Quantifying Stormwater Recycling Risks and Benefits:

Summary Report

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Disclaimer

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Cover Photo:
Stormwater storage pond at Royal Park

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Executive Summary

Improved management of urban water resources is of state and national importance as the use of water resources in many parts of Victoria and Australia is approaching the limits of sustainability. More integrated management of urban water is needed if the water requirements of the expected population are to be provided for without further deterioration of the environment and compromise to public health. One of the focal points of proposed urban national water management programs is the use of stormwater as an urban water supply source.

Stormwater harvesting projects are becoming increasingly popular yet our understanding of the performance of the schemes that recycle general stormwater is limited and little knowledge exists on human and environmental risks posed by these systems. One of the key limiting factors is lack of appropriate data for use in formal risk assessments.

To address this issue, Round 3 of the Smart Water Fund has supported the *Quantifying Stormwater Recycling Risks and Benefits* research project. This project has provided crucial knowledge about the actual water harvesting performance of urban stormwater harvesting systems (runoff from paved and unpaved urban areas), the level of microorganisms and other water contaminants moving through the system (from collection to point-of-use) and the associated environmental and human health risk posed.

This report represents Stage 3 of the Quantifying Stormwater Recycling Risks and Benefits project and summarises the overall outcomes and recommendations. Included is a summary of the results of the detailed assessments undertaken on each system during Stage 2.

The overall project provided valuable insight for the design and management of stormwater harvesting and reuse projects. The data collection and analysis program demonstrated the value of monitoring the actual performance of a system in comparison to design estimates, along with the benefit of adopting a risk management approach to evaluating human health risks. The key conclusions and recommendations of the project are summarised below.

The water volume monitoring and analysis demonstrated the importance of accounting for inter-annual variability in rainfall when calculating harvest volumes and system demand; changes in catchment surface characteristics; and long-term trends such as climate change will all have an important impact on actual system yields. Long-term average projections are not sufficient to describe the yield and performance of stormwater harvesting systems. For all three monitored sites storage capacity was NOT the most important constraint to yield, dispelling a widely held view that this is the key limitation to stormwater recycling in Australia. The investigation also identified that some stormwater treatment devices can dramatically reduce inflows and hence harvest volumes for full-scale systems. This loss needs to be accounted for in treatment train selection and system design.

The evaluation of treatment train performance demonstrated that a single microbial surrogate (such as *E. coli*) is not sufficient to represent the behaviour of all microbial groups as differences exist in the environmental behaviour of the different pathogen groups (viruses, bacterial and protozoan cysts). Treatment performance was evaluated using native and spike microbial surrogate organisms. Through this evaluation three limitations in using native surrogates were identified: 1. Variability in the inflow concentration of native surrogate organisms (more than 3 orders of magnitude) often exceeded the overall removal of the treatment barrier making removal performance difficult to evaluate. 2. Native surrogates were often not present in high enough concentrations to adequately quantify removal performance with outflow concentrations often reported as a high number of non-detects. 3. Secondary faecal contamination of open storage ponds lead to an underestimation of removal performance. In the light of these uncertainties $\log_{10}$ pathogen reduction credits had to be applied conservatively. Challenge testing (full-scale spiking trials) was identified to be able to overcome these limitations by the artificial introduction of a very high and consistent inflow concentration.

Separate consideration of baseline and event conditions was important for evaluating treatment removal performance. Performance of stormwater treatment barriers varies between low flow and event conditions; and even over the course of a single event. Comparison of average inflow and outflow concentrations is unlikely to capture the variability in removal performance. Quantification of removal performance under different scenarios and events is therefore important for any subsequent risk assessment.

