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Addressing off-site nutrient pollution through conventional management actions: a modelling case study.

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Abstract: The ecology of estuaries on the south coast of Western Australia has been disrupted by increased nutrient and sediment discharge from predominantly rural catchments. Seagrass beds have been replaced by macroalgae, and toxic algal blooms threaten human and animal health, and reduce amenity. A range of conventional management actions are available to reduce nutrient loss at source, and it is important to evaluate possible reductions, and costs, so that limited funds can be targeted to realise the greatest moderation of nutrient loss. A lumped landuse nutrient generation rate model was developed for four catchments (Wilson Inlet, Oyster Harbour, Torbay Inlet and Princess Royal Harbour) near Albany Western Australia and the output compared with existing monitoring data. The nutrient moderating effects of five conventional management actions (perennial pastures; vegetated stream buffers; effective fertiliser use; stock control and water management; and effluent management) and their associated costs were implemented at different levels in the model to determine the extent to which these actions could address offsite nutrient pollution, and the cost of doing so. Management actions were implemented in three major scenarios representing the current nutrient reduction efforts, the maximum feasible implementation of each action and the most cost effective set of actions. In each catchment dominated by diffuse nutrient sources, current nutrient reduction efforts amounted to about 10%, whilst the highest possible reductions were of the order of 25-30% above this. In the point source dominated catchment current nutrient reduction efforts amounted to about 40%, with an additional 40% possible. The most cost effective scenarios reduced nitrogen more than phosphorus. Under the most cost effective scenarios, it was estimated that the net cost of management actions over 10 years was budget positive, resulting in a net benefit to the land managers involved. There appears therefore to be limited economic barriers to the adoption of these conventional management actions. However, these maximum possible reductions from the implementation of conventional management actions may not be sufficient to arrest estuarine decline.

Keywords: nutrient management, modelling, cost-effectiveness, best management practices.

1 INTRODUCTION

1.1 South Coast of Western Australia Context

Conventional agricultural development over the last 50 years has contributed to increased nutrient export to rivers, wetlands and estuaries of the south-west of Western Australia (WA) (Hodgkin and Hamilton [1993]). These increased nutrient loads have resulted in increased growth of algae, leading to the loss of seagrass, reductions in summer dissolved oxygen concentrations and anaerobic conditions which stress aquatic wildlife. Seagrass underpins the ecology of the inlets and estuaries in south-western Western Australia as it provides shelter for aquatic wildlife and stabilises estuarine sediment. In the south-west of WA, phosphorus (P) is generally considered to be more limiting for algal growth (Hodgkin and Hamilton [1993]) than nitrogen (N), hence specific management actions for particular nutrients may be required.

1.2 Previous Research

Previous research in south-west WA catchments has concentrated on the identification of nutrient sources, and understanding nutrient delivery processes (Weaver and Reed [1998]). More recent research has explored the nutrient attenuation capacity of specific actions such as vegetated stream buffers (McKergow *et al.* [2002]), however little has been done to evaluate what catchment-wide nutrient reductions are possible for a range of actions in different scenarios.

It is important to evaluate what reductions are possible for what cost, so that limited funds can be targeted to realise the greatest moderation of nutrient loss for the least cost, and also to estimate the effort required to meet water quality targets. Modelling offers some short-term catchment scale insights not affordable through long term implementation and monitoring approaches.

1.3 Modelling Approaches

A number of modelling approaches are available to evaluate scenarios for nutrient load reduction. These include the compartment flux models described by Cassell *et al.*. [2001], and process based models such as CREAMS (Heatwole [1986]), AGNPS (Young *et al.* [1989]) and ANSWERS (Beasley and Huggins [1982]). In addition, Non Point Source (NPS) models have been coupled to Geographical Information Systems (GIS) to evaluate catchment wide nutrient contributions to NPS pollution (Heidtke and Auer [1993]; Poiani and Bedford [1995]). Decision Support Systems (DSS) and Expert Systems (ES) offer some additional possibilities in evaluating probable causes of nutrient pollution, and have potential to recommend management practices for critical source areas (Djodjic [2002]).

