Cost-effectiveness analysis of nitrate removal by constructed treatment wetlands, bioreactors and vegetated drains: Wet Tropics Major Integrated Project

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1. Executive Summary

This report calculates the cost-effectiveness of nitrate removal ($/kg nitrate removed annually) for constructed treatment wetlands, bioreactors and vegetated drains constructed and monitored under the Wet Tropics Major Integrated Project (WTMIP). Cost-effectiveness results are provided for those constructed treatment systems for which nitrate load removal data were available, or could be estimated from the measured performance of equivalent systems in Wet Tropics locations.

The results indicate:

1. On the basis of treatment systems for which nitrate load removal data are available, embellished wetlands, and potentially also landscape wetlands, appear to be considerably more cost-effective for nitrate removal than bioreactors.

2. Indicative cost-effectiveness results for vegetated drains suggest that – provided adequate nitrate removal rates can be achieved without the need for costly earthworks or planting – vegetated drains could potentially deliver nitrate removal at a cost-effectiveness between that of embellished wetlands and bioreactors.

3. When evaluated over a 15-year lifespan, accounting upfront costs and on-going costs – including annual monitoring costs – WTMIP embellished wetland CW02 achieves a cost-effectiveness of 11 to 25 $/kg nitrate removed annually (depending on the discount rate used and the year for which nitrate removal is calculated).

4. On the same basis, WTMIP landscape wetland LW01 achieves a cost-effectiveness of 28 – 31 $/kg nitrate removed annually (although note that the flow rate that was used to estimate nitrate removal by this wetland in 2020 may have been somewhat optimistic).

5. In comparison, when evaluated over a 10-year lifespan, and again accounting upfront costs and on-going costs (including annual monitoring costs), WTMIP bioreactors appear to deliver a cost-effectiveness of between 236 – 1,156 $/kg nitrate removed.

6. An indicative cost-effectiveness of nitrate removal by vegetated drains was estimated by accounting for upfront and on-going costs for three WTMIP vegetated drains over a 15-year lifespan, together with a measured nitrate removal rate from another, similar, WTMIP vegetated drain (for which construction costs are not available). Indicative cost-effectiveness results for these drains range from 49 – 564 $/kg nitrate removed annually.

A key recommendation is that further research should be directed towards understanding why embellished wetland CW02 performs so well in its particular location (11 – 25 $/kg nitrate removed annually), with a view to replicating this level of performance elsewhere.

A second key recommendation is to measure the actual nitrate removal delivered by (low-cost) vegetated drain VD01 to determine whether the indicative cost-effectiveness estimated for this drain (~ 50 $/kg nitrate removed annually), based on the nitrate removal rate measured for vegetated drain Tully D5, is being achieved in practice.

2. Project Brief

The project brief was defined as follows in a Scope of Works provided by Terrain Natural Resource Management (Terrain NRM) on behalf of The Wet Tropics Major Integrated Project (WTMIP) Panel and Delivery Team.

"The WTMIP has been trialling treatment intervention systems in the far north landscape; 15 systems were installed between 2018 and early 2020, consisting of seven bioreactors, three constructed wetlands, one landscape wetland, a high efficiency sediment (HES) basin and three vegetated drain systems.

Of the 15 systems 11 have continued with routine monitoring into 2021: five bioreactors, three constructed wetlands, the landscape wetland and the three drain systems. Event sampling has been conducted at the HES basin, but no routine monitoring has been conducted at this site since 2019.

The Catchment Repair arm of the WTMIP has been tasked with conducting a cost benefit analysis for the treatment intervention systems past and current. Cost benefit analysis will only be possible where there is a value for Kg/N removed per year for an intervention system." (Scope of Works, WTMIP, 10th March 2021).

