CRC for
Water Sensitive Cities

Cost-effective Strategies to Reduce Nitrogen and Phosphorus Emissions in an Urban River Catchment

Canning Catchment case study Western Australia

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Executive Summary

The Swan Canning Catchment is highly valued by the residents of the Perth metropolitan area as a focus for leisure activities and as a source of ecological values. Protecting the Swan Canning Estuary from pollution has been a major concern since the late 19th Century. This concern led to the enactment of the Swan River Improvement Act in 1925. Since then, point source pollution from industry and sewage discharges, has been steadily reduced, but non-point source emissions of nitrogen (N) and phosphorus (P) largely from gardens, agriculture, public open space, sports fields and septic tanks continue to pose an ongoing threat to the ecological health of the Catchment due to eutrophication.

In the long term the risk of eutrophication events is reduced by the abatement of nutrient emissions. Because nutrients are integral to the urban landscape and are widely used in gardens, recreational grassland and agriculture, abatement actions may apply to a diverse set of agents including households, local authorities, farms, and sports clubs such as golf clubs. The control of non-point source pollution (NPSP) has to be achieved by indirect means because the emissions of individual agents cannot be observed. The widespread use of nutrients, non-observability of emissions and rapid urban development mean that abating NPSP in the Swan Canning is a complex environmental management problem. There is also regulatory complexity. A recent strategy report (Department of Parks and Wildlife, 2015, p14) identifies that 21 organisations have statutory management roles in the Swan Canning Catchment. This report also identifies a lack of policy coordination as a potential barrier to effective environmental protection for the Catchment.

The economic analysis in this report applies a catchment wide approach to nutrient pollution in the Canning River and Estuary. A cost-effectiveness analysis assumes a single regulator who aims to minimize the cost of achieving a given level of nutrient reduction. The analysis is across sub-catchments and for a long term planning horizon. The actions considered, by sub-catchments and over time are a feasible set of actions that have either already been applied (education of households, soil amendment, removal of septic tanks and investment in constructed wetlands) or could be considered if legislation was introduced (banning standard fertilizers) further to the restrictions introduced in 2010 on the phosphorus content of domestic fertilizers.

The results indicate that it is more difficult to achieve the targeted reduction of N than it is P. In fact when the set of options currently applied were at their highest level of possible abatement, it was not possible to reach the targeted reduction in N emissions. If an additional policy of banning standard fertiliser was introduced then the target reduction for N would be reached. Infill of septic tanks and constructed wetlands were policies that were applied at most levels of abatement. The cost-effectiveness of constructed wetlands was partly due to an assumption that their net-cost was reduced by a significant amenity value measured from a hedonic pricing study of the effect on house prices due to construction of the Bannister Creek living stream. The total net cost of reducing emissions to the target level of N and P in perpetuity was a present value of $616 million (at a 5% discount rate). Estimates from a non-market valuation of ecological values for the Swan-Canning (Rogers et al, 2012), imply that this expenditure spread over a 20 year period is justified.

The challenge is to find a policy design and legislative framework that can minimize the costs of achieving the abatement targets required to protect the catchment ecosystem. Currently what is lacking is a clear system of incentives for economic agents to abate nutrients to a level that gives long term protection to the Canning River, at least cost. Alternative approaches that push more costs onto polluters might be considered. It is noted that current policies provide weak or no incentives for economic agents (households, farms, sports clubs and LGAs) to take additional abatement actions. If incentive based schemes were introduced along with tighter regulation on the use of standard fertilizers then the government cost of achieving abatement targets could be reduced substantially making the long term management of the Canning less dependent on public funds and therefore more ambitious abatement targets could be achievable within current budgets.

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Abbreviations

ANZECC	Australian and New Zealand Environment and Conservation Council
CRCWSC	Cooperative Research Centre for Water Sensitive Cities
DCA	Development Control Area
DoW	Department of Water
LGA	Local Government Authority
N	Nitrogen
NPSP	Non-point source pollution
P	Phosphorus
Parks and Wildlife	Department of Parks and Wildlife
SRT	Swan River Trust
WALGA	Western Australian Local Government Association
WAOAG	Western Australian Office of the Auditor General

1 Introduction

The quality of surface and groundwater quality in many urban and agricultural catchments is reduced by elevated levels of nitrogen (N) and phosphorus (P) leading to ecological degradation (OECD, 1982). Most of the nutrient emissions comes from non-point source pollution (NPSP) sources due to fertilizer applied to farms, gardens and turf grass for sport fields and public open spaces (Barton and Colmer, 2006). Point sources of nutrient pollution include effluent from septic tanks and intensive livestock units for pig and poultry production. Despite global recognition that widespread and severe ecosystem degradation is caused by non-point source nutrient emissions (Canfield et al., 2010), progress towards finding regulatory solutions to excess nutrient emissions has been slow when compared with the significant progress towards reducing point source industrial, agricultural and residential pollution. A reason for this (Xepapdeas, 2011) is that the emissions of individual agents, that is, farms, local government authorities (LGAs) and households are not observable and therefore cannot be directly regulated. In other words, there is an asymmetry of information between regulators and agents whose actions related to nutrient emissions are hidden. Thus agents cannot be regulated directly to reduce emissions.

The economic importance of the Swan Canning Catchment and Estuary derives from the value of the assets and ecosystem services they provide to the 2.02 million people who live in the Perth metropolitan area (ABS, 2015). These range from use values for fishing, boating and passive use and non-use values due to biodiversity protection (Rogers et al., 2012). These values relate directly or indirectly to water quality and plant nutrient emissions are critical to water quality as they can lead to excessive phytoplankton growth (Peters and Donohue, 2001). As phytoplankton blooms die and settle on the river bed their decay exerts an oxygen demand that can result in hypoxia, a low level of dissolved oxygen. In turn hypoxic conditions are highly damaging to freshwater and estuarine ecosystems. In addition some algae, such as cyanobacteria, are directly toxic to fish and shellfish (Atkins et al, 2001). Algal blooms are partially caused by raised levels of N and P, although the relationship is complex as algal growth is controlled by the limiting nutrient and is also related to salinity and water temperature (Robson and Hamilton, 2004). The general view is that P is the limiting nutrient for algal blooms in fresh water and N in saline water, but new research highlights the complexity of this relationship and most commentators advocate reducing both N and P concentrations to reduce the risk of algal blooms (Elser et al., 2007).

The focus of this report is the Canning Catchment, a sub-catchment of the Swan Canning Catchment and a source of pollutants flowing into the lower Swan Canning Estuary. This catchment was selected as a case study to explore the cost-effectiveness of options for managing nutrient emissions in a mixed peri-urban and urban catchment. The aim of this report is to determine a set of abatement actions for the Canning Catchment that reduces nutrient emissions at least cost across a long term planning horizon. The case study catchment shown in Figure 1, comprises upstream sub-catchments where the dominant land use is native vegetation. These upstream sub-catchments are managed to provide water resources from the Canning Dam and biodiversity protection in State Forest areas and nature reserves. The middle reach sub-catchments around the rapidly urbanizing suburb of Armadale (Western Australian Planning Commission, 2001; Australian Bureau of Statistics, 2015) can be characterised as urban residential, peri-urban small holding agriculture, horticulture and horse paddocks. The lower reach sub-catchments include Southern River which is characterised by high rates of urbanisation and sub-catchments, such as Bannister Creek, were extensively urbanised in the 1960s and 1970s and have stable land-use patterns. A further key feature of the Canning Catchment is the Kent Street Weir which artificially separates the Canning River in the summer into an upstream section which is freshwater and a downstream section which is brackish to saline depending on river flows. The weir boards are removed during winter flows and replaced ahead of summer to prevent the intrusion of saline water upstream.

The aim of this study is to find cost-effective strategies to reduce nutrient emissions and is consistent with CRC for Water Sensitive Cities' (CRCWSC, 2017) vision that:

> "*A water sensitive city of the future is a place where people want to live and work. It is a place that: provides ecosystem services and a healthy natural environment, thereby offering a range of social, ecological, and economic benefits; and consist of water sensitive communities where citizens have the knowledge and desire to make wise choices about water, are actively engaged in decision-making, and demonstrate positive behaviours*" (CRCWSC, 2017)

Most of Australia's major cities are low density settlements located on estuaries and rivers. Some creeks within urban areas are completely urbanised, as is the case in the Canning Catchment and their ecological health is largely governed by nutrient and other pollutant emissions from stormwater drains. Nutrient emissions, by causing eutrophication, threaten ecosystems and reduce the value of ecosystem services provided by urban rivers and streams. The potential solutions to this problem integrate elements of CRCWSC's vision (Wong et al., 2013) especially behaviour change (Dean et al., 2016) and new technologies for managing urban stormwater (for instance, Ocampo et al., 2017), but also legal frameworks for developing new water legislation (Jensen and Gardner, 2016). The approach developed in this paper provides a general method of analysing the economics of managing urban NPSP that can be widely applied to other catchments and can be adapted as new technologies for nutrient abatement become available.

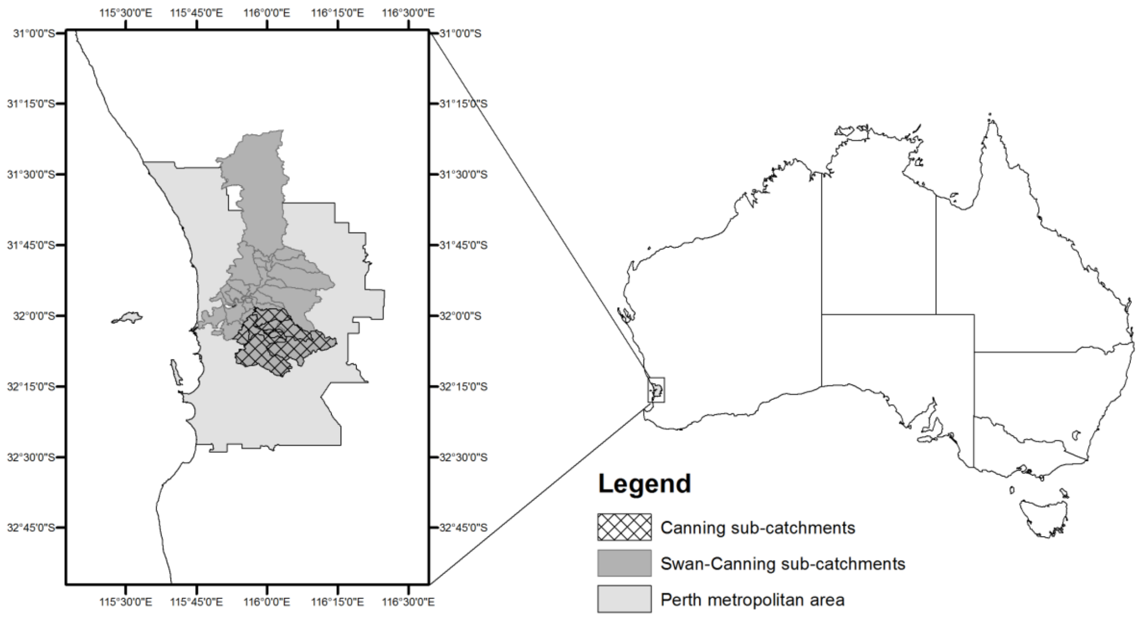


Figure 1: Swan and Canning estuaries

2 Literature review

2.1 Nutrient emissions in the Swan-Canning and Avon Catchment

The estuarine zones of the Swan Canning Catchment (Figure 1) cover an area of about 40 km^2 and extend 60 km upstream from Fremantle to the confluence of Ellen Brook with the Swan River, and 11 km upstream from the Canning Highway Bridge to the Kent Street Weir on the Canning River. The catchment area comprises the Avon River Catchment, which is predominantly broadacre agriculture, with an area of approximately 124,000 km^2 and 30 smaller catchments which drain 2090 km^2 of the Swan Coastal Plain (Kelsey et al 2010a).

The Swan-Canning Catchment has been systematically degraded by land cover change and increased nutrient emissions since the late 19th Century (Graham-Taylor, 2011; Swan River Trust, 2009; Department of Parks and Wildlife, 2015). Graham-Taylor (2011) introduces her historical review with:

> "*The history of the Swan River since European settlement in 1829 can … be read as a story of a slow deterioration in river water quality and an accompanying loss of the vital riparian vegetation that plays so important a role in maintaining a biologically balanced and healthy waterway."* (p129)

In their hydrological modelling analysis of the nutrient exports from the coastal catchments of the Swan Canning Catchment, Kelsey et al (2011, Table 4.5, p81) found that, the main sources of N emissions (described as 'exports in the report) were residential gardens (26%), farms (23%), septic tanks (16%) and recreation (parks and golf courses) (13%). For P the main contributions were from farms (33%), residential gardens (22%), recreational grassland (12%) and septic tanks (8%).