The Quantitative Microbial Risk Assessment identified that the lack of data on the distribution of faecal pathogens in urban stormwater is a significant limitation to undertaking QMRA. The monitoring results for the faecal indicator organisms under event and background conditions at the Royal Park site demonstrated a high variability in faecal contamination. The variability in the concentration of human infectious pathogens of faecal origin is expected to be even greater with long periods of low or zero concentration and peaks of short duration. In addition, the distribution of faecal pathogens in urban stormwater is likely to be site specific, dependent upon the individual catchment and faecal sources. A risk management approach is essential with monitoring programs focussed on the expected sources of pathogens in the catchment, and quantifying the events that mobilise them.

Results from Royal Park demonstrate that if human faecal contamination were present, viral risks would dominate. Viral infection is common in the Australian community. Virions are excreted in very high numbers by infected individuals. These appear to persist in the environment, are not easily removed by sedimentation or sieving, and can be resistant to UV. The microbiological data collection program focussed only on faecal indicator organisms and surrogates. Based on these data it was not possible to identify the source(s) of faecal contamination, and hence the data provided no real evidence for or against the presence of human faecal contamination. The high counts for *Clostridium perfringens* were consistent with the presence of human faecal material - although other sources (including dogs) could account for these values. Review of the Royal Park drainage catchment indicated that human faecal discharges from cracked pipes and poor connections are likely as the area is a large, urban catchment with ageing infrastructure. In addition, sewage overflow events have been identified in the catchment including one notable event during the monitoring program. Therefore, a risk management plan that includes investigations for the possible presence of sewage is warranted.

Open storages that provide a habitat for waterfowl result in secondary faecal contamination and the potential for zoonotic transmission of infection (e.g. *Salmonella* and *Campylobacter* spp.). For transmission to occur, animals must be infected with a strain of pathogen that can cause infection in the human host. The frequency of the occurrence of these infections across species in urban catchments is not well known, and is no doubt constantly changing. If the system receives water contaminated with human faecal material, then the likelihood of waterfowl becoming infected with a human infectious pathogen may increase. When such an infection occurs, pathogen numbers and subsequent health risks can rise rapidly leading to probability of infection and disability adjusted life year (DALY) health burden estimates well above health targets. This scenario could lead to a higher incidence of human infection and the potential for an outbreak with disease burden implications. In this study, the Monash site contained an open storage pond downstream of the key system treatment barriers. Hence should secondary contamination occur at this site, there are no barriers to provide protection for human health. A framework is needed to incorporate the likelihood and consequence of these, most likely rare, infection events into the QMRA and management plan, so that rational decisions can be made to protect public health.

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1. Introduction – Project Overview

Improved management of urban water resources is of state and national importance as the use of water resources in many parts of Victoria and Australia is approaching the limits of sustainability. Better integrated management of urban water is needed if the water requirements of the expected population are to be accomplished without further deterioration of the environment and compromise to public health. One of the focal points of proposed urban national water management programs is the use of stormwater as an urban water supply source.

There has been a recent dramatic increase in stormwater harvesting projects throughout the State of Victoria, using general urban runoff (as opposed to just roof runoff) for non-potable purposes. This increase in stormwater harvesting projects is due to the growing recognition that stormwater is a valuable resource, offering multiple benefits of water conservation and water harvesting. There are strong indications that stormwater harvesting will become even more popular in future and so the level of investment in this alternative source of urban water supply will increase over time. Stormwater is an abundant resource, and the community's acceptance of stormwater harvesting has been reported to be higher than for wastewater recycling (CSIRO 2002) . Recent research has also dispelled the perception that storage is a barrier to stormwater harvesting (Mitchell et al. 2007) and found stormwater harvesting to be beneficial for urban stream health rather than detrimental (Fletcher et al. 2007), largely due to the reduction in runoff volumes and frequency of flow.

Yet our understanding of the performance of the schemes that recycle general stormwater is limited and little knowledge exists on human and environmental risks posed by these systems. One of the key limiting factors is lack of appropriate data for use in formal risk assessments. To address this issue, Round 3 of the Smart Water Fund has supported the *Quantifying Stormwater Recycling Risks and Benefits* research project. This project has provided crucial knowledge about the actual water harvesting performance of urban stormwater harvesting systems (runoff from paved and unpaved urban areas), the level of microorganisms and other water contaminants moving through the system (from collection to point-of-use) and the associated environmental and human health risk posed.

