



Incorporating Fine Sediment Pollution Impacts Into Unsealed Road Management: A Case Study from the Great Barrier Reef Catchment Area

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Abstract

Excess fine sediment is a significant contributor to ecological degradation in the Great Barrier Reef (GBR). Erosion of unsealed formed roads in Queensland, Australia, causes excess fine sediment to be delivered downstream to the GBR lagoon, negatively affecting the World Heritage-listed marine ecosystem (Waterhouse et al, 2024). This paper presents a Cost-Benefit Analysis (CBA) of alternative road management scenarios aimed at reducing fine sediment loads to the GBR, to assess the economic viability of these compared to current practices. The CBA used high-resolution erosion data and cost estimates from case study sites in Queensland. Four road management scenarios were assessed: (1) business-as-usual grading to bare earth, (2) alternative maintenance of drains and batters using vegetation management, (3) major erosion control to address erosion hotspots, and (4) full betterment using bitumen dust seal. Our results show that the alternative maintenance, major erosion control and full betterment road management scenarios were economically viable (i.e. yield positive net present values between AUD\$2.9 to 7.8 million) when compared with the business-as-usual scenario. The management of roads in GBR catchments is publicly funded, as are most mitigation efforts aimed at reducing fine sediment delivery to the GBR, particularly through government programs and initiatives targeting improved land and catchment management. As such, cost savings from implementing changes to existing road management practices will have wider benefits through efficiencies in government spending. Our findings demonstrate the importance of considering indirect, off-site impacts of road erosion in road management decisions to achieve better long-term ecological outcomes.

Introduction

Erosion of unsealed roads can cause both on-site and off-site effects. On-site effects include deterioration of the road surface and increased maintenance needs, while off-site effects are indirect impacts such as fine sediment pollution of local stream networks, downstream rivers and estuaries. For example, erosion of unsealed roads in Queensland, Australia, causes excess fine sediment to travel downstream to the Great Barrier Reef (GBR), adversely impacting the World Heritage-listed marine ecosystem (Mckenzie et al.

2024, Waterhouse et al. 2024). Increased fine sediments and nutrients delivered to the GBR impact coral reefs, seagrass meadows, and many of the marine species associated with these habitats such as fish and dugongs. Excess sediment in the water decreases light penetration, harming seagrasses and corals that rely on sunlight for growth. When sediments settle, they can bury or smother corals and seagrasses, increase disease, damage tissues, reduce growth rates, and alter microbial communities. These effects can also indirectly impact other marine life (Collier et al. 2024).

Unsealed roads are defined as formed or unformed roads with gravel or earth surfaces (ARRB 2020). Unsealed formed gravel roads are widespread across GBR catchments with local government authorities predominantly being the responsible agent for managing these assets.

Quantification of the economic impacts of on-site and off-site effects of erosion of unsealed roads can inform decision-making on road management and erosion control. These types of analyses have previously been done in the context of erosion in the agricultural sector. Barry et al.

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1. Introduction

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Quantification of the economic impacts of on-site and off-site effects of erosion of unsealed roads can inform decision-making on road management and erosion control. These types of analyses have previously been done in the context of erosion in the agricultural sector. Barry et al. (2011) examined the economic benefits of afforestation of agricultural land in New Zealand as a means of reducing erosion. Telles et al. (2013) discussed different methods to estimate the economic effects of agricultural on-site erosion, such as a replacement cost method to calculate costs of compensating for soil nutrient loss, or to calculate the value of lost yield due to erosion. Similarly, Patault et al. (2021) utilized an avoided cost method to determine the economic cost of runoff and erosion over two decades in Normandy, France, by analyzing public expenditure on mitigation measures to avoid damages caused by runoff and erosion.

More recent work by Rolfe, et al. (2018) applied two cost-effectiveness approaches to assess various agricultural water quality improvement projects in GBR catchments to inform better decision-making through prioritization based on specific pollutants. Later work by Star, et al.

(2021) investigated a range of studies delivering water quality benefits, also largely around agricultural practice change, to find a need for a transparent cost-effectiveness analysis framework for water quality outcomes at the GBR.

Other studies have focused on estimating the aggregated cost of erosion at continental or global scales. Sartori et al. (2019) used a sequential modelling approach to estimate the impact of erosion on global agricultural production, and Panagos et al. (2024) estimated the off-site costs to water bodies associated with erosion by assessing the expense of sediment removal from reservoirs across the European Union.

Although the biophysical impacts of unsealed road erosion in Australia have been assessed in several studies (Fu et al. 2010; Motha et al. 2003; Riley and Shrestha 2009), there is limited research that directly estimates erosion from unsealed roads in catchments draining to the GBR. The 2022 Scientific Consensus Statement brought together scientific evidence to understand how land-based activities influence water quality in the GBR and how these influences can be managed (Waterhouse et al. 2024). As part of the Scientific Consensus Statement, Bartley and Murray (2024) examined the most effective management practices for reducing fine sediment loss from the GBR catchments and the costs and cost-effectiveness of these practices. This study noted the lack of information on best management practices for reducing fine sediment export from roads as a significant knowledge gap and important for improving water quality outcomes in the GBR. Furthermore, the authors identified fewer relevant studies for fine sediment loss from roads compared to other land-uses, such as grazing, sugarcane and cropping, and found no known published studies of the costs or effectiveness of road management systems for controlling fine sediment loss in the GBR catchments (Bartley and Murray 2024).

