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Designing Cost-Effective, Socially Acceptable Policy for Mitigating Agricultural Non-Point Source Pollution: *Cryptosporidium* risk in the Myponga Catchment

Bryan, B.A., Kandulu, J., Frizenschaf, J., White, M., Deere, D.A., Bradford, G, Ward, J.R., Proctor, W., Billington, K., Lewis, N., Bonnett, M. and Crossman, N.D.

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EXECUTIVE SUMMARY

Agricultural non-point source pollution in water supply catchments may have significant environmental and human health impacts and its mitigation poses a particularly difficult policy challenge. Water-borne pathogens such as *Cryptosporidium* pose a significant human health risk and catchments provide the first critical pollution 'barrier' in mitigating risk in drinking water supply. In this report we present a case study focussing on mitigating *Cryptosporidium* risk in the Myponga water supply catchment, South Australia. The case study involved a collaboration between:

- CSIRO
- SA Environment Protection Authority
- Adelaide and Mt Lofty Ranges Natural Resource Management Board
- SA Water
- DairySA
- Water Futures Pty Ltd.

The report documents the project in three stages. Stage 1 quantifies the major sources of *Cryptosporidium* risk and the effectiveness of adaptive management strategies. Stage 2 quantifies the cost-effectiveness of a range of catchment-based and treatment-based mitigation strategies. Stage 3 involves the design and sequencing of a mix of policy instruments for enhancing the widespread adoption of catchment-based water quality management by landholders.

In Stage 1, we apply an adaptive management framework to mitigating *Cryptosporidium* risk in source water in the Myponga catchment in South Australia. Firstly, we evaluated the effectiveness of past water quality management programs in relation to the adoption of practices by landholders using a socio-economic survey of land use and management in the catchment. The impact of past management on the mitigation of *Cryptosporidium* risk in source water was also evaluated based on analysis of water quality monitoring data. Quantitative risk assessment is used in planning the next round of management in the adaptive cycle. Specifically, a pathogen budget model was used to identify the major remaining sources of *Cryptosporidium* in the catchment and estimate the mitigation impact of 30 alternative catchment management scenarios. Survey results show that earlier programs have resulted in the comprehensive adoption of best management practices by dairy farmers including exclusion of stock from watercourses and effluent management from 2000 - 2007. *Cryptosporidium* concentrations detected in source water were found to have decreased since 2004, although causality has not been established. However, despite this improvement, *Cryptosporidium* detection rates at the reservoir inlet remain well above the desired target levels thereby necessitating further risk mitigation barriers, particularly at the treatment stage. By far, non-dairy calves were identified as the major remaining source of *Cryptosporidium* in the Myponga catchment. The impact of dairy cattle on *Cryptosporidium* oocysts exported to the reservoir was negligible owing to the widespread adoption of water quality management by dairy farmers. Other potential sources such as sheep, septic tanks and wastewater treatment are also likely to pose a negligible risk to water quality in Myponga. The results suggest that the restriction of watercourse access of non-dairy calves could achieve a further reduction in *Cryptosporidium* export to the Myponga reservoir of around 90% from current levels. The adaptive management framework applied in this study was useful in guiding learning from past management, and in analysing, planning and refocussing the next round of catchment management strategies to achieve water quality targets.

Under the multi-barrier paradigm, water quality management barriers that mitigate risk to consumers are required at multiple points from the catchment to the tap. We present a cost-effectiveness analysis of 13 catchment- and treatment-based management alternatives for mitigating Cryptosporidium risk in the Myponga water supply catchment, South Australia. A broad range of costs and benefits are identified and valued including set-up, operation and maintenance, and opportunity costs, and benefits for ecosystem services including water quality, biodiversity, carbon sequestration, and farm production services. The results suggest that the cost-effectiveness of investment in water quality management can be substantially enhanced by considering the costs of management and the benefits for ecosystem services. Cost-effectiveness of investment in management alternatives is dependent upon the desired level of Cryptosporidium removal effectiveness by both the catchment and treatment barriers. The combination of a spatially targeted 25% restriction in water course access of non-dairy cattle and treatment by enhanced coagulation provides the most cost-effective Cryptosporidium risk mitigation strategy. This combination may achieve 0.614 log-removal at a net cost of A$0.7 million and (net) cost-effectiveness of A$1.14 million per log-removal. Addition risk mitigation can be achieved through the addition of ultra-violet irradiation treatment, and higher levels of water course access restriction for cattle and the adoption of dung beetles in the catchment. Economic valuation of a range of costs and benefits of management priorities can support cost-effective water quality management investment decisions, and inform elements of policy design such as cost-sharing arrangements and spatial targeting.

Stage 3 involved the use of a deliberative multi-criteria evaluation (DMCE) process to design policy to address *Cryptosporidium* contamination in the Myponga catchment. Impediments to, and benefits of, adoption on-farm water quality management were identified using a landholder survey. These formed decision criteria in DMCE. The DMCE approach involved stakeholders in policy design during two community fora held in the catchment. Six policy scenarios were developed and their impact on decision criteria was quantified. The relative importance of decision criteria was quantified using swing weights and consensus was reached on the preferred policy scenario. The mix, sequence, and targeting of instruments in the preferred policy scenario was refined based on information obtained through the deliberative process. Important impediments to adoption included knowledge access, trainer/advisor proficiency, and financial resources. The recommended policy alternative involved targeted information, followed by an incentive program, and finally the regulation of a mandatory code of practice for water quality management. Detailed, catchment-specific context obtained through DMCE was critical for designing an effective mix and sequence of policy instruments.

1. INTRODUCTION

This report documents the methods and results of the project "Designing cost-effective, socially acceptable policy to achieve catchment level water quality objectives – a case study in the Mount Lofty Ranges Watershed". The main driver of the project was a perceived need for innovative ways to manage catchment-based risks to water quality. The project ran for 3 years from February 2006 to February 2009 and was a collaboration of 6 partner organisations:

- CSIRO
- South Australian Environment Protection Authority
- SA Water
- Adelaide and Mt Lofty Ranges Natural Resource Management Board
- Dairy SA
- Water Futures Pty Ltd.

The major funder was the National Action Plan for Salinity and Water Quality through the South Australian Centre for Natural Resource Management. Each of the partner organisations also contributed substantial resources to the project.

The original project aims were:

> *"…to demonstrate the application of a policy design framework (BDA Group and EconSearch, 2005) developed for addressing water quality issues in the Mt Lofty Ranges. This project will also build upon concurrent projects quantifying pathogen pathways in the region and setting management action targets for water quality. A case study will be undertaken in one of the high-risk catchments for drinking water quality impacts (Myponga). We aim to assess the economics of mitigation options, review policy options and impediments, and undertake a community consultative process to test community acceptability. Recommendations for a policy mix that is cost effective and socially acceptable for achieving water quality objectives will be made.*

The problem of *Cryptosporidium* contamination became the major focus of the project due to the exigency of the problem in the Myponga catchment. In fact, Myponga is known nationally for its water quality issues, particularly *Cryptosporidium*, and has been the focus of significant amounts of research and on-ground works to manage water quality. However, we also consider the impact of water quality management on a range of ecosystem services including other aspects of water quality (nutrients, sediment etc.), biodiversity and carbon sequestration related services.

The report documents the project in three stages. Stage 1 quantifies the major sources of *Cryptosporidium* risk and the effectiveness of adaptive management strategies. Stage 2 quantifies the cost-effectives of a range of catchment-based and treatment-based mitigation. Stage 3 involves the design of a mix and sequencing of policy instruments for enhancing the widespread adoption of catchment-based water quality management by landholders and with landholders. The outcome of this assessment is a cost-effective, socially acceptable mix and sequence of policy instruments that is most likely to improve the quality of source water entering the Myponga reservoir, and achieve a range of other ecosystem service benefits.

Versions of the three sections have also been submitted as manuscripts to scientific journals. The reader should consult the published papers as the authoritative source. The papers are:

Bryan, B.A., Kandulu, J.M., Deere, D.A., White, M., Frizenschaf, J., and Crossman, N.D. (in review). Adaptive management for mitigating *Cryptosporidium* risk in source water: A case study in an agricultural catchment in South Australia. Submitted to Journal of Environmental Management, October 2008.

Bryan, B.A. and Kandulu, J.M. (in review). Cost-effective alternatives for mitigating *Cryptosporidium* risk in drinking water and enhancing ecosystem services. Submitted to Water Resources Research, November 2008.

Bryan, B.A. and Kandulu, J.M. (in review). Designing a policy mix and sequence for mitigating agricultural non-point source pollution using deliberative multi-criteria evaluation. Submitted to Agriculture, Ecosystems and Environment, March 2009.

2. THE MYPONGA STUDY AREA

2.1 Geography and Land Use

The Myponga River catchment covers an area of approximately 123 sq km, situated 50 km south of Adelaide, South Australia (Figure 1). The Myponga reservoir in South Australia is the main source of filtered drinking water for more than 50,000 people in the southern coast area from McLaren Vale to Victor Harbor (Figure 1) and provides about 5% of the fresh water supply to the city of Adelaide with a population of over 1.1 million.

Figure 1. Location map of the Myponga study area within the Adelaide and Mt. Lofty Ranges region, South Australia.

The Myponga catchment has an average annual rainfall of approximately 724 mm. Average yield in the Myponga River is 7,507 ML/yr and flows are highly seasonal (Thomas et al. 1999). The Myponga reservoir has a capacity of nearly 28 GL and is entirely catchment fed. Hence, the quality of the source water entering the reservoir is largely influenced by the land use and land management practices in the catchment.

The upper catchment area consists of steep hills along the western boundary, changing to rolling hills on the eastern side of the Myponga River (Thomas et al. 1999). Topography in the mid-catchment area is predominantly undulating, with some lower lying marsh areas existing along the banks of the Myponga River. Thomas et al. (1999) document the disturbance of 90% of the original riparian vegetation in the Myponga catchment and the subsequent impact on ecological health and water quality of watercourses.

Broadscale grazing (mainly beef cattle and sheep, with some horses and deer) is the dominant land use in the Myponga catchment (61%). Most of these properties are hobby farms with a few larger commercial landholders. Native vegetation (13%) and dairying (13%) are also significant land uses by area (Figure 2, Figure 3). Recent trends in land use change include the conversion of significant areas of dairy farms to broadscale grazing (from 30% in 1998 (Thomas et al. 1999) to the 13% today).

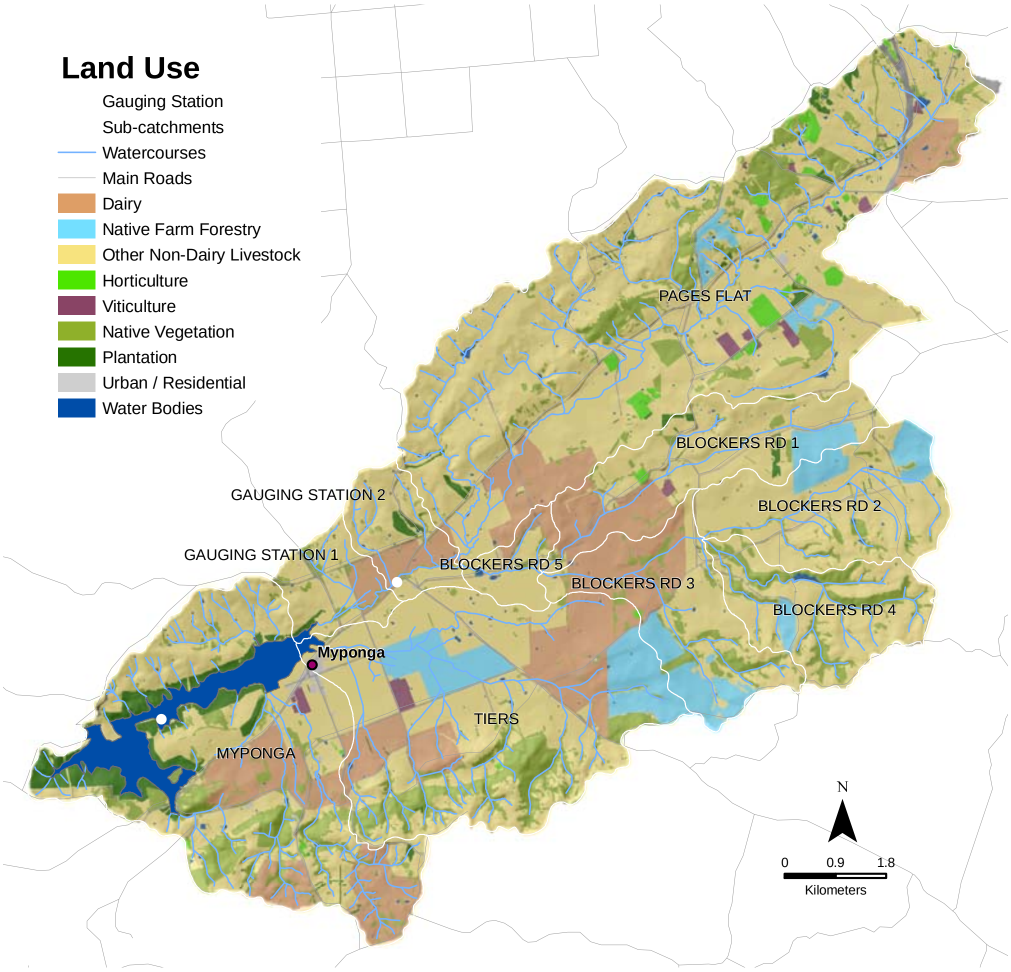

Figure 2. Land use map of the Myponga River catchment study area.

Figure 3. The landscape of the Myponga River catchment.

2.2 Water Quality Management

Management of wastewater in the catchment is a critical issue affecting the quality of source water entering the Myponga reservoir. For most dwellings wastewater is managed largely by on-site sewage management systems (OSMS). A small (0.3ML/day) wastewater treatment plant (WWTP) services the Myponga township (including 4 lagoons) and is located only a few hundred metres from the Myponga creek. Wastewater from this plant is used for irrigating an adjoining livestock grazing pasture.

SA Water (the South Australian Government water utility) is responsible for the quality of potable water provided to the majority of consumers in South Australia. For *Cryptosporidium*, SA Water has a target of 1 oocysts/L in source water with a long term aspiration to achieve 0 oocysts/L. SA Water has adopted the *multi-barrier* approach to achieve this water quality target in accordance with the Australian Drinking Water Guidelines (NHMRC 2004). The *multi-barrier* approach is widely accepted for managing water quality and recommends the provision of water quality protection mechanisms at multiple points from the *catchment* (where raw water is harvested) to the *tap* (or end consumer; NHMRC 2004).

SA Water uses as a guide the USEPA LT2 rule which requires a minimum of 99% removal efficiency of *Cryptosporidium* from raw water to create 'safe' drinking water. The Myponga Water Treatment Plant uses dissolved air floatation filtration and chlorination to treat raw water which has an estimated log removal capacity of *Crytosporidium* oocysts of around 3.5 (Betancourt and Rose 2004). Whilst 3.5 log removal is generally considered adequate for the treatment barrier, SA Water has, consistent with other water utilities around the globe, recognised the risk mitigation benefits in enhancing management across all barriers (Deere et al. 2001). However, the integrity of the Myponga reservoir as a barrier for pathogens has been shown to be compromised during large flow events due to the short-circuiting of inflowing water between the reservoir inlet and the reservoir off-take (Brookes et al., 2004). Hence, catchment-based source control measures are a key barrier in the Myponga catchment.

Over the past 10 years, the management of source water quality in the Myponga catchment has progressed through the problem recognition, analysis and planning, as well as the implementation stages in the management cycle. These are described in detail below:

Problem Recognition - Concerns have been raised about the quality of water sourced from the Myponga river catchment since 1998 including turbidity, nutrient loads, and contamination by *Cryptosporidium* and other pathogens.

Goal Setting – SA Water has established water quality targets for managing *Cryptosporidium* risk as discussed above.

Analysis and Planning – In a thorough assessment of catchment condition, Thomas et al. (1999) report that grazing and dairying has impacted upon 81% of the riparian zone in the Myponga catchment. Based on the catchment assessment and extensive consultation with landholders and other stakeholders, Thomas et al. (1999) identified unrestricted livestock access to watercourses as the greatest threat to water quality in the Myponga catchment.

Management Strategy - In the *Riparian Zone Management Plan* for Myponga (Thomas et al. 1999), the exclusion of stock from watercourse is the highest management priority in addition to the provision of off-stream water points and other complementary activities. Thomas et al. (1999) propose that landholders be supported in implementing these actions through agency funding and information provision.

Implementation - The Myponga catchment has been the focus of a number of initiatives aimed at monitoring and managing water quality. The South Australian Environment Protection Authority (EPA) and others including SA Water, the Adelaide & Mount Lofty Ranges Natural Resources Management Board (AMLR NRMB) and the dairy industry have been active in the catchment since 2000. The major water quality management work in the catchment has been the *Myponga Watercourse Restoration Project 2000-07* (EPA 2008), funded by the SA government. This program has invested more than $496,000 in on-ground water quality management works. A total of 40 landholders have been completing works at 62 sites including (EPA 2008):

- Fencing of approximately 24 km of creek using about 46 km of fencing
- Construction of 33 stock crossings
- Establishment of 22 off-stream watering points
- Removal of many hectares of blackberry, willows, and other woody weeds
- Planting of thousands of native plants (trees, shrubs, sedges and rushes)

2.3 Current Policy Context

The current policy context of the non-point source pollution problem in the Myponga water supply catchment includes:

Education and awareness: A *Land Management Program* is currently provided by the Adelaide and Mt. Lofty Ranges Natural Resource Management Board (AMLR NRM Board) and includes catchment-wide promotion of better land management but is not specifically focussed on pathogen contamination.

Incentives: Limited incentives are provided to the dairy industry by the South Australian Environment Protection Authority. The AMLR NRM Board also runs a modest incentives program called *Sustainable Landscapes* which has included negotiated payment and auction schemes (Connor et al. 2008b). Tax deductions are available for primary producers who undertake water quality management actions such as fencing and restricting livestock access to water courses and restoring riparian areas (ATO, 2008).

Regulation: Minimum environmental duty requirements exist. Regarding livestock in water courses the *Environment Protection Act 1993* general environmental duty (section 25) states that landholders have an obligation not to undertake an activity that may pollute the environment unless all reasonable and practicable measures are taken to minimise any environmental harm. Under the *Natural Resources Management Act 2004* section 131 states that a notice can be served on a landowner directing that specified action be taken to maintain a watercourse in good condition.

3. ADAPTIVE MANAGEMENT FOR MITIGATING *CRYPTOSPORIDIUM* RISK

3.1 Introduction

Traditional management of environmental issues involves the recognition of the problem and setting goals, analysing the problem and planning for management, developing a management strategy to fix the problem, implementing the management strategy, and monitoring and evaluating to determine whether goals have been achieved (Linkov et al. 2006). The adaptive management framework (Holling 1978, Walters 1986) includes an explicit learning and adaptation phase which is used to iteratively inform planning of the next round of management. Adaptive management provides a way of managing environmental systems despite the inherent uncertainty and in doing so, incorporates the previous outcomes of management intervention in a systematic process of 'learning while doing' (Lee 1999, Walters and Holling 1990, Linkov et al. 2006).

Adaptive management is often delineated into *passive* or *active* categories based on differences in the approach to learning (Walters and Holling, 1990; McCarthy and Possingham, 2007). Passive adaptive management implements a single preferred course of action based on the best available modelling and planning. Active adaptive management goes further in implementing a range of competing alternative courses of action framed as formal experimental treatments subject to rigorous (often statistical) evaluation. Passive adaptive management tends to be much simpler and less expensive than the active variant (Wilhere, 2002). However, learning is more limited under passive adaptive management because cause and effect relationships cannot be reliably established (Wilhere, 2002; Gregory et al., 2006b).

Recent reviews identify many theoretical studies that have developed the adaptive management framework for ecosystem management (NRC, 2004; Satterstrom et al., 2005; Gregory et al., 2006a; Linkov et al., 2006; McCarthy and Possingham, 2007). Many regulatory agencies have adopted adaptive management principles in their efforts to manage the interaction between human activity and ecosystems (WWF, 2001; USEPA, 2000, 2007; NOAA, 2008). Adaptive management principles have been invoked at the strategic planning stage in many environmental management domains including habitat restoration (Doyle and Drew, 2008), fisheries management (Rudd, 2004), species conservation (Wilhere, 2002), pest control (Shea et al., 2002) and water quality and quantity (Prato, 2003; Gregory et al., 2006b; Broderick 2008). However, despite the attractiveness of adaptive management and its learning by doing approach, there have been few successful practical applications of the adaptive management framework (Walters, 1997, Satterstrom et al., 2005; Gregory et al., 2006a; Linkov et al., 2006). Critiques have identified many potential problems with implementation of adaptive management primarily related to the capacity and conflicting priorities of stakeholders including scientists, policymakers and stakeholders, in complex jurisdictional and ecological settings (Gregory et al., 2006a). Whilst recent studies have made progress in correcting for these pitfalls (e.g. Broderick 2008), many well intentioned environmental management projects and programs have done little more than use adaptive management in name only due in large part to the difficulties associated with successful implementation described above (Gregory et al., 2006a).