1.1. Current stormwater harvesting guidelines

In response to the recent increase in stormwater harvesting, various departments and agencies at the state and federal levels have been developing guideline documents in the last few years. Notable examples are:

- *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2): Stormwater Harvesting and Reuse* published by the Environment Protection and Heritage Council, the National Health and Medical Research Council and the Natural Resource Management Ministerial Council. This document, released as a draft for public consultation in May 2008 is one of three documents being produced in Phase Two of the national water recycling guidelines development process.
- *Use of Stormwater at Commercial, Industrial and Community Sites* by the Victorian Environmental Protection Agency.
- *Managing Urban Stormwater – Harvesting and Reuse* by Department of Environment and Conservation NSW, published in April 2006.

An important feature of the Australian Guidelines for Water Recycling (Phase 2): Stormwater Harvesting and Reuse, is the employment of a risk-based management approach. The use of health and environmental risk management frameworks to underpin water guidelines has been a consistent national change for all water systems that has occurred in the last few years. The strengths of adopting a risk management framework include its ability to: (1) be applied to a wide range of stormwater harvesting systems, and (2) consider a wide range of physical, infrastructure and operational factors which determine the health and environmental risks associated with a given system.

Risk assessments require data, particularly water quantity and quality data. At present, largely due to the relatively recent experience with stormwater harvesting in Australia, and the cost associated with rigorous data collection programs, there is a lack of suitable data. This lack of data availability was frequently noted in the draft Australian Guidelines for Water Recycling (Phase 2): Stormwater Harvesting and Reuse.

1.2. Project Aims & Objectives

The objective of this project was to undertake a data collection program that would allow the performance of existing full-scale stormwater systems to be evaluated and to support the implementation of quantitative microbial risk assessment. Three existing stormwater harvesting and reuse systems were selected and monitored to evaluate actual performance in terms of:

1. Harvest volumes in comparison to design estimates; and
2. Contaminant removal performance of each component of each treatment train in comparison to design estimates.

The extensive monitoring program undertaken as part of this project included evaluation of both water quantity and quality at each site:

> **Water Quantity:** Flow of water into, through and out of each of the stormwater recycling schemes in order to:
>
> - collect sufficient data to conduct a robust water balance of each system;
> - assess the total system water flux c.f. the design estimates, including the volumes of stormwater harvested (potable substitution volumes); and
> - investigate how the seasonality of stormwater flows and irrigation demand impacts on system capacity requirements (including storage and pumping) and the volume of water harvested.
>
> **Water Quality:** Water quality samples were collected during both dry and wet weather events and monitored for physio-chemical and microbial parameters. Samples were collected at critical points in each system including the inlet and outlet of each component of the treatment train, within the store, and at the point of end-use.
>
> Full details of the monitoring program are included in the Milestone 4 and Milestone 5 reports.

In addition, Quantitative Risk Assessment was undertaken for each full-scale system in order to:

1. Validate treatment barrier performance needs; and
2. Quantify the human health and environmental risks associated with each of the stormwater recycling systems.

The project was undertaken in three stages as illustrated in Figure 1.

