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Integrating hydrology and ecology models into flexible and adaptive decision support tools: the IBIS DSS.

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Abstract: Terminal wetlands in the semi-arid regions of northern NSW are important ecological refuges for native fauna, especially during dry times. Many of these systems have become increasingly stressed by human induced changes in the hydrologic regime of the rivers flowing into the lakes. For example, the Narran Lakes is a Ramsar wetland recognised for its geomorphological significance and the importance of the system as habitat and drought refuges for waterbirds and other species. The high level of regulation in the headwaters of the lake poses considerable obstacles for managers responsible for managing the health of the Narran Lakes.

Decision Support Systems (DSS) can support decision making processes by providing users with a tool that shows the relationships between drivers of a system and outcomes. Drivers of wetland systems can be different management actions (e.g. environmental flow releases) or 'uncontrollable' drivers like climate variability. The complex biophysical, ecological and social context in which wetlands are managed mean that a DSS that supports decision-making should address uncertainty in data, knowledge and predictions, and allow users to explore the sensitivity of outcomes to management actions, uncontrollable drivers and uncertainty. It will be most useful in the long term if used as part of an adaptive process where objectives, strategies and knowledge are continually updated to test hypotheses and reduce key uncertainties, using a monitoring, research and evaluation program which the DSS could be augmented to inform.

The IBIS DSS is being developed to predict the ecological outcomes of environmental flows in wetland systems in NSW. Two applications are in development: one each for the Gwydir Wetlands and Narran Lakes. It is intended to be used by wetland managers to inform and support on-ground management decisions, and model developers who can input new data and rules into the DSS and test hypotheses.

The DSS links hydrologic-hydraulic models to Bayesian Network ecology models. Relationships between hydrology and ecological response are not fully established for either of the Gwydir Wetlands or Narran Lakes systems. For example, what constitutes the start and end of an event and what are the important characteristics of events? Triggers or water requirements for breeding and/or growth, which may or may not be known, can vary between species or over a species life cycle. Also, multiple factors may influence ecological response. In the Narran Lakes application of the IBIS DSS, the likelihood of waterbirds abandoning their nests is determined by the length of a hydrologic event, and the minimum depth under nests, maximum day-to-day decrease in water surface elevation, and number of 'cold' days during the event. The individual impact of these factors on abandonment is known with varying degrees of certainty. However, the combined impact of these factors is not so clear. The IBIS DSS allows users to systematically specify rules that define event characteristics and aid development of the probabilistic data in the Bayesian Network. This allows testing of alternate model structures and adds flexibility to the DSS that lends its use as part of an adaptive monitoring, research and evaluation program.

Keywords: *Decision Support Systems (DSS), wetlands, environmental flows, Narran Lakes*

1. INTRODUCTION

Wetland systems in the arid and semi-arid regions of New South Wales, Australia, provide important habitat and drought refuges to numerous types of fauna, including migratory bird species that are the subject of international agreements (e.g. Kingsford, 1995). The health of many of these wetlands is being threatened by upstream development that has lead to changes in the magnitude, duration and frequency of flooding events (e.g. Thoms, 2003).

To protect and enhance a wetland's ecosystem, managers of the wetland need to identify the ecological assets and functions that need preserving as well as the volume (and timing) of water that needs to be delivered to an asset to achieve a desired environmental outcome. Decision Support Systems (DSS) can support decision making processes by providing managers with a tool that shows the relationships between drivers of a system (e.g. environmental flows) and outcomes (e.g. waterbird breeding events).

In 2008, the NSW Department of Environment and Climate Change (DECC) together with the Commonwealth of Australia commissioned the development of prototype Decision Support Systems (DSS) for the Gwydir Wetlands and the Narran Lakes (The 'DECC Wetlands Project'). Further development of the DSS is part of an on-going project due for completion in June 2010. The DSS packages, and further develops, science and knowledge about the hydrology and ecology of the systems into a form that can be used to test management hypotheses and show potential trade-offs and synergies of management decisions and their impacts on ecological assets. The DSS applications, once fully developed, will support project assessment and decision-making, particularly with respect to the use of environmental flows to maintain and improve ecological assets in the two wetland systems. The DSS are being constructed such that the technology and underlying models can be readily adapted to other wetland systems.