In this study, we provide a practical application of the evaluation stage of a recently completed environmental management program and use this information in the planning stage of the second iteration of the adaptive management cycle to ultimately refocus and refine the management of significant residual issues. We present a case study of the management of the pathogen *Cryptosporidium* in source water entering a drinking water supply in the Myponga catchment in South Australia. *Cryptosporidium* is a parasitic protozoon that can potentially cause gastrointestinal illness in a wide host range including humans, cattle, and sheep is an issue of major importance in catchments supplying water for critical human needs (Baron et al. 2002, NHMRC 2004). The most significant sources of human-infectious *Cryptosporidium parvum* (hereafter simply *Cryptosporidium*) in source water include livestock such as cattle and sheep, especially young stock (Santin et al. 2004, Fayer et al. 2006), and human sources such as failing wastewater systems (Dechesne and Soyeux 2007, McDonald et al. 2008). *Cryptosporidium* shed by wildlife such as kangaroos is typically of a non-human-infectious genotype (Power et al. 2005).

We evaluate the effectiveness of a recently completed water quality management program, based on government-sponsored incentive payments, in motivating activities such as riparian fencing and livestock management by conducting a survey of current land use and management practices in the catchment. The impact of these actions in mitigating *Cryptosporidium* in source water entering the reservoir is assessed using water quality monitoring data. Survey data is then used to populate a pathogen budget model in a quantitative risk assessment of the remaining sources of *Cryptosporidium* in the catchment following the first round of management. Finally, a range of catchment management scenarios are assessed for their potential to mitigate *Cryptosporidium* export. The study provides a practical assessment of the utility of the adaptive management framework in structuring the formal evaluation and refocussing of management priorities in addressing a high priority environmental issue with potentially significant human health and economic implications.

3.2 Methods

In this study we evaluate a recently completed water quality management program in the Myponga catchment. This information is then used to inform analysis and planning for the second round of management actions thereby providing a practical example of an adaptive loop for the management of water quality. Figure 4 illustrates the progression of *Cryptosporidium* management through problem recognition, goal setting, analysis and planning, implementation, and monitoring in the Myponga catchment. In this study, a landholder survey forms the basis of the evaluation of water quality management in the Myponga catchment. The impact of catchment-based water quality management in mitigating *Cryptosporidium* risk is assessed using water quality monitoring data. The outcomes of the evaluation are used in the analysis and planning of the next round of catchment-based management priorities given the impact of previous activities. The major sources of *Cryptosporidium* in the catchment and the most effective management strategies are identified using a quantitative risk assessment.

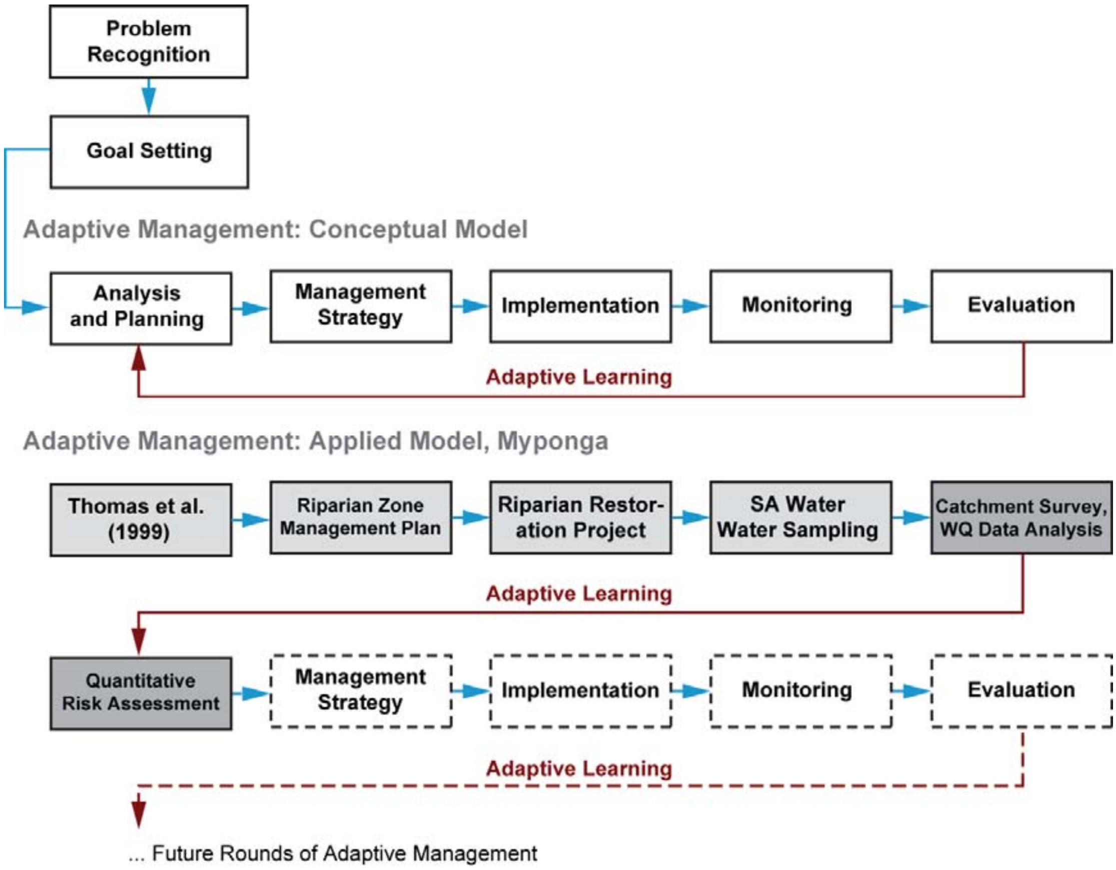

Figure 4. Conceptual model of adaptive management and the applied model as implemented in this study. Light grey boxes are past elements of the management cycle implemented since 1999. Darker grey boxes are presented in this study, and dashed boxes are future elements of the adaptive management cycle.

3.2.1 Landholder Survey

A face-to-face interview and survey of 36 landholders in the Myponga catchment was undertaken during January to April 2007. The survey included more than 50 questions on land use and management relevant to water quality including livestock type, numbers and proportion of juvenile stock, calving/lambing seasonality and management, extent of riparian fencing and setback distances, and seasonal periodicity in stream access by livestock. Dairy farmers were also asked extra questions about effluent and nutrient management practices. The landholder survey was used to quantify the adoption of water quality management practices, inform the evaluation of past management programs, and to parameterise the quantitative risk assessment with current land use and management information.

The survey included a full census of all 16 dairy farmers and a sample of other landholders including 13 broadscale graziers, 1 blue gum plantation owner, 2 horticulturalists, 1 equestrian property owner, and 3 lifestyle landholders. Participants were selected to provide roughly even geographic representation over the 10 sub-catchments (Figure 2). In terms of land area, properties owned and managed by the 36 surveyed landholders covered more than 60% of the Myponga catchment.

3.2.2 Water Quality Data Analysis

Assessment of *Cryptosporidium* oocysts in source water provides a fundamental indicator of the impact of catchment-based mitigation activities. Water quality testing for enteric protozoa in the Myponga catchment has been carried out by SA Water since 1998. Samples were taken near the gauging station (Figure 2) which captures run-off from 62% of the reservoir catchment area. Sampling is triggered by rainfall events rather than peak run-off events when *Cryptosporidium* export is expected to be highest (Signor et al. 2007). This sampling regime leaves some uncertainty around the peak oocyst concentration levels due to the time lag between rainfall and increased stream flow. Thus, the maximum risk of *Cryptosporidium* contamination of source water may be substantially higher than the water quality data suggests (Petterson et al. 2007). The annual median number of oocysts detected per 10 litres was calculated for the years 2000 – 2007 to assess the general trend of *Cryptosporidium* oocyst concentration over time.

3.2.3 Quantitative Risk Assessment

In analysing and planning for the next round of water quality management in the Myponga catchment the *Cryptosporidium* risk posed by all catchment sources needed to be estimated and the most effective catchment-based management strategies identified. Quantitative risk assessment has been found to be a useful tool for quantifying the risk posed by the range of potential catchment-based sources and prioritising effective pathogen management actions (Starkey et al. 2007, Sturdee et al. 2007, Goss and Richards 2008).

A variety of methods have been used in the catchment-based quantitative risk assessment of pathogens including Geographic Information Systems (Kistemann et al. 2001), object-oriented modelling (Elshorbagy et al. 2006), Bayesian methods (Hart et al. 2006), and numerical process models (Ferguson et al. 2007, Starkey et al. 2007). In this study, we used an established numerical process-based pathogen budget model (Ferguson et al. 2007) to estimate *Cryptosporidium* risk to source water in the Myponga catchment. The model was also used to estimate the *Cryptosporidium* mitigation benefits of a number of alternative management scenarios.

The pathogen budget model captures the key processes affecting the generation, fate and transport of microorganisms from humans and animals using data on land use and management, hydrological flows, and information on point sources such as sewage treatment plants and on-site systems (Figure 5). The pathogen budget is expressed in terms of the daily primary pathogen stock, daily dry weather flux deposited within and mobilised by streams, and daily wet weather flux being mobilised to, deposited within, and mobilised by streams.

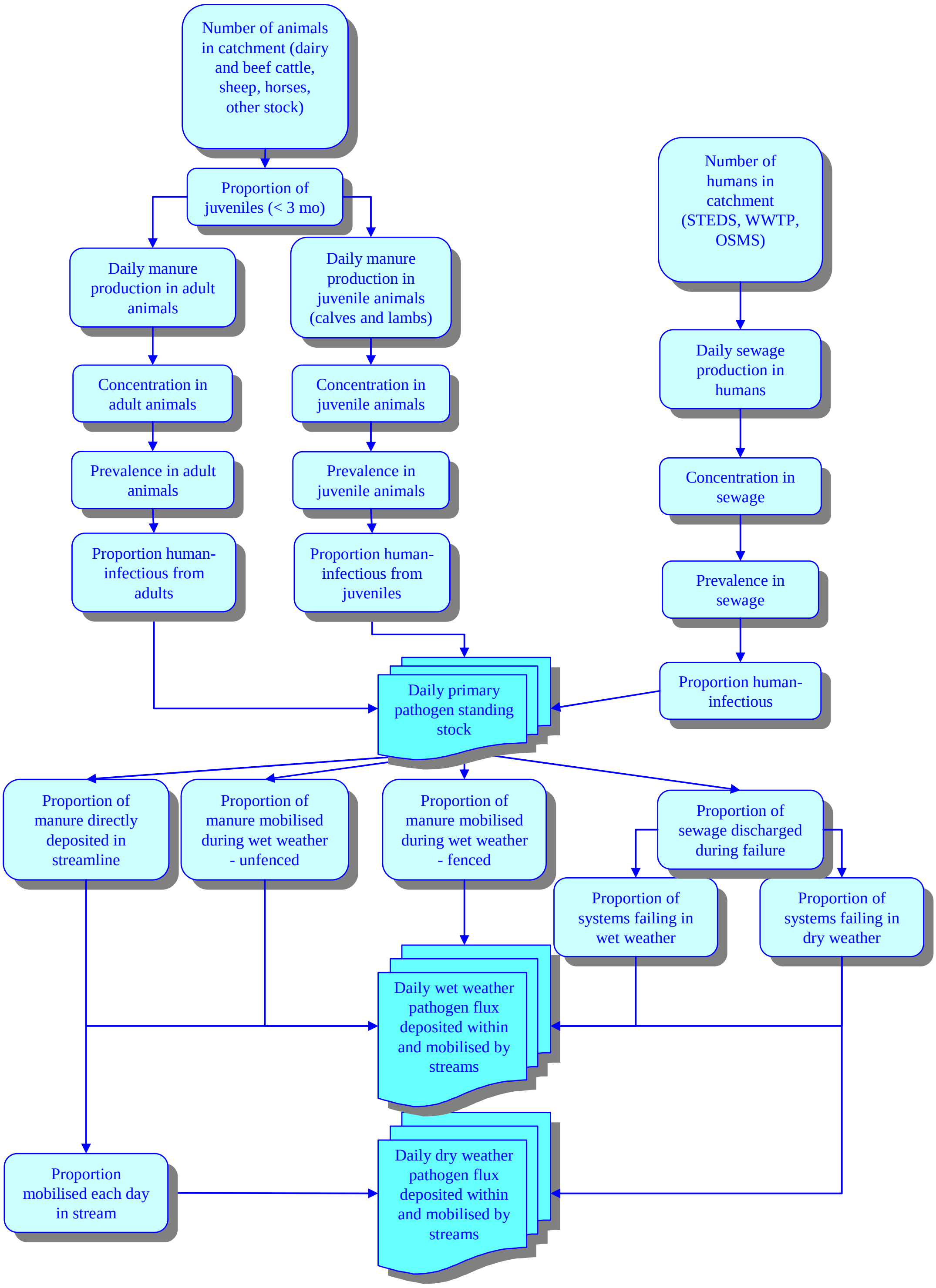

Figure 5. The structure of the pathogen budget model.

A baseline model was developed for the Myponga catchment which included all potential sources of human-infectious *Cryptosporidium* under current land use and management. The survey of land use and management was used as the primary data source to parameterise elements in the pathogen budget model complemented by a previous livestock survey, spatial information on land use and property boundaries, and other data. Catchment-level livestock management data was aggregated through integration of the survey data and extrapolation using spatial information (Table 1). The number of septic tanks was inferred from cadastral data by assuming a single septic tank for each individual property in the catchment outside of the township of Myponga which is serviced by the wastewater treatment plant. Failure rates for the wastewater treatment plant and on site septic tank systems were estimated (Table 1). Several other parameters and assumptions were required to populate the pathogen budget model for Myponga including oocyst shedding rates, export from land, transport through the catchment, and inputs to the reservoir (Appendix 1).

Source	Number of properties in catchment	Persons per property	Number of hosts present in catchment	Proportion of systems failing	Proportion of failing systems contributing to water courses during dry weather	Proportion of failing systems contributing to water courses during wet weather	Proportion with access to water courses
Sewered residential	105	2.5	263	1%	0%	100.0%	
Unsewered residential	456	2.5	1,140	50%	10%	50.0%	
Adult dairy cattle			3,101				95.0%
Dairy calves			1,102				2.7%
Adult non-dairy cattle			5,100				93.6%
Non-dairy calves			5,100				93.6%
Adult sheep			12,147				93.6%
Lambs			12,147				93.6%

Table 1 - Myponga-specific parameter values used in the baseline pathogen budget model.

Parameter	Value	Basis for selection	Reference	Certainty
Manure production rates per day (kg or L)				
Sheep	1.1	Consistent with other studies	ASAE 1999	High
Lamb	1	Only reference found	Dorner 2004	Medium
Beef cow	21	Consistent with other studies	ASAE 1999	High
Dairy cow	55	Consistent with other studies	ASAE 1999	High
Calf (dairy or beef)	5.6	Consistent with other studies	ASAE 1999	High
Horse or foal	23	Consistent with other studies	ASAE 1999	High
Human septic tank	375	Australian data, assumes 2.5 persons per system with 150 L per person	Charles et al 2004	High
Human or infant	0.2	Based on WHO study	Simpson-Hebert 2003	High
Manure deposition rates in stream				
Sheep or lamb	1%	Judgement	Judgement	Low
Beef cow or calf	3.4%	The only study found	Larsen et al 1994	Medium
Dairy cow or calf	3.4%	The only study found	Larsen et al 1994	Medium
Horse or foal	3.4%	Assume similar to cattle	Judgement	Low
Goat/deer/alpaca or juvenile	1%	Assume similar to sheep	Judgement	Low
Period required for suspension of manure input	5 days	Judgement	Judgement	Low
Baseline Cryptosporidium *concentration/g manure*				
Sheep	2,800	Large, long-term study	Sturdee et al 2003	Medium
Lamb	18,000	Large, long-term study	Sturdee et al 2003	Medium
Beef cow	1,371	Large, long-term study	Sturdee et al 2003	Medium
Dairy cow	1,778	Large, long-term study	Sturdee et al 2003	Medium
Calf (beef or dairy)	24,000	Large, long-term study	Sturdee et al 2003	Medium
Horse or foal	2,067	Large, long-term study	Sturdee et al 2003	Medium
Goat/deer/alpaca, adult or juvenile	2,800	No specific study, assume the same as sheep	Ferguson 2005, Davies et al 2005	Medium
Sewage (per L)	336	Total oocysts in raw sewage from Bolivar	Cunliffe D. pers comm	Medium
Human, adult or infant	2,000	Recent data	Medema 2001	Medium
Baseline Cryptosporidium *prevalence*				
Sheep	5.3%	Large, long-term study	Castro-Hermida et al 2007	Medium
Lamb	12.9%	Large, long-term study	Sturdee et al 2003	Medium
Beef cow	19.7%	Large, long-term study	Fayer et al 2006	Medium
Dairy cow	19.7%	Large, long-term study	Fayer et al 2006	Medium
Calf (beef or dairy)	50.3%	Large, long-term study	Santin et al 2004	Medium
Horse or foal	8.9%	Large, long-term study	Sturdee et al 2003	Medium
Sewage	100%	For sewage rather than individual humans; represents a population average	D. Cunliffe pers comm. (SA DHS)	Medium
Baseline Cryptosporidium *human infectious proportion*				
Sheep	1.0%	U. Ryan pers. comm. (Murdoch Univ)	Expert judgement	Low
Lamb (< 3 months old)	70%	U. Ryan pers. comm. (Murdoch Univ)	Expert judgement	Low
Beef cow	0.7%	Large, long-term study	Fayer et al 2006	Low
Dairy cow	0.7%	Large, long-term study	Fayer et al 2006	Low
Calf (beef or dairy; < 3 months old)	85%	Large, long-term study	Santin et al 2004	Low
Horse	1%	Assuming same as adult stock	Judgement	Low
Goat/deer/alpaca	1%	Assuming same as adult stock	Judgement	Low
Sewage	100%	All will be of human infectious genotype	Judgement	High
Human	100%	All will be of human infectious genotype	Judgement	High
Baseline manure mobilisation rates				
Manure deposited within connected source areas	3.4% (cattle) 1% (sheep)	Based on field surveys	Larsen et al 1994	Low
Cryptosporidium mobilisation from land in the absence of riparian fencing and vegetation cover	0.5%	Recent Australian data	Ferguson 2005	Medium
Cryptosporidium mobilisation from land with riparian fencing with > 2.5 m setback and good vegetation cover	0.001%	Recent Australian data	Ferguson 2005	Medium
Baseline sewage system failure rates				
Proportion of sewer pump stations failing and connected during dry weather	1%	Based on estimated failure rates from local experience rather than hard data	Local data	Medium
Proportion of sewer pump stations failing and connected during wet weather	100%	Based on estimated failure rates from local experience rather than hard data	Judgement	Low
Proportion of load reaching stream when sewer pump stations are failing and connected	100%	Since there is no possibility of on-site retention some excess sewage will discharge direct	Judgement	High
Proportion of load reaching stream when OSMS are failing and connected	50%	There is a possibility of some on-site retention	Judgement	Low

Table 2 - Table of parameters used in the pathogen budget modelling.

Scenario analysis was then used to assess the impact of a range of management actions in the catchment in mitigating *Cryptosporidium* export to the reservoir. A range of actions have been identified for managing human-infectious *Cryptosporidium* risk including the management of livestock access to watercourses (Goss and Richards 2008), in particular young stock such as calves and lambs (Starkey et al. 2007, Sturdee et al. 2007). Management of agricultural waste (Fricker and Crabb 1998, Monaghan et al. 2008) and human waste (Ferguson et al. 2003) have also been recognised as effective for mitigating *Cryptosporidium* risk in surface water supplies. Hence, in this study a range of scenarios were selected to cover the range of *Cryptosporidium* management possibilities.

A total of 30 management scenarios were specified after consultation with stakeholders during a widely publicised community forum held in the township of Myponga. The forum was attended by four project team members and 17 community members representing dairy, beef, sheep, and horse industries, and the Fleurieu Group of the AMLR NRM Board.

Management scenarios included the mitigation impact of managing septic tank failures and wastewater treatment plant outputs, as well as limiting livestock access to watercourses. Wastewater scenarios involved selected combinations of halving and eliminating *Cryptosporidium* contribution of OSMS and the WWTP in dry and wet weather. Livestock management scenarios were stratified into three livestock types (dairy cattle, non-dairy cattle, sheep), three livestock age cohorts (all animals, adult stock, young stock), and two levels of watercourse access restrictions (50% access, 5% access). A final scenario of widespread adoption of dung beetles was also assessed.

In scenario analysis the baseline pathogen budget model parameter values were varied to estimate the effect of management actions on reducing *Cryptosporidium* export. The mitigation impact of catchment management scenarios were reported relative to the baseline model by log removal and a measure of effectiveness (% change from baseline).

