SUPPLEMENTARY DATA

Cost-effectiveness of treatment wetlands for nitrogen removal in tropical and subtropical Australia

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Table S1. Considerations, limitations and uncertainties in nitrogen (N) load reduction estimations for treatment wetlands: constructed treatment wetlands (CW), vegetated drain (VD), and sewage treatment plant wetlands (STPW).

Flow measurement	N load reduction estimation
CW1	
Groundwater flow measured in a dry and a wet season to provide dry season and wet season average flow volumes (m^3/day),	Difference in N concentration from inlet to outlet calculated for each monitoring event and averaged. Inlet concentration was the average of both groundwater and surface water inflow. Annual N load reduction estimation (N_{red}) calculated separately for wet season and dry season flow and N reduction: $$Nred = \frac{\Delta N\ Q}{1000}\ d$$ (where ΔN = average N reduction from inlet to outlet (mg L^{-1}), Q = average flow volume (m^3 d^{-1}), d = number of days of inundation. Rainfall is used as a proxy for inundation (i.e. 129 days per year). Confidence: medium due to no surface water flow measurements. Samples collected during a range of wet season and dry season events.
CW2	
Flow estimation based on four months monitoring of changes in water depth using electronic water level loggers, to calculate flow (m^3/day) (February to June 2020, representing a range of flow conditions). Average flow during this period used as wet season flow and minimum flow used as dry season flow for calculating flow outside of this monitoring period.	Difference in N concentration from inlet to outlet calculated for each monitoring event and averaged. Annual N load reduction estimation (N_{red}) calculated by adding together daily N reduction estimates: $$Nred = \sum \frac{\Delta N\ Q}{1000}$$ (where ΔN = average N reduction from inlet to outlet (mg L^{-1}), Q = average flow volume (m^3 d^{-1}), Confidence: high, due to flow monitoring and samples collected across a range of wet season and dry season events.
CW3	

No flow measurement.	Used areal denitrification rate calculated for this site (6.3 mg m^{-2} h^{-1}) as the DIN removal rate (as per Kavehei and others 2021). Annual N load reduction estimation (N_{red}) calculated using areal denitrification rate (converted to kg ha^{-1} d^{-1}): $$Nred = D_t\, d$$ (Where Dt = areal denitrification, d = number of days of inundation) Rainfall is used as a proxy for inundation (i.e. 89 days of denitrification). Confidence: medium due to denitrification measurements quantifying rate of DIN removal. Likely to be an underestimate due to using rainfall as a proxy for inundation.
CW4	
No flow measurement.	Used areal denitrification rate calculated for this site (8.1 mg m^{-2} h^{-1}) as the DIN removal rate (as per methodology in Kavehei and others 2021). Annual N load reduction estimation (N_{red}) calculated using areal denitrification rate (converted to kg ha^{-1} d^{-1}) $$Nred = D_t\, d$$ (Where Dt = areal denitrification, d = number of days of inundation) Rainfall is used as a proxy for inundation (i.e. 129 days of denitrification). Confidence: medium, due to denitrification measurements quantifying rate of DIN removal. Uncertain if rainfall is a suitable proxy for this site due to configuration of inlet and outlet pipes controlling inflow and outflow.
CW5	
Water flows from the MUSIC hydrological model, based on catchment size and retention time (48h) and 10% of the size of wetland to the catchment (26 ha).	Difference in N concentration from inlet to outlet calculated for each monitoring event and averaged. Annual N load reduction (N_{red}) estimated using : $$Nred = \Delta N\, \Delta Q$$ (where ΔN = average N reduction from inlet to outlet (mg L^{-1}), ΔQ = difference between flow in and flow out (ML/yr)