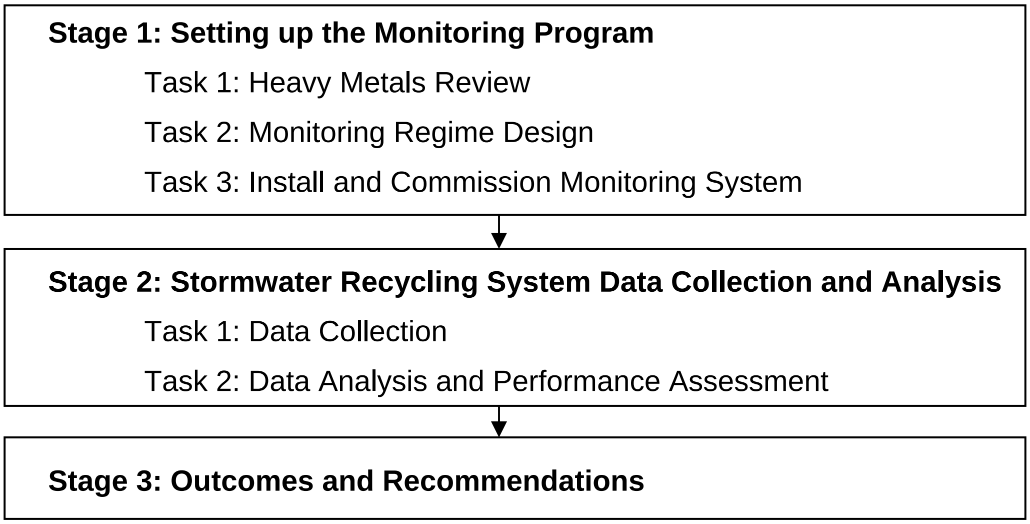


Figure 1. The stages of the Quantifying Stormwater Recycling Risks and Benefits research project

1.3. Purpose of this report

This report represents Stage 3 of the Quantifying Stormwater Recycling Risks and Benefits project and summarises the overall outcomes and recommendations of the project. Included is a summary of the results of the detailed assessments undertaken on each system during Stage 2. Further details of Stage 1 and 2 of the project are available in the following associated reports and publications:

B.E. Hatt, L. Flander, V.G. Mitchell (2006) *Quantifying Stormwater Recycling Risks and Benefits: Heavy Metals Review* June 2006 ISWR Report 06/04

V.G. Mitchell, J. O'Connor, S.R. Petterson, C. Davies, C. Kauncner, D. Roser and N.J. Ashbolt (2008) *Quantifying Stormwater Recycling Risks and Benefits: Data Analysis and Performance Assessment*, 11th International Conference on Urban Drainage, 11ICUD, Edinburgh International Conference Centre, 31st of August to the 5th of September 2008. Edinburgh, Scotland.

Davies, C.M., Mitchell, V.G., Petterson, S., Taylor, G., Lewis, J., Kaucner, C. and Ashbolt, N.J. (2008) Microbial challenge testing of treatment processes for quantifying stormwater recycling risks and management, Water Science and Technology, 57 (6) 843-847, doi:10.2166/wst.2008.194

Burns, M.J. and Mitchell V.G. (2008) Stormwater harvesting: assessing operational system performance, Australian Journal of Water Resources, Vol. 12 (2), pp 153-160, ISSN 1324-1583.

Petterson, S.R., Davies, C.M., Ashbolt, N.J., Mitchell, V.G., Taylor, G.D. and Lewis' J (2007) Quantifying microbial health risks for non-potable reuse of stormwater, In Proceedings of Reuse07, AWA National Water Reuse and Recycling Conference, UNSW, Sydney, 16-18 July 2007.

Petterson, S.R., Mitchell.,V.G., Davies,C.M. O'Connor, J., Kaucner, C., Roser, D. and Ashbolt, N.J. (2009) Issues in using native and spiked microbial surrogates to quantify pathogen removal performance of full-scale stormwater treatment barriers In

Proceedings of 15th Health Related Water Microbiology Symposium, Naxos, Greece, 31 May-5th June, 2009.

2. Description of the Stormwater Harvesting Systems

Three stormwater harvesting schemes were monitored intensively for over a year to understand the dynamics of stormwater collection, treatment, storage and harvesting performance. The three schemes were the Royal Park Stormwater Harvesting System, the Altona Green Stormwater Harvesting System and the Monash Stormwater Harvesting System (Figure 2).