The lack of specific study of sediment loads onto the GBR from unsealed roads then limits the understanding of the economic viability of targeted road management interventions to reduce sediment delivery to the GBR. The recent work by Shellberg, et al. 2026) provided a new approach to modelling erosion rates from unsealed roads. This study then applies a cost-benefit analysis (CBA) framework to assess the economic viability of alternative unsealed road management scenarios, compared with current business-as-usual practices, using data from two case study roads in Queensland, Australia. The CBA approach integrates the costs of different management options with their effectiveness in reducing fine sediment delivery to the GBR, based on high-resolution erosion data. The findings of the study aim to inform

cost-effective and ecologically responsible road management strategies in catchments draining to the GBR lagoon, and for jurisdictions managing unsealed roads in environmentally sensitive catchments more broadly.

2. Method

2.1. Study area

This case study was conducted in Queensland, Australia, where local governments manage approximately 39,000 km of unsealed formed roads, with an additional 600 km managed by the State Government (LGAQ data, cited in Klye et al. 2025).

The focus area was the Cape York Peninsula in Far North Queensland, a remote and sparsely populated region where most roads are unsealed. The study examined eight road segments within the Annan Catchment (Endeavour Basin), located in southeastern Cape York and draining into the northern GBR (Fig. 1). These road segments were situated along Oaky Creek Road and Percy Road near Cooktown, traversing areas with dispersive sodic soils—particularly at creek crossings and in alluvial/colluvial zones derived from the Hodgkinson Formation (comprising weakly metamorphosed sediments such as slates, siltstone, and mudstone). These highly erodible soils are representative of conditions found across unsealed roads in the Cape York Peninsula (Spencer et al. 2016; Shellberg et al., 2026).

The eight road segments, totaling 2.3 km, were each centered on a stream crossing and extended approximately 150 m on either side. For the CBA modelling, the total road length assessed was 21.5 km, comprising 17 km of Oaky Creek Road and 4.5 km of Percy Road, including 10 km of stream crossing approaches (measured from crest to crest).

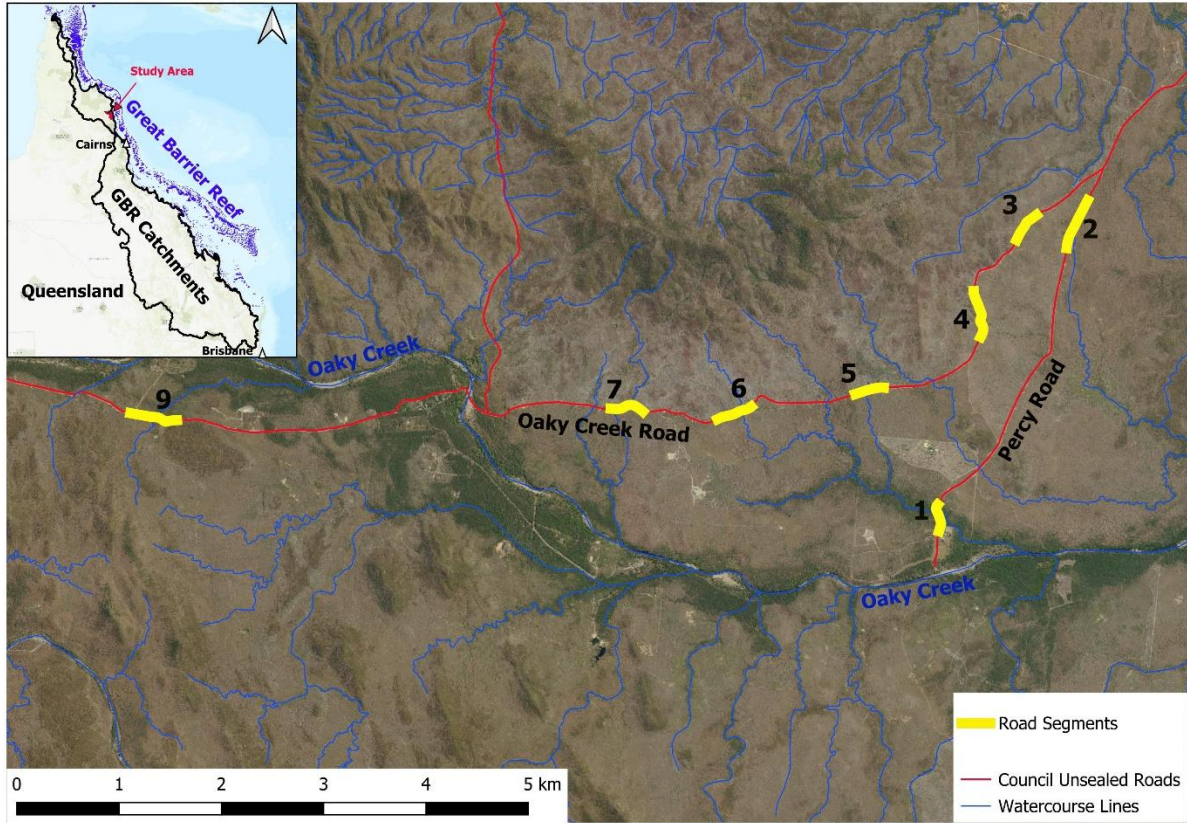


Fig. 1 Map of study area road segments along Percy Road and Oaky Creek Road, in relation to the GBR, Queensland, Australia

2.2. Cost-benefit analysis

CBA is a holistic appraisal method that compares a base case with one or more alternative scenarios. It aggregates all the costs and benefits associated with the various scenarios across an assessment period to estimate the net impact on society. All costs and benefits are expressed in monetary terms and discounted to present values. CBA includes both market impacts, such as investment and operating costs, but also impacts for which there are no market prices, such as changes to water quality.