Many of the models are complex in nature, and their applicability may be limited by the time required for developing input parameters and intense computational requirements. Further, few of the models provide information that allows management investment decisions to be made, because most models only include output detailing nutrient load reductions. An exception is WINCMSS, a tool described by Young *et al.* [1995] that enables land managers to assess the likely impact on nutrient exports of land management and planning decisions, and land use change. Whilst WINCMSS is a relatively simple lumped model based around landuse-specific nutrient export rates, it provides a useful framework on which to base an evaluation of the costs and benefits of scenarios that can result in reduced nutrient loads, an approach suggested elsewhere (Heidtke and Auer [1993]). This can assist managers in making difficult decisions over the targeting of limited financial resources to realise the greatest nutrient reduction for the least cost.

1.4 This Paper

This paper describes the application of the general framework described by Young *et al.* [1995] to the adoption of conventional (currently known and practiced) management actions in catchments on the south coast of WA, including the costs and benefits of doing so. This paper has not explored the redesigning of agriculture, hence these conventional management actions allow the retention of existing land uses.
The approach does not definitively quantify nutrients produced from certain areas or landuses, but provides indicative or relative information to guide decisions on nutrient management. Some modifications to the general framework of Young *et al.* [1995] were necessary to correctly apply some Best Management Practices (BMPs) appropriately, and to overcome some deficiencies in cost accounting. For example, management practices such as vegetated stream buffers moderate nutrient loss from all upstream landuses, rather than having a moderating influence on a specific landuse.

2 MATERIALS AND METHODS

This modelling case study was sited on the south coast of WA near Albany, in catchments with elevated nutrient export to Oyster Harbour, Wilson Inlet, Torbay Inlet and Princess Royal Harbour (PRH) (Figure 1). Broad differences between these catchments can be described in terms of catchment size and landuse composition (Table 1). The major historical differences are that the PRH catchment has been dominated by point sources of nutrients, industry and urban population. The other catchments are dominated by diffuse sources of nutrients from agricultural uses such as broadacre grazing of annual pastures for cattle and sheep production, crops and plantations, with small areas of more intensive use such as annual and perennial horticulture (vegetables, fruit, vineyards) close to regional centres.

2.1 Sub – Catchments

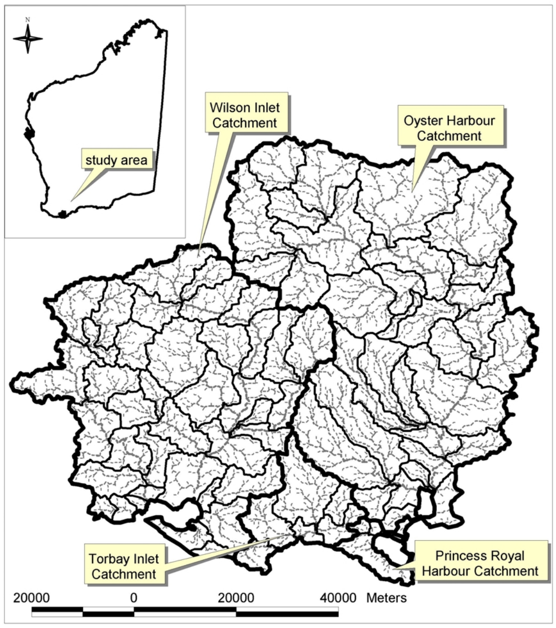

Figure 1. Study area showing catchments, subcatchments and stream network.

A digital elevation model (DEM) of 100 metres resolution was developed to derive catchment and landscape characteristics used to model, modify and report on nutrient export. These characteristics include sub–catchments, slope, mapping units, stream networks, stream order, routing and in–stream nutrient assimilation (Simmons and Cheng [1985]). Sub–catchments (Figure 1) represent an areal unit used to apply and assess management regimes within catchments.

Whilst hydrological catchment boundaries were of primary importance, each sub–catchment represented a relatively homogenous area defined secondarily by physical and socio-economic factors influencing nutrient release to waterways.

Table 1. Study catchments, areas and diffuse landuse composition (%).