2.2 State government initiatives

The ecological health of the Swan Canning has been a public concern since the mid nineteenth century when the major concern was untreated sewage (Graham-Taylor, 2011). Algal blooms were mentioned in the introduction to the Swan River Improvement Act of 1925 (Western Australian Parliamentary Debates (WAPD), 1925, p2490) and were thought at that time to be due to the shallowness of the Swan and this led to dredging and the replacement of wetlands by turfed recreational area along the river banks. Ironically, the expanded turfed area and removal of wetlands significantly increased nutrient emissions. Turf is a source of nutrient emissions through fertilizer application and removing wetlands reduced the capacity of the catchment to assimilate nutrient emissions from urban creeks and drains. Public concerns about the health of the Swan Canning have continued and tend to peak following major algal blooms and fish kill events. For instance, in 2009 a series of algal blooms led the Western Australian Weekend Magazine to run the headline "Our Dying Swan" (Weekend West Magazine, 2009).

In 1988 further legislation was introduced to improve the management of the Swan Canning. The Swan River Trust Act 1988 led to the establishment of the Swan River Trust (SRT) in 1989. The Trust was given the responsibility of managing and planning for the Swan Canning Catchment. SRT's long term objectives related to enhancing ecological health and community benefit. The SRT was given responsibility for managing a river that had been irreversibly damaged by past management practices including bush clearing, grazing, dredging, landfill and the drainage and filling of marshes and mudflats.

The framework for the management of the river is set out in the Swan and Canning Rivers Management Act 2006. The provisions of the act are:

> "*the protection of the Swan and Canning Rivers and associated land to ensure maintenance of ecological and community benefits and amenity; the establishment of a Trust to provide advice and perform other functions in respect of the Swan and Canning Rivers and associated land; the management policies to be followed in relation to the Swan and Canning Rivers and associated land; the establishment of a Foundation with fund-raising and other functions, and for related purposes."* (State Law Publisher, 2006, p1)

The principles of the Act that are directly relevant to this study include:

> *"Environmental practices and procedures should be cost-effective and in proportion to the significance of the environmental risks and consequences being addressed."* (State Law Publisher, 2006, p7)

The Act defines a Riverpark of parts of the Swan, Canning, Helena and Wungong rivers and placed them under the control of the SRT.

The Trust initiated a series of initiatives (Swan River Trust (SRT), 2008; 2009) aimed at improving the ecological health of the Swan Canning. Following an amendment in 2015 (Department of Parks and Wildlife, 2015) to the 2006 Act the statutory functions were reallocated between Department of Parks and Wildlife (Parks and Wildlife) and the SRT: the SRT has a role in policy development and providing strategic advice to Government while Parks and Wildlife is responsible for the operations management of the Riverpark and the Development Control Area (DCA).

2.3 Current management

In the Swan Canning River Protection Strategy (Department of Parks and Wildlife, 2015) the opening statement by the Minster for the Environment acknowledges how complex the regulation of the Swan Canning Catchment has become since the 1925 Act of Parliament addressing water quality in the river. Developing a River Protection Strategy, based on the 2006 Swan and Canning Rivers Management Act, requires the coordinated actions of 21 local government authorities and 15 State Government agencies. The first part of the new policy is that there should be better coordination and better management (p12). It could be argued that the lack of a single regulatory authority backed by legislation with the power to implement a cost–effective policy for nutrient abatement largely explains the difficulty that the policy measures have had in achieving nutrient pollution targets (Western Australian Auditor General, 2014).

The key government agencies that implement State Government policy for the Swan Canning include the Department of Planning, Department of Parks and Wildlife (incorporating SRT), the Department of Water, the Department of Agriculture Western Australia (DAFWA) and the Water Corporation. Each of these organisations has responsibility for different aspects of catchment management and, to an extent, different regions within the overall catchment.

2.3.1 Swan River Trust and Department of Parks and Wildlife

The Department of Parks and Wildlife has control and operational responsibility over the Swan Riverpark and the Development Control Area (DCA). However, neither Parks and Wildlife nor the Trust were given control of the whole catchment. This is critical as nutrient emissions from agriculture are largely derived from the broadacre agricultural areas of the Avon and Ellen Brook catchments (Kelsey et al., 2011). The current role of SRT is a focus on policy development that includes:

> *"Developing policies for the protection and enhancement of the Development Control Area (DCA), the Riverpark and its shoreline. Establishing targets for ecological and community benefits and the amenity of the Riverpark and mechanisms for achieving those."* (Swan and Canning Rivers Management Act, 2006)

In the Healthy Rivers Action Plan (SRT, 2008) the Trust set targets for water quality combined with a set of other initiatives. The RiverWise program (SRT 2014, p58; Department of Parks and Wildlife, 2016) is an educational program combined with pilot incentive-based and behavioural change projects such as the Bennett Spring Project (Ashton-Graham, 2013) that aim to reduce emissions of nutrients from residential gardens.

The Great Gardens program was initiated in 2003 and is a large scale residential garden education scheme which, over a 10 year period from 2003 to 2013, had around 70,000 attendees at workshops. The workshops introduced participants to a range of techniques to improve the productivity of their gardens, whilst also reducing irrigation water use and nutrient leaching (SRT, 2014, p58; GHD, 2007; GHD, 2014). This low cost and highly successful approach to improving garden management on the

Swan Coastal Plain continues as part of The Forever Project with sponsorship from the Water Corporation and Department of Parks and Wildlife.

The Drainage and Nutrient Intervention Program (DNIP) is largely focussed on investment in capital projects that reduced the flow of nutrient emissions from highly modified urban drains and tributaries and one significant agricultural tributary (Ellen Brook) into the estuary. For instance, the Wharf St Wetlands and Civic Parkland project developed a constructed wetland to provide an amenity and to strip nutrients from an urban drain. Wetland construction cost including concept design, detailed design, heritage approvals, surveying, revegetation, sub-surface flow and sub-surface wetland media replacement was $1,674,000. Maintenance was $60,792 in the first year after construction (2009-10) and declined to $7,400 in 2015-16. The figure for 2015-16 is an estimate of the ongoing maintenance costs (Kate Bushby Department of Parks and Wildlife, 2016, personal communication). In most urban settings nutrient stripping is a relatively minor part of the total non-market value of constructed wetlands and in the authors' opinion, it is more likely that their amenity and biodiversity protection values will far exceed the benefits of nutrient abatement. For instance Polyakov et al. (2016) and Tapsuwan et al. (2009) have shown that living streams and wetlands provide amenity values to local residents, which are reflected in increased property prices.

In addition to capital investment, the DNIP also funded the in-stream removal of free reactive P using Phoslock (Robb et al., 2003; Douglas, et al., 2016). Previous applications have shown a cost of approximately $340 per Kg of P removed (Peter Adkins, Department of Parks and Wildlife, 2016, personal communication). Phoslock is a relatively expensive 'last resort' solution to reduce elevated P concentrations in streams and rivers and its performance can vary depending upon the presence of dissolved organic carbon.

Once nutrient levels have led to an algal bloom and the river has become anoxic, the only mitigation option available on a large scale is oxygenation. The River Health Program funds oxygenation plants that cost between $1 million and $1.5 million each to construct and around $1.05 million per year to maintain (Jennifer Stritzke, personal communication, 2014).

2.3.2 Department of Water

The Department of Water (DoW) has a wide remit to protect water resources in WA. In relation to the nutrient emission problem in the Swan Canning Catchment, it provides hydrological modelling of nutrient loads and monitoring of water quality jointly with Parks and Wildlife. The DoW has also been involved in policy initiatives to tighten the management of stormwater from new developments (Department of Water (DoW), 2016). Decision making has been assisted by the Urban Nutrient Decision Outcomes (UNDO) software tool (DoW, 2016) that was developed to assess the export of nutrients from urban developments. This tool allows developers to simulate the emission from a proposed development under different infrastructure designs to meet nutrient export targets mandated for the development area. If a proposed development is not able to meet water quality standards infrastructure modifications may be required before a development receives planning approval from the relevant authorities. Developers also set lot sizes and garden styles for new developments. This is significant as the type of garden and the proportion of a block allocated to lawns and flowerbeds determines the level of nutrient emissions from a property.

2.3.3 Department of Agriculture and Food Western Australia and Department of Environment Regulation

For peri-urban agriculture, DAFWA contributed funding to the Fertilizer Partnership (that was coordinated by the Department of Environment Regulation) and provided $1.5 million through its State NRM Program to the SRT for nutrient management in 2012. A project under the Fertiliser Partnership developed P budgets for farms to educate landholders about how they could reduce P emissions (Ovens et al., 2008). DAFWA also has a role in the larger agricultural catchments that account for a large proportion of the nutrient emissions. These agricultural catchments have the potential, under DAFWA initiatives, to reduce emissions cheaply through fertilizer reductions and land use change (Hennig and Kelsey, 2015).

2.3.4 Water Corporation

The Water Corporation is a government owned company responsible for the majority of water supplies, waste water management and drainage services including urban drains. In the Swan Canning it has had a rolling program of investing in septic tank infills. That is, connecting properties with septic tanks to the main urban sewerage system leads to a permanent reduction in both N and P emissions. The Water Corporation is also actively involved in demand management to reduce the amount of water used in gardens through advertising, block water pricing, garden watering restrictions and education programs.

In 2012, jointly with CSIRO (Water Corporation and CSIRO, 2012) published a significant research report which gives a detailed analysis of nutrient emissions from sub-catchments that are dominated by urban drains, for instance, Mill Street Main Drain and Bannister Creek. The executive summary from that report had two conclusions that are closely align to the results of the cost-effectiveness model. First that sewerage infill was a relatively effective policy leading to a rapid improvement in water quality. Second, was a recommendation that "*Further improvement of water quality should be based on an integrated catchment scale approach*" (Water Corporation and CSIRO, p9)

2.3.5 Policy expenditure

From 2008 to 2016 State Government invested $7 million to build six nutrient stripping wetlands, $11 million on 132 priority river foreshore restoration projects and $10 million to build, upgrade and operate existing oxygenation plants on the Swan and Canning rivers (Department of Parks and Wildlife, 2015).

In their review, the Western Australian Auditor General (WAAG), (2014, p34) reports that overall expenditure by the SRT was $18.2m in 2013-14 of which around 70% is allocated to reduce emissions and improve water quality. The WAAG review reports estimates from the Trust that total expenditure on river management, including the SRT funding, was around $72 million in 2013-14 (WAAG, 2014, p34). The Western Australian Local Government Association (WALGA) (2011) estimate a cost of $930m over a five year period to implement the wide ranging River Protection Strategy (Department of Parks and Wildlife, 2015) including the remediation of urban drains.

2.4 Progress towards reducing nutrient emissions

Evidence on the effectiveness of past management actions to abate nutrient emissions in the Swan Canning Catchment is mixed. At one extreme, the WAAG (2014) report is highly critical of the lack of progress made to protecting the Swan Canning. It argues that despite significant expenditure by the SRT, local authorities, DoW and the Water Corporation, water quality in the middle and upper catchment is failing to meet its long term targets for total N and P (SRT, 2015, p52; Department of Environment, 2004). The results of long term monitoring provided by the DoW for the WAAG (2014) report show that from 1995 to 2013 there have been changes in the following four key indicators. First, increases in chlorophyll-a in the middle and upper Swan and Canning Rivers indicate increased algal growth and low oxygen levels. Median chlorophyll-a concentrations in the middle and upper Swan River have increased to 12-15 ug/L, which is well above the ANZECC (Australian and New Zealand Environment and Conservation Council) water quality guidelines (ANZECC, 2000) level of 3 ug/L. Second, decreases in dissolved oxygen occur in the middle and upper rivers. At 4 mg/L plants and animals become stressed and below 2 mg/L plants and animals may not survive. Third, total N levels are above the ANZECC guidelines of 0.75 mg/L in the middle and upper Swan and Canning Rivers. Fourth, total P levels in the middle and upper Swan and Canning rivers are above the ANZECC guidelines of 0.03 mg/L.

