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Evaluating alternatives for mitigating *Cryptosporidium* risk and generating environmental service benefits in water supply catchments

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Abstract

Evaluations of pathogen management options have focussed on assessing relative removal effectiveness as a basis for prioritising alternative management investment decisions. Using a case study of the Myponga catchment, South Australia, this paper presents results of a cost-effectiveness risk analysis of 13 catchment- and treatment-based water quality management alternatives for mitigating *Cryptosporidium* risk. A range of costs and benefits including set-up and operating costs, farm business costs and benefits, and environmental service benefits are considered in comparing the net cost associated with each management alternative. Considering the broader range of costs and benefits changes the relative cost-effectiveness of water quality management alternatives significantly. Combinations of catchment- and treatment-based management alternatives proved to be relatively more cost-effective at mitigating *Cryptosporidium* risk. Specifically, the combination of spatially targeted water course management upstream of the catchment with reservoir treatment by ultra-violet radiation provides a cost-effective *Cryptosporidium* risk mitigation strategy especially when the adoption of dung beetles and treatment by enhanced coagulation are included as complementary low cost alternatives. Considering the broader range of costs and benefits enhances the potential to increase the cost-effectiveness of investment in *Cryptosporidium* risk mitigation as well as produce a range of significant secondary benefits for water quality, biodiversity, and carbon sequestration.

Keywords: Cryptosporidium; Catchment management; benefit cost; cost effectiveness

1. INTRODUCTION

Millions of people die every year around the world from diarrheal diseases much of which is caused by contaminated drinking water (Hrudey and Hrudey 2004). *Cryptosporidium* is a parasitic water-borne protozoon infecting a wide host range including humans and cause gastrointestinal illnesses (*cryptosporidiosis*) which can lead to mortality. Since the 1993 outbreak of water-borne cryptosporidiosis affecting over 400,000 people in Milwaukee, USA, there have been at least 20 similar outbreaks in the UK, North America and Australia. (Corso et al. 2003).

Catchment water sources characterized by intensive animal husbandry have been associated with *Cryptosporidium* concentrations high enough to pose significant human health risk (Starkey et al. 2007). There are many potential sources of *Cryptosporidium* in contaminated catchments including livestock, wildlife, and human and/or agricultural sewage (Sturdee et al. 2007). Multi-functional water supply catchments providing drinking-water to local communities face the challenge of mitigating *Cryptosporidium* risk and observing strict guidelines for drinking-water quality (WHO 2006)

There are a number of ways Cryptosporidium may be eliminated from water including source control measures that address land use and farm management in catchments, treatment of raw water in water supply reservoirs, and treatment of finished water by domestic and industrial users. Implementation of source-control land-use and management activities upstream of the catchment may involve reducing direct livestock access to streams and better manure and sewage management (Ferguson et al. 2007). Reservoir treatment alternatives include enhanced coagulation, ultraviolet unit, and microfiltration unit (Betancourt and Rose 2004). Domestic and industrial treatment of tap water may involve boiling water and/or installing commercial water filter systems.

So far, the evaluation of *Cryptosporidium* management alternatives has prioritised alternative measures only on the basis of relative effectiveness at reducing *Cryptosporidium* risk to human health (Collick et al. 2006, Ferguson et al. 2007). However, recent studies have incorporated the use of economic and financial decision-support techniques in assessing *Cryptosporidium* management alternatives (Walker and Stedinger. 1999, Ashton. 2001, Barry et al. 1998).

The coincidence of disparate costs of risk avoidance and a budget constraint signals the obvious role for financial and economic analysis. Implementation of each one of the *Cryptosporidium* management alternatives identified would incur disparate direct costs including operation and maintenance (hereafter O&M costs), and opportunity costs and yield heterogeneous benefits both in terms of *Cryptosporidium* mitigation and other environmental benefits (nutrient reduction, biodiversity benefits).

Investment decisions in water quality management alternatives based entirely on effectiveness alone may lead to inefficient investment decisions (Emerton. 2006). Failure to incorporate spill-over costs and benefits of implementing management alternatives may lead to sub-optimal investments that may prove costly in the long run. For example, the loss of wetlands resulting from underinvestment in upstream catchment management activities may not only require upgrading water purification facilities, but also constructing flood control barriers in the long run. Failure to consider the full range of costs and benefits effectively undervalues alternatives that produce important additional benefits other than the one(s) being considered.

Economic decision-support tools such as cost-benefit analysis and cost-effectiveness analysis have been extensively used to evaluate water quality management alternatives (Hutton 2001, Zanou et al. 2004). However, these studies usually restrict the scope of the evaluation to only a select few costs and benefits. Reid (2001) considered a broad range of costs and benefits in evaluating water quality management alternatives. owever, this has yet to be applied in the assessment of mitigation of *Cryptosporidium* risk. Johnson et al (2008) recognizes the need to consider a broader range of economic and environmental costs and benefits in evaluating catchment-based and treatment-based management alternatives for mitigating *Cryptosporidium* risk to better inform investment decisions.

Using a case study in the Myponga River catchment, South Australia, this paper evaluates the relative cost-effectiveness of a range of catchment- and treatment-based management alternatives for mitigating *Cryptosporidium* risk in drinking water supply. A range of costs and benefits are identified, valued, and included in cost-effectiveness analysis. Specifically, economic valuation is used to estimate the set-up and operating costs of management alternatives, costs and benefits to the farm business, and the economic benefits associated with enhanced water purification functions over and above *Cryptosporidium* risk mitigation, biodiversity and carbon benefits. Some less significant environmental service benefits were not quantified including flood regulation, reduced sedimentation and cultural services such as recreational/aesthetic benefits. Some combinations of management measures are also assessed for their cost-effectiveness and risk implications. This study aims to inform management investment decisions on a comprehensive range of costs and benefits, risk and effectiveness tradeoffs associated with various management alternatives.

2. POLICY AND GEOGRAPHIC CONTEXT

The Myponga River catchment (123 km^2) is situated 50 km south of Adelaide, South Australia (Figure 1). Land use upstream of the catchment is dominated by livestock industries with 78% of the catchment area (250 farms) used for broadscale grazing (beef cattle and sheep) and 22% of the catchment used for dairying. The Myponga reservoir downstream of the catchment supplies fresh water to about 50,000 residents every year. All the upstream water uses impact on the quality of water supplied downstream and the biodiversity value of riparian environmentals especially as the catchment has been identified as a critical habitat for threatened bird species (Thomas et al. 1999).