2. THE IBIS DSS

The Narran and Gwydir DSS applications are comprised of daily hydrology/water balance models linked to Bayesian Networks that represent aspects of the ecology (e.g. fish, waterbirds, fish). The overlying interface enables rapid data input and scenario testing and provides users access to supporting information and model documentation as well as reporting and data export functionalities. The models underlying the IBIS DSS have been coded using the Integrated Component Modelling System (ICMS), a model building and delivery environment developed by CSIRO Land and Water (Reed et al. 2000).

Bayesian Networks (BNs) have been used to model ecology in the IBIS DSS as they are an approach suited to integrating information from different disciplines and can utilise a wide range of qualitative and quantitative data. BNs can be readily updated with new or improved data and this, together with the ease in interpreting BN outputs compared with other models and explicit representation of uncertainty, make them suitable for inclusion in DSS for natural resource management (e.g. Ticehurst et al. 2008).

The primary audience for the DSS is NSW DECC as well as managers of the Gwydir Wetlands and Narran Lakes who want to be able to test the impact of alternative input flow and climate scenarios on ecological response and use the outputs to inform their decision making and planning activities. During the development of the prototype DSS, these stakeholders participated in inception meetings to scope the purpose and functionality of the tool. During the development of the prototype DSS it was apparent that there are currently key knowledge gaps and considerable uncertainty in predicting the response of the ecology – be it flora or fauna – to the hydrological regime. IBIS could thus have a role for use by researchers or 'experts' to test hypotheses in model-building in addition to its scenario testing role.

In order to use the DSS, two types of user groups have been specified: 'expert users', who can modify hydrological and ecological rules and thresholds, and 'default users' who cannot alter model settings. When the user starts up the IBIS interface they are presented with a pop-up where they select which type of user they are: Expert or Default. This structure has benefits in managing the complexity of the tool for those users who wish to examine different climate and inflow scenarios without changing the default model settings. Expert users can manipulate, test and set key ecological parameters in the model and define how the model outputs are combined to assess ecological outcomes. Such parameters include threshold inundation depths and durations for (e.g.) waterbird breeding and recruitment, definition of areas of interest and event thresholds. The standard interface (default user) will only allow testing of input flow and climate scenarios using default model settings. Threshold rules and model parameterisations for the default user are defined by model developers in conjunction with hydrological and ecological experts.

Given uncertainty and incomplete knowledge of the relationships between hydrology and ecological response, the code for the DSS models have been written such that the model assumptions and settings can be readily updated as improved information on system behaviour becomes available without requiring changes to the model code. Section 3 illustrates this for the prototype Narran Lakes application of the IBIS DSS.

3. NARRAN LAKES CASE STUDY

3.1. The Narran Lakes

The Narran Lakes, located in the central north of New South Wales is a terminal wetland of the Narran River, a tributary of the Condamine-Balonne River system (Figure 1). The system is comprised of Narran Lake and the Northern Lakes which include Back Lake, Clear Lake, Long Arm and the interconnecting channels and lignum (*Muehlenbeckia florulenta*) floodplains. The wetlands are important waterbird breeding areas, contain large expanses of lignum and support a range of aquatic and semi-aquatic native fauna including reptiles, native fish, amphibians and mammals (NSW NPWS, 2000). Much of the wetlands are included in the Narran Lake Nature Reserve – a Ramsar listed site – and are subject to international agreements for migratory waders.

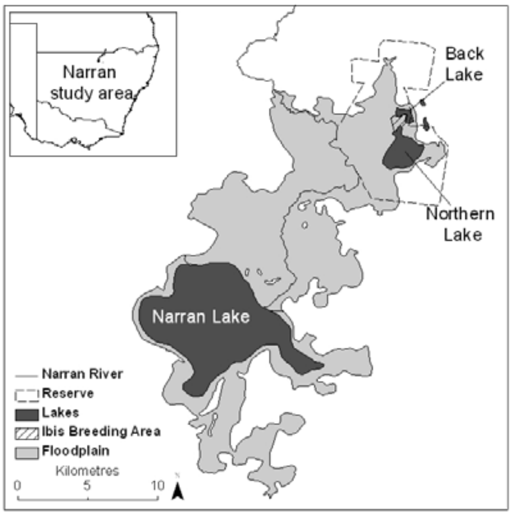

Figure 1. The Narran Lakes.

Although the wetland system, particularly the area encompassed by the nature reserve, is in relatively natural condition (NSW NPWS, 2000) it is under considerable threat from water extractions and regulation upstream of the wetlands. The Condamine-Balonne system has its headwaters in Queensland and considerable development of the water resources and floodplains exists upstream of the Narran Lakes. This development has reduced the magnitude, duration and frequency of flooding events in the Lower Balonne floodplain which includes the Narran River and Lakes (Thoms, 2004).

