Science of the Total Environment 409 (2011) 4497–4503

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Assessing the value of Earth Observation for managing coral reefs: An example from the Great Barrier Reef

Jetske A. Bouma [a,*], Onno Kuik [a], Arnold G. Dekker [b]

[a] Institute for Environmental Studies, VU University, Amsterdam, the Netherlands
[b] CSIRO Land & Water, Canberra, Australia

ARTICLE INFO

Article history:
Received 9 June 2010
Received in revised form 1 July 2011
Accepted 5 July 2011
Available online 21 August 2011

Keywords:
Value of information
Earth Observation
Cost-effectiveness analysis
Marine water quality management
Bayesian decision theory
Coral reef protection

ABSTRACT

The Integrated Global Observing Strategy (IGOS, 2003) argues that further investments in Earth Observation information are required to improve coral reef protection worldwide. The IGOS Strategy does not specify what levels of investments are needed nor does it quantify the benefits associated with better-protected reefs. Evaluating costs and benefits is important for determining optimal investment levels and for convincing policy-makers that investments are required indeed. Few studies have quantitatively assessed the economic benefits of Earth Observation information or evaluated the economic value of information for environmental management. This paper uses an expert elicitation approach based on Bayesian Decision Theory to estimate the possible contribution of global Earth Observation to the management of the Great Barrier Reef. The Great Barrier Reef including its lagoon is a World Heritage Area affected by anthropogenic changes in land-use as well as climate change resulting in increased flows of sediments, nutrients and carbon to the GBR lagoon. Since European settlement, nutrient and sediment loads having increased 5–10 times and the change in water quality is causing damages to the reef. Earth Observation information from ocean and coastal color satellite sensors can provide spatially and temporally dense information on sediment flows. We hypothesize that Earth Observation improves decision-making by enabling better-targeted run-off reduction measures and we assess the benefits (cost savings) of this improved targeting by optimizing run-off reductions under different states of the world. The analysis suggests that the benefits of Earth Observation can indeed be substantial, depending on the perceived accuracy of the information and on the prior beliefs of decision-makers. The results indicate that increasing informational accuracy is the most effective way for developers of Earth Observation information to increase the added value of Earth Observation for managing coral reefs.

1. Introduction

Globally, coral reefs are degrading at an alarming rate (UN, 2010). Observations of coral reefs and their surrounding environments cannot directly stop this process, but they can help target interventions and mobilize public and political support. Mumby et al. (2004) list the contributions of Earth Observation to coral reef management, Earth Observation (EO) referring to the use of satellite imagery to monitor and map the state of the global environment and assess the rate of environmental change. Based on the types of reef and environmental properties that satellite imagery can measure, the contributions of EO to coral reef management include coral reef mapping, early warning of coral reef bleaching and monitoring of the surrounding environment for concentrations of chlorophyll, suspended sediment and algal blooms (Mumby et al., 2004). Given that investments in EO are costly, the added value of these contributions needs to be made explicit in order to convince policy makers that further EO investments are required indeed. Few studies have assessed the value of EO for environmental resource management (see Macauley, 2006 for an overview), and in general studies analyzing the value of information are few (Bouma et al., 2009).

This paper assesses the value of EO for better reef protection, focusing on the Great Barrier Reef (GBR). From consultations with key experts and senior decision-makers it became clear that a key issue concerning the management of the Great Barrier Reef World Heritage Area is receiving water quality management in the GBR lagoon. Decision-makers are uncertain about whether they should stimulate costly measures to reduce the run-off of sediments and their associated pollutants in all the catchments discharging in the GBR lagoon or target specific catchments that affect reef water quality most. EO derived water quality information can reduce this uncertainty by increasing insight into the temporal and spatial variability of different water quality parameters as a function of each catchment's run-off. Specifically, EO information on sediment discharges was mentioned as having potential to significantly contribute to improved management of the GBR. Hence, the analysis

* Corresponding author.
E-mail address: jetske.bouma@ivm.vu.nl (J.A. Bouma).

0048-9697/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2011.07.023

in this paper will focus on the added value of EO river plume and sediment discharge information for better targeted run-off reduction measures in the catchments discharging into the GBR lagoon.

The method we use for assessing the value of EO information is an expert elicitation method based on Bayesian Decision Theory, which measures the extent to which policy-makers are likely to actually use the information to change the decisions they make (Schimmelpfennig and Norton, 2003). Hirshleifer and Riley (1979) theoretically elaborate how this determines the economic value of information, concluding that information only has economic value when it causes real welfare impacts, which depends on the extent to which information is used to improve the decisions made.

To quantify the welfare impacts of better targeted water quality management, we developed a water pollution abatement cost model which minimizes the costs of water pollution abatement across the catchments discharging into the GBR lagoon. To estimate the model we used information from existing studies and from the Great Barrier Reef Water Quality Action Plan. We used the plan as baseline scenario, or to be more specific, as an example of a non-targeted approach: In the plan, catchments with stark increases in sediment and nutrient run-off have higher reduction targets than other catchments, regardless of the impact of the catchment discharges on the reef. Experts argue that discharges from certain catchments are likely to impact reef quality more: EO images have shown that river plumes from the Burdekin and Fitzroy basin, carrying sediment and dissolved organic matter with its associated nutrients and pesticides, reach the outer parts of the GBR, which is not surprising given that these are the two largest catchments discharging into the GBR lagoon. McKergow et al. (2005) argue that targeting interventions to these two catchments would be most effective for improving water quality in the GBR lagoon.