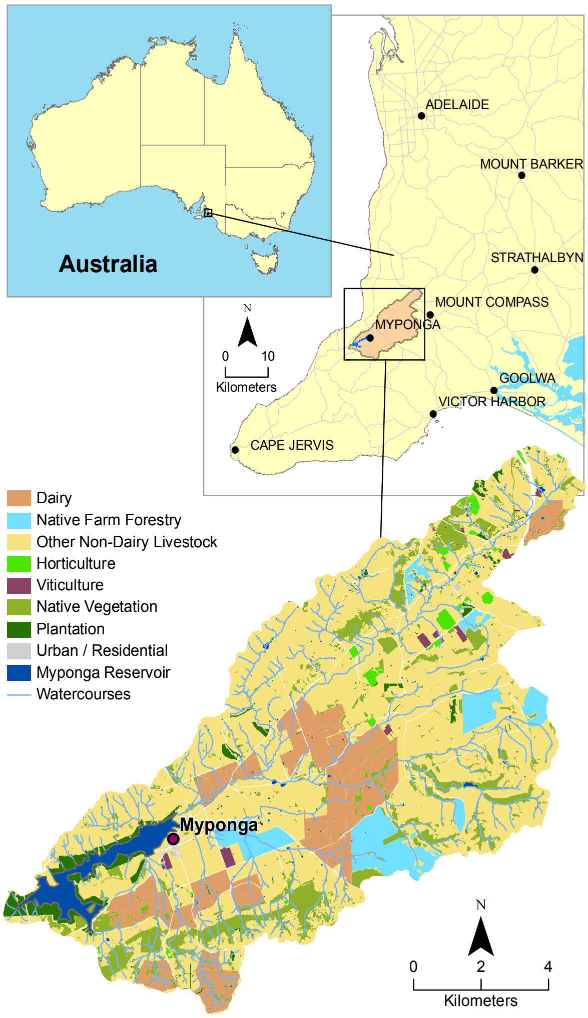

Figure 1 - Location map and land use in the Myponga study area[1].

Currently, water entering the Myponga catchment is treated using Dissolved Air Floatation Filtration and chlorination at the Myponga water treatment plant. *SA Water* considers the current *Cryptosporidium* removal capacity of the Myponga water supply system inadequate to achieve the required standard reliably in the event of an outbreak. Further management is required to enhance protection of water quality targets and mitigate the risk posed to human health by *Cryptosporidium*[2]. Several treatment options for enhancing treatment have been assessed, but incorporating catchment management activities would increase the likelihood of success (Deere et al. 2001)

Improving stream water quality and riparian management practices upstream of the catchment has the potential to increase farm productivity and profitability upstream of the Myponga catchment due to gains in quality of farm products such as milk, and meat, producer image/integrity (Gordon and Nelson. 2007, Zeckoski et al. 2007). Therefore, to the extent that improving land use and riparian management practices increases the production value of their farm, livestock farmers are expected to invest in catchment management strategies. However, the private optimum level of investment in riparian management practices for upstream livestock farmers is likely to be less than the socially optimal level of investment as non market environmental benefits would not be adequately considered in private investment decisions.

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[1] Source: Brett Bryan *CSIRO*

[2] Source: Jacqueline Frizenschaf *SA Water*

Under the current policy framework, livestock farmers would incur the full cost of implementing actions for improving land use and riparian management activities. The benefits would not be solely enjoyed by farmers as successful implementation of catchment *Cryptosporidium* mitigation strategies would yield positive externalities for downstream water consumers and the local community. As well, the environmental service benefits of implementing actions for improving land use and riparian management practices would only be realised in the longer term while costs would be incurred in the short term. Thus the disparity in time preferences of key investors (livestock farmers, environmental managers, local community, water suppliers and consumers) if not addressed would also lead to suboptimal investments. Regardless of who bears the cost therefore (i.e. the polluter or the beneficiary) there is need to identify and measure short- and long-term farm business and environmental costs and benefits. Results can be used to implement policies to internalise external short- and long-term costs and benefits of implementing management alternatives before prioritizing investments in *Cryptosporidium* management.

3. COSTS, BENEFITS AND WATER QUALITY MANAGEMENT INVESTMENT DECISIONS

Cost-benefit analysis has been used to compare the value of water purification services provided by well managed catchments against a number of treatment-based water quality management alternatives. Chichilinisky and Heal (1998) for example estimated that investing US $1-1.5 billion on catchment management avoided an extra US $6-8 billion on infrastructure costs to maintain the quality of New York's water supplies. Reid (2001) estimated that every US $1 invested in watershed protection saved anywhere from US $7.50 to $200 in cost for new water treatment facilities across several US cities.

Cost effectiveness analysis has also been used to evaluate water quality management alternatives (Zanou et al. 2004), in particular, in determining the minimum cost alternatives for managing diffuse source pollution (Gren et al. 1996, Elofsson 2003). A number of studies have considered a range of management alternatives from catchment-based source control, interception, and treatment (Ribaudo et al. 2001). Several studies have been able to identify cost-effective management alternatives for achieving water quality objectives (Rejesus and Hornbaker 1999).

These have largely focused only on highest priority, most readily identifiable and quantifiable values in their cost benefit assessments (Emerton 2004). However, water quality management alternatives, especially catchment management, yield secondary benefits (Chichilinisky and Heal 1998) The need to internalise externalities and conduct more comprehensive cost-benefit assessments in evaluating management alternatives to optimise investment decisions has recently been emphatically articulated in the water quality management literature (Emerton and Bos 2004, Emerton 2007).

A feature of this study is that cost-effectiveness analysis was used to evaluate a range of water quality management alternatives as the mitigation of *Cryptosporidium* risk was the primary objective of management. However, in quantifying the cost side, a range of set-up costs, O&M costs, farm business costs and benefits, and environmental service benefits associated with management alternatives are valued in monetary terms. The impact of including this broader range of costs and benefits on the cost-effectiveness of management alternatives is assessed.