Source: Department of Water

Note: TP is total phosphorus, P SR is the short-run and P LR the long-run phosphorus targets. TN is total nitrogen, N SR is the short-run and N LR the long-run nitrogen targets.

Figure 2: Nutrient emissions in the Southern River sub-catchment 2001 to 2013.

For the Canning Catchment, the evidence from Southern River sub-catchment shown in Figure 2, the main source of nutrient emission in the Canning Catchment, is that since 2001 concentrations of total N have been increasing while concentrations of total P fell in 2006, but has then stabilized. The long term target has not been achieved consistently for N and has never been achieved for P. The total N and P load fluctuates widely and is correlated with the annual flow. The nutrient load is reduced in low flow years, thus the reduction in river flows across the Swan Canning Catchment (SRT, 2015, p56) is suppressing the emissions of nutrients. High rainfall and thus high flow years are likely also to be accompanied by surges of nutrient pollution and these events are often associated with algal blooms and fish kills.

The relationship between emissions and flow is captured in the correlation matrix Table 1. The total load is highly correlated with annual flow, this is partly a result of how total nutrient loads are calculated, but it does indicate why high rainfall years tend to be associated with an increased number of polluting events. Increased flows are also linked to increased concentrations of both nutrients. Finally the concentrations of total P and N are correlated, suggesting that urban development activities tend to increase both pollutants.

Table 1: Correlation matrix of nutrients and river flow in Southern River catchment.

	TN median (mg/L)	TP median (mg/L)	TN load (t/yr)	TP load (t/yr)
Annual Flow GL	0.33	0.50	0.99	0.99
TN median (mg/L)		0.30	0.35	0.34
TP median (mg/L)			0.35	0.34
TN load (t/yr)				0.99

Source: Department of Water Monitoring data (1993-2015)

Further evidence on compliance is given in Table 2, that gives SRT (2015, p55) compliance assessment for the Canning catchment. Notably, overall compliance rates for total nitrogen are stable, with Southern River and Bannister Creek standing out in the Canning Catchment as noncompliant. The situation with total phosphorus shows greater compliance with most sub-catchments meeting short- term concentration targets.

Table 2: Compliance of monitored tributaries discharging into the Canning estuary with long-term total phosphorus and nitrogen targets.

Sub-catchment	2011	2012	2013	2014	2015
Total Nitrogen (TN)					
Bannister Creek	(12) 27	(12) 28	(12) 26	(12) 27	(12) 28
Southern River	(12) 27	(12) 29	(12) 28	(12) 28	(12) 28
Bickley Brook	(12) 16	(12) 14	(12) 13	(12) 13	(12) 13
Yule Brook	(21) 10	(21) 9	(21) 7	(21) 12	(21) 13
Upper Canning River	(21) 4	(21) 5	(21) 4	(21) 6	(21) 5
Total Phosphorus (TP)					
Bannister Creek	(21) 3	(21) 4	(21) 6	(21) 3	(21) 4
Southern River	(12) 24	(12) 25	(12) 21	(12) 18	(12) 17
Bickley Brook	(21) 1	(21) 1	(21) 2	(21) 2	(21) 3
Yule Brook	(21) 3	(21) 6	(21) 5	(21) 5	(21) 4
Upper Canning River	(21) 0	(21) 0	(21) 0	(21) 0	(21) 0

Source SRT, 2015, p55.

Note the number in the brackets gives a statistically derived maximum number of samples above the target levels permitted to occur to meet the target concentrations of TN and TP. The other number gives the actual number of observations above the target. Thus Bannister Creek in 2011 had a target for no more than 12 observations above the short term target for TN, but 27 observation were above the target. The long term target for N is 1 mg. L and for P is 0.1 mg/L.

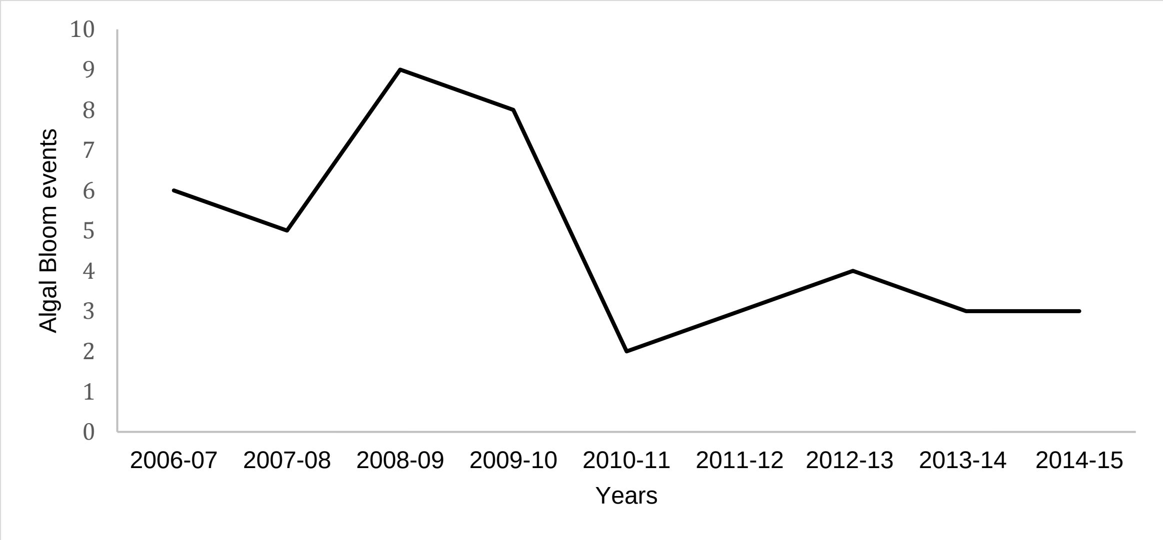
Evidence derived from biological measures of ecosystem health are more mixed. The number of algal blooms, Figure 3 in the Swan-Canning has declined to around two to three per year from 2010-11 to 2014-15. This was down from a peak of nine events in 2008-09. Fish communities are a good indicator of the ecological health of the river as they are susceptible to low dissolved oxygen levels and certain algal species such as Karlodinium are directly toxic to fish (John and Kemp, 2006). Parks and Wildlife and Murdoch University jointly sample and report on fish communities as an indicator of the condition in the Swan Canning Riverpark. The primary purpose of the Fish Community Index is to provide an ecological indicator of estuary condition that complements existing water quality monitoring and evaluation. Based on sampling of fish communities in 2016, the nearshore waters were assessed as good, while offshore waters were assessed as fair (Hallett, 2016). Based on this measure, the ecological condition of the rivers has improved since the mid-2000s although some zones score poorly at times, due to unusual conditions at the time of sampling.

Since 2003, there have been eight significant fish kills in the Canning recorded by the Department of Water and these are given in Table 3. The number of fish killed is difficult to estimate, but event 3 in 2007 at Kent St Weir and event 7 in 2015 in the Canning estuary were major events. The reasons for fish kills are sometimes unclear as dead fish need to be assessed shortly after death to establish a cause. The most usual reason is low dissolved oxygen (DO) levels with or without evidence of toxic algae. A typical fish kill event occurs between March and June (seven out of eight fish kills) and often coincides with the first major rainfall event of the Autumn (three out of eight) where nutrients are flushed into the river leading to an algal bloom followed by reduced levels of dissolved oxygen.

Table 3: Fish kill events in the Canning estuary 2003 to 2015.

Event No	Year	Date start	No. dead fish	Location	Karlodinium/ Heterosigma	Fish pathology	After storm
1	2003	3/06/2003	200	Canning	yes		yes
2	2006	1/04/2006	unknown	Kent St Weir			
3	2007	8/05/2007	39238	Kent St Weir			yes
4	2007	19/11/2007	250	Riverton, Shelly bridge	yes		
5	2009	14/04/2009	2	downstream Kent St Weir	yes		
6	2010	25/03/2010	17	CAS Canning			yes
7	2015	13/05/2015	1000-5000	Canning estuary at Bywater Park	yes	yes	
8	2015	23/06/2015	80-100	Wilson Wetlands			

Source: Department of Water and Department of Parks and Wildlife monitoring data.



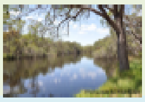
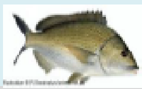
Source Swan River Trust (2015)

Figure 3: Counts of algal bloom events in the Swan-Canning 2006/7 to 2014/15.

2.5 Non-market valuation

Two types of non-market valuation analysis for the Swan-Canning are relevant to this study. Stated preference methods give estimates of willingness to pay for hypothetical improvements in the Swan-Canning ecosystem. Revealed preference estimates, based on hedonic pricing methods applied to house prices, give the value of environmental attributes experienced by householders in the catchment.

Rogers et al. (2012) completed a comprehensive choice experiment, a stated preference method, to assess the value to respondents of ecological attributes of the Swan Canning using a personal expenditure and a budget reallocation payment mechanism. Re-estimated values from this choice experiment for the Local Government Areas within the Canning Catchment are used to value nutrient abatement policies. The attribute linked to the improvement in the general ecological state of the river, indicated by a fish kill attribute, can be used to value improvements in the river ecosystem due to nutrient abatement.

		Option 1 Current state	Option 2	Option 3
	**Foreshore vegetation in good condition**	20% (500 hectares) in good condition	20% (500 hectares) in good condition	40% (1000 hectares) in good condition
	**Average frequency of significant fish kill events**	2 events each year	1 event each year	1 event each year
	**Health of dolphin population**	75% (17 dolphins) in good health	85% (19 dolphins) in good health	95% (21 dolphins) in good health
Cost to you each year, for the next 10 years		$0	$50	$150
Which one would you choose?		☐	☐	☐

Source: Rogers et al., 2012, p77

Figure 4: Example choice set from ecological value survey.

Figure 4 gives an example of the payment card used to assess ecological values. The results of the choice experiment are used to estimate partworths for the ecological attributes. In addition to the estimates for the general Perth population, the partworths were estimated for a sub-sample of 151 respondents drawn from the Canning Catchment LGAs as they are likely to relate more closely to the status of the Canning Catchment and estuary. The estimated willingness to pay ($/person /year) is given in Table 4: The population of Gosnells, Armadale, Kalamunda and Canning LGAs for the most recent year available from LGAs is 354,017 residents. Based on this population estimate, the benefits of reducing fish kills from an average of two to one per annum is used as an indicator of the benefits of improving water quality in the Canning Catchment of $21.9 million per annum. This should be viewed as an approximate value of improving water quality from nutrient abatement as it does not include the willingness to pay for dolphin health, which is related to fish health and water quality through ecosystem linkages.

Table 4: Willingness to pay for changes in ecological attribute level in the Canning Catchment

Attribute change	Willingness to pay
Moving from 20% to 40% vegetation in good condition	$113
Moving from 20% to 60% vegetation in good condition	$126
Moving from 75% to 85% dolphins in good health	$32
Moving from 75% to 95% dolphins in good health	$78
Moving from two fish kill events on average per year to one	$62

Source: Estimates based on data collected by Rogers et al., 2012

3 Cost-effective nutrient abatement

3.1 Introduction

Plant nutrients are integral to a wide range of economic and social activity in urban and agricultural catchments. Economic agents that directly affect nutrient emissions include: farms (mainly peri-urban agriculture), horticultural producers, golf courses, other sports clubs; households (through garden and pet management); local authorities that manage active turf, public golf courses and ornamental parklands and the Water Corporation in conjunction with the State Government that decides on septic tank removal.

Developers indirectly affect nutrient emissions by determining the layout of housing developments including garden areas and landscape packages. Developers are also responsible for installing stormwater management infrastructure, living streams, constructed wetlands and biofilters. They are also able to apply soil amendments during landscaping for gardens and public open space within developments.

Finally the regulators (in the case of the Swan-Canning this is the Department of Parks and Wildlife, the Department of Water and LGAs) are responsible for establishing and enforcing a legal framework for developments and investing in in-stream abatement actions such as operating oxygenation plants and applying in-stream abatements such as Phoslock to remove phosphates from freshwater streams.

The set of actions that agents can apply are classified broadly as recurrent and structural. Recurrent actions include: fertilizer quantity, fertilizer quality (conventional or slow release), and in-stream abatement (for example, Phoslock). Structural abatement, that involves investment activities, include: soil amendment, biofilters, mains sewerage infill (to remove septic tanks) and constructed wetlands.

