flaws.

The second of the qualitative conclusions cannot be verified by the simple statistics in Table 7-1 and shows a limitation in the data analysis capabilities of the current MSE implementation. Analysing signal dynamics is not straightforward and falls outside the scope of the built-in MSE application analyses tools. The MSE application has good exporting facilities and they can be used to transfer the time series data into a package such as R or Matlab for further analysis.

The characteristics of the distributions of discharge values, as indicated by the Q-values in Table 7-1 do not show much contrast between the five scenarios. What became clear from the large difference between the median (Q50) and the mean values is that the distribution is highly skewed with a long righthand tail. This is due to the fact that the discharge values will be between 2 and 10 m^3/s during half of the year (dry season) and will only exceed 5,000 m^3/s (for the daily sample interval scenario) for a couple of days once every decade or so.

The last piece of information gleaned from Table 7-1 is the consistently high CV (coefficient of variation: StDev/Mean) values indicating a large dispersion around the mean in the temporal behaviour of all scenarios. This is to an extent artificial as the standard deviation is measure of dispersion around the mean values and the mean value is not a good descriptor for the time series due to the highly skewed distribution of discharge values, as pointed out in the previous paragraph.

A major drawback of the deterministic mode results is that they do not allow us to test whether the differences between the scenarios are statistically significant (apart from the non-descriptive mean values). Stochastic-mode MSE results allow us to test scenario results.

7.2.2 STOCHASTIC MODE

As explained in Appendix C, the MSE's second mode is the stochastic mode where the same scenarios are being evaluated a number of times with different values for the model's parameters to examine the influence of our ignorance (also known as 'epistemic uncertainty') about the precise parameter values. In this demonstration the same scenarios are evaluated ten times, producing ten time series for each.

The epistemic uncertainty is shown in the two graphs of Figure 7-2, where graph A is an overview of the five scenarios over the ten year evaluation period and graph B zooms in to better show the results.

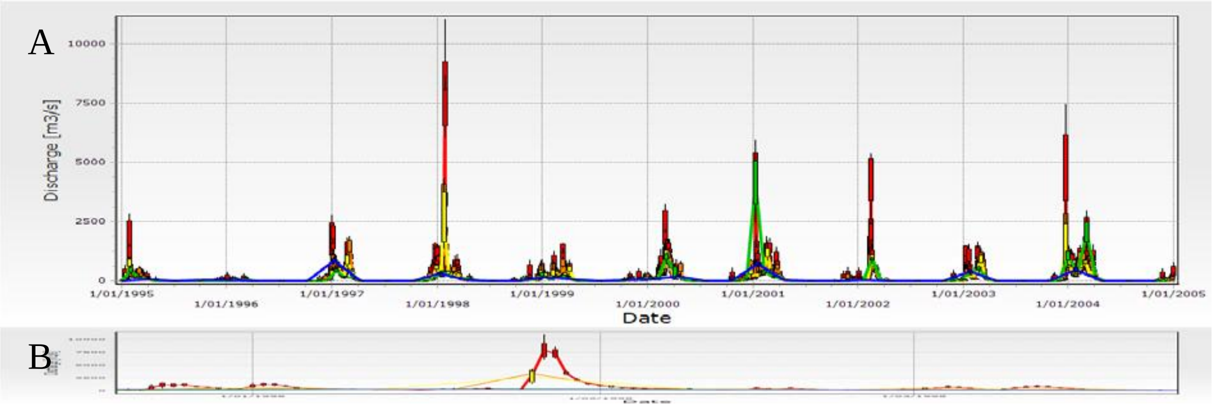


Figure 7-2 The results of varying monitoring intervals from the MSE application in stochastic mode with ten realisations. See text for more details and Figure 7-1 for legend.

Even though the qualitative conclusions from this representation would not alter our assessment of the differences between the sampling regimes, we may notice the considerable uncertainty in the high-discharge values.

Table 7-2and Table 7-3 show (part of) the standard comprehensive statistical summary reportage included in the MSE application. Table 7-2 Ensemble-based, stochastic mode results, (epistemic uncertainty), N = 10.

reports on the ensemble averages and standard deviations of a range of statistical summary variables (e.g. mean, standard deviation, min, max, Q-values). Each of these variables is calculated for each of the ten time series over the ten years of data in the ensemble, resulting in ten values for each. The table reports the mean and standard deviation over those ten values for each of the statistical variables. For example, the average maximum values over the ten time series is now 8,032 ± 1,370 m^3/s, compared to 6,337 m^3/s according to the deterministic mode evaluation. This increased average reflects the fact that the maximum discharge values in some of the stochastic evaluations (see Figure 7-2) now exceed 10,000 m^3/s. If we do a very coarse calculation of the implications based on these findings: having an estimate for the standard deviations of the average maximum discharge based on epistemic uncertainty over a *ten-year period* and assuming normality of the maximum values, we can estimate that the peak-discharge value of around 9,400 m^3/s (mean + 1 stdev: one-sided 84% of events) will be exceeded once every 60 years and a peak-discharge of around 12,000 m^3/s (mean + 2 stdev, one-sided 98%) would be a 1 in 500 year event.

Table 7-2 Ensemble-based, stochastic mode results, (epistemic uncertainty), N = 10.

Scenario	Mean Avg	Mean SD	StDev Avg	StDev SD	%CV Avg	%CV SD	Min Avg	Min SD	Max Avg	Max SD	Q10 Avg	Q10 SD	Q25 Avg	Q25 SD	Q50 Avg	Q50 SD	Q75 Avg	Q75 SD	Q90 Avg	Q90 SD
Daily	118	14.7	342	45.1	288	13.9	0.098	0.207	8,032	1,370	0.917	0.275	1.41	0.438	5.01	1.11	71.4	11.8	372	45.7
Weekly	108	16.5	273	41.5	253	21.6	0.113	0.148	3,384	740	0.708	0.241	1.09	0.365	4.44	1.48	67.8	15.9	360	63.7
Fortnightly	106	21.3	271	77	253	28.1	0.165	0.241	2,680	1,115	0.928	0.164	1.4	0.259	5.18	0.845	66.2	17.4	345	68.6
Monthly	129	18.3	453	91.3	348	29.1	0.13	0.217	4,122	979	0.89	0.158	1.41	0.238	4.82	0.5	60.5	13.8	315	49.9
Quarterly	88.7	8.28	197	16.9	222	7.21	0.273	0.44	866	94.3	0.883	0.362	1.62	0.529	6.27	2.69	59.7	13.8	381	50.6

Table 7-3 Combined ensemble and epoch-based stochastic mode results (temporal + epistemic), N = 50.

Scenario	Mean Avg	Mean SD	StDev Avg	StDev SD	%CV Avg	%CV SD	Min Avg	Min SD	Max Avg	Max SD	Q10 Avg	Q10 SD	Q25 Avg	Q25 SD	Q50 Avg	Q50 SD	Q75 Avg	Q75 SD	Q90 Avg	Q90 SD
Daily	119	51.3	303	157	262	71.2	0.723	0.35	3,237	2,230	0.99	0.389	1.56	0.749	7.51	6.09	103	61.8	366	188
Weekly	109	50.2	241	125	230	57.9	0.577	0.28	1,314	884	0.767	0.317	1.24	0.61	7.33	7.36	116	75.7	386	192
Fortnightly	112	47.6	243	138	219	50.4	0.786	0.315	1,108	751	1.07	0.342	1.76	0.742	12.1	9.51	129	95.5	348	146
Monthly	117	115	282	348	216	55.2	0.791	0.357	958	1220	1.03	0.384	1.89	0.994	14.1	16.6	117	97.4	958	1220
Quarterly	86.3	72.7	151	144	155	35.7	1.14	0.667	310	288	1.14	0.667	6.01	12.8	28.3	29.9	310	288	0	0

Table 7-3 reports the statistical summary of the combined ensemble (epistemic uncertainty) and epoch (temporal) uncertainty, as described in Appendix C. Focusing on the maximum (now *annual*) discharges and their uncertainties.: a very coarse calculation would indicate a lower average annual maximum discharge of 3,237± 2,230 m^3/s, resulting in exceeding the 5,500 m^3/s once in 6 years and 7,750 every 30 years.

The same calculations can be done for the other sample-intervals, resulting in considerably lower estimates. How important such results would be, depends on their application. If such information is to be used to dimension levees or in evacuation planning, underestimation could result in insufficient protection and would justify a more intensive (and more costly) monitoring program to be chosen.

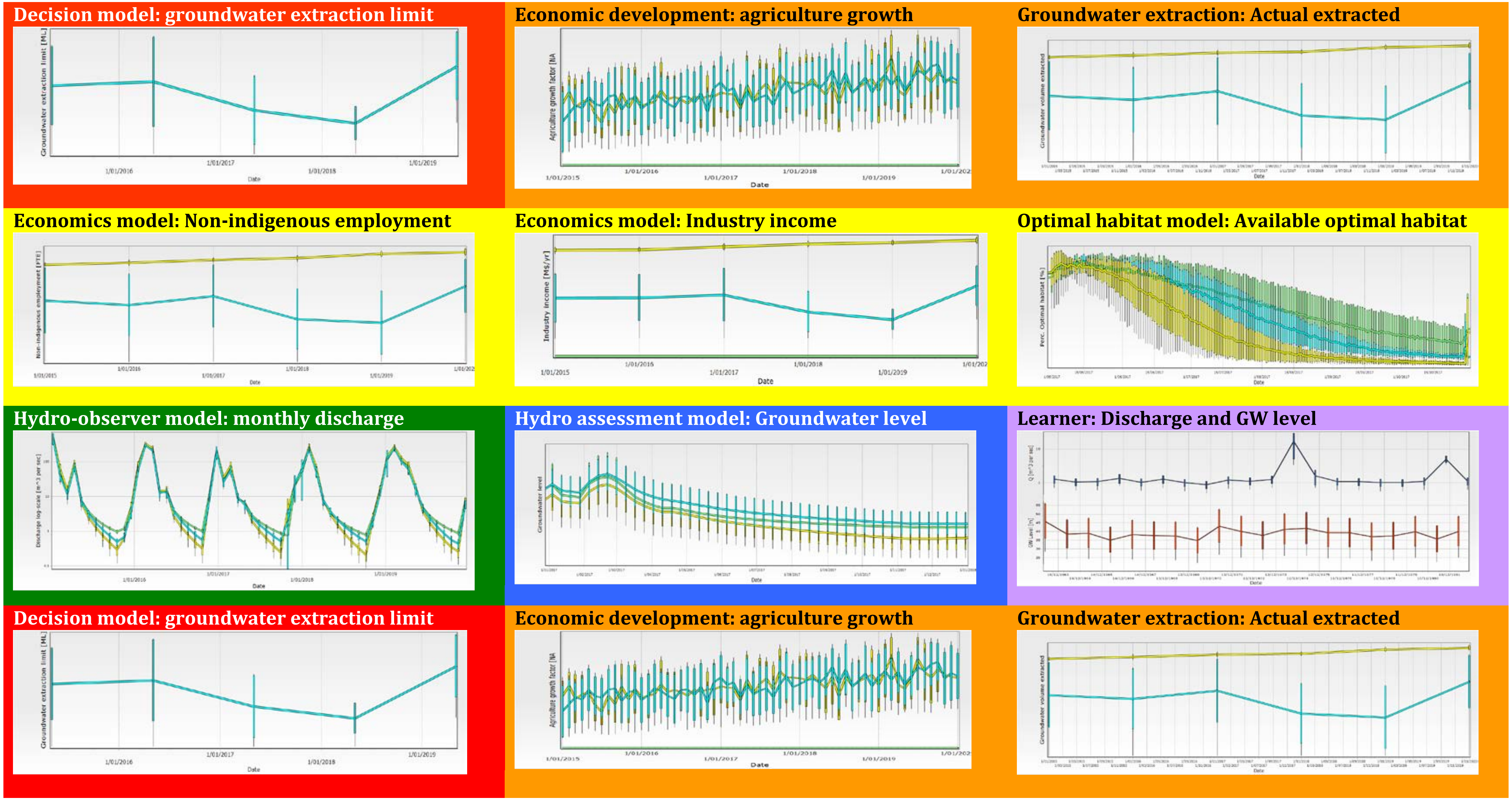


Figure 7-3 Selection of the comprehensive results from the MSE application in stochastic mode. See text for details.

7.3 DEMONSTRATION 2: ECONOMIC TRAJECTORIES SCENARIOS AND WAP

With the model configuration as shown in Figure 6 1, a series of scenarios was run to demonstrate the capabilities of the prototype Daly River MSE application with respect to running integrated, triple-bottom line models. The aim was to show an example of assessing the trade-offs between various economic options. Table 7 4 briefly describes the scenarios that were evaluated for this section.

Before we discuss the economic scenario results in more detail and focus on only a very small subset of the results from the scenarios.

Figure 7-3 shows a selection of the comprehensive results being produced by the prototype Daly River MSE application during scenario evaluations. The six scenarios produce approximately 250 time series. Some time series contain around 21,000 daily results for a 57 year simulation. However, in the rest of this Chapter we will only use a fraction of the available information.

Table 7-4 Economic scenarios evaluated to demonstrate the capability of the Daly River MSE application

Scenario	**Description**
1 No groundwater extraction	No economic model activity at all, and no groundwater water extraction as a consequence
2 Activity 2006 level	Economic activity stable on 2006 level, no WAP
3 5% Tourism Growth	5% annual *tourism* growth, defined by accommodation, cultural/recreational, electricity and construction sectors, no WAP
4 1.5% Overall Growth	All 12 industry sectors grow by 1.5% annually, no WAP
5 5% Overall Growth	All 12 industry sectors grow by 5% annually, no WAP
6 5% Tourism + 1.5% agriculture	5% annual *tourism* growth (see strategies 4 and 5), and 1.5% annual growth in agriculture, no WAP

The six scenarios we will use in the rest of this Chapter focus on activities in the Katherine sub-catchment, as shown by the green outline in Figure 7-5. The economy is represented by 12 sectors (see Figure 6-6) and the growth trajectories of scenarios 2 - 6 are combinations of growth in a subset of those collections. The dynamics of a scenario run is explained in Section 5.8.

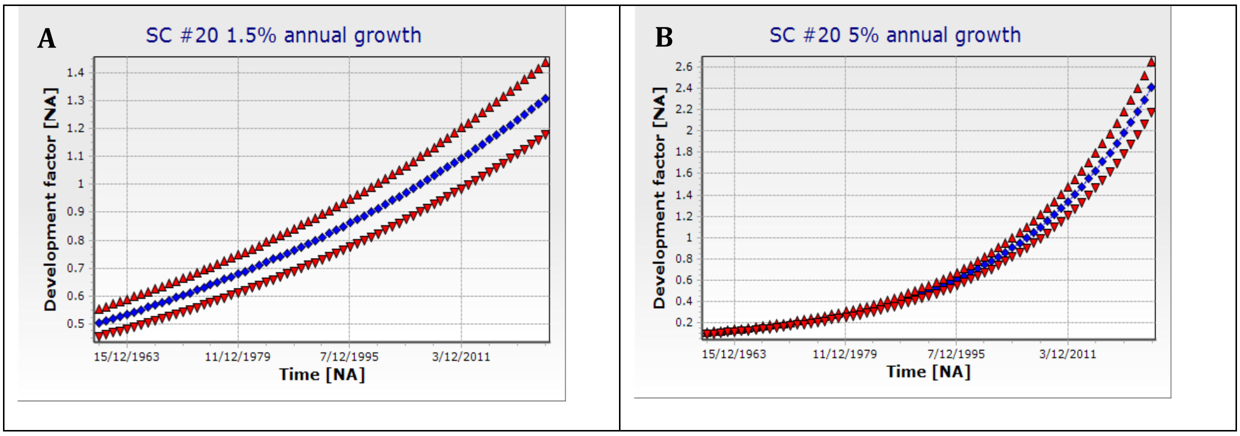


Figure 7-4 Examples of growth trajectories for sectors in the economics model. Graph A and B represent a 1.5% and 5% annual growth resp., both with 2006 as its reference year (development factor = 1). The blue diamonds indicate the average development factor, the red triangles represent the standard deviation.

Scenario 1 (no groundwater extraction) excludes the economy model altogether. Scenario 2 assumes economic activity stays at the 2006 level, Scenarios 3 – 5 are based on combinations of growth trajectories as shown in Figure 7-4. Each of these scenarios was evaluated between 1963 and 2020 with minimum of one day time steps. Only the last five years (between 2015 and 2020) will be reported.

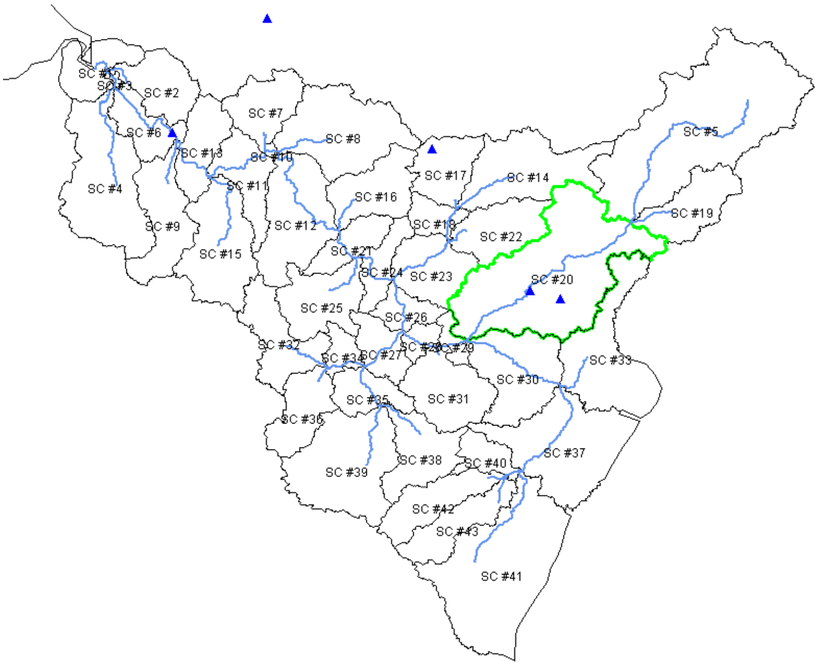


Figure 7-5 The eleven scenarios of the MSE focus on the Katherine subcatchment (green outline).

7.3.1 DETERMINISTIC MODE RESULTS

One key product when reporting on various management options is the decision support table. Decision support tables report the trade-offs between the evaluated scenarios in a consistent and comprehensive way. They consist of measures that represent the key messages from the MSE results (performance indicators) for each scenario. In the examples presented here, the key messages are expressed by our choice of economics, social and environmental indicators and how they perform under the different economic scenarios for the region. Suitable performance indicators need to be chosen to represent the economic, social and environmental performance so the costs and benefits of each of the scenarios can be reported.

As the performance indicator for the *economy* we use the (simulated) average annual industry income (gross value added) in this demonstration. The *social* sector is represented by the (simulated) annual indigenous employment levels.

The *environment* is represented by two indicators: ecology and hydro-physics. The ecology is represented by the Q10 (10th quantile) of the simulated daily Sooty Grunter Juvenile optimal habitat values (see Appendix C for more detail) during the dry season, from May until November. Note that the optimal habitat is a surrogate ecological indicator as other factors need to be taken into account to get a more direct ecological indicator. The hydro-physics is represented by the weekly minimum groundwater level.

Table 7-5 shows for each of the six scenarios (row-headings) the resulting scores for each of the four performance indicators (columns). The cells in the table contain proportional scores for each performance indicator for each scenario. The standardisation is achieved by dividing each performance indicator by its column-maximum. The reason for the standardisation is twofold: firstly, the absolute values of the performance measures may not be relevant to discuss the trade-offs between the various scenarios. Secondly, it prevents discussions about actual values of the various performance measures, thus allowing us to focus on the real goal of this report: discussing Daly River MSE approach and capabilities.

After having produced the first decision support table for the four performance measures and six scenarios, the next task is to use these results. A good start is to discuss its content.

As we included only employment as the social performance indicator and employment is being favoured (in this model) by an expanding economy, we would expect that economic and social indicators will show similar effects. On the other hand, ecology and economy compete for the same resource (dry-season groundwater) and will work in opposite directions. These general considerations are confirmed by the decision support table and should give some confidence in the underlying models and application.

Table 7-5 (and its graphical representation in Figure 7-6) makes explicit the complexity of natural resource management decisions if competing objectives are being considered. The trade-offs between, for instance, ecology and economy in the decision support table show that there is no 'silver bullet' solution. Scenarios with favourable economic performance indicators are likely to attract less favourable outcomes in the ecological indicators, given the current performance measures and response models.

Table 7-5 Decision support table with triple bottom line (relative) performance indicators for six Daly River MSE scenarios in deterministic mode. For details see text.

Strategy	Economy	Social	Ecology	Hydro-Physics
1 No groundwater extraction	0	0	100	100
2 Activity 2006 level	40	47	82	88
3 5% Tourism Growth	47	52	47	87
4 1.5% Overall Growth	55	59	67	84
5 5% Overall Growth	100	100	34	68
6 5% Tourism + 1.5% agri	48	53	71	84

Depending on the relative importance that stakeholders would give to performance measures, different stakeholder groups would favour different options. Though predictable, the MSE results quantify these competitive interests and allow various rankings of options given different weights. Due to the different weighting criteria that different stakeholder groups may want to employ, MSE delivers the product that allows different weightings to be applied, instead of delivering a single 'best' solution. Having quantified the pros and cons of various scenarios, the discussions may go in different directions, depending on a range of factors.

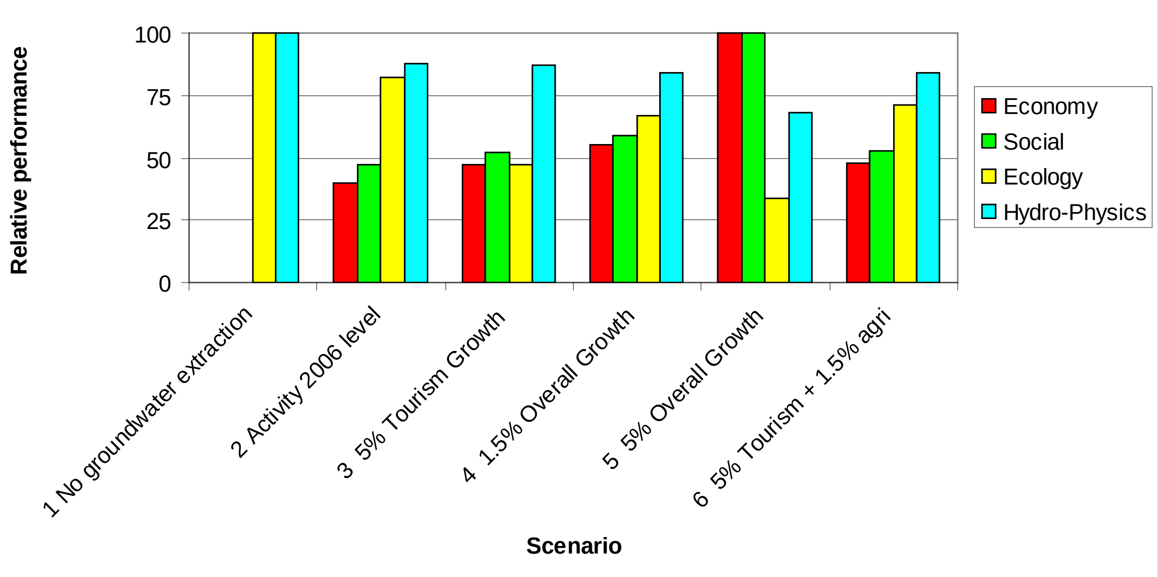


Figure 7-6 Graphic representation of decision support table information may help interpretation. See text for details.

In some situations, stakeholders may want focus on the *most contrasting scenarios* (Scenario 1 and 5) and find out what factors are causing this contrast. The MSE application allows drilling down from the high-level performance indicators to detailed output of individual models. Figure 7-7 shows the outputs of the models that are causing the main contrast between Scenario 1 (No groundwater extraction) and 5 (5% overall annual growth). The blue lines and points represent results from Scenario 1, the orange lines and points represent Scenario 5.

Graphs A and B in Figure 7-7 represent the output of the economics model. The economic model is a linear model and the growth in one factor (e.g. graph A, indigenous employment) follows the growth in another factor (e.g. graph B, annual industry GVA). The 5% steady growth over all sectors of the economy produces good outcomes for the economy. As Scenario 5 does not have any restrictions on the volume of groundwater extracted, it will grow until there is no groundwater left to sustain further growth.

Graph C shows the behaviour of the optimal habitat of Sooty Grunter juveniles during the dry season. The low value of the environmental performance indicator (Q10 of the optimal habitat curves) in the case of Scenario 5 is caused by the optimal habitat being close to zero for almost 2 months per dry season, which may have unwanted implications for the downstream flora and fauna.

These outcomes may result in seeking options to mitigate the negative impacts of strong overall economic growth on groundwater reserves. For instance, growth of a mix of other sectors of the economy or different patterns of water use may be considered. These options may trigger the definition of a new set of scenario evaluations, with feasible actions that would reduce the negative consequences of the previous situation.

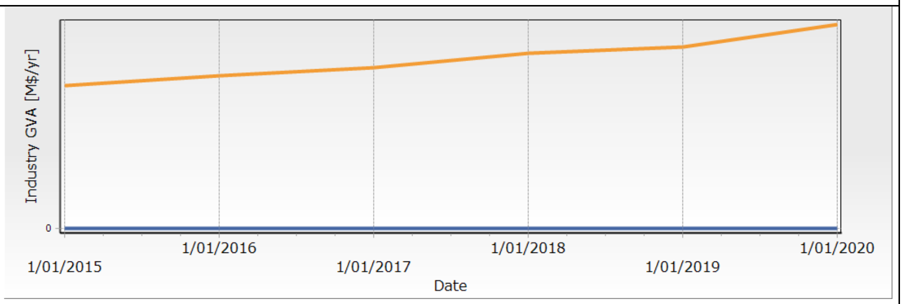
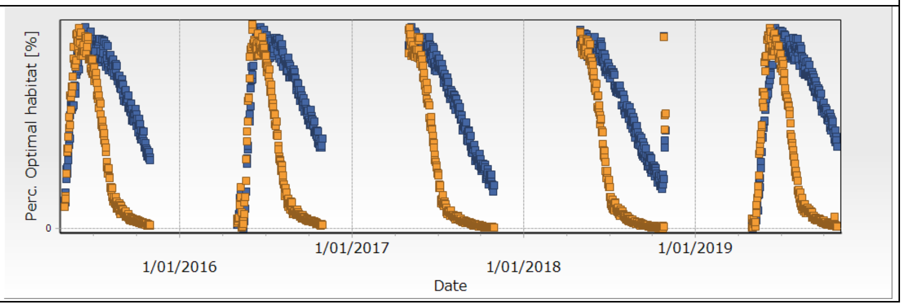
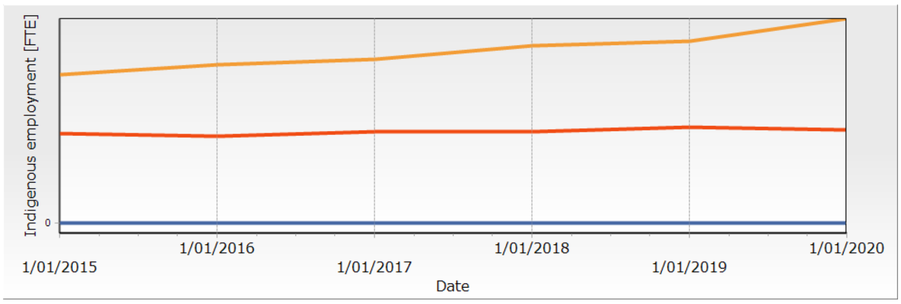
A: Social performance indicator, indigenous employment	
B: Economy performance indicator, annual industry GVA	
C: Environment performance indicator, Sooty Grunter optimal habitat.	

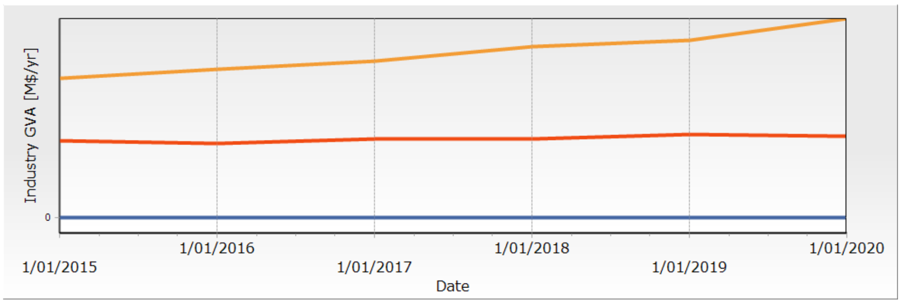
Figure 7-7 The Daly River MSE allows drilling-down to detailed time series information. Blue = Scenario 1, orange = Scenario 5. See text for more details.

In other situations, stakeholders may want to focus on the *overall best performing scenarios* (e.g. Scenario 6: mixed tourism and agriculture development). Figure 7-8 shows the outputs of the models that contrasts Scenarios 1, 5 and 6. The blue lines and points represent results from Scenario 1, the orange lines and points represent scenario 5 and red represents scenario 6.

A: Social performance indicator, indigenous employment



B: Economy performance indicator, annual industry GVA



C: Environment performance indicator, Sooty Grunter optimal habitat.

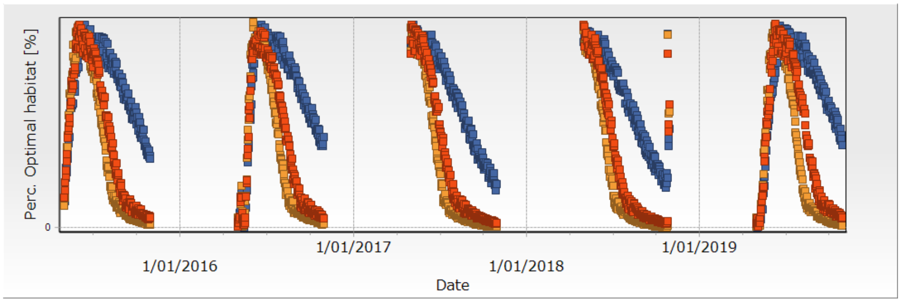


Figure 7-8 Decision support tables are also serving as a key to access more detailed information. Blue = Scenario 1, orange = Scenario 5, red = Scenario 6. See text for more details.

The social and economic performance of Scenario 6, as shown in Figure 7-7 A and B, is about half the performance of the high economic growth scenario (Scenario 5). There is some improvement in the time the environmental indicator is at its lowest value in Scenario 6 compared to Scenario 5, but those improvements are not as pronounced as the socio-economic improvements. This argument may lead to scenarios that try yet other mixes of economic sector development.

These iterations of examining and redefining management scenarios amounts to surveying (the boundaries of) the space of feasible management options and this is precisely what MSE is designed to support.

To keep these demonstrations relatively short, we will not discuss the epoch-based analysis of the scenarios.

7.3.2 STOCHASTIC MODE RESULTS

In the previous section, we assumed that we know everything about the models underlying the results. The reality is that our knowledge is incomplete and it is important reflect this ignorance in the scenario results. Ignorance-based (epistemic) uncertainty relating to our incomplete model knowledge is included in the scenarios by considering parameters to be stochastic variables and drawing their values from appropriate distributions for every evaluation. The decision support table is shown in Table 7-6 Decision support table for Demonstration 2, including epistemic uncertainty.

Table 7-6 Decision support table for Demonstration 2, including epistemic uncertainty. The cells contain the mean +/- standard deviation with N = 10.

Strategy	Economy	Social	Ecology	Hydro-Physics
1 No groundwater extraction	0 +/- 0	0 +/- 0	100 +/- 31	100 +/- 16
2 Activity 2006 level	40 +/- 0	41 +/- 0	14 +/- 8	77 +/- 27
3 5% Tourism Growth	47 +/- 0.05	49 +/- 0.05	21 +/- 9	89 +/- 15
4 1.5% Overall Growth	55 +/- 0.67	56 +/- 0.67	16 +/- 8	89 +/- 19
5 5% Overall Growth	100 +/- 0.66	100 +/- 0.58	7 +/- 6	76 +/- 28
6 5% Tourism + 1.5% agriculture	48 +/- 0.58	50 +/- 0.59	16 +/- 5	90 +/- 15

The trends in the decision support table for the stochastic mode results in Table 7-6 follow the overall trends found in the deterministic mode and presented in Table 7-5. Scenario 1 (no groundwater extraction) still scores high for the environment (ecology and hydro-physics) and the 5% overall growth still scores high for the economic and the (simple) social indicators. However, now we have also a measure of uncertainty around the results. The numbers in Table 7-6 are the average values of statistic measures (e.g. optimal habitat Q10 for ecology) over the ensemble of 10 stochastic realisations, +/- the standard deviations.

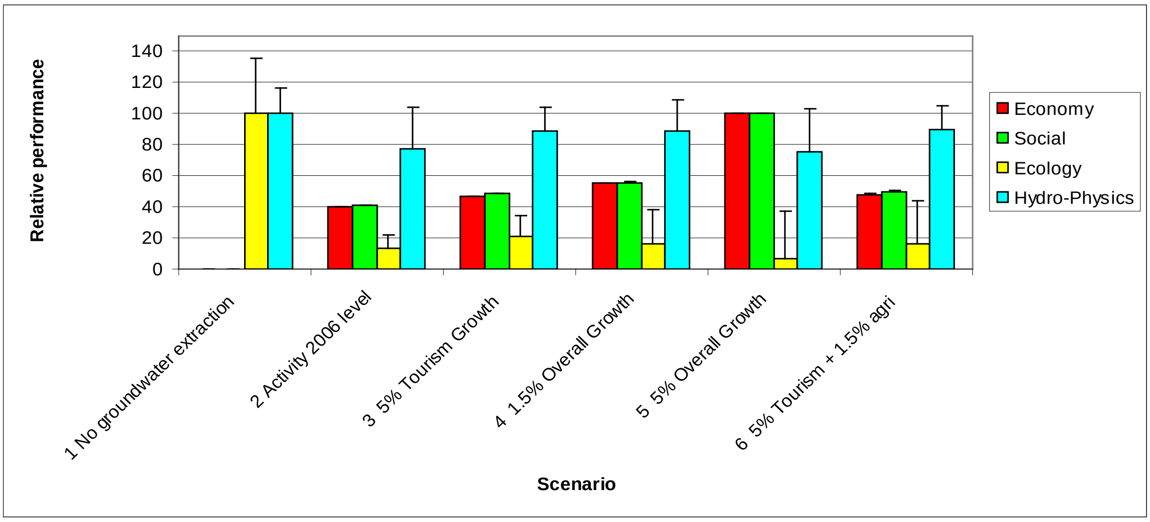


Figure 7-9 Graphical representation of the decision support table for the stochastic-mode scenario results.

Focusing on the uncertainties, the first thing we notice (see also Figure 7-9) is how (unrealistically) small the uncertainties in the economic and social indicators are. The main reason is that the groundwater extraction only depends on whether there is or there isn't any groundwater available and as such is decoupled from the recharge dynamics and from the rain variability. As long as there is enough groundwater to be extracted, it will be extracted, independent of the groundwater level (which does depend on the recharge and the surface water model). The other reason is because we assigned small uncertainties (+/- 10%) to the growth trajectories (see Figure 7-4) so as to better understand the uncertainties generated by the surface/groundwater model.

The ecology and hydro-physics results are coupled to the surface/groundwater model and so inherit their uncertainties from the groundwater model. To see the effects of stochastic evaluation, we take a closer look at the Sooty Grunter juvenile optimal habitat responses to the two 'extreme' scenarios: 1 and 5.

