Appropriate use of catchment models for water-quality target setting and land-use management

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Abstract Management of land use and the setting of water-quality targets on the whole-catchment scale are typically constrained by a lack of observational data on which to base decisions. Typically, GIS-based models are used to interpolate and extrapolate a limited observational data set to cover an entire catchment and these derived values (pseudo-data) are used as input to catchment contaminant generation and transport models. We examine the impact of the intrinsic uncertainty in pseudo-data on predictions made using the catchment sediment and nutrient model, SedNet/ANNEX, and the consequences of this uncertainty for land-use management planning. The use of pseudo-data to estimate bulk soil properties (% clay, % phosphorus, % nitrogen) exhibited both a high bias and high standard deviation when compared with direct measurements. The high bias limits the usefulness of model predictions for setting quantitative targets. The high standard deviation requires model results to be aggregated over scales considerably larger than the intrinsic model grid to facilitate comparison of contaminant export rates between spatial units. Assessment of competing land management scenarios is not severely impacted by model uncertainty provided the interpretation of results is limited to relative changes in contaminant export.

Key words catchment modelling; decision making; uncertainty; Great Barrier Reef; water quality; sediment; nitrogen; phosphorus

BACKGROUND

The Great Barrier Reef World Heritage Area, located on the northeastern coastline of Australia (Fig. 1), is an area of national and international significance, with outstanding natural, social and economic values. Over the past 150 years, reef catchments have been extensively modified leading to a decline in water quality entering the Great Barrier Reef (GBR) lagoon. The health of the GBR is a concern (Arthington *et al.*, 1997; Furnas, 2003), with the degradation of coral reefs attributed to elevated levels of sediment, nutrients and pesticides entering the reef lagoon from adjacent coastal catchments.

A joint Queensland and Australian government initiative has responded to these water quality concerns and threats with the production of the Reef Water Quality Protection Plan (RWQPP). The overall goal of the RWQPP is to halt and reverse the