Uncertainties regarding the linkages between land use, water quality and reef quality are substantial (Wooldridge et al., 2006; Brodie et al., 2008a,b), partly because, at present, ecological and water quality information concerning the GBR is scarce. Although in-situ measurements of certain parameters are available, due to its sheer size coverage for the entire reef is low (Prange et al., 2007). EO information about sediment discharges and river plumes could reduce uncertainty regarding the spatial variability of water quality indicators in the GBR lagoon (Brodie et al., 2010; Dekker et al., 2006). In this paper, we will assume that EO river plume information can actually clarify whether targeting sediment reduction measures to the Burdekin and Fitzroy basin would have the same impact as reducing sediment loads from all catchments[1] discharging into the GBR lagoon. Although scientific proof of this assumption is still missing, the experts interviewed indicated that this would be a realistic scenario to assess. Clearly, reducing sediments would not be sufficient for reaching good water quality, but given that nutrients and pesticides often stick to suspended sediment, reducing sediment is expected to improve water quality in the GBR lagoon.[2]

The remaining part of this paper is structured as follows: In the next section we elaborate the conceptual framework. In Section 3 we introduce the water pollution abatement cost model. Section 4 describes our empirical approach for eliciting decision-makers' perceptions and in Section 5 we present the results. Section 6 discusses the outcomes of the assessment and concludes.

[1] Since in the Northern wet tropics region of the GBR catchment agricultural development is still limited, our analysis focuses on the 21 catchments located in the middle (wet tropics) and southern (dry tropics) part of the GBR catchment (see also Table A.1 in the Annex).

[2] In fact, we also estimated the costs of reducing nutrient run-off in the GBR catchments, but given the double counting associated with reducing sediment and nutrient run-off, we decided to focus on the cost-effectiveness of reducing sediment discharges to the GBR lagoon alone.

2. Conceptual framework

The literature suggests that studies assessing the economic value of information are limited and that few empirical estimates of the benefits of information exist. In the field of environmental resource management there are a couple of studies assessing the value of information, for example Gjerde et al. (1999) and Nordhaus and Popp (1997) in the area of global warming, and Borisova et al. (2005) in the area of water quality management. The value of EO for environmental resource management has been assessed by Kaiser and Pulsipher (2004), Chiabai and Nunes (2006), and Isik et al. (2005), and others, for subjects as varied as El Niño-southern oscillation, the oil price disaster, forest fires, geomagnetic storms, pesticide use and the internet (see Macauley, 2006, for an overview). Most of these studies compare decision-making under uncertainty with decision-making under perfect information, interpreting the difference as the value of information. This basically assumes that information is perfect and that decision-makers act according to the information received. Since this is not necessarily the case, Hirshleifer and Riley (1979) argue that Bayesian decision theory is a more appropriate analytical framework for assessing the economic value of information.

Bayesian decision theory is concerned with decision-making under uncertainty and focuses on the extent to which decision-makers actually use information to update their beliefs. This depends on the content and availability of the information, the perceived accuracy of the information and the prior beliefs decision-makers have (Hirshleifer and Riley, 1979). Inherent difficulties in the modeling of complex decision-making processes have limited the use of Bayesian Decision theory for empirical applications (Yokota and Thompson, 2004). The few studies that did apply Bayesian decision theory to estimate the value of information have done so by reducing the complexity of the decision-making problem by using discrete instead of continuous probability functions and by limiting the number of possible actions and states (see for example, Lybbert et al., 2006; Schimmelpfennig and Norton, 2003 and Bouma et al., 2009). Also in this study we will simplify the decision-making problem by using discrete probability functions, and by reducing the decision-making problem to two possible actions and two potential states.

Bayesian Decision Theory starts by acknowledging that decision-makers are uncertain about the so-called states-of-the-world. Since decision-makers are uncertain, they have to act upon their beliefs regarding these uncertain states of the world. The states of the world may be something like “it rains” or “it is dry” and decision-makers attach a certain probability “π_s” to each expected state of the world ($\Sigma\pi = 1$). The role of information is that it gives a message m about the state of the world. This can reduce the uncertainty of decision-making, that is, if the decision-maker uses the informational message to “update” her beliefs about the state of the world. A formal way of expressing the process of belief updating is reflected in the well-known Bayes theorem:

$$\pi_{s,m} = Pr(s|m) = \frac{Pr(m|s)Pr(s)}{Pr(m)} = \frac{q_{m,s}\pi_s}{q_m} \tag{1}$$

with $\pi_{s,m}$ the posterior probability, or the updated belief, π_s the prior probability, or the belief before the additional information, $q_{m,s}$ the conditional probability of receiving message m given state s (or the perceived accuracy of the information), and q_m the unconditional probability of receiving informational message m. The unconditional probability of receiving message m is related to the conditional probabilities (of receiving message m in state s) by:

$$q_m = \sum_{s=1}^{S} q_{m,s}\pi_s \tag{2}$$

Hence, whether an informational message makes decision-makers change their beliefs depends upon the decision-makers' prior beliefs regarding the state of the world and the perceived accuracy of the informational message. This is a rather intuitive finding: information that challenges existing beliefs and that is perceived to be inaccurate is less likely to be incorporated into decision-making than information that is perceived to be accurate and that supports prior beliefs.

