Uncertainty in diffuse source pollution assessment and mitigation options – who knows?

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Abstract

Reducing diffuse source pollution of waters entering the Great Barrier Reef (GBR) Lagoon from adjacent catchments is a major focus of recent government and science initiatives. The Reef Water Quality Protection Plan of the Commonwealth and Queensland Government (Reefplan) stipulates land management changes to reduce sediments and nutrients transported to the GBR lagoon by 2013 through adopting environmentally sustainable and profitable land management practices. To achieve the aims of the Reefplan, decision makers require a socio-economic and biophysical understanding in order to choose between alternative future management options as well as to assess the risks associated with the trade-offs inherent in their choice. The CSIRO Water for a Healthy Country Flagship research portfolio contains a range of on-ground research activities that collate socio-economic and biophysical information and develop integrated models. The focus of one of the research projects, part of which this paper presents, is to quantify the uncertainty associated with the models and therefore to enable a risks assessment associated with management actions. This paper presents an uncertainty assessment of erosion models, and proposes a way of integrating this biophysical knowledge with socio-economic information. It identifies that in areas where high erosion estimates prove to be of low accuracy (i.e. are associated with high uncertainty), further targeted research to improve erosion estimates are required, whereas areas with high erosion and low bounded uncertainty are candidates for targeted management actions.

Keywords

Uncertainty, risk, sediment, water quality, diffuse source pollution, integration

Introduction

The entry of sediments and nutrients into the Great Barrier Reef (GBR) world heritage area from adjacent catchments has increased markedly since European settlement, with models estimating an eightfold increase in the natural sediment loads (Brodie *et al.*, 2003). This has raised concerns about the polluting effects that may impact on marine ecosystems and marine based industries such as fishing and GBR tourism (eg. Greiner *et al.*, 2005). As a consequence the Queensland and Commonwealth Government developed the Reef Water Quality Protection Plan (Reef Plan) in 2003 to address diffuse source pollution stemming from the GBR adjoining catchments (DEH, 2006). The plan identifies that the reduction of pollutant inputs into the GBR marine environment is necessary by 2013. Figure 1 shows the location of the GBR and its adjacent catchments.

Natural resource management agencies and the science community have initiated model based research for decision making and sustainable management of the GBR catchments. In this context CSIRO has developed a theme within the Water for a Healthy Country Flagship research program that aims for an integrated assessment of land management options. It aims to deliver useful information to decision makers with respect to sustainable social, economic and ecological management. Decision makers also need to know about the trade-offs and risks associated with alternative land management options. This means that knowledge about the quality of predictions and associated uncertainty is essential.

Within the Flagship theme research we have developed a project that aims to improve the predictive capacity of model outputs. We conveniently divide the areas in which we attempt to address uncertainty into three different arenas: (i) a biophysical arena with erosion and sediment as focal points; (ii) an economic arena focussing on enterprises that depend on natural resources; and (iii) a social arena with focus on individual and community wellbeing and livelihoods.

The aim of this research is to demonstrate methods for quantifying and incorporating uncertainty into deterministic models using statistical methods. A categorisation of uncertainty sources is ideally based upon the ability to quantify these uncertainties. Here we distinguish between epistemic and aleatory uncertainty as a convenient way to align the readers understanding and terminology for the subsequent sections. Aleatory uncertainty is the result of measurement and its associated errors. It expresses stochasticity that stems from the variability of repeatable measures. Epistemic uncertainty on the other hand is non repeatable (Bedford *et al.*, 2001). In the context of modeling, epistemic uncertainty is the lack of knowledge about the system and its parameters.

In this paper we present the approach and preliminary results of quantifying uncertainty in the biophysical arena, namely the assessment of erosion that will contribute to sediment delivery to the GBR lagoon using pilot study results. We then use these outputs to identify and discuss consequences of this improved knowledge for applied management and future science. The next section will define uncertainty applicable to the current research, followed by an account of the methods and results of the uncertainty assessment. This in turn forms the basis for the discussion and conclusion.