Net Present Value (NPV) is a key decision rule used in CBA, whereby an option is considered economically viable if it produces an NPV greater than zero, i.e. total discounted benefits exceed total discounted costs over the analysis period.

$$Net\ Present\ Value = \sum_{t=0}^{t=T} \frac{Benefits}{(1+r)^t} - \sum_{t=0}^{t=T} \frac{Costs}{(1+r)^t} \quad (1)$$

where t denotes the year when the value is incurred, T is the time period considered (30 years in this analysis), and r is the discount rate. The discount rate applied in this analysis was 7 percent. Discount rates of 4 percent (low value) and 10 percent (high value) were included in the sensitivity analysis, consistent with Infrastructure Australia guidelines for Economic Appraisal (Infrastructure Australia 2021).

2.2.1. Sensitivity analysis

Within CBA, it is common to have to make assumptions where data is missing or of poor quality. Furthermore, there is often a range of values that could be used for specific benefits or costs. To account for this uncertainty and variability in data inputs, a sensitivity analysis was performed to understand the potential range of possible outcomes and the extent to which individual assumptions affect the overall results. The uncertainty associated with parameters in the analysis was captured using Monte Carlo simulations. This involves establishing ranges for each parameter (minimum, most likely and maximum values) to reflect risk and uncertainty. These values then interact with each other in multiple iterations (e.g., 50,000 iterations) of the model to determine the impact of the aggregate uncertainty. The simulations generate probability distributions for the NPVs, which demonstrate the likelihood of outcomes within the ranges and confidence intervals.

Typically, the range and distribution for each parameter would be based on available data and/or information on an appropriate input distribution (e.g., normal, log-normal, beta distribution). However, there was insufficient information to develop more detailed distributions for each parameter. Hence, a triangular distribution was assumed for all parameters given the lack of information, as per guidance by Boardman et. al. (2018). The triangle distribution uses maximum, most-likely and minimum values for each parameter, with the highest probability around the most likely value. Using the information available for this most-likely value, the minimum-maximum range was based on any available information on realistic ranges, which was primarily advice from contractors and engineers in the study location (though personal communication). Where information on ranges were unavailable, a 20 percent decrease in the more likely value was used for the minimum value, and a 20 percent increase for the maximum value.

2.3. Scenario specification

The eight road segments described above formed part of a study recently undertaken by Shellberg et al. (2026), who used terrestrial laser scanning (TLS) to quantify unsealed road erosion over time across the study sites. Baseline erosion rates from status quo were compared to reductions in erosion from applied Best Management Practices (BMPs) over time (Klye et al. 2025). These measured erosion rates, as published by Shellberg et al. (2026) and presented below in section 2.5, formed a basis for the estimation of fine sediment pollution impacts in the CBA.

The study conducted by Shellberg et al. (2026) allowed for the specification of four scenarios of road management to be assessed in the CBA. The scenarios illustrated in Fig. 2 were:

- *Scenario 1: business-as-usual.* This scenario involved the business-as-usual work carried out by the local government authority, in which graders were used to reshape the road crown, add gravel material, install and re-cut table drains and cut-off v-drains, and remove all vegetation (grass and trees) along road batters and verges.
- *Scenario 2: alternative maintenance.* This scenario involved the cessation of repeated grading of table drains, cut-off drains, verges, and batters, and use of selective herbicide vegetation management measures to prevent tree regrowth, along with spot machinery maintenance of selective drains with erosion problems.
- *Scenario 3: major erosion control.* In addition to the measures of Scenario 2 above, this scenario included a combination of capital improvements to stabilize soil on eroding batters and drains, in addition to construction of rock or concrete bed level floodways at stream crossings.
- *Scenario 4: full betterment.* This scenario included all the measures of Scenario 3 above, plus a bitumen dust seal of the road surface. Note that this is not a full upgrade to a sealed road, but a dust seal of existing alignment.