The 'value' of message m is simply the difference between the utility of the action that is chosen given message m (x_m) and the action that would have been chosen without additional information (x_0):

$$\Delta_{\mathrm{m}} = u\left(x_{\mathrm{m}}, \pi_{\mathrm{s,m}}\right) - u\left(x_{\mathrm{o}}, \pi_{\mathrm{s,m}}\right) \tag{3}$$

Since we do not know in advance which message the information service will produce, the expected value of the information is the expected difference in utilities of actions given the likelihoods of receiving messages m (q_{m}):

$$\Delta(\mu) = E(\Delta_{\mathrm{m}}) = \sum_{m} q_{\mathrm{m}}\left[u\left(x_{\mathrm{m}}, \pi_{\mathrm{s,m}}\right) - u\left(x_{\mathrm{o}}, \pi_{\mathrm{s,m}}\right)\right] \tag{4}$$

To assess the economic value of an informational message, we need to minimally distinguish between two potential actions and two possible states of the world. For our case study, we distinguish between the following two actions: a) to continue with 'business-as-usual', i.e. the (non-targeted) GBR Water Quality Action Plan (X1) or b) to target sediment run-off reductions measures to the Fitzroy and Burdekin catchment alone (X2). The Fitzroy (143,000 km^2) and Burdekin River catchments (133,000 km^2) are the largest catchments discharging into the GBR lagoon. Due to the dry tropical climate in these catchments, with heavy rainfall in the wet season after an extensive dry season, and due to the nature of the land use in these catchments these catchment deliver large amounts of sediments with associated nutrients and contaminants to the GBR lagoon (Devlin et al., in press).

The effectiveness, or welfare impact, of both actions depends on the possible states of the world. We defined the following two states of the world: a) No spatial variability in water quality impacts (S1) and b) spatial variability in water quality impacts (S2). Spatial variability in water quality impacts can be observed through river plumes. Brodie et al. (2010) describe the spatial variability in river plumes as follows: "In high flow events, most the rivers of north-eastern Queensland flow fresh to the mouth and estuarine processes take place on the continental shelf rather than in a traditional estuary. River plumes develop in the GBR lagoon and most commonly spread to the north and offshore under the influence of *Coriolis* force and the prevailing south-easterly wind regime. These plumes, characterised by lowered salinity, turbidity from clay particles discharged from the river and phytoplankton blooms enhanced by the nutrients in the river discharge, may persist in the lagoon for periods of days to weeks."

When spatial variability of water quality impacts is low, targeting the Fitzroy and Burdekin basin is not very effective, but when spatial variability is high it is the most effective approach. By keeping the total impact of the different scenarios constant, we perform a cost-effectiveness of the alternative actions under the different states. Hence, we do not estimate the welfare impact of the different actions but assuming the impact of the different scenarios is similar (i.e. reaches the same total suspended sediment target), we compare the total water pollution abatement costs.

Again, which of the two actions is most cost-effective depends on the 'states-of-the-world': When there is little spatial variability in impacts, the optimal policy is to invest in water pollution abatement along the entire reef (S1), but when the spatial variability of impacts is high it is best to target the Burdekin and Fitzroy alone (S2). Table 1 presents the simplified decision-making problem.

In the next section, we explain how we estimated the different pay-offs.

Table 1
Pay-off matrix of the decision-making problem.

	Actions (x)	
States (s)	x1: Non-targeting	x2: Targeting
S1: No spatial variability in impacts	Payoff (x1|S1)	Payoff (x2|S1)
S2: Spatial variability in impacts	Payoff (x1|S2)	Payoff (x2|S2)

3. The water pollution abatement cost model

We estimated the pay-offs, i.e. the expected utility of the alternative actions, with a cost-minimization model written in the programming language GAMS. Since estimates of the full costs of reaching the GBRs Water Quality Action Plan's targets are not available, we used studies of the costs of pollution abatement in individual GBR catchments (see for example Roebeling et al., 2009; Rolfe and Windle, 2009; Van Grieken, 2008) to estimate the least-cost abatement policy for total suspended sediment (TSS) across catchments and crops.

Two types of interventions can be made to reduce TSS: a) interventions directed at farming practices (ground cover management, crop land management, etc.) and b) interventions directed at catchment conditions (hydrological management in the waterway, wetland or riparian zone protection, etc.). Both types of interventions are intended to lead to lower catchment loads of suspended sediment, leading to discharges into the GBR lagoon. Sediment discharges are especially large from dry tropical catchments (including the Burdekin and the Fitzroy basin): partly this has to do with climate (long dry period followed by heavy rain) but it also has to do with the predominant form of land use, i.e. livestock grazing. High stocking rates of livestock resulted in overgrazing, and lack of land cover led to increased sediment discharge: Since European settlement nutrient and sediment loads have increased 5–10 times (McKergow et al., 2005; Furnas, 2003). In the wet tropics catchments discharging into the GBR lagoon, horticulture and cane production are the predominant forms of land use, both causing substantial nutrient and sediment discharges too (Roebeling et al., 2009). In the model we distinguish between 21 catchments and 2 crops: grazing and sugar cane.

It is important to note that the costs of pollution abatement are higher in the grazing sector than in horticulture and cane sectors because measures in the grazing sector often imply lower stocking rates whereas in the cane and horticulture sector reduced discharges carry some benefits as well (Roebeling et al., 2009; Rolfe and Windle, 2009).

The objective function of the model is:

$$\mathrm{AC} = \min_{\mathrm{a}} \sum_{\mathrm{p}} \sum_{\mathrm{r}} \sum_{\mathrm{i}} f_{\mathrm{pri}}\left(a_{\mathrm{pri}}\right) \tag{5}$$

AC Total abatement cost
f(a) Abatement cost for pollutant *p* from crop *i* in catchment *r* as function of abatement intensity *a*.

We use one constraint for each pollutant. In formula:

$$\bar{A}_{\mathrm{p}} = \sum_{\mathrm{r}} v_{pr} \sum_{\mathrm{i}} P_{\mathrm{pri}} * a_{\mathrm{pri}} \tag{6}$$

$\bar{A}_{\mathrm{p}}$ Total abatement target for pollutant p = {DIN, TSS}
v_{pr} Ecological impact indicator of pollutant p from catchment r
P_{pri} Current pollution levels of pollutant p from catchment r and crop i.