	Confidence: Low, as water quality sampling was not undertaken during high rainfall events due to access constraints and were not representative of the hydrograph. Flow was not monitored.
CW6	
Flow estimation based on changes in water depth to provide an estimate of volume treated (ML yr^{-1})	Difference in N concentration from inlet to outlet calculated for each monitoring event and averaged. Inlet concentration was the average of the two inlets. Annual N load reduction estimation (N_{red}) calculated using: $$Nred = \Delta N\,V$$ (where ΔN = average N reduction from inlet to outlet (mg L^{-1}), V = Total volume treated (ML/yr). Confidence: medium, as the sampling was timed well to capture up to the peak or full hydrograph for irrigation and rainfall events. Accurate flow measurements were not possible due to outlet structure design and re-use of water from the wetland.
CW7	
No flow measurement.	Used denitrification rate estimated for this site (791 µg L^{-1} d^{-1}) as the DIN removal rate (Waltham and Butler 2020). Annual N load reduction estimation (N_{red}) calculated using denitrification rate converted to kg ha^{-1} d^{-1} $$Nred = D_t\,d$$ (Where Dt = denitrification rate, d = number of days of inundation) (88 kg ha^{-2} yr^{-1}) Confidence: low, as flow monitoring was not conducted and samples collected were not representative of the whole hydrograph.
CW8	
No flow measurement.	The lack of flow information for this site and limited sampling that was unlikely to be representative of different flow events and along the hydrograph, precludes an estimation of N load reduction.

<table>
<tr><td colspan="2">VD1 and VD2</td></tr>
<tr><td>One week of flow discharge measurement..</td><td>Used areal denitrification rate calculated for the sites (1.8 and 9.1 mg m^{-2} h^{-1} respectively) as the DIN removal rate (as per methodology in Kavehei and others 2021).

Annual N load reduction estimation (N_{red}) calculated using areal denitrification rate (converted to kg ha^{-1} d^{-1})
$$Nred = D_t\, d$$
(Where Dt = areal denitrification,
d = number of days of inundation)
Rainfall is used as a proxy for inundation (i.e. 89 days of denitrification).
Confidence: medium, due to denitrification measurements quantifying rate of DIN removal.</td></tr>
<tr><td colspan="2">STPW1 and STPW2</td></tr>
<tr><td>Continuous flow discharge (in and outflow) measurements</td><td>Total daily N load at inlet and outlet calculated using water quality and flow monitoring.
Annual N load reduction estimation (N_{red}) calculated using:
$$Nred = \sum \mathrm{Nin} - \mathrm{Nout}$$
(where Nin = daily N inflow (kg),
Nout = daily N outflow (kg),
V = Total volume treated (ML/yr).
Confidence: high, due to continuous flow monitoring and N monitoring.</td></tr>
<tr><td colspan="2">STPW3 and STPW4</td></tr>
<tr><td>Flow estimation based on average dry weather flow design capacity ((m^{-3} d^{-1})., 365 days a year).</td><td>Calculated the average difference in N concentration from inlet to outlet.
Annual N load reduction estimation (N_{red}) calculated using:
$$Nred = \frac{\Delta \mathrm{N}\, Q}{1000}\, d$$
(where ΔN = average N reduction from inlet to outlet (mg L^{-1}),
Q = design flow volume (m^3 d^{-1})
d = number of days of flow.
Confidence: medium, due to using design flow capacity instead of monitoring flows.</td></tr>
</table>

Table S2. Summary of cost data categories provided by project proponents for inclusion in the cost-effectiveness analysis. A '✓' indicates data are available and a '×' indicates data are not available. Project management costs were unavailable for STPW1, STPW2, STPW3 and STPW4 (shown as shaded cells in grey).

Site	Upfront costs			On-going costs
	Design	Project management[a]	Construction[b]	Maintenance & repair[c]
CW1	✓		✓	✓
CW2	✓	×	✓	✓
CW3	✓	×	✓	✓
CW4[d]	✓	✓	✓	✓
CW5	✓	×	✓	×
CW6	✓	✓	✓	✓
CW7	✓	✓	✓	×
CW8	✓	✓	✓	×
VD1[e]	✓	×	×	×
VD2[e]	✓	×	×	×
STPW1[f]	×	×	✓	✓
STPW2	✓	×	✓	✓
STPW3	✓	×	✓	×
STPW4	✓	×	✓	×

[a] For wetlands and drains on farms that have no project management cost, project management cost from CW6, scaled by area, is used instead. [b] Lump sum total upfront cost and construction costs were available for CW7 and CW8 but a breakdown between design cost and project management cost was not provided. [c] Maintenance cost from CW6, scaled by area, is used for CW5, CW7 and CW8; maintenance cost from STPW1, scaled by area, is used for STPW3 and STPW4. [d] Design cost for this wetland includes a specific cost component for a Development Approval for managing acid sulfate soil risk . [e] For VD1 and VD2, construction costs were estimated using an excavation cost function from Waltham et al 2021 (p85,86); maintenance cost was $350 (in AUD expressed in financial year 2003/04 based on Waltham et al. 2021); and repair cost is assumed to be 20% of total construction cost. [f] Design cost for STP1 is assumed to be 15% of total wetland construction cost, consistent with industry practice.