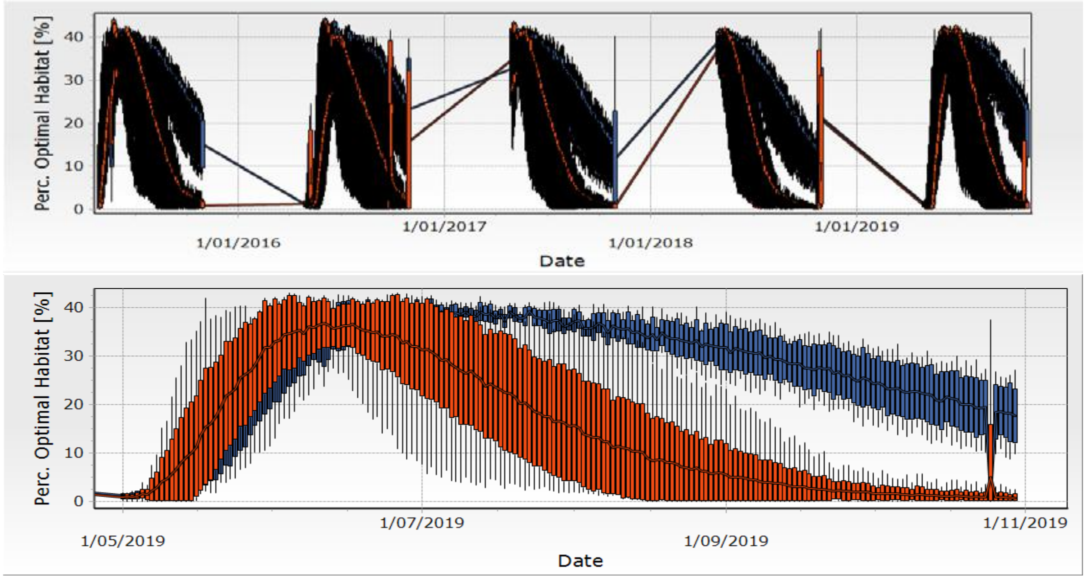


Figure 7-10 The results of stochastic evaluation of two scenarios based on epistemic uncertainty N = 10. See text for details.

The results of the stochastic runs for ecological indicator are shown in Figure 7-10. The top graph shows the results for the last five years of the simulations, the bottom graph zooms in to one year to facilitate visual inspection. The y–axis represents the percentage optimal habitat for Sooty Grunter. The blue trace represents the mean and standard deviation of Scenario 1 (no groundwater extraction) and the orange trace represents Scenario 5 (5% annual growth).

The implications of the results in Figure 7-10 are that our uncertainty in the parameters of the surface water model (epistemic uncertainty) introduces an uncertainty in the results, in this case the optimal habitat variable. The worst case scenario shows that there *may be* no optimal habitat in 2019 for Sooty grunter juveniles for more than 2 months under Scenario 5 (5% overall annual growth). This is quite a different conclusion from the deterministic results where there was only a very short period (if any) without any optimal habitat at the end of the dry season.

The MSE application also has facilities that allow us to look at the combination of uncertainties. As explained in Appendix C, if we pool the one-year-epochs from the ten stochastic evaluations (ensemble) and draw some statistics, the results reflect the uncertainty introduced by our imprecise knowledge and temporal variability. Figure 7-11 shows the results of the temporal and epistemic uncertainty over the last 5 years of the scenario simulation. The legend is the same as for Figure 7-10.

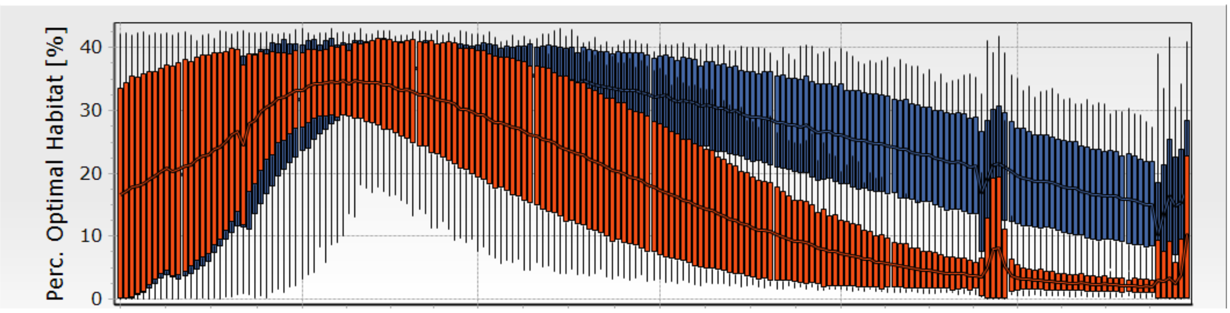


Figure 7-11 The results of stochastic evaluation of two scenarios, combining epistemic uncertainty and temporal variability. N = 50. See text for more details,

The results from this type of analysis also take into account the temporal variability of the system under management, as simulated by the MSE models. However, we must keep in mind that the economic growth did not keep the system in the same state. For instance, the economic activity in 2015 would be around 1.55 times the 2006 level, whilst in 2020 it would have reached about 2.4 times that level. By pooling all years, we are averaging the growth effect over that period but also adding to the variation as part of the temporal variability. As stated before, the ecological indicator is based on the 10th quantile (Q10) of the Sooty Grunter juvenile's optimal habitat availability.

If we're interested in exploring the statistical distributions of the scenario results pertaining to the ecological indicators a bit further, we can drill down into the underlying information through the MSE application's analysis tools. Figure 7-12 is an example of this.

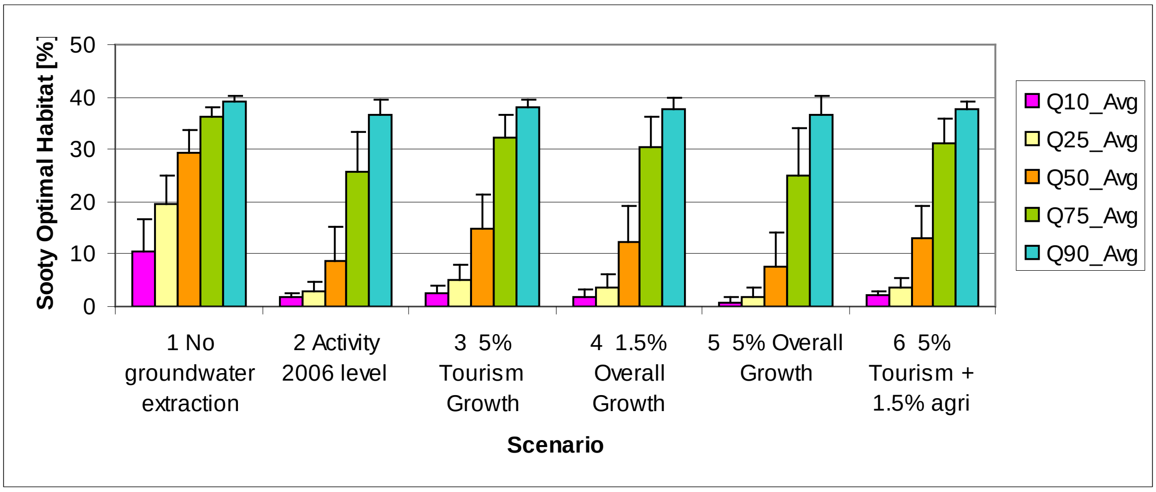


Figure 7-12 Quantiles describe the distributions of values making up the dry-season time series of Sooty Grunter juvenile optimal habitat, here shown for different economic development scenarios.

Figure 7-12 show standard five quantiles (percentiles) in the MSE statistical reporting against each of the six scenarios. This allows us to look at the effects of the scenarios beyond just the 10th quantile (equates to 10% of the values in a time series). For example, the results for Scenarios 2 and 5 show that during 50% of dry-season time the average Sooty Grunter juvenile habitat is below 10% of the river area. Taking into account the uncertainties, there is a 33% chance that all but Scenario 1 would have years where the Q-50 values (or 50% of the time) are below 10% juvenile optimal habitat.

To close off this demonstration, we will have a quick look at the effects of a Water Allocation Plan (WAP) on ecological and economic indicators. The now familiar decision support table in Table 7-7 is simplified by concentrating on two performance indicators: economy and ecology. The scenarios are the two economic growth scenarios, with and without a WAP effecting water quota based on available groundwater. Scenario 1 is again a no-economic activities scenario (no groundwater extraction) standard. The uncertainties in Table 7-7 and Figure 7-13 are based on epistemic uncertainties only.

Table 7-7 Decision support table to examine the effects of a WAP

Scenario	Economy	Ecology
1 No groundwater extraction	0 +/- 0	100 +/- 31
5 5% Overall Growth	100 +/- 0.66	7 +/- 5.8
5a 5% Overall Growth + WAP	31 +/- 12.12	31 +/- 7.3
6 5% Tourism + 1.5% agri	48 +/- 0.58	16 +/- 5
6a 5% Tourism + 1.5% agri + WAP	29 +/- 9.83	31 +/- 4.7

Examining Table 7-7 and Figure 7-13, it becomes clear that the inclusion of the WAP is increases the ecological performance slightly more than it decreases the economic performance. WAP increases the *ecologic* indicator on average by a factor 4.5 for the 5% overall growth scenario and by a factor of 2 for the mixed growth scenario, and it decreases the *economic* performance by a factor 3 for the 5% overall growth scenario and by a factor of 1.6 for the mixed growth scenario.

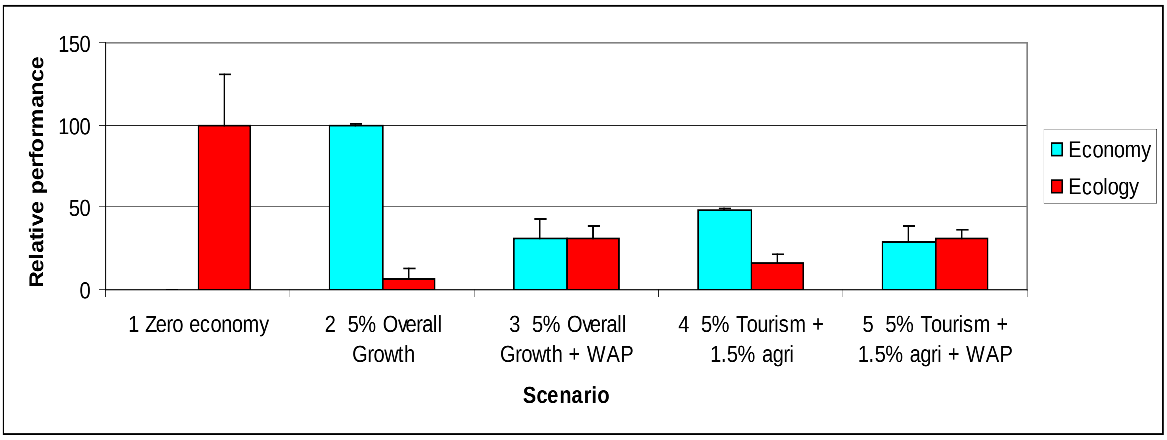


Figure 7-13 The graphical representation of the decision support table for the scenarios examining the simulated WAP effect.

When discussing the previous results presented in Figure 7-9, one observation was that the economics performance indicator uncertainties were very small. The explanation was that the economy model depended on groundwater extraction and the groundwater extraction was in a way disconnected from the groundwater *dynamics*, only limited by total capacity and so not influenced by the epistemic uncertainty in the surface water model. That situation has changed for the economic results when implementing a WAP, as shown by Scenarios 3 and 5. Table 7-7 and Figure 7-13 show that and there is a more noticeable level of uncertainty in economic indicators for the WAP-scenarios. This is the case because the WAP sets extraction quotas based on *expected* groundwater flow as predicted by groundwater *level*, which is influenced by the surface water dynamics via recharge and discharge.

Using the decision support table again as a guide to the underlying details, Figure 7-14 shows the results from drilling down to examine how the WAP changes the behaviour of the ecological performance in more detail.

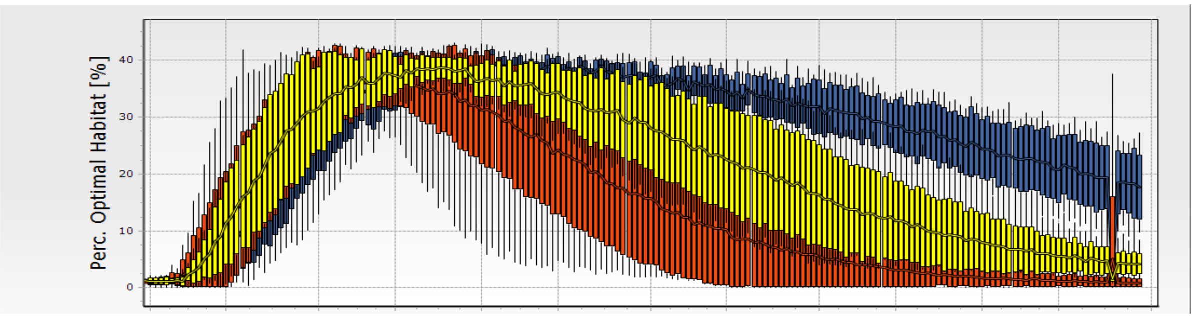


Figure 7-14 Details of the ecological indicator for the 5% annual growth scenario without WAP (red trace) and with WAP (yellow trace). The blue trace represents the No GW extraction scenario.

Figure 7-14 shows that the WAP is preventing the optimal habitat becoming zero for an extended period of time, as simulated for the 5% overall annual growth without the WAP. It also shows that the effects of such economic growth on the optimal habitat are still considerable and should be viewed with respect to other trade-offs such as economics and social performances.

The decisions regarding such trade-offs fall well outside the brief of science and into the domain of decision makers and stakeholders. As demonstrated in this Chapter, the MSE approach can support the negotiation, planning and decision making process by presenting relevant information, based on the best available knowledge and data.

7.4 SUMMARY

This Chapter demonstrated some of the facility in concepts, models, data and software, currently implemented in the prototype Daly River catchment MSE application. Based on two examples, we looked at various approaches to examine scenario results and showed ways to systematically analyse and report those results comprehensively. The decision support table is a high-level and targeted summary of the trade-offs between scenarios. Another very important role of the decision support table is to function as a guide into the extensive archive of results at many levels generated by the MSE application.

This Chapter also emphasises the importance of uncertainty and how the MSE application supports the definition, progression and analysis of uncertainties. Two sources of uncertainty are being analysed: temporal variability and epistemic uncertainty. These two sources have different implications for the process of planning and managing our natural resources.

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8 LEARNINGS AND CONCLUSIONS

8.1 LEARNINGS

There are some lessons that can be learnt through the integration project experience. Some of the lessons are on the scientific program management level; others are on the-project level.

8.1.1 ABOUT INTEGRATION IN SCIENCE PROGRAMS

To be able to fully utilise the expertise and resources of a scientific program such as TRaCK, it is essential to have the need for 'integration' built into the fabric of the program from the start. Integration is not only a sales argument; it is the next step in our approach to science and to science delivery. If we are not able or willing to take that step and go beyond the conventional means of organising and delivering science (often fragmented along discipline domains), science will decrease in relevance for resource management, as resource management must take into account the increasingly complex relationships that exist in the real world.

The concept of integration is a fairly abstract one that needs to be given content if we are to expect tangible results. In practise, this means that we need to define what processes and products will be delivered under the banner of integration and who will be responsible for those products.

Ideally, integration of a body of scientific work commences before the scientific work starts. The earlier integration commences, the greater the benefit. If integration is to be one of the products of the scientific project, then the project needs to be designed and implemented so as to produce integration. Such a design creates a framework in which the products of individual science projects find a place.

As a minimum, a scientific program needs to include the following components and activities in order to facilitate and achieve integration:

- Relationships between research areas should be included in the program design itself.
- An ongoing commitment to a high level of communication between science projects, focussing on integration for the duration of the program.
- An ongoing engagement with the recipients of the program's results (resource managers and other stakeholders) to allow integration to be discussed and monitored.
- Responsibility for each integration activity or component should be clearly defined and included in the key performance indicators and milestone deliverables.

The MSE framework and tools, as described in this report, aim to produce integration of the TRaCK scientific program. Due to its relatively late start date within the overall TRaCK program, its benefits are less pronounced.

Integration of scientific results that were not explicitly designed to be integrated is likely to encounter some, or all, of the following problems:

— *Interactions*: as we connect more processes, the dimensionality of the underlying processes that create responses will rise. However, if not specified as part of the integration agenda, studying *interactions* between those underlying processes are not part of the individual research projects. Worse still, they are likely to be 'standardised' out of existence with the aim to reduce co-variants. Post-hoc integration is likely to fail (or results rendered trivial) as we cannot reconstruct these interactions afterwards. This is the core *methodological* reason for integration being discussed and ratified during program design phase.

- *Connectivity*: if no integration products are defined, individual science projects are likely to choose slightly different independent variables or response variables. For instance, one project may look at responses of fish to varying flow speeds whilst others may look at economics measures as a function of flow quantity. Unless there is an activity that relates flow speed to flow quantity (or vice versa) the results of these two projects cannot be connected. This is a *connectivity* reason to have strong internal communication between the projects

- *Expertise*: designing, implementing, testing, calibrating and validating a complex numerical model often requires experience and expertise that may not be available within the individual science projects. Sharing modelling expertise between the various science projects facilitates integration to a high degree as the resulting models are likely to be developed on software platforms that allow integration. It also prevents the same domain models being developed in different projects with slightly different results. The MSE *tools* development and implementation has both strong scientific and technical software development aspects. We found that the proportion of resources needed to develop a software environment that allows sufficient flexibility to be of use in natural resource management is quite easily under-estimated. In particular, the level of expertise needed for such a job and the scarcity of qualified people in a very tight (global) market is not to be ignored when designing and resourcing the actual integration project. The same argument goes for data management and software development. This is an *expertise*-based reason to organise integration at an early stage.

- *Technology*: if an integration process is not defined, individual projects are likely to develop models on different modelling platforms (different modelling programs, different operating systems etc.). In itself this is not a problem on its own, but when the time comes to reconcile these models within an environment that allows those models to interact in a controlled fashion, the technological hurdles become too complex to overcome. This is a *technology*-based reason to attempt to standardise the various approaches to allow integration on a technical level.

The integration project has learnt from experience that each of these factors are better prevented during the program development as they can be difficult to overcome once science projects are steaming ahead in their various directions.

8.1.2 ABOUT SCIENCE DELIVERY

The MSE *approach* may be looked upon as a way for natural resource management (NRM) organisations to manage their knowledge and information in support of their organisational processes such as resource planning and management program development. In addition, the MSE *approach* may also be regarded by NRM organisations as a framework to manage their science requirements.

Sharing such an approach between NRM organisations, stakeholders and a science program such as TRaCK will facilitate the discussion around what science products are expected and how to deliver them.

Such a shared framework and its derived tools can then function as a receptacle for scientific findings (often in the form of how a system functions or responds to external perturbations) and NRM knowledge (e.g. management objectives, accepted performance indicators, financial and legal constraints, feasible management actions, planning results). Integration with primary clients and stakeholders allows relevant science to be delivered directly into evidence-based management. The earlier this integration occurs within the development of the scientific program, the easier and more effective the science delivery. Another advantage of early integration for science program management is feedback (is the science working?) that would allow adaptations to be made to program focus and resources.

It is important to mention here that the integration objectives as per the brief of the Knowledge Integration and Science Development project (Project 1.4 within Theme 1 of TRaCK) pertains to only one level of integration needed for a program such as TRaCK. The Knowledge and Adoption Theme (Theme 7 of TRaCK) covers a wide range of complementary integration objectives and activities, including advice, communication products, interaction standards etc.

8.2 CONCLUDING REMARKS

Management strategy evaluation *approach* and *tools* have been developed with NRM knowledge integration and science delivery in mind. A collection of integrated models and prototype software tools have been developed and tested. The MSE tools allow us to turn some of the scientific knowledge developed by the TRaCK program into simulated results by applying various combinations of management actions and management decision rules. The models and tools developed to date demonstrate the strength and weaknesses of the implemented MSE approach.

TRaCK internal stakeholders were extensively consulted about the objectives and implementation of the Daly River catchment MSE prototype. The collaboration with TRaCK scientists about how to integrate their knowledge or models into the MSE application was a very instructive and positive experience. Early results of those collaborations show that the synthesis of these knowledge domains has produced interesting new insights.

External stakeholders, particularly water resource managers and advisors, were also consulted. Project 1.4 received encouraging feedback about the direction and early results of the MSE approach and tools. Combining the natural sciences knowledge domain with the natural resource management knowledge domain is proving to be very fruitful in the sense of opening up a new area for scientific exploration. This is in relation to how the sources of uncertainty that are (abundantly) present in highly connected and stochastically driven systems affect our ability to make decisions and the robustness of those decisions. Examining the effects of different management paradigms, such as adaptive management and reactive management, on costs and benefits is another area that is now opening up to more systematic assessment.

MSE for catchment natural resource management is in its early stages of development. The results of the work described in this report are of importance to resource management and scientists interested in synthesis alike. Early indications are that both knowledge domains are benefiting from the bridging function that an integrated approach can provide.

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APPENDIX A SCIENCE INTEGRATION WORKSHOPS

For the first phase of Project 1.4 two main stakeholder groups were identified for the Daly Catchment: the NT's department for Natural Resources, Environment, The Arts and Sport (NRETAS) and the Daly River Management Advisory Committee (DRMAC).

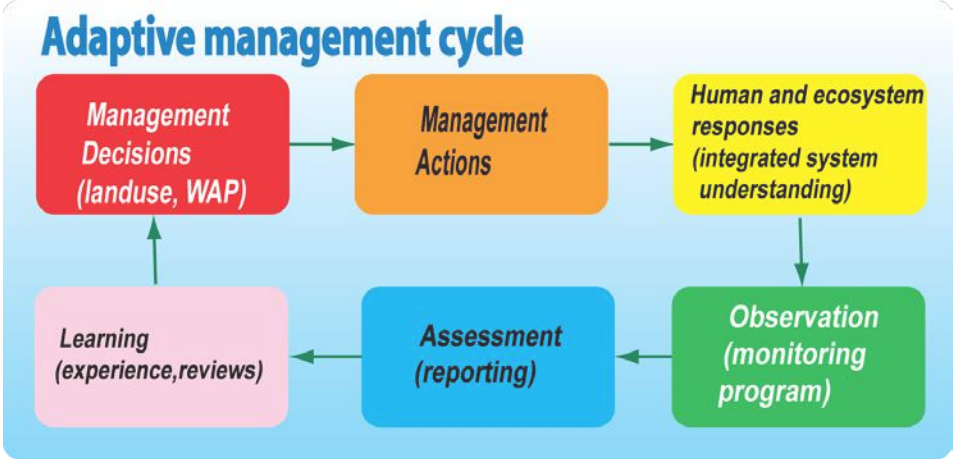


Figure A-1 Management Strategy Evaluation (MSE) is based on the notion of adaptive management. It includes activities from the science and resource management domains. As such, it forms a broad integration framework.

Over the period June – October 2009, P1.4 Staff organised four presentations/workshops with NRETAS Staff. These meetings were to introduce NRETAS Staff to the MSE conceptual framework and MSE software prototype. The MSE prototype software also allowed discussing the data that was collated for the Daly River.

During a more general feedback meeting between NRETAS and TRaCK staff in December 2009 a range of issues were identified and paired with knowledge areas within TRaCK. Pertinent to P1.4 and MSE were the expectations that the MSE framework and software tools would be helpful in (i) the areas of research planning, (ii) the development of monitoring plans to assess river health, (iii) the Living Rivers program, and (iv) adaptive management: how to ensure action when there is a negative response in the river system.

In February 2010, TRaCK P1.4 presented an introduction to MSE concepts to the DRMAC. A follow-up meeting is being planned to demonstrate the MSE prototype software and to seek feedback regarding direction and content of Project 1.4 in the next couple of months.

Results: the interactions (presentations and discussions) with NRETAS Staff have resulted in a good working relationship, a better understanding of the issues where the integrated MSE approach is expected to help. It forms the basis of delivering integrated management option evaluation capability into NT resource management. Project 1.4 sees this relationship as a very important basis for the development of the prototype MSE for the Daly River.

A.1 INTERNAL STAKEHOLDERS MEETINGS AND WORKSHOPS

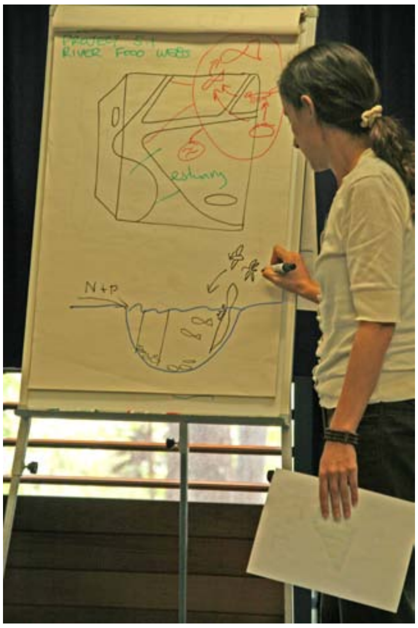


Figure A-2 A conceptual diagram is a creative tool to convey the main objective of a project to non-specialists.

During the Consortium meeting April 2009, TRaCK staff organised the first integration workshop. The half-day workshop was well attended by over 20 TRaCK scientists, mainly project leaders.

This workshop had two main objectives:

- start the discussion between TRaCK scientists about the knowledge developed within their individual projects and how it interrelates.
- identify potential knowledge and links to be incorporated as models into the MSE software.

To that purpose, we asked the various project leaders to construct and discuss a conceptual diagram of their work. The results were varied and reflected the different levels of conceptualisation between the projects. The discussions around each of the projects' conceptual diagram was perceived to be very informative and feedback from the participants was often expressed in terms of surprise about the width of research within TRaCK and the relevance of many of the projects to their own project.

Constructing the conceptual diagrams was a first step in identifying the potential for integration between projects. The second step was to construct a diagram that allowed us to identify the relationships between projects, the interaction matrix .

After the presentation of the work of various projects using conceptual diagrams, the participants were asked which projects would have relevant information for their project. Such inputs were marked with a red tick mark in the matrix in Figure A-3.

	P1.2	P1.3	P2.1	P2.2	P3.1	P3.2	P3.3	P4.1	P4.2	P4.3	P4.4	P5.1	P5.2	P5.3	P5.4	P5.5	P5.6	P5.7	P5.8	P6
P1.2																				
P1.3			✓															✓		
P2.1																				
P2.2	✔				✓							✓	✓	✓		✓		✓	✓	
P3.1			✔			✓												✓	✓	
P3.2												✓	✓	✓		✓		✓	✓	
P3.3				✔	✔	✔			✓			✓	✓	✓	✓	✓	✓	✓	✓	
P4.1										✓	✓		✓	✓		✓		✓		
P4.2				✔							✓		✓	✓	✓			✓		✓
P4.3				✔					✔		✓	✓	✓		✓					
P4.4	✔			✔					✔	✔			✓	✓				✓		
P5.1			✔	✔						✔			✓	✓		✓	✓	✓	✓	✓
P5.2	✔			✔				✔	✔	✔		✔			✓	✓		✓	✓	
P5.3	✔			✔				✔	✔	✔		✔			✓	✓	✓	✓	✓	
P5.4									✔				✔	✔			✓	✓	✓	✓
P5.5	✔		✔	✔								✔	✔					✓	✓	✓
P5.6	✔			✔									✔	✔		✔		✓	✓	
P5.7																				
P5.8	✔											✔	✔	✔	✔	✔		✔		✓
P6				✔																

Figure A-3 The TRaCK projects interaction matrix presents the potential links between projects as identified by TRaCK scientists. A ✔ indicates that a project in the left column potentially has information that would feed into a project on the top row of the spreadsheet, e.g. P2.2 supplies info to P1.2. A ✓ indicates that a project in the left column potentially would be helped with information from a project on the top row of the spreadsheet, e.g. P2.2 could use info from P2.1.

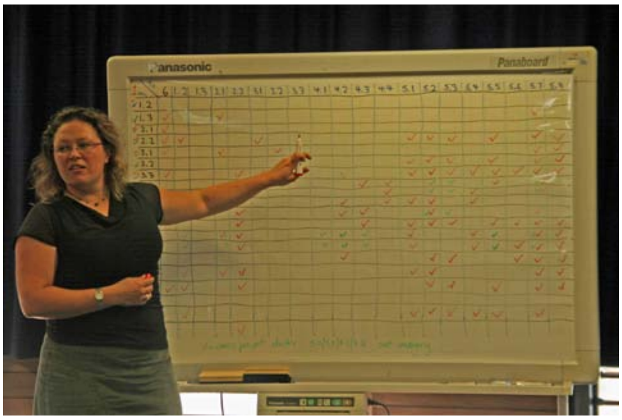


Figure A-4 Dr Dan Warfe keeps track of the many potential interactions between the TRaCK projects.

Subsequently, the participants were asked to identify the projects for which their own project would have relevant information. These were marked with a blue tick mark in the matrix in Figure A-3.

Analysing the interaction matrix we also produced a first classification of the projects based on their relative number of potential input and output links as shown in Figure A-5. For instance, if a project has mainly output links, it was classified as a provider. Even though providers are crucial to the success of the program, they would be less central to integration. Transformers are projects with multiple inputs and outputs. Integration of these projects would be a high priority to realise TRaCK's full potential.

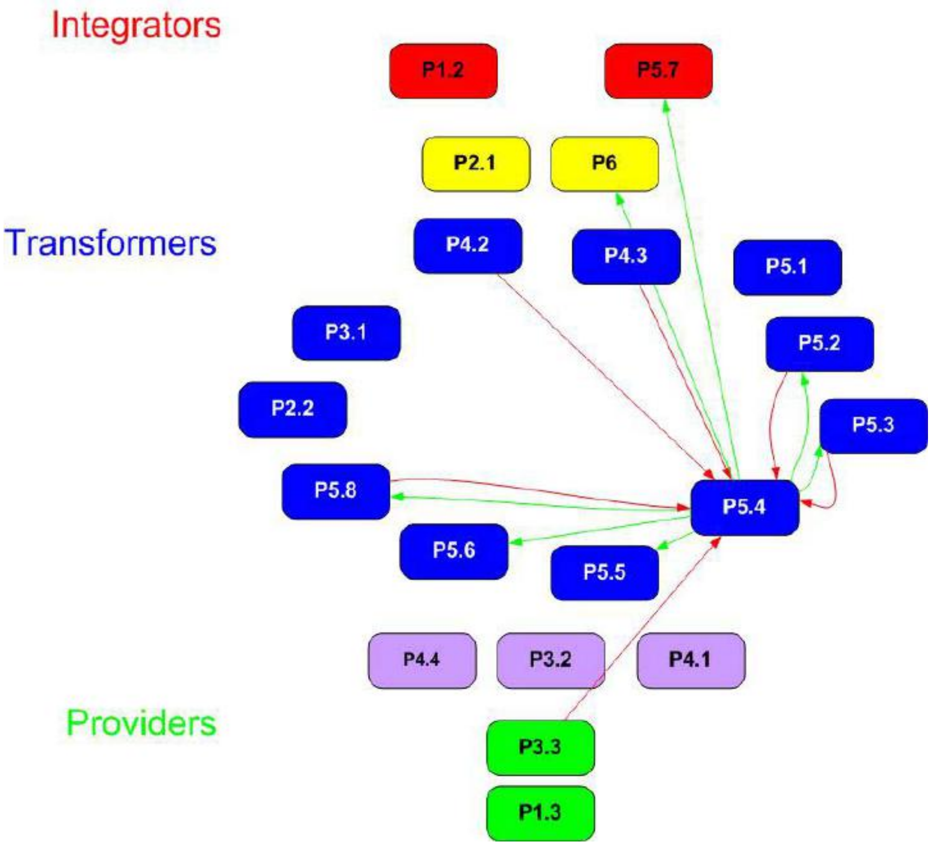


Figure A-5 Classifying TRaCK projects based on their links with other projects, makes their potential (and need) for integration clear. The purple and yellow projects could not be clearly classified in any of the three groups and were positioned on our knowledge of the projects.

Results: The results of this first workshop on TRaCK cross-program integration was a better understanding between projects of the work that was being undertaken within the TRaCK program and the realisation that the potential for integration between projects was very high.

The TRaCK internal stakeholder workshop has helped to lay the foundation for cross-TRaCK integration. It also introduced the notion of MSE as a framework to integrate between science and resource management domains and to integrate knowledge developed across the TRaCK program. The workshop allows us to start an inventory of the considerable potential for integration within a applied science program such as TRaCK and also to learn from the challenges associate with integration.

A.2 TRACK MODEL WORKSHOPS AND MODEL INTEGRATION PLAN

The Integration workshop at the Consortium meeting in April 2009 was the first step in identifying broad areas of potential integration. The second step was to arrange a series of 'science-domain' workshops: hydrology/water budgets, ecology and socio-economics. These workshops were organised between December 2009 and March 2010.

The objective of these workshops was to clarify what knowledge was expected to be delivered in each of the domains, how it could be modelled and how it could be integrated into the MSE software system. This would form the basis of a model integration plan to be presented to the REC for approval.

Status of the objective: The objective to collect information to deliver a model integration plan has been met.

A.2.1 WATER BUDGETS (FLOWS) WORKSHOP

The flows workshop (Darwin, December 01, 2009) was attended by Cathie Barton, Richard Weinmann, Renee Bartolo, Des Yin Foo, Ian Webster, Hmalan Hunter-Xenie, Jon Olley, Paul Rustomji, Peter Cook and Francis Pantus.

Objective: The Flows workshop aims to make an inventory of what knowledge and data TRaCK projects have that can be used as a basis for the MSE response models describing the fate of water and constituents in a tropical catchment, focussing on the Daly River catchment.

To set the scene: hydro-models (turn rain into flow) and transport models (transporting constituents such as sediments and nutrients) are perceived to form the backbone around which most of the TRaCK knowledge centres e.g. aquatic ecology, the socio-economics of water resources. It is therefore of the utmost importance to capture the dynamic behaviour of water and its constituents in the catchment.

Water budgets keep track of water as it rains down on the catchment. Some of it will run off as surface water, some of it will be stored in underground basins and re-appear through springs, but most (around 90%) of the water in catchments such as the Daly will evaporate.

During the dry season, about eight months per year, no rain falls but large parts of the Daly River still flow thanks to its groundwater inputs. Work in Theme 5 indicates that the ecosystem would look considerably different if these dry-season flows would disappear.

The development of current agri-business (e.g. fruit orchards) in the catchment can only be sustained if groundwater is being used to irrigate the crops.

These potentially competing water needs (e.g. river ecological health and human use) are a clear example of how important our understanding of water budgets is to manage the water resources in this region. The TRaCK Partners recognised the importance of knowledge of water and constituents dynamics during its formation and built a scientific program to extend that knowledge. Most of the scientific projects are in their final phase and their expected deliverables, as far as relevant to the MSE integration program, were discussed during the workshop.

To summarise the currently expected products:

Project 4.1 deliverables concentrate on collecting information to help estimate parameters describing soil moisture content and evapo-transpiration. APSIM/SWIMV2 is a model that simulates a water budget at one location (point scale model) and it is not clear how to scale this up to the whole catchment.

Project 4.2 : Dr. Paul Rustomji has developed a sediment transport model for the Daly catchment based on SedNet using the measurements at 10 flow gauging stations and results of sediment tracing experiments.