This Report analyses the cost-effectiveness of nitrate removal by those treatment systems for which costs and annual nitrate load removal data were provided by Terrain NRM. The data supplied report nitrate load removal in terms of annual nitrate removals (kg nitrate removed) for constructed treatment wetlands and bioreactors. Cost-effectiveness of nitrogen removal is reported in $/kg nitrate removed annually for those constructed treatment wetlands and bioreactors for which annual nitrate load removals have been estimated. For constructed treatment wetland CW02, annual removal of ammonium is also reported (kg ammonium removed). Cost-effectiveness of dissolved inorganic nitrogen (DIN) removal can thus be calculated for CW02, with DIN removal regarded as being the sum of nitrate and ammonium removals. A cost-effectiveness of DIN removal ($/kg DIN removed annually) is thus also reported for CW02.

Construction, monitoring and maintenance costs are available for three WTMIP vegetated drains (VD01, VD02 and VD15). Nitrate load removals are not available for these three drains, however annual nitrate (and DIN) load removal has been estimated per metre length of vegetated drain at another WTMIP location (Tully D5). Given the similarity between VD01, VD02, VD15 and Tully D5, the nitrate (and DIN) annual load removal rates per metre of drain length from Tully D5 have been assumed to apply to VD01, VD02, and VD15 also to enable indicative cost-effectiveness results for nitrate (and DIN) removal to be estimated for these three vegetated drains.

3. Objectives

The objectives of the analysis presented in this Report are as follows:

1. To quantify the cost-effectiveness of nitrate removal by the WTMIP's constructed treatment systems for which cost and annual nitrate load removal data have been provided.
2. To present a breakdown of cost ($) and effectiveness (kg nitrate load removed) components for each of the WTMIP's constructed treatment systems for which relevant data have been provided.
3. To summarise cost-effectiveness results and reflect on findings.

4. Method: Cost-effectiveness Analysis

Different treatment systems required different cost outlays and removal different nitrate loads over different operating lifespans. Costs can be categorised into upfront costs that are incurred only once during a project (design, construction (e.g., earthworks, vegetation planting etc.)), and on-going costs that are incurred regularly from completion of the upfront works throughout the lifetime of the project (e.g., annual maintenance and monitoring, and – if appropriate – the opportunity cost of foregone annual gross margin from prior agricultural cropping on the land that was converted to a treatment system).

For a given constructed treatment system, the nitrate load removed may vary year to year depending on the intensity and timing of rainfall relative to fertiliser application on adjacent cropping land, fertiliser inputs applied to cropping land, duration of the wet- and dry-seasons, and inter-year variation in the efficacy of nitrate removal within the treatment system itself.

Cost-effectiveness analysis expresses the ratio of cost incurred ($) to nitrate load removal (kg nitrate removed) for each constructed treatment system (and also the cost-effectiveness of DIN removal for constructed wetland CW02 and indicative estimates of the cost-effectiveness of DIN removal by vegetated drains VD01, VD02 and VD15). As different constructed treatment systems have different operating lifespans, and because the ratio of upfront costs to on-going costs will typically differ between types of treatment system (e.g., the ratio of upfront costs to on-going costs will usually be considerably higher for constructed treatment wetlands than for bioreactors), cost-effectiveness analysis must be applied carefully to provide a meaningful comparison of performance across different treatment systems. To facilitate this, all costs for each constructed treatment system (upfront costs and on-going costs) are discounted to convert them to present value, aggregated and then annualised to produce an annualised equivalent present value cost (APVC).

APVC is calculated in two steps. The first step calculates the total present value cost (TPVC) incurred in constructing, maintaining and monitoring treatment system j over its lifespan T by summing upfront costs incurred at time *t* = 0 and appropriately discounted on-going costs that are expected to arise over the remainder of the system's lifespan.

$$TPVC\ of\ treatment\ system\ j = W_j = C_j + \sum_{t=1}^{T} \frac{M_{j,t}}{(1+r)^t} \quad (1)$$

where:
W_j = total present value cost (TPVC) for treatment system *j*
C_j = upfront costs incurred in constructing treatment system j at time *t* = 0
$M_{j,t}$ = on-going costs incurred post-construction for treatment system j (for year *t* = 1, 2, …, T)
r = real discount rate
T = treatment system operating lifespan