3.3 Results

3.3.1 Evaluation of Past Catchment Management Programs

All dairy farmers reported that they had fenced off their perennial watercourses but 50% of dairy farmers still allowed stock some access. In comparison, only 35% of other landholders reported that they had fenced off perennial watercourses and over 95% still allowed stock some access.

The exclusion of young stock from water courses was particularly well practiced by dairy farmers with only one respondent allowing calves direct access to the creek and 62% of dairy farmer respondents excluding stock by at least 10 metres from watercourses. Other landholders displayed very different calf management practices with more than 90% reporting that calves had direct access to watercourses.

All dairy farms in the catchment have milkshed effluent systems in place that have been audited for regulatory compliance by the SA Environment Protection Authority. There are a number of different types of effluent system being utilised, many of which require regular spreading of effluent due to low storage capacity. The most widely used system is the double lagoon, which generally have sufficient capacity to store effluent produced during wet periods. However, the second most common system - the pit pump sprinkler, requires immediate irrigation. The winter storage of dairy effluent was surveyed and while 49% of dairies store their effluent for at least 1 month during winter, providing the ability to avoid spreading during or preceding rain events, 25% do not or cannot store their effluent at all during wet weather. These farmers reported that the effluent is spread over high, sandy ground away from watercourses in an effort to reduce runoff and for ease of access with the spreader.

Water quality sampling results from 2000 to 2007 show that SA Water's aspirational *Cryptosporidium* concentration level of 0 cells/10L in source water has been exceeded 100% of the time as detected at the inlet of the Myponga reservoir (Figure 6). Between 1 July 2001 and 30 June 2004, 51 water quality related incidents have been reported, 40 of which have been linked to the detection of *Cryptosporidium* at the inlet to the reservoir. The annual median oocyst concentration in samples increased from 2.55 oocysts/10L in 2000, peaked at 8.0 oocysts/10L in 2003/04, and since then has decreased to 5.0 oocysts/10L in 2007 (Figure 6).

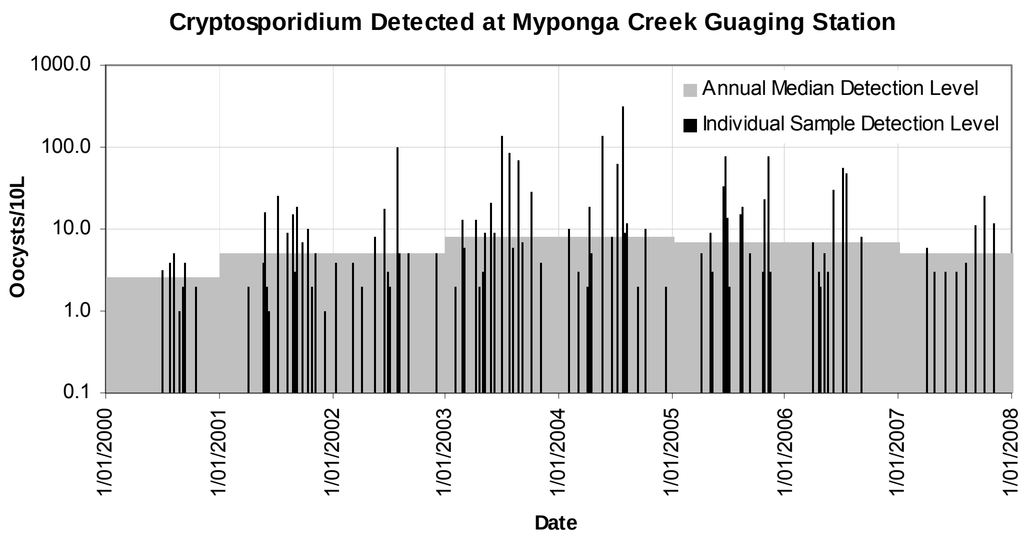

Figure 6. Cryptosporidium oocyst concentration in source water detected at the Myponga Creek gauging station from 2000 to 2008.

3.3.2 Adaptive Learning

In summary, most dairy farmers were found to practice stock and effluent management to minimise pathogen contribution to waterways. In terms of high risk pathogen management, dairy farmers were found to limit the access of young stock to watercourses whilst non-dairy landholders did not. The decline in annual median oocyst concentration since 2004 coincides with the ongoing catchment management activities occurring in the catchment over the past 10 years. Although a causal relationship cannot reliably be established, the monitoring data may reflect an initial beneficial impact of past catchment management programs on *Cryptosporidium* export. The results may also be influenced by a number of other factors such as land use change, uncertainty related to the current sampling method (rainfall rather than runoff–triggered), or changes in runoff patterns. Despite these reductions since 2004, oocyst levels still exceed SA Water targets and exert ongoing pressure on the treatment system as a reliable mitigation barrier. Hence, *Cryptosporidium* concentrations in source water pose an ongoing health risk to consumers.

An opportunity exists to further reduce *Cryptosporidium* export to the Myponga reservoir through catchment-based management activities in a second round of the adaptive management cycle. Modelling and analysis is required to quantify the contribution of remaining sources to *Cryptosporidium* export and then to evaluate the potential positive impacts on water quality from managing these sources. The results of these analyses may then inform the next round of planning and help identify the most effective management strategies in the adaptive management cycle.

3.3.3 Analysis and Planning of the Next Round of Catchment Management

Under baseline land use and management conditions the pathogen budget model outputs suggest that almost all of the total human infectious *Cryptosporidium* stock in Myponga catchment is generated by non-dairy calves (78%), dairy calves (17%) and lambs (5%). Negligible *Cryptosporidium* oocyst stock is generated by adult livestock or other sources such as OSMS and WWTW (Table 3).

Under the baseline conditions the model estimates that only about 1.4% of the total stock is exported to the Myponga reservoir with around 65% of the exported stock occurring in wet weather (Table 3). Overwhelmingly, the most significant source of human infectious *Cryptosporidium* exported to the Myponga reservoir is non-dairy calves which account for 97% of that exported in dry weather and 95% in wet weather (Table 3). Lambs are the next highest source of *Cryptosporidium* exported at 4% and 2% in wet and dry weather, respectively. The only other significant source of *Cryptosporidium* export is dairy calves (Table 3).

Source	Total infectious oocyst stock	%	Dry Exports	%	Wet Exports	%	Risk Rank
Non-dairy calves	2.93E+11	78%	1.87E+09	97%	3.24E+09	95%	1
Lambs	1.97E+10	5%	3.70E+07	2%	1.29E+08	4%	2
Dairy calves	6.33E+10	17%	1.17E+07	1%	2.09E+07	1%	3
Unsewered residential	5.75E+07	0%	2.87E+06	0%	1.44E+07	0%	4
Adult dairy cattle	5.97E+08	0%	3.86E+06	0%	6.70E+06	0%	5
Adult non-dairy cattle	2.89E+08	0%	1.84E+06	0%	3.20E+06	0%	6
Sewered residential	1.32E+07	0%	1.00E+00	0%	1.32E+05	0%	7
Adult sheep	1.98E+07	0%	3.71E+04	0%	1.30E+05	0%	8
Total	**3.77E+11**	**100%**	**1.92E+09**	**100%**	**3.41E+09**	**100%**	

Table 3 - Total daily stock of human infectious *Cryptosporidium* oocyst generated and exported in the Myponga River Catchment including a relative ranking of sources.

Assessment of management scenarios suggests that the vast majority of the possible reduction in *Cryptosporidium* oocysts exported to the Myponga reservoir (91.8% in wet weather and 89.7% in dry weather, Scenario 18 Table 4) could be achieved through restricting watercourse access of non-dairy calves to 5%. Only slightly greater mitigation benefit (91.9% in dry weather and 89.8% in wet weather, Scenario 20 Table 4) could be achieved through restricting watercourse access of all non-dairy cattle to 5%. A small further benefit in *Cryptosporidium* export (93.7 in dry weather and 93.4 in wet weather, Scenario 24 Table 4) can be achieved through restricting the watercourse access of all non-dairy stock (including sheep) to 5% (Table 4). Roughly half of this reduction in *Cryptosporidium* export (around 45%) can be achieved by restricting stock watercourse access to 50% rather than 5% (Scenarios 17, 19 & 23 Table 4).

The widespread adoption of dung beetles leading to 50% less manure available for export (Scenario 31 Table 4) could lead to a 21.7% reduction in *Cryptosporidium* export in wet weather due to the reduction in manure available for transport into watercourses during wet weather. No benefit is achieved in dry weather because dung beetles do not alter rates of direct defecation into watercourses by livestock.

A number of other scenarios had very small positive benefits in mitigating *Cryptosporidium* export in the Myponga catchment. Restricting sheep (Scenario 26) and lamb (Scenario 30) watercourse access to 5% results in a 3.6% reduction in wet weather and only about half this benefit during dry weather (Table 4) due to the preference of sheep to spend less time in watercourses compared to cattle.

Management of OSMS and WWTW compliance would have only a very minor effect (<0.4%) on *Cryptosporidium* export to the Myponga reservoir (Table 4). A number of the dairy cattle and calf management scenarios involved setting watercourse access rates to levels higher than are currently found in the Myponga catchment and this results in a net increase in *Cryptosporidium* export (represented by negative removal and effectiveness figures in Table 4).

ID	Management Scenario	***Cryptosporidium* Export** (Log$_{10}$ oocysts /day)		**Removal** (Log$_{10}$ oocysts /day)		**Removal Efficiency** (%)		**Rank**
		Dry	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	
1	Baseline	9.28	9.53	0.00	0.00	0.0	0.0	**22**
OSMS and WWTW Management Scenarios								
2	Halving of dry weather OSMS inputs	9.28	9.53	0.00	0.00	0.0	0.0	**22**
3	Eliminating dry weather OSMS inputs	9.28	9.53	0.00	0.00	0.1	0.0	**20**
4	Halving of wet weather WWTW inputs	9.28	9.53	0.00	0.00	-0.1	0.0	**27**
5	Eliminating wet weather WWTW inputs	9.28	9.53	0.00	0.00	-0.1	0.0	**25**
6	Halving of both dry and wet weather OSMS inputs	9.28	9.53	0.00	0.00	0.0	0.2	**17**
7	Eliminating both dry and wet weather OSMS inputs	9.28	9.53	0.00	0.00	0.1	0.4	**14**
8	Halving of both dry and wet weather OSMS inputs and halving wet weather WWTW inputs	9.28	9.53	0.00	0.00	0.0	0.2	**16**
9	Eliminating both dry and wet weather OSMS inputs and eliminating wet weather WWTW inputs	9.28	9.53	0.00	0.00	0.1	0.4	**13**
Dairy Cattle Management Scenarios								
10	Setting adult and juvenile dairy stock access to watercourses to 50%	9.33	9.58	0.04	0.04	-10.6	-10.3	**30**
11	Setting adult and juvenile dairy stock access to watercourses to 5%	9.29	9.53	0.00	0.00	-0.4	-0.3	**28**
12	Reducing adult dairy stock access to watercourses to 50%	9.28	9.53	0.00	0.00	0.0	0.1	**18**
13	Reducing adult dairy stock access to watercourses to 5%	9.28	9.53	0.00	0.00	0.1	0.2	**15**
14	Setting dairy calf stock access to watercourses to 50%	9.33	9.58	0.04	0.04	-10.7	-10.3	**31**
15	Setting dairy calf stock access to watercourses to 5%	9.29	9.54	0.00	0.00	-0.6	-0.5	**29**
16	Reducing juvenile dairy stock access to watercourses to zero	9.28	9.53	0.00	0.00	0.5	0.6	**12**
Non-Dairy Stock Management Scenarios								
17	Reducing all non-dairy stock access to watercourses to 50%	9.02	9.27	-0.27	-0.27	46.1	46.0	**4**
18	Reducing all non-dairy stock access to watercourses to 5%	8.08	8.35	-1.20	-1.18	93.7	93.4	**1**
Non-Dairy Cattle Management Scenarios								
19	Reducing all non-dairy cattle access to watercourses to 50%	9.02	9.28	-0.26	-0.25	45.2	44.2	**5**
20	Reducing all non-dairy cattle access to watercourses to 5%	8.19	8.54	-1.09	-0.99	91.9	89.8	**2**
21	Reducing non-dairy adult cattle access to watercourses to 50%	9.28	9.53	0.00	0.00	0.0	0.0	**21**
22	Reducing non-dairy adult cattle access to watercourses to 5%	9.28	9.53	0.00	0.00	0.0	0.1	**19**
23	Reducing non-dairy calf access to watercourses to 50%	9.02	9.28	-0.26	-0.25	45.2	44.2	**6**
24	Reducing non-dairy calf access to watercourses to 5%	8.20	8.54	-1.09	-0.99	91.8	89.7	**3**
Sheep Management Scenarios								
25	Reducing all sheep access to watercourses to 50%	9.28	9.53	0.00	-0.01	0.8	1.8	**10**
26	Reducing all sheep access to watercourses to 5%	9.28	9.52	-0.01	-0.02	1.7	3.6	**8**
27	Reducing adult sheep access to watercourses to 50%	9.28	9.53	0.00	0.00	-0.1	0.0	**26**
28	Reducing adult sheep access to watercourses to 5%	9.28	9.53	0.00	0.00	-0.1	0.0	**24**
29	Reducing lamb access to watercourses to 50%	9.28	9.53	0.00	-0.01	0.8	1.8	**11**
30	Reducing lamb access to watercourses to 5%	9.28	9.52	-0.01	-0.02	1.7	3.6	**9**
Other Management Scenarios								
31	Universal adoption of dung beetles leading to 50% reduction in available manure for export	9.28	9.43	0.00	-0.11	-0.1	21.7	**7**

Table 4 - Daily *Cryptosporidium* export (Log$_{10}$) under the baseline and management scenarios showing mitigation efficiency (% reduction in daily oocyst export) of management scenarios during dry and wet periods for the Myponga catchment.

3.4 Discussion

In Myponga, the management of *Cryptosporidium* in source water has progressed through the problem recognition and target setting in the late 1990s. The catchment assessment of Thomas et al. (1999) and the revelation of unacceptably high *Cryptosporidium* levels through ongoing water quality sampling by SA Water since the late 1990s spurned substantial attention to the management of source water quality in the Myponga catchment, in particular through the Myponga Watercourse Restoration Project.

This case study of water quality in the Myponga catchment documents a shift from traditional management to passive adaptive management. In this case study the passive approach to adaptive management, rather than the active variant, was adopted because of two factors. Firstly, given the identification of a single management action likely to reduce the vast majority of *Cryptosporidium* export it was hard to justify devoting scarce effort and investment on other actions likely to be far less effective. Second, the passive approach is far simpler and problem-oriented than the more science-focussed hypothesis-testing associated with active adaptive management (Wilhere 2002, McCarthy and Possingham 2007). The simpler approach was necessary to encourage community engagement and therefore to get management actions happening on-ground – a key factor identified in the success of adaptive management (Broderick 2008). Active adaptive management was considered to pose too high a risk in getting both the community and policy makers off-side (Gregory et al. 2006a) and jeopardising the impact of the research on improving in water quality and associated human health. Passive adaptive management provided an acceptable middle ground between the potential contribution of science and the exigency of managing water quality.

In the evaluation of past management programs our survey results suggested that the implementation of source water quality management programs led to the widespread adoption of best practice livestock management in relation to watercourses, effluent management and other practices by dairy farmers. However, low rates of adoption were found amongst other landholders. The differential rates of adoption in management could in part be explained by the greater organisational strength and structure of the dairy industry and the long involvement of the dairy industry in changing management practices of individual landholders. Non-dairy landholders including the beef cattle industry, sheep graziers, horse owners, lifestyle properties and hobby farmers are a more diffuse group. Hence, the elements that may enhance the adoption of water quality management including best-practice management guidelines, industry standards, information distribution, and regulatory controls are not as well developed amongst this landholder group.

The analysis of water quality sampling data suggests that median *Cryptosporidium* concentrations in source water peaked in 2003/04 and have been in decline since. This may be a sign that past management actions and land use change are starting to have some effect. However, whilst some improvement can be seen, water quality targets have not been achieved for *Cryptosporidium* in Myponga. Similar general improvements in water quality have been found elsewhere following livestock management, including a decrease in dairying land use and adoption of effluent management (Wilcock et al. 2006, Goss and Richards 2008, Monaghan et al. 2008). Wilcock et al. (2006) describe some improvement to a range of water quality parameters following management activities and land use change in the Toenepi catchment in New Zealand. However, substantial additional management was required in Toenepi to reach water quality targets as it is in Myponga. Hence, the need for and benefit of adaptive management in refining, refocussing and reinvigorating catchment management is evident.

The profound learning that occurred following evaluation was that management actions can lead to an improvement in resource condition – an outcome often speculated but seldom illustrated empirically. Whilst cause and effect can not be statistically established in passive adaptive management such as that implemented here (Wilhere, 2002; Gregory et al., 2006b), the coincidence of substantial effort in watercourse management and a decrease in median oocyst concentration is encouraging. This coincidence and the good agreement of water quality sampling and subsequent water quality modelling (EPA 2008) both reinforces to scientists that managing the watercourse access of livestock is heading along the right track for managing *Cryptosporidium*, and encourages landholders who see their efforts having some impact.

In the analysing and planning the next round of management in the adaptive management cycle non-dairy calves were identified as the predominant source of *Cryptosporidium* export due to both their greater number and the lack of management in relation to watercourse access. By far the greatest reduction (93%) in *Cryptosporidium* export to the Myponga reservoir was achieved when the watercourse access of calves was restricted. These results are in good agreement with Starkey et al. (2007) who found that a similar order of magnitude effect could be produced by managing pre-weaned calves in the Catskill/Delaware catchments, and similar studies elsewhere (Goss and Richards 2008). The next step is to develop a management strategy with the Myponga community and implement it to mitigate the potential risk the *Cryptosporidium* in source water poses to human health.

3.5 Conclusion

The Myponga case study presented here provides a practical and successful example of the passive adaptive management cycle. The contamination of source water by *Cryptosporidium* was identified as a problem in the late 1990s and significant catchment-based management has been undertaken to target the problem since 2000. The application of the passive adaptive management framework in this study occurred both through the learning derived from evaluation of the outcomes of past management programs and through undertaking a new, more detailed analysis and planning. This information is used to refocus, refine and re-prioritise the next round of management of *Cryptosporidium* risk in source water. In the evaluation of past environmental management programs dairy farmers were found to have embraced best-practice livestock and effluent management practices for enhancing water quality whilst the uptake amongst other broadscale graziers has been limited. Analysis of water quality monitoring data reveals a peak in median concentrations in 2003/04 with a steady decline since. Evaluation of the nature and impact of past management programs suggests that whilst they may have had a limited beneficial impact on *Cryptosporidium* in source water, detected concentrations still pose an unacceptable risk to human health. Quantitative risk assessment provided a systematic reassessment of the major remaining contributors of *Cryptosporidium* export to the reservoir and identified the most effective management actions given past mitigation activities. The results suggest that the most effective management strategy now is to restrict non-dairy calf access to watercourses. Passive adaptive management was found to be an acceptable compromise between the need for scientific assessment and planning, the engagement of stakeholders, and the exigency of efficient management for an important environmental and human health problem.

4. COST-EFFECTIVENESS OF ALTERNATIVES FOR MITIGATING *CRYPTOSPORIDIUM* RISK

4.1 Introduction

Declining water quality, particularly through microbial contamination, is a major problem facing communities around the world (Hrudey and Hrudey 2004). *Cryptosporidium* is a parasitic water-borne protozoon commonly found to contaminate fresh water supplies. It can infect a wide host range including humans and cause gastrointestinal illnesses (termed *cryptosporidiosis*) which can lead to mortality in the immuno-compromised (NHMRC 2004). Contamination of drinking water supplies has caused cryptosporidiosis outbreaks amongst human populations incurring significant human health and economic impacts (MacKenzie et al. 1994, Corso et al. 2003).

Cryptosporidium concentrations in water sourced from catchments dominated by agriculture and other human land uses have been found to pose a significant human health risk (Starkey et al. 2007). In these multi-use catchments, many potential sources of *Cryptosporidium* exist including livestock, wildlife, and agricultural and human effluent (Goss and Richards 2008). Compounding this, the water quality regulation service provided by natural ecosystems (Nasser and Oman 1999) has often been disrupted through land clearance, development and agricultural practices. Management to mitigate *Cryptosporidium* risk is a high priority in multi-use drinking water supply catchments.

Broadly, *Cryptosporidium* risk can be mitigated by both catchment- and treatment-based measures. Catchment-based measures to mitigate *Cryptosporidium* risk may involve a range of land use and management activities for reducing the impact of key sources such as livestock and effluent (Ferguson et al. 2007). Treatment-based measures involve the use of various filtration and disinfection processes to treat raw water and mitigate *Cryptosporidium* risk in finished water (Betancourt and Rose 2004, Smeets et al. 2007). The *multi-barrier* paradigm is widely recognized as the best way to manage risk posed by *Cryptosporidium* and other pollutants in water supply (Deere et al. 2001). This approach recommends that barriers to pollutants be established at multiple points along the water supply system from the *catchment to the tap*.