Landuse	Oyster Harbour	Wilson Inlet	Torbay Inlet	PRH
	(%)	(%)	(%)	(%)
Remnant Vegetation	28	51	34	74
Grazing	56	33	53	10
Cropping	2	<1	<1	<1
Horticulture	1	<1	4	<1
Plantation	11	15	5	2
Sewered Urban	<1	<1	<1	3
Unsewered urban	<1	<1	<1	2
Peri Urban[1]	<1	<1	2	7
Total Area (km^2)	**2989**	**2258**	**320**	**81**

2.2 Mapping Units

Soil characteristics such as the content of aluminium and iron oxides, can significantly influence nutrient retention and release (Allen *et al.* [1991]), and provide some control over the magnitude and form of P export (Heathwaite [1997]). A continuous P retention surface based on ammonium oxalate extractable iron (Fe) (Tamm [1922]) was derived from a soil survey reported by Weaver and Reed [1998]. This surface was classified into soils with low (<800mg kg^{-1}) and high (>800mg kg^{-1}) Fe. Soils with low Fe were deemed to have low P retention and were susceptible to P leaching, whilst soils with high Fe were more likely to accumulate applied P, and lose P via surface runoff and erosion pathways.

Land slope has some influence over nutrient transport as it controls hydrological pathways, connectivity, and erosion potential (Wells and King [1989]). An arbitrary classification of the DEM into low slope (<4%) and high slope (>4%) was made to differentiate between land units less (<4%) or more likely (>4%) to contribute particulate nutrients to waterways.

The intersection of the two soil Fe classes with the two slope classes provided four mapping units representing inherent characteristics that influence nutrient export from different landuses. These mapping units and their characteristics were:

LILE Low Fe, low slope. Includes low lying very sandy soils susceptible to nutrient leaching and comprises around 60% of the study area.
LIHE Low Fe, high slope, 5% of study area.
HILE High Fe, low slope. These soils are the least susceptible to either nutrient leaching or soil erosion, 20% of the study area.
HIHE High Fe, high slope. These soils are prone to soil erosion, 15% of the study area.

2.3 Assimilation

Only a proportion of nutrients generated at source by landuses reaches downstream waterbodies. This process, known as nutrient assimilation (Simmons and Cheng [1985]), needs to be accounted for if the impacts of management actions, whether catchment wide or spatially explicit, are to be determined. To that end, assimilation coefficients based on the Bransby-Williams formula were determined for each sub–catchment using the method of Davis *et al.* [1996].

2.4 Landuse

Land-uses were mapped using unsupervised satellite image classification, aerial photo interpretation, cadastral and sewer location data and national data (NLWRA [2001]). Land use was differentiated further by combining the mapping unit coverage with the land use map, providing 40 possible combinations of mapping units and land use classes (Table 2).

Point sources were identified and mapped using data from state and local government agencies, satellite imagery, and aerial photo interpretation.

2.5 Landuse nutrient generation rates

Nutrient generation rates for an average rainfall year (50 percentile) for specific land-uses (Table 2) were generated in two ways:

[1] Peri-Urban - property > 0.3ha and < 5ha, adjoining a recognised urban area.

- Directly from existing monitored catchments in the study area; and
- indirectly, through examination of a range of published sources locally and overseas (Marston *et al.* [1995]; Young *et al.* [1996]; Young *et al.* [1997]).

Nutrient generation by point sources such as piggeries and dairies was based on published figures for standard animal units, combined with herd size and composition to provide average export values per animal (Marston *et al.* [1995]; Vanderholm [1984]). Where other point sources such as sewage treatment plants had monitored nutrient exports, these were incorporated.