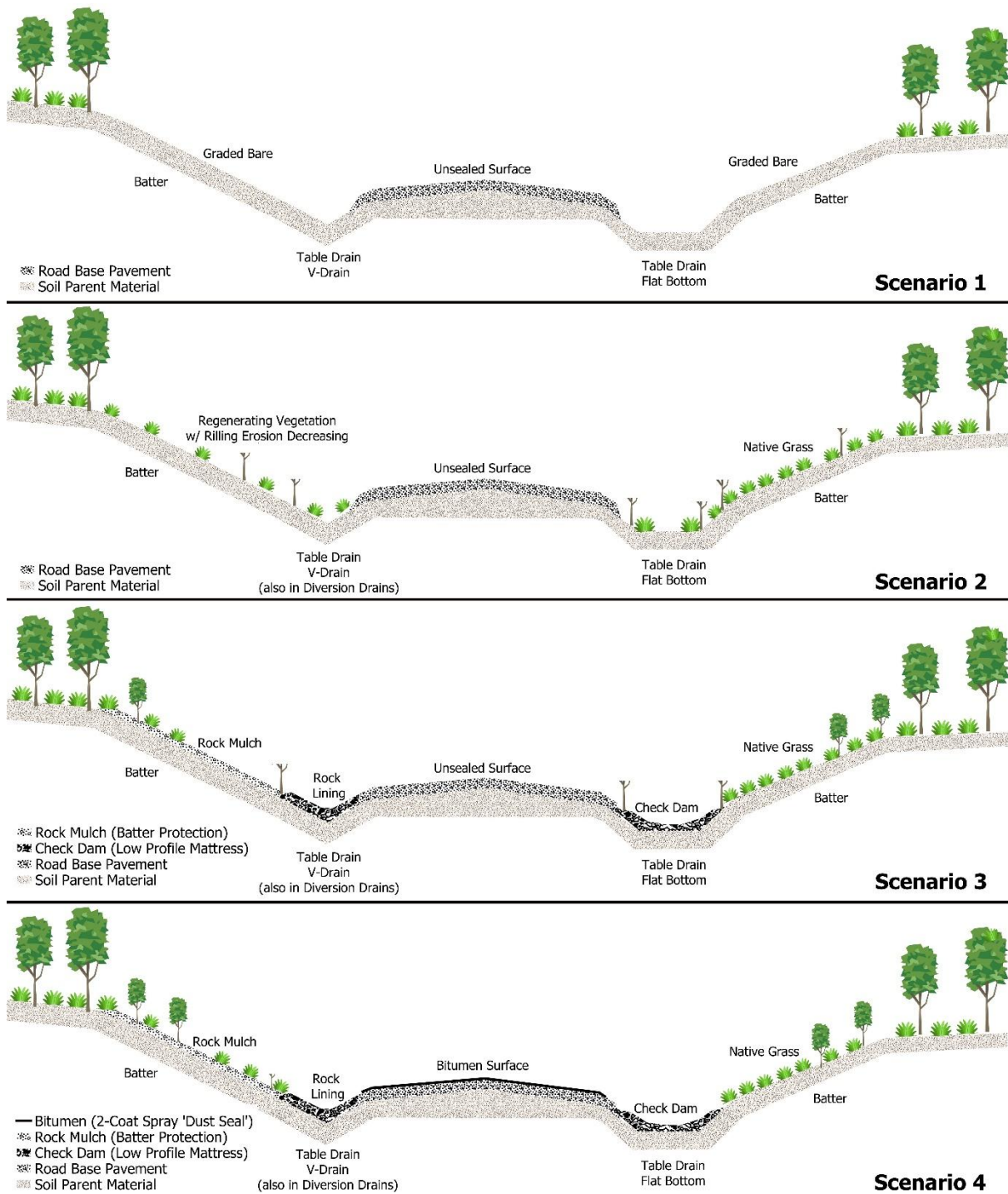


Fig. 2 Conceptual diagram of the four scenarios analyzed in the CBA

2.4. Financial costs

Capital and ongoing costs were included in the CBA for each scenario. Scenario 1 (business-as-usual) involved like-for-like repairs of the roads, returning them to their pre-disaster condition. This included ongoing costs to grade the road surface, verges and batters. The

other scenarios involved varying degrees of erosion control measures to improve the resistance of the roads to erosion risks. Scenario 2 (alternative maintenance) involved vegetation erosion control, while Scenario 3 (major erosion control) and Scenario 4 (full betterment) involved betterment works requiring capital investments, in addition to vegetation erosion control.

The financial costs associated with the scenarios were provided by Cook Shire Council (CSC) records for costs of recent road projects and maintenance, and South Cape York Catchments (SCYC), a Natural & Cultural Resource Management organization on Cape York Peninsula, for recent trial investments in erosion control measures. These costs were based on information on major repairs to unsealed roads in the study area that are triggered following government-declared natural disasters, which occur most years through annual monsoons. An overview of these costs, and the value ranges used in the sensitivity analysis, is given in Table 1. All values in this study are presented in Financial Year (FY) 2024 Australian dollars.

Table 1. Data inputs to the CBA for estimating financial costs, FY2024 AUD\$

Parameter	Unit	Applicable scenario(s)	Value^a (range)
Capital costs			
Concrete floodway	AUD\$/crossing	3, 4	60,000 (45,000 – 75,000) ^b
Rock floodway	AUD\$/crossing	3, 4	30,000 (10,000 – 50,000) ^b
Rock mulch, rock grade control structures, and gully rock chutes	AUD\$/crossing	3, 4	25,000 (20,000 – 30,000) ^c
Bitumen dust seal	AUD\$/km	4	110,000 (88,000 – 132,000) ^c
Grading to prepare road surface for bitumen dust seal	AUD\$/km	4	5,000 (4,000 – 6,000) ^c
Ongoing costs			
Business-as-usual maintenance Oaky Creek Road	AUD\$/km/year	1	19,720 (15,776 – 23,664) ^c
Business-as-usual maintenance Percy Road	AUD\$/km/year	1	19,888 (15,910 – 23,865) ^c
% of business-as-usual maintenance costs in Alternative Maintenance scenario	%	2	70 (60 – 80) ^b
% of business-as-usual maintenance costs in Major Erosion Control scenario	%	3	70 (60 – 80) ^b
<i>Invasive grader grass spraying (non-selective herbicides)</i>			
Year 1 and 2	AUD\$/km/year	2, 3	1,500 (1,200 – 1,800) ^c
Year 3 onwards	AUD\$/km/year	2, 3	800 (640 – 960) ^c
<i>Woody weeds (broadleaf herbicide)</i>			
Year 1	AUD\$/km/year	2, 3	2,705 (2,164 – 3,246) ^c
Year 2 follow up	AUD\$/km/year	2, 3	1,122 (898 – 1,346) ^c
Year 3 follow up	AUD\$/km/year	2, 3	650 (500 – 800) ^b
Year 4 onwards	AUD\$/km/year	2, 3	400 (320 – 480) ^c
Maintenance of bitumen dust seal	AUD\$/km/year	4	5,500 (4,400 – 6,600) ^c
Drain cleaning in Full Betterment scenario	AUD\$/km/year	4	200 (160 – 240) ^c

a Cost estimates from CSC, for costs of recent road projects and maintenance, and SCYC, for recent trial investments in erosion control measures and contractor quotes.

b High and low values based on advice from contractor quotes, engineers and SCYC.

c High and low values based on +/- 20 % variation from more likely estimates.