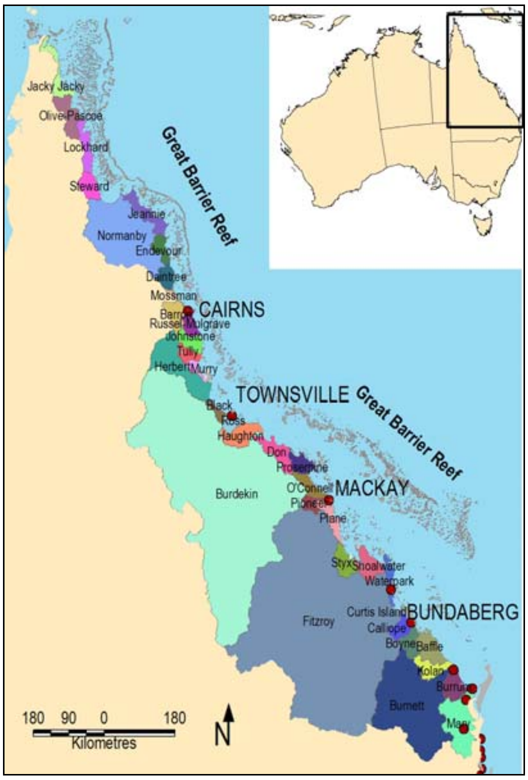

Figure 1. Catchments adjacent to the Great Barrier Reef lagoon

Methods

In the development of the uncertainty assessment method there is a need to address the data and model components as two different aspects. Data availability, quality and resolution vary spatially throughout the GBR, while the modelling approach is consistent throughout the GBR in terms of focusing on erosion on the one hand and sediment transport on the other. Therefore, we identified methods that allow incorporation of different types of data (including expert knowledge) and proposed methods that address erosion models and sediment transport models separately, yet are still complementary to each other. The initial research outcomes presented in this paper deal with the Burdekin catchment as a pilot study area, but the methods are extendable to all GBR (Figure 1).

Currently, sediment modelling employs the Sednet model, which was also the main model providing estimates for the National Land and Water Resources Audit (NLWRA, 2001). Sednet determines the total sediment load at the end of the catchment. The model includes modules that calculate hillslope, gully and riverbank erosion. An initial estimation suggests that 14% of the total eroded and transported sediments reach the lagoon (Brodie *et al.*, 2003). As the methods underpinning the Sednet model are already established (Brodie *et al.*, 2003; Prosser *et al.*, 2001), we will only present details that are important for the erosion uncertainty calculation. Subsequent sections will focus specifically on hillslope erosion component of the sediment generation. The underlying assumption here is that that if we can reduce the generation of sediments on the hillslopes, this will also reduce the sediment loads reaching the GBR lagoon in the long-term.

The erosion modelling component of Sednet is based upon the revised universal soil loss equation (RUSLE) that multiplies (in our case) five components to calculate hillslope erosion as mean annual soil loss of an area unit (Renard *et al.*, 1997). The factors are rainfall-erosivity (R), soil-erodability (K), hillslope length (L), hillslope gradient factor (S) and ground cover (C). Summing up the product of these factors over a grid provides the total erosion potential for a catchment. The total amount of the sediments from a watershed is the result of multiplying the erosion with a hillslope delivery ratio. The streamlink of the watershed then reroutes the sediments to the subsequent stream link or deposits them within a floodplain (Prosser *et al.*, 2001). As this paper concentrates on hillslope erosion we will not consider the calculation of this sediment transport or storage any further. Figure 2 shows the schematics of the hillslope erosion calculation.

Using the RUSLE, we can now calculate the uncertainty around hillslope erosion through employing an approximation. This approximation is based on the Edgeworth expansion, which allows to determine a bounded measure of uncertainty (Barndorff-Nielson *et al.*, 1989). The approximation assumes a Gamma distribution for the uncertainty surrounding each of the RUSLE factors. The choice of distribution reflected the shape of the data derived for each factor, but certainly other distributions could be considered.

Assuming initially independence between the uncertainty surrounding each factor, we can estimate the uncertainty distribution via the Edgeworth expansion as we sum this calculation across the watershed. This allows the calculation of the 10^{th} and 90^{th} percentiles of the distribution. This is a conservative estimate of the error representing an 80% confidence interval. A multiplication of 2.56 makes the results comparable to a coefficient of variation, which represents the error (as a percentage) increase or decrease from the mean. The advantage of this approach is twofold, (i) it is less computer intensive than a sensitivity analysis (Fenti *et al.*, 2005; Newham *et al.*, 2003; Schwarz, 1975), bootstrapping (Blukacz *et al.*, 2005) or Bayesian approaches (Bates *et al.*, 2003; Pool *et al.*, 2000; Raftery *et al.*, 1995) and (ii) it is readily implemented across larger regions such as the entire GBR catchments.