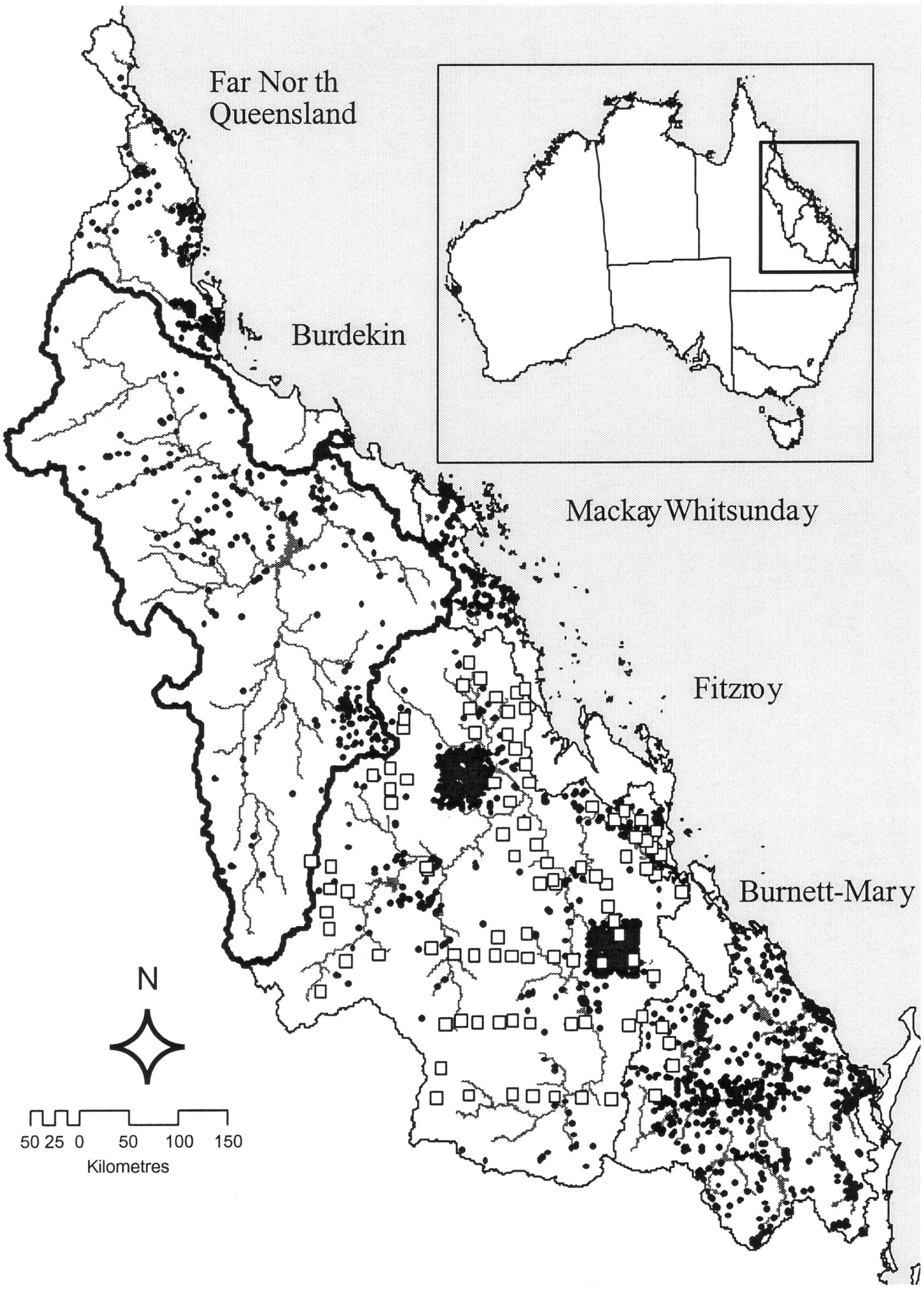

Fig. 1 GBRL modelled catchments. Bold outline shows the Burdekin catchment. Black circles denote SALI soil sample sites and squares show CSIRO soil sample sites in the Fitzroy catchment.

decline in water quality entering the reef within ten years, with the specific objectives to: (1) reduce the load of pollutants from diffuse sources in the water entering the Reef; and (2) rehabilitate and conserve areas of the Reef catchment that have a role in removing water borne pollutants.

The RWQPP relies on the funding and institutional support of the Australian Government working in association with State and Territory Governments, the aim being to facilitate integrated delivery of Natural Resource Management priority issues. Investments are driven by regional Natural Resource Management Plans (http://www.nrm.gov.au). These regional plans are developed by local communities and supported by Government and the best available science to improve natural resources on a regional scale.

There are six Regional NRM Bodies in Queensland adjacent to the GBR (Cape York, Far North Queensland, Burdekin Dry Tropics, Mackay/Whitsunday, Fitzroy Basin Association, and Burnett/Mary). These regional bodies are responsible through their regional plans for meeting the RWQPP actions to identify sub-catchment hotspot areas and develop water-quality targets for their region, as identified above.

In this paper, we focus on the first RWQPP objective and the use of the numerical catchment model, SedNet/ANNEX, to facilitate the development of end-of-catchment water-quality targets and the identification of sub-catchment hotspots responsible for delivering disproportionate quantities of sediment, nutrient and pesticides to the Reef.

Catchment models are often relied upon to support catchment management activities because they allow competing strategies to be evaluated for effectiveness prior to implementation. For many end-users the ideal model would provide both high temporal (daily to monthly) and spatial (paddock to farm) resolution because these are the scales at which management interventions are executed and their performance monitored. Model predictions must be accurate if they are to provide a foundation for reliable management action target setting, e.g. end-of-catchment sediment or nutrient export loads. Finally, it is most important for catchment models to provide an appropriate resolution of nutrient species, i.e. dissolved *versus* particulate, as it is the dissolved inorganic fraction that typically poses the most immediate environmental concern due to its much higher bioavailablility.

In the GBR region, few of these model characteristics can be realised simultaneously. High temporal and spatial resolution requires a level of detail in parameterisation that is seldom available due to scarcity of field observations. Model accuracy is constrained by sub-grid scale heterogeneity both in dominant transport and transformation processes, and by the spatial resolution of catchment features such as slope, vegetation cover, soil type, etc., some of which also vary temporally. Ultimately, one must choose scales at which to aggregate model process representation and input data. Typically this involves a trade-off between spatial and temporal resolution on the one hand and model prediction accuracy on the other.