So far, the evaluation of *Cryptosporidium* management alternatives have focussed on those most effective at reducing *Cryptosporidium* risk to human health (Ferguson et al. 2007, Smeets et al. 2007, Bryan et al. submitted). Evaluation techniques have included the analysis of hazards and critical control points (HACCP, Deere et al. 2001) and quantitative microbial or ecological risk assessment (Haas et al. 1999, Starkey et al. 2007, Goss and Richards 2008). However, recent studies have recognized the importance of economic factors in evaluating water quality management alternatives, in particular, the cost to landholders (Monaghan et al. 2007).

Water quality management alternatives for mitigating *Cryptosporidium* risk in drinking water incur costs such as set-up costs, operating and maintenance costs, and opportunity costs. The primary benefit of water quality management alternatives is *Cryptosporidium* risk mitigation effectiveness, but they may also provide other additional secondary benefits (or positive *externalities*). Catchment-based management alternatives in particular may produce a range of additional ecosystem goods and services beyond risk mitigation such as water quality services (e.g. other pathogens, sediment, nutrients), biodiversity-related services, carbon sequestration services, food and fibre provision; flood, erosion, and pest regulation; aesthetic, recreational and other cultural services (Zedler 2003, Lovell and Sullivan 2006).

Given that budgets are often limited and sourced from the public purse it is prudent to prioritize investment in the most cost-effective water quality management alternatives (Mannino et al. 2008). Planning for investment in water quality management alternatives on the basis of effectiveness alone may lead to inefficient investment decisions (Poe 1999, Skop and Schou 1999, Schou and Birr-Pedersen 2006).

Established tools such as cost-benefit analysis and cost-effectiveness analysis have been used to evaluate water quality management alternatives (Eisen-Hecht and Kramer 2002, Zanou et al. 2004). However, these studies usually restrict the scope of the evaluation to only a select few costs and benefits. The economic valuation of ecosystem services provides a useful tool for quantifying a broad range of benefits associated with water quality management, particularly catchment-based management actions (Tong et al. 2007). Some studies have considered a broad range of costs and benefits in evaluating water quality management alternatives (Loomis et al. 2000, Reid 2001, Bateman et al. 2006, Yang et al. 2008) although not in the context of *Cryptosporidium* risk mitigation. There is a need to consider a broad suite of economic and environmental costs and benefits evaluating catchment-based and treatment-based management alternatives for mitigating *Cryptosporidium* risk (Johnson et al. 2008).

In this study we evaluate the cost-effectiveness of a range of catchment- and treatment-based management alternatives for mitigating *Cryptosporidium* risk in drinking water supply under the multi-barrier paradigm using a case study in the Myponga River catchment, South Australia. A range of costs and benefits are identified, valued, and included in cost-effectiveness analysis. Specifically, the set-up, operation and maintenance, and opportunity costs of management alternatives, and the economic benefits associated with enhanced ecosystem services of water quality (beyond *Cryptosporidium* risk mitigation), biodiversity, carbon sequestration, and farm productivity are valued. This study aims to inform management investment decisions under the multi-barrier paradigm in prioritising alternatives that cost-effectively mitigate *Cryptosporidium* risk and produce a range of ecosystem service benefits at the same time.

4.2 Costs, benefits and water quality management investment decisions

A range of decision tools have been used in the integrated assessment of the costs and benefits of management alternatives to support the prioritisation of cost-effective water quality investment decisions. Cost-benefit analysis is a standard tool used by governments to evaluate the feasibility of public infrastructure investment decisions. Cost-benefit analysis aims to quantify all costs and benefits in monetary terms and decisions can be made based on the net present monetary value of an investment. Several cost-benefit analyses have found that the economic benefits of catchment-based water quality management exceeded costs (Eisen-Hecht and Kramer 2002, Shepherd et al. 2007) and compares favourably against water quality treatment (Chichilinisky and Heal 1998, Reid 2001).

Cost-effectiveness analysis is used for assessing the best way of achieving specific objectives (e.g. *Cryptosporidium* risk mitigation). Costs and benefits are monetarized but the objective is measured in other units (log removal is a commonly used measure describing the order of magnitude of pathogen removal effectiveness) and decisions are made based on relative cost-effectiveness of alternatives. Cost-effectiveness analysis has widely been used to identify the minimum cost investment alternatives for attaining non-point source agricultural pollution objectives from catchment-based source control, to interception and treatment (Rejesus and Hornbaker 1999, Ribaudo et al. 2001; Weinberg et al. 2002, Elofsson 2003, Zanou et al. 2004; Fröschl et al. 2008; Mannino et al. 2008).

These studies have tended to focus only on a select few of the highest priority, most readily identifiable and quantifiable values in their cost benefit assessments (Emerton and Bos 2004). However, water quality management alternatives, especially catchment-based source control measures, can have multiple additional or secondary benefits (Chichilinisky and Heal 1998, Rein 1999, Lovell and Sullivan 2006). Poe (1999) and Schou and Birr-Pedersen (2006) both demonstrated that inclusion of secondary benefits can significantly affect the results of cost-effectiveness analyses in environmental management. Multi-criteria and cost-utility analyses (Hajkowicz and Wheeler 2008, Hajkowicz et al. 2008) have considered a broad range of costs and benefits in the evaluation of water quality management investment decisions. Recently, calls have been made to value and include these externalities more broadly in the cost-benefit assessment of ecosystems and catchments as a component of water infrastructure in evaluating investment decisions (Emerton and Bos 2004, Emerton 2007).

The concept of ecosystem goods and services (hereafter *ecosystem services*) provides a framework for consideration of a broad range of environmental costs and benefits in the evaluation of water quality management investments (Millennium Ecosystem Assessment 2005). Ecosystem services include the range of provisioning (e.g. food, fresh water), regulating (e.g. climate regulation, erosion regulation), cultural (e.g. recreation, cultural heritage), and supporting (e.g. water cycling, photosynthesis) services that sustain and fulfill human life generated by natural, functioning ecosystems and environments (Daily 1997). The economic valuation of ecosystem services (Costanza et al. 1997) provides a way of quantifying in monetary terms a wider range of costs and benefits associated with water quality (Emerton and Bos 2004). Whilst the total economic value of water quality and other ecosystem services generated by watersheds (Reid 2001, Zheng et al. 2008) and wetlands (Loomis et al. 2000, Zedler 2003, Tong et al. 2007, Yang et al. 2008) has been found to be substantial, few studies have valued a range of ecosystem service benefits in the evaluation of water quality management alternatives (e.g. Ribaudo et al. 2001).

Cost-effectiveness analysis was used in this study to evaluate water quality management alternatives as the mitigation of *Cryptosporidium* risk was the primary objective of management. In evaluating the cost-effectiveness of management alternatives *Cryptosporidium* risk mitigation benefit is quantified in units of log-removal. All other costs and benefits associated with management alternatives are valued and incorporated into a single cost term. The most cost-effective management alternatives are those with the lowest marginal cost of achieving management benefits (e.g. $/log removal).

4.3 Methods

A selection of catchment- and treatment-based management alternatives are evaluated in this study for their cost-effectiveness in mitigating *Cryptosporidium* risk and generating secondary ecosystem service benefits. The risk mitigation effectiveness of management alternatives in the Myponga catchment is estimated using a pathogen model and previous studies. A range of management costs and ecosystem service benefits are valued in monetary terms using market-based economic valuation techniques. Quantification of the costs and benefits of management alternatives are calculated in present value terms. In general, costs are calculated as the sum of initial set-up costs and annual ongoing maintenance and opportunity costs discounted to present value terms. Benefits for the ecosystem services of water quality, biodiversity, carbon sequestration, and farm production occurring over time are also discounted to present value terms. It is assumed that maintenance will first be required after twelve months of establishment. A discount rate (r) of 6% per annum was used (average of interest rate on savings and interest rate on long-term bond yields 2007/08 from Reserve Bank of Australia data) over an analysis time frame (T) of 50 years (the time taken for planted trees to reach maturity). The parameters used in calculating costs and ecosystem service benefit values of water quality management alternatives were assembled from various sources based on market prices for the year 2007/08.

4.3.1 Catchment-based Management Alternatives

Geographic Information Base

A spatial database of land use and management was created using a Geographic Information System (GIS). High spatial resolution state government cadastre and land use databases were used to identify land use on individual properties in the Myponga catchment. A 1:40,000 scale GIS-based hydrology database provided information on the spatial location of water courses across the catchment. A farm level map of livestock management across the catchment was created by combining a survey of 36 landholders in the Myponga catchment with a previous livestock survey. The analysis in this study was targeted at the 146 non-dairy livestock properties which were both traversed by watercourses and ran cattle.

Cryptosporidium *Risk Mitigation Effectiveness*

A pathogen budget model (Ferguson et al. 2007) was used to identify the dominant catchment-based sources of *Cryptosporidium* (e.g. livestock, wildlife, waste water treatment, septic tanks). The results suggest that most of the *Cryptosporidium* oocysts exported to the Myponga reservoir originate largely from non-dairy cattle. This is due to their greater numbers and the very low adoption rates of water quality management practices found among non-dairy compared to dairy landholders (Bryan et al. in review). Restricting total non-dairy cattle numbers with access to water courses by 25%, 50%, and 95% can mitigate 23% (0.114 log), 45% (0.257 log), and 91% (1.04 log) of the *Cryptosporidium* risk, respectively. In addition, pathogen modelling results also show that an average removal effectiveness of 10.8% (0.053 log, Bryan et al. in review) can be achieved through the introduction of dung beetle populations as digestion by dung beetles can effectively inactivate *Cryptosporidium* oocysts. Hence, in this study we evaluated the cost-effectiveness of non-dairy cattle water course access restriction and the universal adoption of dung beetles in mitigating *Cryptosporidium* risk.

Management Costs

A set of practical and complementary management practices were defined that restrict water course access of non-dairy cattle, enhance water quality, and restore riparian ecosystems, and were workable for Myponga farm businesses at the same time. These practices included fencing off a 10 metre buffer around water courses (Sullivan et al. 2007), revegetating riparian buffer habitat, and establishing off-stream stock shelter plantings and watering points, and stock crossings.

Costs associated with catchment-based water course management actions include set-up costs, operation and maintenance costs, and the opportunity costs of foregone agricultural production. The present value of water quality management costs PVC_i was calculated for each property i such that:

$$PVC_i = PVC_{F,i} + PVC_X + PVC_W + PVC_{R,i} + PVC_{O,i}$$ Equation 1

Where $PVC_{F,i}$ is the present value cost of fencing off a 10m buffer around water courses, calculated as (Table 5):

$$PVC_{F,i} = \left(USC_F \times L_i\right) + \sum_{t=1}^{T} \frac{MC_F}{(1+r)^t}$$ Equation 2

PVC_X is the present value cost of installing one stock crossing per property with a life expectancy of 10 years, calculated as (Table 5):

$$PVC_X = \left(\sum_{t_X} \frac{USC_X}{(1+r)^{t_X}} \right) + \sum_{t=1}^{T} \frac{MC_X}{(1+r)^t}, \text{ for } t_X = 0, 11, 21, 31, 41$$ Equation 3

PVC_W is the present value cost of installing one off-stream watering point per property with a life expectancy of 15 years, calculated as (Table 5):

$$PVC_W = \left(\sum_{t_W} \frac{USC_W}{(1+r)^{t_W}} \right) + \sum_{t=1}^{T} \frac{MC_W}{(1+r)^t}, \text{ for } t_W = 0, 16, 31, 46$$ Equation 4

$PVC_{R,i}$ is the present value of the cost of restoring riparian buffer areas and one off-stream shelter area per property (0.375 ha), calculated as (Table 5):

$$PVC_{R,i} = \left(USC_R \times (AB_i + AS) \times d \right) + \sum_{t=1}^{T} \frac{MC_R}{(1+r)^t}$$ Equation 5

and $PVC_{O,i}$ is the present value of the opportunity cost of foregone agricultural production in the riparian buffer and off-stream shelter areas, calculated based on typical returns per hectare as (Table 5):

$$PVC_{O,i} = \sum_{t=1}^{T} \frac{OC \times (AB_i + AS)}{(1+r)^t}$$ Equation 6

For the universal adoption of dung beetles the present value of set-up, and operation and maintenance costs were calculated as (Table 5):

$$PVC_D = \frac{AT}{ac} \times USC_D \times j$$ Equation 7

Parameters	Symbol	Value	Source
Fencing			
Unit set-up cost (A$/km)	USC_F	9000	Based on commercial quotes from Andrew Tindale Fencing
Length of riparian fencing (km)	L_i		Length required to fence off the 10m buffer calculated for each property using GIS
Operation and Maintenance cost (A$/yr)	MC_F	300	Estimate based on fencing repairs per property required in the Myponga Watercourse Restoration Project (EPA 2008)
Stock Crossings			
Unit set-up costs (A$/crossing)	USC_X	5000	Based on commercial quotes from Wenham Earthmovers Pty. Ltd.
Operation and Maintenance cost (A$/yr)	MC_X	1000	Estimate per property based on repairs done as part of the Myponga Watercourse Restoration Project (EPA 2008)
Off-stream Watering			
Unit set-up costs (A$/system)	USC_W	7500	Based on commercial quote from HRI Hardware Rural & Irrigation
Operation and Maintenance cost (A$/yr)	MC_W	400	Estimated cost per property provided by rural supplies company used during Myponga Watercourse Restoration Project (EPA 2008)
Restoration/Revegetation			
Unit set-up costs (A$/plant)	USC_R	2	Based on commercial quotes from Fleurieu Natives for Revegetation - Revegetation contractor engaged during Myponga Watercourse Restoration Project (EPA 2008)
Operation and Maintenance cost (A$/yr)	MC_R	300	Estimated cost per property based on commercial weed control quotes from RG and MJ Stone - Weed control contractor engaged during Myponga Watercourse Restoration Project (EPA 2008)
Planting density (plants/ha)	d	2667	Based on *Eucalyptus globulus* plantings after Schoenborn and Duncan (2001)
Riparian buffer area (ha)	AB_i		Area covered by 10m buffer around watercourses calculated for each property using GIS
Area of off-stream shelter (ha)	AS	0.375	Assuming 1000 plants per property and 2667 plants per ha
Opportunity Cost			
Cost per hectare (A$/ha/yr)	OC	40	Based on estimates used by Connor et al. (2008)
Universal Adoption of Dung Beetles			
Unit set-up costs (A$/colony)	USC_D	500	Commercial quote from Creation Care
Number of species required	j	3	Three species specified to insure against population declines from species-specific threats (Mathison and Ditrich 1999)
Area covered by 1 colony (1500 dung beetles) (ha)	ac	50	Estimate from Mathison and Ditrich (1999)
Total management area	AT	6115	Total area of properties with non-dairy cattle access to water courses in Myponga catchment from GIS data calculated from GIS data

Table 5. Values used for set-up, operation and maintenance, and opportunity cost parameters.

Ecosystem Service Benefits

The total present value of ecosystem service benefits from water course management PVB_i was calculated as the sum of the present value of benefits for water quality services (pathogen, sediment and nutrient reduction) $PVB_{WQ,i}$, biodiversity services $PVB_{B,i}$, carbon sequestration $PVB_{C,i}$, and farm production services $PVB_{P,i}$:

$$PVB_i = PVB_{WQ,i} + PVB_{B,i} + PVB_{C,i} + PVB_{P,i} \quad \text{Equation 8}$$

No significant ecosystem services produced by the adoption of dung beetles were identified.

Water Quality Benefits

It is well established that the exclusion of cattle from water courses and the restoration of riparian areas for biodiversity, can have multiple water quality service benefits beyond the mitigation of *Cryptosporidium* risk. These include the provision of fresh water, water purification and waste treatment, erosion regulation, water cycling and other services (Millennium Ecosystem Assessment 2005).

Livestock cause erosion and destabilisation of stream banks and beds, mobilisation of sediment and increased water turbidity, and the pugging and compaction of soils, and the contribution of a range of human-infectious pathogens and nutrients (Byers et al. 2005). A well-vegetated riparian zone can protect water courses against non-point source pollutants from adjacent agricultural land by slowing surface run-off and trapping pollutants (Blanco-Canqui et al. 2004, Sullivan et al. 2007). Restricting livestock access to water courses and the restoration of riparian buffer zones can improve the quality of source water (Parkyn et al. 2003, Byers et al. 2005, Lovell and Sullivan 2006).

In this study, the present value of water quality services was estimated based on the avoided maintenance costs associated with treatment for pathogens and turbidity through enhanced coagulation, and nutrients through copper sulphate dosing of the reservoir (Table 5 and Table 6):

$$PVB_{WQ,i} = \frac{AB_i}{AB_{Tot}} \times RE \times \sum_{t=1}^{T} \frac{MC_{EC} + MC_{CS}}{(1+r)^t} \qquad \text{Equation 9}$$

Biodiversity Benefits

The exclusion of livestock from water courses and the restoration of riparian areas can enhance biodiversity assets and increase ecosystem services generated by biodiversity such as the provisioning of genetic and pharmaceutical resources, pest and disease regulation, pollination, recreation, and cultural heritage (Millennium Ecosystem Assessment 2005). Exclusion of livestock from water courses can reduce the direct herbivory and trampling of biota and the erosion and sedimentation processes caused by livestock (Parkyn et al. 2003, Lovell and Sullivan 2006). Restoration of riparian buffers can further improve the structure and function of both riparian and aquatic habitats, reduces algal blooms, increase dissolved oxygen in the water, and restore water temperature and light regimes (Parkyn et al. 2003), and connect terrestrial species populations in the landscape (Lovell and Sullivan 2006).

A benefits transfer technique was used to estimate the biodiversity value of riparian habitats in the Myponga catchment. A representative market price for land used solely for biodiversity conservation p_B was derived from the Victorian BushTender auction for conservation contracts cited on the Ecosystem Marketplace website (http://www.ecosystemmarketplace.com). The present value of biodiversity services produced by restored riparian buffer and off-stream shelter areas was calculated for each property *i* as (Table 5 and Table 6):

$$PVB_{B,i} = \sum_{t=1}^{T} \frac{p_B \times (AB_i + AS)}{(1+r)^t}$$ Equation 10

Carbon Sequestration Benefits

Riparian zone restoration and the planting of off-stream shelter areas sequesters atmospheric carbon dioxide in plant biomass. This process provides a climate regulation service in reducing greenhouse gas concentration and mitigating climate change (Pacala and Socolow 2004). The amount of carbon sequestered by ecological restoration is dependent upon both tree species and environmental characteristics such as climate and soils (Stavins and Richards 2005) and these vary over the Myponga catchment.

Carbon sequestration rates were modelled for the Myponga catchment using the 3-PG Spatial model (Landsberg and Waring 1997). *Eucalyptus globulus* is a well-studied native Australian tree species suited to the area and was used to approximate the carbon sequestration rates of a suite of local endemic species (Sands and Landsberg 2001). Spatial data was input into 3-PG including an existing soils database and long term average annual rainfall and temperature data layers modelled using the ESOCLIM model. The present value of the benefits of carbon sequestration services produced by the riparian buffer and off-stream shelter plantings was calculated for each property *i* based on the price of carbon traded on the European market as (Table 5 and Table 6):

$$PVB_{C,i} = \sum_{t=1}^{T} \frac{p_C \times CS_{E.glob} \times (AB_i + AS)}{(1+r)^t}$$ Equation 11

Farm Production Benefits

Water course management such as water course access restriction and off-stream shelter and watering may have benefits for farm productivity through reduced incidence of injury and disease, and increased milk and meat production resulting from improved drinking water quality for livestock (Gordon and Nelson 2007, Zeckoski et al. 2007). The increase in farm production benefits is assumed to occur in year 1 and is valued using the market price of cattle from agricultural statistics data (Bryan and Marvanek 2004). The present value of the farm production services was calculated for each property *i* as (Table 6):

$$PVB_{P,i} = p_H \times w \times N_i$$ Equation 12

Parameters	Symbol	Value	Description
Water Quality Service Values			
Capital/fixed costs (A$)	C_{EC}	0	Avoided costs of turbidity and pathogen mitigation through enhanced coagulation. This process is currently used in Myponga by SA Water hence A$0 capital cost estimate. Maintenance costs estimated by SA Water.
Operation and maintenance costs (A$/yr)	MC_{EC}	33,500	
Pollutant removal efficiency	RE	90%	Estimate of nutrient, sediment, pesticide and pathogen removal efficiency of excluding stock from watercourses and establishing a 10m riparian buffer based on Blanco-Canqui et al. 2004, Sullivan et al. 2007).
Nutrient load-related annual expenditure by SA Water (A$/yr)	MC_{CS}	140,000	SA Water estimates based on algal bloom mitigation via copper sulphate dosing twice a year - cost: A$130,000 to A$150,000 per year depending on copper price
Total riparian buffer area (ha)	AB_{Tot}	601.9	Total area created by creating a 10m buffer around all water sources traversing properties with non-dairy cattle calculated using GIS data
Biodiversity Service Values			
Biodiversity value (A$/ha/yr)	p_B	137	Average present value market price for land used solely for biodiversity conservation obtained from the Australian BushTender Program and Ecosystem Marketplace prices http://ecosystemmarketplace.com/pages/marketwatch
Carbon Sequestration Service Values			
Carbon sequestration rate (tonnes/ha/yr)	$CS_{E.glob}$	17.00	Mean carbon dioxide equivalent (CO_2^{-e}) sequestration rate of *Eucalyptus globulus* at a planting density of 2667 plants/ha. Modelled across the Myponga catchment using 3-PG Spatial (Sands and Landsberg 2001)
Price (A$/tonne)	p_C	11.30	Based on a European carbon market price of €8/tonne CO_2^{-e}. €1=A$1.62 (Stavins and Richards 2005, Connor et al. 2008, http://ecosystemmarketplace.com/pages/marketwatch)
Production Benefit values			
Expected weight gain (kg)	w	5%	Based on a weight gain per head used by Zeckoski et al. (2007)
Price per head (A$)	p_H	546	Based on sale price from Bryan and Marvanek (2004)
Number of cattle (#)	N_i		Number of cattle on each property *i*, derived from landholder survey and state government data

Table 6. Parameters used to estimate ecosystem service benefit values of catchment-based water quality management practices.