Thus, abatement costs are minimized given a constraint on the effectiveness of the abatement policy on the protection of the Reef.

The effectiveness is the product of the total pollution flowing into the GBR lagoon and an "ecological impact" indicator that determines the relative damage of pollutants from different catchments to the reef. Basically, this ecological impact factor is 1 for all catchments when we assume no spatial variability in impacts between catchments discharging near the reef, and it is 1 for the Burdekin and Fitzroy catchment and 0 for most other catchments when we assume spatial variability in sediment impacts is high. The ecological impacts factor is subsequently multiplied by a scale factor to ensure that the total pollution load is identical in both scenarios.

Data on current pollution level of TSS per catchment were taken from the GBR Marine Park Authority (Brodie et al., 2001). For the allocation of pollution across sugar cane and other crops we estimated pollution coefficients (tonnes per km^2) for sugar cane from the work of Roebeling et al. (2009) for the wet tropics, and Van Grieken (2008) for the dry tropics. Pollution from other crops was estimated by subtracting pollution from sugar cane production from total pollution loads per catchment as presented in Brodie et al. (2001). We then estimated quadratic abatement cost functions for TSS from sugar cane and grazing from Roebeling et al. (2009), see Fig. 1.

Roebeling et al. suggest that abatement in sugar cane is financially beneficial at lower rates of abatement (negative cost) because of win–win management practices such as reduced or zero tillage, economic optimum rates of fertilizer application, nitrogen replacement and split nitrogen application maintain production at lower costs. The costs rise sharply, however, when the rate of abatement exceeds 40%. The abatement cost curve of TSS on grazing land is relatively flat, with abatement cost in the range of 150–200 AUSD per tonne. Because the cost data in Roebeling et al. relate to one catchment in the wet tropics (the Tully-Murray catchment), we compared the cost data with data from other studies from other catchments (Rolfe and Windle, 2009; Donaghy et al., 2007; Alam et al., 2008; Lu et al., 2004), both from the wet and dry tropics, to make sure our cost estimates are in line. Rolfe and Windle (2009) report on the results of a number of water quality auctions in GBR catchments. In such auctions, landholders are invited to submit tenders specifying their proposed water quality improvement actions and their compensation (bid) levels. The average price per tonne of sediment reduction from cane producers in the Mackay/Whitsunday region was AUSD 4.06. A similar auction in the Burdekin catchment resulted in an average price of sediment reduction from cattle rangers of AUSD 89 per tonne. Donaghy et al. (2007) used a bio-economic model to estimate sediment abatement costs in the Fitzroy basin. Under different modeling assumptions they derived abatement costs between AUSD 60 and AUSD 240 per tonne

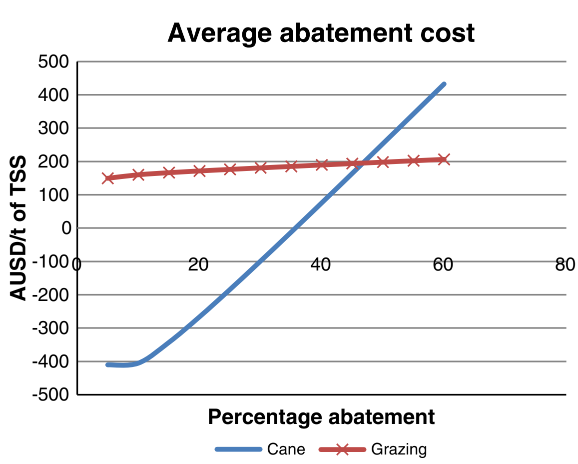

Fig. 1. Average cost curves of total suspended sediment (TSS) reduction in cane and grazing, Tully–Murray basin (Source: Roebeling et al., 2009).

of sediment from grazing activities. Alam et al. (2008) estimated the costs of rural diffuse mitigation measures in South-East Queensland. Lu et al. (2004) did a study for another region in Australia (Murray-Darling basin in eastern Australia), using a spatial-optimization model.

We conclude from this small review that the range of cost estimates from the available studies is large, but well within the orders of magnitude suggested by the estimates presented in Fig. 1. The variation undoubtedly reflects real differences between farms and catchments, but an unknown part of the variation is also likely to be due to methodological differences between the studies. With this caveat in mind, we applied the Roebeling et al. abatement cost functions to all catchments. In accordance to Roebeling et al., in our study we set a technical maximum of 60% to TSS abatement per crop and per catchment, since higher sediment reductions are simply too costly.

We carried out four simulations. The first simulation is a cost-effective abatement policy under the assumption of equal ecological damage from the pollution from all catchments (i.e. ecological impact factor for all catchments is equal to 1). Hence, the state-of-the-world is 'no spatial variability' (S1) and the action is the non-targeted approach (X1). At the overall and catchment level this simulation resembles the abatement policy plan of GBRMPA, the GBR Water Quality Action Plan, although there are (minor) differences in abatement rates for individual catchments.

In the second simulation, the no-targeting policy is implemented (X1), while in fact damage from a unit of pollution differs from catchment to catchment (S2). In this case, the intensity of abatement may have to be adjusted to meet the overall pollution targets, and the overall costs increase (see Table 2).

The third simulation is a cost-effective simulation under the assumption of different ecological damages from the pollution from different catchments (S2). Hence, abatement levels are higher in the Burdekin and Fitzroy catchment than in the other catchments. We call this policy approach "targeting" (i.e. abatement effort is targeted to those catchments that cause most damage) (X2), and since policy measures are effectively targeted this is in fact the least cost approach (see Table 2).