BRIEF HISTORY OF SEDIMENT AND NUTRIENT MODELLING IN THE GBR CATCHMENTS

There have been a number of applications of catchment sediment and nutrient load modelling in various GBR catchments at a range of scales. Moss *et al.* (1993) estimated sediment and nutrient exports from Queensland coastal catchments using a desktop approach, as a preliminary assessment of the impact of land-based activities. In 2001, the National Land and Water Resources Audit (the Audit) undertook a whole-of-GBR estimate of sediment and nutrient loads; it was calculated using SedNet/ANNEX (Young *et al.*, 2001). As time has progressed the SedNet/ANNEX model was revised and input data refined to improve the accuracy of model predictions. In 2003, Brodie *et al.* (2003) completed a comprehensive SedNet/ANNEX modelling study of

GBR catchments and added the capability of ANNEX to simulate dissolved organic nutrients and modify loads based on residence times experienced by flows in downstream reservoirs.

Whereas the Audit and Brodie *et al.* (2003) modelling used a spatial resolution of 250 m, there has been higher spatial resolution modelling of some individual GBR catchments using SedNet/ANNEX. These have typically been performed at a resolution of ~100 m for the Mary (DeRose *et al.*, 2002), Herbert (Bartley *et al.*, 2003), and Bowen (Bartley *et al.*, 2004) catchments and for the Douglas Shire (Ellis *et al.*, 2005) as well. Kinsey-Henderson *et al.* (2005) have applied SedNet to the Weany Creek sub-catchment of the Burdekin using a resolution of 5 m to investigate the effect of employing spatially variable hillslope delivery ratios.

On an individual catchment basis, a range of models have been utilised, including simple approaches such as CMSS in the Barron River catchment (Cogle *et al.*, 2000) to application of EMSS in the Maroochy River catchment (Searle, 2005) and in the Fitzroy River basin. In the Johnstone River catchment there was sufficient data available to allow the use of the very data-intensive and highly parameterised model HSPF (Walton & Hunter, 1997) that includes both surface and groundwater in estimating loads. Bormans *et al.* (2004) applied the much simpler SedNet/ANNEX model to the Johnstone catchment also and found that its predictions compared reasonably well with those of HSPF; the ANNEX TP and TN loads were 10% and 28% higher than those predicted using HSPF.

SedNet/ANNEX was the model chosen to support the target setting process in our work because it was used by the Audit and for other modelling activities in GBR catchments (Prosser *et al.*, 2001; Brodie *et al.*, 2003; Bartley, 2003). Not only is SedNet/ANNEX a respected model, it could also readily use updated base layer information and provide quantitative estimates of long-term average annual sediment and nutrient loads for a range of resource management scenarios and, importantly, the underlying biophysical processes could be easily and clearly presented.

THE SedNet/ANNEX MODEL

The SedNet model estimates the mean annual load of coarse and fine sediment from a catchment generated by three processes: hillslope, gully and river bank erosion (Fig. 2). Hillslope erosion is computed using the Revised Universal Soil loss Equation (RUSLE) to compute a generation rate and attenuating this load by application of a hillslope sediment delivery ratio. The sediment supplied by hillslope erosion is assumed to consist entirely of top soil. Gully erosion is computed as the product of gully density, gully head migration rate, and the typical gully cross-sectional area. The model itself calculates the rate of riverbank erosion as the product of bank migration rate, bank height and bank length. Gully and bank erosion are assumed to consist entirely of subsoil. These three sediment sources are the inputs of sediment to the river network. Once delivered to streams, sediment is routed through the river network accounting for losses to the flood plain, riverbed and reservoir deposition along the way. The model outputs both the local sediment generation rate and the proportion of this sediment delivered to the end of the model domain. The latter feature facilitates the prioritisation