Changes in behaviour in relation to fertilizer use may be induced by educational programs such as the Great Gardens project (The Forever Project, 2016) that encourage households, smallholders and farmers to change fertilizer input behaviour. These schemes can be thought of as developing a stock of community awareness that depreciates through time following the initial education and awareness campaign.

The social welfare function in relation to nutrient pollution abatement accounts for the benefits and costs related to achieving given levels of nutrient abatement from a set of actions. Nutrient abatement is valued as a set of improvements in recognisable water quality such as improved water clarity and reduced fish kills. Recurring actions and investments incur costs, but in some cases generate benefits. Thus a constructed wetland or a living stream have a value in terms of nutrient abatement, but also has an indirect use or non-use value (Polyakov et al., 2016).

3.2 Empirical modelling assumptions and methodology

The empirical model is a large mathematical programming model that minimizes cost subject to nutrient emission constraints expressed as percent of the maximum target emissions. For simplicity the same percentage reduction of emissions is applied to both nitrogen and phosphorous. The details of the model are given in the next sub-section. The model minimizes costs over a long (indefinite) time horizon because some investments, such as septic tank infill and constructed wetlands are long term investments. The objective is to minimize the present-value of cost over the planning horizon and, depending on the assumption applied, these costs may be net of the direct benefits of the actions taken. For instance, constructed wetlands have a cost of construction and maintenance, but they also provide a non-market benefit to the population in the surrounding area. Other costs are recurrent, for instance applying slow release fertilizers to public open space, and are assumed to have no additional non-market benefit.

The objective function aggregates cost across different groups in the catchment and does not separate out the cost that apply to different groups of residents, local government authorities, sports clubs and farms. Therefore the costs of constructed wetland appear as a capital investment cost in the year that they are incurred and there is no attempt in the optimization to treat costs incurred by different agents separately. This assumes that a dollar of cost incurred by the state government and by a developer or a sport club are equal.[1]

Emissions are calculated by allocating land in different catchments to treatments that reduce nutrient emissions. Not all abatement measures strictly relate to land use. For instance, constructed wetlands relate to locations in the catchment rather than specific land uses. Finally for phosphorus, there is the potential to use Phoslock which is the only in-stream treatment.

The Appendix presents a theoretical model of optimal spatial and temporal abatement in a catchment with an upstream and a downstream sub-catchments. In this model the returns to investment are represented by a current period and one future period that accounts for the costs over all future periods. There are three efficiency conditions for either a cost minimizing, budget constrained or welfare maximizing catchment abatement plan. The first condition is an optimal static levels of recurrent abatement (emissions) across a sub-catchment. The second is optimal abatement between structural abatement and recurrent abatements. The third is optimal investment in structural abatement across sub-catchments.

Underpinning the economic model is a simple hydrological model that represents nutrient transport from sub-catchments to the Canning Estuary. The hydrology of nutrient transport in urban catchments is complex and difficult to model (Kelsey et al., 2011; Water Corporation and CSIRO, 2012; Barron and Barr, 2009a, 2009b). A spatial and temporal economic analysis of optimal policies requires optimization to find the least cost solution (Doole and Pannell, 2012). Optimization is not feasible for large spatial and dynamic hydrological models that operate on short times periods. To allow an economic analysis the economic model includes a simplified linear representation of nutrient transport within the Canning Catchment derived from the results of SQUARE hydrology model (Kelsey et al., 2010a). There are also a set of restrictive assumptions applied to determine the effects of policy actions. The key assumptions implicit in the structure of the model and the data are as follows:

> *(A1) Nutrient transport in the Canning Catchment is represented by a static, linear and deterministic annual load model based on sub-catchment transport coefficients and sub-catchment and land use annual nutrient loads. This representation is not able to account for "legacy" nutrient emissions from past agricultural fertilizer applications which are a factor in groundwater dominated sub-catchments such as Southern River.*
>
> *(A2) The cost of sewage infill depends on the property size and emissions from all septic tanks are the same for a sub-catchment.*
>
> *(A3) Constructed wetlands have a constant construction and maintenance cost per ha.*
>
> *(A4) Behaviour change has a constant adoption rate and decline in adoption across the catchment over time following the initial education campaign.*
>
> *(A5) The efficacy in terms of nutrient abatement of banning standard fertilizers and requiring that all LGAs use slow release N on public open space assumes a baseline that no slow release fertilizer is currently used.*
>
> *(A6 The planning horizon is infinite, this can be interpreted for practical purposes as being 100 years.*
>
> *(A7) Land currently designated for housing development is developed by the end of the first 10 years in the planning horizon.*

These assumptions reflect two considerations. First some (A1) and (A4) are necessary to ensure a tractable economic model in that they impose linearity. Second, all assumptions reflect a lack of data on aspects of nutrient applications and household behaviour.

[1] Strictly expenditure by state and local government agencies should be adjusted to account for the marginal cost of raising public funds (Campbell and Bond, 1997).

3.3 Empirical Model structure

The empirical model is an application of the theoretical model adapted to the conditions and policy options found in the Canning catchment. The sub-catchments are defined in terms of areas of different land uses. We model nonpoint source pollution in M sub-catchments $i \in [1 \ldots M]$ and *L* land uses $l \in [1 \ldots L]$ where $s_{i,l,t}$ is the area of a land use *l* in catchment *i* in year *t*. Land use in the catchment changes over the planning horizon on the basis that land currently under development is converted to urban residential by the end of the first 10 years of the planning horizon. This means that areas of the different land uses are constant after the first decade.

There are two nutrient pollutants in the model $m \in (N, P)$. The input of nutrient *m* in fertilisers in each catchment *i*, land use *l* in year *t* is $q_{i,l,t,m}$, per unit area and the transmission or leaching rates are $\theta_{i,l,t}$. There are also emissions from $st_{i,t}$ from septic tanks in each sub-catchment with emissions per septic tank $\gamma_{i,m}$ and transmission rates $\varphi_{i,m}$ of effluent from septic tanks. Septic tanks are removed through investment in extending the mains sewage network.

We model abatement at four stages: first a reduction of nutrient applications at a land-use and sub-catchment level; second removing septic tanks; third interception at a catchment level (using constructed wetlands), and fourth removing P directly from the river using Phoslock in the Canning River.

At a sub-catchment-land use level: $x_{i,l,t}$ is land allocated to a lower fertilizer emission alternative and $0 \le \psi_{i,l,m} \le 1$ is the proportional reduction in emissions. Emissions are reduced by households and local authorities allocating land uses $s_{i,l,t}$ such as gardens and sports fields to low fertilizer or low emission regimes $x_{i,l,t}$. The total emissions over sub-catchments and time is given by:

$$e^{h}_{i,l,m,t} = q_{i,l,m,t}(s_{i,l,t} + \psi_{i,l} x_{i,l,t}); \quad s^{0}_{i,l,t} = \quad s_{i,l,t} + x_{i,l,t} \tag{1}$$

Where $s^{0}_{i,l,t}$ is the total area in both high emission and reduced emission land uses.

The initial number of septic tanks in a sub-catchment is st^{0}_{i}. Infill is given by $k^{st}_{i,t}$ and is the infill by sub-catchment and year. Once a septic tank is removed, emissions are assumed to be zero for all following periods and there is no capital depreciation. The emissions from septic tanks are given by:

$$e^{st}_{i,l,m,t} = (st_0 - k^{st}_{i,t})\gamma_{i,m}\varphi_{i,m} \tag{2}$$

Investment in constructed wetlands which strip nutrients from streams is represented as follows. At a sub-catchment level $k^{cw}_{i,t}$ is the area of wetland and $\alpha^{cw}_{i,m}$ is the nutrient removal per ha of the constructed wetlands in each catchment. We assume that constructed wetlands are effective from the year of construction. Emission reductions are given by $\alpha^{cw}_{i,m} k^{cw}_{i,t}$.

At the whole catchment level: z_t is the quantity of in-stream treatment applied in period *t* and ω_m is nutrient removal per unit. Bringing the four components of emissions together, the total emissions of nutrient *m* in year *t* is:

$$e_{m,t} = \sum_{i=1}^{M} \left\{ \sum_{l=1}^{L} e^{h}_{i,l,m,t} + e^{st}_{i,l,m,t} - \alpha^{cw}_{i,m} k^{cw}_{i,t} \right\} - \omega_m z_{m,t} \tag{3}$$

The cost of abatement in year *t* is

$$c_t = \sum_{i=1}^{M} \left\{ \sum_{l=1}^{L} c_{i,l} x_{i,l,t} + w_i^{st} I_{i,t}^{st} + w_i^{cw} I_{i,t}^{cw} + w^{cwoper} k_{i,t}^{cw} \right\} + w^z z_{m,t} \quad (4)$$

Where w_i^{st} is the cost of connecting a septic tank, w_i^{cw} is the cost of investing in a constructed wetland per ha and w^{cwoper} is the operational cost of a constructed wetland.

The equations of capital investments are:

$$k_{i,t}^{st} = I_{i,t}^{st} + k_{i,t-1}^{st}; \quad (5)$$

for septic tanks and

$$k_{i,t}^{cw} = I_{i,t}^{cw} + k_{i,t-1}^{cw}; \quad (6)$$

for constructed wetlands.

The model minimizes the net present value of abatement costs subject to the constraint that ten years average emission does not exceed nutrient export targets:

$$\text{Minimum } \sum_{t=1}^{T_1} c_t \delta^t + \sum_{t=T-T_1+1}^{T} c_t \delta^t \left(1 + \frac{\delta^{T+1}}{1-\delta} \right) \quad (7)$$

Subject to (1) to (6) and the emission target:

$$\bar{e}_m \geq e_{m,t} \quad (8)$$

Where δ is a discount factor and the second term on the right-hand side the terminal condition that gives the cost of the last 10 years repeated in perpetuity, $\bar{e}_m$ is the target nutrient emission. The target nutrient levels are set as proportions of the emission calculated without abatement measures. Implicit in the targets set for a cost-effectiveness analysis is a marginal social cost of nutrient pollution.

3.4 Data

Appendix 2 presents the data tables used in the empirical model. Table A2.1 gives land use by sub-catchment. Table A2.2 and A2.3 gives nutrient inputs. Tables A2.4 and A2.5 gives the transfer coefficients (Joel Hall, DoW, personal communication).

The sub-catchments, shown in Figure 5, with the highest levels of emissions per ha for both N and P are the Lower Canning and Southern River. Bannister Creek has a high level of P emissions per ha. From Appendix 2, Table A2.6, it is notable that high emission catchments on a per ha basis are those with a high proportions of urban land use. The Southern River Catchment was identified as a Priority 1 catchment for nutrient emissions (SRT, 2010) as it accounts for a large proportion of the nutrient load in the Canning River. In the Swan-Canning catchment as a whole the main sources of nutrients are the large agricultural catchments, the Avon and Ellen Brook (Kelsey et al., 2010; Kelsey et al., 2015).

Land use classification was based on the cadastral maps, zoning maps (Metropolitan Planning Scheme and Local Planning Schemes) and corrected using aerial photos. Areas of land uses by catchments are in Table A2.1.

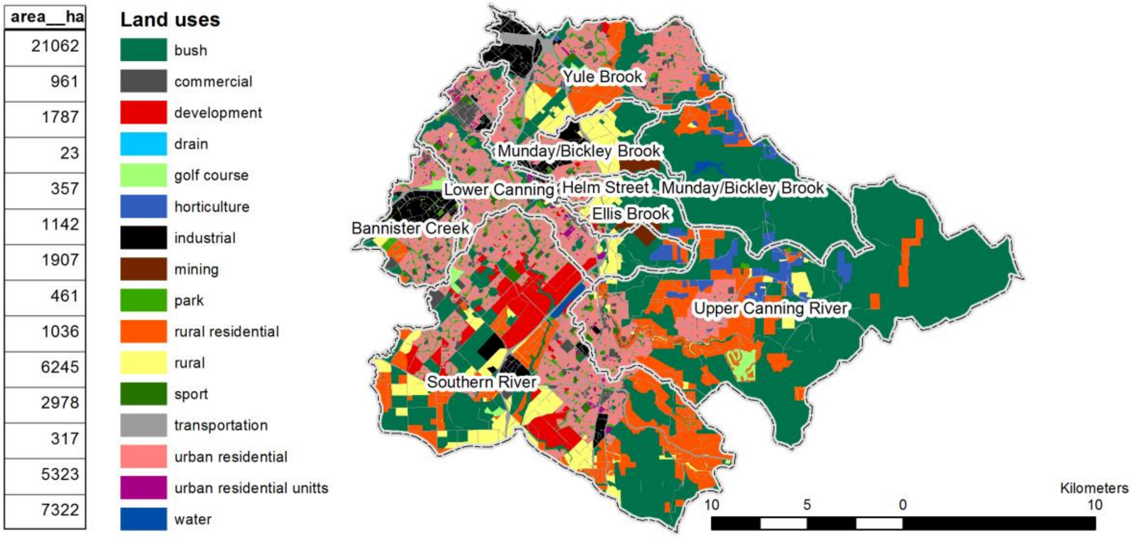


Figure: 5 Land Use in the Canning Catchment, 2015.