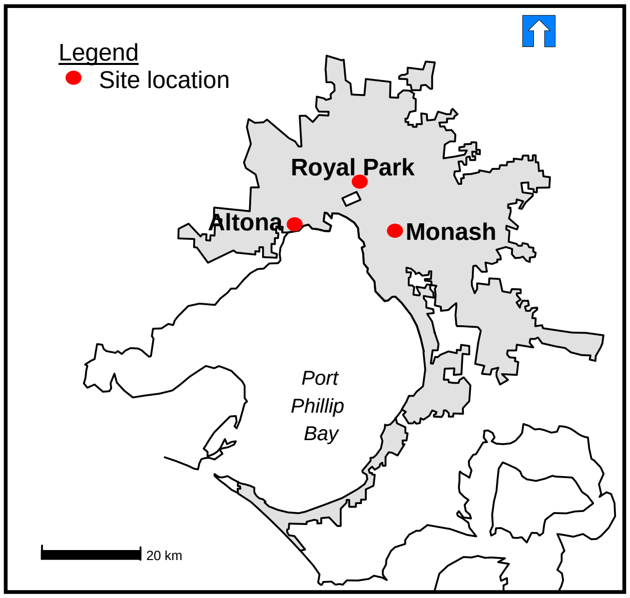


Figure 2: Location of the sites within Melbourne

The sites were selected based on the following criteria:

- Designed specifically to harvest stormwater;
- Constructed and fully operational in the Spring of 2006;
- The treatment barriers which have a biological component had been established sufficiently long enough to represent their longer-term behaviour during the monitoring period;
- Were well documented, allowing the post implementation performance to be assessed against the design estimates (including the volume of potable substitution, pollution reduction and end use water quality);
- Constructed in such a manner that the individual components of the system (such as the multiple treatment barriers) were suitable for monitoring;
- Support and cooperation of the designers, owners and the operators of the systems, as necessary for the success of the research project;
- Representative of the range of current Victorian industry practice in the field of stormwater harvesting; and
- Collectively contain a wide range of features that are likely to be contained in future stormwater harvesting systems.

To expand on the last criterion, the three systems were specifically selected to capture the following diverse features, including catchment land use and size, volume of potable substitution and the type and number of treatment barriers. Each of the sites contained one or more unique features of interest, as noted below.

2.1. Royal Park Stormwater Harvesting System

The Royal Park Stormwater Harvesting System is located in Royal Park, in the Melbourne suburb of Parkville. Stormwater runoff from the 187 ha mixed land use catchment was diverted from the Royal Park Main Drain into the stormwater harvesting system via an online sedimentation basin (Figure 3). The diverted stormwater flows through a 0.8 ha constructed treatment wetland (named Trin Warren Tam-Boore, meaning Bellbird Waterhole) into a 0.97 ha pond which had 12 ML of active storage capacity. The overflow from the storage pond returned into the Royal Park Main Drain that flowed into Moonee Ponds Creek. The stormwater was harvested by being pumped from the storage pond, via a UV disinfection unit, up the hill to two balancing stores. The balancing stores had the ability to mix the stormwater with potable water if desired, or use potable water as a back up supply when there was a shortfall in the availability of stormwater in the storage pond. The water held in the balancing stores was then pumped into the purpose built recycled water reticulation system, delivering stormwater to the Royal Park Golf Course, the Western, Ryder, Ransford and McAlister ovals for open space irrigation and also to two hydrants for water cartage truck filling (to water street trees and replenish water features such as fountains).

The 1984 Royal Park Master Plan proposed the development of a wetland at the Royal Park Site to provide a range of benefits to the local community including increased biodiversity, visual amenity and recreation. Then, in 1997, the original Royal Park Master Plan was amended, providing provision for a stormwater harvesting system to be established at the site as part of the proposed wetland. In 2002, the City of Melbourne contracted Ecological Engineering to undertake a preliminary feasibility study of establishing a stormwater harvesting system, and in 2004 Ecological Engineering prepared the conceptual system design. The broad design objectives were to reduce potable water usage within the City of Melbourne, improve the quality of stormwater entering the Moonee Ponds Creek, increase biodiversity in the surrounding area, provide a focal point for visitors, provide educational opportunities for local schools, and implement one of the key objectives of the Royal Park Master Plan. Ecological Engineering's conceptual design documentation reported that the annual average irrigation demand for the golf course and ovals was an estimated 94 ML/y, whereas the system has the capacity to provide 74 ML/y of this demand, on average. The shortfall was being met through potable backup supply.