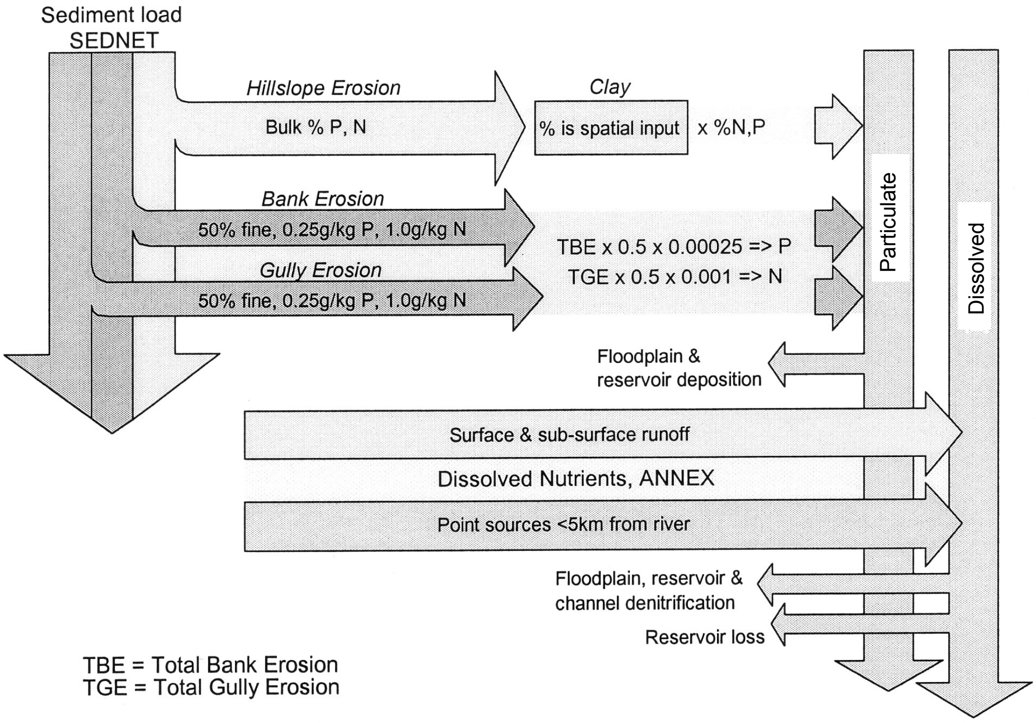

Fig. 2 SedNet/ANNEX model sediment and nutrient load sources and sinks.

of regions for remedial catchment management works. A compre-hensive description of the modelling algorithms and concepts is given by Wilkinson *et al*. (2004).

The ANNEX model is used to compute both particulate nutrient loads from the SedNet sediment load results as well as dissolved nutrient loads arising from both diffuse and point sources. ANNEX maps the mean annual sediment loads predicted by SedNet into mean annual nutrient loads in two ways depending on whether the sediment originates in topsoil due to hillslope erosion or subsoil due to bank and gully erosion. The basic concepts and equations used by ANNEX are described in detail by Young *et al*. (2001) and Wilkinson *et al*. (2004) and only a review of the methodology is presented here.

The subsoil provided by bank and gully erosion is assumed to consist of 50% fine and 50% coarse material, and all nitrogen and phosphorus are assumed to be bound to the fine fraction. The phosphorus content of subsoils is fixed at 0.25 g-P kg^{-1} (0.025% P by weight) and nitrogen is fixed at 1 g-N kg^{-1} (0.1% N by weight). Although it is possible to accommodate spatially variable subsoil nutrient contents in the model, in practice this has not been done due mainly to limited availability of field data to parameterise the model and the fact that, on average, the assumed concentrations are quite representative of measured subsoil properties.

The amount of particulate nutrients mobilised by hillslope erosion is equal to the total sediment generated multiplied by the bulk soil nutrient concentration. The particulate nutrients are assumed to be bound exclusively to the clay fraction of the sediment which is assumed to be preferentially transported to the river channel. Both the bulk nutrient content and clay fraction are spatially variable soil properties taken from the mapping of Australia by Henderson *et al*. (2001). The hillslope delivery ratio used by SedNet determines the fraction of the total eroded soil that reaches the stream channel and should it be less than the clay fraction; the nutrient content of the sediment reaching the channel is enriched.