4. METHODS

A selection of catchment- and treatment-based management alternatives are evaluated in this study for their cost-effectiveness at mitigating *Cryptosporidium* risk and generating secondary environmental service benefits. The risk mitigation effectiveness under each management scenarios (RE_s) in the Myponga catchment was estimated as a percentage using a pathogen model (Ferguson et al. 2007) and given as:

$$\mathrm{RE}_s = \frac{(\mathrm{C}_0 - \mathrm{C}_s)}{\mathrm{C}_0} \qquad \text{Equation 1}$$

Where RE_s is *Cryptosporidium* removal efficiency (%) of management scenario s; C_0 is the baseline/initial amount of *Cryptosporidium* recorded; and C_s is the quantity of *cryptosporidium* recorded after implementing management scenario s. Effectiveness can also expressed as log-removal effectiveness LRE_s where:

$$LRE_s = \log\left(\frac{1}{1-RE_s}\right) \qquad \text{Equation2}$$

A range of costs and benefits associated are valued in monetary terms using market-based economic valuation techniques. A screening process was used to determine the most important secondary environmental benefits generated by catchment-based water quality management for valuation in this study (**Figure 2**). Quantification of the costs and benefits of management alternatives are calculated in annualised present value terms. A discount rate (r) of 6% per annum is used over an analysis time frame (T) of 50 years.

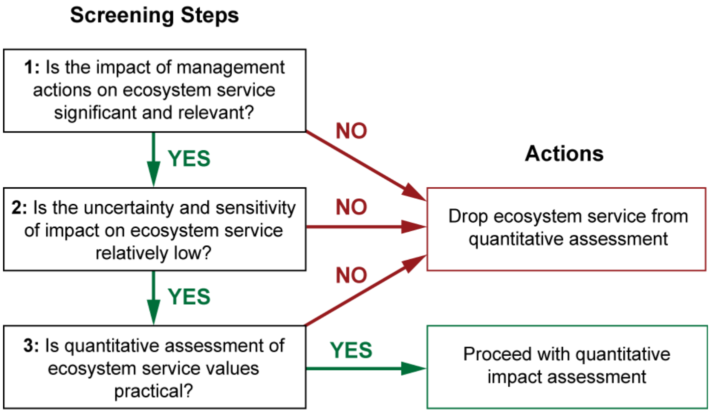

Figure 2. The screening process for selecting environmental service benefits for quantitative assessment and valuation of the impact of management alternatives.

4.1. Catchment-based Management Alternatives

The process of working out costs and benefits of implementing catchment management activities was largely supported by a spatial database in *ARC GIS.* The database contained several farm-level attributes including stock type, stock density, and length of stream bordered by farm. Using previous surveys of livestock farmers in the Myponga catchment, a farm-level map of livestock management practices across the catchment was created. A GIS-based hydrology database provided information on the spatial location of water courses across the catchment. From these, a map showing the distribution of streams open to unrestricted stock access across the entire catchment was constructed in *Arc GIS*[3]. Using this knowledge-base, we were able to

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[3] Source: Brett Bryan *CSIRO*

calculate the length of fencing required on each farm and the stream buffer area bordered by each farm.

4.1.1. *Cryptosporidium* Risk Mitigation Effectiveness

A pathogen budget model (Ferguson et al. 2007) used to identify the dominant catchment-based sources of *Cryptosporidium* revealed that the majority of the *Cryptosporidium* in the Myponga river catchment is derived from non dairy cattle. This conclusion is substantiated by land-use observations related to widespread cattle agricultural activity and poor water course management especially among non dairy cattle farmers. *Cryptosporidium* removal efficiencies (RE) of between 45% and 90% can be achieved by restricting the watercourse access of non-dairy cattle (to 50% and 5%, respectively) (Equation 2). Pathogen modelling results also show that a removal efficiency of up to 23% can be achieved through the adoption of dung beetles across the Myponga catchment. Hence, in this study we evaluate the cost-effectiveness of three non-dairy cattle water course access restriction targets (low – 25%, medium – 50%, and high – 95%), and the universal adoption of dung beetles in mitigating *Cryptosporidium* risk.

4.1.2. Water Course Management Scenarios

A set of effective, practical and complementary management practices for restricting non-dairy cattle from direct access to water courses were defined. These practices included fencing off water courses using a 10 metre buffer zone, revegetating riparian buffers with native species, establishing a single off-stream stock shelter planting per property (0.375 ha), providing alternative off-stream watering points, and installing stock crossings.

The disproportionate spatial distribution of non-dairy cattle densities and water course access across the catchment means that some areas tend to be the source of disproportionately large amounts of pollution than others. Targeting specific critical *Cryptosporidium*-source areas for management is likely to enhance the cost-effectiveness of risk management (Strauss et al 2007). However, water course management presents the opportunity to maximise significant spill-over environmental benefits while meeting water quality targets. Hence, we specify three spatial allocation objectives (minimum fencing cost (MINOC), maximum environmental benefit (MAXEB), and random spatial allocation (RAND)) in assessing the cost-effectiveness of achieving the three water course management targets. In total, a set of nine water course management alternatives s was assessed, where $s \in S${25MINOC, 25MAXEB, 25RAND, 50MINOC, 50MAXEB, 50RAND, 95MINOC, 95MAXEB, 95RAND}.

In targeting properties for catchment-based management under the minimum fencing cost strategy, the variable $MINOC_i$ was calculated to equal $n_i \div l_i$ where n_i is the total number of non-dairy cattle with unrestricted access to water courses and l_i is the length of fencing required to create a 10m buffer around water courses for each property i. Properties were then ranked in descending order of $MINOC_i$ and selected for management until the cumulative sum of cattle numbers exceeded the 25%, 50%, and 95% water course access restriction access restriction targets, respectively (Figure 3). This targets those properties for management that pose the greatest *Cryptosporidium* risk to water supplies and where this risk is less expensive to mitigate in terms of the significant cost of fencing. In targeting properties under the maximum environmental benefit strategy the variable $MAXEB_i$ was calculated to equal $n_i * ab_i$ where ab_i is the total area of riparian buffer per property. Properties were then ranked in descending order of $MAXEB_i$ and selected for management until the stock exclusion targets were met (Figure 3). The rationale is that those properties that pose the greatest *Cryptosporidium* risk are targeted especially where the cattle impact upon a larger riparian area and hence achieve greater environmental service benefits. For the random spatial allocation strategy, properties were ranked in random order and selected for management until the non-dairy cattle water course access restriction targets were achieved.

The fundamental reason for formulating the scenarios is to allow for easy derivation of the tradeoffs involved in shifting from low cost investment strategies with low *Cryptosporidium* removal efficiencies to high cost investment strategies with high *Cryptosporidium* removal efficiencies were also quantified. Also, this enables easy calculation of the costs and benefits of shifting from a minimum cost strategies to a maximum environmental return strategies at all the three levels of investment.