NRETAS models: combined FEFLOW (groundwater model, incl Oolloo and Tindall) and MIKE11 (surface water) model for the Daly catchment. The model returns reasonable numbers but is slow, more than one day per simulation.

Project 5.3 and 1.4 Dr Doug Ward and Renee Bartolo: A floodplain inundation model is being developed for 'wettest wet' and 'driest dry' years. Vegetation and fire maps excepted around April 2010.

Project 4.3: Hydrodynamics modelling: Dr. Ian Webster CSIRO-L&W. The modelling was based on the Hydrologic Engineering Centers River Analysis System (HEC-RAS) software. The hydrodynamics model provides a transport framework (water depths and flow speeds) along the main channel. This allows the development of simulation models for biogeochemical modelling of nutrients, phytoplankton, & photosynthesis analysis, nutrient uptake and light availability. The hydrodynamics model is being used to model plant biomass and production.

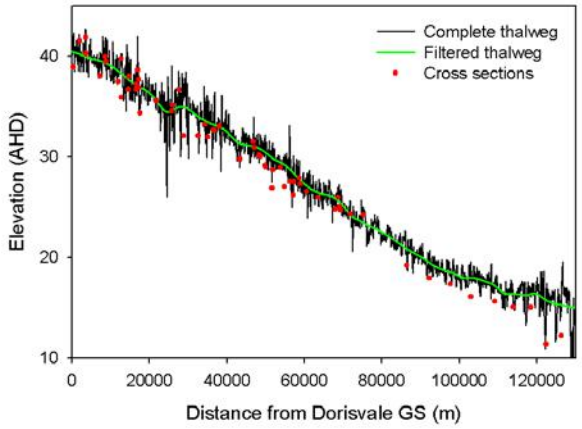


Figure A-6 River profile of a 120 km stretch of the Daly River, modelled and measured

Dr. Ian Webster, CSIRO L&W.

Results of the flows workshop in terms of P1.4 needs: At this stage it seems unlikely that a catchment-wide hydrodynamics model for the Daly River that could be used as a basis for the MSE response models will be readily available though the TRaCK program. The models discussed either do not cover the catchment, are to slow (or too expensive) to be part of a management options evaluation system or cannot be used within an adaptive scheme (software technical issue). P1.4 is looking at options to resolve this issue at least for its MSE prototype development which relies on having some flow dynamics that respond to rain and management actions.

Parts of the ongoing TRaCK hydro work have the potential to simplify the task of configuring a simple catchment (placeholder) model which is already under construction within P1.4.

Such information would include:

- ET values (P4.1),
- soil moisture estimates (P4.1),
- sediment transport parameters (SedNet)
- information on travel time and storage (NRETAS FEFLow/MIKE11)
- surface water and groundwater discharges to help calibrate the MSE placeholder hydrodynamics model
- flow speeds and water depth as function of discharge (P4.3)

The primary process models would be helpful to extract relationships between ecological processes and hydrology.

A.2.2 AQUATIC ECOLOGY WORKSHOP

The aquatic ecology workshop (Brisbane, December 8 - 9, 2009) was attended by: Dan Warfe, Pete Bayliss, Neil Pettit, Mark Kennard, Brad Pusey, Michele Burford, Michael Douglas, Barbara Robson, Ian Halliday, Doug Ward and Francis Pantus,.

The objective of the workshop was to chart the key biological and ecological (interaction between biology and physics) processes and identify opportunities to model these processes as part of the suite of MSE response models.

Setting the scene: the physical forces that shape the catchment change dramatically between the dry (June-September) and the wet (February-March) season. The biology of the catchment's waterways and floodplains is largely driven by four elements: amount of water in the landscape, fire, light in the water column and nutrient availability as indicated in Figure A-7.

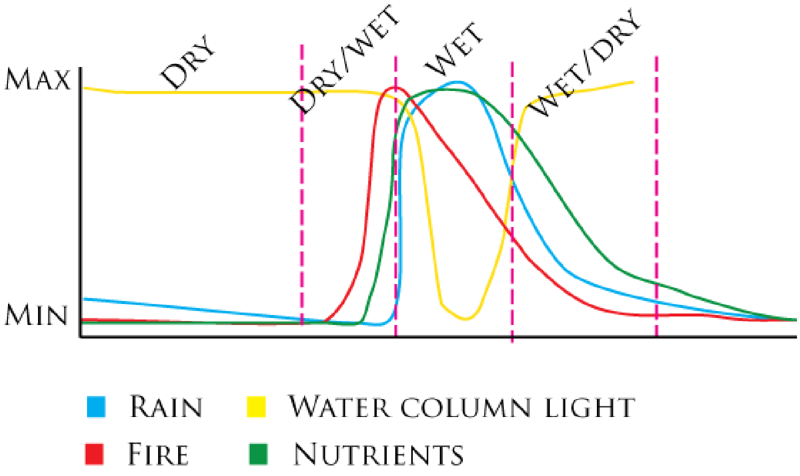


Figure A-7 Four elements strongly influence the biotic activity in the Daly catchment: water, fire, nutrients and light.

However, these forces affect the biological components differently depending on the ecological domain (e.g. tributaries/catchment, floodplain, and estuary). To make an inventory of these different effects, the participants were asked to discuss the differences between 12 discrete food-web models (three spatial domains, four temporal domains). A diagram of the discrete spatio-temporal domains is shown in Figure A-8.

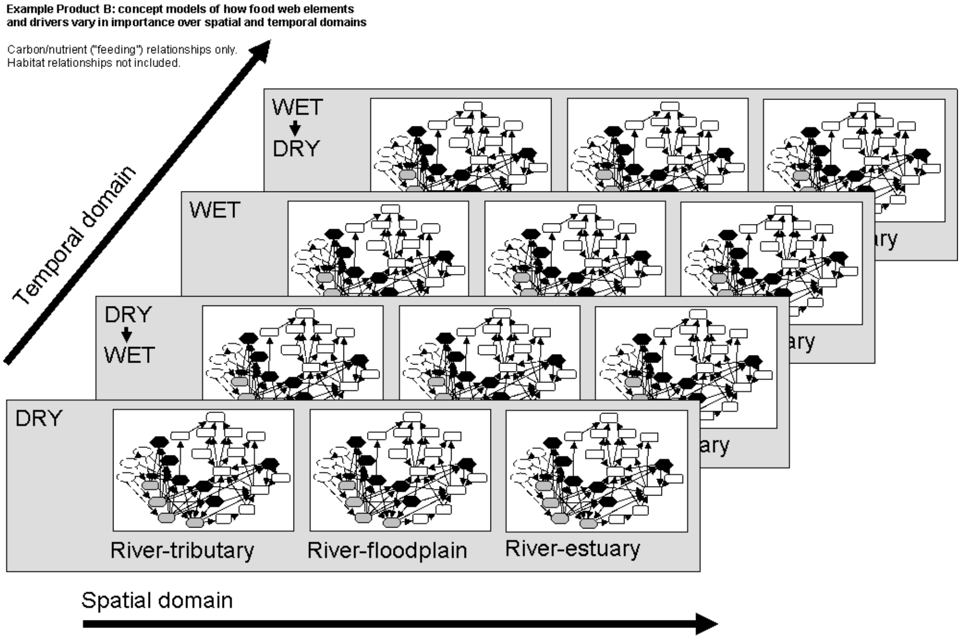


Figure A-8 Dealing with the spatial and temporal domains allows us to take snapshots (graphics: Dr. Dan Warfe)

An example of results from these discussions of food-web changes as for different tropical seasons and spatial domains is shown in Figure A-9.

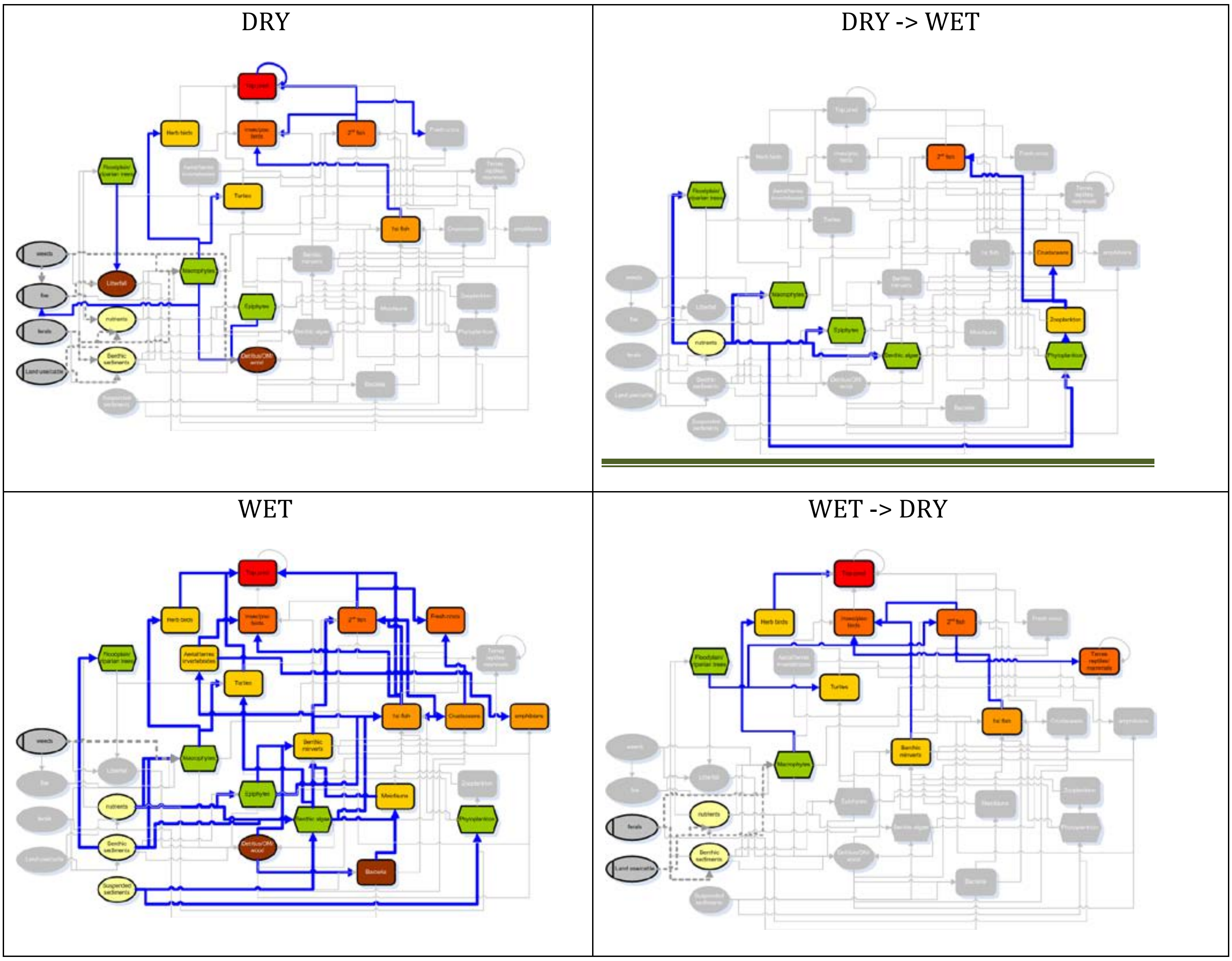


Figure A-9 Examples of conceptual models of food-webs in a generalized tropical floodplain. These models resulted from discussions between workshop participants (graphics by Dr. Dan Warfe, CDU).

The results of this work gave us a good top-down view of what are drivers and key processes within a generalised tropical catchment. Potentially this information could be captured using food-web interaction models such as Ecosim. However, at this stage there is insufficient information for the Daly River catchment to support the implementation and calibration of such models available.

During the workshop we also discussed the activities of other projects relevant to the MSE response models. Here follows a short summary:

Project 4.3: Materials Budgets, Modelling plant biomass and production, Dr Barbara Robson, CSIRO L&W.

The model is based on a 2D hydrodynamic model of a 100-km stretch of the river, developed at CDU. Using this, along with our water quality and flow data and habitat maps for 2008, a habitat model was produced describing approximately 60 habitat types defined by sediment type, depth and velocity response to flow variations (Figure A-10). This forms the basis of a biomass model that tracks changes in biomass of five plant and algae groups over time, as plants establish themselves in the river over the course of the dry season and are washed away by higher flows in the wet season.

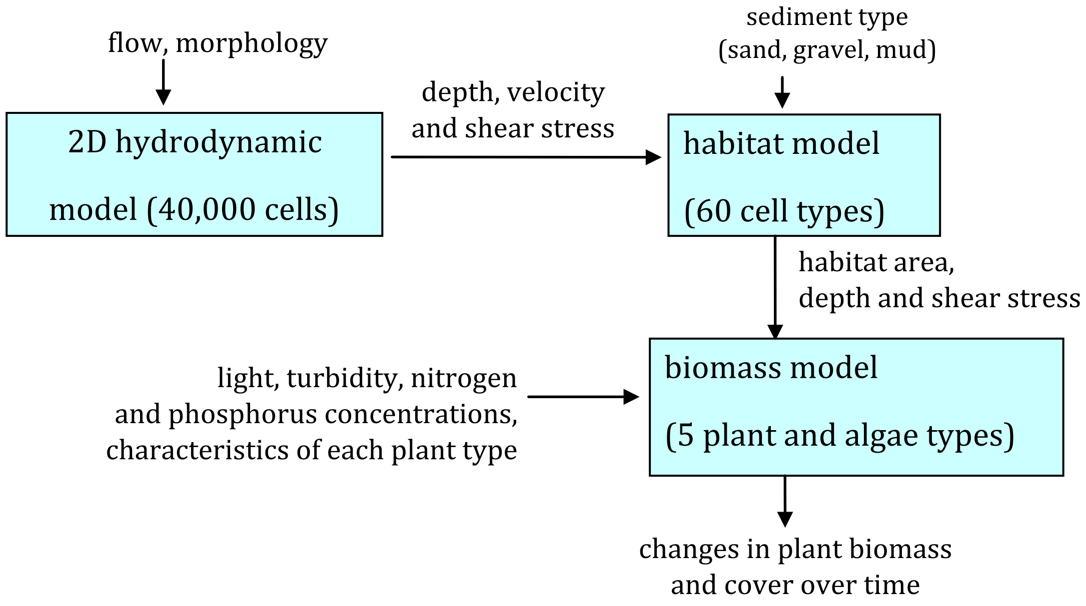


Figure A-10 **Diagram representing the benthic algae and water plants model developed by Dr Barbara Robson, CSIRO.**

Project 5.5: Daly River Fish & Flows Project, Dr Mark Kennard et al.: Risk assessment.

Using NRETAS extraction scenarios and models as boundary inputs for high-resolution models of Daly reaches, the relative risk that groundwater extraction poses to about 40 species was assessed. Figure A-11 gives an overview of what models and data were used for the risk assessment. Discharge rating curves (habitat descriptors as a function of discharge) were derived for Galloping Jacks in the Katherine River.

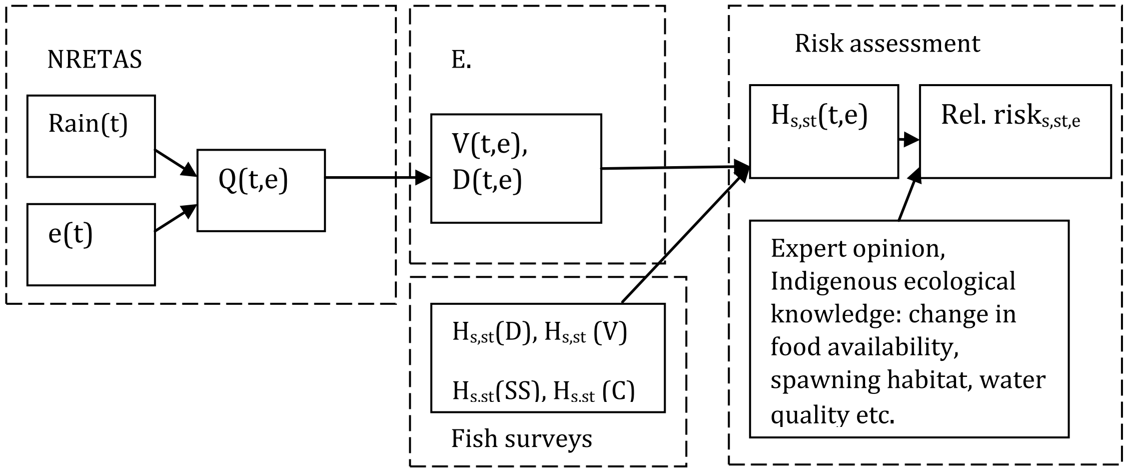


Figure A-11 **Schematic view of relative risk assessment under water extraction scenarios (Chan et al., 2011). Symbols used: e = extraction, Q = discharge, V = flow velocity, D = water depth, H = habitat availability, SS = substrate, C = cover, s = species, st = life stage, t = time.**

Project 5.5: Daly River Fish & Flows Project, Dr Mark Kennard, A/Prof Michael Douglas et al.: Fish distributions and Bayesian Believe Networks.

The Bayesian Believe Models developed for the Daly river estimate the abundance of a fish species based on dry season flow under various groundwater extraction scenarios. They are based on three sources of information: (i) estimates of the available water (depth, speed, and duration) given groundwater extraction, (ii) habitat suitability information transforming estimated available water into expected available habitat and (iii) expert knowledge to tie together these information sources and add 'best available ecological knowledge' to turn flows into abundance estimates using a Bayesian framework as shown in Figure A-12.

The water availability was estimated using NRETAS MIKESHE/FEFLOW model results for three groundwater extraction scenarios. The water availability over time is turned into % area of available suitable habitat for juvenile and adult fish over time using a high-resolution MIKE11 model (Dr. E. Valentine, CDU) model estimating water depth and velocity. Fish surveys allowed the construction of habitat suitability curves (habitat index vs depth, habitat index vs velocity).

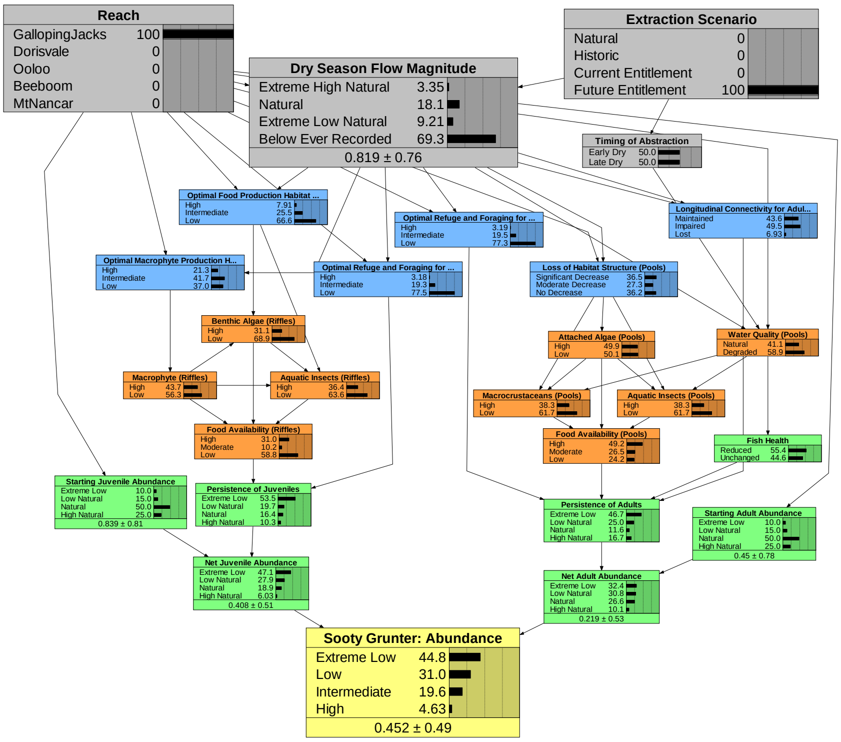


Figure A-12 The Bayesian models developed for the Daly River Catchment estimate the abundance of a fish species based on dry season flow under various groundwater extraction scenarios. This diagram shows the results for the Sooty Grunter if the water entitlements were to be fully used (graphic: Dr Mark Kennard)

Project 5.2: Commercial and recreational barramundi CPUE: Dr Ian Halliday and Dr Peter Bayliss. The barramundi CPUE data, surveyed from different sources (Classic fishing tournament, tour boats and commercial operators) was related to the river flows. The regression equation is . $\log_{10}(CPUE) \propto \log_{10}(Flow_{WetSeason})$ and the regression results can be found in Table F-3. The $Flow_{WetSeason}$ is the accumulated daily flow over the Sept-Aug period.

Table A-1 Results of regressing log(CPUE) onto log(Flow) (Dr Peter Bayliss).

Source	Intercept	RC	N	R^2	P
Classic	-1.47	0.27	18	0.51	<0.001
Tour boats	-0.88	0.15	18	0.43	<0.01
Commercial	- 0.33	0.22	23	0.28	<0.006

Project 5.2: Floodplain health and Magpie geese: Dr Peter Bayliss. Similar work to the Barramundi relationship with seasonal flow has been done for Magpie Geese on the floodplain.

Results: the models that have high potential to be included in the first round of MSE modelling (simple, direct relationships with flows) are the barramundi CPUE vs seasonal flow models (Bayliss et al.) and possibly the magpie geese models. The barra models are of importance as they potentially link the river flow to the aboriginal food substitution and household economy models (Dr Sue Jackson).

The fish species models(Bayesian) risk assessment models (Chan et al., 2011) depend on high-resolution hydro-modelling and we're examining how we could included these models into the MSE framework as well. Extrapolating discharge curve information may be from Galloping Jack to a broader reach of the Daly channel may be one way to tackle this problem.

A.2.3 SOCIO-ECONOMICS WORKSHOP

The socio-economics (SE) workshop (Darwin, March 17 - 18, 2009) was attended by Sue Jackson, Natalie Stoeckl, Hmalan Hunter-Xenie, Anna Straton, John McKenzie, Jon Altman, Michael Douglas, Michael Storrs, Owen Stanley, Silva Larson and Francis Pantus.

The objective of the workshop was to identify and prioritise candidate models for implementation in the MSE prototype software.

The first step to identify and prioritise was to create a simple framework for SE that could be used as a guideline to identify work done within TRaCK in the SE domain. The six components as shown in Table F-3 are a subset of the assessment framework for tropical river systems as described by Larson, S. and Alexandridis, K. (2009). Table F-3 also points to TRaCK projects that are engaged with developing knowledge with regards of those performance measures.

Table A-2 To perform an quick-scan exploration of the socio-economic knowledge domain within TRaCK, a table of socio-economic components and example performance measures for each of them was constructed. The P-numbers indicate the projects that may have collected information on these performance measures. Question marks indicate knowledge gaps.

Performance Measures	Socio-economic Components					
	Demography and people	**Economics**	**Environmental**	**Values**	**Institutional arrangements**	**Infra-structure**
	#People P3.1a	Income distribution P3.1b	Land use ??	Cultural values P1.2, P2.1, P2.2, P6	Participation/ legal compliance P1.3, P1.2, P6, agent-base model Stratton et al.	Australian Census 2006 (AS) Built-up areas
	Rate of change P3.1a	Expenditure distrib. P2.2	Water quality, quantity, availability	Cultural identity P2.2 (abor)	Customary law ??	Roads (AS)
	Net migration P3.1a	Gross regional prod.	Areas of high risk	Water use and values for industry, government, business	Formal/ informal institutions P6	Airstrips (AS)
	Settlement P3.1a	Diversity of industries P3.1b, P6.2	Consumptive water use P6.2??	Individual values, P??, Taylor et al. forthcoming	Distrib of property rights P6.2	Telecom and access to telecom (AS)
	Life expectation P6	Unemployment rate P3.1	Aborigine-consumptive water use	Community use of water P3.1	Incentive schemes P6.3/4/5	Schools (AS)
	Education level P6		Areas of high value P2.2 (where, what, why), Change stories P1.2, P6	Non-residents proportion P2.1, small sample size		Medical (AS)
	% Native English speakers P6					Fences (AS)
						Bores and dams (AS)

After having created some overview of SE work done within TRaCK, the second step was to map those knowledge areas and explore their relationships. The results are shown in Figure A-13.

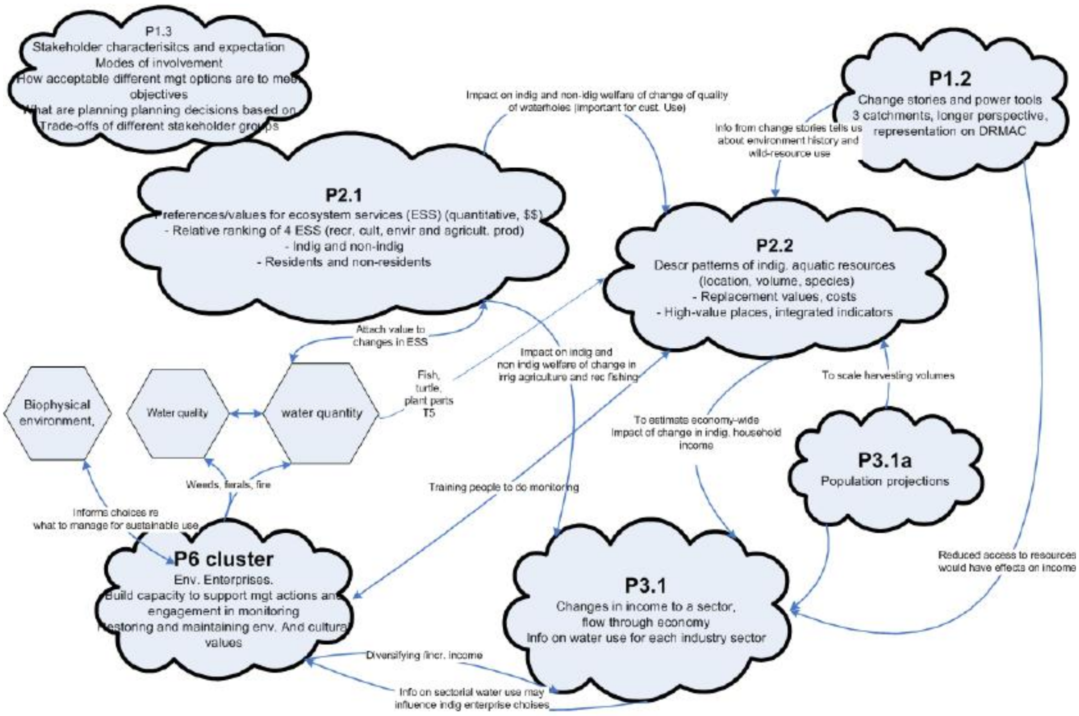


Figure A-13 A map of the main TRaCK socio-economic knowledge domains (clouds) and their mutual relationships and relationships with other knowledge domains (hexagonal boxes).

During the final step we discussed which knowledge domains would be most suitable to be converted into models to form a part of the Daly prototype MSE. The criteria for this choice were (i) relevance of a knowledge domain to the Daly River catchment, (ii) ease of converting a particular SE domain into numerical models, and (iii) clear connections with the flows and/or ecology domains to allow the dependencies to be made explicit.

Results: the two models selected by the workshop participants were the patterns of aboriginal use of aquatic resources and their replacement costs (P2.2, Dr Sue Jackson) and the subsequent impact of this resource use on the broader NT economy (P3.1 Dr Natalie Stoeckl).

A.2.4 MODEL INTEGRATION PLAN

The model integration plan describes the components of the response models within the MSE framework. Based on the results of the three workshops, Figure A-14 shows the candidate models that are currently considered for inclusion based on the three P1.4 internal workshops. This is by no means a definitive set of models and as more information may come available over the next months the model implementation plan may change considerably.

The MSE response model represents our knowledge of the system we try to understand and manage. The diagram in Figure A-14 shows candidate models that are presently under consideration to be included in the MSE prototype. For the demonstration of the MSE framework and principles, it is important to include representatives of the main TRaCK knowledge domains hydrodynamics, ecology and socio-economics. For the practical application of a *future* Daly River MSE system, adding environmental hazards would also have high priority.

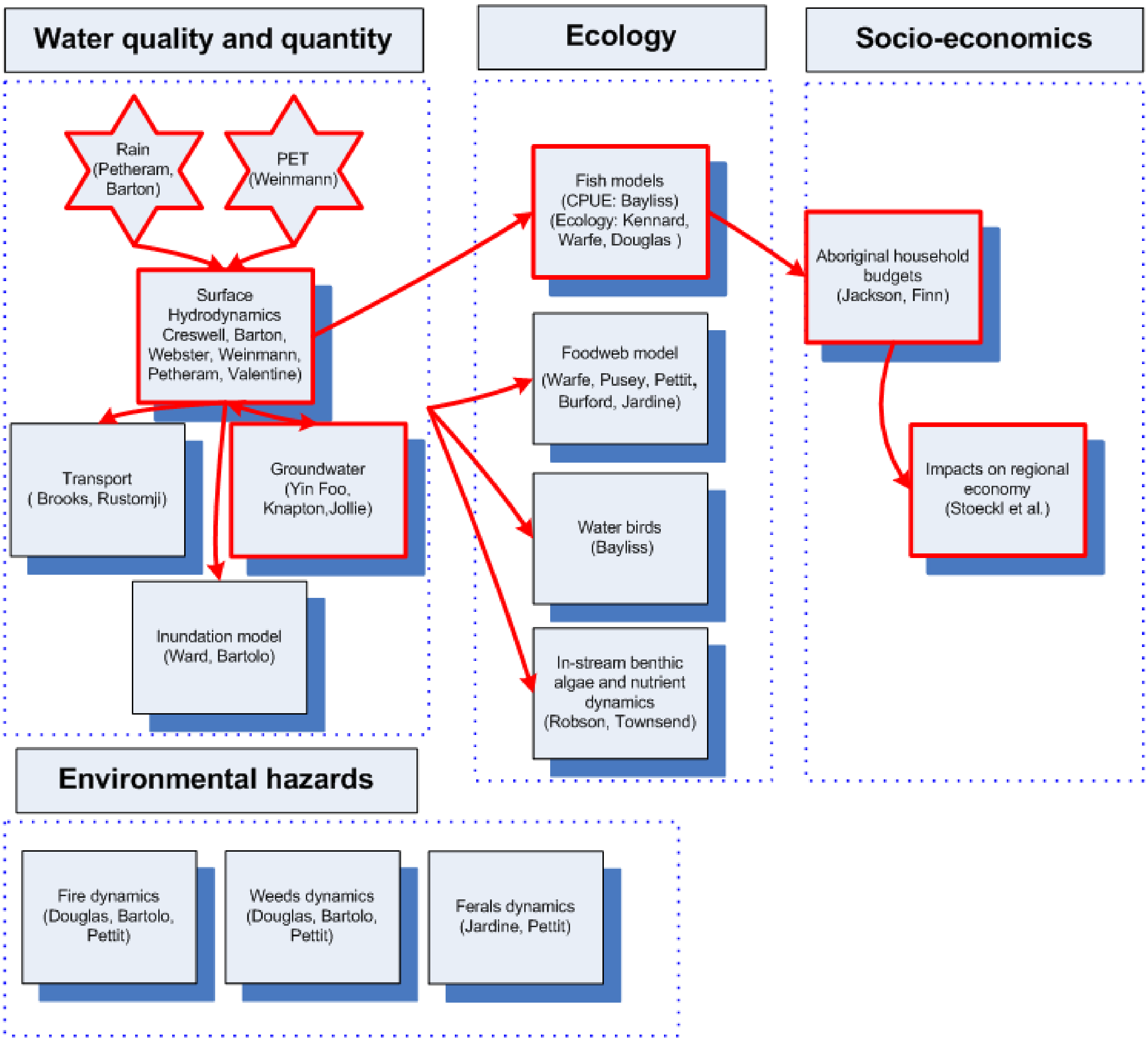


Figure A-14 The MSE response model represents our knowledge of the system we try to understand and manage. This diagram represents candidate models (and their connections) that are presently under consideration to be included in the MSE prototype. The red outlines signify high-priority models.

Figure A-14 gives a broad overview of the results of the three workshop discussions. The names are indicative only. The star-shaped boxes represent external drivers and the square boxes represent models that have the highest priority to be implemented.

Surface and groundwater dynamics, priority 1: central to the Daly River catchment prototype MSE is our knowledge regarding water dynamics.

In absence of a readily usable model, Project 1.4 implemented a 'placeholder' hydrodynamics model to simulate some dynamics to demonstrate the workings of a MSE in the Daly River catchment. The Daly River dry season flows depend heavily on the groundwater-fed flows, and aquatic ecosystems are found to be sensitive to these dry-weather flows. This implies that simulation models for groundwater are also needed to connect with the aquatic ecosystem knowledge domains within TRaCK. If groundwater is represented in the response models, important management levers such as the planned water allocation measures can be evaluated.

Transport and inundation, priority 2: the transport of sediment and nutrients, especially during the wet season, may be especially important to the receiving environment: the estuaries and coastal floodplains. Management actions changing the land-use of significant areas of land may influence the availability and transport of nutrients and sediments. Without mechanisms to simulate these changes, land-use based management actions would not be effectively represented in the MSE. The dynamics of floodplain inundation, combined with transport models, would allow the connection between weather events and floodplain biology to be made explicit. Especially for ecological implications of climate change scenarios, these connections would be important.

Ecology/ biology, priority 1: the model most ready to be implemented and linked to the hydrodynamics is the barramundi catch per unit effort (CPUE) model. The Barramundi CPUE as a measure of abundance would also (at least conceptually) link the socio-economics domain with the hydrodynamics through the use of barramundi as a aboriginal households subsistence fishery.

Socio-economics, priority 1: Aboriginal household budgets may be subsidised by the use of subsistent fishing e.g. barramundi. Changes in fish abundance may affect the aboriginal household budgets and through. The effects of shifts in the use of aboriginal household budgets may also have effects on the wider economy. Adding models to estimate the effect of barramundi abundance on indigenous household budgets and their effects on regional economy are seen as a high priority task.

APPENDIX B MSE SOFTWARE DESCRIPTION

The activities of software design, development, implementation and testing are central to Project 1.4 in order to realise the concepts of the MSE, integrate models and deliver flexible scenario evaluation capability.

This Appendix is dedicated to describing the MSE application software in detail. It relies on a combination of standardised software design diagrams drawn from the Unified Modelling Language (OMG, 2010), and where appropriate, free-form diagrams. For key UML diagrams, legends have been provided to aid readers in understanding the 'gist' of these diagrams without first needing familiarity with the UML standard. To aid in this, UML notes (rectangles with the top-right corner "folded over") appear where necessary to describe concepts in natural language.

