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Utilising catchment modelling as a tool for monitoring Reef Rescue outcomes in the Great Barrier Reef catchment area

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Abstract: Water quality improvement plans (WQIPs) are currently being implemented within the Great Barrier Reef (GBR) catchment area through the Australian Government 'Reef Rescue' package to reduce the runoff of sediments, nutrients and pesticides into the GBR lagoon. End-of-catchment pollutant load targets have been set for a selection of priority GBR catchments to determine the effectiveness of catchment management actions over time. However, our ability to detect changes in water quality at the end-of-catchment and to assess this against the set targets over short time frames (i.e. a few years) is limited. This is particularly so for large dry tropical catchments such as the Burdekin River, which has high inter and intra annual flow variability, and where considerable time lags exist before water quality improvement may occur at the end-of-catchment. Due to lag times in response to changed management practices and a noisy water quality signal associated with inter-annual flow variability, it would take greater than 10 years to detect reductions in pollutant loads which is outside the current targets of the Reef Rescue timeframe. In addition, the level of uncertainty in the calculation of pollutant loads can equal or exceed the proposed resource condition or pollutant load targets. Hence the only way to assess the effectiveness of management actions on water quality in the short term in such a system is to utilise modelling tools (e.g. SedNet or WaterCAST models), to predict material transport and delivery and management scenario forecasting. Receiving water models, such as ChloroSim are also required to relate these end-of-catchment pollutant loads to ecosystem response. Water quality guidelines (trigger values) for the Great Barrier Reef can be then used within these receiving water models to revise end-of-river targets.

This paper provides an overview of challenges currently faced by natural resource managers and science providers tasked with measuring Reef Rescue outcomes in the GBR catchment and lagoon, and presents a coupled monitoring and modelling approach recently developed for the Burdekin, Black-Ross and Tully-Murray WQIPs. We note that this approach also has errors which may propagate through the scaling of monitoring and modelling data (e.g. paddock to sub-catchment scale, end-of-catchment to marine) and that other means, such as Bayesian Belief Networks may be required to reduce these additive errors. Our 'up-scaling' approach from the paddock to the GBR lagoon provides a clear framework to assist in assessing the performance of water quality improvement in the GBR as a result of the Reef Rescue initiative.

Keywords: *Sediment and nutrient runoff; Reef Rescue; target setting; catchment modelling and monitoring.*

1. INTRODUCTION

In response to the threats posed to the Great Barrier Reef (GBR) from agricultural runoff along the northern and central Queensland coastline (Fabricius *et al.* 2005; Devantier *et al.* 2006), the Australian and Queensland Governments established the joint Reef Water Quality Protection Plan ('Reef Plan') in 2003 (Anon 2003). More recently, the Australian Government announced the Reef Rescue initiative which is a $200M commitment over five years (2008-2013) and provides incentive programs, monitoring and reporting to address water quality issues in the GBR. As part of Reef Plan, regional Water Quality Improvement Plans (WQIPs) have been developed for many of the catchments and natural resource management regions of the Great Barrier Reef Catchment Area (GBRCA), including the Mossman, Daintree, Barron and Tully/Murray catchments of the Wet Tropics region, Black-Ross catchments (Townsville), Burdekin Dry Tropics region, Mackay Whitsunday region and the Burnett Baffle catchments of the Burnett Mary region. Within each WQIP region, resource condition or pollutant load targets have been set that are linked to on-ground investment activities currently being implemented through the Reef Rescue initiative to provide a reduction in sediment, nutrient and pesticide loads at the end of each catchment. These resource condition targets are also linked to marine trigger values for key indicators of pollution (e.g. turbidity, chlorophyll) designed to protect the ecosystems of the GBR, including seagrass, mangrove and coral reef ecosystems. Trigger value guidelines for these indicators have recently been set for the enclosed coastal, open coastal/inshore and marine offshore waters of the GBR lagoon by the Great Barrier Reef Marine Park Authority (GBRMPA, 2008).