3.2. The Narran Lakes Application

The Narran Lakes application of the DSS is being developed to provide managers of the Narran Lakes with a tool that can demonstrate the (beneficial or negative) impacts on ecological assets that may occur due to current and/or alternative management of flows in the Narran River and the Condamine-Balonne system upstream of Narran River. By integrating best available modelling and knowledge of the hydrology and ecology of the system in an adaptive tool that can be updated as improved data and models are developed it is intended that the Narran application could be used to support decisions about how best to strategically plan water releases into the lakes, both in short (1 year) and long timeframes (100 years).

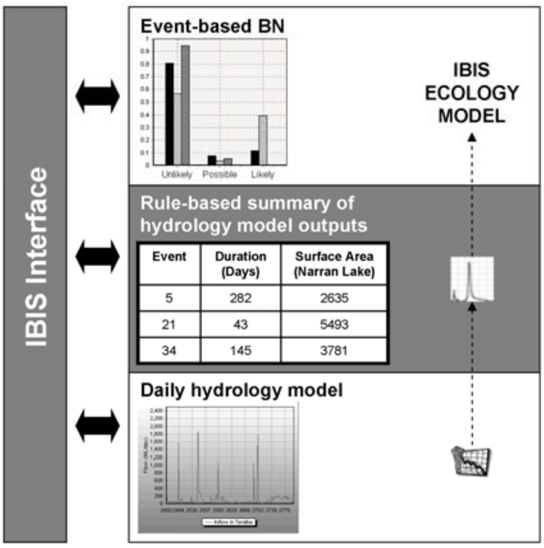

Figure 2. Structure of the Narran Lakes IBIS.

The DSS model for the Narran links daily outputs from a hydrology model (Rayburg and Thoms, 2008) to straw-necked Ibis response models through routines that summarise the inundation time-series data into ecologically relevant time periods (i.e. flow events). The BN uses the event summary together with other data (e.g. long term trends in bird numbers) to describe the likely ecological response of Ibis to the hydrology regime (Figure 2).

The DSS runs the hydrological model of the Narran Lakes system developed by Rayburg and Thoms (2008) through an executable program which outputs daily predictions of inflow to the system (at Wilby Wilby gauge) and water surface elevation and surface area of the Northern Lakes and Narran Lake.

Simple use of objects and links are used to develop the model underlying the Narran application of the IBIS DSS (Figure 3). Most objects in Figure 3 have a model associated with it that takes input data and calculates outputs which may be passed through to other models. A summary of each object type is given in Table 1.

The outputs of the ecology response model are the number of Ibis fledglings and the ratio of the number of fledglings to the number of nests. This ratio provides an indication of the level of recruitment in response to each flood event (and across the entire hydrological record). These outputs are defined by the number of birds at the lakes, the suitability of an event to trigger breeding, the number of nests and the likelihood of birds abandoning their nests. The determinants of each of these components are listed in Table 1.

Table 1. Objects in the Narran DSS

Icon	Object class	Description/Model Code
	UC Model Outputs	No model – outputs from the hydrology model which are passed to the Event Summary object.
	Input data	No model – input data (e.g. probability tables) that is passed to various objects (Abandonment, Breeding Triggers, Number of Birds, Number of Nests, Combination and Final)
	Event summary	This code takes the time series outputs from the model and calculates a number of summary statistics for each event. These are defined from a set of thresholds and rules.
∑	Annual Inflows	Sums up the daily inflow time series to annual inflow.
	Abandonment	For each event, abandonment is related to • Inundation duration (days) • Depth under nest (m) • The maximum change in water surface elevation (WSE) during the event (m) • The number of consecutive days below a temperature threshold (days) Each object has a model that relates the relevant event statistics to the likelihood of being in a particular class of (e.g.) inundation duration.
	Breeding Triggers	The suitability of an event to trigger breeding is related to • Water surface elevation (WSE) in the northern lakes • Surface area on Narran Lake Each object has a model that relates the relevant event statistics to the likelihood of being in a particular class of (e.g.) WSE in the northern lakes.
	Number of Birds	The number of birds at the lakes is related to • Observations of long term trends in bird numbers (decreasing, no change, increasing) • Regional rainfall (low, average, high) This part of the model is constrained by poor data and imperfect knowledge and the same condition (e.g. high rainfall, decreasing long term trends in bird numbers) is currently applied to all events.
	Number of Nests	The number of nests is related to • Annual actual inflow • The time since the last breeding event (years) The annual actual inflow object (NestInflows in Figure 3) has a model that relates the relevant event statistics to the likelihood of being in a particular class of inflow. The relationship between time since last breeding and the number of nests is not well understood and there is no data to quantify this relationship. Users are currently constrained to applying the same condition (e.g. two years) to all events.
	Combination	This object type is used to weight combinations of parent variables, as represented in conditional probability tables (CPTs) for nodes in the Bayesian Network. Users can define rules for combining data (see Section 4.1). The options are • Weighted average • Override (partial or complete) • Worst case • Best Case
●	Final	This object type is used to generate joint probabilities for the nodes in the Bayesian Network using CPTs from the combination model and outputs from the input objects (, , , or ●).