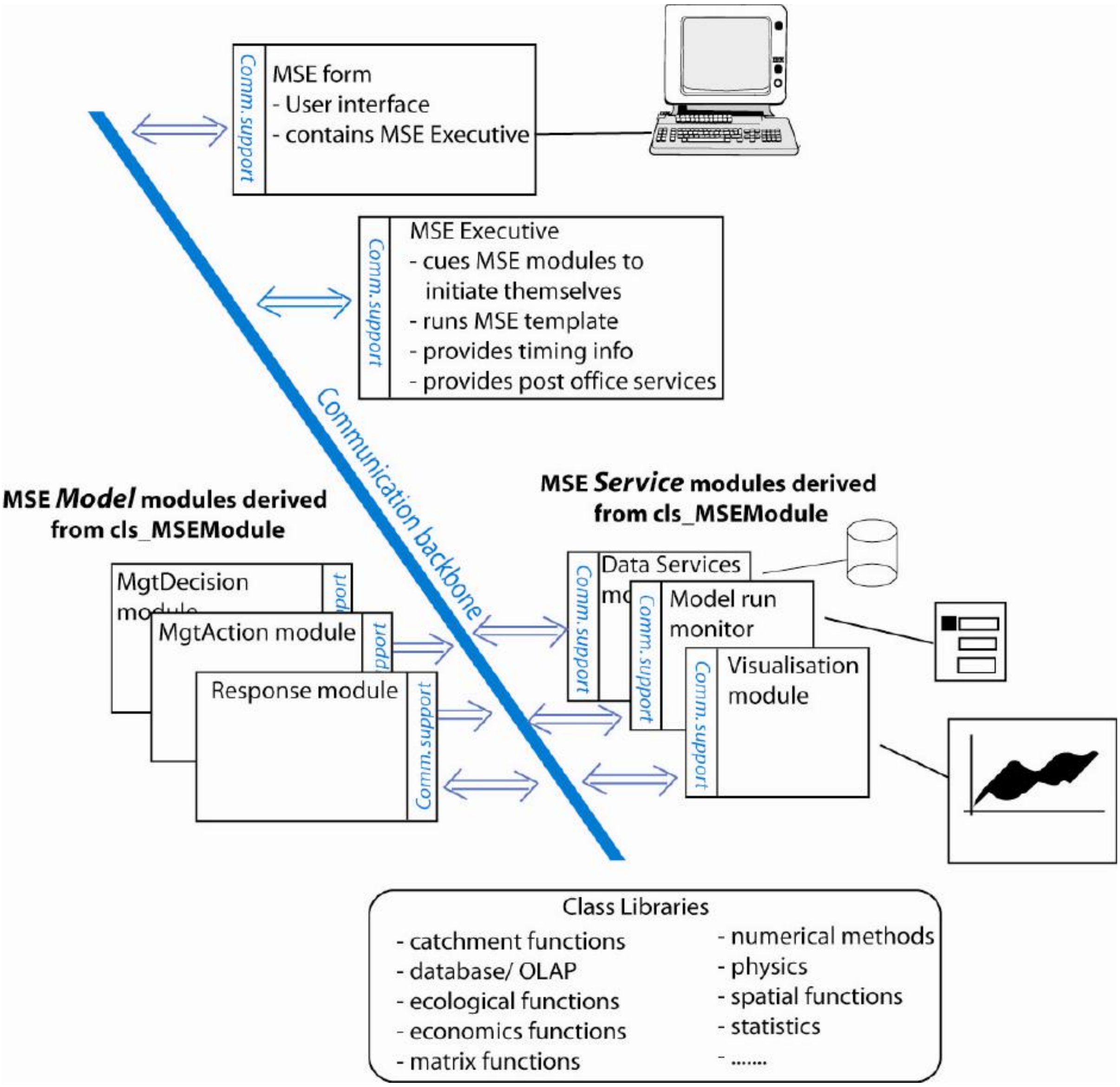


Figure B-1 The MSE Application Software Architecture

Figure B-1 is a diagram showing the overall software architecture of the MSE system. Forms (user screens), and two types of modules (*service* and *model*) all interact via a communication backbone. The *MSEExecutive* supplies special-purpose communications support to allow the other parts of the system to make effective use of the communications backbone. These various parts are constructed from of a number of 'foundational' class libraries.

The architecture itself places heavy emphasis on flexibility. The communication backbone allows a 'plug-and-play' approach combining a range of models, implemented in software modules, into management scenarios. The basis of the 'plug-and-play' architecture is a set of standards that allow models to communicate with each other. Together with the ability to run models on the fly, this delivers the required flexibility. 'On the fly' here means that the choice of which model to run is not hard-coded in the software but specified in a database. By changing the settings in database we change the outcome of the scenario.

The final form of the architecture depicted in Figure B-1 is by no means accidental. The architecture has come about through the application of a software development philosophy expressed as a number of guidelines, which are discussed below.

B.1 SOFTWARE DEVELOPMENT PHILOSOPHY

Sufficiently complex software applications adopt guidelines for their design, extension and maintenance. These guidelines must often balance the force of broadly catering to the breadth of activities the software must perform against the competing force of restricting the possible range of activities to ensure a consistent application that is easily extendable and maintainable. Failure to adopt and enforce guidelines can often result in a software application disparagingly nicknamed a "big ball of mud"(Brown et al., 1998).

As MSE systems tend to be deployed in naturally complex domains, we manage this complexity by adopting a set of guidelines to help with consistent design and implementation. The guidelines adopted are listed below:

- Apply a top-down approach to architecture and design
- Ensure a layered architecture (with MSE core functions and support via specialised utilities)
- Deploy a Component-Oriented Architecture (for functional delegation and autonomous modules)
- Maximise Application Flexibility (Runtime and Specification Flexibility)
- Implement Iteratively (width-first, thin-layer implementation)
- Where Possible "Buy, don't Build"
- Keep options open with respect to web-based user interfaces and distributed computing

Each of these guidelines is discussed in more detail in the following Sections, describing the fit of the MSE application to each guideline.

B.2 TOP-DOWN APPROACH TO ARCHITECTURE AND DESIGN

Taking a top-down approach to architecture and design means to start at a high level of abstraction and iteratively decomposing abstract concepts into progressively more detailed levels of functionality until we arrive at a level of executable software. We take as our starting point for this top-down decomposition, the MSE conceptual model described in Section 2.2.

The practical consequences of this guideline are that a considerable amount of time during the initial design was devoted to discussing overall project deliverables and trialling various aspects of MSE phasing, software modules, interface standards, all within the general framework laid down by the MSE conceptual model.

At the highest level of application abstraction, key system-level objects are defined, and act to guide further functionality that must operate on those objects. Figure B-2 identifies the key system-level objects of the MSE application, and their relationship to each-other via a UML Class Diagram.

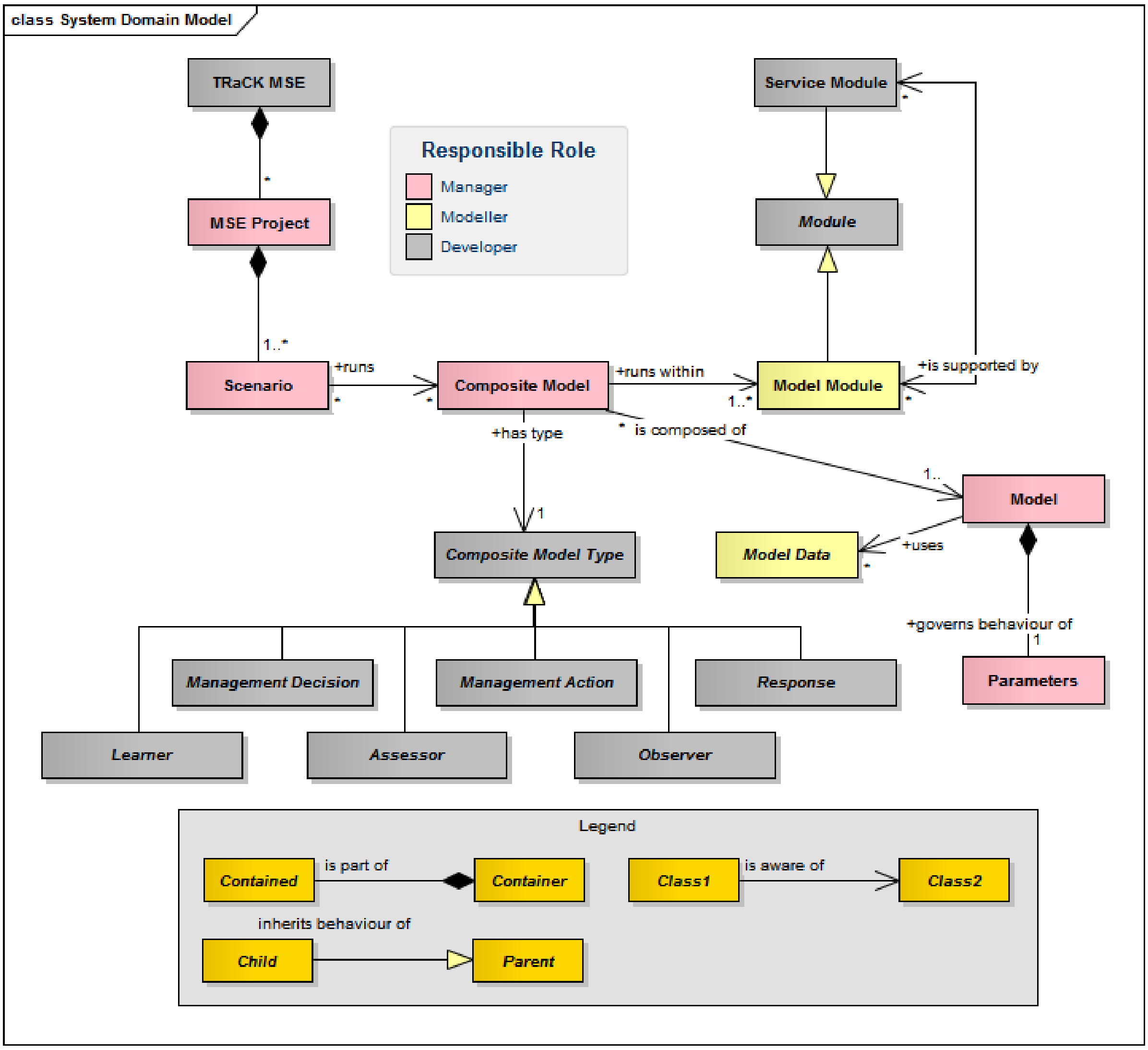


Figure B-2 Elements of the MSE Application

The MSE application allows a user to define a number of projects. An *MSE Project* typically represents the management of a single catchment area. For instance, the TRaCK MSE system might be expected to have a project devoted to each of the Daly, Fitzroy and Mitchell catchments. A scenario is considered part of a project, and a project needs at least one scenario to be useful.

Each scenario is configured to run a set of composite models. A scenario can be configured to run at most a single composite model per composite model type (described below). It is possible for a scenario to not run a composite model for a given module type, allowing for flexibility in deployment. For instance, a scenario might be configured to simply run a *Management Action* model and a *Response* model to allow them to engage in a *Management Scenario Evaluation* (discussed in Section 2.2).

Once defined, a composite model can be shared between any number of scenarios, giving them a lifecycle independent of any one scenario. A number of models of the same model type can be composed together into a single composite model. A typical example of this is to compose a single composite system response model from several response models. One model might simulate surface and groundwater flows through the catchment, another might simulate optimal fish habitats, and yet another might simulate impact of fish numbers on the local economy.

There is a general concept of a "Module" within the MSE application, representing a stand-alone software component. Model modules run "model" programming code. Service modules offer commonly needed services to other model or service modules.

Generally speaking, a resource manager (or appropriate delegate) is responsible for creating and configuring projects, scenarios and models. Modellers are responsible for creating model module code, and for defining and/or sourcing 3rd-party data required to allow the model to run. Infrastructure programmers of the MSE system are responsible for the overall running system, service modules, and ensuring adequate communications between various modules.

B.2.1 ENSURING A LAYERED ARCHITECTURE

A further decomposition of the top-down approach to architecture is to layer the software. A common technique here is to group the software into a number of logical packages and to place those packages into layers of dependency. The MSE application is layered as per the package dependency diagram in Figure B-3.

The MSE is logically partitioned into three logical layers in a *relaxed or loosely-layered architecture style* (Buschmann et al., 1996). In this style, a package at a higher level of abstraction may only depend on packages at a (not necessarily adjacent) lower layer. Layer 0 contains the *GenLib* package, containing general-purpose code. Layer 1 contains the *Base* package which acts to supply base communications infrastructure, and relies on code in the *GenLib* package. Layer 2 contains the *Model* and *Service* packages containing model code, and support services code respectively. They both rely on the *Base* and *GenLib* packages, but neither of these two *Module* packages depends on the other. In this way we can ensure that model, service, communication and generally applicable code have appropriate dependencies and do not have code that bleeds across package boundaries. This results in easier to maintain and enhance code.

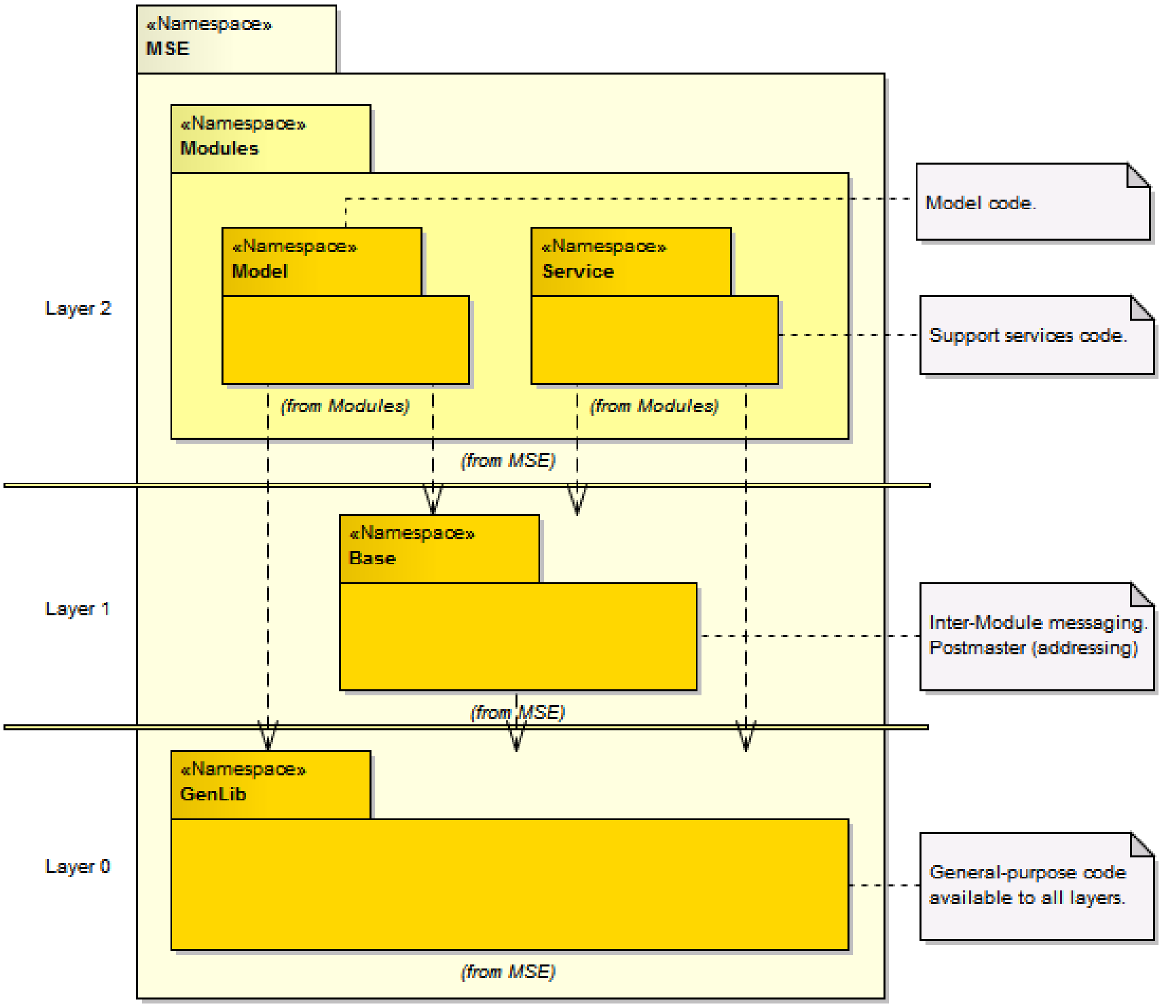


Figure B-3 MSE Package Dependency Diagram

B.2.2 DEPLOY A COMPONENT-ORIENTED ARCHITECTURE

We delegate functionality into a number of stand-alone software components (or modules) at the highest software layer of the MSE Application (*Model* and *Service* code from above). Such an approach is an example of independent component architecture style (Bass et al., 1997). Functional delegation means that, where possible, there is a one-to-one relationship between a key MSE task and a component responsible for that task. All expertise and data needed to perform a task are concentrated in one place and nowhere else.

For instance, there would be no 'knowledge' of the observation task in a Learner component, only in the Observer component. Such a component is relatively autonomous in that it not only knows its own task but also where to get its relevant data and instructions from, and which other components it needs to communicate with. The key software components of the MSE application are captured as a UML component diagram in Figure B-4.

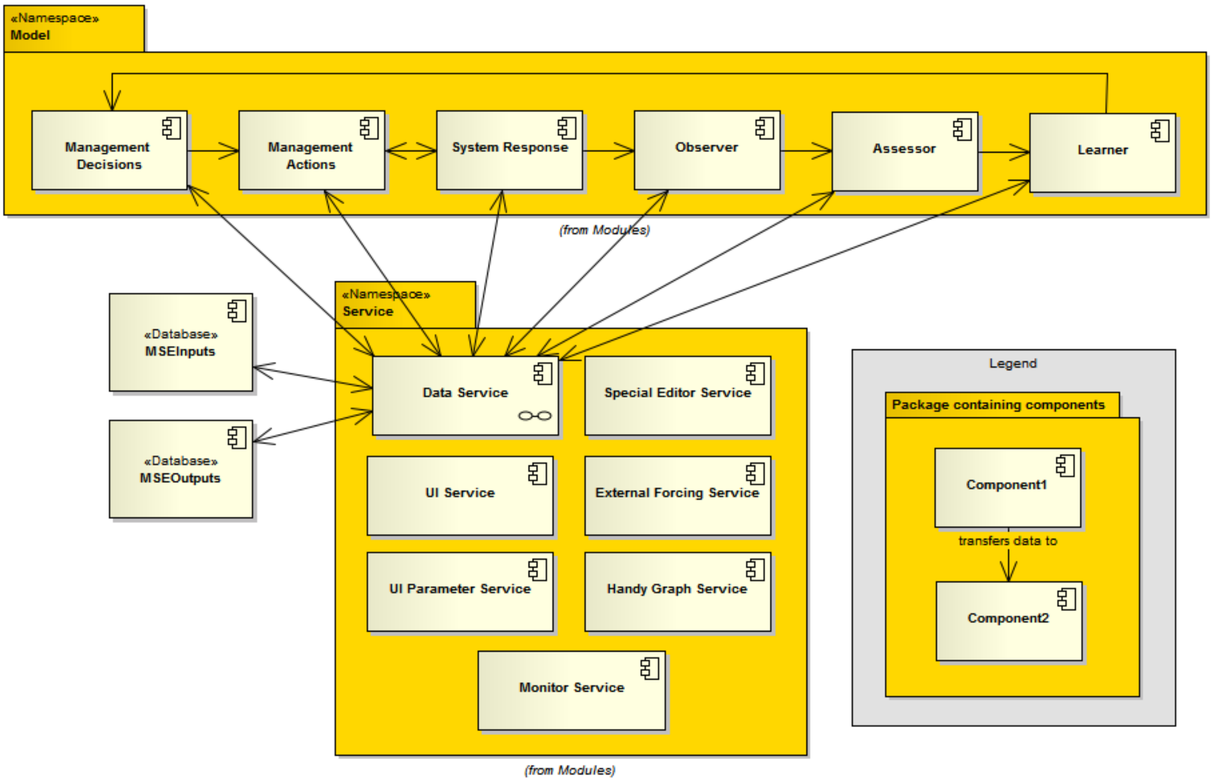


Figure B-4 **Major Components of the MSE Application**

In Figure B-4 directed lines indicate only typical interaction between components. It is entirely possible for a component to talk to any other one if the need arises. We simplify the diagram here to point out only common interactions between components.

The reason for consistently delegating expertise to single components is manifold. For instance, it makes it much easier to replace such a component with another, without any changes to the rest of the software, increasing flexibility. Delegation also makes it easier to trace where a certain task is done, and such an intuitive structure helps in testing, debugging and maintenance. For a system like MSE software, maintenance and debugging tasks can grow exponentially with the complexity of the system, and a 'divide and conquer' strategy is needed to combat that tendency.

The consequence of this approach is that during the design phase 'areas of expertise' need to be recognised within the overall MSE task. To enable each autonomous component to interact with others, appropriate standards for inter-component communication need to be defined and are described in more detail below.

Figure B-5 is a UML class diagram showing (for example) the dependencies of the *DataService* component across the architecture layers of the MSE application (see Figure B-3).

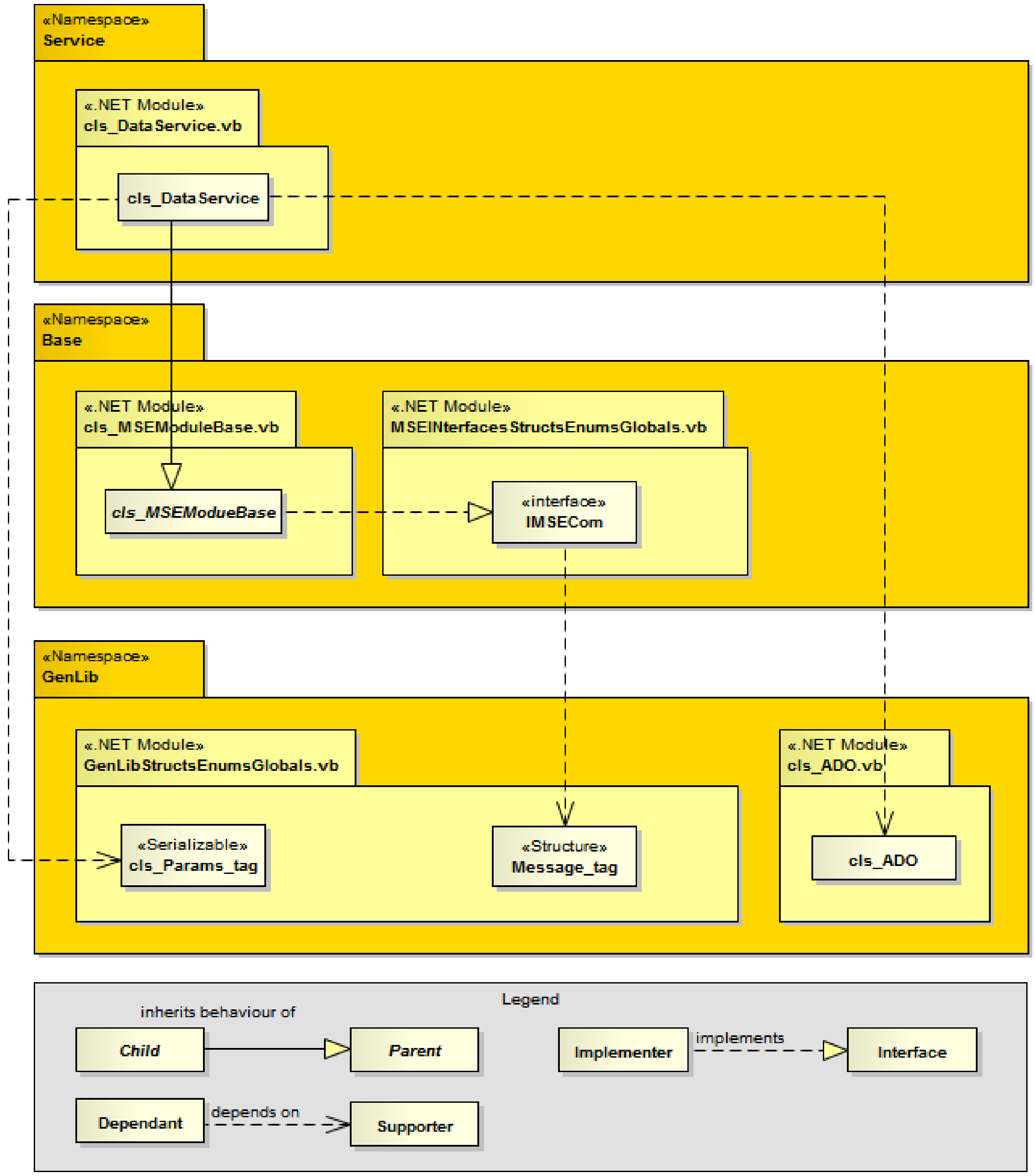


Figure B-5 Data Service Dependency Diagram

The *DataService* class is an extension of the *MSEModuleBase* class. This *MSEModuleBase* class supplies communications code common to all MSE components. By extending it, the *DataService* class is capable of plugging into the communication backbone of the MSE application, allowing it to send and receive messages with other MSE components. The *MSEModuleBase* class implements the *IMSECom* interface, which acts to ensure that all component communication is via a standardised, agreed-to protocol. This interface relies on the *Message_tag* structure which acts as the message container as data is transferred between components.

The *DataService* component acts to marshal all data to and from databases that the MSE application interacts with. A key aspect of this is the transfer of model parameters, which are stored in the *cls_Params_tag* in a running MSE application. Finally, of the many types of possible database interactions available, the DataService relies on the Microsoft ADO framework. An ADO wrapper, allowing convenient access to 3rd-party ADO functionality is contained in the *cls_ADO* class. The *DataService* delegates ADO database interactions to this class.

We see from Figure B-5 that the lower-level composition of programming comes together to build a software component that conforms to the architecture layering depicted in Figure B-3.

B.2.3 MAXIMISE APPLICATION FLEXIBILITY

Given the wide range of possible models and services the MSE application may need to run, flexibility is a key driver. The need for flexibility is inherent to the MSE process itself. The core of MSE is to vary not only parameters within a rigid model but also to examine the influence of much bigger changes, even to different ways of assessing, observing or representing the system. This may result in module and communication changes by changing the MSE specification itself.

There are thus two key aspects to how the MSE Application achieves sufficient flexibility. The first aspect involves maximising runtime flexibility via a standardised communication protocol between components. The second aspect involves maximising specification flexibility by describing required behaviour within a database, rather than hard-coding it into the programming of the MSE application.

RUNTIME FLEXIBILITY

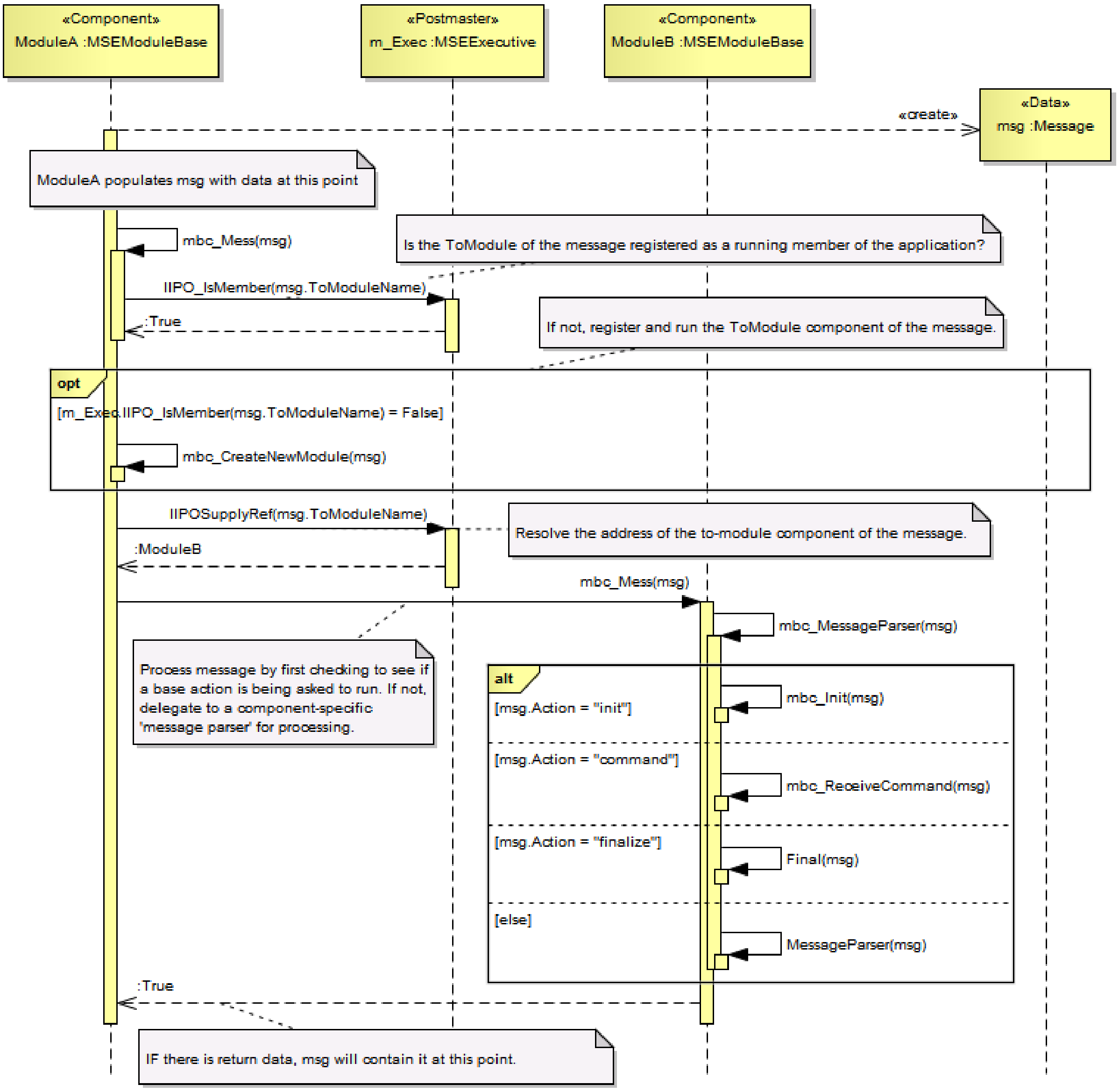
Runtime flexibility is achieved by ensuring that the hard-coded relationships between autonomous software components are kept to a minimum, allowing a degree of freedom of re-arranging and changing software components based on the MSE definition.

The MSE Application has implemented its own lightweight middleware messaging system, sitting in the *Base* package of the software architecture. Software components inherit/implement key classes from this package and become messaging-enabled. The middleware is best categorised as a *Procedure-Oriented Middleware* (Bishop and Karne, 2000). However, as we'll describe later, its isolation into a distinct architecture layer paves the way for a future distributed computing model, simply by altering how this middleware layer enables inter-component communication.

Figure B-6is a UML sequence diagram describing the sequence of activities that goes into a typical successful message exchange between two components in the MSE application. Read from top to bottom, it shows how objects interact over time with earlier interactions closer to the top of the diagram.

The diagram shows two components/modules (*ModuleA* and *ModuleB)* exchanging a message (*msg*) using a messaging postmaster (*m_Exec*) to resolve module address information. *ModuleA* starts by creating a message and passing that message to its message-handling functionality (*mbc_Mess*). This function checks to see if the to-module is currently registered as a running member of the MSE application. If not, *ModuleA* triggers a process to register and run the to-module component identified in the message. Once running, the postmaster *m_Exec* resolves the address of the to-module (*ModuleB* in this example) and informs *ModuleA* of the address. *ModuleA* then contacts *ModuleB* directly and passes the message to *ModuleB* for processing.

All modules have a number of 'base' actions that may be triggered via messaging. Upon receipt of a message addressed to it, *ModuleB* checks to see if it is being asked to run one of these base actions. If not, *ModuleB* passes its message onto a special *MessageParser* function that allows individual modules to support their own actions above and beyond the base set supplied by the messaging framework. In this way, we are able to flexibly extend individual modules to process messages applicable only to those modules.



ModuleA populates msg with data at this point

Is the ToModule of the message registered as a running member of the application?

If not, register and run the ToModule component of the message.

Resolve the address of the to-module component of the message.

Process message by first checking to see if a base action is being asked to run. If not, delegate to a component-specific 'message parser' for processing.

IF there is return data, msg will contain it at this point.

Figure B-6 Typical Messaging Sequence Diagram

Messages have a 'status' to track where a message is within its lifecycle. Statuses can be divided two groups, 1) those set by a sender module, and 2) those set by a receiver module. Figure B-7 shows a UML state transition diagram of the lifecycle of MSE application messages.

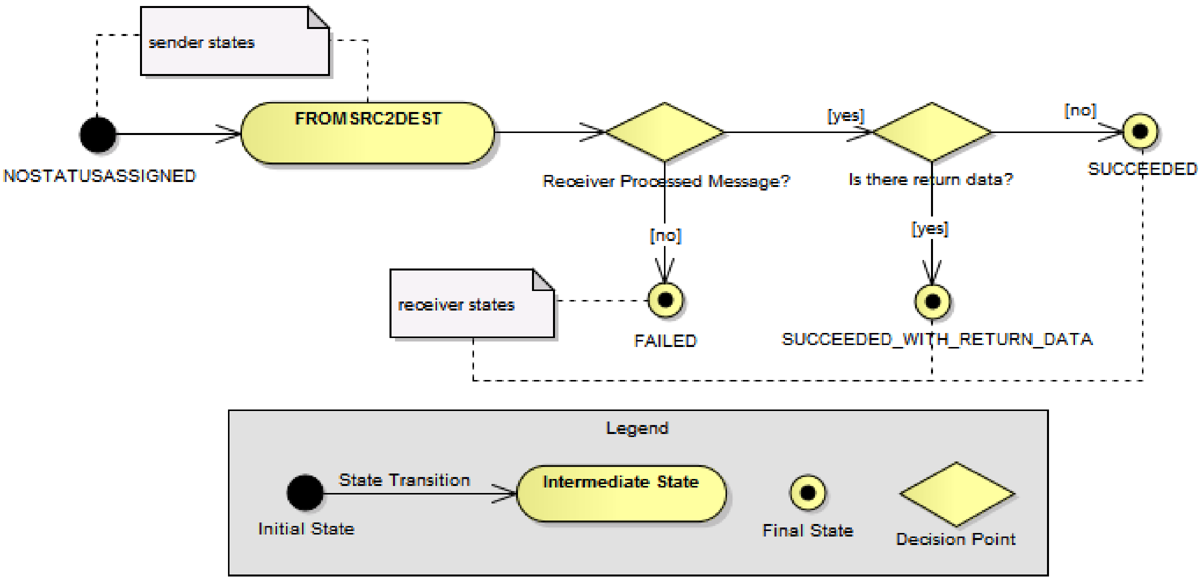


Figure B-7 **Message State Transition Diagram**

SPECIFICATION FLEXIBILITY

Another consequence of the need for flexibility is that the MSE Application minimises the amount of hard-coded 'framework' and is geared to adapt its structure based on external specifications. These specifications are stored in a database instead of being hard-coded into the software. The software components are thus said to have adopted a data-centric architectural style using a repository coordination model (Bass et al., 1997).

In practical terms, this means that behaviour for the following activities is driven by a database repository:

- Sub-model behaviour described via parameters specific to a particular sub-model
- The composition of a number of sub-models into a single model.
- The composition of a number of models together to a) form a particular scenario, and b) specify necessary model interactions for that scenario.
- The composition of a number of scenarios into a complete specification for a single management strategy evaluation.

In this manner we achieve a highly flexible way of altering system behaviour (from macro through to micro concerns) by modifying database entries instead of having to revisit the programming of the MSE application.

B.3 IMPLEMENT ITERATIVELY

A common maxim in software engineering is to "make it work, make it right, make it fast." It reminds software engineers that there's no point in getting a system working "right" if you first can't get it to just work, and there's no point in getting it to work "fast" if you can't get it first working "right". A typical approach that reflects this maxim is to iteratively implement a system, starting with a very basic framework that at least can be run whilst further functionality is incrementally added in later iterations.

The reason for this approach is to prevent the overall system's functionality becoming skewed by some of the complexity of the details, typically called "analysis paralysis". By implementing in such an iterative fashion, we ensure that the communication infra-structure (both standards and software), which is critical for a modular, tiered and flexible approach, is implemented and tested before the complexity of the MSE detail (typically peaking in model code) is layered in on top.