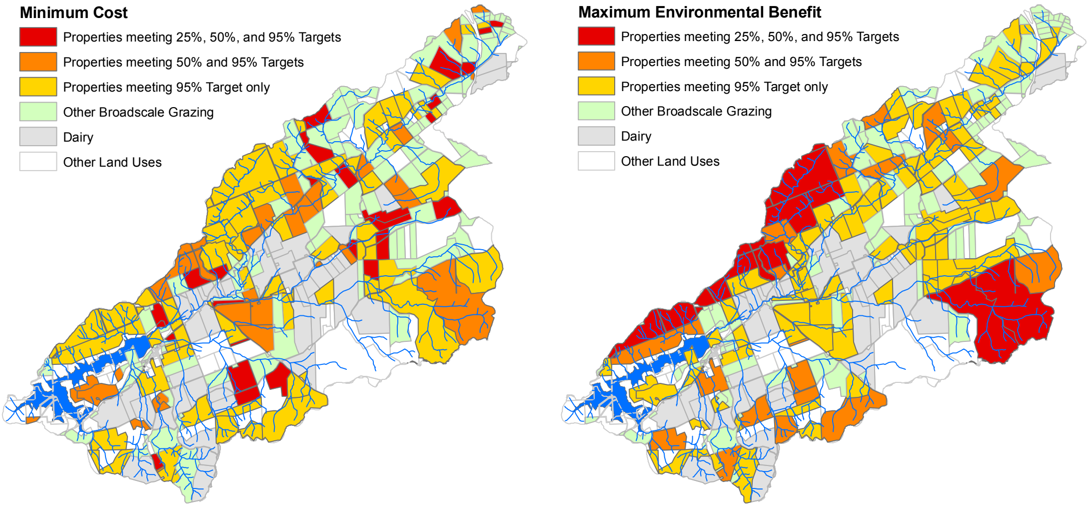

Figure 3. Non-dairy properties identified for management for each of the 25%, 50%, and 95% non-dairy cattle water course access restriction targets under the minimum fencing cost and maximum environmental benefit spatial targeting strategies[4].

Four variables were calculated based on the properties selected for management under each scenario that feed into cost-benefit analysis (Table 1). For the random allocation strategies, values for the four variables in Table 1 were taken as the mean values over 1,000 Monte Carlo simulations, a computational algorithm in Excel that repeated random selections of farms for management across the catchment until the stock exclusion targets were met.

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[4] Source: Brett Brian CSIRO

		Scenarios (*S*)								
Variable	**Symbol**	**25MINOC**	**25MAXEB**	**25RAND**	**50MINOC**	**50MAXEB**	**50RAND**	**95MINOC**	**95MAXEB**	**95RAND**
Length of riparian buffer fencing (km)	L_s	16.3	76.9	70.6	61.5	146.8	143.6	235.4	279.7	276.0
Number of properties managed	N_s	27.0	4.0	37.5	54.0	19.0	72.7	110.0	101.0	136.7
Riparian buffer area (ha)	AB_s	31.8	153.7	143.9	122.2	295.8	143.6	474.9	569.1	561.8
Total area of revegetation (ha)	AR_s	41.9	155.2	158.0	142.5	302.9	170.9	516.1	607.0	613.1

Table 1. Values for variables under each non-dairy cattle water course access restriction scenario.

4.1.3. Set-up and O&M Costs

Set-up and M&O costs include a range of direct costs associated with establishment and ongoing running and maintenance costs associated with catchment-based management actions. The variables and parameters used in calculating set-up and operating costs of catchment-based management alternatives are defined in Table 1 and Table 2, respectively. Parameter values for the Myponga catchment were assembled based on empirical estimates and market prices for the year 2007/08 (Table 2). For each non-dairy water course access restriction scenario *s*, the present value of set-up and operating costs were calculated such that:

$$PVC_s = PVC_{F,s} + PVC_{X,s} + PVC_{W,s} + PVC_{R,s} \qquad \text{Equation 3}$$

Where, under scenario *s*, $PVC_{F,s}$ is the present value of cost of fencing off a 10m water course buffer, calculated as:

$$PVC_{F,s} = L_s * USC_F + \frac{MC_F}{r} * (1 - \frac{1}{(1+r)^T}) \qquad \text{Equation 4}$$

$PVC_{X,s}$ is the present value cost of installing stock crossings, calculated as:

$$PVC_{X,s} = \left(\sum_{t_X} \frac{(USC_X * k_X * N_s)}{(1+r)^{t_X}} \right) + \frac{MC_X}{r} * (1 - \frac{1}{(1+r)^T}), \text{ for } t_X = 0,11,21,31,41 \qquad \text{Equation 5}$$

$PVC_{W,s}$ is the present value cost of installing off-stream watering points, calculated as:

$$PVC_{W,s} = \left(\sum_{t_W} \frac{(USC_W * k_W * N_s)}{(1+r)^{t_W}} \right) + \frac{MC_W}{r} * (1 - \frac{1}{(1+r)^T}), \text{ for } t_W = 0,16,31,46 \qquad \text{Equation 6}$$

and $PVC_{R,s}$ is the present value of cost of restoring riparian buffer areas and off-stream shelter areas, calculated as:

$$PVC_{R,s} = AR_s * d * USC_R + \frac{MC_R}{r} * (1 - \frac{1}{(1+r)^T}) \qquad \text{Equation 7}$$

For the universal adoption of dung beetles catchment-based management alternative the present value of set-up and operating costs were calculated as:

$$PVC_D = \frac{AT}{ac} * USC_D * j \qquad \text{Equation 8}$$

Parameters	Symbol	Value	Source
Fencing			
Unit set-up cost ($/km)	USC_F	9,000	Based on commercial quotes from Andrew Tindale Fencing
O&M cost ($/yr)	MC_F	300	Estimate based on fencing repairs done as part of Myponga Watercourse Restoration Project (EPA 2008)
Life expectancy (years)	T_F	50	Average of estimates provided by dairy farmers in Myponga
Stock Crossings			
Unit set-up costs ($/farm)	USC_X	5,000	Based on commercial quotes from Wenham Earthmovers Pty. Ltd.
O&M cost ($/farm/yr)	MC_X	1,000	Estimate based on repairs done as part of the Myponga Watercourse Restoration Project (EPA 2008)
Life expectancy (years)	T_X	10	Average of estimates provided by dairy farmers in Myponga
Number of systems/farm	k_X	1	Estimates provided by dairy farmers in Myponga
Off-stream Watering			
Unit set-up costs ($/system)	USC_W	7,500	Based on commercial quote from HRI Hardware Rural & Irrigation
O&M cost ($/farm/yr)	MC_W	400	Estimates provided by rural supplies company used during Myponga Watercourse Restoration Project (EPA 2008)
Life expectancy (years)	T_W	15	Average of estimates provided by dairy farmers in Myponga
Number of systems/farm	k_W	1	Estimates provided by dairy farmers in Myponga
Restoration/Revegetation			
Unit set-up costs ($/plant)	USC_R	2	Based on commercial quotes from Fleurieu Natives for Revegetation - Revegetation contractor engaged during Myponga Watercourse Restoration Project (EPA 2008)
O&M cost ($/farm/yr)	MC_R	300	Based on commercial weed control quotes from RG and MJ Stone - Weed control contractor engaged during Myponga Watercourse Restoration Project (EPA 2008)
Life expectancy (years)	T_R	50	Period of tree establishment and maturation determined based on 3-PG modelling of *Eucalyptus globulus*
Planting density (plants/ha)	d	2,667	Based on Eucalyptus globulus plantings after Schoenborn and Duncan (2001)
Universal Adoption of Dung Beetles			
Unit set-up costs ($/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	6,115	Total area of properties with non-dairy cattle access to water courses in Myponga catchment from GIS data calculated from GIS data