Box S1: Adjusting base cost-effectiveness to include site-specific costs

The base cost-effectiveness reported in the paper can be readily adjusted to include site-specific costs to produce a 'revised' cost-effectiveness estimate appropriate for a wetland situated in a different location. This enables cost-effectiveness estimates to be derived for alternative scenarios and settings.

Base scenario (using 8.5ha treatment wetland CW3, 20-year evaluation period and 5% discount rate as an example)

- Annualised present value cost (APVC): \$4197 ha^{-1} $year^{-1}$
- DIN load removal: 135.17 kg $year^{-1}$
- Cost-effectiveness at wetland site: \$31.05 kg^{-1} DIN removed

Alternative scenario (i.e. base scenario *plus* three additional costs incurred in financial year 2020/21)

1. Development Approval *upfront* cost: \$40,000.
2. Opportunity cost i.e. forgone gross margin from cane which is an *on-going* cost: \$816 ha^{-1} $year^{-1}$
3. Pollutant (i.e. DIN) transport coefficient from wetland site to the Great Barrier Reef (GBR) lagoon: 0.9

All calculations that follow are based on an evaluation period of 20 years and a 5% discount rate. Other evaluation periods (15, 20 and 25 years) and/or discount rates (3%, 7%) can also be used (provided relevant APVC values from Table 5 are used in the base scenario).

<u>Step 1</u>: Annualise the per hectare upfront cost of Development Approval (DA) to convert it from \$/ha to \$/ha/year using Equation 2 (reproduced here as Equation A1):

$$APVC = \frac{Total\ present\ value\ upfront\ cost}{\left(\frac{1-(1+r)^{-T}}{r}\right)} \quad \text{(S1)}$$

Equation S1 indicates that: *Annualised PV cost = Total PV costs ÷ Annuity factor*, where the annuity factor for a 20-year evaluation period (T=20) and 5% discount rate (r = 0.05) is simply:

$$Annuity\ Factor = \frac{1-(1+r)^{-T}}{r} = \frac{1-(1+0.05)^{-20}}{0.05} = 12.46221034 \quad \text{(S2)}$$

$Annualised\ upfront\ costs\ of\ Development\ Approval$

$$= \frac{(\frac{40,000}{8.5})}{12.46221034} = 377.61 \quad \text{(in \$/ha/year)} \qquad \text{(S3)}$$

Step 2: Add the annualised upfront costs of development approval ($377.61 ha^{-1} year^{-1}) and the on-going opportunity cost ($816 ha^{-1} year^{-1}) to the APVC from the base scenario:

$$APVC_{alternative\_scenario} = 4197 + 377.61 + 816 = 5391.61 \quad \text{(in \$/ha/year)} \qquad \text{(S4)}$$

Step 3: Revised or predicted cost-effectiveness at wetland site is calculated using Equation 3 in the paper(reproduced here as Equation A5):

$$CE_{at\_site} = \frac{APVC}{DIN\_removed_{at\_site}} = \frac{5391.61}{135.17} \approx 39.89 \quad \text{(in \$/kg)} \qquad \text{(S5)}$$

Step 4: Revised or predicted cost-effectiveness at end-of-catchment is

$$CE_{end\_of\_catchment} = \frac{CE_{at\_site}}{Transport\ coefficient} = \frac{39.89}{0.9} = 44.32 \quad \text{(in \$/kg)} \qquad \text{(S6)}$$