The MSE application deliberately allows incomplete systems to run, and to make it easy to replace "stand-in" models or services, acting as test stubs, with more evolved software components in a stepwise fashion as we learn from the system's behaviour.

B.4 WHERE POSSIBLE "BUY, DON'T BUILD"

Pieces of functionality encapsulated in software modules are often commercially available. For instance, functionality like map-making and spatial overlays is one of the much-needed spatial functions of an MSE system. That functionality is commercially available as a GIS module which can be embedded in the overall system.

The advantages of such software objects are that they are already autonomous pieces of software, delivering functionality that would cost many times their price if developed in-house. These objects are often well tested and are maintained by the vendor. Perhaps more importantly, however, sourcing software from 3rd parties frees us to more appropriately focus our effort on issues truly unique to the MSE application.

As these 3rd-party products lack our specific interface definitions, they need to be embedded inside a layer of software (called a wrapper) to adapt the object's interface to the MSE interface specification. The MSE environment uses a range of such objects and the Windows/Studio.Net environment is well suited to making use of externally developed objects.

Currently, the MSE application includes 3rd-party components for GIS (MapObjects), database interactions (ADO, DAO and ADO.Net), graphs (Teechart), statistics (S-Plus and R), spreadsheets (Excel), user interface objects (Syncfusion), and Matlab amongst others.

B.5 WEB-BASED USER INTERFACES AND DISTRIBUTED COMPUTING

A web-based user interface allows anyone with a web browser like Internet Explorer to access functionality appropriate to their role from wherever they have network visibility back to a running MSE application. This might be as close as a nearby office, or as far as the other side of the planet.

Distributed computing is the ability to break a computing task up and distribute it across several computers to run at the same time, thus speeding up the completion of that task. It allows scaling up the computing power by adding more computers to process a certain task. For the MSE, you may think of the possibility of running different MSE simulations on different computers in a network.

Web-based access would open up functionality like the MSE system to potential users, especially stakeholders, anywhere in the world whilst the software and possibly the data reside under the control of the development team. This prevents a heavy burden of software distribution, maintenance and client liaison. This functionality is not available in the current version of the MSE software but could be developed, at least partially, without major changes to the current software.

The need for distributed computing is very real as the MSE system is expected to create heavy computing loads. The option of distributing this load over a network of computers needs to be kept open, and the software development environment chosen for this project, Microsoft Visual Studio.Net, already has a range of services (called 'remoting') that supports distributed computing. As discussed earlier, the MSE application already caters to a relatively painless replacement of existing centralised communications with a distributed model by isolating communications programming within its own architecture layer.

APPENDIX C EXAMPLE USE OF THE MSE SOFTWARE ANALYSIS CAPABILITIES

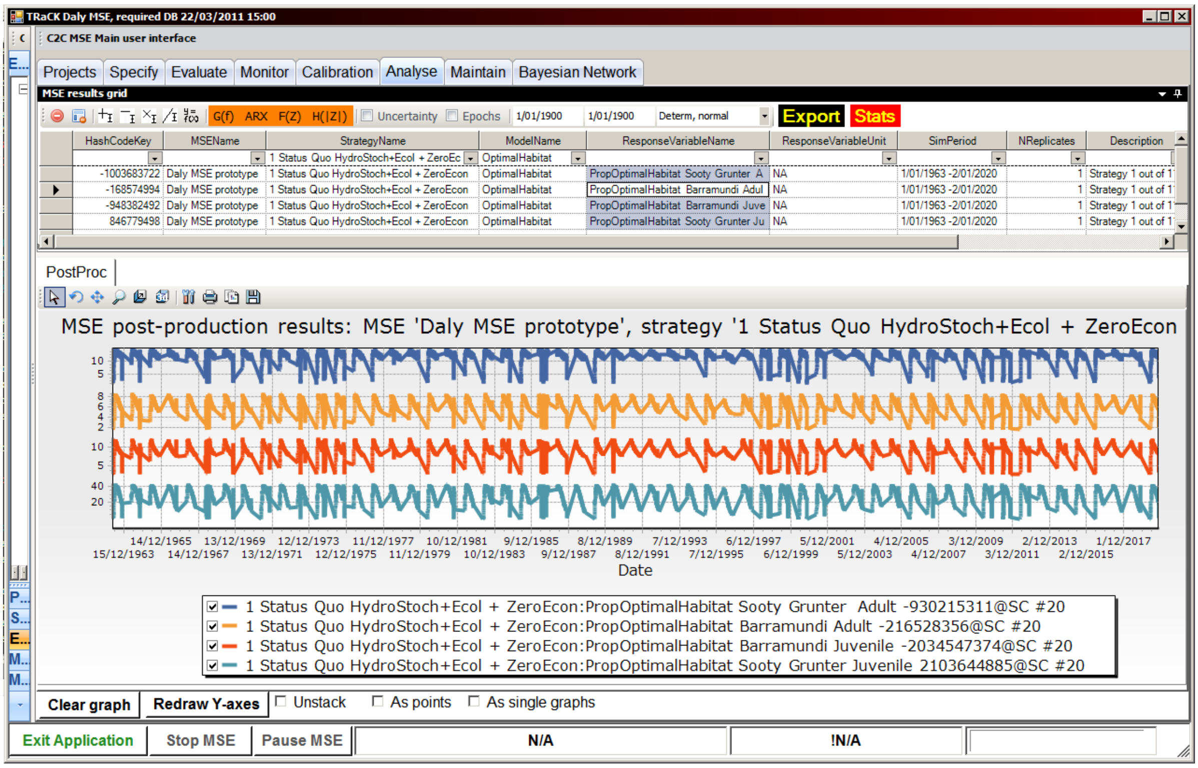
This Appendix complements the discussion on the capabilities of the MSE system contained within Chapter 3. This Appendix focuses on the way in which the user can utilise these analysis capabilities through worked examples.

As described in Section 3.3, access to the evaluation model results is available through the Analyse tab of the MSE software application. Typically, on selection of this tab, the user might select results from models of interest in the results grid at the top of the screen and drop them into the graph at the bottom of the screen.

To help illustrate the power of the analysis tools available, we walk through a hypothetical example of a user manipulating the analysis screen as they analyse the results available after an evaluation. The example starts with a simple question posed to the manager of (say) the Daly River catchment. The question is "What impact does the region's water allocation policy (WAP) have on the ecological health of the catchment?"

Firstly, the user decides they need a good "indicator" for ecological health of the waterways. They decide that changes to the optimal habitat of a key species of the river might be a good starting point. They begin to explore what the MSE application has collected in terms of optimal habitats.

Initially in Figure C-1, the user decides to analyse adult and juvenile barramundi and sooty grunter model results on the same graph. The user chooses the "Status Quo" scenario because that scenario represents the catchment without human pressure on the ecosystem. The user drags the response variable names for the adult and juvenile models down onto the (initially blank) graph, resulting in four distinct result sets on the graph, with annual peaks and troughs.



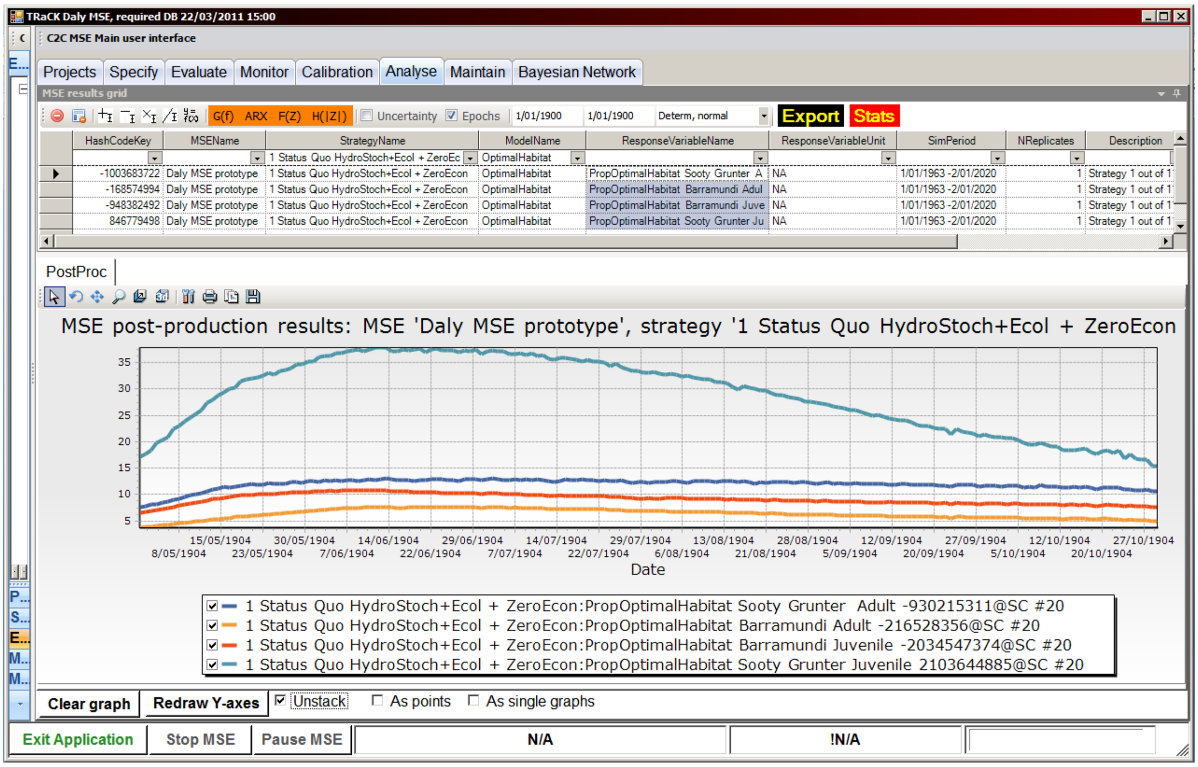
HashCodeKey	MSEName	StrategyName	ModelName	ResponseVariableName	ResponseVariableUnit	SimPeriod	NReplicates	Description
		1 Status Quo HydroStoch+Ecol + ZeroEc	OptimalHabitat					
-1003683722	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	OptimalHabitat	PropOptimalHabitat Sooty Grunter A	NA	1/01/1963 -2/01/2020	1	Strategy 1 out of 1
-168574994	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	OptimalHabitat	PropOptimalHabitat Barramundi Adul	NA	1/01/1963 -2/01/2020	1	Strategy 1 out of 1
-948382492	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	OptimalHabitat	PropOptimalHabitat Barramundi Juve	NA	1/01/1963 -2/01/2020	1	Strategy 1 out of 1
846779498	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	OptimalHabitat	PropOptimalHabitat Sooty Grunter Ju	NA	1/01/1963 -2/01/2020	1	Strategy 1 out of 1

MSE post-production results: MSE 'Daly MSE prototype', strategy '1 Status Quo HydroStoch+Ecol + ZeroEcon

☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Sooty Grunter Adult -930215311@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Barramundi Adult -216528356@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Barramundi Juvenile -2034547374@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Sooty Grunter Juvenile 2103644885@SC #20

Figure C-1 Initial Analysis of Ecological Health Indicators

Deciding that the graphs are too noisy for the range of years sampled, the user chooses instead to overlay all years of the results into a 'single year' or 'epoch' presentation, and to stack the results onto the same range of values. The graph then collapses into one as per Figure C-2.



HashCodeKey	MSEName	StrategyName	ModelName	ResponseVariableName	ResponseVariableUnit	SimPeriod	NReplicates	Description
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-948382492	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	OptimalHabitat	PropOptimalHabitat Barramundi Juve	NA	1/01/1963 -2/01/2020	1	Strategy 1 out of 1
846779498	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	OptimalHabitat	PropOptimalHabitat Sooty Grunter Ju	NA	1/01/1963 -2/01/2020	1	Strategy 1 out of 1

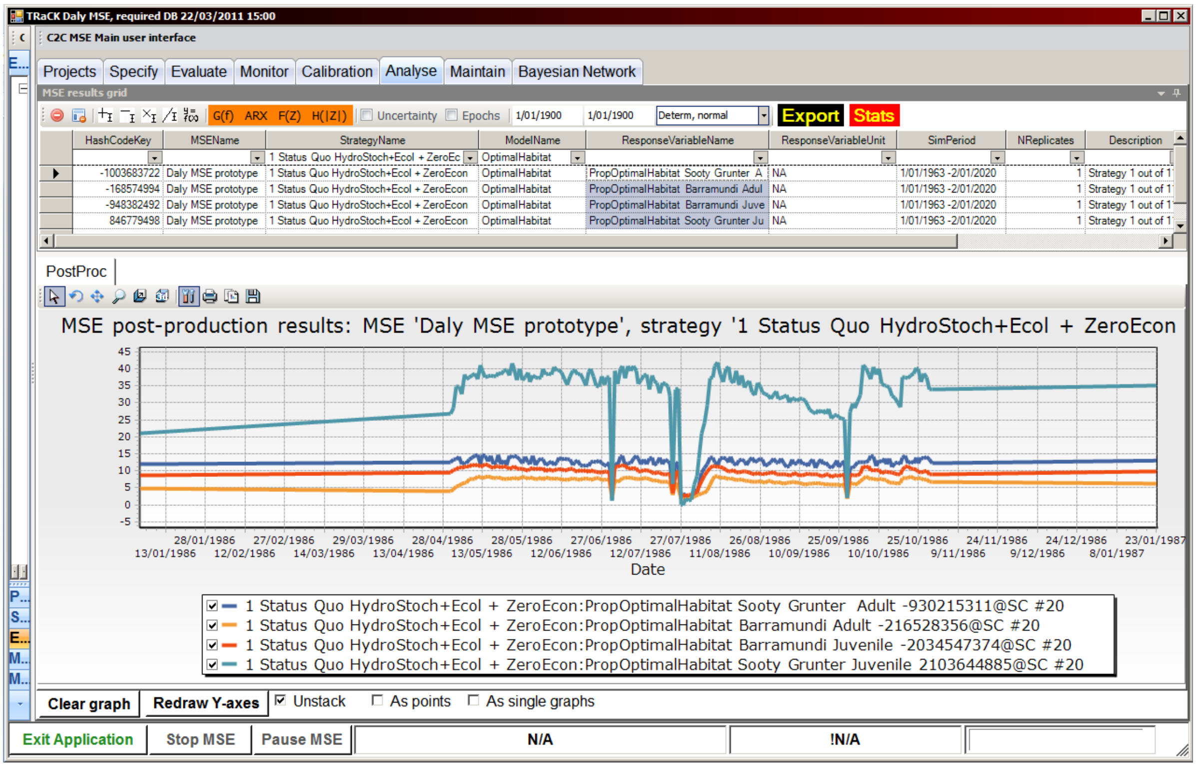
MSE post-production results: MSE 'Daly MSE prototype', strategy '1 Status Quo HydroStoch+Ecol + ZeroEcon

☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Sooty Grunter Adult -930215311@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Barramundi Adult -216528356@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Barramundi Juvenile -2034547374@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Sooty Grunter Juvenile 2103644885@SC #20

Figure C-2 Example Analysis - Overlaying Years showing Uncertainty

The user concludes from Figure C-2, that generally speaking, the optimal habitat for barramundi and sooty grunter have similar trends, but the adult barramundi may be affected by adverse ecological conditions before the other populations modelled, and thus make a better "early-warning" indicator for ecological health.

Whilst deciding on a suitable ecological indicator, the user noticed certain oddities in the optimal habitat models. The user can zoom in on the year 1986, being an atypical year for optimal habitat results, as per Figure C-3.



HashCodeKey	MSEName	StrategyName	ModelName	ResponseVariableName	ResponseVariableUnit	SimPeriod	NReplicates	Description
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MSE post-production results: MSE 'Daly MSE prototype', strategy '1 Status Quo HydroStoch+Ecol + ZeroEcon

☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Sooty Grunter Adult -930215311@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Barramundi Adult -216528356@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Barramundi Juvenile -2034547374@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon:PropOptimalHabitat Sooty Grunter Juvenile 2103644885@SC #20

Figure C-3 Investigating Odd Optimal Habitat Results

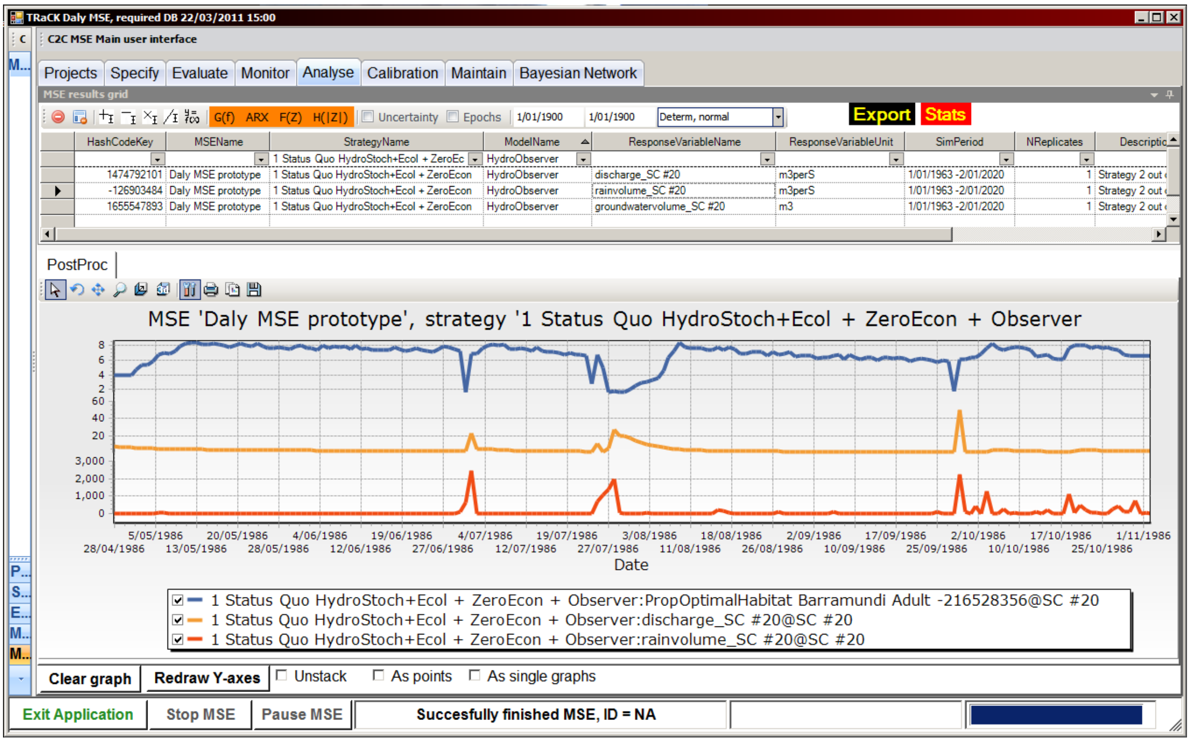
Given that all of the population models experience similar dips over the period, the user removes all but the adult barramundi results, and zooms in on just the period of the dry season (given their knowledge that the optimal habitat model runs only over the dry season of the year). The user progressively tries various other variables on the graph to see if there are correlations with the dips in optimal barramundi habitat.

They soon realise that there is indeed quite a degree of correlation with other results to the dips in barramundi results (nitrogen or phosphorus loads for example). At this point the user reminds themselves that correlation does not necessarily imply causation. The user decides instead to focus on the key input that drives optimal habitat models, which in this case is the groundwater discharge during the dry season.

Upon initially pulling the discharge result onto the graph, the user is disappointed. The discharge line looks completely flat. They then realise that the scale of the graph covers values up to the highest-ever recorded discharge (which includes record-level wet seasons). The user then reduces the scale of the discharge axis to match just the range of values seen over the period of interest. At this scale, the user easily spots the expected correlation between an increase in discharge and a decrease in optimal habitat, as shown in Figure C-4.

Taking it one step further, the user knows that discharge results are generated in the catchment response model and are driven by changes in rain and potential evapotranspiration (PET). PET is an input variable that does not change significantly either temporally or spatially. The user thus expects to find elevated rainfall in the catchment to roughly correspond with the changes in discharge. Acting on this expectation, they drag rainfall detail for the catchment down into the graph, adjust the axis to cover values only within the timespan of interest, and clearly see periods of rainfall that match elevated discharge and consequently, reduced optimal habitat results. This evidence is shown in Figure C-4.

At this point the user has gained a degree of confidence that the atypical optimal habitat results in 1986 are most likely explained by how the models respond to unseasonal rainfalls in the dry season.



HashCodeKey	MSEName	StrategyName	ModelName	ResponseVariableName	ResponseVariableUnit	SimPeriod	NReplicates	Descriptic
		1 Status Quo HydroStoch+Ecol + ZeroEc	HydroObserver					
1474792101	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	HydroObserver	discharge_SC #20	m3perS	1/01/1963 -2/01/2020	1	Strategy 2 out
-126903484	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	HydroObserver	rainvolume_SC #20	m3perS	1/01/1963 -2/01/2020	1	Strategy 2 out
1655547893	Daly MSE prototype	1 Status Quo HydroStoch+Ecol + ZeroEcon	HydroObserver	groundwatervolume_SC #20	m3	1/01/1963 -2/01/2020	1	Strategy 2 out

MSE 'Daly MSE prototype', strategy '1 Status Quo HydroStoch+Ecol + ZeroEcon + Observer

☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon + Observer:PropOptimalHabitat Barramundi Adult -216528356@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon + Observer:discharge_SC #20@SC #20
☑ 1 Status Quo HydroStoch+Ecol + ZeroEcon + Observer:rainvolume_SC #20@SC #20

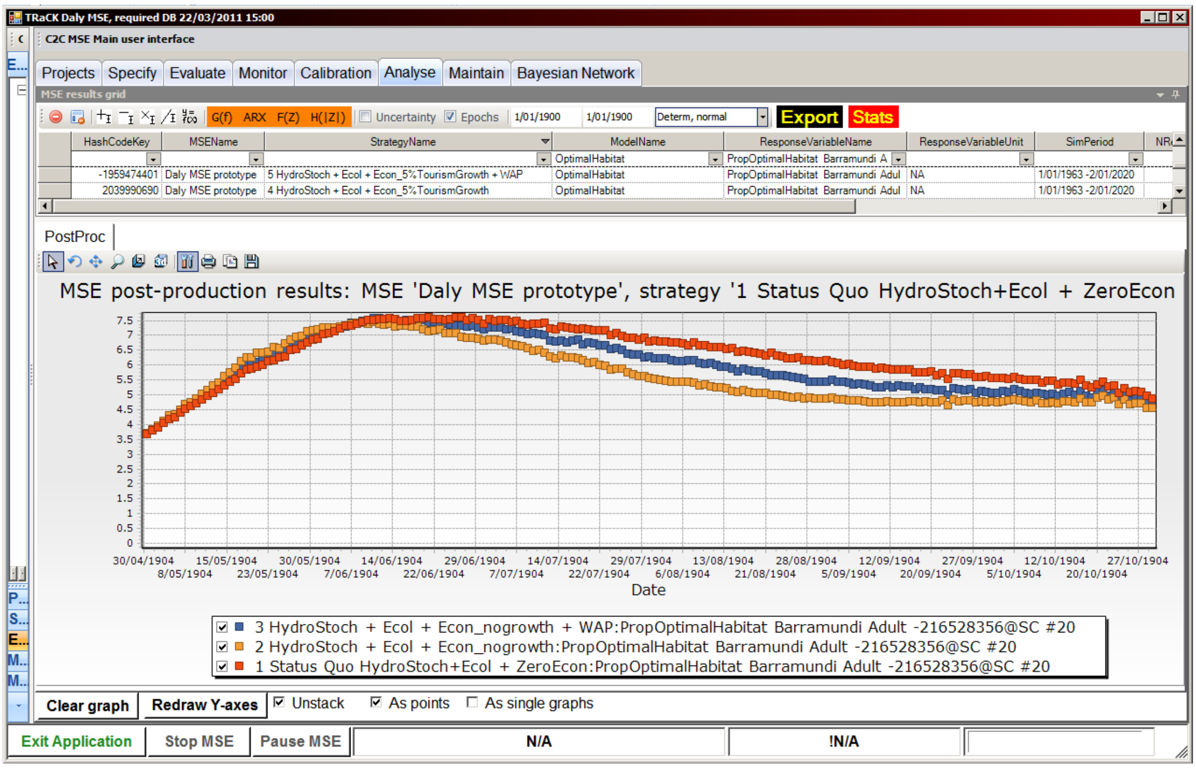
Succesfully finished MSE, ID = NA

Figure C-4 Exploring Drivers for Atypical Optimal Habitat Results in Epoch View (ignore dates)

Having decided on a useful indicator for ecological health of the catchment, and understanding a little of its dynamics, the user attempts to isolate the benefit of having a Water Allocation Plan (WAP). They reset the graph, and combine adult barramundi optimal habitat results for the following scenarios into the one graph:

1. Status-Quo (for an idea on the best-case optimal habitat possible without human activity in the catchment)
2. Economic activity at a certain "contemporary" level that is not growing, but without a WAP.
3. The same level of economic level activity as Scenario 2, but with a WAP.

Again, to reduce unhelpful noise, the user chooses an epoch view of the data, and unstacks the graphs so they share the same vertical axis, allowing the user to better see the typical annual trend. The resulting graph appears in Figure C-5.



☐ Uncertainty ☑ Epochs 1/01/1900 1/01/1900 Determ, normal

HashCodeKey	MSEName	StrategyName	ModelName	ResponseVariableName	ResponseVariableUnit	SimPeriod	NR
			OptimalHabitat	PropOptimalHabitat Barramundi A			
-1959474401	Daly MSE prototype	5 HydroStoch + Ecol + Econ_5%TourismGrowth + WAP	OptimalHabitat	PropOptimalHabitat Barramundi Adul	NA	1/01/1963 -2/01/2020	
2039990690	Daly MSE prototype	4 HydroStoch + Ecol + Econ_5%TourismGrowth	OptimalHabitat	PropOptimalHabitat Barramundi Adul	NA	1/01/1963 -2/01/2020	

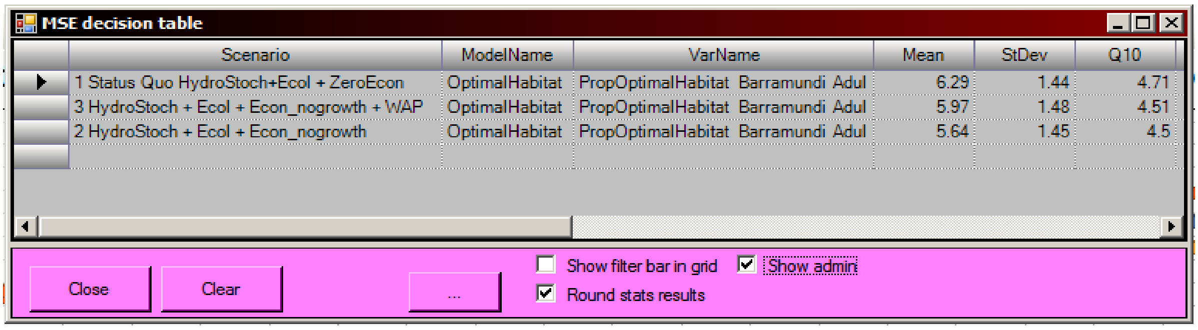
MSE post-production results: MSE 'Daly MSE prototype', strategy '1 Status Quo HydroStoch+Ecol + ZeroEcon

☑ Unstack ☑ As points ☐ As single graphs

Figure C-5 Exploring Water Allocation Policy Benefit in Epoch View (ignore dates)

From Figure C-5, the user learns that the impact of the WAP becomes obvious around mid-June in a typical year: the time that the habitat for adult barramundi starts reducing. For the majority of the dry-season the policy allows a larger adult barramundi habitat than if the economic pressure on the catchment was allowed to draw as much water as desired. As the dry season comes to the close, the benefit becomes less easy to differentiate from the impact of economy's current water demands on the habitat.

Wishing now to consolidate this into a decision table, the user drags the three barramundi results over the "Stats" area of the analysis screen, as per Figure C-6.



Scenario	ModelName	VarName	Mean	StDev	Q10
1 Status Quo HydroStoch+Ecol + ZeroEcon	OptimalHabitat	PropOptimalHabitat Barramundi Adul	6.29	1.44	4.71
3 HydroStoch + Ecol + Econ_nogrowth + WAP	OptimalHabitat	PropOptimalHabitat Barramundi Adul	5.97	1.48	4.51
2 HydroStoch + Ecol + Econ_nogrowth	OptimalHabitat	PropOptimalHabitat Barramundi Adul	5.64	1.45	4.5

☐ Show filter bar in grid ☑ Show admin
☑ Round stats results

Figure C-6 Raw Decision Table for WAP Benefits to Barramundi Optimal Habitat

Though this statistical view shows a large number of differing statistics, the statistic showing the greatest degree of variation between scenarios is the mean value for optimal adult barramundi habitats. With this decision table, the user could then answer their original question by saying that "For current economic activity, inclusion of the WAP results in an average 11% (5.97 divided by 5.64) larger optimal habitat for adult barramundi than would otherwise be the case".

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APPENDIX D DEALING WITH UNCERTAINTY

Uncertainty is the crucial factor in many planning and decision processes (Ruszczynski and Shapiro 2003). This is especially true for natural resource management with its many complex relationships and various sources of uncertainty. MSE supports natural resource management decision processes and would not be very credible if it would ignore uncertainty. There is an abundance of literature about the stochastic approach to uncertainty e.g. (Bendat and Piersol, 1986, Papoulis, 1965, Wu, 2006)

This Appendix explains the use of statistics in presenting example results in Chapter 7 of the report. It focuses on how we represent and visualise two components of uncertainty currently implemented in the prototype Daly River MSE application: *temporal variability* and epistemic (ignorance-based) uncertainties. Temporal variability is part of natural variability and epistemic uncertainties are referred to in the literature as *knowledge* uncertainties.

Whilst the temporal variability is inherent in natural processes (e.g. rainfall over time), the ignorance based uncertainty in this report arises from the use of models as a substrate of our knowledge. This knowledge is imperfect (that is, it contains ignorance), and we need to estimate and include the uncertainty arising from that ignorance in the results we are presenting, particularly where results are used to make management decisions. The discussion on how to deal with the different sources of uncertainty is important as different sources are likely to lead to different actions: in many cases it is easier to obtain more precise knowledge than it is to change the temporal variability of rain.

The (example) results discussed in this report are the outputs of the models as depicted in Figure 6-1. In this Appendix, we will only look at the time series of the juvenile Sooty Grunter habitat availability output from the Optimal Habitat model and only for one scenario where economic activity (and with it groundwater extraction) is absent.

The MSE application has two modes for defining and evaluating scenarios: *deterministic* and *stochastic* mode. In *deterministic* (single-run) mode all parameters are set to their calibrated value and a scenario is simulated (run) only once. At the end of the simulation, we will have single time-series for each module's output. Single time series allow us to assess temporal variability but not ignorance-based uncertainty

In *stochastic* (sample or realised runs) mode, a scenario is simulated a number (N_{repl}) of times. The basis of the stochastic mode is that we assess ignorance-based uncertainty by making each of the model parameters a stochastic variable that can be sampled. A model that uses these random variables becomes a random process (Papoulis 1965, Bendat and Pierson 1986). For each simulation, each of the model parameters marked as stochastic will be sampled from a distribution specified. At the end of the simulations, there will be N_{repl} time-series for each active MSE model's output. More detail on this mode is given in Section D.2 and Section D.3.2. The MSE application uses a range of spatially references information layers (GIS layers or coverages) such as (sub-) catchment boundaries and stream channel positions. The spatial information is not without it own uncertainties with their special challenges (Pantus et al., 2008b), but we will ignore them in report.

Identifying and expressing sources (and levels) of uncertainty is relevant for resource management: different sources of uncertainty may need different management responses.

For instance: inter-annual variability (such as is the case for rainfall) is *not reducible*. Having good estimates of inter-annual variability may lead to a two-pronged management action program: levees to cover 90% of the inter-annual variability, and early warning systems and evacuation plans for the remaining 10%.

On the other hand, ignorance-based uncertainty may be *reducible* by better system knowledge. The appropriate management actions in that case would be in terms of knowledge management: e.g. appropriate levels of monitoring, properly trained analytical staff and more reliable predictive models.

D.1 DETERMINISTIC MODE STATISTICS

Results from deterministic mode scenarios can be statistically summarised by using (all or part of) the time series resulting from any of the active models. In this Section we will look at two ways of reporting on the model outputs:

- calculating statistics over the time series, or
- dividing the original time series into *epochs* (set time intervals containing an important event, e.g. the dry season event in a yearly interval) and dealing with each of these epochs as time series in their own right. A collection of epochs is called an *ensemble*. The statistics calculated for an ensemble uses the statistics of each of the epochs as their input.

The epoch-based approach informs us about the inter-annual variability. In this Appendix the epochs are taken to be one year of length and cut on the calendar year's boundary, which falls well within the Daly River wet season (December – April).

D.1.1 SINGLE TIME SERIES STATISTICS

Figure D-1 shows a time-series output of one of the Daly River MSE response models, the Optimal Habitat model (Chan et al., 2011) and Table D-1 shows a range of statistics that summarise the time series. For the purpose of this example, where we are interested in examining the dry season response of the optimum habitat for some fish species, we record only the response variable during that season (as shown in Figure D-1) and so exclude the wet weather dynamics from our analysis.

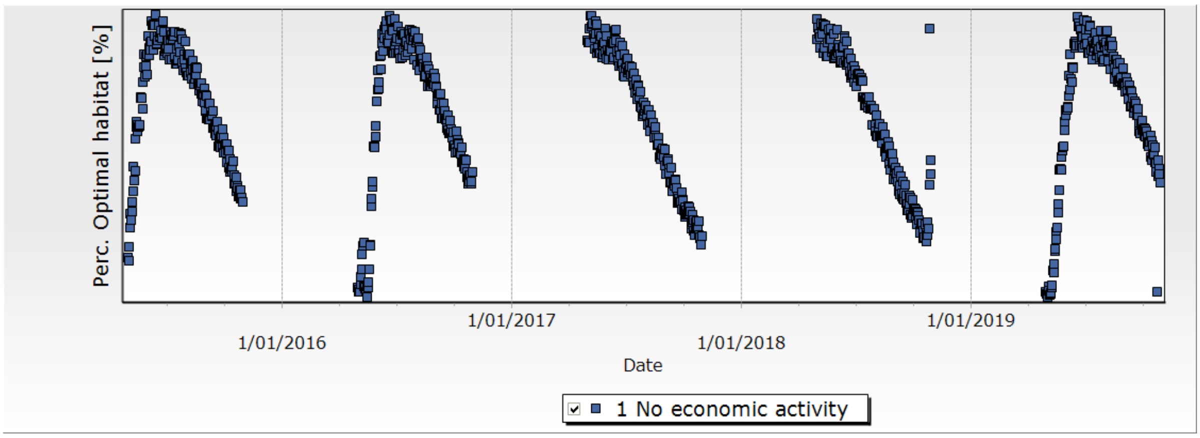

Figure D-1 **The output of the Optimal Habitat response model after a single evaluation. Only the values of the percentage optimal habitat during the dry season (May – November) are being recorded.**

Table D-1 summarises the time series in Figure D-1. Apart from the usual measures (e.g. mean, standard deviation), the table also contains measures that describe the distribution of the values in the time series in terms of quantiles (or percentiles) For instance, Q10 or the 10th quantile is the value of a variable below which fall 10% of the (time series) values, the median value is identical to the Q50 value.