4.3.2 Treatment-based Management Alternatives

The process of conventional treatment at the Myponga treatment plant has been estimated by SA Water to achieve a 3-log *Cryptosporidium* oocyst removal effectiveness. A variety of enhanced treatment processes exist that can further mitigate *Cryptosporidium* risk. Three treatment-based management alternatives were evaluated in this study – enhanced coagulation, ultra-violet irradiation, and microfiltration. The effectiveness of these processes in mitigating *Cryptosporidium* risk was assessed and their set-up, and operation and maintenance costs are valued for input into cost-effectiveness analysis. No significant additional ecosystem service benefits generated by treatment-based management alternatives were identified.

Cryptosporidium *Risk Mitigation Effectiveness*

Enhanced coagulation is currently used in the Myponga Water Treatment Plant and involves the use of additional coagulant in conventional treatment to reduce suspended particulates. SA Water estimate that enhanced coagulation provides an additional *Cryptosporidium* oocyst removal effectiveness of 0.5-log in Myponga. Two other treatment processes found to be particularly effective in treating *Cryptosporidium* include ultra-violet irradiation and microfiltration. Ultra-violet treatment can achieve a 2-log to 4-log removal (Betancourt and Rose 2004) through the ability of ultra-violet radiation from low-pressure mercury lamps to disrupt the chemical bond of organic molecules. Microfiltration involves passing water through a fine membrane (~0.2μm) which is able to achieve >4-log to 6-log removal of *Cryptosporidium* oocysts (Betancourt and Rose 2004). In this study we use the median *Cryptosporidium* risk mitigation effectiveness values of 3-log for ultra-violet and 5-log for microfiltration.

Set-up, Operation and Maintenance Costs

Set-up, operation and maintenance costs (*PVC*) for the three treatment-based water quality management alternatives enhanced coagulation (*EC*), ultra-violet (*UV*), and microfiltration (*MF*) were calculated as (Table 7):

$$PVC_u = C_u + \sum_{t=1}^{T} \frac{MC_u}{(1+r)^t},\ u \in U\{EC, UV, MF\} \qquad \text{Equation 13}$$

Parameters	Symbol	Value	Description
Enhanced Coagulation	See Table 6		
Ultra-violet Irradiation			
Capital/fixed costs (A$)	C_{UV}	2,000,000	SA Water estimates for a system with a design capacity of 50 ML/day
Operation and maintenance costs (A$/yr)	MC_{UV}	100,000	SA Water estimates including power, lamp replacement, and labor costs
Microfiltration			
Capital/fixed costs (A$)	C_{MF}	20,000,000	SA Water estimates of costs of replacing existing plant with a microfiltration plant, including earthmoving required to create additional space required on steep, rocky terrain (A$10-15 million for plant; A$5-10 million for additional earth works
Operation and maintenance costs (A$/yr)	MC_{MF}	300,000	SA Water estimates of costs above existing treatment costs

Table 7. Summary of set-up, operation and maintenance costs for treatment-based alternatives.

4.3.3 Cost-Effectiveness Analysis

Calculating Cost-Effectiveness

Cost-effectiveness analysis is used to evaluate and compare catchment- and treatment-based water quality management alternatives. Cost-benefit analysis is used to quantify the net present value of implementing water quality management alternatives considering set-up, operation and maintenance, and opportunity costs, and ecosystem service benefits. Net present value is calculated for water course management on each non-dairy livestock property *i*, as well as the dung beetle (*D*) and the three treatment-based alternatives U{*EC*, *UV*, *MF*} as:

$$NPV_q = PVC_q - PVB_q, \quad q \in Q\{i, D, U\}$$ Equation 14

Cost-effectiveness ($/log removal) in mitigating *Cryptosporidium* risk in drinking water CE_q is calculated based on cost only:

$$CE_q = PVC_q \div E_q$$ Equation 15

where E_q is the *Cryptosporidium* risk mitigation effectiveness of *q* measured in log removal terms. For individual properties *i*, E_i was estimated using the ratio of cattle on property *i*, N_i to the total number of cattle on non-dairy livestock properties *N*, where *N* = 9608. The net cost-effectiveness ($/log removal) of each management alternative in mitigating *Cryptosporidium* risk in drinking water NCE_q, is calculated using the net present value of *q* considering the full suite of costs and benefits as:

$$NCE_q = NPV_q \div E_q$$ Equation 16

Water Course Management Scenarios

Water course management on individual properties were aggregated into catchment-based water course management scenarios. Three water course management targets (25%, 50%, and 95% non-dairy cattle access restriction) and three spatial allocation objectives (maximum cost-effectiveness (MAXCE), maximum net cost-effectiveness (MAXNCE), and random spatial allocation (RAND)) were assessed in this study. In total, a set of nine water course management alternatives *s* was assessed, where $s \in S${25MAXCE, 25MAXNCE, 25RAND, 50MAXCE, 50MAXNCE, 50RAND, 95MAXCE, 95MAXNCE, 95RAND}. In the catchment-based scenarios, properties were ranked in descending order of cost-effectiveness CE_s and net cost-effectiveness NCE_s and selected for management until the cumulative sum of cattle numbers exceeded the 25%, 50%, and 95% non-dairy cattle water course access restriction targets, respectively (Figure 7). Costs and benefits were summed for the selected properties under each scenario. For the random allocation strategies, properties were selected in random order until cattle numbers exceeded the 25%, 50%, and 95% targets for 1000 Monte Carlo simulations and average costs and benefits were calculated. These aggregate catchment-based water course management scenarios were compared with the dung beetle and treatment-based alternatives in terms of risk mitigation effectiveness, cost-effectiveness, and net cost-effectiveness.

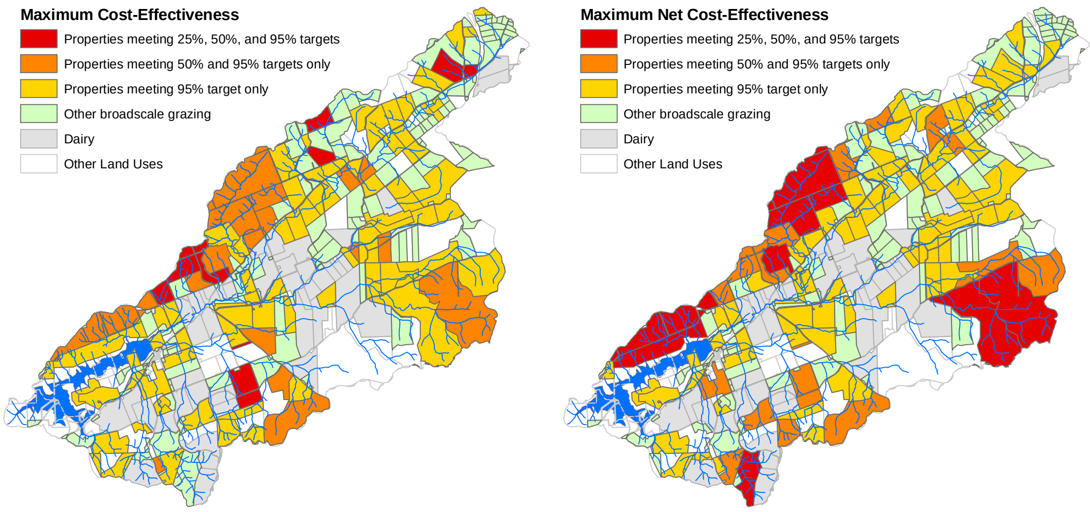

Figure 7. Non-dairy cattle properties identified for management for each of the 25%, 50%, and 95% non-dairy cattle water course access restriction targets under the minimum fencing cost and maximum environmental benefit spatial targeting strategies.

4.3.4 Sensitivity Analysis

Finally, the sensitivity of the net cost-effectiveness ranking of water quality management alternatives to uncertainty in parameter values was assessed by varying individual parameter values considered to both have a strong influence on the model, and to have inherent uncertainty around the parameter values used. The net cost-effectiveness of all 13 water quality management alternatives was recalculated based on a low discount rate (r = 4%), high discount rate (r = 8%), no carbon market (p_C = A$0/tonne), no biodiversity market (p_B = A$0/ha), and high fencing costs (USC_F = A$10,000/km).

4.4 Results

4.4.1 Set-up, Operation and Maintenance Costs

The universal adoption of dung beetles was by far the least expensive water quality management alternative in terms of total cost (Table 8). Amongst the water course management scenarios, costs varied with the access restriction target level and spatial targeting objective. The maximum cost-effectiveness scenarios (MAXCE) were substantially lower in cost than the maximum net cost-effectiveness scenarios (MAXNCE) which, in turn were lower cost than the random scenarios (RAND). Costs of the MAXCE scenarios were consistently around A$3 – 4M less than the RAND scenarios irrespective of target level (Table 8). The contribution of fencing, stock crossing, off-stream watering, and restoration/revegetation costs were similar under the RAND scenarios with opportunity costs significantly less. Under the MAXCE and MAXNCE scenarios, costs for stock crossings and off-stream watering were similar. However, fencing, revegetation, and opportunity costs were much higher under the MAXNCE scenarios as properties with greater areas of water course buffer were selected (Table 8).

Enhanced coagulation was by far the least expensive treatment alternative. The cost of ultra-violet treatment was comparable to the 50MAXCE and 50MAXNCE scenarios whilst the cost of microfiltration was extremely high because of the significant modifications required to the existing plant (Table 8).

Management Alternative	Fencing	Stock Crossing	Off-Stream Watering	Restoration/ Revegetation	Opportunity Cost	Total
25MAXCE	168,102	156,879	111,018	160,928	20,891	617,819
25MAXNCE	813,643	130,732	92,515	738,774	112,704	1,888,369
25RAND	804,564	976,517	691,051	801,505	98,484	3,372,121
50MAXCE	865,981	496,782	351,558	809,646	113,440	2,637,407
50MAXNCE	1,433,658	470,636	333,055	1,321,844	194,907	3,754,100
50RAND	1,628,405	1,895,382	1,341,304	1,614,912	200,487	6,680,490
95MAXCE	2,650,486	2,405,473	1,702,279	2,566,364	335,896	9,660,498
95MAXNCE	2,840,869	2,379,326	1,683,776	2,745,358	364,851	10,014,180
95RAND	3,132,430	3,572,101	2,527,866	3,100,685	386,854	12,719,937
Dung Beetles	-	-	-	-	-	183,450
Enhanced Coagulation	-	-	-	-	-	528,022
Ultra-violet	-	-	-	-	-	3,576,186
Microfiltration	-	-	-	-	-	24,728,558

Table 8. Summary of present value set-up, operation and maintenance, and opportunity costs of the 13 water quality management alternatives.

4.4.2 Ecosystem Service Benefits

Ecosystem service benefits of significant economic value may substantially offset the costs associated with water course management scenarios (Table 9). The MAXNCE scenarios produced the highest ecosystem service values but only slightly more than the RAND scenarios, with the MAXCE scenarios producing substantially less (Table 9). Water quality service benefits accounted for most of the total ecosystem service benefits followed by carbon sequestration services, and biodiversity. Production benefits were limited (Table 9). Convergence in ecosystem service benefit values increased under the higher water course access restrictions targets.

Management Alternative	Water Quality Service Benefits (A$)	Biodiversity Service Benefits (A$)	Carbon Sequestration Service Benefits (A$)	Production Benefits	Total Ecosystem Service Benefits (A$)
25MAXCE	126,692	71,551	100,328	47,884	346,455
25MAXNCE	725,588	386,011	541,261	63,145	1,716,005
25RAND	583,310	337,307	472,969	61,559	1,455,146
50MAXCE	708,844	388,533	544,797	130,549	1,772,722
50MAXNCE	1,240,427	667,557	936,042	125,607	2,969,634
50RAND	1,192,908	686,668	962,838	126,624	2,969,037
95MAXCE	2,043,905	1,150,445	1,613,142	248,976	5,056,468
95MAXNCE	2,233,829	1,249,614	1,752,196	248,812	5,484,450
95RAND	2,306,813	1,324,975	1,857,866	244,858	5,734,512
Dung Beetles	-	-	-	-	-
Enhanced Coagulation	-	-	-	-	-
Ultra-violet	-	-	-	-	-
Microfiltration	-	-	-	-	-

Table 9. Ecosystem service benefits of water quality management alternatives.

4.4.3 Cost-Effectiveness

Water quality management alternatives achieved widely varying levels of *Cryptosporidium* oocyst removal effectiveness. The treatment-based alternatives of microfiltration and ultra-violet are most effective followed by the three water course management alternatives that achieve the 95% access restriction target (Table 10).

In terms of cost-effectiveness, the three treatment-based management alternatives are in the top four (Table 10). Enhanced coagulation is the most cost-effective alternative achieving moderate effectiveness at very low cost. Ultra-violet treatment is next most cost-effective because it is both very effective and relatively inexpensive. Next, the adoption of dung beetles is a very low cost alternative but also very low effectiveness and microfiltration is extremely effective but very costly. The water course management alternatives are not particularly cost-effective when costs only are considered (Table 10).

Enhanced coagulation and ultra-violet treatment were also the most net cost-effective alternatives despite not providing ecosystem service benefits (Table 10). However, dung beetles and microfiltration were ranked much lower and the MAXNCE and MAXCE water course management scenarios were ranked 3rd and 4th highest due to the value of ecosystem service benefits produced (Table 10).

Management Alternative	Effectiveness (E_s, log-removal)	Total Cost (PVC_s, A$)	Total Benefits (PVB_s, A$)	Net Cost (NPV_s, A$)	Cost-effectiveness (CE_s, A$/log-removal)	Net cost-effectiveness (NCE_s, A$/log-removal)	Rank (E_s)	Rank (CE_s)	Rank (NCE_s)
25MAXCE	0.114	617,819	346,455	271,363	5,406,143	2,374,531	10	5	**4**
25MAXNCE	0.114	1,888,369	1,716,005	172,364	16,523,930	1,508,248	10	11	**3**
25RAND	0.114	3,372,121	1,455,146	1,916,975	29,507,317	16,774,247	10	13	13
50MAXCE	0.257	2,637,407	1,772,722	864,685	10,244,999	3,358,867	7	8	6
50MAXNCE	0.257	3,754,100	2,969,634	784,466	14,582,789	3,047,257	7	10	5
50RAND	0.257	6,680,490	2,969,037	3,711,452	25,950,340	14,417,124	7	12	12
95MAXCE	1.043	9,660,498	5,056,468	4,604,030	9,266,425	4,416,222	**3**	6	9
95MAXNCE	1.043	10,014,180	5,484,450	4,529,730	9,605,680	4,344,952	**3**	7	8
95RAND	1.043	12,719,937	5,734,512	6,985,425	12,201,062	6,700,474	**3**	9	11
Dung Beetles	0.053	183,450	-	183,450	3,461,754	3,461,754	13	**3**	7
Enhanced Coagulation	0.500	528,022	-	528,022	1,056,045	1,056,045	6	**1**	**1**
Ultra-violet	3.000	3,576,186	-	3,576,186	1,192,062	1,192,062	**2**	**2**	**2**
Microfiltration	5.000	24,728,558	-	24,728,558	4,945,712	4,945,712	**1**	**4**	10

Table 10. Cost-effectiveness analysis of alternative water quality management alternatives.

4.4.4 Sensitivity Analysis

Sensitivity analysis suggested that the ranking of water course management scenarios based on net cost-effectiveness is sensitive to the presence/absence of markets for both carbon and biodiversity. The net cost-effectiveness of water course management scenarios varies inversely with discount rates as higher discount rates reduce the present value of ecosystem service benefits which tend to occur further into the future. Variation in fencing costs has negligible impact on the ranking of alternatives (Table 11). Enhanced coagulation and ultra-violet treatment and targeted catchment-based water course management are relatively robust to reasonable variation in parameter values (Table 11).

Management Alternative	Baseline		No Carbon Value		High Discount Rate		Low Discount Rate		No Biodiversity Value		High Fencing Cost	
	NCE	Rank	NCE	Rank	NCE	Rank	NCE	Rank	NCE	Rank	NCE	Rank
25MAXCE	2,374,531	**4**	3,252,441	**3**	2,422,179	**3**	2,305,555	6	3,000,630	**3**	2,510,386	**4**
25MAXNCE	1,508,248	**3**	6,244,479	9	4,298,234	6	-3,008,078	**1**	4,885,987	6	2,276,337	**3**
25RAND	16,774,247	13	20,912,903	13	16,031,971	13	17,503,669	13	19,725,813	13	17,294,718	13
50MAXCE	3,358,867	6	5,475,129	6	4,031,674	5	2,279,721	5	4,868,122	5	3,693,857	7
50MAXNCE	3,047,257	5	6,683,310	10	4,804,900	10	208,727	**2**	5,640,382	10	3,629,303	6
50RAND	14,417,124	12	18,157,266	12	14,132,652	12	15,050,338	12	17,084,482	12	14,970,982	12
95MAXCE	4,416,222	9	5,963,560	7	4,545,569	7	4,220,427	9	5,519,737	8	4,545,569	8
95MAXNCE	4,344,952	8	6,025,672	8	4,576,048	8	3,984,050	8	5,543,592	9	4,576,048	9
95RAND	6,700,474	11	8,482,554	11	6,541,147	11	6,982,641	11	7,971,400	11	6,969,128	11
Dung Beetles	3,461,754	7	3,461,754	**4**	3,461,754	**4**	3,461,754	7	3,461,754	**4**	3,461,754	5
Enhanced Coagulation	1,056,045	**1**	1,056,045	**1**	819,643	**1**	1,439,306	**4**	1,056,045	**1**	1,056,045	**1**
Ultra-violet	1,192,062	**2**	1,192,062	**2**	1,074,449	**2**	1,382,739	**3**	1,192,062	**2**	1,192,062	**2**
Microfiltration	4,945,712	10	4,945,712	5	4,734,009	9	5,288,931	10	4,945,712	7	4,945,712	10

Table 11. Sensitivity analysis of net cost-effectiveness of water quality management alternatives.

4.5 Discussion

A multi-barrier approach requires a combination of both catchment- and treatment-based management to reliably mitigate *Cryptosporidium* risk. Evaluation of management alternatives based on effectiveness alone suggested that investment should be directed at treatment by microfiltration and water course management at the 95% access restriction level (*E* = 6.043 log, *NPV* = A$29.33-31.71 million, *NCE* = A$4.85-5.25 million/log-removal). When costs were considered as well, enhanced coagulation and the adoption of dung beetles is the most cost-effective management strategy (*E* = 0.553 log, *NPV* = A$0.71 million, *NCE* = A$1.29 million/log-removal). When costs and ecosystem service benefits are considered, enhanced coagulation and the 25MAXNCE water course management scenario is the most net cost-effective combination (*E* = 0.614 log, *NPV* = A$0.7 million, *NCE* = A$1.14 million/log-removal). Hence, the cost-effectiveness of investment in water quality management can be substantially enhanced by considering the costs of management and the benefits for ecosystem services. However, the *Cryptosporidium* oocyst removal effectiveness varied greatly between these combinations and the investment decision is dependent upon the total log-removal capacity required by catchment-based and treatment-based measures.

Net cost-effectiveness provided a guide for identifying efficient investment options for mitigating *Cryptosporidium* risk, identifying a number of good investments on both the treatment side and the catchment side. These can be packaged into investment options to achieve varying levels of *Cryptosporidium* risk mitigation effectiveness for the catchment and treatment barriers. If an additional 0.5 log-removal is sufficient on the treatment side then enhanced coagulation will be sufficient. However, if greater removal effectiveness is required then ultra-violet disinfection also represents a very cost-effective investment achieving an extra 3-log. On the catchment side, the targeting of water course management on properties according to net cost-effectiveness represents the best strategy. The required level of investment in the catchment is dependent upon the desired level of cattle access restriction and hence, log-removal capacity. In addition, the adoption of dung beetles may provide a complementary catchment-based barrier at low cost. Selected combinations of good investment alternatives for catchment- and treatment-based management of water quality are summarised in Table 12.