4. RELATIONSHIPS BETWEEN HYDROLOGY AND ECOLOGICAL RESPONSE

Relationships between hydrology and ecological response are not fully established for either of the Gwydir Wetlands or Narran Lakes systems. For example, what constitutes the start and end of an event and what are the important characteristics of events? Triggers or water requirements for breeding and/or growth, which may or may not be known, can vary between species or over a species life cycle. Also, multiple factors may influence ecological response. For example, the number of nests may be related to both the annual actual inflow and the time since last breeding (Figure 3). Assuming the individual relationships between each input variable and the dependant variable are well established, how do these individual impacts combine? For example, are there certain thresholds in a particular input variable above or below which that variable solely determines the state of the dependant variable?

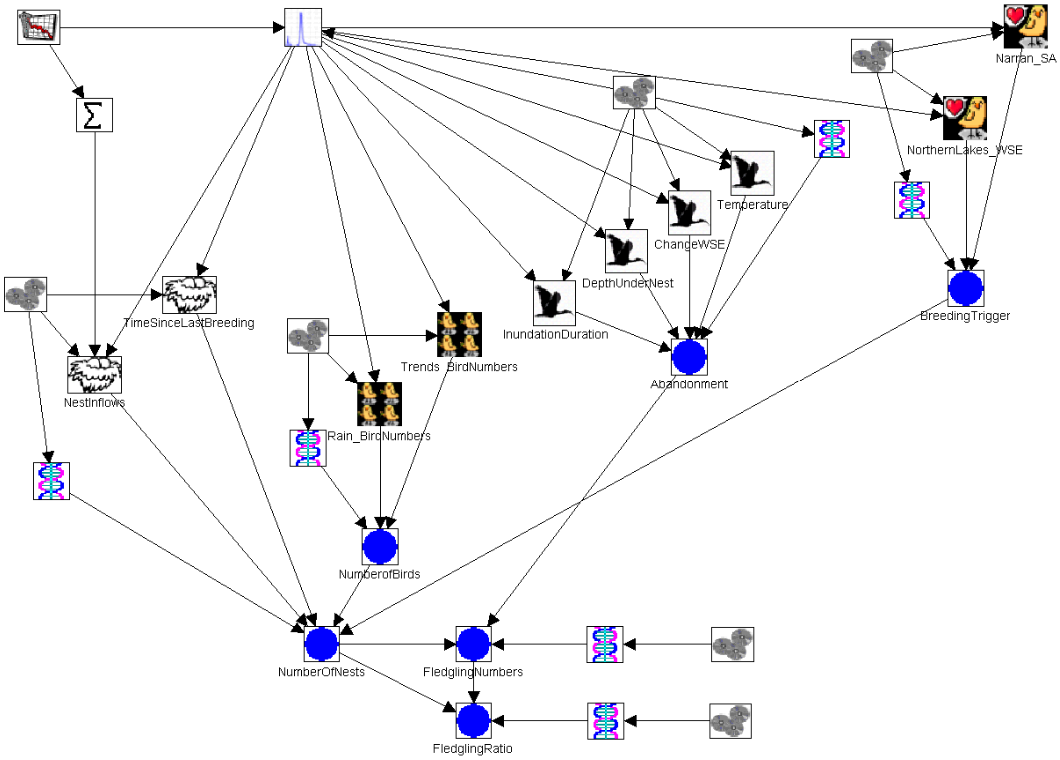

Figure 3. The Narran DSS model

To address these types of issues, Expert Users can define 'event definition' rules and thresholds that define the start and end of an event. They can also set 'BN definition' rules which are used to develop Conditional Probability Tables (CPTs) for objects in the Narran Bayesian Network (ecology) model (see Figure 3). The latter functionality is demonstrated further in this paper.