Several monitoring programs within the GBRCA are led by the natural resource management (NRM) groups of each region with the extent of monitoring undertaken varying greatly across regions, including monitoring at the paddock/plot scale, catchment waterways and the adjacent flood plumes. These activities are undertaken with support from Landcare groups, industry and science providers within each region. End-of-catchment monitoring in the GBRCA is undertaken as part of the State Government's GBR Catchment Loads Monitoring Program and a Marine Monitoring Program is conducted by Great Barrier Reef Marine Park Authority (GBRMPA) (and associated monitoring providers) throughout the GBR lagoon. However, the linkages between catchment and marine monitoring for assessing the performance of investment through the Reef Rescue initiative are poor at present. A *Paddock to Reef Integrated Monitoring Program* is proposed under Reef Rescue to allow better integration up to the GBR scale, as well as along the 'paddock through catchment to reef continuum' at the regional scale. Such integration should allow for better linkages between end-of-catchment load targets (resource condition targets) and the adjacent marine trigger values. However, considerable time lags in responses to changed practices exist within the catchment which limits the usefulness of monitoring activities in detecting changes in pollutant loads or concentrations at the end-of-catchment scale in the short term (<5 years) which may result from on-ground incentive programs. Further complexity results from uncertainties in the estimation of pollutant loads, and the robustness of the pollutant targets themselves, which have been derived from the best available scientific understanding. The following paper provides an overview of these constraints currently faced by natural resource managers and science providers assessing Reef Rescue outcomes in the GBR catchment and lagoon, and suggests a coupled monitoring and modelling approach that could be incorporated into current Reef Rescue activities. This approach was developed by the authors whilst designing the water quality monitoring (and modelling) strategies for the Burdekin, Black-Ross and Tully-Murray WQIPs, and at the GBR-wide scale for the Reef Plan through the *Reef Water Quality Partnership*.

2. MONITORING CONSTRAINTS

There are many constraints associated with monitoring activities within the GBR catchment and lagoon for the purpose of determining the effectiveness of Reef Rescue on-ground investment in improving catchment water quality. Some of these constraints include:

- 'noise' in the monitored signal due to climatic and spatial variability within the catchment;
- varying time lags associated with material transport within catchments and into the GBR lagoon;
- additional time lags associated with catchment management and the resultant changes in water quality at varying downstream catchment scales;
- uncertainties in the estimation of pollutant loads;
- uncertainties in target values currently being set due to available scientific knowledge at the time;
- targets are set with the aim of improving marine ecosystem health but management practices are being implemented at the paddock scale;

- timeframes required by Government for delivery of Reef Rescue performance assessment (e.g. yearly reporting, short term targets < five years).

These constraints restrict the use of monitoring as an isolated management tool, and are discussed in more detail below.

Detecting water quality change with system 'noise' and lag times

One of the requirements of water quality monitoring in the GBR catchments is to detect temporal changes in water quality that result from the implementation of on-ground management actions. However, catchment variability, or 'noise' from natural signals, and lag times associated with particular management actions limit the detection of water quality changes or trends at this scale (see Table 1). The extent of system 'noise' will also vary depending on what water quality parameter is being measured. For instance, sediment lag times may be longer than reductions in dissolved inorganic nitrogen or pesticide concentrations in waterways, where management actions to reduce these later parameters (e.g. optimisation of herbicide application through the use of new technologies such as shielded sprayers) may result in reductions in concentrations within months to two - three years (as shown in Table 1).

The problems of detecting change in a large river resulting from moderate amounts of catchment management action and the complications of flow variability and extended response lags have been clearly shown in the Neuse River in the USA (Stow *et al.* 2001). Figure 1 adapted from Stow *et al.* (2001) shows how a percent nitrogen reduction in loads from the catchment translates into the time needed to detect change at the end of the river to a desired level of statistical rigour. In this case, for example, to measure a 20% reduction in nitrogen load will require 11 years of monitoring. The Burdekin River is both spatially and temporally far more variable than the Neuse

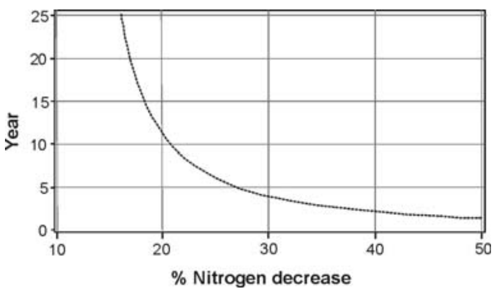

Figure 1: Time required to detect significant reductions in nitrogen load as a result of management intervention in the Neuse River, North Carolina for p-value of 0.05. (Adapted from Stow *et al*. 2001).