Dissolved nutrient loads

ANNEX simulates dissolved nutrient loads by multiplying the mean annual flow by the mean annual concentrations of DIN, DIP, DON and DOP specified for different land-use classes. Due to limited observational data, concentrations could only be specified with any confidence for nine distinct land uses. The Queensland land-use database (QLUMP) considers 94 different land-use classes. It was necessary, therefore, to map the 94 different land uses into the closest of the nine classes for which it was possible to specify dissolved nutrient concentrations. The concentration of dissolved nutrients in any link (stream section) in the model is a weighted mean value based on the areas of different land uses contributing to runoff for that link.

Nutrient sinks

Particulate and dissolved nutrients are lost from the system in different ways. Particulate nutrients are lost as a consequence of sediment deposition on the flood plain and in reservoirs. The amount of sediment deposited by each process is determined by SedNet for each link in the network. The amount of nutrient lost is simply the mean nutrient content of the sediment load multiplied by the amount of sediment deposited. A small proportion of dissolved N and P loads are lost in reservoirs and can be thought of as reflecting the impact of consumption by aquatic organisms. In addition, dissolved inorganic nitrogen is lost by denitrification in the river channel, on the flood plain and in reservoirs.

Input data uncertainty

The uncertainty in the predicted particulate nutrient loads directly reflects the uncertainty in the assumed bulk soil properties, which are applied as input data, in addition to the erosion estimates from SedNet which reflect the assumed spatial distribution of rainfall. In our application of SedNet/ANNEX to the GBR catchments we must rely on pseudo-data to define these soil characteristics because there are few direct measurements of these properties outside of relatively intensively farmed areas in the GBR region. The term pseudo-data refers to soil properties that have been assigned using correlations between various parameters (often measured using remote sensing techniques) and corresponding measurements of the property of interest. We used relationships developed for the National Land and Water Resources Audit which correlated parent material, climate, organisms and relief with soil properties at locations mainly in southeastern Australia (Henderson *et al*., 2001).

Comparison between soil property observations and pseudo-data

The accuracy of TSS and particulate nutrient load predictions will depend on how well the pseudo-data soil properties (referred to as ASRIS) used as input to the model, reflect the observed soil properties. Measurements of soil properties are scarce over much of the GBRL catchments except in a few areas where there is intensive agriculture (Fig. 1). Here we compare the ASRIS values with observed soil properties measured by QNRW (referred to as SALI) throughout Queensland and by CSIRO in the Fitzroy catchment. The Fitzroy is another large (>140 000 km^2) GBRL dry tropical catchment just south of the Burdekin catchment. The frequency distributions of the observed pseudo-data values are shown in Figs 3 and 4.

Observations of soil N and P contents for all of Queensland (SALI, Fig. 3) and for the Fitzroy catchment (CSIRO, Fig. 4(b)) show a high bias relative to the pseudo-data