Table 2. Nutrient generation rates for diffuse land uses with associated errors

Land Use	Mapping Unit	P Generation Rate (kg ha^{-1} yr^{-1}) ± error	N Generation Rate (kg ha^{-1} yr^{-1}) ± error
Remnant Vegetation	LILE/LIHE	0.01 ± 0.01	0.08 ± 0.05
	HILE/HIHE	0.01 ± 0.01	0.05 ± 0.03
Grazing	LILE/LIHE	0.5 ± 0.2	2.5 ± 1.25
	HILE	0.1 ± 0.05	1.2 ± 0.6
	HIHE	0.2 ± 0.1	1 ± 0.5
Cropping	LILE/LIHE	0.5 ± 0.2	2.5 ± 1.25
	HILE	0.1 ± 0.05	1.2 ± 0.6
	HIHE	0.2 ± 0.1	1 ± 0.5
Annual Horticulture	LILE	2 ± 0.7	10 ± 5
	LIHE	2.8 ± 1.4	14 ± 7
	HILE	0.8 ± 0.4	4 ± 2
	HIHE	0.96 ± 0.48	4.8 ± 2.4
Perennial Horticulture	LILE	1.8 ± 0.9	9 ± 4.5
	LIHE	2.1 ± 1.05	10.5 ± 5.25
	HILE	0.6 ± 0.3	3 ± 1.5
	HIHE	0.72 ± 0.36	3.6 ± 1.8
Plantation	LILE	0.25 ± 0.2	1.5 ± 0.75
	LIHE	0.3 ± 0.2	2 ± 1
	HILE	0.08 ± 0.1	0.8 ± 0.4
	HIHE	0.12 ± 0.12	0.8 ± 0.4
Sewered Urban	LILE	0.6 ± 0.3	3 ± 1.5
	LIHE	0.7 ± 0.35	3.5 ± 1.75
	HILE	0.2 ± 0.1	1 ± 0.5
	HIHE	0.24 ± 0.12	1.2 ± 0.6
Un-Sewered Urban	LILE	0.9 ± 0.45	4.5 ± 2.25
	LIHE	1.05 ± 0.52	5.25 ± 2.62
	HILE	0.3 ± 0.15	1.5 ± 0.75
	HIHE	0.36 ± 0.18	1.8 ± 0.9
Peri-Urban	LILE	1.2 ± 1.2	6 ± 6
	LIHE	1.4 ± 1.4	7 ± 7
	HILE	0.4 ± 0.4	2 ± 2
	HIHE	0.48 ± 0.48	2.4 ± 2.4

2.6 Model Calibration

The model was not calibrated, but was compared to existing nutrient load data from long term monitoring of catchment endpoints (Table 5). The reasonable matches found provided some confidence in the utility of the model to derive indicative and relative results.

2.7 Best Management Practices (BMPs)

Five conventional management actions were identified through a review as applicable to the study area, and their cost and nutrient reduction benefits (Table 3) were evaluated in scenarios of different combinations and levels of implementation. The BMPs were vegetated stream buffers (VSB), perennial pasture, minimum tillage, effective fertiliser use and stock control/water management.

Perennial pastures are applicable to grazing, and are used in the study area, particularly in high rainfall areas. Three classes of perennial pasture were specified by annual rainfall, <500mm, 500-750mm and >750mm. Minimum tillage is applicable mainly to cropping. It involves minimum soil disturbance during tillage, with herbicides being used for weed control.

Effective fertiliser use is a set of practices to ensure both the lowest and the most effective use of fertilisers in farming. It includes soil and tissue testing prior to fertiliser application, to identify nutrient specific deficiencies, and the selection the most appropriate fertiliser, rates, and timing. Previous research has identified that most fertiliser applications were made independently of soil test results (Weaver and Reed, [1998]) and a significant number of farms could have forgone a fertiliser application for at least one year. Effective fertiliser use was separated into three classes, applying to broadacre pasture, cropping and horticulture.

Stock control/water management is the practice of keeping stock and vehicles out of streams to avoid erosion and pollution of streams by stock. Because different stream orders will require different works, this was evaluated for first, second, and third or above stream orders.

Table 3 provides figures for the level of N and P reduction, capital costs of BMP implementation and a net cost or benefit per year averaged over ten years for each BMP assessed. These costs were used to provide estimates of capital costs and expected on-going or maintenance costs. When combined with expected productivity benefits, they allow an estimate of net on-going costs or benefits. This is important where high initial capital costs are offset over time with a benefit from productivity increases.

Table 3. Percentage reductions of N and P and Capital and Net on-going costs or (benefits).

BMP		reduction % N	reduction %P	Capital Cost of BMP implementation	²Net Cost or (Benefit) yr^{-1}
VSB	1st order	40	5	\$6,110 km^{-1}	\$475 km^{-1}
VSB	2nd order	40	5	\$5,030 km^{-1}	\$225 km^{-1}
VSB	3rd order+	40	5	\$3,975 km^{-1}	\$175 km^{-1}
perennials		20	30	\$135 ha^{-1}	(\$60) ha^{-1}
minimum tillage		5	10	\$265 ha^{-1}	(\$3) ha^{-1}
effective fertiliser use		5	15	\$10.00 ha^{-1}	(\$9.40) ha^{-1}
Stock Control	1st order	10	5	\$750 km^{-1}	\$50 km^{-1}
Stock Control	2nd order	10	5	\$1250 km^{-1}	\$50 km^{-1}
Stock Control	3rd order+	10	5	\$2000 km^{-1}	\$50 km^{-1}
Effluent Control	Dairy	75	75	\$75 source^{-1}	(\$3) source^{-1}
Effluent Control	Piggery	75	75	\$100 source^{-1}	(\$3) source^{-1}