CV (coefficient of variation) is defined as the ratio of the standard deviation to the absolute mean, $\frac{\sigma}{|\mu|}$, where σ is the standard deviation and $|\mu|$ is the absolute mean. The advantage of using CV is that it is a normalized measure and that makes it possible to compare this measure of uncertainty between various results as obtained from various scenarios for instance. In presenting our results, we will be expressing CV as a percentage (rather than a ratio).

Table D-1 **A statistical summary of the time series from Figure D-1. See text for details**

Scenario	N	# t-pts	Mean	St Dev	CV	Min	Max	Q10	Q25	Q50	Q75	Q90
1 No economic activity	1	915	27.8	10.4	37.4	0.011	42.4	12.6	20.6	30	20.6	39.2

Looking at Figure D-1 it become apparent that the annual maximum values are about the same, and they also appear around the same time of the year. The start values and the end values differ between years.

This inter-annual variability is of interest when making plans and decision around natural resource' and inter-annual variability can be examined through an epoch-based approach.

D.1.2 SINGLE TIME SERIES EPOCH STATISTICS

To examine this inter-annual variability a bit further, we transform the time series in Figure D-1 into an ensemble of (five) one-year epochs and line them up on their year boundary. To study the (distribution of) epochs is to study the inter-annual variability in the original time series.

The result is shown in Figure D-2: the blue squares represents the average of the ensemble (five epochs), the yellow bars represent the standard deviation and the lines at the top and bottom of the bars represent minimum and maximum values (the main source of inter-annual variability in the MSE models used here will be the rainfall, the major external driver of the hydraulic model).

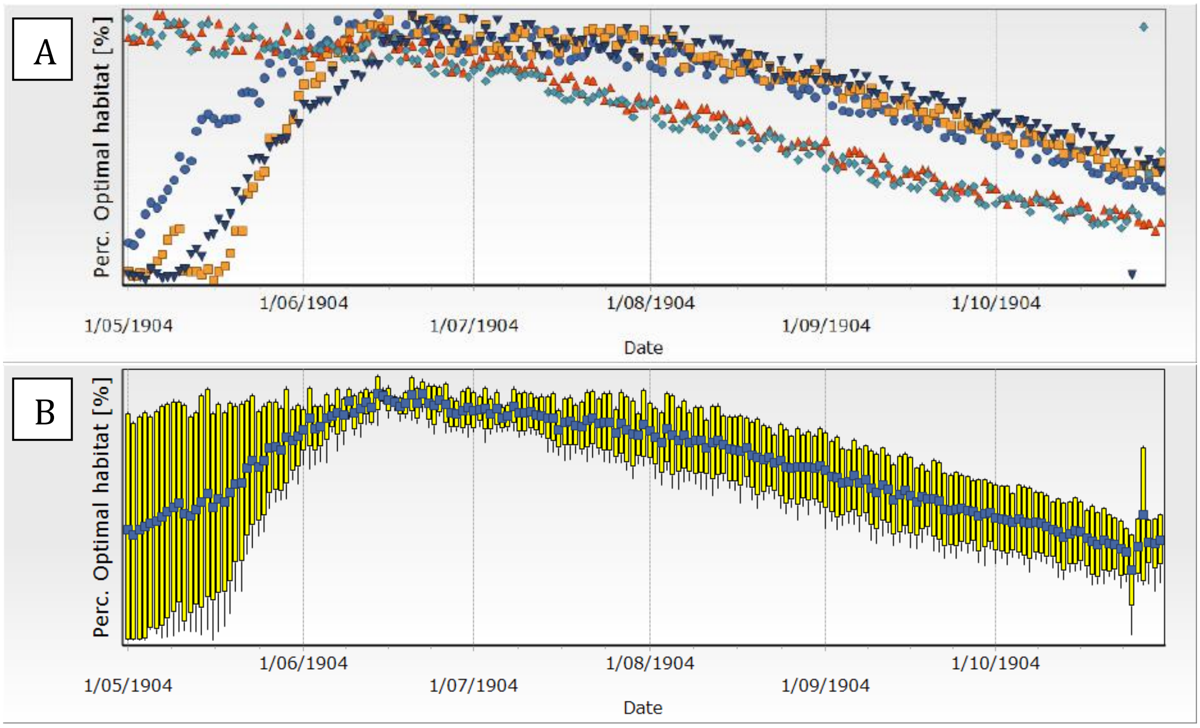

Figure D-2 The result of overlaying the epochs. Graph A shows the five individual epochs, graph B shows the statistical summary for each time. The (dummy) years in the dates on the X–axis are to be ignored. See text for more details.

A set of statistical descriptors (mean, standard deviation, CV, min, max, Q10 etc.), are calculated for each of the five epochs. For each of these statistical descriptors (column headers) , the ensemble-mean, standard deviation and CV is calculated (row headers) and tabulated as shown in Table D-2.

Table D-2 The ensemble statistics describe the inter-annual variability of a single time series.

Scenario	Statistic	N	# t-pts	Mean	St Dev	CV	Min	Max	Q10	Q25	Q50	Q75	Q90
I No economic activity	Ensemble Mean	5	183	27.8	10.3	37.2	4.36	42.1	11.7	20.6	30.4	36.8	39.1
Epochs: Yes	Ensemble StDev			1.29	1.1	4.62	4.08	0.28	3.37	3.32	1.92	0.607	0.379
	Ensemble CV			4.64	10.68	12.42	93.58	0.66	28.80	16.12	6.32	1.65	0.97

As an example of interpreting these results: examining Table D-2 shows that the inter-annual value of the (epoch) mean varies considerably (27.8 ± 10.3). It also shows that the epoch mean (27.8 ± 1.29) and epoch standard deviation (10.3 ± 1.1) are well determined (contain little variability).

Furthermore, for ecological considerations the minimum and Q10 values may be of interest as they may be interpreted as a worst-case indicator. The epoch minimum varies strongly between years (4.36 ± 4.08) whilst the Q10 value varies moderately (11.7 ± 3.37). This may lead to the choice of the Q10 statistic as an informative (be it a further removed) surrogate for a worst-case ecosystem status indicator.

Example conclusions relevant to planning and management (given the assumptions underlying the modelling) may be that 'natural' inter-annual variability, as expressed by the mean-value, is well defined but variable. The Q10 statistic of the available optimal habitat would be an attractive candidate as an informative worst-case ecosystem status indicator.

D.2 STOCHASTIC MODE STATISTICS

The epoch-based approach can be used to describe the temporal variability, as discussed in the previous Section. In this Section another source of uncertainty is examined, uncertainty that simulates our lack of knowledge or ignorance. The approach taken here is that we simulate our ignorance of for instance the precise values model parameter by trying combinations of different parameter values. To generate these combinations, we sample (randomly assign) values of each parameter from its defined distribution. Each set of sampled parameter values is referred to as a *sample* (or realisation) from the stochastic (sampling process). The result from running a scenario once with a realisation of parameters is referred to as a *sample result*.

Our ignorance of actual parameter values include causes such as (unknown) parameter changes over time or space, or the absence of sufficient information to determine them more precisely. To make this ignorance explicit, we evaluate a number of scenarios with various realisations (combinations of) parameters and see what the effect is on the results. The MSE results presented in this Appendix that obtained in stochastic mode are based mainly on specifying the uncertainty for the hydraulic model parameters as a random-uniform distribution with an uncertainty interval of ± 50% of the default value. This is not based on well-established knowledge but on assumptions to be examined at a later stage.

D.2.1 REALISED TIME SERIES STATISTICAL SUMMARIES

Figure D-3 presents the results of ten scenarios. Figure D-3A shows time-series statistics often *realisations* (results of scenario evaluations with stochastic sampled parameter values). Figure D-3B zooms in the first year and shows the individual results of each of the ten evaluations. Figure D-3C shows a statistical summary over the ten time series for each time point. Note that these are different from the results shown in Figure D-2, where the statistics describe the temporal variability and are based on the epoch ensemble, instead of the replicated time series.

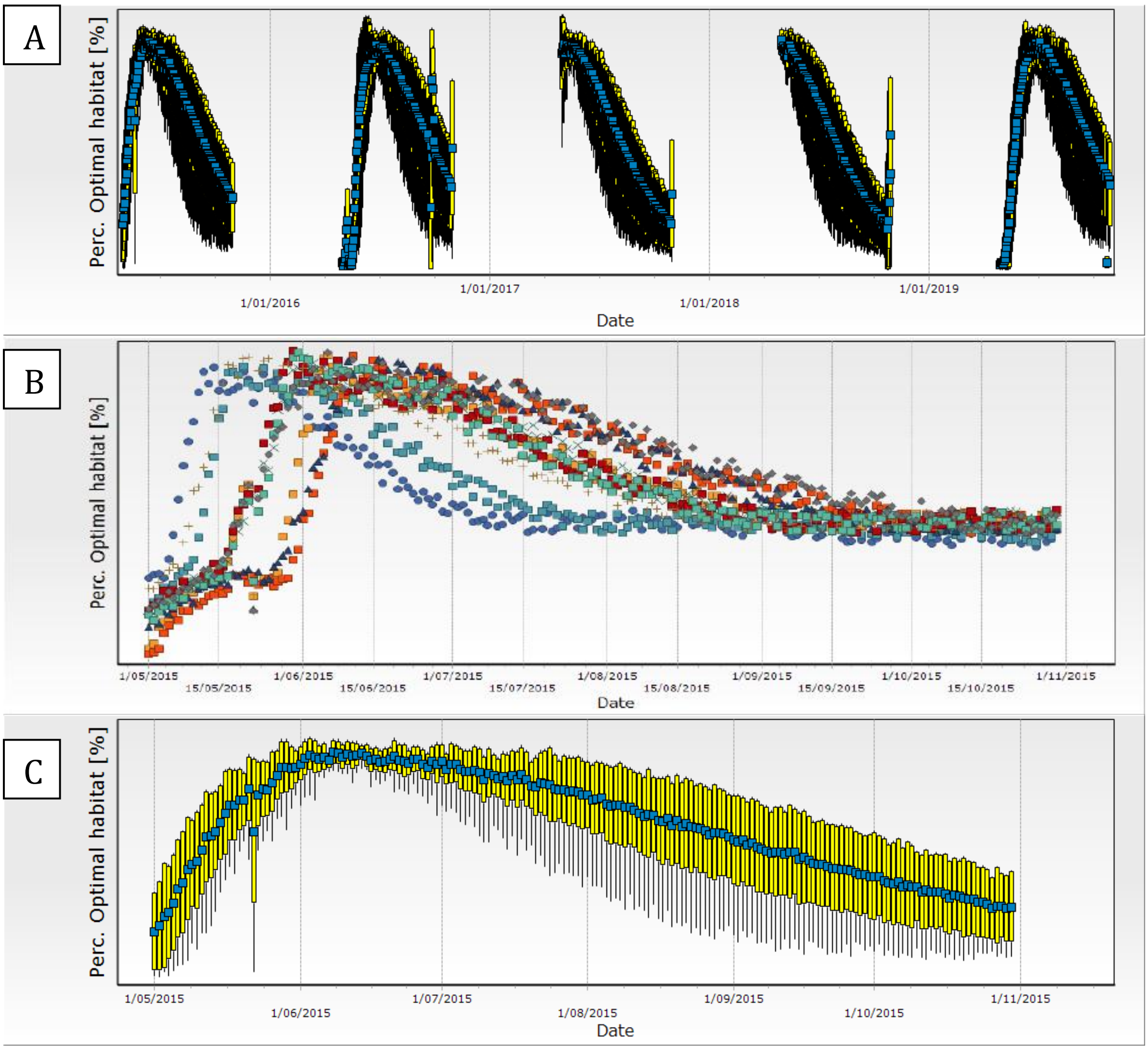

Figure D-3 Graph A shows the results of the last five years of the scenario run of ten replicated evaluations. Graph B zooms in on the first year to show details. Graph C shows a statistical summary of the results in graph B; the blue squares represent the mean values over the stochastic replicates, the yellow bars show the standard deviation of the realised series at each time step.

The results in Table D-2are based on five *epochs* within *one* sampled time series. The results in Table D-3 are calculated using the statistics of each of the ten realised time series and turn them into a statistic over the realisations themselves (not the epochs).

Table D-3 These statistics describe the variability caused by parameter-uncertainty in ten realised scenario evaluations.

Scenario	Statistic	N	# t-pts	Mean	St Dev	CV	Min	Max	Q10	Q25	Q50	Q75	Q90
1 No economic activity	Realisations mean	10	915	24.9	11.3	47.5	0.054	42.7	9.49	16.1	25.9	34.9	38.6
Epochs: No	Realisations st dev			4.19	0.908	13.5	0.039	0.27	4.25	6.64	6.57	2.84	1.01
	Realisations CV			16.83	8.04	28.42	71.78	0.62	44.78	41.24	25.37	8.14	2.62

Example of interpreting these results: Comparing the Q10 values from Table D-3 (9.5 ± 4.25 with CV of 44.8) with Table D-2 (11.7 ± 3.4 with CV of 22.8) and applying a t-test with unequal standard deviation and sample size reveals that the hypothesis of unequal Q10 mean values is to be discarded, and we would treat the means them as equal. This makes sense as they are generated by the same process.

In this example, the CV value of the epoch-based mean Q10 values (temporal uncertainty) is about half the size of the realisation-based mean Q10 (ignorance-based uncertainty) and we could use such knowledge to make decisions on how to manage our ignorance as well as how to manage the natural resources.

D.2.2 SAMPLED TIME SERIES: COMBINED EPOCH AND ENSEMBLE STATISTIC

In this Section, the temporal variability (ensemble-based) and ignorance-based (sample-based) results are combined. Each of the ten time series resulting from the stochastic samples is divided into five epochs, resulting in a total 50 epochs. Figure D-4A shows 15 of those 50 epochs as line graphs, and Figure D-4B shows the (now familiar) statistical summary over time.

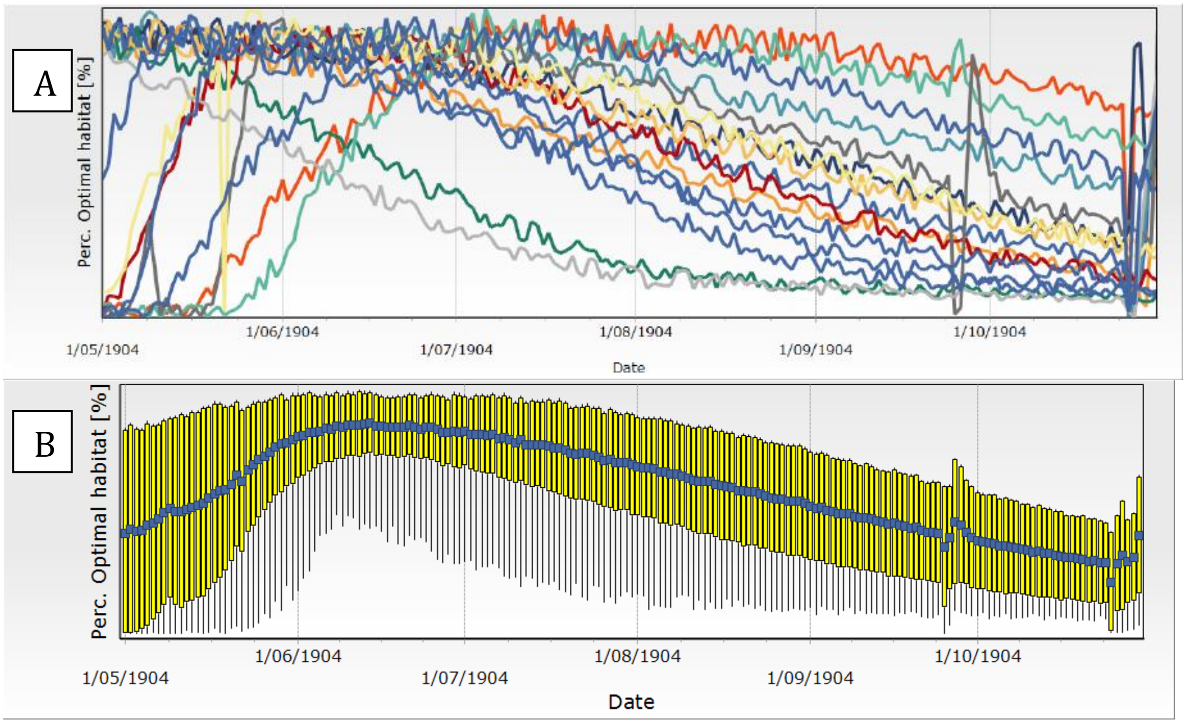

Figure D-4 Graph A shows the individual five epochs of each of the ten realisation results. To keep the graph legible, only the first 15 of the 50 epochs are shown. Graph B shows the uncertainty of the combined 50 epochs over the whole ENSEMBLE.

Table D-4 tabulates the results of the statistical analysis over the 50 epochs. Summarising the Q10 results of the three statistics: *ensemble* (cf. Table D-2): 11.7 ± 3.37, CV 28.8, *realisations* (Table D-3), 9.49 ± 4.25, CV 44.78, and *realisations + ensemble* (cf. Table D-4), 9.2 ± 5.35, CV 58.15.

Performing a t-test on the means (with unequal standard deviation) shows that the three mean Q10 values are not significantly different, as can be expected. Even though CV values without information about the underlying distributions do not allow rigorous statistical testing to determine whether their difference is significant, a possible conclusion from the example given here is that the CV increases with in increasing number of uncertainty sources.

Finally, the approach described in this Appendix opens up ways to assess two (modelled) sources of uncertainty, and would enable us to look at their relative importance. This would be the first step in selecting appropriate management actions to deal with different sources of uncertainty, as mentioned in the introduction of this Appendix.

Table D-4 By dividing each of the ten scenario realisations into five epochs and combining them, we end up with 50 epochs over which to calculate the statistics.

Scenario	Statistic	N	# t-pts	Mean	St Dev	CV	Min	Max	Q10	Q25	Q50	Q75	Q90
1 No economic activity	Realisations + Ensemble mean	50	183	24.9	11.1	47.1	2.8	41.9	9.2	16.4	26	34.7	38.5
Epochs: Yes	Realisations + Ensemble StDev			4.55	1.53	14.7	3.9	0.99	5.35	6.86	6.82	3.71	1.69
	Realisations + Ensemble CV			18.27	13.78	31.21	139.29	2.37	58.15	41.83	26.23	10.69	4.39

D.3 EQUATIONS

The statistics in this Appendix are focused on classifying and quantifying the sources of uncertainty.

D.3.1 DETERMINISTIC MODE STATISTICS

Some nomenclature:

$\{x(I_i)\}$: ensemble of epochs $x(I_i)$
I_i: time interval i of length τ
$I_i = I(t_{i.\tau}, t_{(i-1).\tau})$

Statistical descriptors $D(\{x(I_i)\})$ for each epoch in the ensemble. We used mean, standard deviation, min, max, Q10, Q25, Q50, Q75 and Q90.

For each$_i$ statistical descriptor D_j we calculate the ensemble mean, standard deviation and CV.

$$\hat{\mu}_j = \frac{1}{N_e} \sum_{i=1}^{N_e} D_j(\{x(L_i\})$$

$$\hat{\sigma}_j = \sum_{i=1}^{N_e} \frac{[D_j(\{x(L_i\}) - \hat{\mu}_j)]^2}{N_e - 1}$$

$$CV_j = \begin{cases} \frac{\hat{\mu}_j}{\hat{\sigma}_j} : \hat{\sigma}_j \neq 0, \\ 0 : \hat{\sigma}_j = 0 \end{cases}$$

where N_e is the number of epochs in time series *x*.

D.3.2 STOCHASTIC MODE

In stochastic mode, a range of ensembles emerge:

- ensemble of sampled time series, used to explore ignorance-based uncertainty $\{x(t)\}$
- ensemble of epochs over the average of sample time series $\{\overline{x}(I_i) : i \in 1, N_e\}$, used to explore temporal variability
- ensemble of epochs over all sample time series $\{x_j(I_i) : (i \in 1, N_e), (j \in 1, N_s)\}$ where N_s is the number of sample time series. This ensemble explores the combination of ignorance and temporal variability, and
- ensemble of epochs in each sample function. Currently not used.

Each of the first three ensembles is processed in the way as described in the previous Section.

APPENDIX E DALY CATCHMENT WATER-RELATED CHARACTERISTICS

E.1 RAINFALL

The major source of water input in the Daly catchment is rainfall (precipitation). Rainfall within the Daly River catchment varies significantly both temporally and spatially. Due to the strong wet-dry seasonality, about 96% of the rain falls within the wet season (from November to April inclusive) as shown in Figure E-1 and Figure E-2.

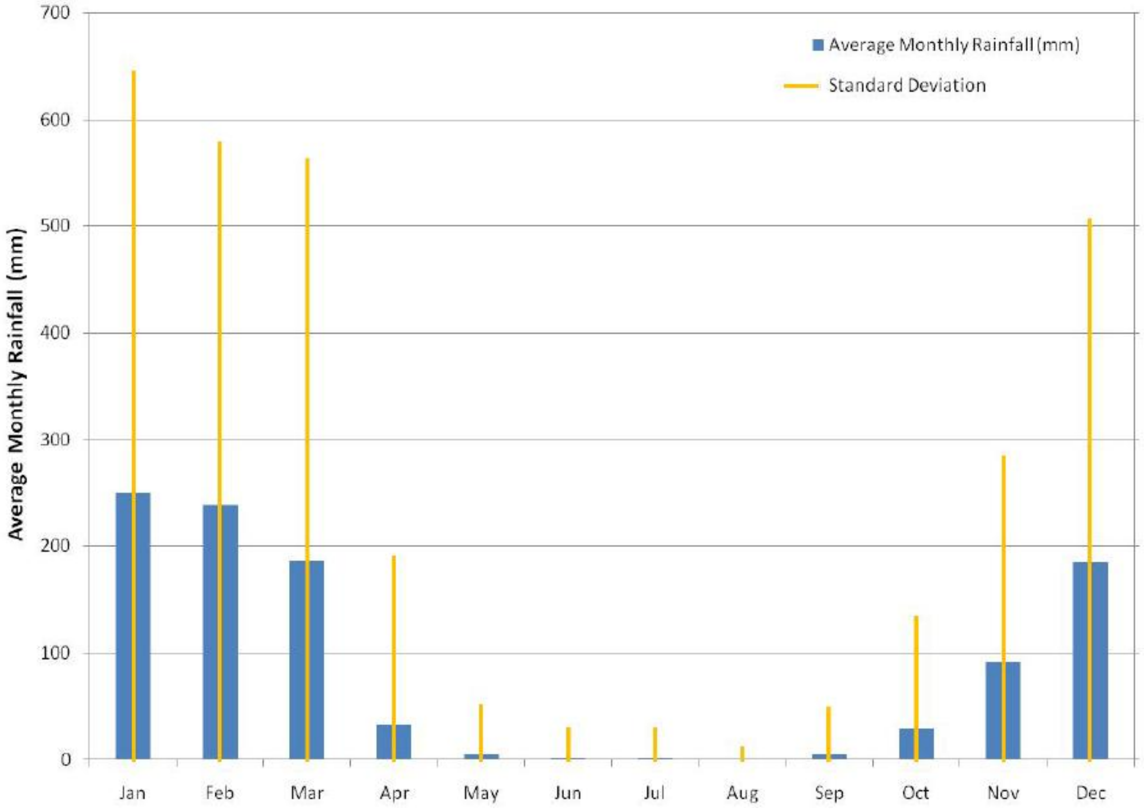

Figure E-1 Temporal Variation in Average Monthly Rainfall: Daly Catchment

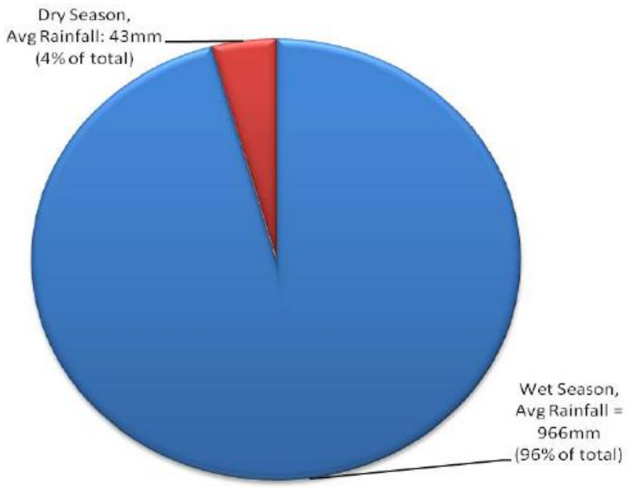

Figure E-2 Average Rainfall Across the Wet and Dry Seasons: Daly Catchment

The spatial variation in rainfall across the catchment is also significant, as shown in Figure E-3. Annual rainfall is greatest in the north and north-western catchment areas with these areas receiving on average up to 1460mm of rain per year. The southern areas of the catchment receive significantly lower annual rainfall depths down to about 700mm per year.

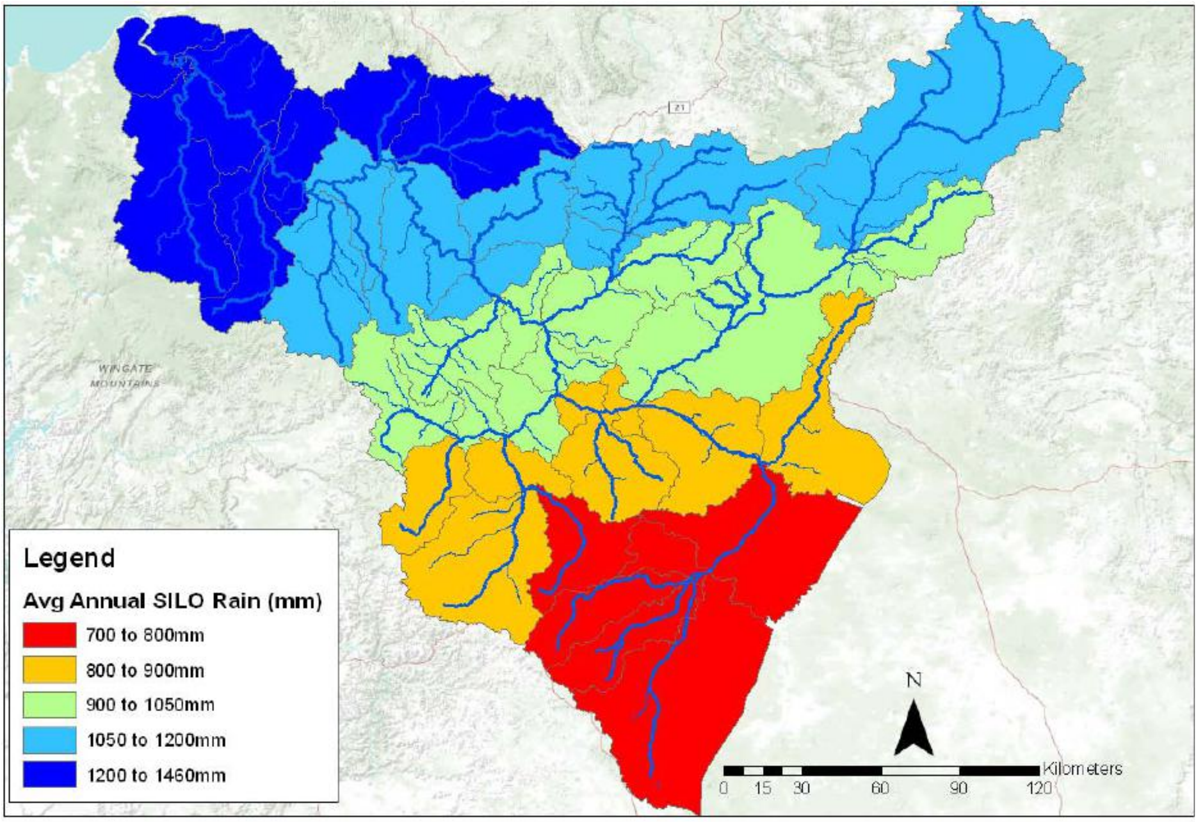

Figure E-3 Spatial Variation in Average Annual Rainfall: Daly Catchment

E.2 EVAPOTRANSPIRATION

Evapotranspiration is the loss of water to the atmosphere due to *evaporation* from the soil, waterbodies and interception sites and *transpiration* from plants. Potential evapotranspiration (PET) is the theoretical maximum evapotranspiration possible if water available was equal to energy available.

Evapotranspiration in the Daly River catchment is significant and represents a relatively large of loss of water to the system, particularly in the dry season when rainfall is low. As shown in Figure E-4, which has the same vertical scale as Figure E-1 to allow comparison, there is only a slight temporal variation in average potential evapotranspiration (PET). Average PET ranges from a maximum of about 200mm/month in the wet season to a low of about 120mm/month in the dry season. There is little spatial variation in average PET across the Daly catchment, as shown in Figure E-5. Average annual PET varies spatially across the Daly catchment from a low of 1900mm per year to a high of 1990mm per year. Given the large variation in rainfall both temporally and spatially, the variation in PET is relatively very small.

As average annual PET (1960mm) greatly exceeds the average annual rainfall (1030mm), the Daly River catchment is generally regarded as water limited. This is true across all months with the exception of January, February and March, during which the average rainfall exceeds the average monthly PET, as shown in Figure E-6. On average during these 3 wet season months, the system is energy-limited. That is, there is more water than energy available to evapotranspire it and *potential* evapotranspiration is likely to be similar to *actual* evapotranspiration. (CSIRO, 2009)reported similar findings during the assessment of the Daly River catchment.

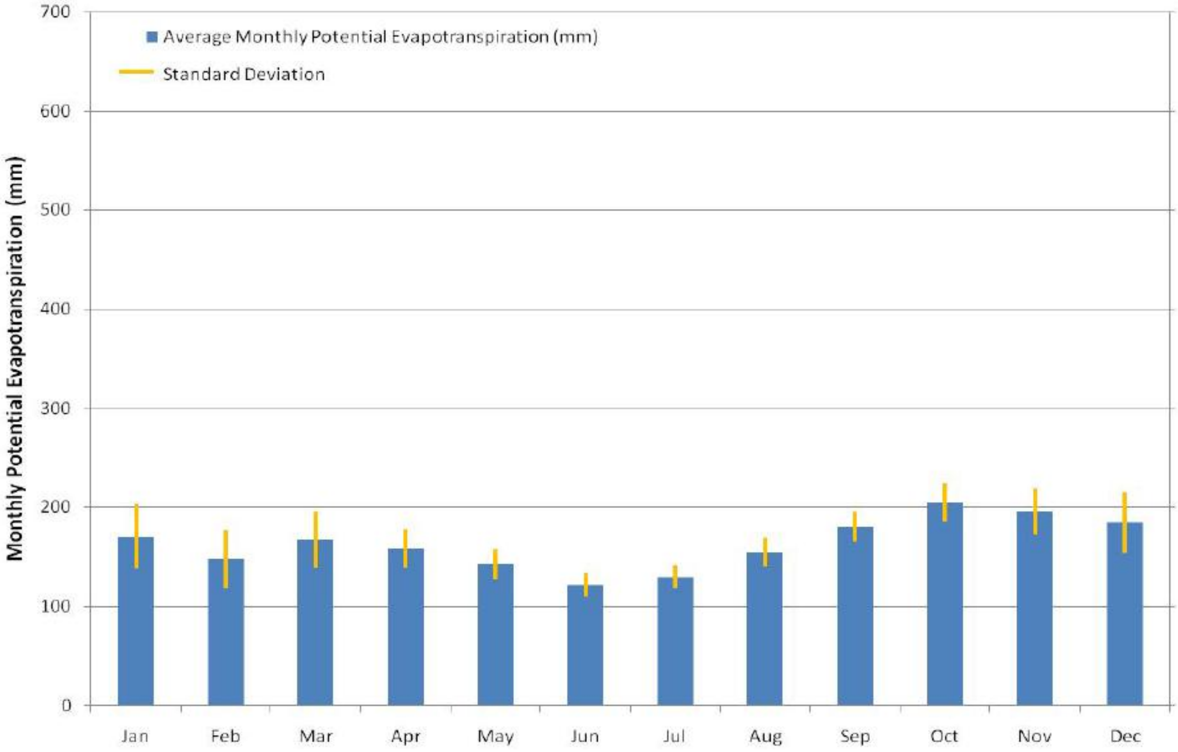

Figure E-4 Temporal Variation in Average Potential Evapotranspiration (PET): Daly

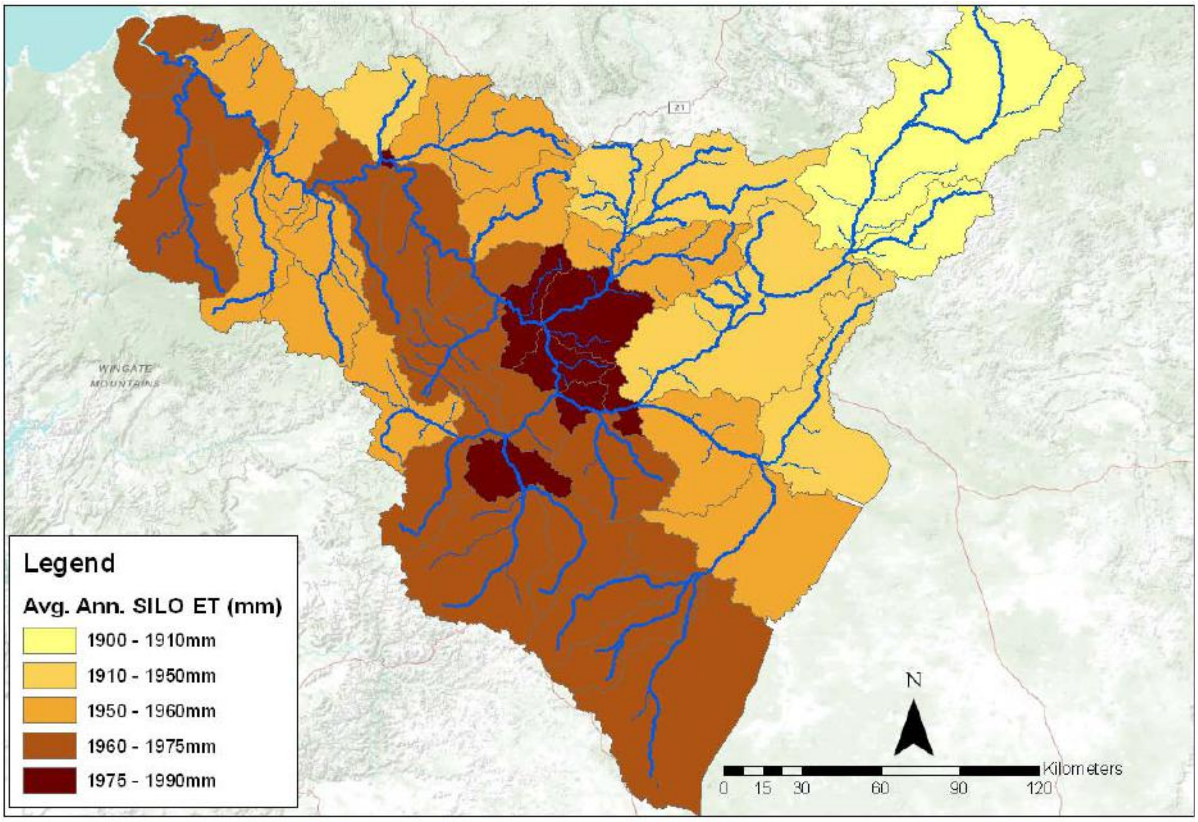

Figure E-5 Spatial Variation in Average Annual PET: Daly Catchment

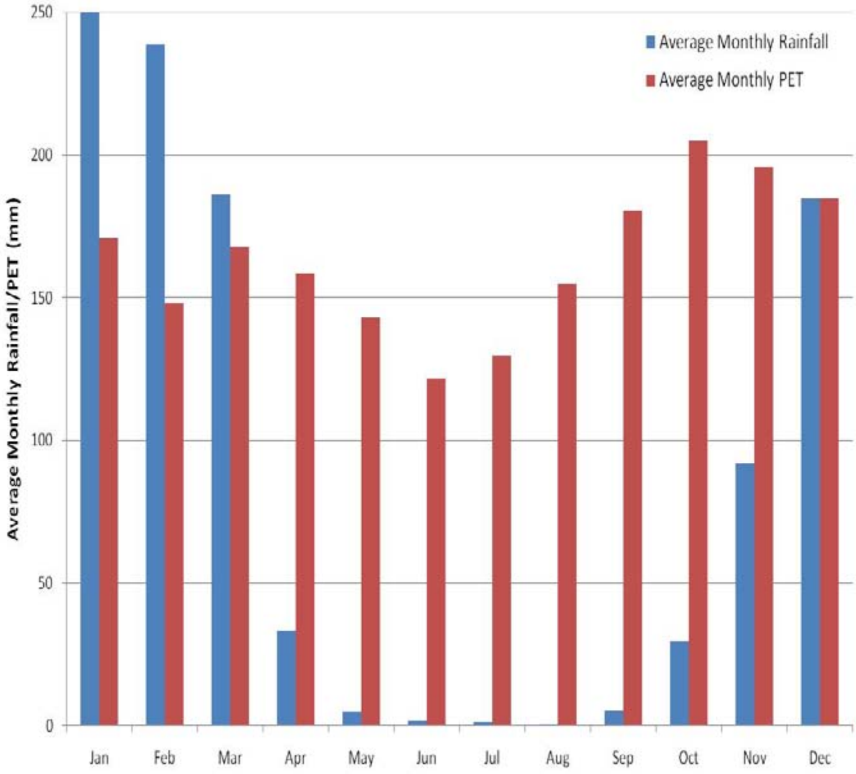

Figure E-6 Comparison of Average Monthly Rainfall & PET: Daly Catchment

E.3 GROUNDWATER

The Daly Basin is a geological basin found under the ground surface of the Daly River catchment. It is one of three basins found across the Northern Territory with the remaining two being the Wiso Basin and the Georgina Basin (Tickell, 2009) . The location of these basins is shown in Figure E-7. The Daly Basin contains two major limestone formations: the Oolloo Dolostone and the Tindall Limestone aquifers. These are separated by an impervious siltsone formation known as the Jinduckin formation. Thus, as shown in Figure E-8, the Daly Basin contains three distinct layers from top to bottom: the Oolloo, the Jinduckin and the Tindall. (Tickell, 2009) indicates that the maximum recorded thickness (depth) of the basin is 709m. The maximum recorded thickness of the Oolloo, Jinduckin and Tindall layers is 225m, 356m and 204m respectively.