4.1. Causal Relationships in the Ecological BN

Variables in the waterbird ecology model are determined by a number of input variables. In the Narran Lakes prototype, the likelihood of abandonment of nests by straw-necked Ibis – as distinct from failure of eggs to hatch or death of young due to other factors – is estimated based on the length of a hydrologic event, and the minimum depth under nests, maximum day-to-day decrease in water surface elevation, and number of 'cold' days during the event.

No published data was identified on the causes and rates of abandonment for straw-necked Ibis. Inundation must be maintained for a length of time to allow for birds to reach breeding condition, build nests, lay and incubate the eggs and finally to feed their young through to successful fledging. The clutch size for straw necked Ibis is generally 3-4 eggs with an incubation period of 24 days. Fledging occurs 28 days after hatching with young being fed for about 14 days after leaving the nest (Carrick, 1962).

The individual impact of the input variables to abandonment was estimated by researchers familiar with the Narran Lakes and waterbird response (Figure 4). For example, an inundation period less than 60 days barely covers the incubation and fledging period for Ibis and is almost certain to result in abandonment (Figure 4). As inundation duration increases to more than 100 days the likelihood of abandonment is greatly reduced: the probability distribution is likely (0.1), possible (0.2) and unlikely (0.7).

If the individual impact of the input factors on abandonment is not well documented then the combined impact of these factors is even less clear. The IBIS DSS allows users to investigate alternative combinations for describing how different aspects of the system effect outcomes. Combinations that can currently be explored are:

- Weighted average – users identify weights to apply to each link and these are used to weight probabilities (*Note* that this is similar to a multi-criteria assessment approach).
- Override (partial or complete) – in some conditions, a particular variable may override all others. For example, if the duration of inundation is insufficient for water birds then abandonment may be highly likely regardless of the depth under nests, the change in water surface elevation (WSE) or temperature. Users can select to do a complete override where an input variable controls the outcome under all of its possible states.
- Worst case – this option selects the worst case from each individual input when generating the probability distributions.

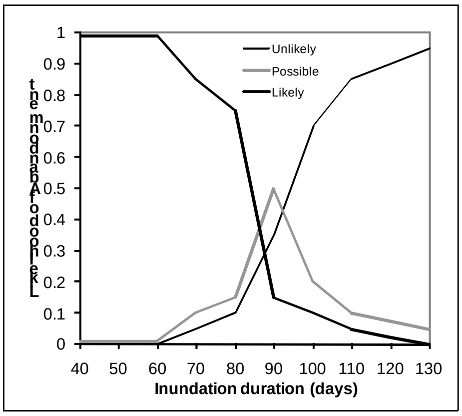

Figure 4. Relationships between *Abandonment* and *InundationDuration*.

- Best Case – this option selects the best case from each individual input when generating the probability distributions.

The effect of some of these rules on the likelihood of abandonment is shown in Figure 5 for the four events summarised in Table 2. These events cover a range of duration periods and seasonality although there is negligible difference between the events in terms of the minimum depth under nest (m) and the largest day-to-day decrease in WSE (m). Event 22 is a short event where the likelihood of abandonment could be expected to be high, while the other events are of a longer duration (>80 days). Differences between the likelihood of abandonment for events 3, 5 and 35 are explained by the inundation duration and the incidence of cold spells where the minimum temperature is below 3°C (Temperature).

Table 2. Characteristics of events referred to in Figure 5.

Event	Event Number			
	3	**5**	**22**	**35**
Hydrology				
Start of event	07/07/1967	31/10/1969	06/10/1986	19/11/2000
End of event	02/10/1967	08/08/1970	17/10/1986	12/04/2001
Event duration (days)	88	282	12	145
Minimum depth under nest (m)	1.1	1.1	1.1	1.1
Largest day-to-day decrease in WSE (m)	-0.02	-0.02	-0.02	-0.01
Temperature (Number of days where the minimum temperature is below 3 ℃)				
No. of cold days	20	53	0	0
No. of 1 day cold spells	2	3	0	0
No. of 2-3 day cold spells	5	8	0	0
No. of 4-5 day cold spells	0	2	0	0
No. of >5 day cold spells	1	3	0	0