2.8 Modelling Framework

The modelling framework used is a modification of that described by Young *et al.* [1995]. The model represents average conditions, and does not incorporate spatial or temporal variations from influences such as rainfall. It allowed the creation of BMP scenarios using up to seven land-use BMPs and three stream-based BMPs. Stream BMPs are applied after land-use BMPs, better simulating their affects on all sub-catchment landuses.

The model provided a range of results, including nutrient reductions, costs and benefits (productivity returns where applicable), costs per kg, and net costs or benefits (implementation and on-going (maintenance) costs minus productivity returns averaged over 10 years). The reductions indicated in scenarios are compared to a base level where no management has been implemented. External costs and benefits (such as amenity or ecosystem services) are not accounted for.

2.9 Scenarios

Scenario modelling combined BMPs in a number of ways (see examples in Table 4) to achieve different outcomes.

- Highest possible nutrient reduction;
- Most cost effective nutrient reduction (N and P combined); or
- Most cost-effective P or N reduction.

Table 4. Levels (%) of BMP implementation in different scenarios for a point source dominated catchment (PRH) and a diffuse source dominated catchment (Oyster Harbour)

BMPs↓ / Scenarios →		Princess Royal Harbour: Status Quo	Princess Royal Harbour: Highest Possible	Princess Royal Harbour: Cost Effective P	Princess Royal Harbour: Cost Effective N	Oyster Harbour: Status Quo	Oyster Harbour: Highest Possible	Oyster Harbour: Cost Effective P	Oyster Harbour: Cost Effective N
Perennials 500-750						5	65	65	65
Perennials >750		90		100	100	45	95	95	95
Effective Fertiliser (grazing)		15		65	75	15	65	65	65
Effective Fertiliser (horticulture)		25		85	85	25	75		
Stock control	1st order	5		65					
Stock control	2nd order	10				5			45
Stock control	3rd order+	40				40			80
VSB	1st order	5	65		65	3	63	41	63
VSB	2nd order	10	70		70	5	65		65
VSB	3rd order+	50			100	50	100		100
Minimum Tillage						90		100	
Effluent Management (dairies)									
Effluent Management (piggeries)							60	60	
Closure of point sources		100							
Seafood processing to sewer		100							
Landfill to Sewer			100		100				
Vegetable Processing to Sewer		50	100	100					
Fertiliser manufacture management		80	100						

Nutrient specific scenarios were examined to provide insights into approaches that deal better with one nutrient over another, particularly since nutrient limitations had been identified (Hodgkin and Hamilton [1993]).

An estimate of the impact of existing nutrient reduction efforts was modelled through a "status quo" scenario. These scenarios differed in only small degrees between the three diffuse-dominated catchments (Wilson and Torbay Inlets and Oyster Harbour), while the mainly point-source dominated PRH was quite different (Table 2). The highest possible nutrient reduction scenarios for diffuse catchments were very similar, implementing perennial pastures and VSB, supported by animal effluent management and effective fertiliser use.

[2] Benefits are shown in parenthesis. Net benefits or costs are an annual value excluding capital costs

3 RESULTS AND DISCUSSION

Despite limitations, this simple lumped-model provides indicative or relative information to guide decisions on nutrient management. (Heidtke and Auer [1993]). Whilst the model was not calibrated, data available for comparison from catchment endpoint monitoring, matches reasonably well (Table 5).

A comparison of the nutrient model results to monitoring results is shown in Table 5 and indicates that the model under-estimates nutrient production, especially of N, although the N prediction for Oyster Harbour falls within the range from a 10 year monitoring period of catchment endpoints. For both Wilson Inlet and Oyster Harbour the model accurately estimates P export. The un-assimilated model estimates of N are much closer to the monitoring results. This suggests that more work is required on assimilation effects.

Table 5. Model results compared to monitoring (mean tonnes year^{-1}±range) for Oyster Harbour (1990-2000) and Wilson Inlet (1995-1999).