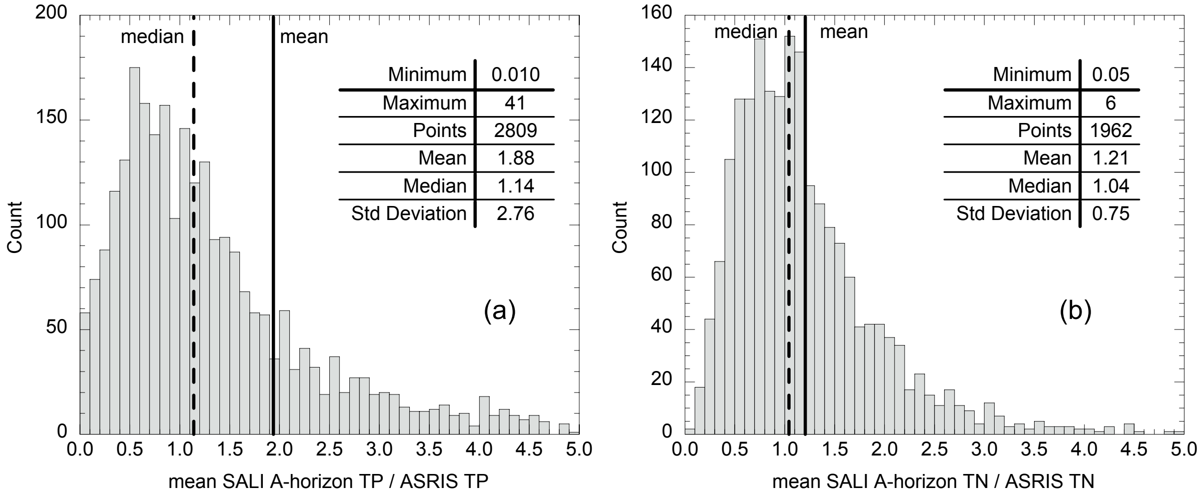

Fig. 3 (a) Measured soil P content (SALI) *versus* pseudo-data (ASRIS). (b) Measured soil N content (SALI) *versus* pseudo-data (ASRIS).

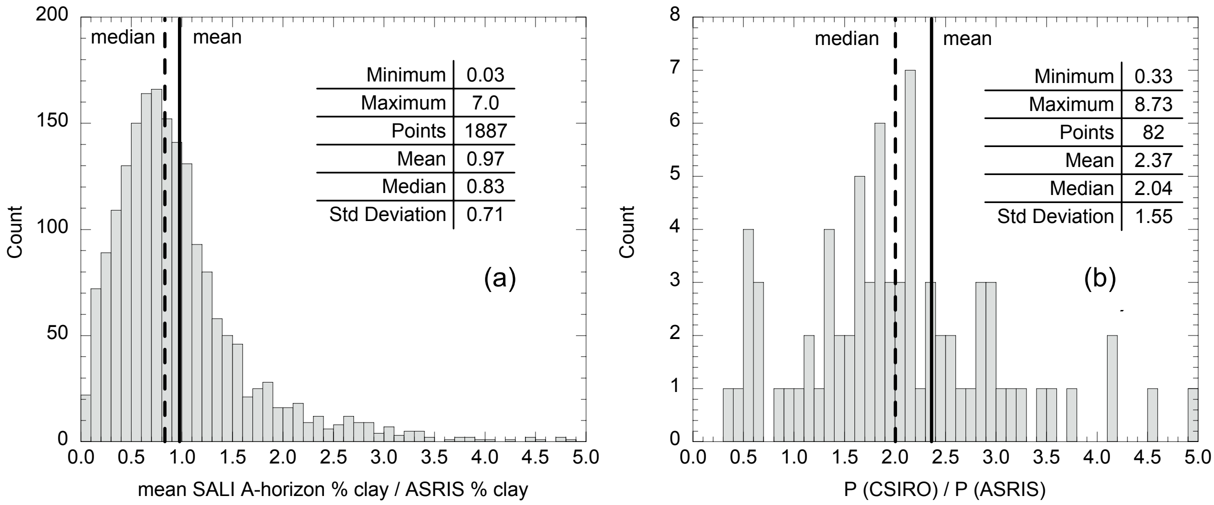

Fig. 4 (a) Measured clay content (SALI) *versus* pseudo-data (ASRIS). (b) Fitzroy catchment measured soil P content (CSIRO) *versus* pseudo-data (ASRIS).

(ASRIS) used as input to SedNet/ANNEX. Measured soil N and P are on average 21% and 88% higher across Queensland (SALI) than assumed by the model. The bias in soil P is even greater when one considers just the Fitzroy catchment where observed values from samples collected on a regular grid across the entire catchment averaged 137% more soil P than the corresponding locations in the ASRIS database. In contrast, the mean observed soil clay content matches the pseudo-data well (Fig. 4(a)). In all cases the distributions are characterised by large standard deviations ranging from 62–147% of the respective mean values.

Comparisons between modelled and observed contaminant loads

Field measurements of nutrient and suspended sediment concentrations as well as discharge are available from a number of locations within the Burdekin River catchment spanning various periods of time. These data allow us to assess the performance of SedNet/ANNEX predictions. Here, we focus on loads measured at Inkerman, which is located just upstream of the mouth of the Burdekin River and has the longest period of record.

Sediment and nutrient loads in the Burdekin River at Inkerman are taken from the analysis by Mitchell *et al*. (2006) of long-term monitoring grab sample data collected by Furnas (2003) (TSS July 1995–June 2000; PN, DIN July 1991–June 2000) and event monitoring data collected by ACTFR and QNRW from July 2004 through June 2006 (Bainbridge *et al*., 2006a,b).