In each panel of Figure 5, the black columns show, for an event, the probability distribution when each input variable (*InundationDuration*, *DepthUnderNest*, *ChangeWSE*, and *Temperature*) is assumed to have equal weighting. Event 22, despite a very short duration (12 days), has a 56% likelihood that abandonment of nests will not occur ('Unlikely'). This is not realistic given the inundation requirements for incubation and fledgling (~60 days). It could be expected that a minimum threshold of inundation duration is necessary for Ibis **not** to abandon their nests. The orange columns in Figure 5 shows the probability distribution when a partial override is implemented. When the inundation duration is less than 60 days the outcome of the *Abandonment* variable is determined solely by the *InundationDuration* variable. Otherwise, an equal weighting is applied. This results in almost certain abandonment of nests predicted by the ecology model for event 22 ('Likely').

The blue columns in Figure 5 show the probability distribution with the settings defined in the Narran prototype model. Settings in the prototype DSS will be reviewed with a wider audience in future development of the DSS and compared to observed data where available. A partial override is applied such that when the inundation duration is less than 60 days the outcome of the *Abandonment* variable is determined solely by the *InundationDuration* variable. Otherwise a weighted average is applied where the *InundationDuration* (weight = 0.4) and the *DepthUnderNest* (weight = 0.4) variables have a stronger influence on abandonment than the *ChangeWSE* (weight = 0.1) and the *Temperature* (weight = 0.1) variables. The difference in *Abandonment* between events 5 and 34 is due to the incidence of cold spells during the event – the events have the same state for all other input variables. Reducing the influence of temperature gives a lower likelihood of abandonment for event 5 than when even weightings are applied.

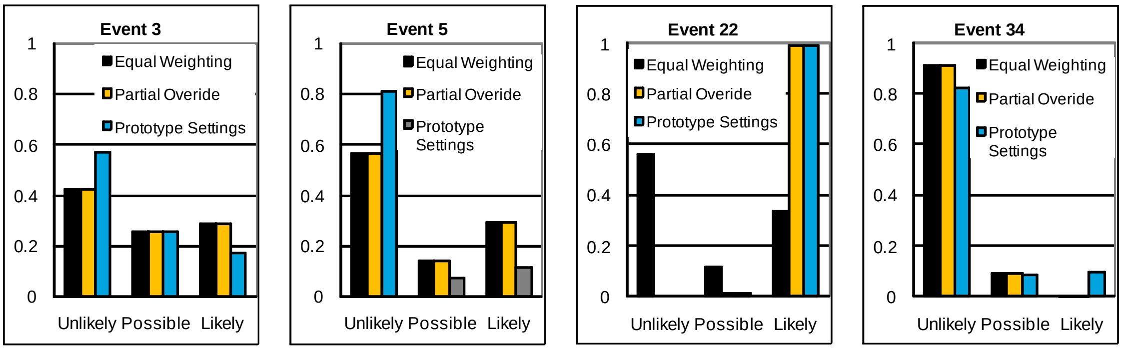

Figure 5. Impact of 'BN definition' rules on the likelihood of abandonment.

5. DISCUSSION AND CONCLUSIONS

The IBIS DSS is being constructed to predict the ecological outcomes of environmental flows in wetland systems in NSW. Hydrological models are linked to Bayesian Networks which model the response of key ecological assets. The DSS allows users to define rules that define event characteristics and aid development of the probabilistic data in the Bayesian Network. This allows testing of different model structures and adds flexibility to the DSS that lends its use as part of an adaptive monitoring, research and evaluation program.

The complex biophysical, ecological and social context in which wetlands are managed mean that for the IBIS DSS to support decision-making it must address uncertainty in data, knowledge and predictions, and allow users to explore the sensitivity of outcomes to management actions (e.g. environmental flow releases), uncontrollable drivers (e.g. climate variability) and uncertainty. The DSS will be most useful in the long term if it is used as part of an adaptive process where objectives, strategies and knowledge are continually updated to test hypotheses and reduce key uncertainties.

The level of consultation and participation with stakeholders in the prototype project was limited to inception and delivery meetings. While useful in scoping the purpose of the DSS and the functionality for the prototype and providing feedback on the prototypes, the second phase of development (in 2009/10) will involve more intensive and on-going participation of these stakeholders. Initial activities will involve workshops where the prototype DSS can be tested and critiqued and used to improve definition of the purpose of the DSS.

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