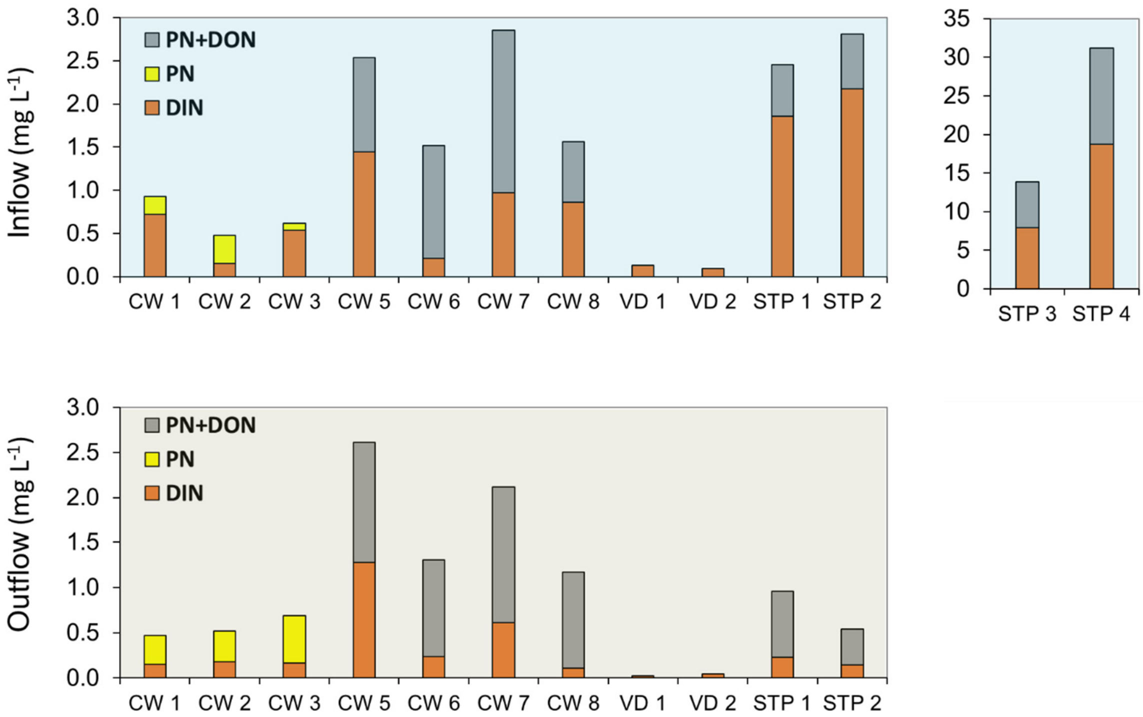
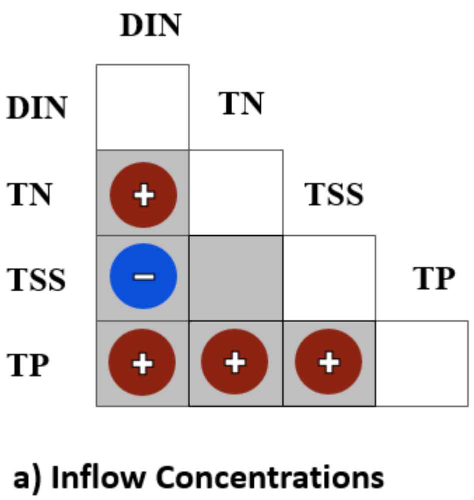


Figure S1. Inflow and outflow concentrations (mg L^{-1}) and contribution to total nitrogen (TN) of the different species: particulate N (PN), dissolved organic N (PON) and dissolved inorganic N (DIN) for treatment wetlands. There were no DON measurements for CW1, CW2 and CW3. CW = constructed wetlands, VD = vegetated drains and STPW= sewage treatment plant wetlands.