Contaminant loads were calculated for each year by linearly interpolating grab sample concentration data in time and then integrating the product of discharge, Q, and concentration, C i.e. $Load = \int Q(t)C(t)\mathrm{d}t$. This method has been shown to produce the least biased estimate of event loads from stratified sampling data (Letcher *et al*., 1999).

Because SedNet/ANNEX predicted loads represent long-term (>10 year) annual averages, it is necessary to scale the measured loads to place them on a comparable basis with the observations. This is done by multiplying the measured load for any specific water year (which runs from 1 July through 30 June of the following calendar year) by the ratio of the mean annual flow (MAF) to the annual discharge for that water year.

The justification for this procedure in the Burdekin is based on the nature of flow and material delivery in the river. Virtually all flow (generally greater than 90%) and material delivery takes place in periods of high flow – called "event flow" (Lewis *et al*., 2006). Base flow contributes little of the total flow and even less (effectively zero) of the total sediment and nutrient delivery to Inkerman and the mouth of the river. So the total flow can be considered the same as the total event flow and all material delivery considered to take place in events and scaled accordingly.

A potential weakness in this procedure occurs if there is a strong correlation between discharge and concentration. Data presented by Mitchell *et al*. (2006) show dissolved nutrient concentrations were virtually independent of discharge for all but the lowest flow conditions, whereas suspended sediment concentration varied weakly (as the 0.25 power) with discharge. Therefore, this simple scaling procedure seems a reasonable method to facilitate comparison observed with modelled loads.

The measured annual loads are shown in Table 1 and the scaled observed annual loads compared with the corresponding model predictions in Table 2. Furnas (2003) has independently estimated the mean annual TSS load as 3.8 Mt, based on transmissometer data with much higher temporal resolution, which supports the scaled grab sample value of 3.5 Mt. Compared to the loads calculated from the field data, the SedNet/ANNEX estimates were 20% less for TSS, 11% less for DIN, and 74% more for PN loads. We regard these comparisons as fair, very good and very poor, respectively.

The underestimate of TSS load may reflect several factors. A large proportion (~75%) of TSS generated upstream of Burdekin Falls Dam is predicted to be trapped by the dam. The reservoir trapping algorithm is based on the work of Brune (1953) and Heinemann (1981) which correlate trapping efficiency with hydraulic residence time. This correlation has not been rigorously confirmed for rivers characterised by dry tropical hydrology, i.e. where the vast bulk of inflow occurs over a period of a few weeks each year. There is some evidence from the Burdekin River that the actual trapping efficiency of the dam may be closer to 40%. This would lift modelled TSS delivery at Inkerman closer to the observed range of 3.5–3.8 Mt.

The DIN comparison is very good, being helped by the fact there is no loss of DIN to any extent anywhere in the system. This implies that the specified export concentrations for the various land-use classes were basically correct thereby justifying the use of the plot-scale study data relating dissolved nutrient concentrations in receiving waters to upstream land use. Note that these concentrations were specified *a priori* to the use of the model and based solely on experimental results from various GBR catchments; no calibration procedure was used to improve the model's fit to observed loads.

The overestimate of the PN load (74% too high) is particularly worrisome. Given the fact that TSS is under-predicted by 20%, we are left to conclude that the amount of

Table 1 Observed annual loads of suspended sediment (TSS), particulate nitrogen (PN) and dissolved inorganic nitrogen (DIN) in the Burdekin River at Inkerman.

Year	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	04/05	05/06	Mean
Flow (million ML)	0.53	0.55	2.9	0.77	2.2	8.7	9.0	6.0	13	4.3	2.0	4.6
Measured TSS load (Mt)					1.5	6.8	3.5	1.4	4.0	2.7	0.5	2.9
Measured PN load (t)	43	37	3200	380	3400	9500	4300	3400	6400	2000	960	3100
Measured DIN load (t)	17	16	920	120	520	2700	1500	1900	1500	1300	350	990

Table 2 Observed and scaled mean annual loads for TSS, PN, and DIN for the Burdekin River at Inkerman compared to SedNet/ANNEX predictions.