Catchment		P	N
Oyster Harbour	Monitoring	22.3±14	159±155
	Modelling	22.7±10	110±54
Wilson Inlet	Monitoring	10±3	176±56
	Modelling	9.5±4	52.2±23

The model was not intended to replace monitoring, nor was it a primary aim to derive accurate estimates of nutrient loads. Rather the aim was to provide relative and indicative results to guide nutrient management.

For diffuse-source dominated catchments, this case study indicates that nutrient reductions of 25-30% over existing efforts are possible whilst providing financial benefits to land managers, notably farmers (Table 5 to Table 8), that can more than offset the capital and on-going costs of BMP implementation. It would appear that reductions in excess of this are not realistically possible with current land uses using conventional management actions (Table 6). However, the significant financial benefits to land managers (farmers) may give them the capacity to implement even higher levels of management.

This contrasts with D'Arcy and Frost [2001], who suggest that diffuse control measures are unlikely to return financial benefits to farmers, and may require financial incentives to encourage implementation. While such measures may improve uptake, good nutrient management is in the financial interests of farmers. There may be indirect economic benefits from public funding for nutrient reduction management, through increased farm profitability and the long-term community benefits of a more viable farm sector. In addition, there may be other benefits in the form of ecosystem services (Daily [1997]).

Potential nutrient reductions in the point-source dominated Princess Royal Harbour are even higher (Table 10, Table 6), but do not provide similar direct benefit. This indicates the very different management approach, including the use of infrastructure (eg large-scale sewerage treatment facility) to remove or deal with the nutrient problem. Costs would be even higher if the economic impacts of industry closure in the catchment, which has contributed in part to nutrient reductions, were included.

Table 6. Summary of "targeted realistic" nutrient reductions, capital costs, and net cost (benefits)

Catchment	%P	%N	Capital Cost	[3]Net Cost (Benefit) yr^{-1}
Princess Royal Harbour	80%	68%	$2.25M	$400,000
Oyster Harbour	27%	33%	$13M	($940,000)
Torbay Inlet	38%	24%	$1.5M	($260,000)
Wilson Inlet	29%	32%	$7M	($211,000)

The three diffuse-dominated catchments were similar in terms of the levels of reduction, and the associated cost and benefits. This was true for both existing efforts (the Status Quo scenario) and the other scenarios evaluated (Tables 6 to 9). This indicates that there has already been some improvement in on-farm nutrient use efficiency, albeit limited. The major difference between Highest Possible and most Cost-Effective scenarios is in the level of N reduction. This is due to the very high costs associated with VSB, which have high N removal capacity. The most cost-effective scenarios use targeted VSB on a sub-catchment basis to maximise N removal at the least cost. The limited capacity of VSB to reduce P loss is in marked contrast to many other studies and is related to unique nutrient transport pathways and forms present in the study catchments (McKergow *et al.* [2002]).

Perennial pastures and effective fertiliser use are the most cost-effective of the broadscale landuse measures. The highest nutrient reductions relative to costs are probably to be

[3] Benefits are shown in parenthesis. Net costs or benefits (including capital costs) are accumulated then averaged over 10 years

found in animal effluent management. All of these should be high management priorities.

Table 7. Wilson Inlet Scenarios[4]

	Status Quo	Highest Possible	Most Cost-Effective
% P Reduced	9%	29%	29%
% N Reduced	13%	41%	32%
$ (kg P)$^{-1}$	($58.78)	$204.10	($77.50)
$ (kg N)$^{-1}$	($7.75)	$21.92	($14.45)
Capital Cost ($M)	$4.4	$15.1	$7.0
Net cost year^{-1} ($M)	($0.07)	$0.48	($0.20)

Table 8. Torbay Inlet Scenarios[4]

	Status Quo	Highest Possible	Most Cost-Effective
% P Reduced	7%	40%	38%
% N Reduced	12%	44%	24%
$ (kg P)$^{-1}$	($269)	($3.90)	($138.70)
$ (kg N)$^{-1}$	($34)	($0.90)	($79.24)
Capital Cost ($M)	$1.6	$2.25	$1.45
Net cost year^{-1} ($M)	($0.1)	($0.008)	($0.26)

Table 9. Oyster Harbour Scenarios[4]