2.4.1. Capital costs

Scenario 3 (major erosion control) and Scenario 4 (full betterment) included capital costs for the initial works required. These investments comprised rock mulch, rock grade control structures, and gully rock chutes, along with armored floodways at each stream crossing. It was assumed that 50 percent of the floodways would be made from concrete and 50 percent from rock. Furthermore, it was assumed that there is on average one stream crossing per km along the case study roads.

In addition to these investments, Scenario 4 included a bitumen dust seal, which would need resealing after 20 years. Additional grading and rolling to prepare the road surface for the bitumen dust seal was included.

For the analysis, it was assumed that the bitumen dust seal was applied to the whole length of road in the study area (21.5 km). However, the fine sediment savings were only estimated for the 10 km of stream crossings (crest to crest) with relevant data. Thus, the sediment savings from the bitumen dust seal are conservative and do not include the additional savings from sealing segments with less (but not zero) connectivity to streams.

2.4.2. Ongoing costs

The ongoing unit costs described in this section were used to estimate the total ongoing costs across the 30-year assessment period for the CBA.

Scenario 1: business-as-usual

The ongoing costs for Scenario 1 (business-as-usual) were based on road works carried out by CSC in previous years. Data was provided by CSC for Oaky Creek and Percy Roads for the financial years 2017–2023. The average annual costs over this period (indexed to FY2024 AUD\$) were used as proxies for annual future maintenance works and assumed constant (in real terms) over the evaluation period.

Scenario 2: alternative maintenance

Previous and current engineers in CSC and SCYC staff estimated that the cessation of grading works of road verges and drains (but not the formed road prism) would reduce annual ongoing costs from grading by between 20 percent and 40 percent. For the CBA, an average estimate of 30 percent reduction in annual costs was used for estimation, with the range provided tested in the sensitivity analysis.

This scenario included the cost of selective broadleaf herbicide to manage woody tree regrowth, and non-selective herbicides used for patchy invasive grass control (e.g., grader grass). Slashing vegetation (cut or mow) is an alternative method that could be used, with similar or slightly lower costs compared to the use of herbicides. However, slashing was not included in the analysis shown here.

Scenario 3: major erosion control

Scenario 3 (major erosion control) included the same ongoing costs as scenario 2 (alternative maintenance). While Scenario 3 would include additional maintenance of erosion control measures, it was assumed that these interventions would reduce other road maintenance costs by approximately the same amount. There may be a net reduction of maintenance costs after a few years' stabilization period, however the level of ongoing costs was assumed constant over time in this analysis as a conservative approach.

Scenario 4: full betterment

It was assumed that the bitumen dust seal would require annual maintenance costs of about 5 percent of the initial capital costs of applying the bitumen dust seal. This is considered a conservative estimate. Vegetation management costs were the same as in scenarios 2 and 3. Some minor drain cleaning was assumed to be needed at patchy problem areas.

The unit-rates for capital and ongoing costs in Table 1 were multiplied by total length for Oaky Creek (17 km) and Percy (4.5 km) Roads for the CBA.

2.5. Quantification of avoided fine sediment pollution

Incorporating the impacts of fine sediment pollution from unsealed road erosion is important for providing a broader perspective on how road management decisions affect the study area. The value of options that mitigate fine sediment loads to the GBR is not typically understood in monetary terms. As a result, economic valuation techniques were required to capture these values appropriately.

In this analysis, fine sediment delivery from the different scenarios was valued using an 'avoided cost' method, which infers the value placed on the non-market impacts by examining what would have been paid otherwise to mitigate the negative impacts. Here, the avoided cost refers to the expense of fine sediment abatement actions.

There is uncertainty about the actual actions that would otherwise have been invested in to abate equivalent fine sediment loads into the GBR. This study used the cost-effectiveness of previous abatement actions in the region as a basis for the avoided abatement cost, specifically the cost-effectiveness of Federal Government Reef Trust gully control investments on the Cape York Peninsula (Normanby and Annan catchments), between 2017 and 2024 (Reef Trust unpublished data). The overall average cost-effectiveness for these investments of AUD\$1,624/ton/year was used in the CBA as the most likely value. It should be noted that the cost-effectiveness of investments can vary significantly depending on the activities undertaken to reduce fine sediment and the inputs required for these activities. For example, destocking of areas for sediment control will generally be more cost-effective than projects targeting gully or road erosion control, as the latter require machinery and other capital investments. Furthermore, Star et al. (2021) reviewed the use of cost-effectiveness estimates for reduced fine sediment loads in GBR catchments from changes to farm management practices. The authors noted that there were large variations in cost estimates both within and between studies—ranging from negative values to almost AUD\$500,000 /ton—attributable to the different locations, practice changes being studied, theoretical frameworks, and assumptions. Thus, sensitivity analysis was critical and for this study, the low and high ends of the range for the cost-effectiveness, AUD\$70 /ton/year and AUD\$5,745 /ton/year respectively, were used to account for alternative activities that could be undertaken to address comparable fine sediment loads. This range of values was consistent with a previous review of reference projects targeting fine sediment on the Cape York Peninsula (Alluvium Consulting Australia 2023). Wilkinson et al. (2019) estimated that the GBR wide gully program (2015-2018) had a cost-effectiveness of AUD\$1,500 /ton/year, which is lower than the Cape York Peninsula average, due to less remote work areas. More recently, the target erosion control program cost (projects plus administration) for Reef Trust investment on the Cape York Peninsula for the period 2024-2030 was AUD\$3,100 /ton/year (J. Price-Declé pers. comm. 2024).

The avoided abatement cost value of AUD\$1,624 /ton/year was multiplied by the annual erosion rates (tons/year < 20 µm) measured at the study sites. The erosion rates for the different scenarios were provided by SCYC, based on measurements at the selected road segments along Oaky Creek and Percy Roads (Shellberg et al., 2026).