	Mean obs	Scaled obs	SedNet/ANNEX
Discharge for TSS (10^6 ML)	6.5	8.4	8.4
TSS (Mt)	2.9	3.5	2.8
Discharge for PN, DIN (10^6 ML)	4.6	8.4	8.4
PN (t)	3100	5700	9900
DIN (t)	990	1800	1600

nutrient assumed to be associated with the sediment is very much too high. Recall that SedNet/ANNEX assumes that all nutrients are carried by the clay fraction and that both the clay fraction and soil bulk nutrient concentrations are specified using “pseudo-data” that were determined indirectly from remote sensing data and then mapped into %clay, %N and %P using correlations derived largely from data outside the GBR catchments.

DISCUSSION

Dissolved nutrient loads were modelled using effectively an event mean concentration approach where the EMC was derived from plot-scale experiments that investigate receiving water quality downstream from specific land uses. Modelled dissolved nutrient loads compared very well with measured loads which suggests that the approach taken by ANNEX is reasonably robust.

Suspended sediment loads were modelled using a process-oriented approach that explicitly computes sediment supplied from gully and bank erosion plus hillslope erosion based on the RUSLE. The modelled TSS loads matched observations reasonably well but are subject to uncertainty arising from trapping in Burdekin Falls Dam.

The very poor prediction of particulate nutrient loads is doubly troublesome. The soil property pseudo-data used as input was biased low by from 20% (N) to 88% (P) whereas soil clay content matched observations, on average, quite well. The low bias in soil N and P would suggest that modelled particulate nutrient loads would be too low assuming that sediment loads were accurately predicted. Given that sediment loads were under-predicted by 20% and soil N and P contents were also lower than observed, we would expect that model to significantly under-predict particulate nutrient loads. However, the modelled loads were nearly twice as high as the corresponding measured loads.

The source of the error in the particulate nutrient load estimates is uncertain. It may reflect a deficiency in the model’s representation of particulate nutrient sources, sinks and transport, or it may relate to correlations between errors in the assumed clay content and soil nutrient concentrations. The latter possibility is currently being investigated. Although it is possible for particulate nutrients to be transformed into soluble forms, this would not be consistent with our results which showed a good simulation of the dissolved nutrient loads. Clearly, there is either a significant nutrient sink term missing from the model, or there is a large error in the particulate nutrients associated with the sediment particles.

The uncertainties associated with sediment and nutrient load predictions have direct management implications. An early expectation of the modelling project was that we would provide nutrient load targets for use by catchment management groups. The very large (factor of two) uncertainty in particulate nutrient loads, and the dominance of PN and PP in the overall TN and TP load budgets, makes the specification of quantitative targets based on model predictions for these constituents unrealistic. There is no apparent spatial pattern in the distribution of soil nutrient content errors which, coupled with its large standard deviation, greatly limits ability to discriminate between particulate nutrient loads generated in different subcatchments based on model predictions. On the other hand, using model predictions to inform quantitative targets for suspended sediment and dissolved nutrients may be a more realistic objective.

Fortunately, the observed bias and large standard deviations in input pseudo-data does not impact significantly upon our ability to use the model to compare alternative management scenarios. In this case, the model results are reported as percentage reductions in contaminant loads owing to different land-use management practices. We are much more comfortable with the idea of using the insights provided by the model to develop aspirational management targets such as percentage reductions in particular loads from specific subcatchments. SedNet/ANNEX has proved to be a valuable tool for identifying parts of the landscape that are likely to be most responsive to management interventions (e.g. changed pasture management, revegetation of riparian zones, etc.).

From the perspective of GBR health, it is fortunate that model predictions of dissolved nutrient loads appear to be reasonably accurate. It is the dissolved nutrient load that poses the greatest threat to the Reef by providing nutrients that are immediately bioavailable (causing short-term algal blooms) and capable of travelling much further offshore where they threaten more of the Reef. Particulate nutrients tend to sediment out of the water column within a short distance of the coast and require transformation before they become bioavailable to any great extent. By identifying those areas that contribute the most to the dissolved nutrient export, SedNet/ANNEX is facilitating the management of the Great Barrier Reef.

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