	Status Quo	Highest Possible	Most Cost-Effective P	Most Cost-Effective N
% P Reduced	7%	30%	27%	26%
% N Reduced	10%	42%	24%	33%
$ (kg P)$^{-1}$	($85)	$30.89	($217)	($209)
$ (kg N)$^{-1}$	($12)	$4.40	($66.80)	($34.40)
Capital Cost ($M)	$4.3	$20.5	$13.1	$13.6
Net cost year^{-1} ($M)	($0.14)	$0.18	($1.08)	($0.94)

Table 10. Princess Royal Harbour Scenarios[4]

	Status Quo	Highest Possible	Most Cost-Effective P	Most Cost-Effective N
% P Reduced	40%	80%	80%	41%
% N Reduced	47%	86%	55%	68%
$ (kg P)$^{-1}$	$7300	$200	$52	$2000
$ (kg N)$^{-1}$	$1150	$38.70	$50	$22
Capital Cost ($M)	$15 (est.)	$2.25	$0.80	$0.77
Net cost year^{-1} ($M)	-	$0.41	$0.11	$0.13

The preferred BMPs for maximum P reductions are perennial pastures, effluent management, and effective fertiliser use. For N, the highest reductions were from VSB, water management on streams, effluent management and perennial pastures. In terms of cost and benefits however, the preferred BMPs for P reduction are perennial pasture, effective fertiliser use and effluent management. None of the BMPs provides a high reduction of N without significant costs, while only perennial pastures provide high returns with a moderate reduction in N export.

The BMPs investigated here can be considered as part of an integrated management system, in particular for grazing-based land-uses. Such a system would include the following elements:

- Reductions in nutrient inputs to the farm through effective fertiliser management;
- Reductions in nutrient exports from the farm through effluent control and animal management near streams;
- Improved utilisation of nutrients through the use of perennial pastures;
- Improved retention of nutrients leaving the farm through VSB;
- Increased assimilation of nutrients in the receiving waterways through VSB.

It is therefore appropriate to view the nutrient management system costs and benefits on the basis of an integrated package.

The scenarios investigated here indicate maximum reductions of 25-30% above current levels for diffuse dominated catchments, and 40% above current levels for point source dominated catchments. The modelling has already been used in the production of a nutrient action plan for Wilson inlet, and in the development of a similar plan for the Torbay Inlet. In these cases, funds for on-ground work are being more effectively targeted through modelling the cost effectiveness of specific actions for specific land uses in specific sub catchments.

More accurate modelling would be possible following the acquisition of finer scale and more detailed data. However, modelling is not a substitute for on ground implementation, rather, it is an adjunct to processes that bring about behavioural change in land management.

The question remains however: is this level of reduction enough to reverse declining environmental quality in estuaries? A recent review of south-western estuaries of WA suggests that reductions of up to 70% may be required to meet external loading targets, however even greater reductions be required to also run down internal loadings from accumulated nutrients (Deeley, [2001]). The

[4] Benefits are shown in parenthesis. Net costs or benefits (including capital costs) are accumulated then averaged over 10 years

results presented here suggest that for further reductions we must look to greater changes in agricultural systems, and more nutrient-benign land uses that consider nutrient balance.

4 CONCLUSIONS

The modelling described here assessed the utility of conventional management actions to reduce nutrient export from the study catchments. It provides a guide to land managers who currently have no capacity to examine the effect of management actions.

The case studies indicate that for catchments dominated by diffuse nutrient sources, current nutrient reduction efforts are about 10%, whilst the highest reductions are 25-30% greater. In the point source dominated catchment, current nutrient reduction efforts amount to 40%, with 40% more possible. The most cost effective scenarios reduced N more than P. Under the cost effective scenarios, the net cost of management actions over 10 years was budget positive, providing net benefit to land managers. There appears therefore to be limited economic barriers to the adoption of these conventional management actions.

However, nutrient reductions greater than those indicated may be required to reverse environmental decline in some estuaries, and this will require landuse change in addition to land management. For this to occur, we may need to extend recognition of the problems, and alternative solutions, beyond land managers and into the broader community.

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6 REFERENCES

Allen, D.G., R.C. Jeffery, and R. D'Ercole, Phosphate and sulphate adsorption properties of soils from the coastal plains of the southwest of Western Australia. Agricultural Chemistry Laboratory, Government Chemical Laboratories, Perth, Western Australia, 1991.