Table 1: Timeframes for water quality trends/signals to be detected for three parameter examples at varying spatial scales from paddock to reef as a result of management actions implemented.

Manage-ment actions/ remedial activity	Water Quality Parameter		
	Suspended sediment	**Dissolved Nitrogen**	**Herbicides**
	Erosion control mechanisms for grazing lands *e.g. riparian fencing & wet season spelling*	Reduction of fertiliser use in cropping lands *e.g. implement Six Easy Steps*	Minimise/optimise pesticide use through new technologies *e.g. shielded sprayers, control traffic*
Timeframe of water quality trends/signals being detected at different spatial scales			
Paddock/ Plot Scale	▪ Change likely to be detected after two-three wet seasons *e.g. Virginia Park Station*	▪ Months – three years, dependant on the nitrogen stored in the system (e.g. soil, organic matter) *e.g. BRIA paddock*	▪ Months – one year, dependant on previous usage and residuals in the system. *e.g. Tully paddock*
Local Scale e.g. immediate drainage line/ local waterway	▪ Likely to be detected within 5-10 years depending on system noise *e.g. Weany Ck*	▪ Likely to be detected within one-three years, depending on rate of adoption within local area and system noise *e.g. local cane drain*	▪ Likely to be detected < one year due to relatively short half life (i.e. diuron half life in soil is 90 days, and likely complete life < 2 years) *e.g. local cane drain*
Sub-catchment Scale	▪ Greater than 10 years, even for major scale land management interventions across the sub-catchment *e.g. Fanning River*	▪ If sugarcane is dominant land use in catchment & management change is widely adopted then could expect to measure change <10 years, particularly if detailed pre-monitoring data is available *e.g. Upper Barratta Ck*	▪ If sugarcane is dominant land use in catchment & management change is widely adopted then could expect to measure change within 2 years, particularly if there is detailed pre-monitoring data that is available *e.g. Davidson Ck*
End-of-catchment Scale	▪ Dilution of signal as only small % of total catchment area under improved management at any one time, and hydrological variability or noise is high. Likely > 50 years (major erosion control management intervention across the Burdekin). *e.g. Burdekin R (Inkerman)*	▪ If sugarcane is dominant land use in catchment & management change is widely adopted then could expect to measure change < 10 years, particularly if there is detailed pre-monitoring data that is available *e.g. Barratta Ck (Bruce Hwy)*	▪ Change detected < 2 years, however may be dilution effect depending on amount of cane in catchment, and proportion of uptake by the industry within this catchment *e.g. Tully River (Euramo)*
Estuarine & Marine Scale e.g. coastal waters within adjacent bay	▪ Limited likelihood of detecting signal from this management action due to size of catchment. Likely > 50 years before change in turbidity. *e.g. Upstart Bay*	▪ Likely to detect change in chlorophyll from this management action (major nitrogen fertiliser reduction across the lower Burdekin sugar lands) < 20 years, with variability due to other sources of nutrients (e.g. Burdekin plume), seasonal variations in nitrogen cycling & sea water mixing. *e.g. Bowling Green Bay*	▪ Changes likely to be detected within two years in the floodplume, however signal may be difficult to detect if the coastal waters are also influenced by larger river flood plumes (e.g. Herbert or Murray Rivers) *e.g. Dunk Is. & Family Is. Group*

Note the Burdekin Rangelands (SS), lower Burdekin (DIN) and Tully floodplain (herbicides) have been used as examples to demonstrate varying scales.

River and much longer timeframes (>50 years) may be required to detect changes due to management actions. The longer term dataset (1987-2000) of nitrogen species loads in the Tully River, a smaller river with low flow variability located within the Wet Tropics has also demonstrated that it can take up to fifteen years or more to detect changes in nitrogen loads as a result of management practice change (Mitchell *et al*. 2001).