In the fourth simulation, a targeting approach is followed, while in fact there is no difference in damage from pollution from different catchments. Hence, the intensity of abatement has to be increased in the Burdekin and Fitzroy basin and the total costs increase (x2/s1).

Of the four options, abatement cost is lowest with a policy of targeting when in fact there is spatial variability in impacts (X2|S2: AUSD 481 million per year). Abatement cost of this policy is much higher however when there is no spatial variability (X2|S1: AUSD 936 million per year). With a non-targeting policy, abatement cost is lowest with no spatial variability (X1|S1: AUSD 811 million per year) and highest with spatial variability (X1|S2: AUSD 866 million per year).

Which policy would be best depends on the probabilities of the states. At present, there are no scientific studies that estimate the probability of the different states. We only know that decision-makers currently choose action 1, which suggests a perceived probability of

Table 2
Total abatement cost of the different simulations (million AUD/year).[a]

States (s)	Actions (x)	
	x1: Non-targeting	x2: Targeting
S1: No spatial variability in impacts	811	936
S2: Spatial variability in impacts	866	481

[a] When we include the costs of nutrient abatement, the costs of x1/s1 are 1471 AUD million/year, x1/s2 1531 AUD million/year, x2/s2 1392 AUD million/year and x2/s1 AUD 1521 million/year. However, these figures do not account for the fact that sediment reduction measures also reduce nutrient run-off, and vice versa.

state 1 of at least 75%.[3] Since asking decision-making about their prior beliefs is unlikely to generate trustworthy results (Rabin, 1998) we did not attempt to collect information about decision-makers' prior belief functions, but instead we estimated the value of EO information for the full range of prior beliefs.

Recalling the theory, in order to estimate the value of information we need information about the expected utility of alternative actions and about the perceived "accuracy" of the information as well. In the next section, we explain how we collected information about the perceived accuracy of EO information, using a questionnaire and expert interviews.

4. Perceptions of informational accuracy

To elicit decision-makers' perceptions of the accuracy of EO information, we developed a questionnaire in close cooperation with CSIRO Land & Water, the University Queensland and the Queensland Environmental Protection Agency. With the questionnaire, we wanted to collect information about decision-makers perceptions of the use and usefulness of EO information for GBR management, their perceptions of the accuracy of EO information and their expectations and beliefs. Here, we concentrate on the results of the questionnaire with regard to informational accuracy.

We interpreted informational accuracy as the perceived type-I and type-II errors of EO information: A type-I error occurring when an informational message incorrectly rejects the 'true' state and a type-II error occurring when the informational message fails to reject the 'false' state. To assess the perceived type-I errors we asked respondents to give an indication of the present (without EO) and expected future (with EO) 'informedness' of decision-making, 'informedness' referring to the certainty with which decisions are being made.[4] The type-I error of EO information was then determined as the remaining uncertainty, or 1- the expected 'informedness' of decision-making with access to EO. To determine the type-II errors, we inquired about the perceived accuracy of EO information, or the probability that EO indicates, for example, a certain concentration of sediments when this is in reality not the case.

We sent the questionnaire to approximately 70 researchers, water managers and policy-makers. Respondents were selected by CSIRO on the basis of their position and exposure to EO. Explicit attention was paid to respondent representation from research and policy circles and direct or indirect involvement in the management of the GBR. We sent the questionnaire around mid May 2008, and respondents had till mid July to respond. By the time the deadline closed, 27 respondents had replied, or approximately 40%. Of the 27 respondent roughly 40% are water managers and 60% are senior policy makers and experts. Of these respondents 31% had considerable EO experience, 38% some and 31% little (of which 4% none). Respondent's evaluations of the questionnaire indicated that most respondents were confident about the estimates they gave. Researchers and experienced EO users were more confident than managers and inexperienced EO users, but even the least confident were quite confident about the answers they gave. Hence, even for a complex environmental decision-making problem like the one addressed in this study, decision-makers seem able to express their perceptions of informational accuracy. In Table 3 we present the results.

Interpreting 1- the future informedness of decision-making as the type-I error of EO, the perceived type-I errors of having a monitoring system with additional EO investment are approximately 28%. For an indication of the perceived type-II error of an EO enhanced monitoring system we used the accuracy estimate itself (67%). Due to unclear wording we encountered some difficulties in the interpretation of results. Some respondents gave estimates for the perceived accuracy of EO information (generally, in the range of 50–100%) whereas other respondents gave estimates for the probability of EO information being wrong (in the range of 0–50%). We corrected the second set of answers by subtracting all estimates below 50% from 100%, and cross-checked outcomes with the maximum accuracy estimates respondents gave later in the questionnaire.

Testing for the influence of the respondent's background and level of EO experience, we find that when grouping respondents by professional background, there are no significant differences in 'informedness' estimates between groups. When we group respondents by their experience with EO information there are significant differences between groups (5% significance level, non-parametric Kruskal–Wallis test), but groups only differ in their estimates of the current 'informedness' of decision-making, and not in their estimates of the future 'informedness' of decision-making. Since these are the future 'informedness' estimates we are interested in, we can use the average figures for our analysis, i.e. a type-I error of 28% and a type-II error of 33%.

5. The value of Earth Observation

Using the decision-makers perceptions of informational accuracy (Table 3) and the expected utility of alternative water quality decision-making (Table 2) we can now estimate the value of EO sediment discharge information for a range of prior beliefs. When we use the type I and type II as presented in Table 3, the value of EO information, $\Delta(\mu)$, can be calculated with the help of Eq. (4).