3.4.1 Infill of septic tanks

Infill of septic tanks involves the removal of a septic tank on the property and connection of the property to the reticulated sewer system. We assume that this action is a one-off investment resulting in the permanent removal of nutrient emissions. There is a large variation of property sizes, soil conditions, and distance to the existing sewer network. The efficacy of septic tank removal depends on nutrient output and soil properties. Information on typical nutrient output and nutrient transmission rates is based on modelling by Kelsey et al. (2011), the data was provided by Joel Hall (DoW, personal communication), see Table A2.4 and A2.5. We made the assumptions that the cost of infill would depend on property size, which is related to the density of properties in each location. The sizes of the properties requiring connection to the sewage system vary from 0.01 to 5 ha with 1st quartile 0.15 ha, median 0.2 ha, and 3rd quartile 0.5 ha.

The Water Corporation suggested the typical cost for a property that would be considered for infill in the study area would be $30,000 per connection (Sergey Volotovskiy, Water Corporation, personal communication) and could be as expensive as $80,000 per connection in the least favourable conditions. Although infill of septic tanks is not mandatory for properties greater than 0.2 ha and these properties normally would not be considered (Sergey Volotovskiy, Water Corporation, personal communication), we include an option to remove septic tanks on these properties following previous modelling by Kelsey et al. (2010a). To reflect the variability of conditions we assumed the cost of connecting properties of 0.01-0.15, 0.15-0.20 ha, 0.20-0.5 ha, and 0.5-5 ha would be $20,000, $30,000, $50,000, and $80,000, respectively.

There are three sources of uncertainty related to modelling septic tank removal. First is the integrity of existing septic tanks. This issue has been raised in a number of studies (NSW Department of Local Government, 2000; Sydney Catchment Authority, 2012). The other issue is the private value associated with a residential property converting from a septic tank to mains sewage. The third issue is the cost of sewage infill and how this relates to the capacity of the sewage system in sub-catchments.

3.4.2 Behaviour change for residential properties relating to garden fertilizer use

Following Ashton-Graham (2013) and Suh et al. (2006), we assume that educational campaigns can be implemented in two ways: ‘intensive’ that involves calling on households and face-to-face interaction, and 'low intensity' through a telephone campaign. Assumptions about resident adoption, efficacy, and costs are listed in Table 5. We assume that the effectiveness of education declines linearly over time due to dis-adoption. Thus to maintain effectiveness educational programs need to be repeated.

Table 5: Assumptions about efficacy, adoption and costs of urban behaviour change

Type	Percent households adopting reduced fertiliser application	Reduction of fertilizer application (in participating households)	Cost per household of education	Years to education effect falls to zero
Intensive	25%	50%	$475	10
Low intensity	5%	50%	$50	10

3.4.3 Fertilizer Action Plan and Fertiliser Partnership

The Fertilizer Partnership applies to agricultural and urban properties. It encourages improved fertiliser efficiency while maintaining productivity on agricultural properties through reducing the applications of highly water soluble P in bulk fertiliser. It also encourages the use of soil testing to reduce excess P use and address issues of acidity, low sulphur, low potassium and other constraints that can limit crop productivity and thus fertilizer uptake by plants. The average cost of soil testing is about $3500 per property which is carried out every 3 years. Assuming the average agricultural property is 40 ha, the cost per year is $30/ha. We assume that farms in the scheme reduce P emission by 30%. It should be noted that consistent with the Fertiliser Partnership, the maximum P content in domestic use (non-bulk) fertilisers has been limited for several years under the Environmental Regulation (Packaged Fertiliser) Regulations 2010 (State Law Publisher, 2010).

3.4.4 Constructed wetlands

The construction cost of wetlands is a one-off capital cost. Based on Wharf Street wetland, construction cost is $1,674,000/ha (Mark Cugley, personal communication). The annual maintenance cost is assumed to be 1% of construction cost. We also assume that constructed wetlands generate public amenity benefits valued at $109,000/ha/year, from estimates of amenity benefits for Bannister Creek living stream (Polyakov et al., 2016).

The effectiveness of constructed wetlands is assumed to be permanent. Table 6 below presents N and P reduction when maximum area of constructed wetlands was implemented in each catchment. We assume that nutrient reduction is proportional to the area of implemented constructed wetlands.

Table 6: Assumptions about N and P reduction with maximum area of constructed wetlands by catchment

Catchment	N reduction, kg/year	P reduction, kg/year	Maximum area, ha
Bannister Creek	1210.1	155.819	21.8
Ellis Brook	6.226	0.468	4.8
Helm Street	98.712	8.515	4.8
Lower Canning	315.34	77.272	25.7
Munday/Bickley Brook	0	0	3.6
Southern River	425.37	88.364	15.6
Upper Canning River	0	0	0
Yule Brook	366.445	45.716	18.4

Source: Kelsey et al., 2010a, Table 6.23, Table 6.22

3.4.5 Phoslock

Phoslock has the capacity to remove up to 1 kg of P for every 100 kg applied. We assume that it can be applied in the Canning River and that the cost of removing P is $340/kg (Mark Cugley, personal communication). We assume that Phoslock is active for three years after application.

3.4.6 Slow release fertilisers on Public Open Space

We model three types of Public Open Space (POS): golf courses, active (sport) and passive POS. We assume that nutrient abatement strategy is by the application of slow release fertilisers. The cost is $200/ha/year based on switching from Energy Turf regular fertiliser to Turf Gold Au slow release fertiliser. The efficacy is a 20% reduction of N compared to standard fertilizer (Shuman 2003; SERCUL, 2014).

3.4.7 Banning standard fertilisers

If, hypothetically, standard fertilisers were banned (beyond current limits on P content of domestic fertilizers) slow release fertilisers would be used instead for all land uses. The efficacy and costs are the same as in the “Slow release fertilisers on Public Open Space” option above. This option is assumed to be binary, that is when selected it is applied for all land uses were fertilizer is currently applied.

3.4.8 Soil amendment (imported fill) on new developments

We consider using soil amendments such as Iron Man Gypsum (IMG) amendment of subsoil drains to treat nutrients in urban groundwater discharge. This action is implemented at the development stage of greenfield residential developments. We assume that the cost of installed IMG mix is $64/m^3, the length of drain is 200 m/ha of development, application of the mix is 2 m^3/m of drain resulting in a cost of $25,604/ha (based on data provided by Mark Cugley, personal communication). We further assume that the treatment removes 80% of P and 20% of N.

3.5 Results

3.5.1 Emission exports

Calculated nutrient exports by catchment, as well as nutrient exports published in (Swan River Trust, 2009) and maximum acceptable loads are presented in Table 7. The discrepancies between modelled loads and loads from Swan River Trust (2009) are due to updated land use data related to development and a more detailed classification of residential land use in our study.

Table 7: Annual loads and maximum acceptable loads by catchment

Catchment	Annual load modelled, tonnes/year		Average annual loads, tonnes/year (Swan River Trust 2009)		Maximum acceptable loads, tonnes/year (Swan River Trust 2009)	
	N	P	N	P	N	P
Bannister Creek	10.77	0.68	12.10	0.82	3.90	0.55
Ellis Brook	0.77	0.02	0.70	0.02	0.70	0.02
Helm Street	1.40	0.05	1.70	0.07	0.50	0.04
Lower Canning	6.30	0.77	7.90	0.97	2.50	0.40
Munday/Bickley Brook	4.10	0.12	2.90	0.14	2.30	0.14
Southern River	20.76	2.11	21.30	2.21	11.40	1.15
Upper Canning River	7.53	0.37	7.50	0.42	7.50	0.42
Yule Brook	6.45	0.35	7.50	0.43	5.60	0.43
Total	58.07	4.48	61.60	5.08	34.40	3.15

3.5.2 Modelling scenarios

Reduction of nutrient exports are modelled using a combination of abatement actions that achieve a target level of emissions in the catchments of the study area at the minimum net present value of capital and annual costs. The modelling timeframe can be viewed to be a very long term planning horizon. This horizon is divided into three sub-periods: the first 10 years, years 11 to 20, and years 21 and onwards. During the first 10 years all land that is currently planned for development is assumed to be converted to residential land use. We assume that both investment and recurrent abatement action can be established for this period. During the second sub-period, only recurrent abatement actions are considered. The optimal abatement actions established for years 11-20 are assumed to be repeated indefinitely during the third sub-period.

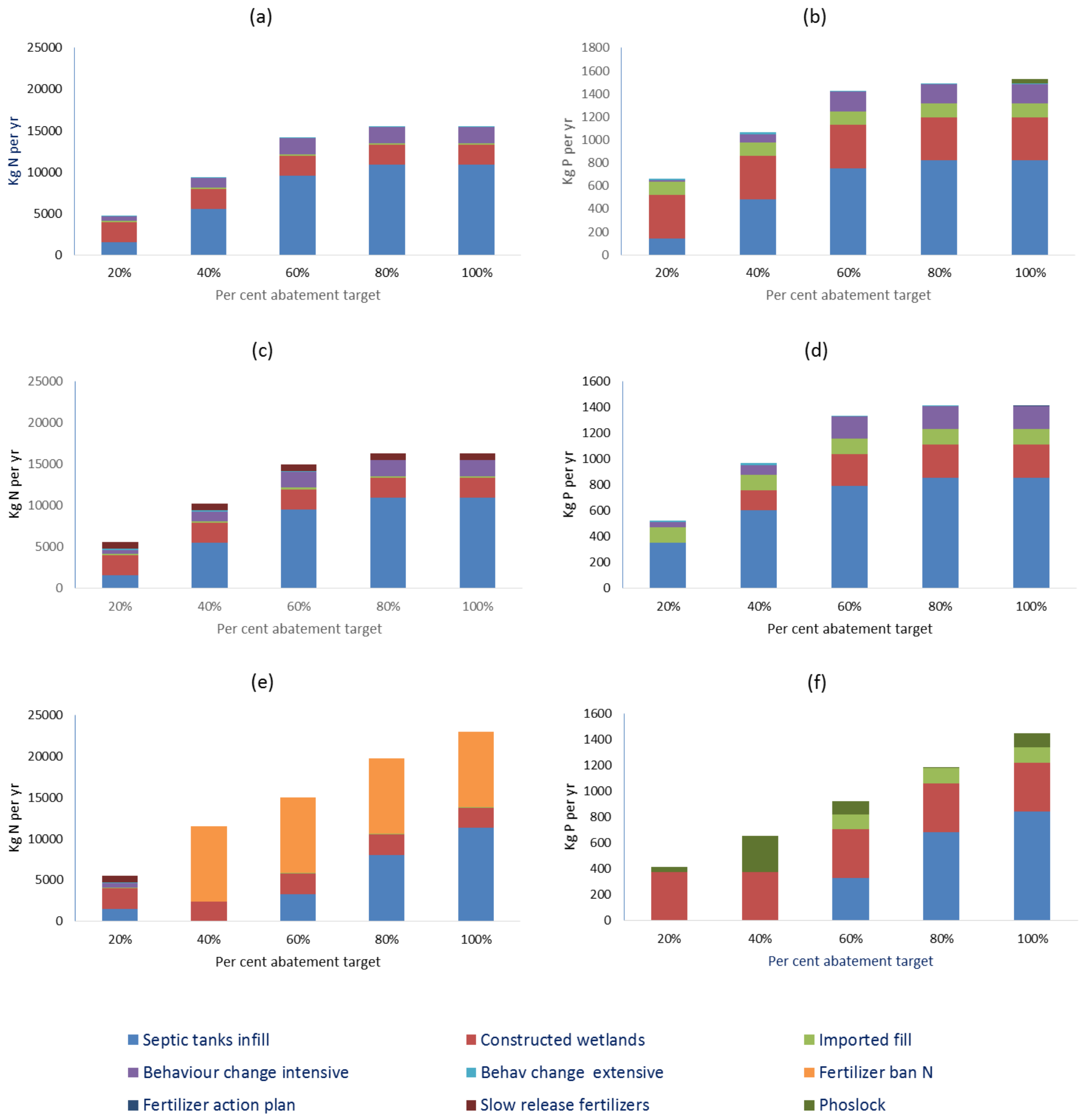
A series of reduction targets are calculated as percentages of emission reduction to achieve maximum acceptable N and P loads defined by Swan River Trust (2009) (Table 7). We define 5 targets with 20% increment (20%, 40%, 60%, 80%, and 100% of emission reduction from current level to maximum acceptable loads for both N and P, where the estimated current level of emissions represent a 0% reduction and the maximum acceptable load is a 100% reduction on current). For example, emission targets are 58.1 (0%), 53.3 (20%), 48.6 (40%), 43.9 (60%), 39.1 (80%), 34.4 (100%) tonnes/year for N emissions, and 4.5 (0%), 4.2 (20%), 3.9 (40%), 3.7 (60%), 3.4 (80%), 3.2 (100%) tonnes/year for P emissions. This means that the target reduction for N from the current modelled baseline, given as column 1 in Table 7, less the maximum acceptable load given as column 5 in Table 7, that is 58.07 minus 34.40, gives 23.67 tonnes/year. A 20% abatement is given as 20% of 23.67 which 4.73 tonnes/year.