The two limestone layers within the Daly geological basin (the Oolloo and the Tindall) host widespread productive aquifers. An aquifer is an underground body of rock or sediment that holds and allows water to move through it (Tickell, 2009). Water held or moving through the aquifer is typically called groundwater.

E.3.1 RECHARGE

Recharge of the aquifer occurs when surface water infiltrates through soil layers into the aquifer system, thus becoming groundwater. The mechanisms by which this occurs are: diffuse, point source and stream bed. The amount of recharge depends primarily upon the amount of rainfall, losses due to evapotranspiration, soil type and local geology. Due to the reliance of recharge upon rainfall, recharge of the Daly aquifers occurs in the wet season. Local geological factors affecting recharge include the depth of the aquifer below the ground surface and the type of overlying layers. In the Daly, some areas of the aquifers are covered by Cretaceous aged clay and sandstone, making the aquifer “confined”. Recharge to the aquifer still occurs through these rocks, but at a reduced rate compared to an unconfined section of aquifer. Recharge is negligible in areas of the Tindall aquifer confined by the Jinduckin formation, as this formation is impermeable to water moving downwards (Tickell, 2009).

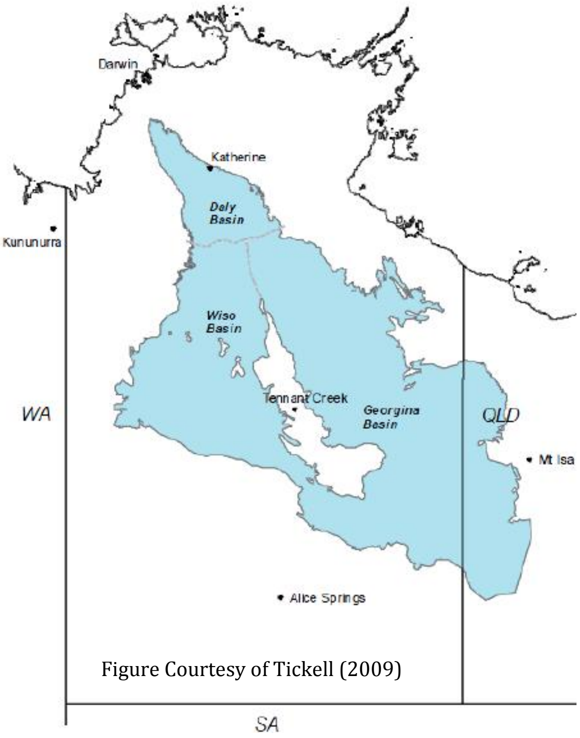

Figure Courtesy of Tickell (2009)

Figure E-7 Limestone Basins Across Central-Northern Australia (Tickell, 2009)

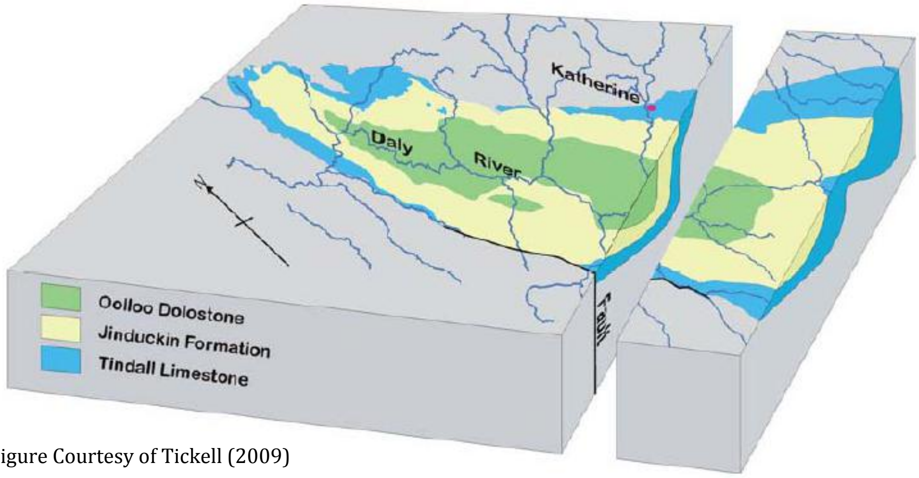

Figure Courtesy of Tickell (2009)

Figure E-8 3D View of the Daly Geological Basin (Tickell, 2009)

E.3.2 GROUNDWATER FLOW

Flow through the aquifer is governed by gravity (that is, water moves from a higher elevation to a lower elevation) and the ease with which the water can move though the cavities and fractures within the aquifer rock. Flow in the Oolloo aquifer is relatively simple with groundwater moving in a north-westerly direction from higher to lower elevations, as shown in Figure E-9. Discharge from the aquifer occurs primarily to the middle reaches of the Daly River with some smaller discharge to the lower reaches of the Katherine River. Flow in the Tindall aquifer is more complex as the majority of this aquifer is confined by the Jinduckin formation. Recharge to the aquifer can only occur on the fringes of the Tindall formation and groundwater takes the most direct path to a discharge zone. This has resulted in at least six separate groundwater catchments (Tickell, 2009). Figure E-10 shows that the main rivers into which the Tindall discharges are the Roper, Katherine, Flora, Edith, Fergusson, Douglas and Daly Rivers.

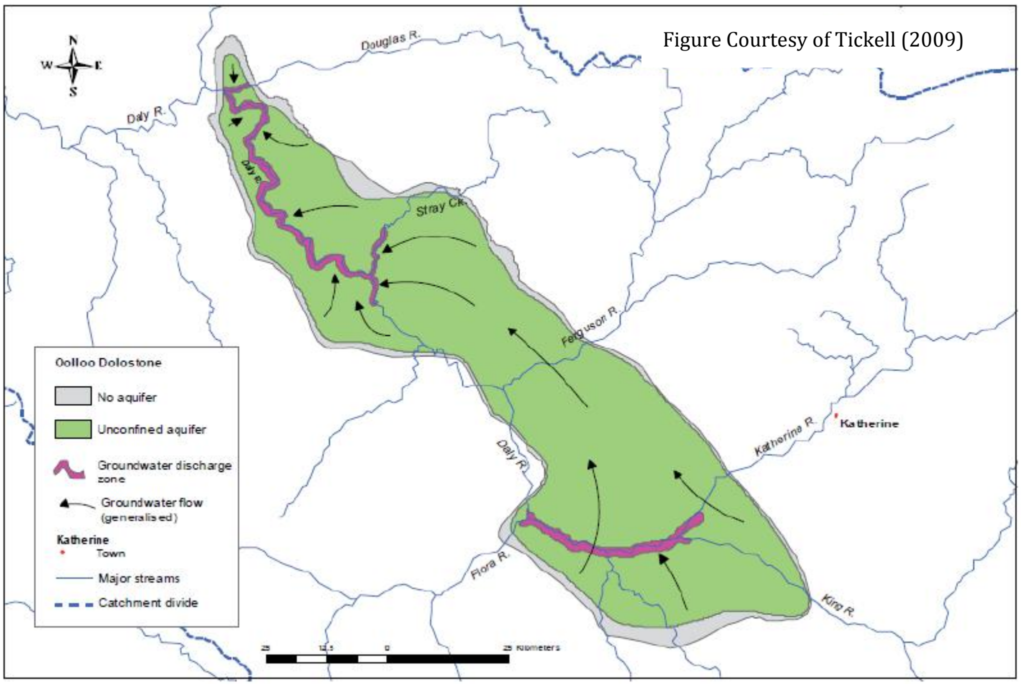
Figure Courtesy of Tickell (2009)

Figure E-9 Oolloo Aquifer: Groundwater Flow & Discharge Zones (Tickell, 2009)

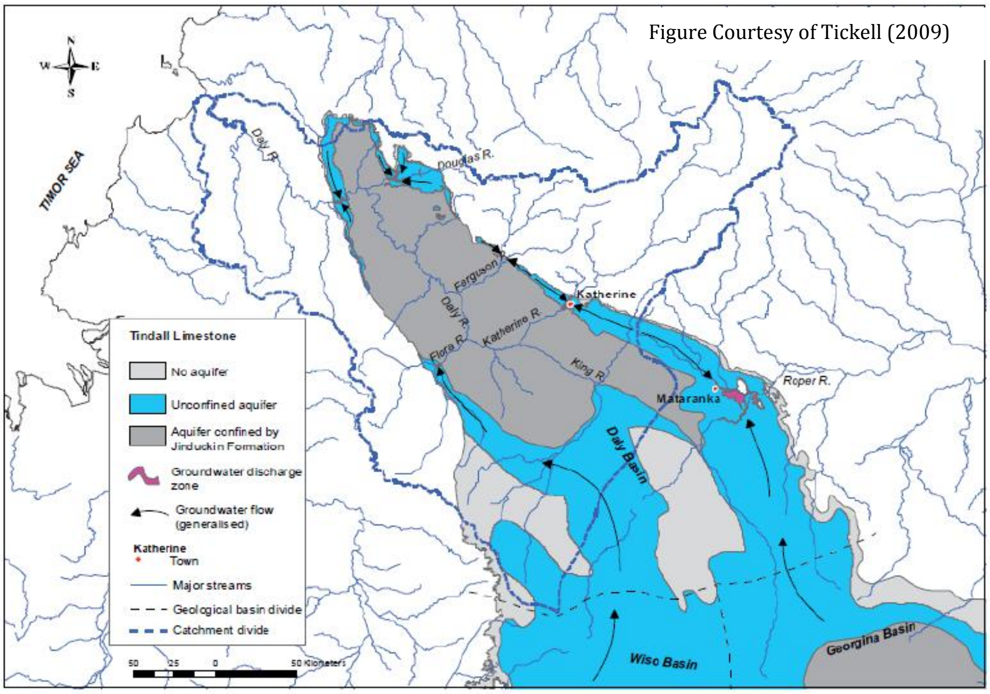
Figure Courtesy of Tickell (2009)

Figure E-10 Tindall Aquifer: Groundwater Flow & Discharge Zones (Tickell, 2009)

E.3.3 GROUNDWATER DISCHARGE

Discharge from the aquifer occurs when groundwater exits the aquifer and returns to the surface. The component of river flow that is sourced from groundwater discharge is called *baseflow*. Discharge can occur at any time of year but it has far greater relative significance through the dry season in the Daly catchment. Discharge in the Daly occurs via two main mechanisms: stream bed seepage and discrete springs (such as at Katherine thermal pool). Tickell (2009) observes that it is generally quicker to get water into an aquifer system than it is to get water out. In the Daly, recharge takes place over a 3 to 4 month period, while it can take more than 12 months for that water to discharge. This slow discharge allows rivers in the Daly catchment to flow year round, making the Daly a perennial system. It is unusual for rivers within the wet-dry tropics to flow all year round as they typically become dry when rain and runoff cease. Thus, the perennial flow supports a unique and diverse ecosystem.

Figure E-11 summarises the hydrogeological processes in the Daly catchment. Streamflow measurements at the end of the dry season provide an indication of the groundwater contributions to surface flow for the years of measurement.

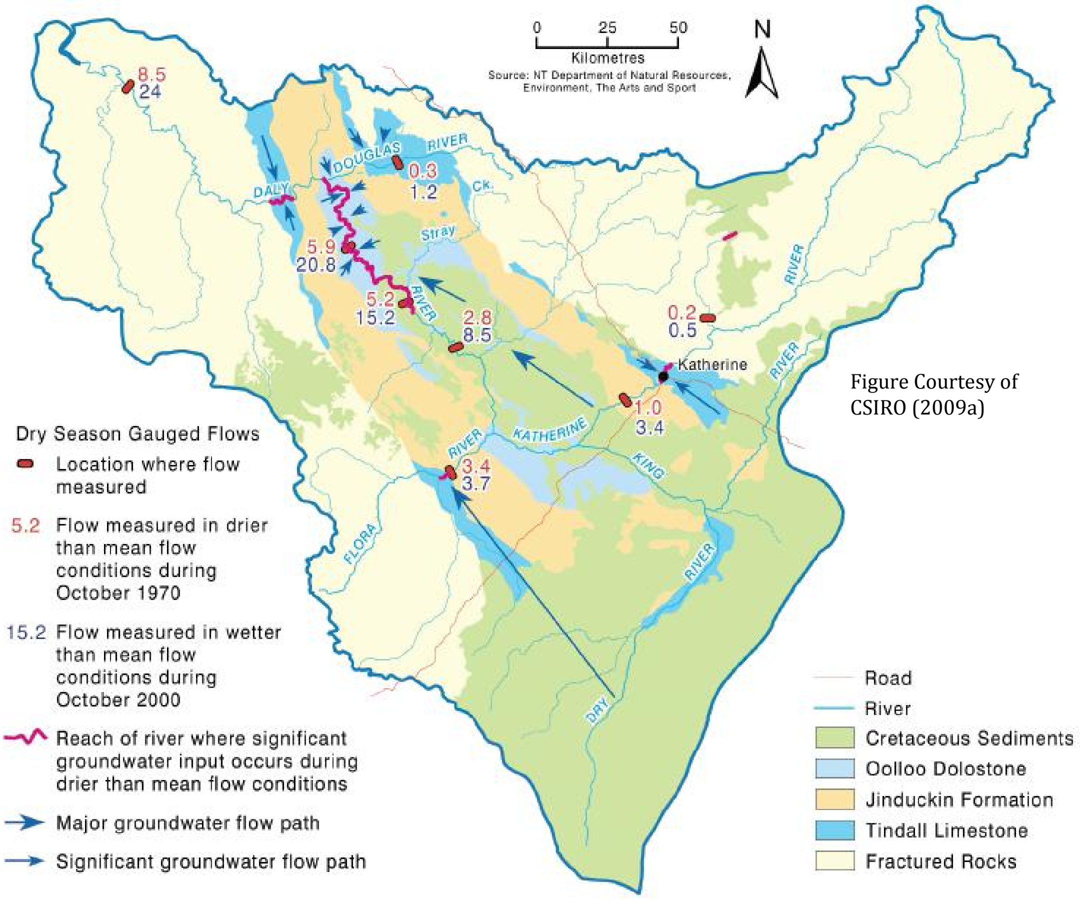

Figure Courtesy of CSIRO (2009a)

Figure E-11 Daly Catchment Hydrogeology (CSIRO, 2009)

APPENDIX F WATER MODEL CALIBRATION

F.1 FLOW DATA

Flow data is the primary historical record set against which the catchment water model output is compared during calibration. Calibration to flow occurs when a time series of *observed*[2] flow is compared with the time series of *modelled* flow. Calibration aims to minimise the differences between the *observed* flow and the *modelled* flow. One means of minimising this difference is to adjust the model parameters (within realistic bounds) to allow the modelled flow to better reflect the observed flow. However, it is important to note that the process of calibration may also lead to the modeller questioning the schematisation of the model and/or the accuracy of the measured input data itself. Observed flow at a particular location is compared to modelled flow from within the model at the same location.

Project 1.4 has sourced available observed daily flow data from NRETAS for each flow gauge station within the Daly River catchment. The flow gauges within the Daly catchment operated by NRETAS are shown in Figure F-1.

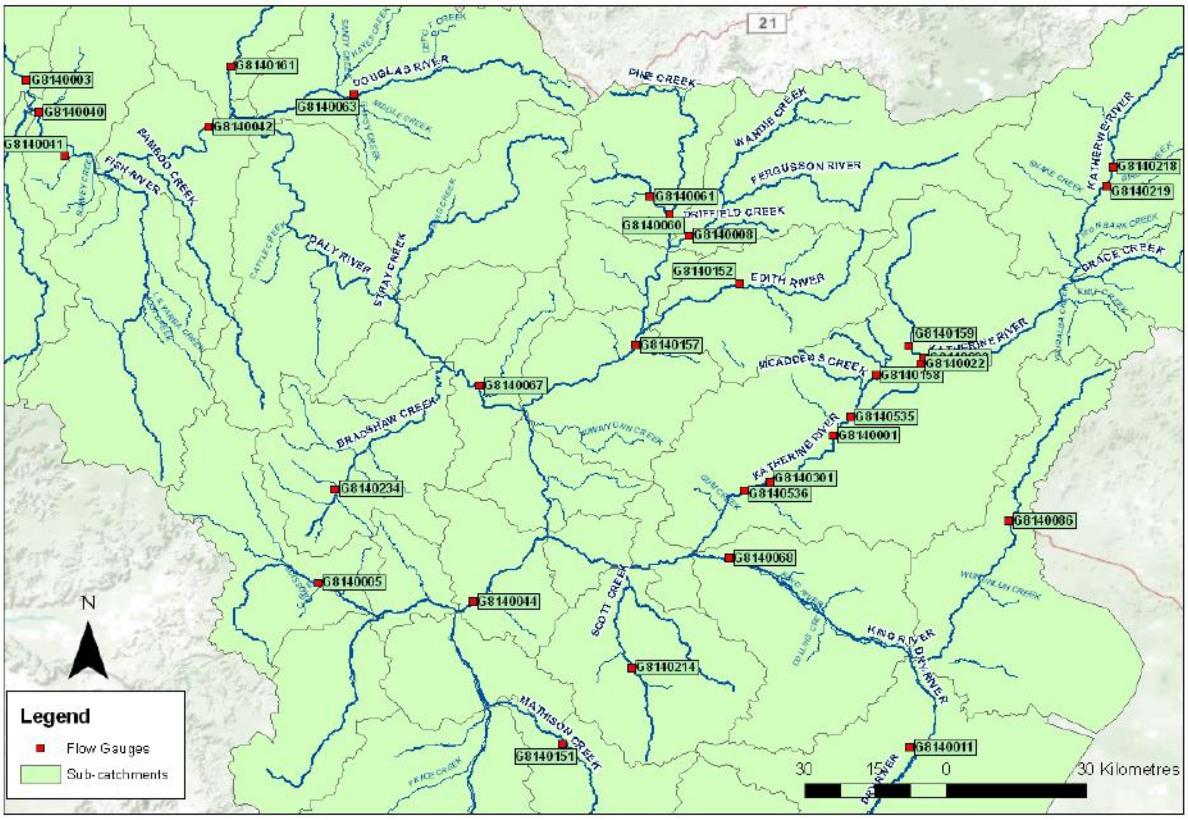

Figure F-1 Location of NRETAS Flow Gauges within the Daly River catchment

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[2] Flow is **not** directly measured; it is derived from recorded water level. For the purpose of distinguishing between a real world flow and a modelled flow, the terminology of *observed* flow (derived from measurements in the field) and *modelled* flow (output results from the water model) is adopted here.

Rating information for each gauge has also been obtained to provide an indication of reliability. P1.4 has undertaken statistical and critical review of the flow records in order to determine which records and stations are acceptable for the purpose of calibration and calculation of flow statistics.

NRETAS assigns a quality code to each daily observed **stage** value. Only stage (and corresponding derived flow) records that are of acceptable quality are included in the calibration data. Peter Jolly (ex-NRETAS and currently Jolly Consulting) and Des Yinfoo (NRETAS, pers. comm.. 17 Dec 2010) have advised that the quality code assigned to each recorded stage value relates to the **recorded stage only**. The code does not provide information on the quality of the derived discharge. It is possible that the stage record is of acceptable quality but that the derived discharge is not. This may be the case due to problems with the rating curve or similar. This issue is dealt with in a gauge-by-gauge basis, based on anecdotal information provided by Peter Jolly (ex-NRETAS, pers. comm.. 17 Dec 2010).

As a starting point in the assessment of acceptable quality data, this study uses the same assumptions as CSIRO (Petheram et al., 2009). These assumptions are summarised in Table F-1. Figure F-2 shows the proportion of acceptable flow data for the period 1980 to 2009. Figures contained in Appendix G demonstrate the acceptability of flow gauge data at each gauge station based on the quality codes described above. Further details on each the flow gauge stations are provided in the table in Appendix G, with a summary provided in this Section in Table F-2.

Table F-1 Acceptable Flow Data Based on Quality Codes

NRETAS Flow Quality Codes	Description	Acceptability
<96	Good to Satisfactory	Acceptable
175	Dry – below orifice (assume zero flow)	Acceptable
176	Wet – below orifice (assume zero flow)	Acceptable
All others	Poor data, rating under review, exceeded rating lookup table etc	Unacceptable

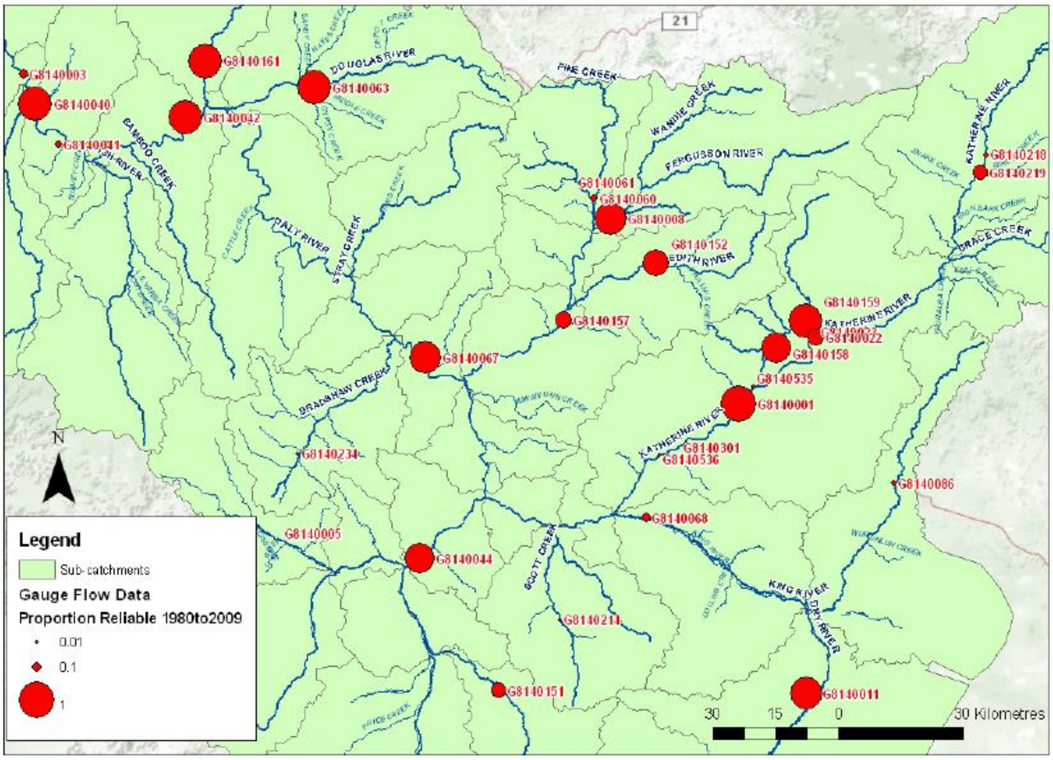


Figure F-2 Proportion of Acceptable Flow Data in the Daly for Period 1980 to 2009

Table F-2 Summary of Daly River Flow Gauges

Site	River	Location	Status	Catchment Area (km^2)	First Data Available	Last Data Available
G8140001	**Katherine River**	**Railway Bridge**	**Open**	**8,640**	**Mar-1957**[a]	**Aug-2009**
G8140003	Daly River	Police Station	Open	48,400	Jun-1952	Jan-2010
G8140005	Flora River		Closed	829	Nov-1967	Nov-1986
G8140008	**Fergusson River**	**Railway Bridge**	**Open**	**1,490**	**Jun-1957**	**Jul-2009**
G8140011	**Dry River**	**Manbulloo Boundary**	**Open**	**6,290**	**May-1967**	**Nov-2008**
G8140022	Katherine River	Nitmilluk Centre	Open	6,400*	Oct-1998	Oct-2009
G8140023	Katherine River	Gorge Caravan Park	Closed	6,404	Mar-1973	Oct-2004
G8140040	**Daly River**	**Mt Nancar**	**Open**	**47,100**	**Jan-1967**	**Jul-2009**
G8140041	Daly River	Gourley	Closed	46,300	Nov-1959	Aug-1981
G8140042	**Daly River**	**2km d/s Beeboom Crossing**	**Open**	**41,000**	**Nov-1981**	**Oct-2009**
G8140044	**Flora River**	**U/S of Kathleen Falls**	**Open**	**5,900**	**Jan-1966**	**Jul-2009**
G8140060	Cullen River	Rail Bridge	Open	445	Jan-1959	Jul-2009
G8140061	Cullen River		Closed	306	Oct-1957	May-1978
G8140063	Douglas River	D/S Old Douglas Homestead	Open	842	Sep-1957	Oct-2009
G8140067	**Daly River**	**U/S Dorisvale Crossing**	**Open**	**35,800**	**Aug-1960**	**Jul-2009**
G8140068	King River	Vic Hwy	Open	11,000	Nov-1959	Feb-2010

Site	River	Location	Status	Catchment Area (km^2)	First Data Available	Last Data Available
G8140086	King River		Open	484	Jan-1964	Feb-2010
G8140151	Mathison Ck	Vic Hwy	Closed	725	Dec-1963	Jun-1987
G8140152	Edith River	U/S Stuart Hwy	Open	590	Jun-1962	Jul-2009
G8140157	**Fergusson River**	**U/S Bondi Ck**	**Open**	**4,200***	**Sep-2000**	**Oct-2009**
G8140158	McAddens Creek	Dam Site	Open	133	Nov-1962	Aug-2009
G8140159	Seventeen Mile Creek	Waterfall View	Open	619	Nov-1962	May-2009
G8140161	Green Ant Creek	Tipperary	Open	435	Aug-1966	Oct-2009
G8140214	Scott Creek		Closed	528	Jan-1969	Jun-1987
G8140218	Katherine River	Mt Ebsworth	Closed	3,700	Sep-1964	Jan-2000
G8140219	Katherine River	D/S Birdie Ck Confluence	Open	4,080*	Aug-1997	Aug-2009
G8140234	Bradshaw Ck		Closed	240	Aug-1965	Jun-1981
G8140301	Katherine River	Galloping Jacks	-	N/A	Aug-1974	Sep-2008
G8140535	Katherine River	Ironwood Station	Open	7,800*	Dec-2008	Aug-2009
G8140536	Katherine River	Wilden Station	Open	9,300*	Aug-2008	Aug-2009

* Catchment area not available from NRETAS – estimated instead.

[a] Prior to 1960, G8140001 was located upstream of the railway bridge at the works yard and the river heights were read by a gauge reader (NRETAS, 2000).

Bold rows indicate that model calibration undertaken at these gauge sites

F.2 PRELIMINARY CALIBRATION OF THE WATER MODEL

F.2.1 BACKGROUND

Calibration of the Daly catchment water model has been undertaken using manual calibration techniques, moving from the upper catchments to the lower catchments. While SIMHYD models are most commonly calibrated using automated techniques (eg Chiew et al., 2010, Tan et al., 2005, Vaze et al., 2008, etc), manual calibration in the Daly catchment is expected to provide better results due to the following factors.

- The large size of the Daly catchment,
- The availability of flow gauges throughout the catchment allowing progressive calibration of sections of the catchment water model
- The inclusion of flow routing algorithms (and associated parameters) between sub-catchments, and
- The relatively small number of calibrations to be undertaken as part of this project (8 Daly Catchment calibration points compared to (for example) about 300 (Chiew and Siriwardena, 2005a) or 184 (Reichl et al., 2009)).

The Nash-Sutcliffe Coefficient of Efficiency (NSE)(Nash and Sutcliffe, 1970) is used to provide an indication of model performance. The NSE equation is provided below.

$$NSE = 1 - \frac{\sum_{t=1}^{T} (Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T} (Q_o^t - \overline{Q_o})^2}$$

Where Q_o is observed discharge, $\overline{Q}$ is mean of the observed discharge, Q_m is modelled discharge, and Q_o^t is observed discharge at time t.

NSE can range from -∞ to 1. A NSE of 1 indicates a perfect fit between modelled discharge and observed discharge. An NSE of 0 indicates that the model discharge is as accurate as the mean of the observed data and an NSE of <0 indicates that the mean of the observed data is a better predictor of observed flow than the model. Thus, the closer NSE is to 1, the better the model is at achieving the observed flows. In general, an NSE of above 0.6 indicates a satisfactory calibration and an NSE of above 0.8 indicates a good calibration.

F.2.2 RESULTS

The calibration of the Daly River catchment water model is regarded as preliminary as the components of the groundwater model are not yet finalised. Preliminary calibration has been undertaken on the observed flows for the gauges bolded in Table F-2. Preliminary calibration results at some of these gauges are summarised in Figure F-3 and Table F-3. Table F-3 also provides a subjective rating for the calibration at each gauge.

In general, preliminary calibration of the water model to monthly flow totals is very good. However, as explained previously, the water model needs to produce daily flows with reasonable accuracy. In general, preliminary calibration of the water model to daily flows is good. However, preliminary calibration to daily flows in the dry season is poor. As dry season flows are of critical importance in the Daly River (refer to Section 4.3.2), it is necessary to improve the water model's ability to reproduce these flows. With this aim in mind, the groundwater component of the water model is currently being upgraded to enable the model to better reproduce the groundwater behaviour and associated dry season flows.