In addition to the 'average' value of information (VOI), we calculated the 95% sensitivity range of value of information estimates, using the standard deviation of the informational accuracy estimates as presented in Table 3 (i.e. VOI 95% high and low). Finally, the figure presents the value of information when information is perfect (VOI perfect): Given that respondents indicated in the questionnaire that they expected the maximum accuracy of EO information to be 80% (i.e. type-I error of 20% and type-II error of 20%), we estimated the value of perfect information based on these results. Fig. 2 illustrates the outcomes graphically, for the whole range of prior beliefs.

Table 3
Results of the questionnaire, with respect to EO river plume information.

Present 'informedness'[a] of decision-making[a]	42% (16.8)
Future 'informedness'[b] of decision-making[b]	72% (16.7)
Impact of EO on 'informedness' of decision-making	30% (18.7)
Perceived accuracy of EO[c]	67% (18.3)

Standard deviations between brackets.
[a] We asked respondents: 'If 100% represents a situation of fully informed decision-making regarding X and 0% represents a situation with no information, what do you believe to be the informedness' of decision-making if decision-makers have NO access to satellite observation (i.e. solely rely on in situ measurements)?
[b] We asked respondents: 'Now, with full access to satellite imagery derived X information, what do you believe the situation to be, i.e. how well-informed is decision-making then?'
[c] We asked respondents 'Given an image like X, what do you expect to be the probability that the satellite-based information indicates low water clarity when 'in situ' measurements indicate water clarity is good? (i.e. the accuracy of satellite-based river plume information).

[3] Considering the expected utility of the two actions for different probabilities of state 1, the expected utility of $X2$ exceeds that of X1 when the probability of state 1 falls below 75%. Given that decision-makers currently favor X1, and assuming they are rational, the prior belief in state 1 is thus likely to be at least 75%.

[4] Alternatively, Holthausen and Verrecchia (1990) define informedness as 'the extent to which agents become more knowledgeable'. We chose to explicitly mention the certainty of decision-making in our definition, in line with our use of Bayesian Decision Theory.

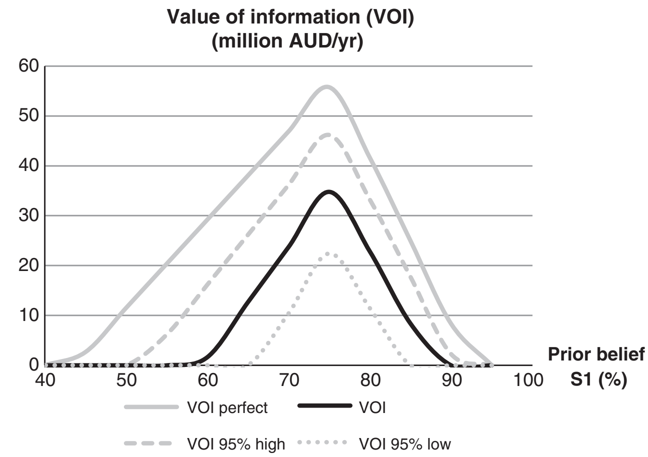

Fig. 2. The value of EO information for a range of state1 probability beliefs.

The results indicate that EO information has most value (i.e. 37 million AUD/year on average) when the prior belief in state 1 is around 75%. This is because for decision-makers with a prior belief in state 1 of 75% the expected utility of action 1 (continue with GBRMPA water quality plan) and action 2 (target only the Burdekin and Fitzroy basin) is the same. Hence, decision-makers are most uncertain about their decision-making and their willingness to pay for information peaks. Once they become more certain about the desired course of action, their willingness-to-pay decreases as they are more certain about the decision they should make.

What the figure also shows is that improving the accuracy of EO, i.e. getting closer to the perfect information curve, not only increases its value (i.e. to maximally 55 million AUD/year),[5] but also increases the range of prior beliefs over which information is considered economically valuable. Whereas those that perceive EO information to be the least accurate (represented by VOI 95% low) are only willing to pay for EO information if their prior belief in state 1 is somewhere between 65% and 85%, decision-makers that perceive EO information to be highly accurate (represented by VOI high) are much more willing-to-pay for EO information, for a much wider range of prior beliefs. Increasing informational accuracy and more importantly, making sure that decision-makers are aware of these improvements, is thus an important strategy for securing EO investment funds.

What is still lacking from the figures are EO investment costs. Although data on the costs of EO investment are, unfortunately, lacking, studies have shown that monitoring costs often decrease with increased use of EO: Bouma et al. (2009) indicate that EO reduces the costs of water quality monitoring and Mumby et al. (1999) suggest that in the GBR region EO is the most cost-effective data collection tool. EO may require major capital investments, however, and in the next and final section of this paper we will discuss whether such investments make economic sense.

6. Discussion

The main aim of this research was to examine whether additional investments in Earth Observation to better protect the Great Barrier Reef World Heritage Area make economic sense. The analysis indicates that investments in EO river plume information can generate benefits up to 37 million AUD/year, depending on decision-makers' current perceptions of the spatial variability of water quality impacts on the reef. Whether benefits are sufficient to compensate the costs of investment could not be determined: Australia has no own ocean color satellites and basically receives raw EO data for free. Although the processing of EO data also requires significant investment it is only a fraction of the 200 to 1000 million dollars that the design and launch of an ocean color satellite might cost. The analysis in this paper has shown that there is a business case for additional investments in EO ocean color satellites, given the potential cost savings that the Australian government may derive. Please note that the figure of 37 million AUD/year attributes the combined impact of improved data collection, analysis and interpretation to the availability of Earth Observation data. Hence, net cost savings are likely to be lower, but likely to be positive still.