Different treatment systems will have different lifespans, and varying distributions of upfront and on-going costs. To enable comparison of treatment systems with different lifespans, the second step converts the total present value cost (W_j) in absolute $, from equation (1), into an *annualised equivalent present value cost* (*APVC*) in $ per year, using the following formula:

$$APVC\ of\ wetland\ j = AW_j = W_j \Big/ \left[\frac{1-(1+r)^{-T}}{r}\right] \quad (2)$$

where all of the terms are as defined previously for equation (1).

The term in brackets on the right-hand side of equation (2) is referred to as the annuity factor (Brent, 2006). By applying the appropriate annuity factor (for a given system lifetime and real annual discount rate), the APVC reports that *constant* annual cost which, if incurred in each year of the treatment system's lifetime, and discounted appropriately, would produce a TPVC that matches the total present value cost (as calculated in equation (1)) for the particular treatment system concerned. The APVC provides an 'annualised cost' against which annual nitrate (or DIN) load removals can be compared to evaluate the cost-effectiveness of the treatment system.

APVC provides a consistent cost basis for cost-effectiveness comparisons across treatment systems with different lifetimes and different cost profiles. Cost-effectiveness of nitrate (or DIN) removal is the appropriate metric to use to compare the 'value for money' delivered by constructed treatment systems with different cost profiles, nitrate (or DIN) removal rates and lifetimes. Cost-effectiveness is calculated by dividing annualised equivalent present value cost (AW_j) by annual nitrate (or DIN) removal as follows:

$$CE_j \text{ (\$/kg nitrate removed)} = \frac{AW_j \text{ (\$/year)}}{N_j \text{ (kg nitrate/year)}} \quad (3)$$

Where:

CE_j = cost-effectiveness of treatment system *j*

AW_j = annualised equivalent present value cost of treatment system *j*

N_j = annual nitrate (or DIN) load removal by treatment system *j*

The cost-effectiveness results produced are for nitrate (or DIN) removal at the treatment system's outlet. A delivery ratio would need to be applied to convert on-site nitrate (or DIN) removal to its end of-catchment equivalent. The results presented in this Report are for the cost-effectiveness of nitrate (or DIN) removal at the treatment system outlet.

5. Data

The following data were provided on upfront costs, on-going costs and annual nitrate load removals for the various treatment systems (together with annual DIN load removals for constructed wetland CW02, and annual nitrate and DIN load removals per unit length for vegetated drain Tully D5 that were assumed to be indicative of the nitrate and DIN load removal performance of vegetated drains VD01, VD02 and VD15).

5.1. Cost data

The data in Table 1, Table 2 and Table 3 on upfront and on-going costs were provided for the nominated constructed treatment wetlands, bioreactors and vegetated drains, respectively. Total present value cost and annualised equivalent value cost are calculated over a 15-year lifetime for constructed wetlands and vegetated drains, and a 10-year lifetime for bioreactors, consistent with US Department of Agriculture Natural Resource Conservation Service, (2019) [for wetlands], and Christianson et al., (2012) and US Department of Agriculture Natural Resources Conservation Service, (2017) [for bioreactors]. Following common practice in evaluating practice changes and land use changes to reduce nitrogen losses from agriculture in Great Barrier Reef catchments, annual real discount rates of 5% (e.g. Roebeling et al., 2007; Waltham et al., 2021, 2017) and 7% (e.g. Alluvium, 2016; Rust and Star, 2018; Star et al., 2018, 2017) are used for calculation of total present value cost and annualised equivalent value cost.

5.2. Nitrate removal data

The data in Table 5 and Table 5 on annual nitrate load removals were provided for the nominated constructed treatment wetlands and bioreactors, respectively. Table 4 also reports annual DIN removal for constructed wetland CW02. Table 6 reports indicative annual nitrate (and DIN) load removals assumed for vegetated drains VD01, VD02 and VD15, based on the annual nitrate and DIN load removals per unit length reported for vegetated drain Tully D5.