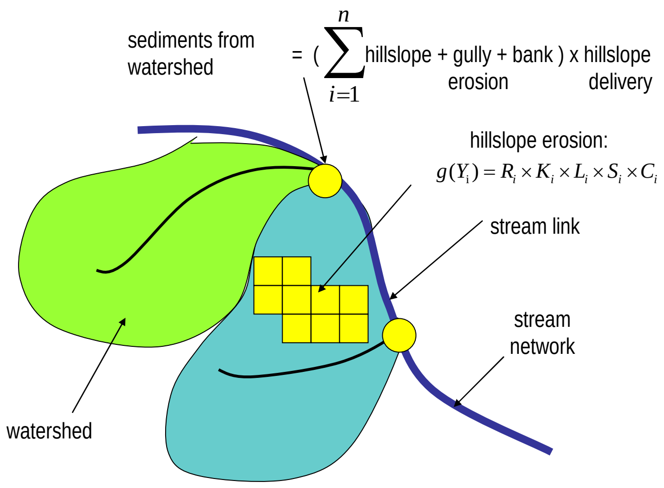

Figure 2. Conceptualisation of erosion and sediment transport from the watershed to stream link

Results

SedNet erosion calculations in watersheds across the GBR ranged from 1 t/yr to approximately 130,000 t/yr, with a total of 8,088,971 t/year. The confidence interval ranged from <0.1% to approx 140%. Figure 3 shows the spatial distribution of the erosion calculations across catchments by colour and the corresponding uncertainty represented by the third dimension of the graph. High erosion values are associated with larger errors and occur in the eastern and northern part of the Burdekin. Many of the catchments in the south exhibit little or no erosion and have little error associated with it.

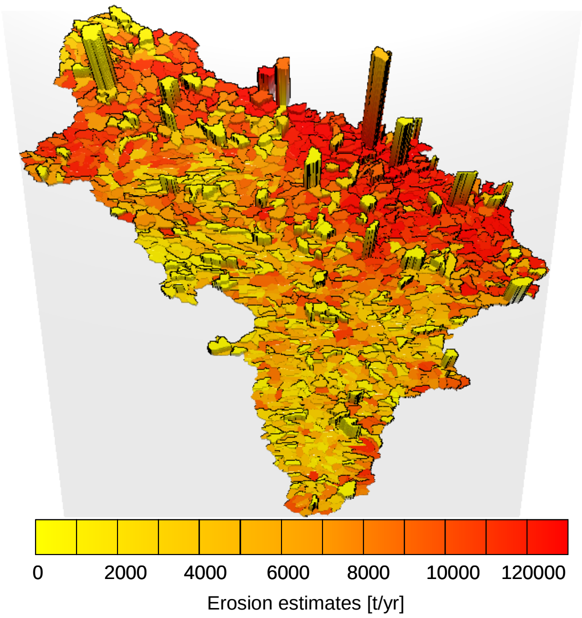

Figure 3. Visualisation of hillslope erosion and precision as proportion of the erosion (height) for the Burdekin catchment.

Discussion

Why should we care about uncertainty?

Prioritisation of investment and management actions requires knowledge about the location and severity of erosion. The Sednet model identifies hotspots areas where erosion is high. The Sednet RUSLE component also allows for an understanding of the erosion process. This understanding makes it possible to identify on-ground intervention options. Basically, interventions need to focus on prevention of dislodgement and movement of soil, namely increased soil cover (with vegetation) to reduce rainfall erosivity, strategic vegetation locations in the landscape to reduce overland flows, prevention of trampling in gully and riverbank areas, and reduction of physical impact in steep slope areas. A secondary effect of increased organic soil cover also improves the soil-structure in the longer term, therefore improving the soils' ability to withstand erosion.

For a large area such as the GBR it means focussing resources on to areas where erosion is highest and where there is a high chance of succeeding with erosion mitigation. This is the difficult task of natural resource managers; it involves combining biophysical understanding and socio-economic knowledge about the capacity and willingness of people to undertake mitigation actions (Curtis *et al.*, 2003; Cary *et al.*, 2001). While these measures are easily identified, they are less likely to be implemented in a farming enterprise if the benefits are below the costs. It also means that a business is unlikely to implement measures that will benefit society but come at a cost to the enterprise, unless supported through labour or cost subsidies (Herr *et al.*, 2004). This compensation could come in the form of targeted investment, a task that NRM bodies are currently undertaking (see below).