Combinations	**Effectiveness (log-removal)**			**Net Cost (A$)**	**Net Cost-Effectiveness (A$/log-removal)**
	Catchment	Treatment	Total		
Enhanced Coagulation + 25MAXNCE	0.500	0.114	0.614	700,386	1,140,173
Enhanced Coagulation + 25MAXNCE + Dung Beetles	0.500	0.167	0.667	883,836	1,324,547
Enhanced Coagulation + 95MAXNCE	0.500	1.043	1.543	5,057,753	3,278,875
Enhanced Coagulation + 95MAXNCE + Dung Beetles	0.500	1.096	1.596	5,241,203	3,284,949
Enhanced Coagulation + Ultra-violet + 25MAXNCE	3.500	0.114	3.614	4,276,572	1,183,243
Enhanced Coagulation + Ultra-violet + 25MAXNCE + Dung Beetles	3.500	0.167	3.667	4,460,022	1,216,168
Enhanced Coagulation + Ultra-violet + 95MAXNCE	3.500	1.043	4.543	8,633,939	1,900,691
Enhanced Coagulation + Ultra-violet + 95MAXNCE + Dung Beetles	3.500	1.096	4.596	8,817,389	1,918,692

Table 12. Net cost-effective combinations of catchment- and treatment-based water quality management alternatives.

Effectiveness in reducing *Cryptosporidium* oocysts concentrations in water supply is the primary objective in the evaluation of management alternatives in this study as it has been in many previous studies due to the risk posed to human health (Haas et al. 1999, Ferguson et al. 2007, Starkey et al. 2007, Smeets et al. 2007, Goss and Richards 2008, Bryan et al. in review). However, in this study the costs and benefits of management alternatives are quantified and integrated to assess their relative net cost-effectiveness. Cost-effectiveness analysis allows the primary *Cryptosporidium* risk mitigation objective to remain paramount and enables the explicit evaluation of the performance of selected management alternatives against water quality objectives such as log-removal. Further, it enables the economic valuation of the benefits and costs of management alternatives typically required by government to support infrastructure investment decisions.

Assessment of the costs and benefits of water quality management alternatives in this study can also inform policy and implementation strategies and help identify who should pay (i.e. the beneficiary or the polluter). Under the *polluter pays* principle, waste generated by cattle is treated as a negative externality that is harming a water supply. Under this principle, landholders would normally incur the most of the costs of water quality management. However, the benefits of management such as the provision of fresh water and other ecosystem services, largely accrue to the broader community (van Vuuren et al. 1997, Chichilinisky and Heal 1998, Reid 2001) over the long run. Hence, the optimal level of investment in water quality management by landholders would rarely account for these external benefits and policy based on this principle is not likely to achieve the desired water quality outcomes.

Under the *beneficiary-pays* principle most of the costs of management would be borne by the public. In Myponga, a practical cost-sharing approach is required for managing water quality. For treatment-based management, the benefit of healthy drinking water is shared by the community. In this case, the cost of treatment may be borne by government on behalf of the community. For catchment-based water course management, benefits may accrue to both landholders and the community. Hence, a cost-sharing arrangement may be most appropriate. The public cost-share may be jointly provided by the water utility (SA Water) and the regional environmental management agency (AMLR NRM Board) with the latter contributing towards the costs of water course management for the production of additional ecosystem services. The private cost-share may be accessed through the careful design of suasive, incentive-based, and regulatory policy instruments to address impediments to adoption (Bewsell et al. 2007, Bryan and Kandulu in review) and target the most cost-effective properties (Hajkowicz et al. 2008, Gerber et al. 2008, Polasky et al. 2008, Crossman and Bryan 2009). The adoption of dung beetles has no appreciable private benefits for landholders and the program is likely to be most successful if coordinated and implemented by government. These principles may be broadly applicable to other water supply catchments with agricultural non-point source pollution problems.

With minor modifications, the methods used in this study are transferable to other small catchments affected by agricultural non-point source pollution, especially by pathogens such as *Cryptosporidium*. Each unique application is reliant upon catchment-specific farm-level land use and management data, particularly cattle stocking rates. Catchment-specific ecosystem services will also need to be identified and valued for inclusion in cost-effectiveness analysis based on their relevance and significance.

Adapting methods to larger or less connected catchments may require consideration of spatially explicit pathogen fate and transport processes affecting the contribution of land use in particular areas in the catchment to non-point source pollution (Ferguson et al. 2007, Haydon and Deletic 2006). Also, applying heterogeneous values to biodiversity may also enhance the spatial targeting of high biodiversity value areas. In larger catchments, alternative survey, rapid assessment, or remote sensing techniques may be required to acquire farm-level land use and management information.

Further enhancement may also be made to the methods through quantitative probabilistic assessment (Haas et al. 1999) of the reduction in risk achieved through the increased reliability of multiple pollution barriers, rather than using aggregate log-removal as a measure of effectiveness. In addition, the consideration of costs and benefits may be extended to include other positive externalities (e.g. cultural ecosystem services generated by water course management) and negative externalities (e.g. carbon footprint of water treatment) associated with water quality management options.

4.6 Conclusion

Using a case study of the Myponga water supply catchment in South Australia, this paper evaluates the cost-effectiveness of a range of catchment- and treatment-based management alternatives for managing *Cryptosporidium* risk under the multi-barrier paradigm. Each alternative differs in oocyst removal effectiveness, set-up, operation and maintenance, and opportunity costs, and ecosystem services. The primary objective is to mitigate *Cryptosporidium* risk in water supply. When management alternatives are evaluated on the basis of *Cryptosporidium* removal effectiveness alone, treatment by microfiltration is by far the preferred investment and catchment-based alternatives are much less effective. However, efficient investment in environmental management requires the consideration of both costs and the broad range of benefits in decision-making. When set-up, operation and maintenance, and opportunity costs were considered, investment priorities changed significantly to include treatment by enhanced coagulation and ultra-violet, and catchment management through adoption of dung beetles. When a broader range of costs and ecosystem service benefits were considered in the analysis, targeted catchment-based water course management was a cost-effective investment comparable with treatment options. The results show that investment decisions made on the basis of cost alone undervalue the additional ecosystem service benefits produced by water course management and hence may lead to sub-optimal investment decisions. This may hold more generally for water quality management and policy decisions in other catchments. Cost-effectiveness analysis based on economic valuation of a broad range of costs and benefits provides an informed basis for internalizing additional ecosystem services benefits produced by water course management. It also provides a basis for informing elements of policy such as the cost-sharing arrangements and the use of market-based instruments to target high priority properties for management.

5. POLICY DESIGN FOR MITIGATING CRYPTOSPORIDIUM CONTAMINATION

5.1 Introduction

Management of the quality of fresh water resources is one of the major challenges confronting managers in water supply catchments throughout the world (UNEP, 2007). Whilst much progress has been made in controlling pollution from point sources, controlling non-point source pollution, principally from agriculture, remains an elusive challenge (Russell and Shogren, 1993; Gunningham and Sinclair, 2005). Broadacre livestock agriculture is one of the most common and significant non-point sources of surface water pollution (Wang, 2006; Monaghan et al., 2007; Collins et al., 2007) such as sediments (Byers et al., 2005), nutrients (Strauss et al., 2007), and pathogens (Ferguson et al., 2007). Pathogens such as *Cryptosporidium* are a particularly important focus for management in water supply catchments because of the risk posed to human health (MacKenzie et al., 1994).

Catchment-based source control measures to manage water quality typically involve the adoption of a suite of practices such as reducing livestock access to streams through fencing and the provision of off-stream watering and shelter, riparian restoration and erosion control programs, and manure and effluent management (Bewsell et al., 2007; Collins et al. 2007). To achieve both environmental and human health outcomes, widespread adoption of on-farm water quality management measures by farmers is required across water supply catchments (Wilcock et al., 2006).

However, there are many impediments to the widespread adoption of on-farm water quality management measures. A common impediment to the adoption of water quality management is the potential financial cost to landholders (Kim et al., 2008; Greiner et al., 2009). Whilst water quality management practices can produce significant private (Lardner et al., 2005) and public benefits (Lovell and Sullivan, 2006), they are not likely to offset the costs to farmers (van Vuuren et al. 1997; Bryan and Kandulu, In Review). In addition, other factors such as the availability of skilled labour, access to information, social networks, farmer attitudes and beliefs, and lack of institutional support can also impede adoption (Rhodes et al., 2002; Macgregor and Warren, 2006; Kim et al., 2008; Prokopy et al. 2008). Impediments to adoption of water quality management can vary significantly both between catchments and between individual farmers within catchments (Pannell et al. 2006; Bewsell et al. 2007).

A suite of policy instruments including regulatory standards, economic incentives, and suasive mechanisms can be used to increase the adoption of on-farm water quality management by farmers (Sterner, 2003; Tietenberg, 2007; Connor et al., 2008a). Policy needs to directly address these impediments to efficiently motivate the widespread adoption of management measures (Prokopy et al., 2008) to avoid the potentially significant environmental and human health consequences of non-point source pollution in water supply catchments (MacKenzie et al., 1994; Horan and

Ribaudo, 1999; Corso et al., 2003). There is a need for the careful selection and design of policy given the diversity of impediments to adoption and the range of policy instruments available. Policy selection and design needs to involve a detailed, context-specific understanding of both the impediments operating in each catchment and the ability of policy instruments to overcome them (Jack et al., 2008). Further, a mix of complementary policy instruments may be required to address multiple impediments to water quality management and achieve widespread adoption in water supply catchments.

Recent studies have proposed methodologies for the selection and design of environmental policy instruments to address context-specific impediments to adoption. Romstadt (2004) and Pannell (2008) provide approaches for selecting policy instruments for promoting adoption of conservation practices based on economic characteristics of the problem such as the net private versus public benefits resulting from management. Using a qualitative assessment based on economic theory, Bewsell et al. (2007) identified that policy instruments enhancing on-farm benefits and supported by regulation could effectively increase the adoption of water quality management. Connor et al. (2008a) developed a screening process for selecting environmental policy instruments for mitigating agricultural non-point source pollution with a focus on market-based instruments.

Multi-Criteria Analysis (MCA) is an established and effective procedure for supporting complex decision making processes when multiple incommensurate criteria need to be considered (Nijkamp et al., 1990; Prato, 1999; Prato and Herath, 2007) and is particularly suited to the policy design problem. Broadly, MCA involves structuring the decision problem by identifying a range of alternatives and a range of criteria which these alternatives address. The relative importance of criteria can be quantified and those alternatives that perform better against the more important criteria are the preferred options (Hajkowicz and Collins, 2007). A recent review by Hajkowicz and Collins (2007) found that MCA has been widely applied in water policy and supply planning. Applications of MCA in the context of water quality mainly focus on identifying preferred management options (e.g. Hajkowicz and Wheeler, 2008) with only limited application to the policy design problem. Agri-environment and land use policies have been evaluated using MCA (Moran et al., 2008; Prato, 2008). With regard to non-point source pollution, Ward et al. (2008) demonstrated the utility of a simple multi-criteria approach to suggest policy design features for overcoming a range of impediments to the efficient functioning of market-based instruments for addressing dryland salinity. These studies suggest that MCA has significant untapped potential to support the policy design process for the management of agricultural non-point source pollution.

Participatory or *deliberative* multi-criteria evaluation (DMCE, Proctor and Drechsler, 2006; Renn, 2006) extends standard MCA by incorporating a deliberative stage with a special focus on capturing the arguments and reasoning used by participants (Stirling, 2006; MacLeod et al., 2007). This process can be used to enrich understanding of the problem context for both decision-makers and stakeholders (Mustajoki et al., 2004; Proctor and Drechsler, 2006; Renn, 2006) and further inform the policy design process.

In this study we design a policy mix inclusive of regulatory, incentive-based, and suasive instruments to address the most important impediments to adoption of water quality management using a DMCE process. The DMCE process is applied to an agricultural non-point source pollution problem using a case study of *Cryptosporidium* contamination in the Myponga water supply catchment in South Australia. The DMCE process for policy design involves five steps: 1) using a landholder survey identify impediments to adoption and benefits of water quality management for use as criteria in DMCE; 2) identify policy instruments including economic incentives, regulation, and suasion for overcoming specific impediments to adoption and develop policy scenarios as alternatives in DMCE; 3) quantify the impact of policy scenarios on overcoming impediments to adoption and achieving water quality and other ecosystem service benefits; 4) assess the relative significance of the identified impediments to, and benefits of, on-farm water quality management and identify the preferred policy scenario; and 5) design and refine the preferred policy scenario alternative based on detailed, catchment-specific contextual understanding of water quality management issues obtained through the deliberative process.

5.2 Multi-Criteria Evaluation Model

The full DMCE process is presented in the case study (Section 5.3) whilst the formal model of multi-criteria evaluation is presented below. In this study, a set of decision criteria J were identified and a set of policy scenario alternatives I were developed to address these criteria. The impact x_{ij} of each policy scenario i on each decision criterion j was estimated for all i in I and j in J.

A number of techniques are available for assigning weights to criteria in multi-criteria evaluation (Al-Kloub et al., 1997). These include the simple direct entry technique, ranking and scoring techniques based on multi-attribute value (or utility) theory (MAUT, Keeney and Raiffa, 1976) such as SMART (Edwards and Barron, 1994) and swing weights (von Winterfeldt and Edwards, 1986), and pair-wise techniques such as trade-off analysis (Keeney and Raiffa, 1976) and the Analytical Hierarchy Process (Saaty, 1980). In this study, the swing weights technique was selected due to the simplicity, speed, practicality, and intuitive nature of the technique, and the fact that criteria ranges are explicitly considered.

To derive swing weights the set of decision criteria was presented to participants described by their worst and best levels. Participants were then asked to select the criterion they considered to be most important to change (or *swing*) from their worst to their best level through the implementation of alternatives. The criterion was assigned a swing weight w_j, where $w_j = 100$. Sequentially, swing weights for other criteria were scored relative to the most important criterion based on the importance of changing from worst to best level. For these criteria $w_j \leq 100$. A swing weight of zero was allocated if the change from the worst to best level was considered to have no importance.

Swing weights were then linearly transformed to weights w'_j which sum to 1 over all criteria j in J:

$$w'_j = \frac{w_j}{\sum_{j \in J} w_j} \quad \text{Equation 17}$$

There are also many techniques available for multi-criteria evaluation which enable the assessment of alternatives based on their impact on multiple incommensurate and differentially weighted criteria. These techniques include weighted summation (Keeney and Raiffa, 1976), outranking techniques such as ELECTRE (see Figueira et al., 2005 for a review) and PROMETHEE (see Brans and Mareschal, 2005 for a review), and mathematical programming such as goal, preference, and compromise programming (Zeleny, 1973). Hajkowicz and Higgins (2008) found strong agreement between several techniques tested. Hence, in this study we opted for a MAUT-based weighted summation approach due to its simplicity and transparency (Zanakis et al. 1998).

The weighted summation approach involves calculation of a multi-attribute utility score. First, the raw impact scores x_{ij} were converted into utility scores between 0 and 1 based on their minimum and maximum values using a linear transform (Hajkowicz and Higgins, 2008):

$$u_{ij} = \frac{x_{ij} - \min_{i \in I}(x_{ij})}{\max_{i \in I}(x_{ij}) - \min_{i \in I}(x_{ij})} \quad \text{Equation 18}$$

For criteria with numeric values this was a straightforward process. An intermediary step was taken with criteria with ordinal scales to convert classes to integer values where the least preferred class was given the value of 1 and classes were numbered sequentially up to the most preferred which was given a value corresponding to the number of classes. For example, for a criteria with seven classes, None = 1, Very Low = 2, Low = 3, …, Extremely High = 7. The integer values were then subject to the linear transformation in Equation 2. The multi-attribute utility of each policy scenario was then calculated as the product of the impact on each criterion multiplied by the weight for the criterion, summed over all criteria. Policy scenario alternatives were then ranked and selected based on maximum utility:

$$\underset{j \in J}{\text{maximize}} \sum_{i \in I} w'_j u_{ij} \quad \text{Equation 19}$$

5.3 Case Study

5.3.1 Identifying Decision Criteria

A landholder survey was used to identify the impediments to adoption of water quality management practices for controlling non-point pollution in the Myponga River catchment. A questionnaire was prepared and delivered in face-to-face interviews with landholders in the Myponga catchment during January to April 2007. Overall, 36 landholders were interviewed who together manage more than 60% of the catchment by area. Participants included all 16 dairy farmers, and a sample of other landholders including 13 broadscale graziers, 1 blue gum plantation owner, 2 horticulturalists, 1 equestrian property owner, and 3 lifestyle landholders selected from across the catchment.

Participants were asked more than 50 questions on land use and management relevant to water quality. A range of questions were included on landholder attitudes towards adoption of on-farm water quality management. Participants were asked about: their general attitudes and decision-making; the extent to which they have undertaken water quality management practices; the factors that would encourage their involvement in new natural resource management initiatives; their major impediments to adoption of water quality management practices, and; their attitude to various policy measures to enhance adoption.

The survey questionnaire was structured to enable identification of common themes associated with the adoption of water quality management among respondents. Survey responses were systematically analysed and the major impediments to adoption of water quality management in Myponga catchment were classified. Six major impediments to the adoption of on-farm water quality management practices were found (Table 13).

DESCRIPTION OF IMPEDIMENT	**SIGNIFICANCE IN THE CATCHMENT**
KNOWLEDGE ACCESS – Lack of awareness of impacts of land use activities and knowledge of how to undertake water quality management practices	**2** dairy and **3** non-dairy respondents required on-farm extension programs on fencing to progress **2** dairy and **2** non-dairy livestock respondents required information on fencing to progress.
WORKFORCE AVAILABILITY/LABOUR SCARCITY – Limited availability of labour and time to undertake on-ground works, especially in the absence of adequate incentives	**4** dairy and **5** non-dairy respondents cited a shortage of time to undertake fencing
TRAINER/ADVISOR PROFICIENCY – Limited availability of knowledgeable and experienced advisors as a major impediment to adoption.	**1** dairy and **2** non-dairy respondents expressed lack of confidence in information provided by advisors and rely on own knowledge & experience to make farm decisions.
ORGANISATIONAL STRENGTH – Lack of structural and institutional arrangements for support of adoption through industry groups or social networks	**6** respondents said they are motivated by programs driven by industry bodies (intra- and inter-industry bodies)
REGULATORY SUPPORT/IMPEDIMENT – Absence of appropriate regulatory support mechanisms and the need to remove regulatory impediments	**3** dairy and **4** non-dairy respondents cited allowing crash grazing would progress fencing activities. Aligning legislation/regulation with appropriate enforcement mechanisms and removing prohibitive regulation would enhance adoption in the area
FINANCIAL RESOURCES – Adoption of water quality management has a high direct cost and poses a risk to farm income	**5** dairy and **9** non-dairy respondents cited lack of financial resources and insufficient incentives

Table 13 - Impediments to the adoption of water quality management practices in the Myponga River catchment.

The impact on government financial resources was also included as an impediment to adoption as some stakeholders may consider on-farm management to be the responsibility of landholders (i.e. *polluter pays*) and an inappropriate use of public money. Together, the two financial resources impediments (landholders and government) capture the cost-sharing arrangements of policy alternatives.

In addition to impediments, five ecosystem service benefits produced by the adoption of on-farm water quality management actions were identified as being potentially important or valuable from the landholder survey and a previous cost-benefit analysis (Bryan and Kandulu, In Review). These include water quality, biodiversity, carbon sequestration, health risk mitigation, and landscape amenity. Water quality benefits include reductions in levels of *Cryptosporidium* and other pathogens, nutrients, and sediment. Biodiversity benefits relate to the regulating and cultural services produced by restored riparian habitat. Carbon sequestration refers to the climate regulation services produced by the atmospheric carbon dioxide sequestered in restored habitat and soils. Health risk refers to the reduction in risk to human populations through reduced concentrations of *Cryptosporidium* and other pathogens. Landscape aesthetics covers cultural services produced by an increase in riparian and terrestrial ecosystems such as recreation and aesthetic beauty. These five ecosystem service benefits and seven impediments to adoption were included to create a set of 12 decision criteria for assessing policy alternatives in the DMCE process.

5.3.2 Identifying Instruments and Developing Policy Scenario Alternatives

Alternative policy instruments were suggested as potentially suitable for addressing the six major impediments to adoption of water quality management in the Myponga catchment (Table 14). Policy instruments were selected based on economic theory, published guidelines, and the experiences of a range of case studies for mitigating diffuse source pollution (Sterner, 2003; Harrington et al., 2004; BDA Group and EconSearch, 2005).