6. Cost-effectiveness Results

Table 5 and Table 5 report the cost-effectiveness of nitrate removal for those wetlands and bioreactors for which annual nitrate removal data were available. Table 4 also reports the cost-effectiveness of DIN removal for constructed wetland CW02. Table 6 reports indicative cost-effectiveness results for vegetated drains VD01, VD02 and VD15.

Table 1: Upfront and on-going costs for WTMIP constructed treatment wetlands. Present value cost and annualised equivalent present value cost for each wetland are calculated at 5% and 7% real annual discount rates ***over an operational lifetime of 15 years****.*

Wetland	Area (ha)	Upfront costs ($)				On-going costs ($/year)			Total Present Value Cost ($)		Annualised Equivalent Present Value Cost ($/year)	
		Design	Earthworks	Planting	Total Upfront	Opportunity cost	Maintenance cost	Monitoring[‡] cost	At 5% discount rate	At 7% discount rate	At 5% discount rate	At 7% discount rate
LW01	8.5	138,158	248,395	0	386,553	2,541*	1,000	2,880	453,206	445,039	43,663	48,863
CW01	0.3	10,000	5,058	0	15,058	0	320	1,280	31,665	29,631	3,051	3,253
CW02	1.4	25,000	128,160	0	153,160	0	1,000	1,360	177,656	174,655	17,116	19,176
CW03	1.2	62,897	384,950	82,251	530,098	15,330**	1,000	1,920	719,527	696,317	69,321	76,452

[‡] Monitoring cost for a 6-month wet season. Monitoring cost calculated by extrapolation from monitoring costs of 3 months of the wet season in 2020/21.

* Opportunity cost of foregone gross margin from cattle grazing, using the gross margin quoted for Tully soil type S3 (‘slowly drained gradational of duplex textured soil’ from Murtha and Smith (1994), reported in Roebeling et al. (2007 p.3)) at a stocking density of 2 animal units/ha in (Roebeling et al., 2007; Figure 10, p.23).

**Opportunity cost of foregone gross margin from banana production, using the gross margin quoted by (van Grieken et al., 2010; Table 24, p.15), converted to 2019 AUD$ via the Reserve Bank of Australia Inflation Calculator (https://www.rba.gov.au/calculator/).

Table 2: Upfront and on-going costs for WTMIP bioreactors. Present value cost and annualised equivalent present value cost for each bioreactor are calculated at 5% and 7% real annual discount rates ***over an operational lifetime of 10 years****.*

Bioreactor	Area (ha)	Upfront costs ($)				On-going costs ($/year)			Total Present Value Cost ($)		Annualised Equivalent Present Value Cost ($/year)	
		Design	Earthworks	Planting	Total Upfront	Opportunity cost	Maintenance cost	Monitoring[‡] cost	At 5% discount rate	At 7% discount rate	At 5% discount rate	At 7% discount rate
BR01	0.0350	8,987	9,744	0	18,731	0	480	320	24,908	24,349	3,226	3,467
BR02	0.0015	8,987	3,900	0	12,887	0	250	800	20,995	20,262	2,719	2,885
BR03	0.0010	8,987	6,600	0	15,587	0	400	400	21,764	21,206	2,819	3,019
BR04	0.0015	8,987	3,850	0	12,837	0	250	800	20,945	20,212	2,712	2,878
BR05	0.0010	8,987	7,281	0	16,268	0	300	1,200	27,851	24,696	3,607	3,516
BR06	0.0015	8,987	12,885	0	21,872	0	1,645	1,280	44,458	42,416	5,758	6,039
BR07	0.0080	8,987	6,000	0	14,987	0	300	300	19,620	19,201	2,541	2,734

[‡] Monitoring cost for a 6-month wet season. Monitoring cost calculated by extrapolation from monitoring costs of 3 months of the wet season in 2020/21.