The study used a before-after, control-impact (BACI) study design to calculate erosion volumes and tonnage via Terrestrial LiDAR Scanning (TLS) at different sites over two average rainfall years by comparing:

1. The typical machinery disturbance at all segments (2021–2022, *before*)
2. Treatments with Best Management Practices to reduce erosion at selected segments (2022–2023, *after*)
3. Control site with status quo machinery disturbance (2021–2023, *control*).

BACI study results were used to estimate average erosion rates per km of road length (tons/km/year < 20 µm) for each scenario. The data were normalized to the erosion rate reduction in the control site on the second year, 2022-2023, compared to the first year, 2021-2022, due to differences in rainfall magnitude and intensity (Shellberg et al., 2026)

The erosion rate data, along with the avoided abatement cost value, formed the basis for estimating avoided pollution costs from fine sediment delivery in the CBA (Table 2). These data were only applied to the 10 km of stream crossings (crest-to-crest) of Oaky Creek and Percy Roads, not the 21.5 km total used in the full analysis. Thus, erosion savings from alternative management for the full lengths of these roads are conservative.

Table 2. Data inputs to the CBA for quantifying avoided fine sediment pollution, FY2024 AUD\$

Parameter	Unit	Value (range)
Erosion rates		
Scenario 1: business-as-usual	tons/km/year < 20 µm	55.3 (44.3 – 66.4) ^a
Scenario 2: alternative maintenance	tons/km/year < 20 µm	46.5 (37.2 – 55.8) ^a
Scenario 3: major erosion control	tons/km/year < 20 µm	31.7 (25.3 – 38.0) ^a
Scenario 4: full betterment	tons/km/year < 20 µm	17.6 (14.1 – 21.1) ^a
Avoided abatement cost		
Avoided abatement cost value	AUD\$/ton/year	1,624 (70 – 5,745) ^b

^a Erosion rates estimated by Shellberg, et al. (2026). High and low values based on +/- 20 % variation from more likely estimates.

^b High and low values based on the maximum and minimum cost-effectiveness (AUD\$/ton/year) of Reef Trust gully control investments on Cape York Peninsula (Normanby and Annan catchments), between 2017 and 2024 (Reef Trust, unpublished data).

3. Results

The results of the CBA include the estimation of the total costs for each scenario, benefits from avoided fine sediment pollution, and appraisal of scenarios using NPV. When an NPV is larger than zero, the total discounted benefits exceed total discounted costs over the assessment period, and a scenario would be considered economically viable. Sensitivity

ranges are presented along with the NPVs to illustrate the uncertainty associated with the data inputs.

The total costs were estimated for each scenario and presented in present value terms in Table 3. These costs were categorized into three main groups: capital costs (as explained in section 2.4.1), ongoing costs (as explained in 2.4.2) and fine sediment pollution costs (as explained in section 2.5). The avoided fine sediment pollution costs resulting from the implementation of erosion control measures represent the benefits of the erosion control measures. All costs were discounted and aggregated across the 30-year assessment period. The total societal costs for each scenario were calculated by aggregating the financial and fine sediment pollution costs described above. Only the ‘most likely’ values were used as inputs for this initial analysis.

Table 3. Present value of societal costs, million AUD\$ (FY2024)

Scenario	Capital costs (million)	Ongoing costs (million)	Fine sediment pollution costs (million)	Total societal costs (million)	% change in total societal costs relative to Scenario 1
Scenario 1: business-as-usual	0	5.3	11.3	16.6	
Scenario 2: alternative maintenance	0	4.2	9.6	13.8	-17%
Scenario 3: major erosion control	1.4	4.2	6.8	12.4	-25%
Scenario 4: full betterment	4.3	2.2	4.2	10.7	-36%

Note: the results presented in this table are based on the ‘most likely’ values only. Sensitivity analysis was then used to test relative performance of options as outlined below and illustrated in Table 4.

The results show that scenarios 2, 3, and 4 all led to lower total societal costs relative to Scenario 1 (business-as-usual), with cost reductions of 17 percent, 25 percent and 36 percent respectively (Table 3). Scenario 4 (full betterment) achieved the lowest total societal costs, despite having the highest financial costs across all scenarios. Fine sediment pollution costs were highest under Scenario 1 (business-as-usual), 2.7 times greater than those in Scenario 4 (full betterment). Notably, Scenario 2 (alternative maintenance) resulted in both lower financial and fine sediment pollution costs compared to Scenario 1 (business-as-usual).

NPVs were calculated by subtracting the estimated costs for each alternative road management scenario from the costs of Scenario 1 (business-as-usual). These are shown in Table 4, with ranges showing the P10 and P90 values from the Monte Carlo simulations in the sensitivity analysis. Table 4. NPVs for road management scenarios, million AUD\$ (FY2024)

Scenario	NPV (million) (Range)
Scenario 2: alternative maintenance	2.9 (1.2 – 6.6)

Scenario 3: major erosion control	5.2 (1.6 – 11.6)
Scenario 4: full betterment	7.8 (2.1 – 17.4)

The results illustrate that scenarios 2, 3, and 4 are all economically viable, with NPVs greater than zero, and thus provide better economic outcomes than the current business-as-usual approach. This also holds when considering the sensitivity of results to possible ranges of the different input values. The benefits associated with the alternative road management scenarios are driven by the benefits of reduced fine sediment delivery, as well as lower ongoing costs. While the results would indicate Scenario 4 (full betterment) performing materially better than the other scenarios, it also had the largest range of uncertainty. Due to uncertainty of the results, the differences in estimated NPVs across scenarios may not be significant enough to clearly identify a preference of Scenario 4 (full betterment) over Scenario 2 (alternative maintenance) and Scenario 3 (major erosion control).