IMPEDIMENT	POTENTIAL POLICY SOLUTIONS
KNOWLEDGE ACCESS	**Suasion:** General education programs; guidelines and codes of practice; training programs; extension services
WORKFORCE AVAILABILITY/ LABOUR SCARCITY	**Incentives:** Public provision of contractor services; subsidised contractor services; accreditation schemes; stewardship schemes; subsidies and grants; rebates
TRAINER/ADVISOR PROFICIENCY	**Suasion:** Advisor training and performance monitoring schemes
ORGANISATIONAL STRENGTH	**Suasion:** Industry codes of practice; **Incentives:** subsidised information campaigns by industry associations; public-funded information campaigns by industry associations
REGULATORY SUPPORT/IMPEDIMENT	**Regulation:** Process-based standards; licensing; mandatory management plans; placing a ban on risky farm practices and acquisition; removing prohibitive regulation
FINANCIAL RESOURCES	**Incentives:** Accreditation schemes; stewardship payment schemes; subsidies and grants; public provision

Table 14 - Policy instruments suitable for addressing specific impediments to adoption of water quality management practices.

Policy scenarios were developed in consultation with community stakeholders in the Myponga River catchment. A first community forum was held on the evening of

October 1st, 2008 at Myponga. More than 55 local landholders known to the project team were invited by mail and telephone. The forum was attended by 10 local landholders in addition to representatives from project partner agencies (CSIRO, Environmental Protection Authority, SA Water, DairySA, and AMLR NRM Board). During the forum participants were presented the results of the landholder survey, pathogen modelling, and cost-benefit analysis of the water quality problem in the Myponga catchment with a focus on *Cryptosporidium*. Participants were also introduced to the process of multi-criteria evaluation and the intention of applying the technique to the selection of policy alternatives for management of water quality in the Myponga River catchment. Participants appreciated the need for management, the inevitability of policy intervention for addressing water quality concerns in the catchment, and their opportunity to contribute to the development of that policy.

Using the potential policy solutions (Table 14) and the contextual information obtained during discussion at the community forum, a set of six policy scenarios was constructed for inclusion in the DMCE process. Scenarios are potential policy alternatives for achieving water quality and human health objectives in the catchment over 20 years. They are summarised below:

Status Quo – Existing policy continues unchanged (Section 2.3). Little increase in adoption of water quality management practices occurs and water quality continues at same poor/unsatisfactory level.

Suasion – Existing incentives and regulation are complemented by a dramatic increase in the amount of information provided to landholders through awareness raising, education and information, and recognition. The cost of adoption is largely borne by landholders and cost of policy implementation is borne by government. A limited increase in adoption of water quality management and associated improvement in water quality is expected.

Incentives – Existing regulations are complemented by a range of financial incentives for land stewardship such as auctions, payments schemes, subsidies, and rebates. This is supported by a limited increase in education and awareness. The cost of adoption is shared by landholders and government, with the cost of policy implementation borne by government. A moderate increase in adoption of water quality management and associated improvement in water quality is expected.

Regulation – Existing regulations are strengthened to enforce the uniform adoption of water quality management through the introduction of legislative controls, standards, bans on degrading practices, and compliance monitoring. These are supported by limited education and information, and financial incentives. Costs of adoption are largely borne by landholders with some contribution by government with the costs of policy implementation and compliance monitoring borne by government. The increase in adoption and resultant water quality improvements are expected to be very high.

Buy Back – Involves the buy back of livestock properties across the catchment at market price by government and subsequent removal of livestock and conversion to carbon forest. This process is complemented by a communication and awareness campaign. The costs of property purchase and policy implementation are borne by government. The increase in adoption and resultant water quality improvements are expected to be very high.

Policy Mix - This includes suasion, incentives, and regulation sequenced in a way that is likely to motivate adoption through addressing impediments. For example, suasion and education first, followed by a broad incentives program and supported by a robust regulatory framework. The cost of adoption is shared by landholders and government, with the cost of policy implementation borne by government. The increase in adoption and resultant water quality improvements are expected to be high.

5.3.3 Quantifying the Impact of Policy Scenarios on Criteria

The impact of each policy scenario on each decision criterion was estimated using a variety of techniques (Table 15). The impact of policy scenarios on overcoming the non-financial impediments to adoption was estimated based on economic theory, contextual knowledge of the catchment from the landholder survey and first community forum, and other case studies for mitigating agricultural non-point source pollution (Sterner, 2003; Harrington et al., 2004; BDA Group and EconSearch, 2005).

Financial and ecosystem services impacts of the Status Quo scenario were summarised from expenditure and adoption rates in the catchment since 2001 (EPA, 2008). The Regulation scenario was considered to result in the fencing, stock exclusion, and the establishment and restoration of a 10 m buffer around all water courses on livestock properties. Financial cost and ecosystem service benefits were taken from previous modelling (Bryan and Kandulu, In Press).

The Suasion, Incentives, and Policy Mix scenarios were considered to be less effective than Regulation in motivating adoption (Section 5.3.2).The financial and ecosystem service impacts for these scenarios were estimated relative to the expected success of the policy compared to Regulation. Financial costs under the Buy Back scenario were calculated based on the purchase of all livestock properties with water course access totalling 6,115ha. A median price of $15,000/ha was used on the basis of sales data from 68 local properties over 20ha sold from 2005 – 2008. The impact of policy scenarios on financial impediments were separated to reflect the likely cost sharing arrangements between landholders and government as described in Section 5.3.2. Landscape amenity impacts were estimated based on the scenic beauty and recreation potential of the likely outcome of the policy scenario.

	Criteria	Measurement Units	Status Quo	Suasion	Incentives	Regulation	Buy Back	Policy Mix
Impediments to Adoption	Knowledge Access	None – Very Low – Low – Moderate – High – Very High – Extremely High	Low	Very High	Moderate	Low	None	Very High
	Workforce Availability	None – Very Low – Low – Moderate – High – Very High – Extremely High	Low	Low	Moderate	Low	None	Very High
	Trainer/Advisory Proficiency	None – Very Low – Low – Moderate – High – Very High – Extremely High	Low	Very High	Moderate	Low	None	Very High
	Organisational Strength	None – Very Low – Low – Moderate – High – Very High – Extremely High	Low	Low High	Low High	Low Moderate	None	High Very High
	Regulatory Support/Impediments	None – Very Low – Low – Moderate – High – Very High – Extremely High	Moderate	Moderate	Moderate	Extremely High	High None	Very High
	Financial Resources (Landholders)	$K	-200	-2,000	-2,250	-7,000	+92,000	-2,100
	Financial Resources (Government)	$K	-500	-500	-3,250	-5,000	-108,000	-8,000
Ecosystem Services Benefits	Water Quality	Very Poor – Poor – Fair – Good – Very Good – Excellent	Poor	Poor	Fair	Excellent	Excellent	Very Good
	Biodiversity	Riparian Habitat (ha)	10	100	300	600	6,115	500
	Carbon Sequestration	# Cars Off the Road	2.5	464	1,391	2,782	103,955	2,319
	Health Risk	None – Very Low – Low – Moderate – High – Very High – Extremely High	Very High	High	Moderate	Low Very Low	None	Very Low Low
	Landscape Amenity	None – Very Low – Low – Moderate – High – Very High – Extremely High	Moderate	Moderate	High	Very High	Moderate	Very High High

Table 15 – Matrix quantifying the impact of policy scenarios on decision criteria. Impacts on non-financial impediments to adoption are estimated in terms of how well the impediment is addressed by the policy scenario. Financial impediments reflect the estimated costs of the policy scenario and the cost share between landholders and government. Ecosystem service benefits were estimated in terms of the expected impact of policy scenario given the likely success of the scenario. Grey reflects original values changed after group discussion in the DMCE session.

5.3.4 Deliberative Multi-Criteria Evaluation Process

A process of deliberative multi-criteria evaluation of policy scenarios was undertaken with community stakeholders in the Myponga River catchment (Proctor and Dreschler, 2006). during a second community forum in Myponga on the evening of November 5th, 2008. In addition to a mail and telephone invitation strategy, a half-page article was published in a local newspaper issuing a general invitation to the community. A total of 14 people attended the forum. Six local landholders participated in the DMCE session including five that attended the first forum. This group included 1 dairy farmer, 1 ex-dairy farmer, 1 sheep hobby farmer, 1 beef hobby farmer, and 2 mixed farmers. To support the decision-making of this group two local natural resource management representatives and six representatives from project partner agencies with expertise in water quality, catchment and land management, and economics and policy were also present.

The aim of the community forum was for the local stakeholders to arrive at a consensus view of the best policy alternative to address water quality objectives in the Myponga catchment. The forum was facilitated and every effort was made to ensure the full understanding and engagement of all participants, and that group decision-making processes.

At the beginning of the forum participants were again presented a synopsis of the water quality problem in the Myponga catchment. The structure of the DMCE process was explained as were the policy scenario alternatives and criteria, and the impact of scenarios on criteria. Participants were given a collection of supporting documentation including a summary of impediments to the adoption (Table 13) and policy options for addressing these (Table 14), detailed descriptions of the policy scenario alternatives, and a copy of the impact matrix (Table 15).

The Buy Back policy scenario was immediately ruled out by the government water utility SA Water due to the prohibitive costs involved in outright purchase and maintenance, and the potential social costs for the catchment. After this refinement and a few changes to the impact scores (Table 15) the group was satisfied with the criteria, policy scenarios, and the impact matrix.

In the next stage, participants were asked to apply their detailed local knowledge of farm management issues and landholder attitudes to weight the significance of each of the impediments to adoption, and ecosystem service benefits of on-farm water quality management. The set of 12 decision criteria (Table 15) was presented to participants described by their worst and best levels using the *Logical Decisions* software package (Smith, 2007). The group was asked to assign a swing weight of 100 to the criterion/criteria they consider to be most important to change from the worst to best level through the implementation of policy scenarios. The group then assigned swings weights to the other criteria relative to the most important criterion. Participants were given the opportunity to ask questions of clarification of the experts at any time during the DMCE process. Deriving weights was an iterative process where swing weights were repeatedly revised as new information came to hand through discussion between group members and through interactions with experts until consensus was reached.

The next step in the DMCE process was to identify the best policy scenario alternative as a function of the weighted impact of alternatives against the decision criteria using multi-criteria evaluation. Policy scenarios were ranked using Logical Decisions and the result was presented to the group. Finally, participants were asked whether they agreed with the ranking and given one last opportunity to ask questions or refine any of the components. Participants quickly reached consensus over the final ranking and weighting of policy scenarios.

During the DMCE session and particularly during the discussion of policy scenarios and deriving swing weights for criteria, detailed, context-specific information on issues surrounding water quality management in the Myponga River catchment was captured. This information was used to refine the design of the composition and scheduling of instruments in the preferred policy scenario alternative.

After the community forum, the results of the multi-criteria evaluation were explored using three techniques. Firstly, multi-attribute utility was calculated for the impediments to adoption and ecosystem services benefits criteria subsets and policy scenario alternative were plotted. Second, the utility of policy alternatives against individual criteria was graphed. Third, the impact of changing weights on the five highest weighted individual criteria was assessed through sensitivity analysis.

5.3.5 Results of Multi-Criteria Evaluation

The Financial Resources (Landholders) impediment to adoption was initially selected as the single most important criterion. However, after rounds of discussion, five criteria were considered to be equally most important including Knowledge Access, Trainer/Advisor Proficiency, Financial Resources (Landholders), Biodiversity, and Health Risk (Figure 8). Participants expressed a lack of full awareness of the impact of farm activities on water quality and the environment and hence considered Knowledge Access and Trainer/Advisor Proficiency as key elements to enhancing adoption of water quality management on-farm. Biodiversity, in particular, was seen as a primary reason why landholders have undertaken water quality management in the catchment. Health Risk was also weighted equal highest due to the potentially dire impact of a *Cryptosporidium* outbreak on the community despite the fact that most landholders drink rain water not water from the Myponga reservoir.

Regulatory Support/Impediments was attributed the next highest weight (Figure 8) due to the perceived need to enforce land management restrictions on lifestyle properties. Workforce Availability and Water Quality were attributed half the weighting of the five most important criteria. It was reinforced in discussion of the Workforce Availability criterion that contractor assistance is required to achieve the amount of water quality management required. Water Quality was considered important through the impact on livestock health. Landscape amenity was discussed but it was considered that it would not be impacted much. Financial Resources (Government) received minimal weighting as participants thought that it shouldn’t matter how much government spends. Participants held the view that whatever it costs to fix the water quality problem, it would still be much less than the potentially enormous cost of doing nothing, should a “boil water” notice need to be issued to the community, or worse, an outbreak occur.

Both Organisational Strength and Carbon Sequestration were considered to have no importance in the context of policy for enhancing the adoption of water quality management in the Myponga River catchment (Figure 8). Improving Organisational Strength was considered to be pointless due to the diffuse nature of the group of lifestyle property landholders contributing to the problem. Little was known of the ability of restored riparian habitat to sequester carbon nor its link to mitigating climate change.

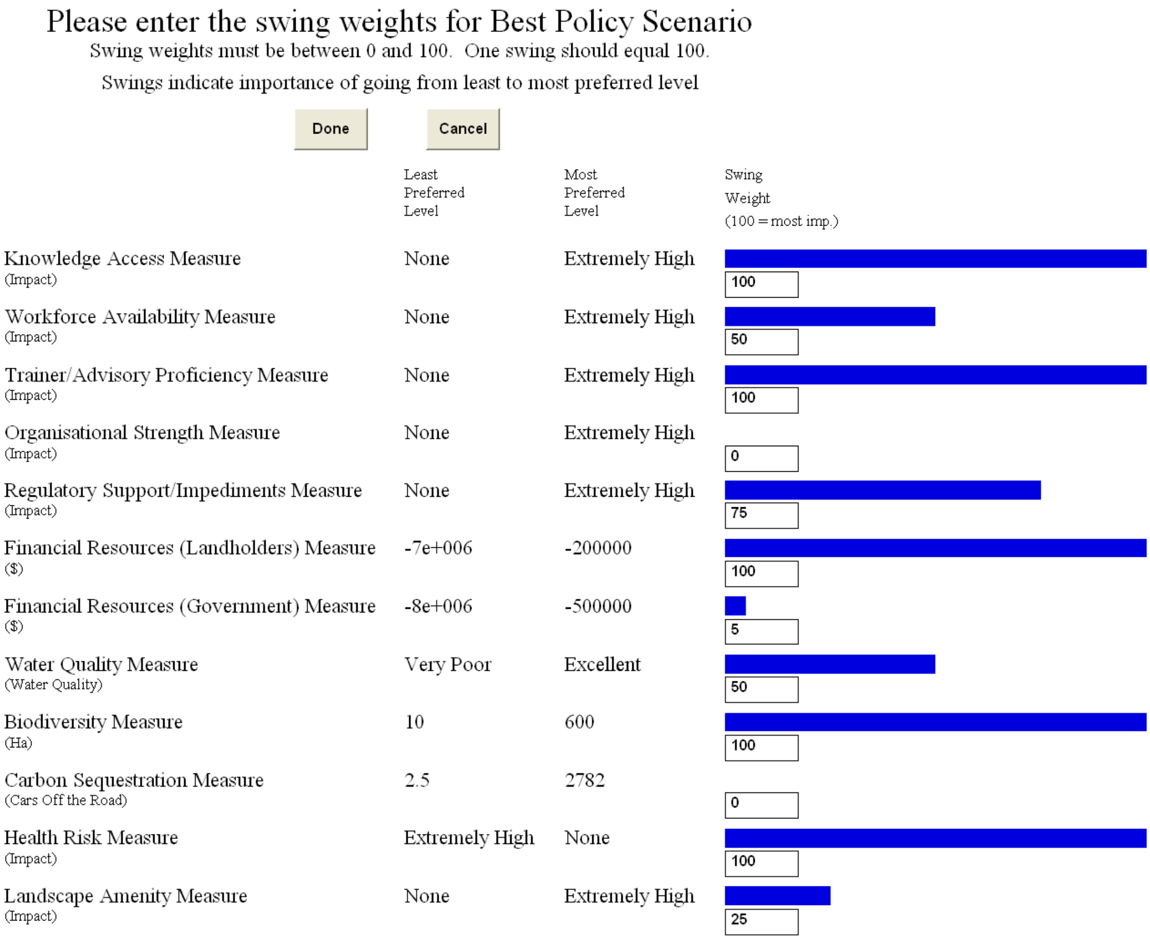

Figure 8 – Final consensus on swing weights w_j on decision criteria illustrated using the actual interface in Logical Decisions presented to participants in the DMCE session in Myponga.

With a multi-attribute utility score over all criteria of 0.779, the policy mix scenario was the highest ranked policy scenario alternative. The Regulation, Incentives, and Suasion scenarios were next highest rank, with the status quo ranked lowest (Figure 9).

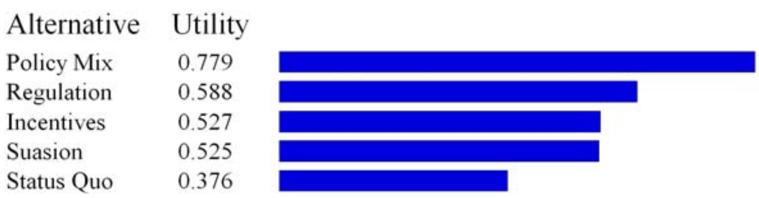

Figure 9 – Final ranking of policy scenarios based on utility u_j.

Policy scenario alternatives performed markedly differently against individual criteria as reflected in the utility scores (Figure 10). The preferred Policy Mix alternative has a high utility score for all criteria except Financial Resources (Government). The low score for this criterion is a result of the cost-sharing arrangements specified under this scenario reflecting the need for public funding for on-ground works which largely produce public benefits (Pannell, 2008; Bryan and Kandulu, In Review). Regulation has a low utility score for all impediments to adoption especially Financial Resources (Landholders) as landholders are burdened with the financial costs of on-ground works under this scenario. It performs well however in overcoming regulatory impediments to adoption. Regulation also has the highest utility scores for ecosystem service benefits as it was presumed that most landholders comply with legislative enforcement of water quality management. The Incentives scenario has a moderate utility score for all criteria with the highest utility for Financial Resources (Landholders) because of the increase in government incentives. The Suasion scenario has the highest utility scores for Knowledge Access, Trainer/Advisor Proficiency because of the focus on knowledge access, and Financial Resources (Government) as it involves limited public expenditure. Status Quo has low utility for all criteria except Financial Resources as this alternative involves limited public and private expenditure and is expected to have limited benefit (Figure 10).

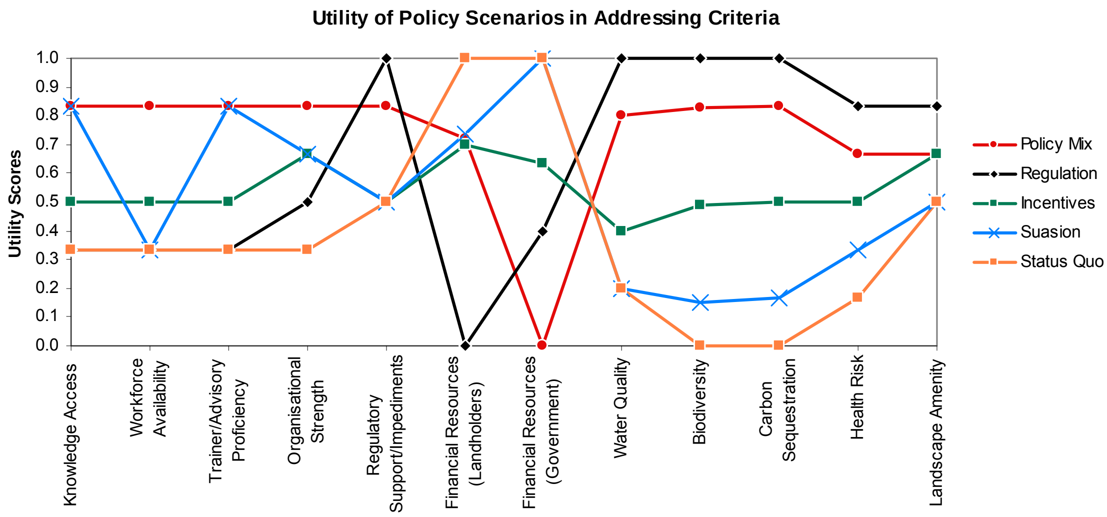

Figure 10 – Utility of policy scenario alternatives for the 12 decision criteria.

When individual criteria were broadly aggregated by impediments to adoption and ecosystem service benefits (Table 15), policy scenario alternatives were found to perform differentially (Figure 11). Policy Mix both addresses impediments to adoption and produces benefits for ecosystem services. Whilst Regulation produces greater ecosystem service benefits it does not address many impediments to adoption. With similar utility scores to Regulation, Incentives achieves more of a balance between addressing impediments and producing benefits whilst Suasion addresses impediments more strongly than it produces benefits.