The results are presented for three scenarios, summarised in Table 8. Scenario 1 is viewed as a feasible policy given, the current set of policy measured. It differs from Scenario 3 only with respect to the inclusion in Scenario 1 of the non-market benefits due to constructed wetlands. Scenario 1 has our preferred definition of net cost. However, Scenario 3 is a useful comparison for Scenario 1 as it gives an estimate of the present-value of costs to residents, developers and, critically, State and local government. Scenario 2, has the same net-cost function as Scenario 1, but it includes a ban on standard nitrogen fertilizers. This policy, which is not currently under consideration by the State government, has two advantages. First, it allows the nitrogen emission target to be almost achieved, with the set of abatement actions included in Scenarios 1 and 3 set at their maximum possible levels, it is infeasible. Second, it has elements of an efficient economic policy in that polluters pay more for their fertilizer and, through the price effect, are also likely to reduce demand for fertilizer.

The cost-effective solutions for the three scenarios are presented in Table A2.9. Column (C1) gives the emission reduction targets. Columns (C2) and (C3) show emissions for each target level.

Columns (C4) to (C6) give investment in structural abatements during the first decade of the planning horizon: namely infill of septic tanks, constructed wetlands, and imported fill on new developments. Columns (C7) to (C12) present average annual levels of abatement actions that are annual (recurrent) or periodic. Columns (C13) to (C15) gives costs: (C13) total capital cost; (C14) average annual cost of recurrent and periodic abatement measures over the first decade; (C15) is the net present cost of the policy net of any public benefits in perpetuity at a 5% discount rate.

The results are also summarised in Figure 6 which indicates the source of abatement in each scenario. Across all cases, septic tank infill gives the key policy for N abatement. In Scenario 2 banning standard fertilizer is a significant source of N abatement across abatement targets. In Scenario 2, the fertilizer ban substitutes for behaviour change. This policy shifts costs onto households, but this increase in cost may be slight as the quality of fertilizer applied by households is improved.



Note: Graphs (a) and (b) give the sources of abatement for N and P for Scenario 1, (c) and (d) for Scenario 3, where there is no amenity value of wetland and (e) and (f) for Scenario 2 where there is a ban on standard N fertilizer.

Figure 6: Nutrient reduction by abatement actions for Scenarios 1 to 3 and abatement levels.

Scenario 1

Scenario 1 allows all abatement actions except banning standard fertilisers, and it includes the amenity value of constructed wetlands. This scenario achieves only 60% of the reduction target for N. Under this scenario, for lower targets, the preferred abatement actions are constructed wetlands, slow release fertilisers on public open space, behaviour change, and infill of septic tanks. As the percent of the abatement target increases, abatement from behaviour change and septic tank infill increase. At the 80% and 100% target optimal solutions include imported fill on new development and application of Phoslock, which indicates that these are relatively expensive abatement actions.

Scenario 2

In Scenario 2, which allows banning standard fertilisers, maximum acceptable N load is nearly achieved with slightly lower present value of cost than the base case scenario (which also does not achieve the N target). Banning standard fertiliser is not selected at 20% of target. When it is selected, behaviour change and slow release fertilisers are not selected (by assumption – these are alternative actions). Banning standard fertilisers allows a higher target to be achieved because it is applied to more land uses and, unlike behaviour change, there is no dis-adoption. However, it requires the application of Phoslock to meet the P target.

Scenario 3

Scenario 3 is similar to Scenario 1 but it does not account for the amenity value of constructed wetlands. The implication is that constructed wetlands become less cost-effective and is not selected at the 20% of target. Instead the target is reached by the infill of septic tanks and higher levels of slow release fertilisers, and a low level of peri-urban agriculture recruited to the Fertiliser Partnership. The net present cost of abatement is 30% higher than Scenario 1.

Table 8: Summary of Scenarios 1 to 3.

	All actions except banning standard fertilizer	All actions including banning standard fertilizer	Costs are net of the non-market amenity value of constructed wetlands
Scenario 1	✓		✓
Scenario 2		✓	✓
Scenario 3	✓		

The results of this study are summarised in Figure 7 in terms of N emission abatement. Notably the emission costs are to a large extent driven by the requirements to reduce N emissions. As N and P tend to be applied and abated together, apart from Phoslock which only abates P and slow release fertilizer which is only available for N (in this model only coated urea is considered as a slow release fertilizer suitable for wide area application). N is the most difficult and expensive nutrient to remove. In fact the Scenario 1 and 3 action set it is not able to fully achieve the N abatement target. At low levels of abatement, septic tank infill, constructed wetlands and slow release fertilizer provide least cost abatement actions.

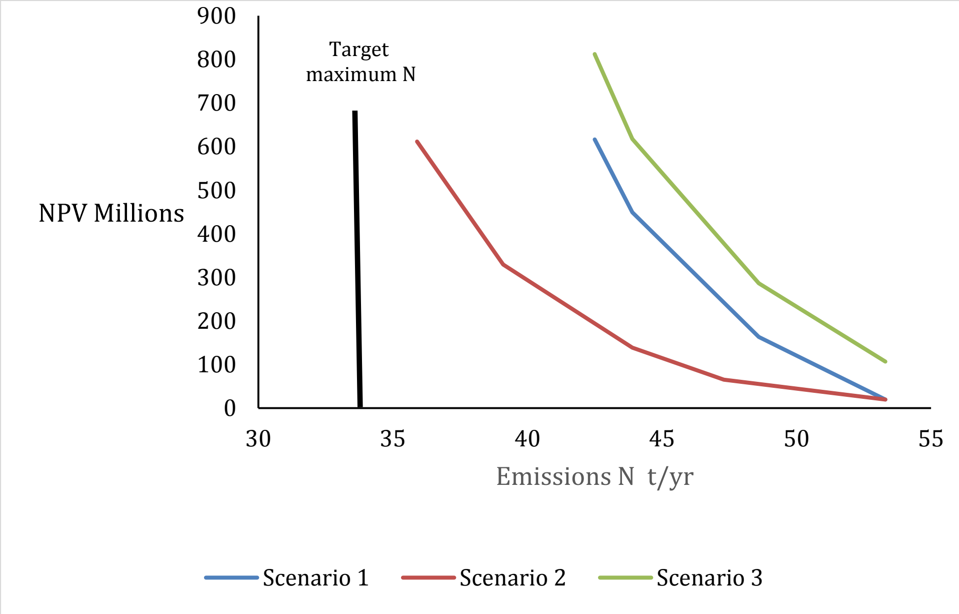


Figure 7: Abatement cost against nitrogen emissions.

4 Discussion and Conclusion

4.2 Discussion of results

Economic assessment of WSC technologies and regulation for Australian cities

Nelson (2011, p341) describes non-point source pollution as the "unfinished business of water quality regulation in Australia". This remains the case. As Australian cities spread into broadacre agricultural, horticultural and peri-urban agricultural land uses, agricultural NPSP emissions are replaced by urban-based NPSP emissions. This has been the pattern of development in the Canning Catchment over the last twenty years which has transitioned from a predominant livestock agriculture and forestry land use to peri-urban agriculture, horticulture and low density development to the current phase of high density urban development. A similar pattern has been identified for the Yarra Catchment in Victoria (Bessell-Browne, 2000).

To our knowledge this paper is the first to provide a systematic cost-effectiveness analysis of the management of nutrient emission in the Swan-Canning and one of the first to consider efficient abatement policy for an urban catchment. In contrast, there have been numerous studies of NPSP in agricultural catchments, see for instance Doole and Pannell (2012). The main difference between economic models of agricultural NPSP and urban NPSP is the importance of infrastructure investment and the large number of highly diverse agents in the urban environment.

Implications of adopting a cost-effective policy analysis

In many catchments the most cost effective policy is to address a NPSP problem in the upper agricultural region of the catchment and this is the case in the Swan-Avon and its sub-catchments where the largest proportion of nutrient emissions derives from relatively low value dryland broadacre agriculture and, within an effective regulatory framework,[2] the NPSP problem could be entirely addressed by low cost abatement by agriculture. The situation in the Canning catchment is different

[2] Could include a ban on highly soluble nitrogen fertilizer in sensitive zones, fencing creek lines to avoid stock entering creeks, using buffer strips along creek lines, reducing stocking rates and revegetating high emission areas (Hennig and Kelsey, 2015).

as the catchment is largely urbanised, thus there is some scope for reducing agricultural emissions, but most abatement of nutrient emission has to come from urban land uses.

Fully achieving the current emission targets is only possible with restrictive regulation of the consumer fertilizer market and regulations on local authorities and golf course use of conventional fast-release fertilizer.

The importance of the non-market values of WSC technologies

There is evidence that constructed wetlands and living streams provide non-market benefits to households in the catchment. As these developments tend to increase house prices they should be politically easier to implement than a ban on fertilizer. However, these schemes would represent a significant call on government funds. The cost of other policies, such as a ban on conventional fertilizer would be covered by households and local authorities.

Is the government expenditure on nutrient abatement in the Canning catchment of $811.8 million (present value of the cost in perpetuity, scenario 3) justified by the non-market benefits of nutrient abatement? A conservative estimate of the benefits of abatement derived from Rogers et al. (2012) , summarised in Section 2.6 above, is a willingness to pay (WTP) by the general public of $21.9 million per year by the residents of the Canning catchment. If this is converted to a WTP in perpetuity by dividing the annual WTP by the discount rate, here assumed to be 5%, then this gives us $438 million which may be viewed as a lower bound estimate as the population benefitting is restricted to the 354,017 residents of the Canning. If a 60% reduction in N and P is capable of achieving an average of one fewer fish kills per year in the Canning, then the policy is justified by the non-market benefit.

4.3 Discussion of future options

If the policy objective is to maintain nutrient emissions below critical levels that cause further degradation to the estuary, then the set of policy options included in the baseline scenario are not able to reach N abatement standards. The set of actions are those that are currently applied in the catchment. They use education, infrastructure projects and regulation of new developments through the planning process to include soil amendment to reduce emissions.

The high costs and limited efficacy of the current action set possibly requires a radical shift in the set of actions considered and the level of regulation applied to those land-uses responsible for the majority of emissions. Since the early 1990s there has been a shift towards considering so-called market-based policy instruments to address pollution problems (Productivity Commission, 2009). To date, incentive-based and polluter pays policies – market-based instruments - have played a relatively limited role in managing NPSP:

> *"In a situation characterized by … informational asymmetries, the environmental regulator cannot use the standard instruments of environmental policy, such as emissions taxes, tradable emissions permits, deposit-refund system"…*(Xepapadeas , 2011, p358)."