Table 3: Upfront and on-going costs for WTMIP vegetated drains. Present value cost and annualised equivalent present value cost for each vegetated drain are calculated at 5% and 7% real annual discount rates ***over an assumed operational lifetime of 15 years****.*

Wetland	Length (m)	Upfront costs ($)				On-going costs ($/year)			Total Present Value Cost ($)		Annualised Equivalent Present Value Cost ($/year)	
		Design	Earthworks	Planting	Total Upfront	Opportunity cost	Maintenance cost	Monitoring‡ cost	At 5% discount rate	At 7% discount rate	At 5% discount rate	At 7% discount rate
VD01	135	2,500	0	0	2,500	0	250	300	8,209	7,509	791	824
VD02	300	2,500	36,770	0	39,270	0	1,200	1,200	64,181	61,129	6,183	6,712
VD15	140	35,000	15,722	9,135	59,857	0	1,622	1,280	89,879	86,288	8,669	9,474

‡ Monitoring cost for a 6-month wet season. Monitoring cost calculated by extrapolation from monitoring costs of 3 months of the wet season in 2020/21.

Table 4: Annual nitrate and DIN load removals and cost-effectiveness of nitrate and DIN removal for nominated WTMIP constructed treatment wetlands, evaluated for ***an operational lifetime of 15 years****.*

Wetland	Area (ha)	Annual nitrate load removal (kg nitrate/year)	Cost-effectiveness ($/kg nitrate removed)		Annual DIN load removal (kg DIN/year)	Cost-effectiveness of DIN removal ($/kg DIN removed)	
			At 5% discount rate	At 7% discount rate		At 5% discount rate	At 7% discount rate
LW01	8.5	1570*	28	31			
CW01	0.3	-	-	-			
CW02**	1.4	775**	22**	25**	1373**	12**	14**
CW02***	1.4	1569***	11***	12***	1825***	9***	11***
CW03	1.2	-	-	-			

*Nitrate load removal reported for LW01 in July 2020 Report. Based on an assumed flow rate of 1 $m^3 s^{-1}$ through the wetland for a 6-month wet season. This flow rate may be somewhat optimistic.

** Nitrate (or DIN) load removal for CW02 calculated for the 2020 wet and dry seasons combined.

***Nitrate (or DIN) load removal for CW02 projected for 2021, based on calculated nitrate load removal for the 2021 wet season and assuming that the ratio of wet season : dry season load removal in 2021 will be the same as that reported for 2020.

*Table 5: Annual nitrate load removals and cost-effectiveness of nitrate removal for nominated WTMIP bioreactors, evaluated for **an operational lifetime of 10 years**.*

Bioreactor	Area (ha)	Annual nitrate load removal (kg nitrate/year)	Cost-effectiveness ($/kg nitrate removed)	
			At 5% discount rate	At 7% discount rate
BR01	0.0350	3.0	1,075	1,156
BR02	0.0015	10.2	267	283
BR03	0.0010	-	-	-
BR04	0.0015	11.5	236	250
BR05	0.0010	-	-	-
BR06	0.0015	-	-	-
BR07	0.0080	-	-	-

*Table 6: Indicative annual nitrate and DIN load removals and cost-effectiveness of nitrate and DIN removal for WTMIP vegetated drains, evaluated for **an operational lifetime of 15 years**.*

Drain	Length (m)	Indicative Annual nitrate load removal (kg nitrate/year)	Indicative Cost-effectiveness ($/kg nitrate removed)		Indicative Annual DIN load removal (kg DIN/year)	Indicative Cost-effectiveness of DIN removal ($/kg DIN removed)	
			At 5% discount rate	At 7% discount rate		At 5% discount rate	At 7% discount rate
VD01	135	16.2*	49	51	43.2**	18	19
VD02	300	36.0*	172	186	96.0**	64	70
VD15	140	16.8*	516	564	44.8**	194	211

* Indicative annual nitrate load removal estimated by applying the annual nitrate load removal rate of 0.12 kg nitrate/m/year from vegetated drain Tully D5.