Pollutant load estimation

While several methods are available to calculate the total load of terrestrial materials through a sampled point of a waterway, each method is designed specifically for a particular catchment type (e.g. catchment area, stream type, climatic etc.) as well as the stream flow and concentration data available. As a result there can be large discrepancies in loads calculated using different methods. The uncertainty in total load can be further increased by sample collection techniques, for example the location within a waterway, sampling frequency during flow events, and variability in concentrations between events due to different antecedent conditions (e.g. Lewis *et al*. 2007). However, with appropriate knowledge of catchment type, environmental conditions and incorporating a targeted sampling approach and suitable calculation method, the uncertainty of load estimates can be considerably reduced. For example, Kuhnert *et al.* (2008) show that uncertainties of ± 20% in the suspended sediment load and ± 10% in the dissolved nutrient loads can be achieved with these considerations for the Burdekin River catchment. These load measurement uncertainties need to be considered when monitoring programs are developed to measure a reduction in pollutant loads as a result of improved management practices. For instance, it is unlikely in this example that on-ground investment targeted at reducing suspended sediment loads by 10% can be monitored/measured at the catchment scale given the uncertainty values associated with the load calculations.

Target setting and Government timeframes

Targets in the WQIP process are required to justify the level of investment based on a known ‘required’ level of pollutant reduction to meet GBR ecosystem health requirements. Historically, although targets were set (e.g. Brodie *et al*. 2001), the process was relatively ad hoc and lacked scientific transparency. The current target setting process using linked models from paddock to reef allows analysis of management options by running scenarios and can assess potential progress towards scientifically valid targets for various management options. The limits of current target setting processes are highlighted in Eberhard *et al*. (2008) and include the issues related to system variability mentioned above, and incomplete understanding of the linkages between management actions, end-of-catchment loads and marine ecosystem response.

The initial target of Reef Plan (2003) was ‘*To halt or reverse the decline of water quality entering the reef within 10 years*’, that is by 2013 (Anon, 2003). Subsequent to Reef Plan, regional WQIPs have recently set more robust, scientifically derived quantitative targets for both short (5 years) and long term timeframes (50 years). Examples from the draft Burdekin WQIP include the long term (by 2058) resource condition target of ‘attaining a minimum 40% reduction in mean annual sediment load at the end-of-Burdekin catchment’, and the short term (by 2013) target of ‘attaining a 25% reduction of nitrogen (nitrate) load entering the GBR from lower Burdekin sugar lands from current (2008)’ i.e. a reduction from ~ 3,000 t/yr to 2,250 t/yr (Dight, 2009).

In addition, the Reef Rescue Program has set targets for the whole GBR (see right) within the Federal Government’s 2009-2010 Caring for Our Country Business Plan (Commonwealth of Australia, 2008). It is clear that to effectively monitor progress towards these targets results will need to be provided in less than five years.

The Reef Rescue initiative also requires annual reporting of progress towards the Reef Water Quality Report. These policy frameworks are driving a combined monitoring and modelling approach for performance assessment of water quality improvement in the GBR.

Reef Rescue Five-year Outcome Targets:

- Reduce discharge of dissolved nutrients and chemicals from agricultural lands to GBR lagoon by 25%
- Reduce discharge of sediments and nutrients from agricultural lands to the GBR lagoon by 10%

Reef Rescue Management Action Targets:

- To increase the number of farmers who have adopted land management practices that will improve the quality of water reaching the reef lagoon by a further 1300 over three years.
- To increase the number of pastoralists who have improved ground cover monitoring and management in areas where run-off from grazing is contributing significantly to sediment loads and a decline in the quality of water reaching the reef lagoon by a further 1500 over three years.

(Commonwealth of Australia, 2008)

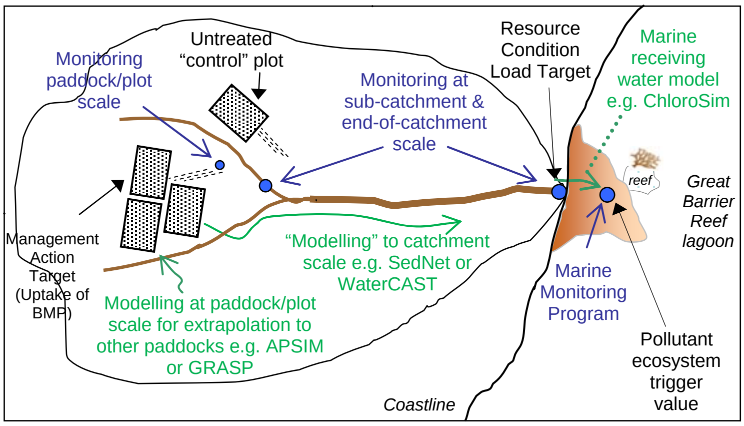

Figure 2: Monitoring from paddock/plot to marine ecosystem scale. Management action targets, resource condition targets, and GBR lagoon guideline trigger values are also highlighted.