If EO developers further improve the accuracy of EO information, benefits could increase up to 55 million AUD/year. This would also increase the range of decision-makers willing to pay for EO information, as higher accuracy makes information economically valuable for a larger group. Although it may not be possible to exactly determine whether decision-makers attach a probability to state 1 of 62% or 74%, the outcomes provide a platform to discuss the conditions under which informational investments make sense. Moreover, the approach illustrates that it is important for researchers to actively update decision-makers' beliefs: When decision-makers are unaware of the progress in informational accuracy, they might underestimate its value and, ignoring the uncertainties of their own decision-making, they could easily overlook the added value that information could have. Raising awareness concerning the added value of informational investments is thus an important investment for researchers to make.

With regard to the suitability of Bayesian decision theory for assessing the value of information, the analysis has shown that Bayesian decision theory provides important insight into the factors determining the economic value of information. Applying Bayesian decision theory does require an understanding of how information might contribute to improved decision-making and how it could influence the perceived probability distribution of the different states of the world. For very innovative applications such an understanding might be lacking, making it more difficult to convince decision-makers that investments are required in EO. Also, applying Bayesian decision theory to real world problems requires simplification of the decision-making problem to a manageable number of states and actions and the use of a discrete instead of a continuous probability function. As a result, outcomes are likely to represent extreme values in the full spectrum of value of information estimates, with the actual value of information laying somewhere in between. This could be a problem when outcomes are interpreted as real financial figures, and it is important to stress that figures represent an order of magnitude estimate of the economic value of information in the current setting of coral reef management and with the current water pollution abatement costs.

Including possible other water quality variables such as the colored dissolved organic matter as a proxy for carbon flux and chlorophyll as a proxy for nutrients could increase the value of EO derived information. However, since the economic value of information ultimately depends on the difference in expected utility between the alternative actions, more information does not necessarily generate a higher economic return. Further research is required to estimate other possible contributions of EO to coral reef management and analyze whether the findings hold in other contexts as well.

Acknowledgements

We could not have developed the questionnaire without the help and major inputs from Jane Waterhouse (CSIRO), Dave Rissik (Environmental Protection Agency), Stuart Phinn and Chris Roelfsema (University of Queensland) and Birte Schoettker (CSIRO/University of Queensland). Also, we would like to thank the respondents who participated in the survey for their efforts and their time. The research was funded by the European Commission under FP6 in the framework of the GEOBENE project (www.geo-bene.eu).

[5] Please note that the difference with non-perfect average value of information estimate follows from higher accuracy figures, i.e. 80% instead of respectively 72% (type-I error) and 67% (type-II error).

Annex

Table A.1
Characterization of catchments with targets of GBR water quality action plan.

River basin	Type	Total area	Sugar cane	Grazing	Sediment run-off	Nutrient run-off	TSS target	DIN target
		km^2	km^2	km^2	TSS (ton)	DIN (ton)	%	%
Baffle creek	Dry	3996	14	3495	103376	874	50	33
Burdekin	Dry	130126	193	128640	2443232	11134	50	33
Burnett	Dry	33248	231	27944	728607	1244	50	33
Calliope	dry	2236	0	2032	60772	235	50	33
Fitzroy	dry	142537	0	124732	2635482	6579	50	33
Kolan	dry	2901	161	2349	61589	444	50	33
Styx	dry	3012	0	2961	136000	642	50	33
Boyne	dry	2590	0	2226	16974	314	33	33
Prosperine	wet	2535	196	2070	227314	1169	50	50
Plane creek	wet	2539	549	1830	114860	1612	50	50
Pioneer	wet	1570	296	1166	288343	471	50	50
O'Conell	wet	2387	264	1904	366309	1666	50	50
Johnstone	wet	2325	394	493	305142	1849	50	50
Tully	wet	1683	247	316	88084	1303	33	50
Rusell-Mulgrave	wet	1983	232	55	222425	1441	33	50
Murray	wet	1107	58	520	17098	440	33	50
Mossman	wet	466	57	15	15131	231	33	50
Herbert	wet	9843	691	7330	664787	1588	33	50
Haughton	wet	4044	528	3441	172454	801	33	50
Don	wet	3695	47	3582	509528	812	33	33
Barron	wet	2902	76	227	45877	321	33	33

DIN: Dissolved inorganic nitrogen, TSS: Total suspended sediment. Source: Brodie et al. (2001).

References

Alam K, Rolfe J, Donaghy P. Assessing the cost-effectiveness of water quality interventions in South-East Queensland. Aust J Environ Manage 2008;15(1):30–40.

Borisova T, Shortle J, Horan RD, Abler D. Value of information for water quality management. Water Resour Res 2005;41:1–11.

Bouma JA, Van der Woerd H, Kuik O. Assessing the value of information for water quality management in the North Sea. J Environ Manage 2009;90(2):1280–8.

Brodie J, Furnas M, Ghonim S, Haynes D, Mitchell A, Morris S, et al. Great Barrier Reef Catchment Water Quality Action Plan. Townsville: Great Barrier Reef Marine Park Authority; 2001. 116 pp.

Brodie J, Binney J, Fabricius K, Gordon I, Hoegh-Guldberg O, Hunter H, et al. Scientific Consensus Statement on Water Quality in the Great Barrier Reef. Brisbane: Reef Water Quality Protection Plan Secretariat; 2008a.

Brodie J, Binney J, Fabricius K, Gordon I, Hoegh-Guldberg O, Hunter H, et al. Synthesis of evidence to support the Scientific Consensus Statement on Water Quality in the Great Barrier Reef. Brisbane: Reef Water Quality Protection Plan Secretariat; 2008b.