Table 2. Values used for set-up and operating cost parameters.

4.1.4. Farm Business Costs and Benefits

The restriction of non-dairy cattle water course access through fencing and revegetation of riparian buffers, provision of stock crossings, off-stream watering points and shelter plantings may have significant impacts on farm productivity. Gordon and Nelson (2007) found a link between farm productivity and drinking water quality for livestock. Benefits from livestock ingesting greater quantities of cleaner water include reduced incidences of diseases, and increased milk and meat production. Zeckoski et al. (2007) estimate an additional weight gain of 5% due to off-stream watering. In this case, based on a conservative sale price of $440 per head[5] and a count of 9,608 cattle, restricting the water course access of all non-dairy cattle in the Myponga catchment would increase agricultural revenue by $211,376 per year.

However, excluding stock from water courses may also incur productivity costs including loss of productive land (shelter plantings and stream buffers), and weeds spreading from riparian buffer areas. Based on opportunity cost estimates of

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[5] Source: Jack Landgberg PIRSA Livestock

$40/ha/year (Connor et al. 2008) it is estimated that the value of foregone productive land due to riparian buffer exclusion and off-stream shelter areas in Myponga is $27,599 per year. Using estimates of weed management costs of $300 per year for chemical spraying and $1,000 upfront for mechanical weed removal per property[6] the annualised cost of controlling weeds was estimated to equal $53,472 per year. Hence, the total productivity loss of restricting the water course access of all non-dairy cattle in the Myponga catchment was $81,071 per year, giving a net present value productivity benefit of $130,305 per year. This modest monetary impact of stock exclusion in terms of farm productivity costs and benefits is not enough to affect overall outcomes and does not warrant further consideration in the analysis.

4.1.5. Environmental Service Benefits

Three types of significant environmental service benefits produced by water course management were identified through the screening process (**Figure 2**) including water quality services (pathogen, sediment and nutrient reduction), biodiversity services, and carbon sequestration services. No significant environmental services produced by universal adoption of dung beetles were identified.

The total present value of secondary environmental service benefits of each non-dairy water course management alternative *s* was calculated as:

$$PVB_s = PVB_{WQ,s} + PVB_{B,s} + PVB_{C,s} \qquad \text{Equation 9}$$

where $PVB_{WQ,s}$ is the present value of water quality services, PVB_B is the present value of biodiversity services, and $PVB_{C,s}$ is the present value of carbon sequestration services produced by water course management.

4.1.5.1. Water Quality Service Benefits

Livestock cause erosion of stream banks and beds, and increase sedimentation and water turbidity. The defecation of livestock directly into water courses can also introduce a range of pollutants including a range of other human-infectious pathogens, and aquatic environmental nutrients (Byers et al. 2005).

A well-vegetated riparian zone can buffer water courses against these non-point source pollutants from adjacent agricultural land. Riparian vegetation slows the rate of surface run-off and traps sediment, nutrients such as nitrogen and phosphorus (Byers et al. 2005) from agricultural land.

Restricting livestock access to water courses and the restoration of riparian buffer zones can improve the quality of source water entering the reservoir (Parkyn et al. 2003, Byers et al. 2005) and thereby reduce the need for treatment for pathogens, turbidity, and nutrients. The present value of water quality services generated under each water course access restriction scenario was estimated based on avoided treatment costs as:

$$PVB_{WQ,s} = \frac{AB_s}{AB_{Tot}} * RE * \; [C_{EC} + \frac{(OC_{EC} + OC_{CS})}{r} * (1 - \frac{1}{(1+r)^T})] \qquad \text{Equation 10}$$

Variables and parameters used in valuing the environmental service benefits of water course management alternatives are defined in Table 1 and Table 3, respectively.

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[6] Source: Geoffrey Bradford Senior Watershed NRM Officer Mount Lofty Ranges Watershed Protection Office

Parameter values for the Myponga catchment were assembled based on market prices from a range of sources for the year 2007/08 (Table 3).

Parameters	Symbol	Value	Description
Water Quality Service Values			
Turbidity and pathogen mitigation through enhanced coagulation			SA Water estimates of costs of the enhanced coagulation process currently used. Based on the principle that pathogens adsorb to particulate matter, a reduction in finished water turbidity as part of the treatment process would also increase the removal effectiveness for pathogens.
Capital/fixed costs ($)	C_{EC}	120,000	
O&M costs ($/yr)	OC_{EC}	100,000	
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 Coyne et al. 1995, Blanco-Canqui et al. 2004, Sullivan et al. 2007).
Nutrient load-related annual expenditure by SA Water ($)	OC_{CS}	140,000	SA Water estimates based on algal bloom mitigation via copper sulphate dosing twice a year - cost: $130,000 to $150,000 per year depending on copper price
Total riparian buffer area	AB_{Tot}	602	Total area created by creating a 10m buffer around all water sources traversing properties with non-dairy cattle calculated using GIS data
Biodiversity Service Values			
Biodiversity value ($/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 2,667 plants/ha. Modelled across the Myponga catchment using 3-PG Spatial (Sands and Landsberg 2001)
Price ($/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)

Table 3. Parameters used to estimate environmental service values of catchment-based water quality management practices.

4.1.5.2. Biodiversity Service Benefits

Livestock impact directly on the biodiversity and ecology of riparian ecosystems through feeding on plants and trampling. Aquatic habitats can also be significantly degraded through erosion, and sedimentation. Exclusion of livestock from water courses can reduce or eliminate these degrading processes, promote environmental regeneration, and enhance habitat and biodiversity (Parkyn et al. 2003).