One way of avoiding the asymmetric information problem is to redefine the environmental target from being the nutrient emissions of individual economic agents, which are unobservable, to land-use, infrastructure, fertilizer product standards and ambient emissions (at DoW monitoring sites) all of which are observable. Further if the Department of Parks and Wildlife, for instance, assumes the role of catchment authority with regulatory powers over the whole Swan-Canning and Avon catchment, then it may be possible to give LGA's responsibility for improving the monitored emissions in their sub-catchments. For instance, City of Armadale would have responsibility for Southern River, City of Gosnells for a section of the Lower Canning and so on. Using the equivalent of the Land Fill Levy (Government of Western Australia, 2008) LGAs would be penalised for exceeding emission targets for their sub-catchments but would have flexibility in terms of how they reduce their own emissions on public open space and promote household behaviour change. If a LGA is unable to meet its emission targets for the sub-catchments that it is responsible for, then the catchment authority could allow the LGA to contribute to abatement projects in low cost agricultural catchments such as Ellen Brook and the Avon. Within the LGAs, the main target for initiatives should be to convert garden lawns and verges (for instance, City of Nedlands, 2017; Water Corporation, 2017) to native perennials through low cost subsidy schemes. In planning applications developers should be required to limit the turf area in initial garden packages. Evidence from an unpublished hedonic pricing study for Southern River indicates that reducing the lawn area to less than 50% of the garden area has a negligible effect on the value of property. The justification of alternative policies is that they reduce the cost of achieving nutrient abatement targets and therefore it is optimal for society to aim to achieve lower emission targets.

5 Summary

This paper reviews the recent history and roles of organizations in the management of NPSP in the Swan Canning. Pollution has been a long standing problem for the catchment. While considerable progress has been made in addressing point source pollution, NPSP remains a major threat to the ecological health of the lower catchment.

The cost-effectiveness analysis determines the least cost actions to abate N and P pollution in the Canning catchment. It finds the current range of actions are not able to meet the N abatement target, but can reach the P target. If a further policy of a ban on standard N fertilizer is introduced this makes the N abatement target achievable.

The cost of achieving target emission levels, given current polices, is around $800 million over a 20 year period (present-value of total government cost at 5%) and this represents a substantial government expenditure even when the cost is spread over a 20 to thirty year period. Alternative approaches that push more costs onto polluters might be considered. It is noted that current policies provide weak or no incentives for economic agents (households, farms, sporting clubs and LGAs) to take additional abatement actions. If incentive based schemes were introduced along with tighter regulation on the use of standard fertilizers then the government cost of achieving abatement targets could be reduced substantially making the long term management of the Canning Catchment less dependent on public funds and more ambitious abatement targets achievable.

Appendix 1 Theoretical Model

The social cost function related to nutrient emissions in an urban sub-catchment can be described by the following spatial-temporal optimization problem for a single pollutant. The objective is to minimize the net social cost of nutrient emissions:

$$J_{i,t}(e_{i,t}, e^h_{i,t}, I_{i,t}\, k_{i,t}) = c_s e_{i,t} + c_h\left(e^h_{i,t}\right) + I_{i,t} - b_i k_{i,t} \qquad i \in (us, ds),\; j \neq i, \tag{A1}$$

The linear social cost of nutrient emissions is given by $c_s e_{i,t}$ the social cost emissions $e_{i,t}$ in sub-catchment *i* at time *t*. The cost of abatement $c_h\left(e^h_{i,t}\right)$ is a function of emissions with the following properties. The baseline level of emissions $\hat{e}_i$ has a zero cost, thus $c_h\left(\hat{e}_i\right) = 0$ as emissions increase $c'_h\left(\hat{e}_i\right) \leq 0$, $c''_h\left(e_{i,t}\right) \geq 0$ and $e_{i,t} \in [0, \hat{e}_i]$. The term $e^h_{i,t}$ gives emissions from gardens by households. In this model recurrent emissions by households, local authorities and companies are treated in a similar way, but for simplicity only once source is considered. Capital investment in emission abatement infrastructure, such as constructed wetlands, is given by $I_{i,t}$, the social value of capital projects is given by $b_i k_{i,t}$ and is treated as a cost reduction.

If the social costs of emissions and the social benefit of investments are difficult to determine, the objective function can be recast as minimizing market costs subject to an emission target and this form of the model is used in the empirical optimization model as scenario 3. The objective function is:

$$J_{i,t}(e_{i,t}, e^h_{i,t}, I_{i,t}\, k_{i,t}) = c_h\left(e^h_{i,t}\right) + I_{i,t} \qquad i \in (us, ds),\; j \neq i,$$

Emissions are represented as the emission of households $e^h_{i,t}$ reduced by the nutrient removal effects of water infrastructure. Overall emissions in a sub-catchment during period *t* are defined as:

$$e_{i,t} = e^h_{i,t} - \alpha_i k_{i,t} + \tau_{j,i} e_{j,t} \qquad j \neq i$$

and the equation for capital formation is given by

$$k_{i,t} = I_{i,t} + \varphi k_{i,t-1}$$

where φ accounts for asset depreciation $0 \leq \varphi \leq 1$.

If there are two catchments an upstream (*us*) and downstream catchment (*ds*) ; $i \in \{us, ds\}$. The overall river regulator's problem over the two catchments is to minimise the value function $V[k_{i,0}]$ of an optimal policy from an initial vector of capital investments of $k_{i,0}$ over the planning horizon from *t=1,…,T*.

$$V[k_{i,0}] = Minimum\left[\sum_{i \grave{o} us,ds} \sum_{t=1}^{T} \delta^t J_{it}\right]$$

Subject to:

$$e_{i,t} = e_{i,t}^h - \alpha k_{i,t} + \tau_{j,i} e_{j,t}; \quad i, j \in \{us, ds\}; \quad i \neq j$$

$$k_{i,t} = I_{i,t} + \varphi k_{i,t-1};$$

where δ^t is a discount factor for time *t*.

This model and its empirical representation can be analysed in three different ways. First if there is reliable evidence on the market and non-market costs of emissions, then the optimal solution to (A1) could be derived. A number of studies have assessed non-market values for river pollution (Rogers et al 2012). These values are not, however, routinely used in policy design (Rogers et al. 2015) because the relevant non-market values are not available and can only be determined accurately by expensive survey methods.

The theoretical model can be applied in two other ways. Typically targets for emissions are set in the sub-catchments and a reasonable policy aim would be to achieve maximum emission targets at least cost

$$e_{i,t} \leq \bar{e}_{i,t} \qquad \forall i, t$$

The targets $\bar{e}_{i,t}$ could be fixed through time or varying depending on the capacity of the catchment to abate nutrients either through infrastructure investment or behaviour change. Both these forms of investment would reduce the cost of achieving maximum emission targets and this may induce the regulator to adopt more ambitious (tighter) targets. Another equivalent formulation of the regulators problem is to minimize cost for a given budget constraint.

Optimal Policy

In this subsection we present results for the direct optimisation of the social welfare function and show that the other forms of target constrained and budget constrained optimisation are related.

$$V[\mathbf{k}_0] = \sum_{i=us,ds} c_s e_{i,t} + c_h\left(e_{i,t}^h\right) + I_{i,t} - b_{i,t} k_{i,t} + \delta V[\mathbf{k}_1]$$

Where $V[\mathbf{k}_0]$ is a value function giving the least cost for a vector of initial capital investment across sub-catchments up to the end of the planning horizon *T*. If this function is rewritten to include the constraint equations it becomes for the downstream sub-catchment:

$$\begin{aligned} V[\mathbf{k}_0] = c_s\{ & e_{ds,1}^h + \tau_{us,ds}(e_{us,1}^h - \alpha_{us}(I_{us,1} + \varphi k_{us,0}) - \alpha_{ds}(I_{i,1} + \varphi k_{ds,0})\} + \\ & c_s\{e_{us,1}^h - \alpha_{us}(I_{us,1} + \varphi k_{us,0})\} + \\ & c_h\left(e_{ds,1}^h\right) + c_h\left(e_{us,1}^h\right) + I_{ds,1} + I_{us,1} \\ & - b_{ds} k_{ds,1} - b_{us} k_{us,1} + \delta V[\varphi \mathbf{k}_0 + \mathbf{I}] \end{aligned}$$

The first order conditions for recurring emission abatement through household behaviour change is :

$$c_s(1 + \tau_{i,j}) = -c_h^{'}(e_{i,t}^h) \qquad i, j \in \{us, ds\}; \quad i \neq j \qquad \text{(A2)}$$

That is emissions are reduced up to the point where the marginal benefit c_s of abatement adjusted for emission transfer in terms of reduced environmental cost equals the marginal cost of abatement $-c_h^{'}(e_{i,t}^h)$. This determines the optimal level of emissions in a catchment.

Using (A2) to substitute for c_s , relative emissions in the two catchments is given by:

$$(1+\tau_{i,j})/(1+\tau_{j,i}) = c_h^{'}(e_{i,t}^h)/c_h^{'}(e_{j,t}^h) \qquad i, j \in \{us, ds\}; \quad i \neq j; \quad \forall t \in 1,...,T \qquad \text{(A3)}$$

This gives the optimal condition for static recurrent abatement and indicates the optimal rate of substitution between emissions from different sub-catchments. With identical costs in each sub-catchment and, if transport coefficients between sub-catchments are zero $\tau_{i,j} = \tau_{j,i} = 0$, optimal emissions would be the same $e_{i,t}^h = e_{j,t}^h$ in all time periods. This marginal condition implies that optimal upstream emissions are less than downstream emissions due to the emission transport effect. For instance, if $\tau_{us,ds} > \tau_{ds,us}$ it follows that:

$$(1+\tau_{us,ds})/(1+\tau_{ds,us}) > 0 \Rightarrow -c_h^{'}(e_{us,t}^h) > -c_h^{'}(e_{ds,t}^h)$$

and the optimal solution is:

$$\hat{e}_{us,t}^h < \hat{e}_{ds,t}^h$$

Dynamic efficiency is defined by:

$$\alpha_i c_s (1+\tau_{i,j}) = 1 - b_i + \delta V_{I_i} \qquad \text{(A4)}$$

Substituting in for marginal social cost from (A2) gives:

$$-\alpha_{us} c_h^{'}(e_{us,t}^h) = 1 - b_{us,t} + V_{I_{us,t}} \qquad \text{(A5)}$$

The results (A5) gives the efficient substitution of structural abatement for recurrent abatement.

Efficient allocation between structural abatement across sub-catchments is given by:

$$\alpha_i (1+\tau_{i,j})/\alpha_j (1+\tau_{j,i}) = (1 - b_i + \delta V_{I_i})/(1 - b_j + \delta V_{I_j}) \quad i, j \in \{us, ds\}; \quad i \neq j; \quad \forall t \in 1,...,T \qquad \text{(A6)}$$

Dynamic efficiency entails that the marginal cost of investment, net of non-market benefits and adjusted for efficacy and transfer coefficients is equated across catchments.

In summary there are three efficiency conditions for either a cost minimizing, budget constrained or welfare maximizing catchment abatement plan. The first is (A3) which defines optimal static levels of recurrent abatement (emissions) across sub-catchment. Condition (A5) determines the optimal abatement between structural abatement and recurrent abatements. Finally (A6) determines the relative investment in structural abatement in different sub-catchments.

Appendix A2 Sub-catchment data

Table A2.1: Areas of land uses (ha) and number of septic tanks by catchments.