** Indicative annual DIN load removal estimated by applying the annual DIN load removal rate of 0.32 kg DIN/m/year from vegetated drain Tully D5.

7. Discussion

The differences in the cost-effectiveness results for nitrate removal by constructed treatment wetlands and bioreactors in Table 4 and Table 5 (11 – 31 $/kg nitrate removed annually for the wetlands compared with 236 – 1,156 $/kg nitrate removed annually for the bioreactors), and the indicative cost-effectiveness estimates for nitrate removal by vegetated drains in Table 6 (49 – 564 $/kg nitrate removed annually for the vegetated drains), follow directly from the differences in annualised costs and nitrate removal rates between the different treatment systems.

Leaving CW01 aside[1], the annualised present value costs of constructed wetlands LW01 and CW02 are 3 to 27 times higher than the annualised present value costs of the bioreactors; however, the annual nitrate load removals delivered by LW01 and CW02 are between 70 and 520 times higher than those reported for the bioreactors. Annualised present value costs for vegetated drains VD02 and VD15 are, respectively, similar to, and three times higher than, those of the bioreactors; however, indicative annual nitrate load removal by VD15 is around 50% higher than that achieved by BR02 and BR04, whereas indicative annual nitrate load removal by VD02 is approximately three times that achieved by BR02 and BR04. Consequently, the indicative cost-effectiveness of VD02 (172 $/kg nitrate removed annually) is somewhat better than that of these bioreactors (~ 250 $/kg nitrate removed), whereas the indicative cost-effectiveness of VD15 (~ 500 $/kg nitrate removed annually) is markedly worse. Annualised cost for vegetated drain VD01 is very low, and its indicative annual nitrate load removal is somewhat higher than BR02 and BR04. Consequently, if the indicative level of annual nitrate removal can indeed be achieved at these low costs (i.e., without the need for *any* earthworks or planting costs) vegetated drains such as VD01 could potentially provide the second most cost-effective nitrate removal option (~ 50 $/kg nitrate removed annually) among the treatment systems considered here.

The indicative cost-effectiveness of DIN load removal (18 – 211 $/kg DIN removed annually) by the vegetated drains is considerably better than the cost-effectiveness of their nitrate load removal. This is a consequence of the high ammonium removal rate recorded for vegetated drain Tully D5.

Annualised present value costs are calculated over a 15-year lifespan for the wetlands and drains, and a 10-year lifespan for the bioreactors, but for all wetlands except CW01 the total present value cost of construction and operation exceeds that for any of the bioreactors by a factor of three or more, and exceeds that for any of the vegetated drains by a factor of two or more. Thus, the

[1] CW01 is much smaller (0.3ha) than the other constructed treatment wetlands.

difference in reported nitrate removal rate is the primary factor that explains the considerable difference in cost-effectiveness between the three types of treatment system.

On-going maintenance and monitoring costs comprise a much larger proportion of total present value costs for the bioreactors and vegetated drains than for the constructed wetlands. It is, however, appropriate to include these costs in performance evaluation because nitrate (or DIN) load removal will have to be monitored if, for example, a proponent intends a treatment system to generate revenues from the Reef Credits scheme (https://www.reefcredit.org).

There is a modest difference in the cost-effectiveness of nitrate removal between CW02 and LW01[2]. CW02 appears to perform extremely well, based on nitrate load removals calculated for two wet seasons. A key recommendation is therefore that further research should be directed towards understanding why the CW02 embellished wetland performs so well in its particular location, with a view to replicating this level of performance elsewhere.

A second key recommendation is to measure the actual nitrate removal delivered by VD01 to determine whether the indicative cost-effectiveness estimated for this drain (based on the nitrate (and DIN) removal rate measured for Tully D5) is being achieved in practice.

[2] Note that the 2020 nitrate load removal for LW01 applied what may now appear to be a somewhat optimistic flow rate through the wetland.

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