A benefits transfer technique was used to estimate the biodiversity value of riparian habitats in the Myponga catchment. Using the average market price for land used solely for biodiversity conservation p_B from the Victorian BushTender [7]auction for conservation contracts, the present value of biodiversity services for each water course access restriction scenario was calculated as (Table 1 and Table 3):

$$PVB_{B,s} = \frac{p_B * AB_s}{r} * (1 - \frac{1}{(1+r)^T})$$

Equation 11

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[7] A biodiversity stewardship payment scheme for implementing management activities that improve the biodiversity value of land ($/ha)

4.1.5.3. Carbon Sequestration Service Benefits

Riparian zone restoration and the planting of off-stream shelter areas sequesters atmospheric carbon dioxide. The amount of carbon sequestered by ecological restoration is dependent upon 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[8] (Landsberg and Waring 1997). *Eucalyptus globulus* is the tree species suited to high rainfall areas such as Myponga and was used to approximate the carbon sequestration rates of a suite of local endemic species (Sands and Landsberg 2001)[9]. The carbon dioxide equivalent (CO_2^{-e}) sequestration capacity calculated based on the 3-PG outputs ranged from 14.8 – 18.5 (tonnes CO_2^{-e}/ha/year) across the Myponga catchment. Using a carbon price from the European market, the present value of the carbon services under each water course access restriction scenario was calculated. (Table 1 and Table 3):

$$PVB_{C,s} = \frac{p_C * CS_{E.glob} * AR_s}{r} * (1 - \frac{1}{(1+r)^T}) \qquad \text{Equation 12}$$

4.2. Treatment-based Management Alternatives

Cryptosporidium oocysts are recalcitrant to conventional treatment processes of coagulation, sedimentation, filtration, and chlorination (Betancourt and Rose 2004). The process of conventional treatment at the Myponga treatment plant has been estimated by SA Water to achieve a *Cryptosporidium* log removal effectiveness (*LR*) of 3(See equations 2 and 3). 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 operating costs are valued for input into cost-effectiveness analysis. No significant additional environmental service benefits generated by treatment-based management alternatives were identified through the screening process (**Figure 2**).

4.2.1. *Cryptosporidium* Risk Mitigation Effectiveness

Under the baseline scenario, enhanced coagulation has been estimated by *SA Water* to provide an additional *Cryptosporidium* log-removal effectiveness of 0.5 in Myponga (See equation 2). Ultra-violet treatment can achieve a log removal of 2 to 4 (Betancourt and Rose 2004). Microfiltration involves passing water through a fine membrane and is able to achieve a *Cryptosporidium* log removal of >4 to 6 (Betancourt and Rose 2004).The median *Cryptosporidium* risk mitigation effectiveness values of 3 for ultra-violet and 5 for microfiltration were used in this analysis.

4.2.2. Set-up and Operating Costs

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

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[8] Models carbon dynamics of an environment by analysing area-specific characteristics such as tree species, age, plant density etc.

[9] Source: Neville Crossman *CSIRO*

$$PVC = C + [\frac{OC}{r} * (1 - \frac{1}{(1+r)^T})]$$ Equation 13

Table 4 documents the symbology for the set-up and operating costs and presents the values used for the Myponga case study.

Parameters	Symbol	Value	Description
Enhanced Coagulation			
Capital/fixed costs ($)	C_{EC}	120,000	SA Water estimates of capital costs for enhanced coagulation treatment
Operating costs ($/yr)	OC_{EC}	33,500	SA Water estimates, including slight additional workload from additional application of coagulant, monitoring, and maintenance
Ultra-violet Irradiation			
Capital/fixed costs ($)	C_{UV}	2,000,000	SA Water estimates for a system with a design capacity of 50 ML/day
Operating costs ($/yr)	OC_{UV}	100,000	SA Water estimates including power, lamp replacement, and labour costs
Microfiltration			
Capital/fixed costs ($)	C_{MF}	20,000,000	SA Water estimates of costs of replacing existing plant with a microfiltration plant, including earthmoving required to create additional space required on steep, rocky terrain
Operating costs ($/yr)	OC_{MF}	300,000	SA Water estimates of costs above existing treatment costs

Table 4. Summary of set-up and operating costs for treatment-based alternatives.

4.3. Cost-Effectiveness Analysis

Cost-effectiveness analysis is used to evaluate and compare the full set of 13 catchment- and treatment-based water quality management alternatives *Q*. The net present value of implementing each water quality management alternative *q* considers both set-up and operating costs, and environmental service benefits as:

$$PVNC_q = PVC_q - PVB_q,\ q \in\ Q\{S, D, EC, UV, MF\}$$ Equation 14

The total cost-effectiveness of each management alternative in mitigating *Cryptosporidium* risk in drinking water CE_q, is calculated based on set-up and operating costs only as:

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

where LRE_q is the *Cryptosporidium* risk mitigation effectiveness of alternative *q*. The net cost-effectiveness of each management alternative in mitigating *Cryptosporidium* risk in drinking water CE_q, is calculated using the net present value of alternative *q* as:

$$NCE_q = PVNC_q \div\ LRE_q$$ Equation 16

Finally, water quality management alternatives were ranked by cost-effectiveness and net cost-effectiveness. The margin of error and the likelihood of generating errors enough to affect conclusions underpinning the findings of this study were analysed using a sensitivity analysis. to the prevalence of uncertainty in parameter values was assessed by varying individual parameter values considered to have inherent uncertainty around the parameter value used. Net cost-effectiveness scenarios were calculated using a low discount rate ($r = 4\%$), high discount rate ($r = 8\%$), assuming no carbon market ($p_C = \$0$/tonne), assuming no biodiversity market ($p_B = \$0$/ha), and assuming a high fencing cost ($USC_F = \$12,000$/km).

5. RESULTS

5.1. Set-up and Operating Costs

Overall, universal adoption of dung beetles had the least absolute present value of total set-up and operating costs of implementation (Table 5). Amongst the water course management scenarios, costs varied with the access restriction target level and spatial targeting objective. Spatial targeting of properties with high numbers of non-dairy cattle either through the minimisation of fencing costs or the maximisation of environmental benefits reduced the set-up and operating costs of achieving targets by around \$1.5 – 2million compared to a random approach (Table 5). The relative contribution of fencing, stock crossing, off-stream watering, and revegetation costs to the total set-up and operating costs under various scenarios is sensitive to aggregate spatial dimensions under each scenario and determine the magnitude of the absolute value of O&M costs. The components of set-up O&M costs showing the greatest disparity across the scenarios is the cost of installing stock crossings and off-stream watering systems. Random scenarios tend to include a large number of farms with relatively few numbers of non-dairy cattle. This approach therefore incurs higher costs of installing stock crossings and off-stream watering systems (on each farm) than approaches that target farms with large numbers of cattle only.