Brodie J, Schroeder, Th, Rohde K, Faithful J, Masters B, Dekker AG, et al. Dispersal of suspended sediments and nutrients in the Great Barrier Reef lagoon during river discharge events: conclusions from satellite remote sensing and concurrent flood plume sampling. Mar Freshwater Res 2010;61(6):651–64.

Chiabai A, Nunes P. Economic Valuation of Oceanographic Forecasting Services: A Cost-Benefit Exercise. FEEM working paper 104.2006. Milano: Fondazione Eni Enrico Mattei; 2006.

Dekker AG, Brodie J, Steven A. Cattle, crops and coral: Flood plumes and the Great Barrier Reef. In: Stephanie Renfrow, editor. NASA Distributed Archive Center Annual Report 2006. Boulder, Co, USA: NASA National Snow and Ice Data Center DAAC; 2006.

Devlin, M., Schroeder, T., McKinna, L., Brodie, J., Brando, V.E. and Dekker, A.G., in press. Monitoring and mapping of flood plumes in the Great Barrier Reef based on in-situ and remote sensing observations. In: Ni-Bin Chang, editor. Ch8 in Advances in Environmental Remote Sensing and Systems Analysis. CRC Press On Line.

Donaghy P, Rolfe J, Gaffney J. Unravelling the economic and environmental trade-offs of reducing sediment movement from grazed pastures. Paper presented at the 51st AARES Annual conference, 13–16 February 2007, Queenstown, New Zealand; 2007.

Furnas M. Catchments and corals: Terrestrial runoff to the Great Barrier Reef. Townsville: Australian Institute of Marine Science; 2003. 334 pp.

Gjerde J, Grepperud S, Kverndokk S. Optimal climate policy under the possibility of a catastrophe. Resour Energy Econ 1999;21:289–317.

Hirshleifer J, Riley JG. The analytics of uncertainty and information- An expository survey. J Econ Lit 1979;17:1375–421.

Holthausen R, Verrecchia R. The Effect of Informedness and Consensus on Price and Volume Behavior. Acc Rev 1990;65(1):191–208.

IGOS (Integrated Global Observing Strategy). Coral reef sub-theme report.coral.unep.ch/igoscr.htm; 2003.

Isik M, Hudson D, Coble KH. The value of site-specific information and the environment: Technology adoption and pesticide use under uncertainty. J Environ Manage 2005;76:245–54.

Kaiser MJ, Pulsipher AG. The potential value of improved ocean observation systems in the Gulf of Mexico. Mar Policy 2004;28:469–89.

Lu H, Moran LC, Prosse IP, DeRose R. Investments prioritization based on broadscale spatial budgeting to meet downstream targets for suspended sediment loads. Water Resour Res 2004(40). doi:10.1029/2003WR002966.

Lybbert TJ, Barrett CB, McPeak JG, Luseno WK. Bayesian herders: Updating of rainfall beliefs in response to external forecasts. World Dev 2006;35(3):480–97.

Macauley MK. The value of information: measuring the contribution of space-derived earthscience data to resource management. Space Policy 2006;22:274–82.

McKergow L, Prosser IP, Hughes AO, Brodie J. Sources of sediment to the Great Barrier Reef World Heritage Area. Mar Pollut Bull 2005;51:200–11.

Mumby PJ, Green EP, Edwards AJ, Clark CD. The cost-effectiveness of remote sensing for tropical coastal resources assessment and management. J Environ Manage 1999;55:157–66.

Mumby PJ, Skirving W, Strong AE, Hardy JT, LeDrew EF, Hochberg EJ, et al. Remote sensing of coral reefs and their physical environment. Mar Pollut Bull 2004;48:219–28.

Nordhaus WD, Popp D. What is the value of scientific knowledge. An application to global warming using the PRICE model. Energy J 1997;18(1):1–46.

Prange J, Haynes D, Schaffelke B, Waterhouse J. Annual Marine Monitoring Report. Townsville, Australia: Great Barrier Reef Marine Park Authority; 2007.

Rabin M. Psychology and economics. J Econ Lit 1998;36:11–46.

Roebeling P, Van Grieken ME, Webster AJ, Thorburn P, Biggs J. Cost-effective water quality improvement in linked terrestrial and marine ecosystems: a spatial environmental-economic modelling approach. Mar Freshwater Res 2009;60:1150–8.

Rolfe J, Windle J. Pricing water quality improvements with auction mechanisms: case studies for the Great Barrier Reef. Paper presented at the 17th Annual conference of the European Association of Environmental and Resource Economists, June 2009 in Amsterdam, the Netherlands; 2009.

Schimmelpfennig DE, Norton GW. What is the value of agricultural economics research. Am J Agric Econ 2003;85(1):81–94.

UN. High-level meeting of the general assembly as a contribution to the international year of biodiversity, A/64/865. United Nations General Assembly; 2010 http://www.cbd.int/doc/un/unga65/iyb-hle-unsg-doc.pdf.

Van Grieken M. Project 3.7.5: Socio-economic constraints to and incentives for the adoption of land use and management options for water quality. MTSRF Milestone Report Project 3.7.5. Australia: Reef and Rainforest Research Centre; 2008.

Wooldridge S, Brodie J, Furnas M. Exposure of inner-shelf reefs to nutrient enriched run-off entering the Great Barrier Reef lagoon: post-European changes and the design of water quality targets'. Mar Pollut Bull 2006;52:1467–79.

Yokota F, Thompson KM. Value of information analysis in environmental health risk management decisions: Past, present and future. Risk Anal 2004;24(3):635–50.