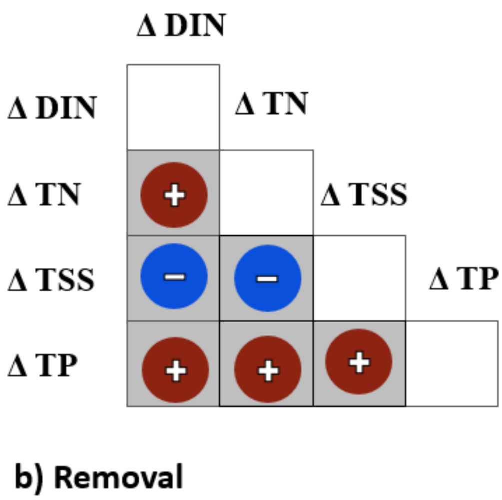


Figure S2. Correlation ($p < 0.01$) among inflow water parameters (DIN, TN, TSS and TP) and removal (Δ mg L^{-1}).

Table S3. Cost-effectiveness analysis under varying discount rates and evaluation periods for constructed treatment wetlands (CW) and vegetated drains (VD) in tropical Australia. APVC = annualised present value cost, CE = cost-effectiveness metric. Currency is in Australian Dollars (A$)

Treatment System ID	Discount rate: 3% per annum					
	15 years		20 years		25 years	
	APVC A$ yr^{-1} ha^{-1}	CE A$ $kgDIN^{-1}$	APVC A$ yr^{-1} ha^{-1}	CE A$ kg DIN^{-1}	APVC A$ yr^{-1} ha^{-1}	CE A$ $kgDIN^{-1}$
CW1	8,995	24	7,345	20	6,369	17
CW3	4,429	33	3,578	26	3,075	23
CW4	10,536	42	8,863	35	7,874	31
VD2	3,887	50	3,507	45	3,167	41
CW7	7,898	90	6,564	75	5,775	66
VD1	5,753	102	5,199	92	4,676	83
CW6	7,107	173	5,929	144	5,232	127
CW5	7,124	651	5,942	543	5,244	479
CW2	45,682	866	36,825	698	31,588	599
	Discount rate: 5% per annum					
	15 years		20 years		25 years	
CW1	10,106	27	8,527	23	7,616	21
W3	5,014	37	4,197	31	3,725	28
CTW4	11,699	47	10,096	40	9,172	37
VD2	4,224	54	3,848	49	3,540	45
CW7	8,912	101	7,614	87	6,865	78
VD1	6,256	111	5,703	101	5,233	93
CW6	7,988	194	6,844	166	6,184	150
CW5	7,898	722	6,769	619	6,118	559
CW2	51,543	977	43,084	816	38,190	724
	Discount rate: 7% per annum					
	15 years		20 years		25 years	
CW1	11,269	30	9,782	26	8,953	24

CW3	5,629	42	4,857	36	4,427	33
CW4	12,915	52	11,405	46	10,564	42
VD2	4,576	59	4,211	54	3,938	50
CW7	9,997	114	8,755	99	8,063	92
VD1	6,779	120	6,242	111	5,827	103
CW6	8,928	217	7,836	190	7,227	175
CW5	8,705	796	7,644	699	7,053	645
CW2	57,665	1,093	49,701	942	45,263	858

Table S4. Cost-effectiveness analysis under varying discount rates and evaluation periods for sewage treatment plant wetlands (STPW) in subtropical Australia. Currency is in Australian Dollars (A$)

Treatment System ID	Discount rate: 3% per annum					
	15 years		20 years		25 years	
	APVC	CE	APVC	CE	APVC	CE
STPW4	232,375	116	187,604	93	161,127	80
STPW2	99,269	629	84,800	538	76,223	483
STPW1	81,626	1,028	66,640	839	57,777	728
STPW3	205,158	1,066	165,764	861	142,467	740
Treatment System ID	Discount rate: 5% per annum					
	15 years		20 years		25 years	
	APVC	CE	APVC	CE	APVC	CE
STPW4	266,527	133	222,976	111	197,845	99
STPW2	108,029	685	94,436	599	86,572	640
STPW1	93,126	1,173	78,552	990	70,142	907
STPW3	235,224	1,221	196,904	1023	174,792	908
Treatment System ID	Discount rate: 7% per annum					
	15 years		20 years		25 years	
	APVC	CE	APVC	CE	APVC	CE
STPW4	303,050	151	261,387	130	238,171	119
STPW2	116,955	741	104,390	662	97,371	617
STPW1	105,416	1,362	91,476	1,152	83,709	1,055
STPW3	267,377	1,389	230,718	1,198	210,290	1,092