Enhanced coagulation was the least expensive treatment alternative. The cost of ultra-violet treatment was comparable to the 50% access restriction scenarios whilst the cost of microfiltration was extremely high largely because of high set –up costs of installing a new plant (Table 5).

Management Alternative	Fencing	Stock Crossing	Off-Stream Watering	Restoration/ Revegetation	Total
25MINOC	151,397	560,570	372,728	172,546	1,257,242
25MAXEB	696,984	104,586	74,012	625,553	1,501,135
25RAND	640,073	980,570	693,919	636,668	2,951,230
50MINOC	558,384	1,411,908	999,164	574,749	3,544,205
50MAXEB	1,325,497	496,782	351,558	1,216,624	3,390,461
50RAND	1,297,247	1,899,853	1,344,468	1,283,854	5,825,422
95MINOC	2,123,528	2,876,109	2,035,334	2,069,539	9,104,510
95MAXEB	2,522,427	2,640,791	1,868,807	2,432,901	9,464,926
95RAND	2,488,742	3,574,088	2,529,273	2,457,422	11,049,525
Dung Beetles	-	-	-	-	183,450
Enhanced Coagulation	-	-	-	-	648,022
Ultra-violet	-	-	-	-	3,380,075
Microfiltration	-	-	-	-	28,140,224

Table 5. Summary of present value set-up and operating costs of water quality management alternatives.

5.2. Environmental Service Benefits

Table 6 shows that water quality service benefits account for most of the total environmental service benefits followed by carbon sequestration services and biodiversity. All water course management alternatives produce significant environmental service benefits. Environmental service values increase with the riparian area managed under the increasing water course access restriction targets. The minimum fencing cost alternatives produce substantially less environmental service benefits as properties with smaller riparian areas were targeted. The maximum environmental benefit targeting scenarios produce the highest environmental service values but only slightly more than the random targeting scenarios. The shift from minimum cost strategies to maximum environmental benefit strategies yields positive additional net returns at all three levels of investment.

Management Alternative	Water Quality Service Benefits ($)	Biodiversity Service Benefits ($)	Carbon Sequestration Service Benefits ($)	Total Ecosystem Service Benefits ($)
25MINOC	270,869	90,584	127,016	488,469
25MAXEB	1,308,090	335,106	469,883	2,113,078
25RAND	1,224,803	341,106	478,295	2,044,203
50MINOC	1,040,411	307,684	431,431	1,779,526
50MAXEB	2,517,767	654,152	917,246	4,089,165
50RAND	2,489,528	690,442	968,130	4,148,100
95MINOC	4,041,964	1,114,536	1,562,790	6,719,290
95MAXEB	4,843,774	1,310,670	1,837,808	7,992,251
95RAND	4,782,014	1,323,906	1,856,367	7,962,286
Dung Beetles	-	-	-	-
Enhanced Coagulation	-	-	-	-
Ultra-violet	-	-	-	-
Microfiltration	-	-	-	-

Table 6. Environmental service benefits of water quality management alternatives.

5.3. Cost Effectiveness

The water quality management alternatives assessed in this study achieve varying levels of *Cryptosporidium* removal effectiveness. The treatment-based alternatives of microfiltration and ultra-violet are the most effective followed by the three water course management alternatives that achieve the 95% access restriction target (Table 7).

The net present values of management alternatives range from a net benefit of nearly $700,000 for the 50MAXEB scenario to a net cost of nearly $30 million (Table 7). The results suggest that the environmental services benefits may substantially offset or exceed the set-up and operating costs associated with water course management scenarios, especially under the maximum environmental benefits scenarios.

Overall, the trade-off between cost and effectiveness is evident from results of this analysis with the exception of Ultra-violet treatment which is both very effective and relatively inexpensive. Treatment-based management alternatives make up the top four most cost-effective alternatives when set-up and O&M costs only are considered. (Table 7). Enhanced coagulation and the universal adoption of dung beetles are low cost but also relatively less effective alternatives. Microfiltration is extremely effective but also very costly. The water course management alternatives are not very cost-effectiveness when set-up and operation costs only are considered (Table 7).

Incorporation of the broader range of environmental service benefits in the calculation of net cost-effectiveness affects the ranking of water quality management alternatives considerably in favour of catchment-based management (Table 7). In particular, the maximum environmental benefit water course management alternatives at 25% and 50% water course restriction, respectively, are the most cost-effective as additional environmental service benefits achieved through managing larger riparian area more than off-set additional costs (Table 7). In addition, dung beetles and microfiltration become relatively cost-ineffective especially because they do not yield any significant environmental service benefits. The relative cost-effectiveness of both ultra-violet and enhanced coagulation treatment still holds despite not providing environmental service benefits (Table 7).

Management Alternative	Effectiveness (E, log-removal)	Total Cost ($)	Total Benefits ($)	Net Cost ($)	Cost-effectiveness (CE, $/log-removal)	Net cost-effectiveness (NCE, $/log-removal)	Rank (E)	Rank (CE)	Rank (NCE)
25MINOC	0.114	1,257,242	488,469	768,773	11,001,339	6,727,051	10	8	11
25MAXEB	0.114	1,501,135	2,113,078	-611,943	13,135,491	-5,354,733	10	9	**1**
25RAND	0.114	2,951,230	2,044,203	907,026	25,824,363	7,936,820	10	13	13
50MINOC	0.257	3,544,205	1,779,526	1,764,679	13,767,451	6,854,890	7	11	12
50MAXEB	0.257	3,390,461	4,089,165	-698,704	13,170,236	-2,714,112	7	10	**2**
50RAND	0.257	5,825,422	4,148,100	1,677,322	22,628,833	6,515,551	7	12	10
95MINOC	1.043	9,104,510	6,719,290	2,385,220	8,733,117	2,287,921	**3**	**5**	6
95MAXEB	1.043	9,464,926	7,992,251	1,472,674	9,078,830	1,412,601	**3**	6	**5**
95RAND	1.043	11,049,525	7,962,286	3,087,238	10,598,790	2,961,303	**3**	7	7
Dung Beetles	0.053	183,450	0	183,450	3,461,754	3,461,754	13	**3**	8
Enhanced Coagulation	0.500	648,022	0	648,022	1,296,045	1,296,045	6	**2**	**4**
Ultra-Violet	3.000	3,576,186	0	3,576,186	1,192,062	1,192,062	**2**	**1**	**3**
Microfiltration	5.000	28,728,558	0	28,728,558	5,745,712	5,745,712	**1**	**4**	9

Table 7. Cost-effectiveness analysis of alternative water quality management alternatives.