3. COUPLED MONITORING AND MODELLING APPROACH

Due to the monitoring challenges outlined above, we recommend a coupled monitoring and modelling approach for assessing the water quality benefit of improved land management practices on ecosystems in receiving waters (e.g. freshwater wetlands, mangroves, seagrass and coral reefs). To ensure that model outputs are reasonably accurate, water quality monitoring data are required to both parameterise the model (plot scale water quality data) and validate the model (catchment scale monitoring data). Figure 2 illustrates schematically the sequential monitoring and modelling steps which link paddock scale management practice implementation to ecosystem resource condition targets in the GBR lagoon.

Paddock/plot scale runoff monitoring provides information on the unit degree of water quality improvement for specific management practices e.g. reduction of dissolved inorganic nitrogen (DIN) loss from paddock in kg/ha (e.g. 1 kg/ha) or mg/L after implementation of the fertiliser management program 'Six Easy Steps' (6ES) (Schroeder *et al.* 2005). Untreated "control" paddock water quality data are also required to determine the water quality change resulting from the improved practice.

The next step in this process is to use the paddock scale monitoring data as input into a catchment model which provides a measure of end-of-catchment load given a known amount of management action across the catchment. The simplest model is of the catchment management support system (CMSS) type (e.g. Davis *et al.* 1998), where export coefficients for individual land use under specific management practices are aggregated to the catchment scale. For example, if 500 hectares of sugar cane cultivation in a catchment changes from a conventional fertiliser regime to '6ES' then the total improvement in water quality at a catchment scale can be calculated to a 500 kg reduction (500 ha x 1kg/ha - using the simplest model) from the current DIN load. This simple model assumes no trapping, lag time or denitrification occurring from the paddock to river mouth. These are realistic assumptions for DIN in smaller catchments containing sugarcane, however they would not be for suspended sediment in dry, larger river catchments such as the Burdekin River, where the high degree of spatial and temporal heterogeneity means that to detect change in any reasonable timeframe (say within ten years) a coupled monitoring and modelling approach is required.

To overcome the limitations of the simple model used above, more sophisticated models are available which do take into account trapping on floodplains, system lag times and biological processes (i.e. denitrification) e.g. SedNet (e.g. McKergow *et al.* 2005) and WaterCAST (formerly E2; www.toolkit.net.au/watercast). While SedNet can be used in this situation at a catchment scale and has routines which account for sediment trapping and other in-catchment processes, it is a long-term, time-averaged model which does not explicitly model system dynamics such as vegetation change, and as such limits its usefulness of predicting changes in pollutant loads at an annual scale. However SedNet is powerful at identifying the spatial sources of suspended sediment and nutrients within the catchment, and hence can be compared to monitoring data at a number of scales within the catchment e.g. at small sub-catchment scales (e.g. Bartley *et al.* 2007), at catchment scales (e.g. Wilkinson *et al.* 2009) and other large river basins (e.g. Bainbridge *et al.* 2007; Fentie *et al.* 2005). WaterCAST can produce annual loads due to its short time-step capabilities but is weaker than SedNet as it does not currently represent catchment trapping mechanisms and dissolved nutrients.

Linking end-of-catchment loads with marine trigger values requires a receiving water model such as the ChloroSim model (Wooldridge *et al.* 2006) to relate pollutant loads to ecosystem response. Currently this type of model is only available for some priority pollutants and GBR targets (e.g. nitrate end-of-catchment loads and chlorophyll concentrations in the GBR lagoon from ChloroSim) and it is a priority research area to develop these relationships for all pollutants. To link the whole series of monitoring and modelling steps together is difficult due to the propagation of error and uncertainty between the individual steps (Brodie *et al.* in press). One method which addresses some of these problems is the use of the Bayesian Belief Networks

(BBN) as a model integration tool (see Thomas *et al.* 2005; Shenton *et al.* 2007). These approaches are currently being trialled within the GBRCA regions and at the GBR-wide scale (e.g. Lynam *et al.* in press).