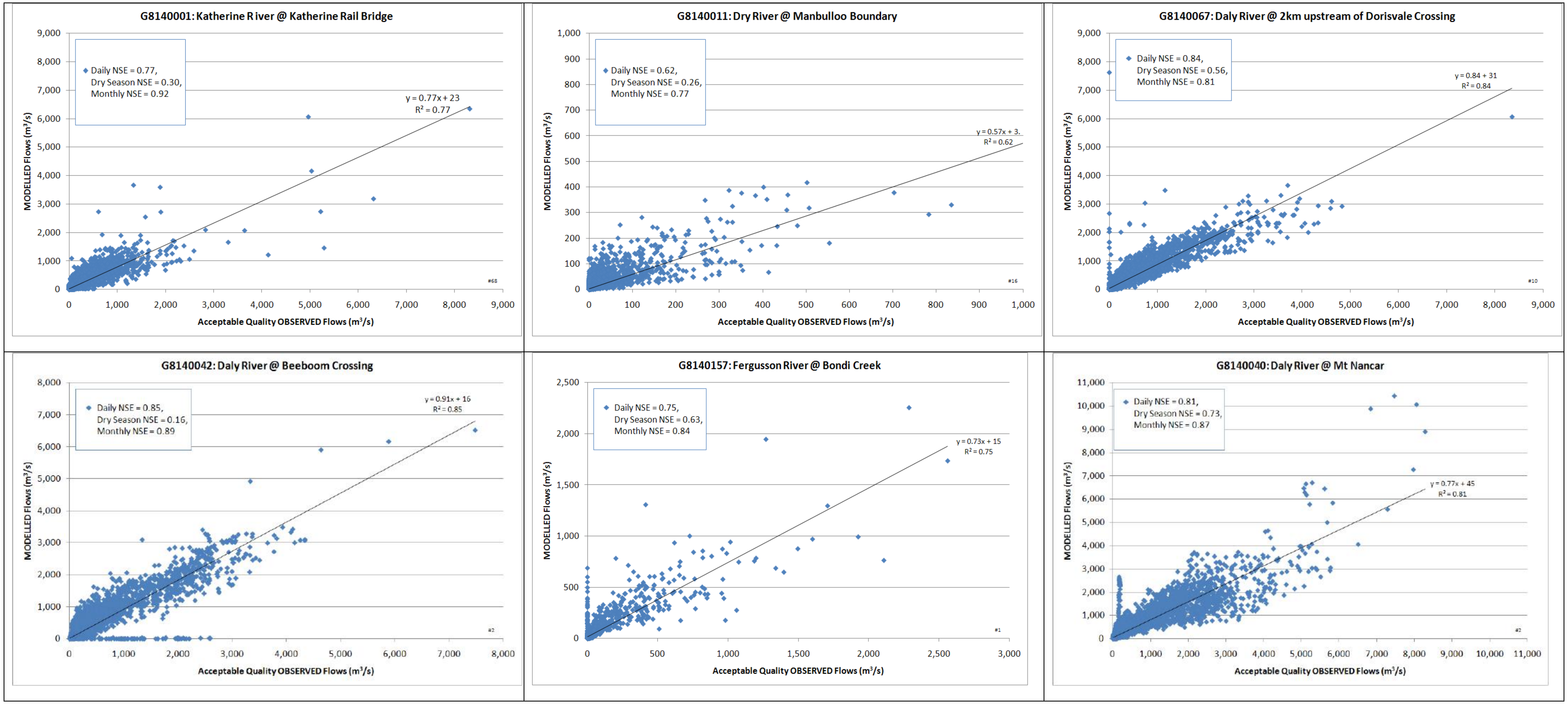


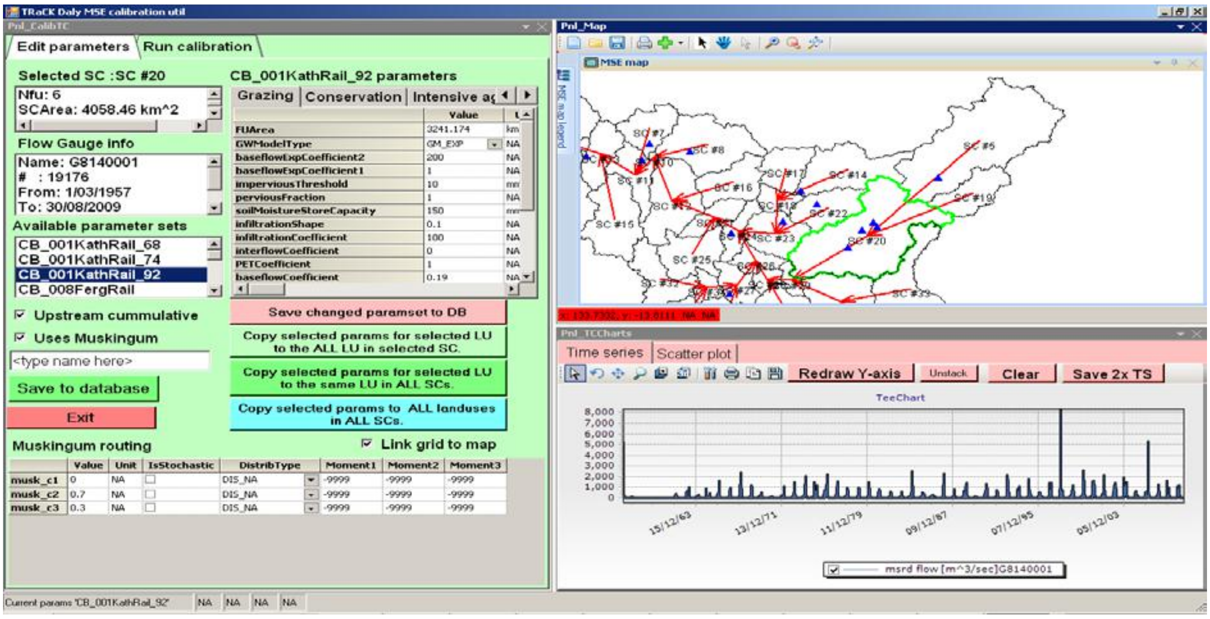
Figure F-3 Preliminary Calibration Scatter Plot Examples

Table F-3 Summary of Preliminary Calibration NSE Values

Gauge ID	River	Location	Calibration to Daily Flows		Calibration to Daily Flows in Dry Season Only		Calibration to Monthly Flows	
			Daily NSE	Calibration Rating	Daily NSE	Calibration Rating	Daily NSE	Calibration Rating
G8140001	Katherine	Rail Bridge	0.77	Good	0.3	Poor	0.92	Excellent
G8140008	Fergusson	Rail Bridge	0.56	Poor	0.11	Poor	0.88	Very Good
G8140011	Dry	Manbulloo	0.62	Fair	0.26	Poor	0.77	Good
G8140040	Daly	Nancar	0.83	Very Good	0.36	Poor	0.88	Very Good
G8140042	Daly	Beeboom	0.85	Very Good	0.16	Poor	0.9	Excellent
G8140044	Flora	Kathleen Falls	0.67	Fair	-0.09	Very Poor	0.87	Very Good
G8140067	Daly	Dorisvale	0.82	Very Good	0.56	Poor	0.81	Very Good
G8140152	Edith	Stuart Hwy	0.4	Poor	0.04	Poor	0.77	Good
G8140157	Fergusson	Bondi	0.75	Good	0.63	Fair	0.84	Very Good

F.3 CALIBRATION SOFTWARE MODULE

Within the MSE software, the calibration software module is designed to assist with the calibration of the catchment water model. It allows a measured flow gauge station to be selected along with a corresponding sub-catchment and flows from each compared directly using the charting tool in the Graphical User Interface (GUI). Model parameters for each functional unit within each sub-catchment are presented within the GUI. These are able to be changed individually, within the sub-catchment, across functional unit groupings, or across sub-catchments. An example of the Parameter screen within the calibration module is shown in Figure F-4. Model output includes daily time-series and scatter plots of measured and predicted flows, summed daily flows, ratio of measured and predicted summed flow, RMS, and the Nash-Sutcliffe Efficiency Coefficient. An example of the Run screen within the calibration module is shown in Figure F-5.



Selected SC :SC #20

Nfu: 6
SCArea: 4058.46 km^2

Flow Gauge info

Name: G8140001
: 19176
From: 1/03/1957
To: 30/08/2009

Available parameter sets

CB_001KathRail_68
CB_001KathRail_74
CB_001KathRail_92
CB_008FergRail

☑ Upstream cummulative

☑ Uses Muskingum

<type name here>

CB_001KathRail_92 parameters

	Value	
FUArea	3241.174	km
GWModelType	GM_EXP	NA
baseflowExpCoefficient2	200	NA
baseflowExpCoefficient1	1	NA
imperviousThreshold	10	mm
perviousFraction	1	NA
soilMoistureStoreCapacity	150	mm
infiltrationShape	0.1	NA
infiltrationCoefficient	100	NA
interflowCoefficient	0	NA
PETCoefficient	1	NA
baseflowCoefficient	0.19	NA

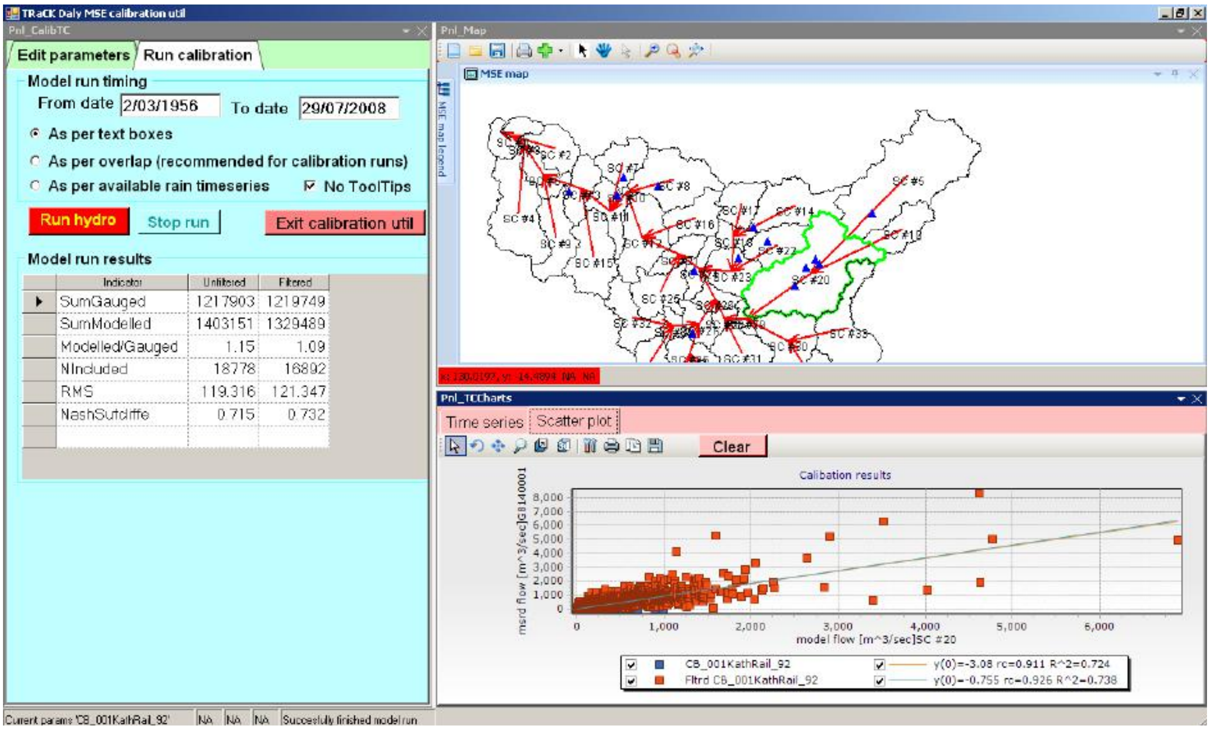
Muskingum routing

☑ Link grid to map

	Value	Unit	IsStochastic	DistribType	Moment1	Moment2	Moment3
musk_c1	0	NA	☐	DIS_NA	-9999	-9999	-9999
musk_c2	0.7	NA	☐	DIS_NA	-9999	-9999	-9999
musk_c3	0.3	NA	☐	DIS_NA	-9999	-9999	-9999

Current params 'CB_001KathRail_92' NA NA NA NA

Figure F-4 Example of the calibration parameter screen within the MSE Software



Model run timing

From date 2/03/1956 To date 29/07/2008

● As per text boxes

○ As per overlap (recommended for calibration runs)

○ As per available rain timeseries ☑ No ToolTips

Model run results

Indicator	Unfiltered	Filtered
SumGauged	1217903	1219749
SumModelled	1403151	1329489
Modelled/Gauged	1.15	1.09
NIncluded	18778	16892
RMS	119.316	121.347
NashSutcliffe	0.715	0.732

☑	■	CB_001KathRail_92	☑ y(0)=-3.08 rc=0.911 R^2=0.724
☑	■	Fltrd CB_001KathRail_92	☑ y(0)=-0.755 rc=0.926 R^2=0.738

Current params 'CB_001KathRail_92' NA NA NA Succesfully finished model run

Figure F-5 Example of the calibration run screen within the MSE software

APPENDIX G DALY CATCHMENT FLOW GAUGE DETAILS

[1] Supplied by NRETAS
[2] Estimated
Shaded cells indicate gauges that are not used in MSE calibration

										Data Statistics for Period 1980 to 2009					Data Statistics for Complete Water Years (Sep-Aug) Across Full Record				
Site	River	Location	Status	Catchment Area	First Data	Last Data Available	No. Years	Proportion of Data Reliable	Equivalent Data Years	Number Water Years Across Data Set	Number Complete Water Years	Number Data Fragments	Proportion Reliable Data	Proportion Reliable Wet Season Data	Number Complete Water Years	Mean Annual Flow (m^3/s)	Mean Annual Runoff (mm)	Coefficient of Variation	Mean Annual Runoff (from Moliere, 2008)
G8140001	Katherine River	Railway Bridge	Open	8,640[1]	Mar-1957	Aug-2009	52	0.90	47	30	15	18	0.96	0.96	25	85	310	0.50	268
G8140003	Daly River	Police Station	Open	48,400[1]	Jun-1952	Jan-2010	58	0.80	46	31	21	4	1.00	0.99	28	222	144	1.03	
G8140005	Flora River		Closed	829[1]	Nov-1967	Nov-1986	19	0.00	0	7	0	0	0.00	0.00	0				
G8140008	Fergusson River	Railway Bridge	Open	1,490[1]	Jun-1957	Jul-2009	52	0.87	46	30	16	14	0.87	0.85	21	15	305	0.63	309
G8140011	Dry River	Manbulloo Boundary	Open	6,290[1]	May-1967	Nov-2008	42	0.91	38	29	18	11	0.87	0.84	25	4	18	1.32	27
G8140022	Katherine River	Nitmiluk Centre	Open	*6,400*[2]	Oct-1998	Oct-2009	11	0.71	8	11	6	9	0.26	0.26	6	73	358	0.63	
G8140023	Katherine River	Gorge Caravan Park	Closed	6,404[1]	Mar-1973	Oct-2004	32	0.95	30	25	0	45	0.78	0.75	0				
G8140040	Daly River	Mt Nancar	Open	47,100[1]	Jan-1967	Jul-2009	43	0.90	38	30	20	16	0.94	0.94	23	273	181	0.63	147
G8140041	Daly River	Gourley	Closed	46,300[1]	Nov-1959	Aug-1981	22	0.94	20	2	1	2	0.05	0.05	14	164	112	0.85	
G8140042	Daly River	2km d/s Beeboom Crossing	Open	41,000[1]	Nov-1981	Oct-2009	28	0.95	27	28	15	24	0.88	0.85	15	220	168	0.66	
G8140044	Flora River	U/S of Kathleen Falls	Open	5,900[1]	Jan-1966	Jul-2009	44	0.61	26	30	10	57	0.74	0.81	8	38	200	1.07	178
G8140060	Cullen River	Rail Bridge	Open	445[1]	Jan-1959	Jul-2009	50	0.05	3	30	0	5	0.09	0.04	0				
G8140061	Cullen River		Closed	306[1]	Oct-1957	May-1978	21	0.77	16	0	0	0	0.00	0.00	6	5	486	0.51	
G8140063	Douglas River	D/S Old Douglas Homestead	Open	842[1]	Sep-1957	Oct-2009	52	0.94	49	30	5	119	0.93	0.89	10	2	93	0.75	222
G8140067	Daly River	U/S Dorisvale Crossing	Open	35,800[1]	Aug-1960	Jul-2009	49	0.79	39	30	12	43	0.85	0.85	13	173	148	0.62	149

										Data Statistics for Period 1980 to 2009					Data Statistics for Complete Water Years (Sep-Aug) Across Full Record				
Site	River	Location	Status	Catchment Area	First Data	Last Data Available	No. Years	Proportion of Data Reliable	Equivalent Data Years	Number Water Years Across Data Set	Number Complete Water Years	Number Data Fragments	Proportion Reliable Data	Proportion Reliable Wet Season Data	Number Complete Water Years	Mean Annual Flow (m^3/s)	Mean Annual Runoff (mm)	Coefficient of Variation	Mean Annual Runoff (from Moliere, 2008)
G8140068	King River	Vic Hwy	Open	11,000[1]	Nov-1959	Feb-2010	50	0.29	14	31	0	10	0.11	0.04	0				
G8140086	King River		Open	484[1]	Jan-1964	Feb-2010	46	0.12	6	31	0	11	0.03	0.01	0				
G8140151	Mathison Ck	Vic Hwy	Closed	725[1]	Dec-1963	Jun-1987	23	0.68	16	8	0	29	0.15	0.14	0				
G8140152	Edith River	U/S Stuart Hwy	Open	590[1]	Jun-1962	Jul-2009	47	0.75	35	30	13	32	0.64	0.67	21	7	382	0.64	396
G8140157	Fergusson River	U/S Bondi Ck	Open	*4,200*[2]	Sep-2000	Oct-2009	9	0.83	8	9	1	46	0.25	0.24	1	14	107		
G8140158	McAddens Creek	Dam Site	Open	133[1]	Nov-1962	Aug-2009	47	0.84	39	30	13	14	0.76	0.77	20	1	322	0.90	275
G8140159	Seventeen Mile Creek	Waterfall View	Open	619[1]	Nov-1962	May-2009	47	0.92	43	30	17	14	0.87	0.89	28	4	193	0.82	194
G8140161	Green Ant Creek	Tipperary	Open	435[1]	Aug-1966	Oct-2009	43	0.90	39	30	15	25	0.91	0.89	15	3	208	0.60	184
G8140214	Scott Creek		Closed	528[1]	Jan-1969	Jun-1987	18	0.18	3	8	0	4	0.02	0.02	0				
G8140218	Katherine River	Mt Ep	Closed	3,700[1]	Sep-1964	Jan-2000	35	0.04	1	21	0	7	0.04	0.04	0				
G8140219	Katherine River	D/S Birdie Ck Confluence	Open	*4,080*[2]	Aug-1997	Aug-2009	12	0.62	7	12	0	209	0.25	0.22	0				
G8140234	Bradshaw Ck		Closed	240[1]	Aug-1965	Jun-1981	16	0.46	7	2	0	4	0.02	0.01	0				
G8140301	Katherine River	Galloping Jacks	Gauged but no recordings	N/A	Aug-1974	Sep-2008	34	0.00	0	0	21	25	0.00		1		1	0.00	
G8140535	Katherine River	Ironwood Station	Open	7,800[2]	Dec-2008	Aug-2009	1	0.42	0	1	0	1	0.01	0.02	0				
G8140536	Katherine River	Wilden Station	Open	9,300[2]	Aug-2008	Aug-2009	1	0.60	1	1	0	2	0.02	0.01	0				

[1] Supplied by NRETAS

[2] Estimated

Shaded cells indicate gauges that are not used in MSE calibration

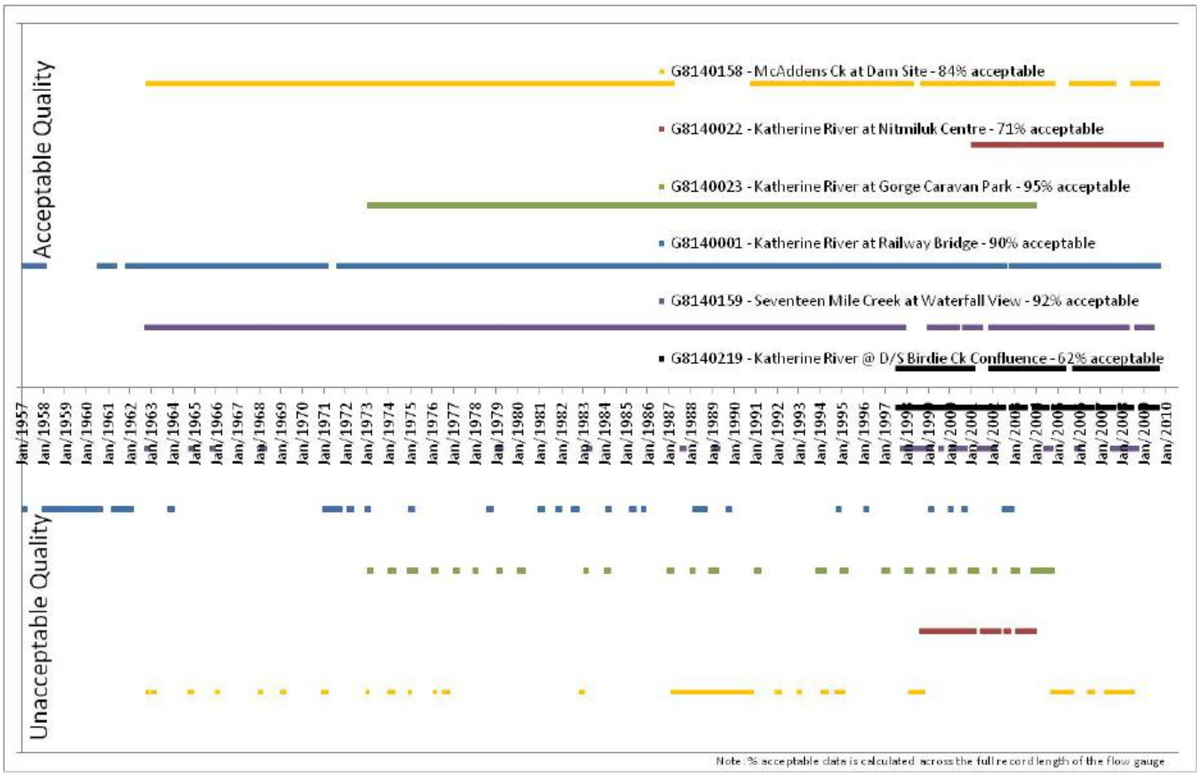


Figure G-1 Daily Flow Data Quality: Gauges in the Katherine River & Tributaries

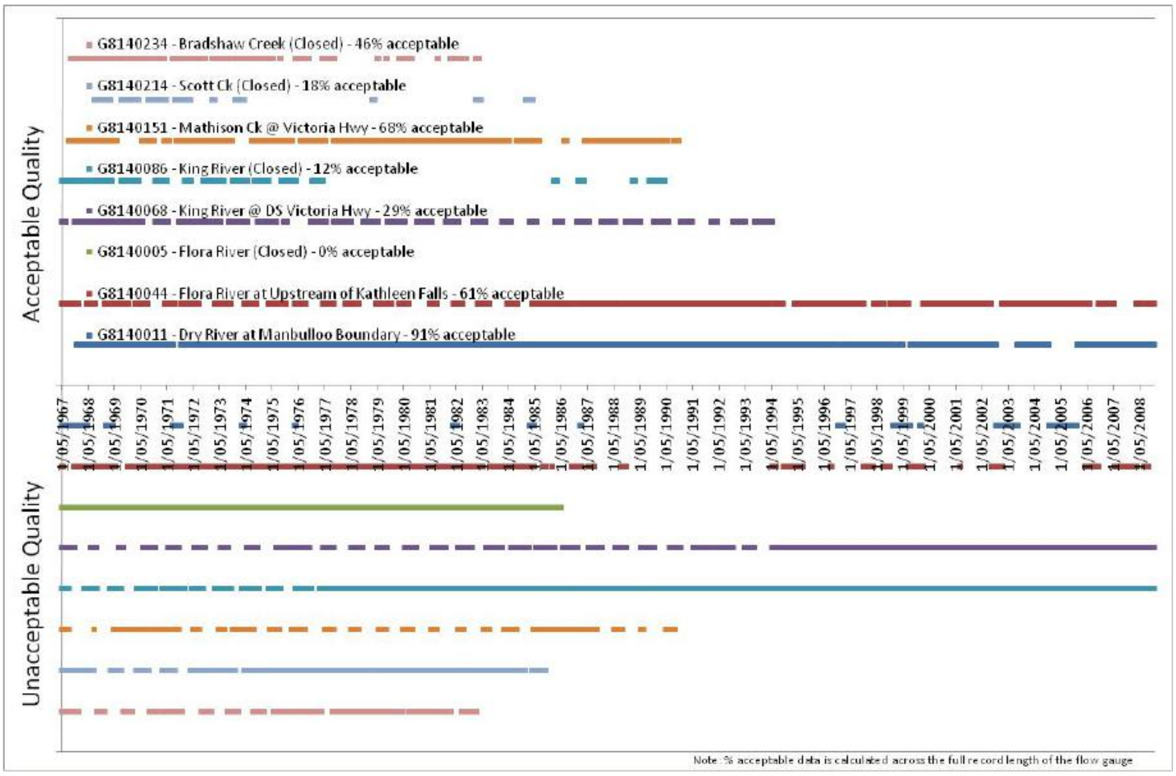


Figure G-2 Flow Data Quality: Gauges in the Southern Tributaries

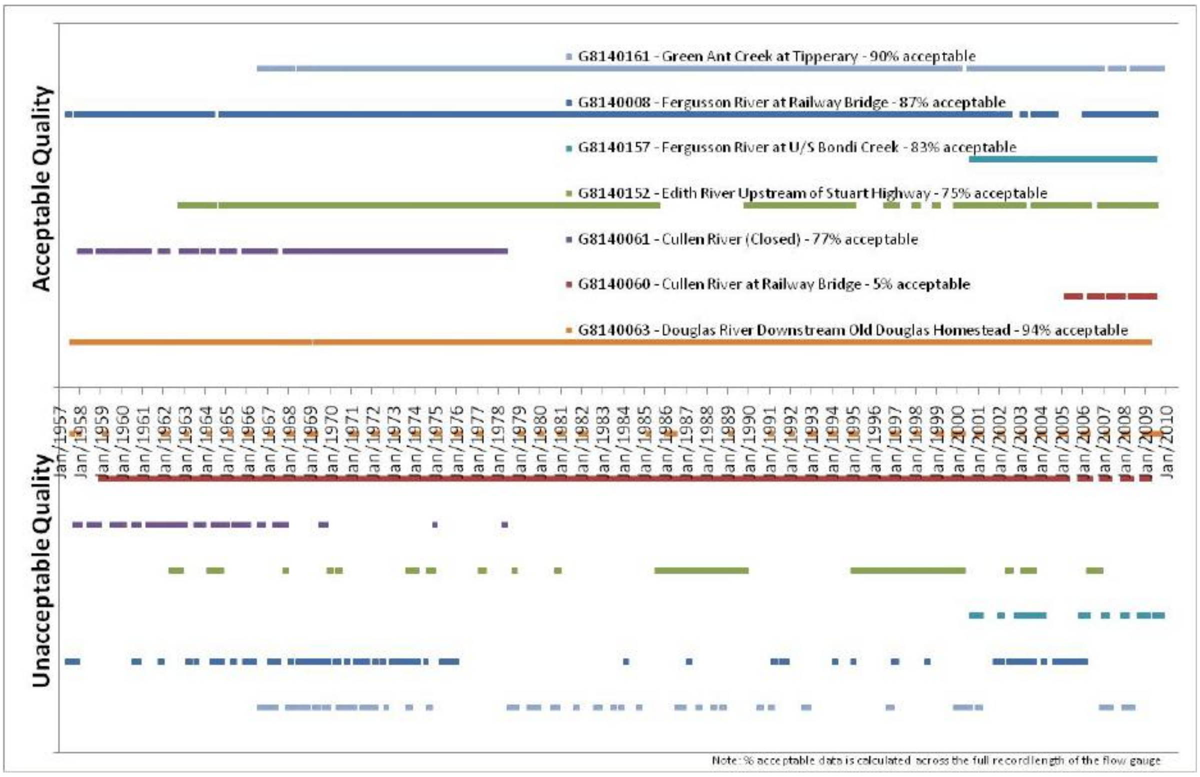


Figure G-3 Flow Data Quality: Gauges in the Northern Tributaries

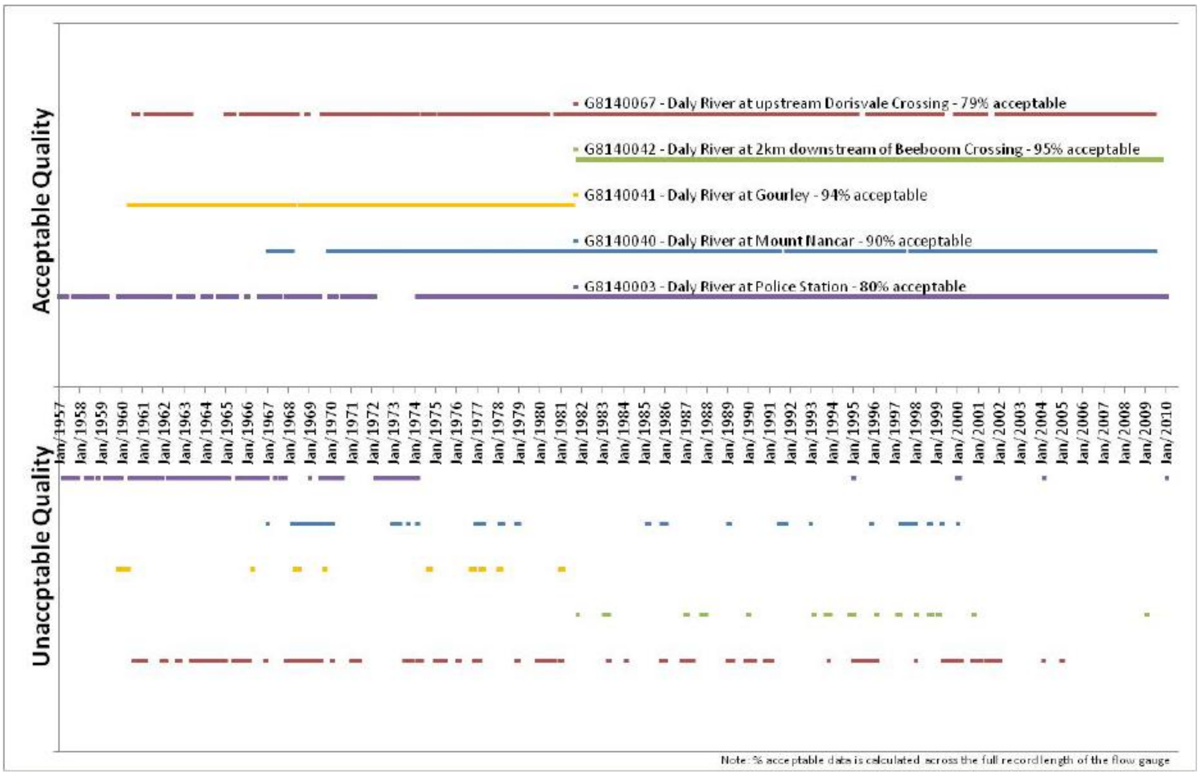


Figure G-4 Flow Data Quality: Gauges in the Daly River Main Channel

APPENDIX H GLOSSARY

Adaptive management	An approach that involves learning from management actions, and using that learning to improve the next stage of management (Holling, 1978).
AHD	Australian Height Datum: the most common datum to which the majority of vertical control for mapping is referred in Australia.
Ambient	Referring to the background environmental condition.
Aquatic	Consisting of, relating to, or being in water.
Aquifer	An underground body of rock or sediment that holds and allows water to move through it.
Attenuation	In relation to flow of water: reduction in the amplitude (height) of the water surface as the water moves downstream in a watercourse.
Baseflow	The flow of water entering stream channels from groundwater sources.
Catchment	An area of land bounded by natural features such as hills, from which drainage flows to a common point, usually ending in a river or creek and eventually the sea.
Class	Programming language construct which acts as a *blueprint* for functional units (objects) within a program.
Component	A cohesive, modular software package, service or module that encapsulates a set of related functions (or data).
Consumptive use	In relation to water: the use of water that reduces the supply (e.g. extraction of water for human consumption and agricultural use).
CSIRO	Commonwealth Scientific and Industrial Research Organisation.
CV	Coefficient of Variation: a normalised measure of variability.
Decision support table	Allow the trade-offs between the evaluated scenarios to be visualised in a consistent and comprehensive matter. They consist of measures that represent the key messages from the MSE results (performance indicators) for each scenario.
DEM	Digital Elevation Model: a digital representation of the elevation (height above a datum) of the Earth's surface.
Deterministic	Describes a process whereby the outcomes for a particular set of initial conditions are always the same. A deterministic process is one which contains no randomness
Dry Season	A term typically used in the tropical regions of the world to describe that part of the year in which very little rainfall occurs. In the case of the Daly River and this Study, the dry season is defined as occurring

	between May and October inclusive.
Ecosystem	An interdependent and dynamic system of living organisms with their physical and geographical environment.
Ecosystem services	Benefits people obtain from ecosystems.
Ensemble	Pertains to stochastic realisations through repeated evaluation with different parameter values
Epoch	A period in time characterised by a specific event or repeating pattern.
Epoch-based approach	A method for quantifying temporal variability by comparing statistical measures of time series epochs.
Epistemic uncertainty	Uncertainty that arises from limited knowledge of the workings of a process, where experimental evidence is insufficient, ambiguous or conflicting, or where agreement between stakeholders on the quantification of (natural) uncertainty is not attained. Often referred to as knowledge- or epistemic uncertainty
Estuarine	The tidal part of a river where sea water mixes with fresh water.
ET	Evapotranspiration: the transfer of water to the atmosphere due to *evaporation* from the soil, waterbodies, interception sites and *transpiration* from plants.
Evaporation	Vaporisation of a liquid from a surface.
FEFLOW model	**F**inite **E**lement subsurface **FLOW** model, a computational hydrodynamic model for simulating groundwater flow.
Finite element	Method for numerically calculating solutions of differential equations.
Functional areas	A grouping of key activities performed during the management process.
Groundwater	Water in the saturated zone beneath the land surface.
GUI	Graphical User Interface: an image-based interface which allows users to interact with software.
Hydrogeological	Area of geology which deals with the groundwater distribution and movement.
Hydrograph	A graph of the water surface level (or discharge) with respect to time at a specific point along a watercourse.
Hydrologic	Relating to the effect of rainfall and evapotranspiration on the occurrence and character of water on or below the land surface.
Hydro-physics	Used to describe the water related components within the Daily MSE Application.
***If–then* rules**	*If* a particular condition is met, *then* perform a specific set of actions.
Ignorance-based	See: epistemic uncertainty

uncertainty	
Inter-annual variability	Related to *epoch-based approach*, describes the variability of a variable from year to year.
Management action	Activities undertaken by managers "on the ground".
Management scenarios	A set of management actions which are enacted without explicit feedback from previous management results.
Management strategy	A set of (pre-agreed) rules for selecting management actions based on (monitoring, assessment and learning) feedback from previous iterations through the adaptive management loop.,
Model	In the context of this document, a model is an idealised representation of the properties and interactions of a system under study.
Modelled flow	Flow that is output from a water model
MSE	Management Strategy Evaluation: an approach to support natural resource management with a set of concepts, standards and outputs that allows policies and 'what-if' management scenarios to be evaluated for their impacts on social, environmental and economic values.
MSE framework	The conceptual structure which underpins the implementation of management strategy evaluation. MSE framework outlines the *functional areas* which makeup the management processes that is simulated by an MSE application and requirements such as the reportage of trade-offs and explicit treatment of uncertainty.
Muskingum routing	Numerical method for simulating delays and attenuation of water flow within a channel; see references for details (Cunge, 1969, Ponce et al., 1996).
NASY	Northern Australia Sustainable Yields: a *CSIRO* project which assessed the historical, recent and likely future availability of water in Northern Australia.
Non-consumptive use	In relation to water: the use of water that does not reduce the supply (e.g. fishing, boating, swimming and ecosystem requirements)
NRETAS	NT government department of Natural Resources, Environment, The Arts and Sport.
NRM	Natural Resource Management
NSE	Nash-Sutcliffe Coefficient of Efficiency: used to quantify the predictive power of a *hydrologic* model.
Nutrient load	An estimate of the total amount of a nutrient (nitrogen or phosphorus) entering a waterway over a particular time interval (units of N or P per year).
Observed flow	Flow derived from recorded measurements in the field, also referred to

	as measured flow.
Perennial	In relation to flow of water: water flow that occurs throughout the year and does not cease.
Performance measures/indicators	Measures that indicate how well management is performing against the objectives. They inform the manager about the discrepancy between the objectives and the actual status of the system under management.
PET	Potential Evapotranspiration: the theoretical maximum evapotranspiration assuming the system had an unlimited supply of available water.
Plug-and-play approach	Characterised by the ability to simply replace, add and remove system components. Requires a modular design approach and a set of strict *input-output* specifications for modules.
Pumpage	Groundwater extraction.
Quantile	A regular interval of a cumulative distribution function, often called percentile. For instance, Q10 or the 10th quantile is the value of a variable below which fall 10% of the values.
Random variable	The random outcome of an experiment or measurement.
Recharge	In relation to an aquifer: occurs when surface water infiltrates through soil layers into the aquifer system, thus becoming groundwater.
Riparian	Of or pertaining to the bank of a river; beside or along the bank of a river, pond or small lake.
SILO	An online database of about 120 years of continuous daily weather records from around 3,800 Bureau of Meteorology stations across Australia.
SIMHYD model	One of a suite of conceptual models offered within the eWater rainfall runoff library toolkit (http://www.toolkit.net.au/Tools/RRL)(Podger, 2004)
Stochastic process	The time-evolution of a random variable is called a stochastic process
Streamflow	Flow of water within a channel.
Temporal variability	Changes over time .e.g. rainfall changes over time.
Top-down approach	A method for solving problems by beginning with high level structure and functions, and then working down towards lower level detail.
TRaCK	Tropical Rivers and Coastal Knowledge: science program pertaining to Northern rivers and catchments.
Transpiration	In conjunction with evaporation: transfer of water from plants to the atmosphere.
UML	Unified Modelling Language: used to schematically describe software

	architecture and function.
Uncertainty	A state of insufficient knowledge to describe a phenomenon in deterministic terms. Note that uncertainty is not the same as risk but risk may arise from uncertainty.
WAP	Water Allocation Plan: a Northern Territory Government regulation which annually allocates maximum groundwater extraction volumes to individual licences; see Section 4.3.3 for more details.
Waterbody	Any part of the earth covered with water: includes creeks, rivers, lakes, and oceans.
Wet Season	A term typically used in the tropical regions of the world to describe that part of the year in which almost all the rainfall occurs. In the case of the Daly River and this Study, the wet season is defined as occurring between November and April inclusive.

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INDEX

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