5.3.1. Sensitivity Analysis

Sensitivity analysis suggests that the top four most cost-effective water quality management alternatives are robust to reasonable variation in parameter values (Table 8). Neither the absence of a carbon or biodiversity market nor an increase in fencing costs affects the ranking of the maximum environmental benefit water course management alternatives. Only under a lower interest rate does the fourth most cost-effective alternative (enhanced coagulation) slip to sixth, ultra-violet slips to fourth, and the 95MAXEB alternative moves to third most cost-effective. This is because under a lower discount rate the future environmental service benefits generated by the water course management alternatives in general and the 95MAXEB alternative in particular, are worth more in present value terms. The internal rate of return defined as the rate of interest at which the net cost-effectiveness changes from positive to negative or vice versa was found to be a highly unlikely event.

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**
25MINOC	6,727,051	11	7,838,490	10	6,498,288	10	7,097,929	10	7,519,696	10	7,154,853	10
25MAXEB	-5,354,733	**1**	-1,243,086	**1**	-1,518,156	**1**	-11,569,208	**1**	-2,422,429	**1**	-3,335,569	**1**
25RAND	7,936,820	13	12,122,079	13	10,992,605	12	7,163,471	12	10,921,622	13	11,661,090	12
50MINOC	6,854,890	12	8,530,781	11	6,691,882	11	7,152,223	11	8,050,086	11	7,571,780	11
50MAXEB	-2,714,112	**2**	848,926	**2**	234,538	**2**	-7,482,933	**2**	-173,059	**2**	-1,003,938	**2**
50RAND	6,515,551	10	10,276,250	12	13,917,611	13	15,550,803	13	9,197,570	12	16,477,739	13
95MINOC	2,287,921	6	3,786,962	7	2,872,459	6	1,356,879	5	3,356,993	6	2,965,378	6
95MAXEB	1,412,601	5	3,175,440	5	2,340,528	5	-76,518	**3**	2,669,805	5	2,217,599	5
95RAND	2,961,303	7	4,741,944	8	4,329,570	8	2,461,604	7	4,231,203	8	4,533,007	8
Dung Beetles	3,461,754	8	3,461,754	6	3,461,754	7	3,461,754	8	3,461,754	7	3,461,754	7
Enhanced Coagulation	1,296,045	**4**	1,296,045	**4**	1,059,643	**4**	1,679,306	6	1,296,045	**4**	1,296,045	**4**
Ultra-Violet	1,192,062	**3**	1,192,062	**3**	805,837	**3**	1,037,055	**4**	1,192,062	**3**	1,192,062	**3**
Microfiltration	5,745,712	9	5,745,712	9	4,611,674	9	5,074,109	9	5,745,712	9	5,745,712	9

Table 8. Sensitivity analysis of net cost-effectiveness of alternative water quality management alternatives.

6. DISCUSSION

The probability of meeting water quality targets reliably depends on the capacity and reliability of the whole system and not the capacity of any single unit process (Asano 1998). Experience has shown that the mitigation of human health risks from drinking water relies on improved whole of system management and operation (Ferguson and Croke 2005, Rizak and Hrudey 2007). A comprehensive approach to risk management therefore, should focus on measures of control that extend from the catchment right through to the distributor. The enhancement of both catchment-based and treatment-based management is more likely to reliably achieve *Cryptosporidium* risk mitigation targets (Deere et al. 2001).

The reliability of *Cryptosporidium* management alternatives varies enormously. Portfolio theory suggests investing in combinations of management alternatives with different risk characteristics through diversification when costs and effects are uncertain. This insight, which implies options should be evaluated and chosen as packages rather than individually, opens up a new dimension of cost-effective risk analysis for water quality managers. For example Deere et al (2001) found that a implementing a combination of catchment and treatment based measures is the best way to manage risk posed by *Cryptosporidium*.

Evaluation of management alternatives based on effectiveness alone suggests that investment should be directed at treatment by microfiltration and water course management at the 95% access restriction level. This combination incurs a net cost of nearly $32 million. Ultra-violet as a treatment option and the adoption of dung beetles as a catchment-based management strategy are the least cost management alternatives for mitigating *Cryptosporidium* risk. This combination costs $3.76 million and achieves an additional log-removal of 3.053 giving a net cost-effectiveness ratio of about $1.2 million per log-removal. When a range of costs and benefits are considered the combination of ultra-violet treatment and the 25% access restriction maximum environmental benefit water course management alternative are the superior options. Theis combination achieves an additional log-removal of 3.114 for a net cost of $2.96 million giving a net cost-effectiveness of around $0.95 million per log-removal.

On the catchment side the results suggest that water course management using the maximum environmental benefit targeting approach is the most cost-effective due to the generation of significant environmental service values. In addition, the adoption of dung beetles may be used to complement water course management and provide an extra catchment-based barrier in mitigating *Cryptosporidium* risk at low cost. This combination of both catchment- and treatment-based management would achieve an additional log-removal of 3.67 - 4.6 for a net cost of $3.8 - $5.88 million.

7. 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. Each alternative differs in removal effectiveness, set-up and operating costs, impacts on farm productivity and environmental services. The primary objective of the analysis 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 the preferred investment as catchment-based alternatives are much less effective and benefits take longer to be realised. However, efficient investment in environmental management requires the consideration of both costs and the broad range of benefits in decision-making. When only set-up and O&M costs are considered treatment by ultra-violet and enhanced coagulation and adoption of dung beetles become more attractive. Incorporating a broader range of costs and benefits in cost-effectiveness analysis affects investment priorities to focus on water course management strategies for maximizing environmental benefits, and ultra-violet treatment. In addition, both enhanced coagulation and the adoption of dung beetles are worth considering as additional low cost complementary alternatives for enhancing reliability of *Cryptosporidium* risk mitigation measures. The results show that investment decisions made on the basis of set up and operating costs alone undervalue the additional environmental service benefits produced by water course management and hence may lead to sub-optimal investment decisions. Cost-effectiveness analysis based on economic valuation of a broad range of costs and benefits provides an informed basis for internalizing additional environmental services benefits produced by water course management. It also provides a basis for cost-sharing arrangements and targeting of high priority farms for management to further enhance cost-effectiveness.

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