The complete process required to assess the effectiveness of Reef Plan is outlined in Figure 3 below. This flow chart was developed for the Tully-Murray, Burdekin and Black-Ross WQIP monitoring (and modelling) strategies, and outlines the monitoring, modelling and auditing steps required from the paddock/plot scale through to the GBR lagoon.

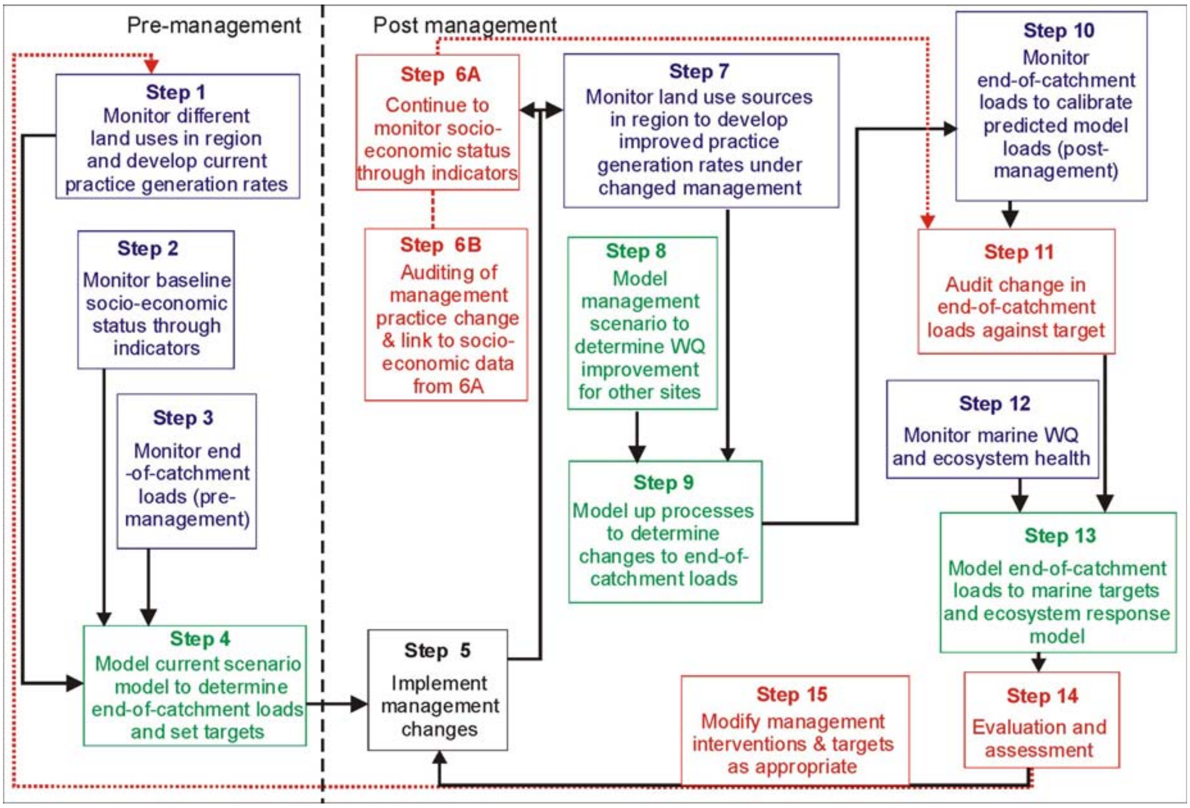

Figure 3: Flow chat outlining process for assessing management effectiveness and response for marine ecosystem health, with monitoring (blue), modelling (green) and auditing (red) processes coloured accordingly.

4. CONCLUSIONS

Our ‘up-scaling’ approach from the paddock to the Great Barrier Reef lagoon provides a clear framework to assist mangers and science providers in assessing the performance of the Reef Rescue initiative against its five-year outcome targets. A combination of monitoring activities and modelling tools link on-ground management at the paddock or plot scale to end-of-catchment resource condition loads, and finally to marine trigger values required for ecosystem protection. This combined approach overcomes many of the uncertainties associated with monitoring at shorter time scales as well as the shortfalls of the models available through data input and calibration. We note that this approach also has errors which may propagate through the scaling of monitoring and modelling data (e.g. paddock to sub-catchment scale, end-of-river to marine) and that other means, such as Bayesian Belief Networks may be required to reduce these additive errors.

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