Beasley, D.B., and L.F. Huggins, ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation) User's Manual. Chicago: U.S. Environmental Protection Agency Report No. 905/9-82-001, 1982.

Cassell, E.A., R.L. Kort, D.W Meals, S.G. Aschmann, J.M. Dorioz and D.P. Anderson. Dynamic phosphorus mass balance modelling of large watersheds: long-term implications of management strategies. *Water Science & Technology*, 43, 153-162, 2001.

Daily, G.C. (ed) Nature's Services – Societal Dependence on Natural Ecosystems, Washington DC: Island Press,1997.

D'Arcy, B. and A Frost, The role of best management practices in alleviating water quality problems associated with diffuse pollution. *The Science of the Total Environment*, 265, 359-367, 2001.

Davis, R., B. Young, and S. Cuddy, CMSS Tutorial Book. Technical Memorandum 96.1, CSIRO. Institute of Natural Resources and Environment, Division of Water Resources, Canberra, 1996.

Deeley, D. M., Evaluating indicators of ecological health for estuaries in Southwestern Australia, unpublished PhD thesis, Murdoch University, 2001.

Djodjic, F., H. Montas, A. Shirmohammadi, L. Bergstrom, and B. Ulen, A decision support system for phosphorus management at a watershed scale. *Journal of Environmental Quality*, 31, 937-945, 2002.

Heatwole, D.C., A.B. Bottcher, and L.B. Baldwin, Basin scale model for evaluating Best Management Practice Implementation Programs. *Transactions of the American Society of Agricultural Engineers.* 29(2), 439-444, 1986.

Heathwaite, A.L., Sources and pathways of phosphorus loss from agriculture. In *Phosphorus Loss from Soil to Water*, eds H. Tunney, O.T. Carton, P.C. Brookes and A.E. Johnston, CAB International, 205-223, 1997

Heidtke, T.M. and M.T. Auer, Application of a GIS-Based Nonpoint Source Nutrient Loading Model for Assessment of Land Development Scenarios and Water Quality in Owasco Lake, New-York. *Water Science and Technology*, 28, 595-604, 1993.

Hodgkin, E.P. and B.H. Hamilton. Fertilisers and eutrophication in southwestern Australia: Setting the scene. *Fertilizer Research*, 36, 95-103, 1993.

Poiani, K.A. and B.L. Bedford, GIS based nonpoint source pollution modelling: Considerations for wetlands. *Journal of Soil and Water Conservation*, 50, 613-619, 1995.

Simmons, B.L. and D.M.H Cheng, Rate and pathways of phosphorus assimilation in the Nepean River at Camden, New South Wales. *Water Research*, 19, 1089-1095, 1985.

Tamm, O., Eine Methode zur Bestimmung de der anorganischen Komponente des Bodens. Meddelanden fran Statens skogsforsoksanstalt Stockholm, 19: 387-404, 1922.

Weaver, D.M. and A.E.G. Reed. Patterns of nutrient status and fertiliser practice on soils of the south coast of Western Australia. *Agriculture Ecosystems & Environment*, 67, 37-53, 1998.

Weaver, D.M., A.E.G. Reed and J. Grant, Relationships Between Stream Order and Management Priority: a Water Quality Case Study. In proceedings of the Third Australian Stream Management Conference, eds Rutherfurd, I., Sheldon, E., Brierley, G. and Kenyon, C. August 27 - 29, 2001, Brisbane, pp 647-652, 2001

Young, R.A., C.A. Onstad, D.D. Bosch and W.P. Anderson, AGNPS, a non-point source pollution model for evaluating agricultural watersheds. *Journal of Soil and Water Conservation,* 44, 168-173, 1989.

Young, W.J., T.F. Farley, J.R. Davis. Nutrient management at the catchment scale using a decision support system. *Water Science and Technology*, 32, 277-282, 1995.

Young, W.J., F.M. Marston, J.R. Davis. Nutrient exports and land use in Australian catchments. *Journal of Environmental Management*, 47, 165-183, 1996.

Young, W.J., Marston, F.M and Davis, J.R. NEXSYS: An Expert System for Estimating Diffuse Source Nutrient Export Rates. AI Applications, 11(2), 11-18. 1997.