The sensitivity analysis also shows the degree to which a given assumption affects the results. This helps identify the assumptions that have the greatest influence on the variation in NPVs. The level of influence each assumption has on the NPV in each scenario is measured as a percentage contribution to variance in NPV. The Monte Carlo simulations identified that the uncertainty around the avoided fine sediment abatement costs was the key driver of aggregate uncertainty of the results, accounting for 35 percent of the aggregate uncertainty in the NPV in Scenario 2 (alternative maintenance) and between 80–90 percent of the aggregate uncertainty in the NPVs for Scenario 3 (major erosion control) and Scenario 4 (full betterment). The level of fine sediment delivery also contributed significantly to the uncertainty of the NPV in Scenario 2, at just over 34 percent, but only had a minor influence on the variation of results in Scenario 3 and 4.

3.1. Threshold analysis

Given the large uncertainty associated with the assumed avoided fine sediment pollution abatement cost, a threshold analysis was undertaken to determine the minimum abatement cost required for the scenarios to remain economically viable. Specifically, the threshold analysis addressed the question: *What abatement cost would result in an NPV of zero?*

The analysis produced threshold values of AUD\$114 /ton/year for Scenario 3 (major erosion control) and AUD\$271 /ton/year for Scenario 4 (full betterment). These values fall within the low end of the sensitivity ranges used in the CBA. This suggests that, even under

conservative assumptions about the benefits to the GBR from reduced fine sediment pollution, scenarios 3 and 4 are likely to be economically viable compared to the business-as-usual scenario. Scenario 2 (alternative maintenance) was economically viable compared to Scenario 1 (business-as-usual), even without accounting for lower fine sediment pollution costs.

3.2. Qualitative assessment of additional impacts

In addition to financial costs and the impacts of fine sediment pollution, other potential impacts were identified and assessed qualitatively, as described below, and not included in the CBA. These included the spread of weeds (from grading) and regional biosecurity, impacts on wildlife, road safety, road closures and vehicle wear and tear. The alternative road management scenarios (scenarios 2 to 4) were generally expected to lead to a positive or neutral change for these impact categories, as discussed below.

Weed spread, invasion, landowner biosecurity, and biodiversity loss from annual grading. In Scenario 1 (business-as-usual), grading of batters and drains leads to the spreading of grader grass and other invasive weeds. It can also contribute to woody weed thickening (melaleuca, eucalyptus). The extent of grader grass spread can be significant. Potential impacts from the spread of grader grass include reduced agricultural production, increased fire risk, loss of biodiversity and reduced road safety (CSC 2022; Keir and Vogler 2006).

Scenarios 2 to 4 would be expected to reduce the spread of grader grass and other weeds because they all involve the cessation of annual grading of table drains, cut-off drains, verges and batters, allowing native vegetation to regenerate in these areas and stabilize soils.

Impacts on wildlife. While there may be impacts on wildlife based on different road management approaches based on anecdotal commentary from local engineers, a rapid literature review did not show conclusive evidence that could demonstrate that there would be impacts on wildlife from the scenarios assessed in the CBA. Further primary research is warranted to fill this knowledge gap.

Road safety. Compared to sealed roads, the performance of unsealed roads is typified by higher accident risks per vehicle-kilometers travelled associated with corrugated, potholed, dusty, slippery (when wet) and loose (dry) surfaces (Austroads 2009). The impacts from the alternative road management scenarios were considered inconclusive, or a slight positive expected impact from the scenario including bitumen dust seal (Scenario 4).

Vehicle wear and tear: Unsealed roads can increase the wear and tear of vehicles. It may result in more frequent tire repairs and replacement of parts, misalignment, increased risk of rust etc. Scenario 3 (major erosion control) and Scenario 4 (full betterment) were expected to reduce vehicle wear and tear, with Scenario 4 having the most positive impact.

4. Discussion and conclusion

This study provides a novel contribution to the field of environmental management by demonstrating that implementing changes to existing road management practices in GBR catchments will reduce the impact of fine sediment on the water quality of the GBR. In addition to improving environmental outcomes, our findings also demonstrate that implementing changes to existing road management practices will reduce ongoing costs to maintain the roads over the long-term. The management of roads in GBR catchments is publicly funded, as are most mitigation efforts aimed at reducing fine sediment delivery to the GBR, particularly through government programs and initiatives targeting improved land and catchment management. As such, cost savings from implementing changes to existing road management practices will have wider benefits through efficiencies in government spending.

Methodologically, this study demonstrates the value of integrating biophysical data into a CBA to inform decision-making. Conventional approaches to unsealed road management often emphasize financial costs alone. By explicitly incorporating environmental values into the assessment framework, this study offers a transparent and replicable method that supports more holistic decision-making. The application to a study location adjacent to a significant and ecologically sensitive environment in the GBR, provided a pertinent context for application of this approach.

Our findings highlight the need for more considered decision-making in the management of unsealed roads. There is a trade-off between higher upfront costs for betterment works compared to less costly like-for-like repairs in the short term. In the context of GBR catchments, which are often exposed to extreme weather events (e.g. cyclones, extreme rainfall), repairs to unsealed local government roads are largely funded through Disaster Recovery Funding Arrangements (DRFA) from the Australian Government. Under the Reconstruction of Essential Public Assets (REPA) category within DRFA, funding is restricted to restoring damaged assets to their pre-disaster state. This “like-for-like”

requirement creates a disincentive to invest in resilience and does not account for the external costs of sediment delivery to the GBR. Such requirements may lead to suboptimal outcomes, with investment directed toward restoring roads to their original condition after each disaster, rather than toward betterment repairs that would make roads less susceptible to erosion in future extreme weather events.