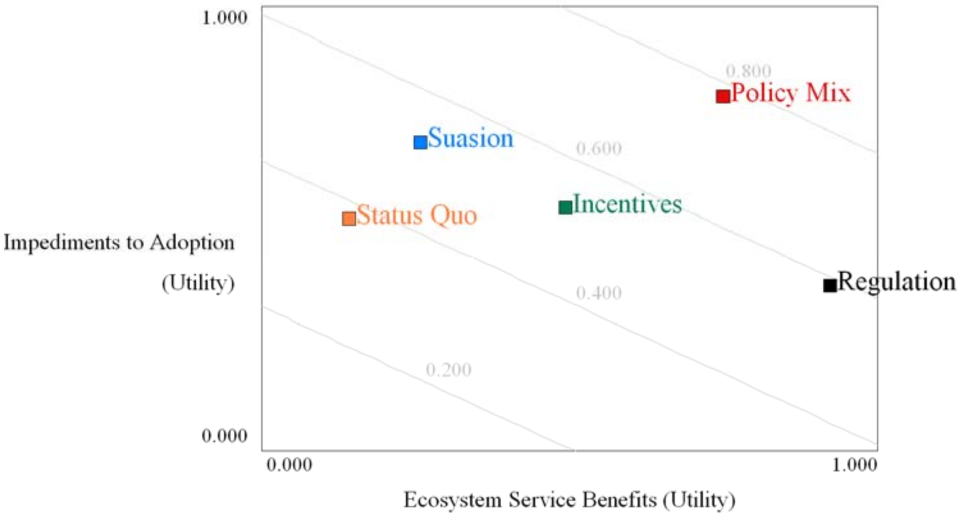

Figure 11 – Utility of policy scenario alternatives in addressing impediments to adoption and producing ecosystem service benefits. Multi-attribute utility for impediments to adoption is graphed against that for ecosystem service benefits. Grey lines are multi-attribute utility indifference curves.

Sensitivity analysis (Figure 12) demonstrates the robustness of the highest ranked Policy Mix alternative to changes in weights of the five most influential decision criteria (w_j = 100). The sensitivity of the multi-attribute utility scores and the ranking of policy scenario alternatives was the same for Knowledge Access and Trainer/Advisory Proficiency as they had identical impact scores (Table 15) and weights (Figure 8). Irrespective of the weighting on these criteria the Policy Mix scenario retains the highest ranking and Status Quo the lowest ranking. However, the Regulation scenario decreases in utility and Suasion increases markedly with an increase in weighting on Knowledge Access and Trainer/Advisory Proficiency. The ranking of the Policy Mix scenario is robust to a change in weight on the Financial Resources (Landholders) criterion until the weight exceeds 65% where Status Quo outranks the Policy Mix scenario because of its low cost to landholders. The utility of Regulation decreases sharply with an increase in weight because of the cost to landholders under this scenario. As the weights on both the Biodiversity and Health Risk criteria are increased beyond 60% the Regulation scenario outranks Policy Mix due to the likely effectiveness of this scenario and resultant benefits for both Biodiversity and Health Risk.

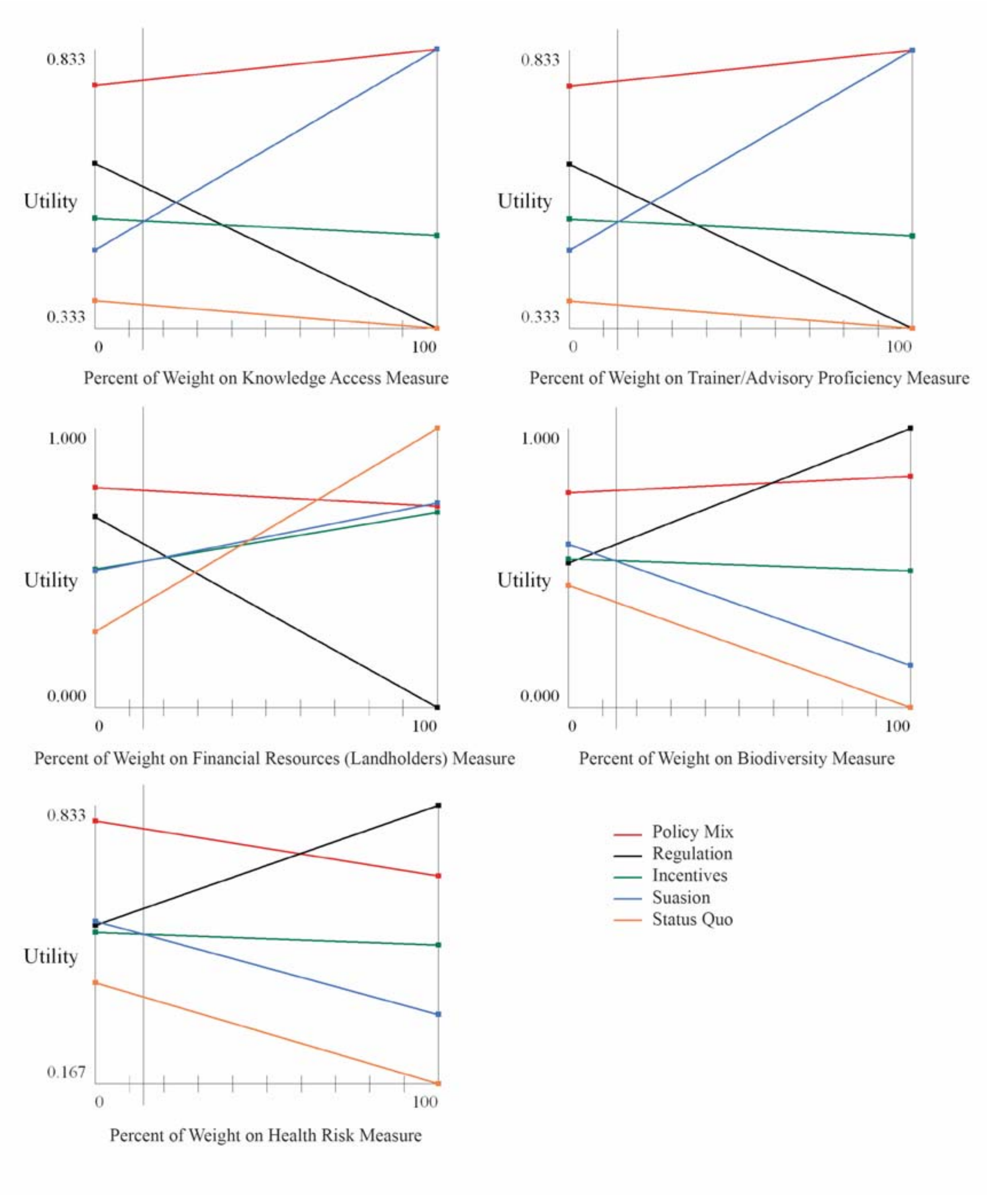

Figure 12 – Sensitivity of the ranking of policy scenario alternatives to changes in weights of the five most highly weighted decision criteria.

5.3.6 Refinement of the Policy Mix Scenario

Information obtained in the DMCE sessions revealed a highly context-specific set of issues surrounding the management of land and water resources in Myponga. Below we synthesise and use this contextual detail to refine the design of a mix and sequence of policy instruments which may be more effective for motivating the widespread adoption of water quality management.

Specific Context of the Water Quality Problem

Group discussion explored in depth a perceived disparity in the impact on water quality between professional farmers and hobby farmers, anecdotally corroborating the findings of the landholder survey. Essentially, participants felt that professional dairy and beef farmers tended to manage livestock in ways that were more sustainable for land and water resources. Conversely, hobby farmers were often known to engage in a range of unsustainable land use and management practices including overstocking, allowing unfettered livestock access to water courses, and a lack of herd rotation.

These practices were seen as resulting from a variety of causes. A lack of information, advice, and know-how limits the ability of hobby farmers to undertake sustainable land management. The group perceived that tax deductions available to primary producers provide a perverse incentive for hobby farmers to increase stocking densities beyond carrying capacity. In addition, some hobby farms are non-residential. Not living on the property may further limit the motivation of landholders to manage the property sustainably. There was also a general feeling that the diffuse group of hobby farmers tended not to be interested in or prioritise sustainable land and water resource management. Overall, participants agreed that carefully designed policy approaches were required to address these issues and effectively encourage adoption of water quality management particularly by hobby farmers.

Targeting for Cost-Effective Outcomes

Rich discussion in the DMCE focused on the need to target the major contributors to the water quality problem in the Myponga river catchment. Contribution to *Cryptosporidium* contamination is heterogeneous across the Myponga River catchment, with specific properties contributing disproportionately large oocyst loads (Bryan et al., In Review). The diffuse and heterogeneous nature of *Cryptosporidium* contamination suggests that policy for enhancing water quality management should be focussed on critical source areas within the Myponga River catchment rather than universal controls (Strauss et al. 2007). Significant cost savings and water quality benefits can be gained by targeting properties where more stock have access to water courses (Bryan and Kandulu, In Review). Spatial information describing priority areas for mitigating *Cryptosporidium* based on cost-effectiveness, provided by Bryan and Kandulu (In Review), needs to underpin all relevant policy instruments.

Information and Suasion

There was a general desire amongst DMCE participants for more specific information and a lack of confidence in current technical knowledge of the appropriateness of water quality management techniques. A broad education and awareness campaign around issues of overstocking and riparian management targeting several forms of local media may encourage the adoption by some landholders who incur minimal private costs. A targeted approach to increasing education and awareness of water quality management issues may be undertaken through extension services and landholder training. Whilst this can incur higher costs to government, past experience in the catchment outlined by the Environmental Protection Authority (EPA, 2008) suggests that it may be substantially more effective in enhancing adoption.

However, there were also concerns amongst the group that suasive instruments are likely to fail because targeted hobby farmers show little interest in participating and have little support from social networks. In addition, the high turn-over rate of lifestyle properties in the catchment means that suasive efforts will need to be ongoing. In this case, more structured instruments such as the development of a code of practice for sustainable land use and management in water supply catchments, enforced later through regulation, may be more effective. The code of practice would need to include guidelines on best practice management of livestock, water courses, riparian zones, and effluent.

These suasive instruments should occur first in the scheduling of policy instruments. Suasive measures are likely to encourage limited adoption very cheaply but provide an essential informational support for other policy instruments.

Economic Incentives

The high weighting on the Financial Resources (Landholders) and Workforce Availability criteria and subsequent discussion in the DMCE suggest that economic incentives need to form the core policy instrument for enhancing the widespread adoption of water quality management in the Myponga River catchment. The use of incentives involves both the removal of perverse incentives and the establishment of payment schemes. Removal of perverse taxation incentives may be achieved by requiring that landholders demonstrate compliance with a code of practice to be eligible for deductions.

Market-based economic incentives such as auctions or payments for ecosystem services may achieve adoption more cost-effectively through allowing compliance flexibility rather than prescribing actions, which is particularly important with heterogeneous contributors (Baumol and Oates, 1971). When underpinned by a robust metric, these instruments have the potential to cost-effectively encourage management in high priority locations (Connor et al., 2008b). Auctions (or more accurately, *reverse* auctions) for water quality management contracts enable landholders to bid for funds to undertake on-ground works with the most cost-effective bids winning (Latacz-Lohmann and van der Hamsvoort, 1997). Payments for ecosystem services can also be targeted at the highest priority areas with cost-effectiveness achieved through heterogeneous costs of management by landholders (Jack et al., 2008). Incentives may occur simultaneously with or follow the suasive instruments above. The establishment of incentives programs and markets for ecosystem services may also need to be supported by appropriate regulatory institutions. The inclusion of ongoing maintenance payments in incentive schemes may alleviate concern about ongoing maintenance cost of on-ground works.

With regards to cost-sharing, cost to government was not considered important in solving the water quality problem in Myponga due to the largely public benefits of water quality management (van Vuuren et al., 1997) and the large avoided costs of an outbreak of *Cryptosporidiosis*. Hence, arguably, all of the administration and implementation (monitoring and enforcement) costs of an incentives program, and the bulk of the direct costs of water quality management should be borne by government. Participants considered that water pricing could be increased to cover public costs in a *user-pays* system.

Regulation

Participants felt strongly that existing regulatory institutions did not incorporate practical flexibility for land management such as allowing crash grazing (a short, intense grazing period) in dry weather, and this was an impediment to adoption. There was general agreement amongst participants that stronger regulation was an essential component of an effective policy mix "*There needs to be proper monitoring of stocking rates by government or at least a means for other people to report if someone is not doing the right thing. Those that don't should be penalised*". Whilst a number of regulatory options exist and may be effective in Myponga, the enforcement of a mandatory code of practice for land use and management in water supply catchments may be most appropriate. The code of practice combines the suasive benefits of increased education and awareness with the enhanced certainty of regulation. Monitoring and enforcement of compliance may be relatively simply done (e.g. by aerial survey or farm visits) although this presents an ongoing cost to government. Information and incentives are required to support regulatory requirements of landholders.

The mandatory code of practice may be applied immediately to properties undergoing a change of ownership to oblige new landholders to comply. Additionally, the imminence of regulation may be communicated to landholders early on to increase adoption through suasion and participation in incentive schemes. However, given the heterogeneous distribution of *Cryptosporidium* sources in the catchment (Bryan and Kandulu, In Review) uniform regulation risks imposing high costs on some landholders with little benefit for water quality (Gunningham and Sinclair, 2005). To minimise this impact, full implementation of regulation such as a mandatory code of practice needs to come last in the sequence. In this way, the major contributors to the water quality problem can be addressed more cost-effectively through suasion and incentive-based measures. Ideally, regulation of a code of practice will mostly affect people moving into the catchment ensuring they manage land and water resources sustainably.

Other Minor Policy Features

Government-funded land buy back and land use change may be appropriate on a case-by-case basis. Attitudes to land buy back amongst the group ranged from very receptive to deep suspicion and resentment held over past schemes in the 1960s. Some landholders may also be willing to restructure farms from livestock to other more sustainable land uses.

5.4 Discussion

Policy design in this study involved tailoring a mix of policy instruments to effectively address impediments to adoption of water quality management. Each policy instrument has strengths and weaknesses, and none is robust enough to successfully address all important impediments in all contexts (Gunningham and Sinclair, 2005). Single-instrument policies are likely to be of limited effectiveness or worse, result in unintended adverse effects (Macgregor and Warren, 2002; Kaine and Johnson, 2004). Rather, a complementary package of instruments is more likely to succeed. A better strategy is to harness the strengths of individual policy instruments while compensating for their weaknesses by the use of additional complementary instruments (Gunningham and Sinclair, 2005). A mix of regulatory, suasive and incentive-based instruments as recommended in this study have been successfully applied in addressing non-point source pollution elsewhere (e.g. WFD, 2000).

The sequencing of policy instruments is probably as important as the mix. In this study, we followed the principle that policy sequencing that starts with less interventionist measures (encouragement) and is followed and complemented by more interventionist measures (enforcement) is more politically acceptable and equitable (Gunningham and Sinclair, 2005). In this study, the logical sequencing was also dictated by both the relative significance of impediments to adoption where the most important impediments (Knowledge Access, Trainer/Advisor Proficiency, Financial Resources (Landholders)) were addressed first. In the study area these two principles were complementary. However, in some catchments these principles may conflict (e.g. the most important impediment may be regulation-based). Some pragmatic compromise between these principles may be required in this case.

Underpinning all policy instruments is the necessity for targeting the most sites where the most significant improvements to water quality can be made. The increased cost-effectiveness of quantitative metrics, especially spatially explicit ones, in targeting policy is well established (Strauss et al., 2007; Connor et al., 2008b; Crossman and Bryan, 2009). Spatial metrics enable specific landholders to be approached through extension, and offered training and information. Spatial metrics can also form the benefits measure to enhance the cost-effectiveness of incentive schemes.

Critical to the design of the mix, sequencing, and targeting of policy instruments is the need for a detailed understanding of the catchment-specific context of the water quality problem. In line with other studies (Davies and Hodge, 2006; Bewsell et al. 2007; Moran et al., 2007; Kim et al., 2008) the landholder survey was found to be a useful tool for identifying the attitudes and drivers of management adoption amongst landholders. In this case, the survey provided an understanding of the broad impediments to and perceived benefits of adoption of water quality management. However, this broad understanding was only able to suggest an equally broad class of policy type (e.g. suasion, incentives, regulation). A deeper understanding of the catchment context is required to inform the design of an effective mix and scheduling of specific policy instruments (e.g. code of practice, reverse auction, etc.). Several authors have highlighted this complex nature of non-point source pollution and recognise the importance of understanding different aspects of the problem and using diverse policy mechanisms to address all aspects of the problem and enhance policy effectiveness (Gunningham and Sinclair 2005; Greiner and Miller, 2008; Greiner et al., 2008; Prokopy et al., 2008).

The DMCE process used in this study complemented the landholder survey by obtaining more detailed information on the catchment-specific context of the water quality problem in Myponga to support the policy design process. Multi-criteria evaluation supported effective policy design by providing structure and transparency to the complex decision making process, and clarified trade-offs. The process accommodated the views of various stakeholders and groups with the ultimate goal of achieving compromise and consensus on the best way forward (Proctor and Drechsler, 2006). The policy selection and design problem was well suited to multi-criteria evaluation. The DMCE process directly facilitated the quantification of weights reflecting the relative importance of impediments and benefits. The DMCE process also facilitated compromise and consensus on policy solutions as those alternatives that best address the most important impediments and achieve greatest benefits emerge as the preferred options.

The deliberative aspect of the multi-criteria evaluation process further enhanced the depth and breadth of understanding of the issues surrounding water quality management in the catchment in this study. This level of understanding was critical for tailoring an effective policy mix and sequence in this case study and, we suspect, for policy design in general. Invaluable context was uncovered (e.g. the perverse tax incentives and attendant overstocking problems) during the iterative and deliberative process of presenting background information, discussing impediments to adoption, and discussing how policy instruments and scenarios can be used to overcome impediments.

At the same time, participants' understanding of the causes and solutions of the water quality problem in the study area increased through the participatory process (Mustajoki et al., 2004; Renn, 2006). This was evidenced by the increased sophistication of the discussion and questions in the DMCE session. Hopefully, participants will communicate these messages more broadly in the community. In addition, participants were more accepting of the policy outcomes having been part of the design process.

Limitations to the policy design process in this study centred around uncertainty in the data on livestock and water quality management in the catchments. Through both the landholder survey and the DMCE process there may have been incentive to over-estimate rates of adoption especially amongst the more politically savvy dairy farmers. Thereby, the contribution of hobby farmers to the water quality problem may be slightly overemphasised. The effect of this uncertainty was minimised through policy design. Whilst, hobby farmers are targeted by incentive programs, suasion and regulation strategies cast a broad net which eventually captures dairy farmers who have over-reported their adoption of water quality management.

The ability to motivate adoption of management by landholders is a key determinant of the likely efficiency and ultimate success of environmental policy intervention (Connor et al., 2008a). In this study we approached the policy design process from the perspective of enhancing the widespread adoption of water quality management by landholders. The process inherently considers factors affecting policy choices including institutional feasibility, technical feasibility, and focuses on efficiency (Connor et al., 2008a). A limitation is that the cost of implementation and hence, the overall cost-effectiveness of policy, was not considered and may be a factor in final implementation of a policy solution by government.

5.5 Conclusion

In combination, the landholder survey and DMCE process provided information for policy design to achieve widespread adoption of water quality management for mitigating *Cryptosporidium* contamination in the Myponga River water supply catchment. The design of a mix of complementary policy instruments in this study was necessary to overcome the suite of impediments to the adoption of water quality management. By addressing the most important impediments, achieving the rates of adoption required to meet water quality and human health targets in water supply catchments is more likely. Adoption is further enhanced by the sequencing of instruments to start with encouragement and end with enforcement and, if possible, address the most important impediments first. Targeting of policy instruments at the highest contributing properties is also suggested for enhancing cost-effectiveness of achieving water quality and human health targets. The trend in the Myponga River catchment for continued conversion of larger commercial farms to small lifestyle properties is common to peri-urban catchments worldwide. This trend can potentially increase the risk of significant negative environmental and human health impacts from non-point source pollutants such as *Cryptosporidium* in water supply catchments. These risks may be mitigated by a carefully designed and targeted mix and sequence of policy instruments based on detailed, catchment-specific contextual information.

6. CONCLUDING REMARKS

The research process presented in this report attempted to address the complete picture of agricultural non-point source pollution in a water supply catchment as demonstrated with a focus on *Cryptosporidium* in Myponga. The sources of *Cryptosporidium* risk were quantified and the most cost-effective management alternatives were identified considering a full suite of potential costs and benefits. This information is sufficient for agencies to build a business case for capital expenditure on catchment-and treatment-based management to achieve the desired level of *Cryptosporidium* risk mitigation. Suggestions were provided on how to estimate the share of public and private costs. A policy solution was identified with the community, for the community, thereby enhancing the likelihood of widespread adoption. Whilst it is not without limitations, the process used in this study provides a blueprint for action in Myponga and similar investigations into the management of agricultural non-point source pollution elsewhere with the aim of being both cost-effective and socially acceptable.

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