To prioritise and identify target areas for mitigation, resources managers need to overlay erosion hotspots and information on the capacity of the local communities. From these hotspot-capacity overlays they need to identify areas where targeted investment is likely to yield desired results. This demands strategies for prioritisation that incorporate a risk assessment of the different investment options. Risk consists of an event with known probability and its consequences. Managers have difficulties assessing actions within a risk framework if the models do not provide probabilities. It means they have to deal with epistemic uncertainties. In the context of decision making, epistemic uncertainty describes the gap between what is known and what needs to be known to make an informed decision (Ben-Haim, 2004) or to predict potential outcomes. Transferring epistemic uncertainty to measured aleatory uncertainty (*ie* variability) means closing this gap. Current catchment model outputs for the GBR have no uncertainty assessment incorporated into the calculation; they only provide a mean value and so are laden with epistemic uncertainty. This means that without addressing uncertainty in GBR catchment models, a reliable risk assessment of actions, prioritisation and targeted investment is extremely difficult, if not impossible.

Using the results of the uncertainty assessment for NRM and Reef Plan goals
Currently NRM bodies, who are responsible for the on-ground implementation of the national action plan for salinity and water quality (NAP) and the National Heritage Trust (NHT) goals (Commonwealth of Australia, 2006), are in the process of investment planning and prioritisation of actions aimed at NAP and NHT goals. At the same time, researchers are developing models in the biophysical, social and economic arenas to provide the information required to support this process. With the combined outputs of the erosion model and its uncertainty assessment they will be able to identify erosion hotspots and their reliability. Subsequently, in areas of high erosion and high precision (i.e. low uncertainty) they can start identifying management actions. These outputs also include social and economic targets (including targeted research where needed) to help identify potential mitigation options. Catchments where high erosion estimates have low precisions (*ie* high uncertainty) identify areas to focus on improving the quality of the erosion estimates. Clearly this requires a commitment to adaptive research and management. Adaptive research and management has been acknowledged in the Reef plan, which is designed to be reviewed and reiterated in the future.

In summary, the combined output of erosion modelling and the associated uncertainty assessment enables (i) the determination of areas for intervention, (ii) the identification of areas for further research, and (iii) the prioritisation of areas, after overlaying intervention options with the capacity of the community to implement these.

Conclusion and future work

Ideally with the collation of further information, epistemic uncertainty is transferable into quantifiable uncertainty, thus increasing the model's ability to describe the system at hand sufficiently for meaningful predictions. However, the resource constraints and the existence of non-epistemic uncertainty, which is related to ambiguity and vagueness (Colyvan, 2004), means that it is impossible to quantify all uncertainty. The approach our research takes to address this is to concentrate on first-order uncertainty and in the future, where there is insufficient data, to incorporate expert knowledge within a Bayesian framework.

Incorporating uncertainty assessment into NRM research will improve the rigor of scientific results and as such make science-based management decisions more defendable. Furthermore, it supports the use of the results within a risk assessment framework for management decisions.

The mitigation of erosion for the GBR is a complicated and iterative process which means that comprehensive solutions will be unavailable in the short term. Our approach identifies hotspots for identifying subsequent actions such as intervention or further targeted research aiming at future intervention options. This is in line with the iterative approach outlined in the Reefplan. The Reefplan acknowledges the need for an iterative process as it is expectant of ongoing review, evaluation and reassessment where required. The first reassessment cycle is scheduled in 2010 (The State of Queensland and Commonwealth of Australian, 2003). This means, NRM in the GBR has embraced adaptive management. Furthermore, narrowing down the area for identifying subsequent actions to hotspots is an adaptive and targeted approach that will result in an efficient way of focusing limited resources.

Integrating the social and economic arenas with biophysical information to support NRM planning requires the ability to assess model uncertainties and prediction uncertainties. Our future work is directed at building the capacity for NRM planning requirements. As such, we suggest that the uncertainty assessment framework needs to be adaptive and focus on prioritising using a hotspots approach. This will, in an iterative way, enable forecasting (i) where and what future research is needed, (ii) where actions are potentially successful and, (iii) where and in what arenas future investment is required to fill NRM specific knowledge gaps.

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