Importantly, fine sediment from annual erosion and machine disturbance is transported downstream, creating persistent impacts to the ecological health of the GBR. Findings from this study suggest that alternative maintenance strategies (e.g. Scenario 2) and betterments (e.g. scenarios 3 and 4) can be proposed to reduce long-term public expenditure and sediment pollution impacts.

In addition to adverse environmental impacts, poor water quality from sedimentation can cause negative social and economic impacts. This can include commercial and recreational fishing, recreation for locals, tourism and aesthetic qualities. The Reef 2050 Long-Term Sustainability Plan is the Australian and Queensland Government's overarching framework for protecting and managing the GBR to 2050. The Reef 2050 Water Quality Improvement Plan (Australian Government and Queensland Government 2018) sets out targets to decrease anthropogenic (human caused) fine sediment yields to the GBR, in line with the overarching goal of the Long-Term Sustainability Plan. The Water Quality Improvement Plan has a 2025 water quality target of 10 percent reduction in anthropogenic end-of-catchment fine sediment loads for the Endeavour Basin on Cape York Peninsula (targets vary by basin). At the time of writing, the Water Quality Improvement Plan is under review, with new targets to be set for future reductions. The findings of this study offer a practical contribution toward achieving these targets for anthropogenic activities by reducing fine sediment delivery from unsealed road erosion.

In summary, this study highlights implications for policy and practice in Australia and internationally, particularly for jurisdictions managing unsealed roads in environmentally sensitive catchments. The findings underscore the need to embed environmental values within policy and investment assessment frameworks, align funding mechanisms with long-term resilience objectives, and to recognize the cross-sectoral impacts of road management decisions. Together, these lessons point to the value of proactive, integrated approaches that support long-term ecological health and fiscal efficiency.

4.1. Limitations

There were limitations with this project that could be explored in further research, outlined in the sections below.

4.1.1. Scope of valued impacts

In addition to financial costs and fine sediment pollution, other potential impacts associated with different road management scenarios were identified and qualitatively assessed in this study. This includes the spread of invasive weeds, impacts on wildlife, road safety, road closures, and vehicle wear and tear. These were identified and discussed qualitatively in our study. The qualitative assessment found that the alternative road management scenarios would result in either neutral or positive impacts on these categories. Hence, valuation of these impacts may further substantiate the case for specific scenarios and could represent topics for future study.

4.1.2. Reducing uncertainty of avoided abatement costs

The use of the average cost-effectiveness of Reef Trust gully control investments on the Cape York Peninsula provides a defensible and regionally relevant basis for valuing avoided fine sediment abatement costs. To account for uncertainty regarding which alternative abatement actions might otherwise be undertaken, a wide sensitivity range was applied. Future research may explore a smaller subset of likely avoided abatement actions that would act as more representative proxies for the valuation of benefits. This could have consideration of comparable actions and sediment savings based on biophysical attributes of specific sites.

4.1.3. Consideration of increasing risks from climate change

Short duration and high-intensity rainfall events are widely accepted as one of the main drivers of erosion and sediment transport from roads (Fu et al. 2010; MacDonald et al. 2001). Intense rainfall has higher erosivity, resulting in higher rates of sediment detachment (Dunkerley 2019). Intense rainfall also generates more overland flow, which controls the transport of sediment from source areas to receiving waterways (Dunkerley 2019). To understand the implications of climate change for erosion from roads, it is therefore most meaningful to examine the potential changes in the frequency of intense storm events as opposed to changes in annual rainfall. However, the ability of regional climate change models to resolve changes in the intensity of short duration (sub-daily) rainfall events is limited

(Martel et al. 2021), and this makes it difficult to assess implications of climate change for erosion.

As rainfall intensity increases, there will be a tendency for a general increase in erosion and sediment delivery from unsealed roads. This increase may mean there is the potential for roads to become a more dominant source of sediment delivery to the GBR. An assessment of the likely impacts of climate change was not included in this study. However, incorporation of detailed rainfall and erosion modelling could shed light on the likely outcomes over the longer-term and could be a topic for future study.

4.1.4. Extending analysis across the catchment

There are likely cost-efficiency gains if specific road management scenarios are delivered at a catchment-scale, particularly where substantial initial capital investment is required. Funding catchment-scale works would require detailed costing and benefit values, the latter particularly critical where public funding is sought. Some factors to consider when extrapolating include whether there are location-specific conditions that may impact the level of costs or benefits. For example:

- *Remote vs. more central locations:* Road works at remote locations could involve higher costs as construction workers need on-site accommodation for the duration of the project.
- *Existing infrastructure and road conditions:* For areas where there are already some erosion control measures in place, such as concrete floodways or culverts, this would reduce the capital costs associated with the betterment scenarios.
- *Delivery rate:* The delivery rate for fine sediment from the unsealed roads to the Reef is around 90 percent in Annan or coastal catchments on the Cape York Peninsula (McCloskey et al. 2021). The Normanby catchment has a 30-50 percent delivery rate in contrast, however with even more dispersive and erodible soils (Howley et al. 2021; McCloskey et al. 2021). For areas with lower delivery rates, this would impact the level of fine sediment avoided from erosion control measures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Anne Erlandsen: Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review and editing. Amar Doshi: Methodology, Supervision, Writing – original draft, Writing – review and editing. Steve Charlton-Henderson: Data Curation, Methodology. Kristen Joyse: Writing – original draft. Petter Nyman: Writing – original draft.

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