Land use	Catchments								Total
	Bannister Creek	Ellis Brook	Helm Street	Lower Canning	Munday/ Bickley Brook	Southern River	Upper Canning River	Yule Brook	
Residential, units	23.8	1.7	5.5	126.0	2.6	45.7	11.8	14.1	231.3
Residential <400 m^2	36.9	0.7	1.8	86.2	5.4	131.6	14.8	17.6	295.0
Residential 400-600 m2	132.7	2.8	6.6	145.1	51.5	446.2	7.7	92.7	885.3
Residential 600-730 m2	272.0	1.0	57.5	414.6	68.7	793.6	94.6	210.4	1,912.4
Residential 730 m^2- 1 ha	226.1	16.1	79.1	924.6	169.2	1,193.5	1,191.4	1,217.1	5,017.2
Residential block	41.1	55.9	0.0	92.9	407.9	2,146.5	2,072.0	640.4	5,456.7
Commercial	109.1	14.3	7.9	250.2	13.8	347.7	81.3	136.4	960.6
Industrial	551.9	3.3	7.6	81.8	345.6	395.5	26.5	494.6	1,906.9
Transportation	484.2	72.5	81.1	875.0	292.4	1,769.2	696.2	1,052.4	5,323.1
Mining	0.0	167.7	3.0	99.8	190.2	0.0	0.0	0.0	460.8
Development	3.1	17.6	5.0	71.3	6.1	1,642.4	5.7	36.1	1,787.3
Horticulture	0.0	37.4	0.0	102.8	268.0	0.0	704.9	28.7	1,141.9
Rural/agricultural	36.8	183.5	81.0	176.4	496.1	1,371.6	277.0	356.1	2,978.4
POS passive	162.5	22.7	32.5	247.9	37.4	295.0	65.4	173.1	1,036.4
POS active	25.7	5.3	7.9	89.3	10.1	106.9	38.6	33.2	316.9
Golf courses	56.3	0.0	0.0	0.7	0.0	88.3	153.5	58.4	357.2
Bush/native	175.4	586.9	228.8	821.8	4,934.4	4,049.1	9,256.7	1,008.5	21,061.6
Water	0.1	2.3	0.0	39.8	99.7	84.6	19.1	0.0	245.6
Drain	2.2	0.0	1.8	6.3	0.0	7.4	0.1	4.8	22.7
Total	2,340.0	1,191.8	607.0	4,652.7	7,399.2	14,915.0	14,717.2	5,574.6	51,397.4
Septic tanks, number	149	157	40	486	480	2119	3443	5236	12,110

Table A2.2: Nitrogen input, kg/ha/year.

Land use	Catchments							
	Bannister Creek	Ellis Brook	Helm Street	Lower Canning	Munday/ Bickley Brook	Southern River	Upper Canning River	Yule Brook
Residential, units	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Residential <400 m^2	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
Residential 400-600 m^2	91.1	91.1	91.1	91.1	91.1	91.1	91.1	91.1
Residential 600-730 m^2	100.6	100.6	100.6	100.6	100.6	100.6	100.6	100.6
Residential 730 m^2- 1 ha	74.2	74.2	74.2	74.2	74.2	74.2	74.2	74.2
Residential block	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2
Commercial	36.2	91.0	49.5	44.9	66.3	70.2	69.7	73.0
Industrial	3.1	0.9	4.8	4.0	2.9	4.4	4.0	4.0
Transportation	3.1	0.9	4.8	4.0	2.9	4.4	4.0	4.0
Mining	3.1	0.9	4.8	4.0	2.9	4.4	4.0	4.0
Development	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Horticulture	28.8	138.3	143.4	140.2	131.4	125.3	141.7	138.0
Rural/agricultural	71.0	70.6	71.0	71.0	71.0	71.0	71.0	71.0
POS passive	66.0	66.0	66.0	66.0	66.0	66.0	66.0	66.0
POS active	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0
Golf courses	159.0	159.0	159.0	159.0	159.0	159.0	159.0	159.0
Bush/native	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A2.3: Phosphorus input, kg/ha/year

Land use	Catchments							
	Bannister Creek	Ellis Brook	Helm Street	Lower Canning	Munday/ Bickley Brook	Southern River	Upper Canning River	Yule Brook
Residential, units	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Residential <400 m^2	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Residential 400-600 m^2	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8
Residential 600-730 m^2	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5
Residential 730 m^2- 1 ha	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
Residential block	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Commercial	9.5	21.9	12.6	11.5	16.2	17.0	17.1	17.7
Industrial	1.6	0.4	2.4	2.0	1.5	2.2	2.0	2.0
Transportation	1.6	0.4	2.4	2.0	1.5	2.2	2.0	2.0
Mining	1.6	0.4	2.4	2.0	1.5	2.2	2.0	2.0
Development	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Horticulture	5.3	122.3	127.6	124.3	115.0	108.4	126.0	97.4
Rural/agricultural	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7
POS passive	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
POS active	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Golf courses	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Bush/native	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A2.4: Nitrogen transmission rates

Land use	Catchments							
	Bannister Creek	Ellis Brook	Helm Street	Lower Canning	Munday/ Bickley Brook	Southern River	Upper Canning River	Yule Brook
Residential, units	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Residential <400 m^2	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Residential 400-600 m^2	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Residential 600-730 m^2	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Residential 730 m^2- 1 ha	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Residential block	0.075	0.030	0.050	0.021	0.025	0.026	0.013	0.010
Commercial	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Industrial	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Transportation	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Mining	0.120	0.030	0.065	0.033	0.038	0.041	0.021	0.017
Horticulture	0.075	0.022	0.050	0.021	0.025	0.041	0.013	0.010
Rural/agricultural	0.075	0.022	0.050	0.021	0.025	0.025	0.013	0.010
POS passive	0.080	0.022	0.050	0.021	0.025	0.026	0.013	0.010
POS active	0.080	0.022	0.050	0.021	0.025	0.026	0.013	0.010
Golf courses	0.080	0.022	0.050	0.021	0.025	0.026	0.013	0.010

Table A2.5: Phosphorus transmission rates

Land use	Catchments							
	Bannister Creek	Ellis Brook	Helm Street	Lower Canning	Munday/ Bickley Brook	Southern River	Upper Canning River	Yule Brook
Residential, units	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0040
Residential <400 m^2	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0040
Residential 400-600 m^2	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0040
Residential 600-730 m^2	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0040
Residential 730 m^2- 1 ha	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0040
Residential block	0.0240	0.0040	0.0016	0.0060	0.0010	0.0050	0.0025	0.0025
Commercial	0.0340	0.0040	0.0130	0.0180	0.0120	0.0220	0.0041	0.0050
Industrial	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0120
Transportation	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0120
Mining	0.0340	0.0040	0.0130	0.0180	0.0120	0.0230	0.0041	0.0120
Horticulture	0.0240	0.0003	0.0016	0.0020	0.0004	0.0020	0.0015	0.0018
Rural/agricultural	0.0240	0.0030	0.0016	0.0020	0.0004	0.0050	0.0025	0.0025
POS passive	0.0240	0.0030	0.0080	0.0120	0.0087	0.0200	0.0025	0.0025
POS active	0.0240	0.0030	0.0080	0.0120	0.0087	0.0200	0.0025	0.0025
Golf courses	0.0240	0.0030	0.0080	0.0120	0.0087	0.0200	0.0025	0.0025

Table A2.6: Nutrients inputs, transmission rates, and count of septic tanks by catchment

Catchment	N Input/ household, kg	P Input/ household, kg	N Rate	P Rate	Number of septic tanks
Bannister Creek	21.8	4.3	0.200	0.080	149
Ellis Brook	18.9	3.8	0.080	0.010	157
Helm Street	23.2	5.4	0.120	0.025	40
Lower Canning	15.3	3.1	0.090	0.040	486
Munday/Bickley Brook	16.2	3.2	0.090	0.010	480
Southern River	22.1	4.4	0.090	0.050	2119
Yule Brook	15.7	3.1	0.040	0.010	3443
Upper Canning River	14.3	2.9	0.040	0.010	5236

Table A2.7: Nutrient emissions by sub-catchment for the Canning Catchment

Catchment	Area (ha)	N Input (kg/yr)	P Input (kg/yr)	N export (kg/yr)	P export (kg/yr)	Total area (%)	Total N Export (%)	Total P Export (%)	N exports per ha	P exports per ha
Bannister	2357	106133	24221	1210	820	4.4	2.5	17.2	0.514	0.008
Ellis	1174	14805	7928	623	16	2.2	1.3	0.3	0.530	0.001
Helm	600	24922	6092	1645	66	1.1	3.5	1.4	2.740	0.003
Lower Canning	4430	245386	63465	7883	966	8.3	16.6	20.3	1.779	0.004
Munday/Bickley	7372	114468	43839	3727	136	13.9	7.8	2.8	0.506	0.001
Southern River	14950	564764	122413	21269	2209	28.1	44.7	46.4	1.423	0.004
Yule	7372	114468	43839	3727	136	13.9	7.8	2.8	0.506	0.001
Upper Canning	14891	400520	152612	7535	418	28.0	15.8	8.8	0.506	0.001
Total	53146	1585465	464410	47619	4766	100.0	100.0	100.0	0.90	0.00

Table A2.8: Land use by catchment (ha)

Catchment	Resident-ial	Hortic-ulture & Planta-tion	Recreati on	Viticultur e	Horses	Farm	Lifestyle block / hobby farm	Comm-rcial & edu-cation	Conser vation and natural	Indust-ry, manufa cturing and transpo rt	Total	% of area	% of high emitting land uses[1]
Bannister	534	6	109	0	1	0	89	146	361	1111	2357	4.6	37.5
Ellis	27	49	3	0	7	1	0	42	694	352	1174	2.3	10.4
Helm	141	8	11	0	0	48	38	13	262	79	600	1.2	43.2
Lower Canning	1437	78	279	2	17	0	163	217	1176	1062	4430	8.6	49.1
Munday/Bickley	171	255	53	20	17	78	506	59	5553	661	7372	14.4	15.2
Southern River	1608	174	399	4	212	1924	1145	400	7288	1797	14950	29.1	37.8
Yule	1296	88	237	0	60	74	755	192	1315	1553	5568	10.8	47.4
Upper Canning	1004	687	271	248	8	188	627	114	11271	473	14891	29.0	19.4
Total	6217	1345	1362	273	320	2313	3322	1183	27920	7088	51342	100.0	30.7
% of area	12.1	2.6	2.7	0.5	0.6	4.5	6.5	2.3	54.4	13.8	100.0		

Note 1: High emission land uses are residential, horticulture, and plantations, farms and Lifestyle block / hobby farm

Table A2.9: Combination of actions to achieve series of emission targets, average or sum over 1st decade

Target (% of)	Export N, t/yr	Export P, t/yr	Infill septic tanks, number	Constructed wetlands, ha	Imported fill on new development, ha	Behaviour change intensive, ha/yr	Behaviour change by phone, ha /yr	Ban regular fertilisers, 0/1	Fertiliser action plan, ha/yr	Slow release fertilisers, ha/yr	Phoslock, t/yr	Capital cost over 10 years, $M	Annual cost, $M/yr	Present value of cost, $M
(C1)	**(C2)**	**(C3)**	**(C4)**	**(C5)**	**(C6)**	**(C7)**	**(C8)**	**(C9)**	**(C10)**	**(C11)**	**(C12)**	**(C13)**	**(C14)**	**(C15)**
Base case scenario														
20%	53.3	4.0	1,089	94.7	0	566	169	No	0	1,240	0	197.4	2.1	19.7
40%	48.6	3.6	4,166	94.7	0	697	345	No	0	1,652	0	335.1	2.9	163.4
60%	43.9	3.3	10,689	94.7	8	1,135	29	No	0	1,711	0	609.3	5.0	448.9
80%	42.5	3.1	12,097	94.7	1,787	1,212	59	No	0	1,711	0	736.9	5.0	616.3
100%	42.5	3.1	12,097	94.7	1,787	1,212	59	No	37	1,711	0	736.9	5.0	616.3
Scenario: Ban regular fertilisers														
20%	53.3	4.0	1,089	94.7	0	566	169	No	0	1,240	0	197.4	2.1	19.7
40%	47.3	3.9	0	94.7	0	0	0	Yes	0	0	23.8	158.5	5.7	65.3
60%	43.9	3.7	1,928	94.7	0	0	0	Yes	0	0	17.2	239.3	5.7	138.7
80%	39.1	3.4	7,315	94.7	3	0	0	Yes	0	0	9.5	436.9	5.7	329.2
100%	35.9	3.2	12,097	94.7	1,787	0	0	Yes	0	0	10.1	736.9	5.7	611.5
Scenario: No amenity value of constructed wetlands														
20%	53.3	4.2	2,743	0.0	0	592	195	No	21	1,492	0	98.6	0.8	106.7
40%	48.6	3.7	5,920	21.8	3	710	298	No	0	1,659	0	268.9	1.7	286.2
60%	43.9	3.4	11,670	44.5	8	1,208	45	No	0	1,711	0	574.2	4.0	617.4
80%	42.5	3.2	12,097	91.1	1,787	1,235	35	No	0	1,711	0	730.9	4.3	811.7
100%	42.5	3.1	12,097	91.1	1,787	1,235	35	No	106	1,711	3.8	730.9	4.3	811.8

Notes: The total cost of capital (column 12) and the annual cost are given at current value.

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