Grogan Richards Pty Ltd carried out the detailed design and by 2005, the stormwater harvesting system at Royal Park commenced construction. The construction of the wetland and storage pond was completed in mid 2006 while the rest of the system (including the balancing stores and reticulation network) were completed in late 2006.

For this project the key features of interest were:

- a large, multiple land use catchment, which contains ageing water infrastructure. (c.f. Altona Green and Monash which are small infill development sites);
- a wetland, which is a technology widely used in stormwater management systems;
- a UV treatment unit within its treatment train, so is the only case study site considered in this project which disinfects the stormwater prior to its use; and
- active maintenance and operation by well trained staff.

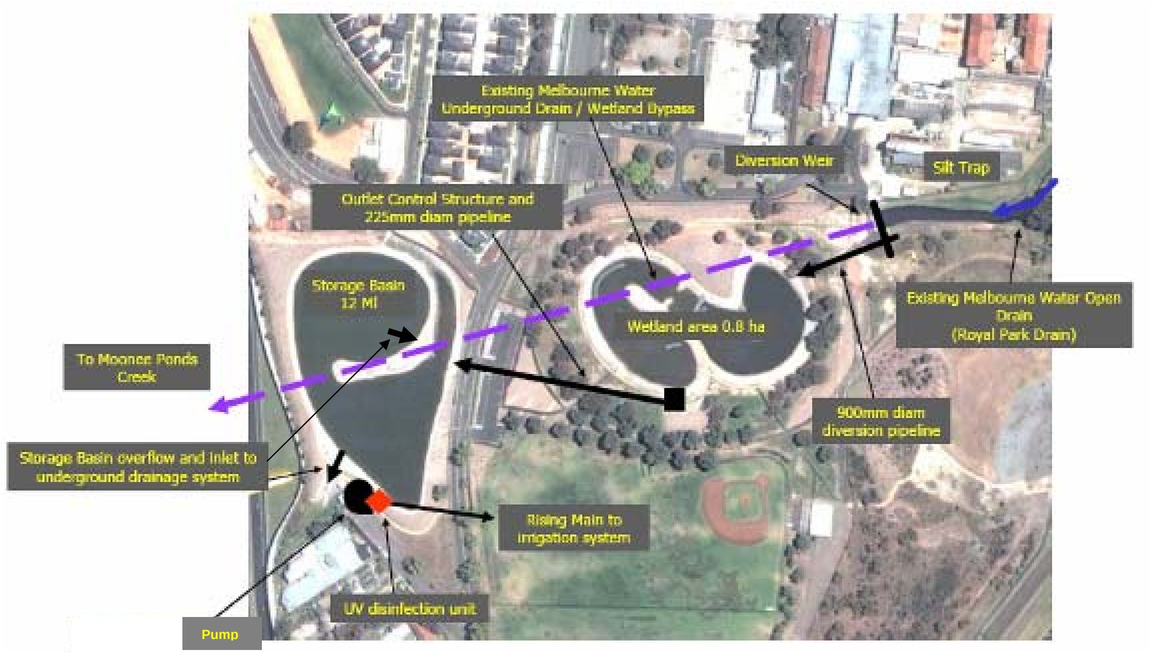


Figure 3: Schematic of the Royal Park harvesting system (Ecological Engineering, 2006)

The catchment ***Royal Park Main Drain Off take***

Wetland ***Storage pond***

UV disinfection units ***Balancing stores***

Irrigation area (Ryder Oval)

Figure 4: Photos of the Royal Park Stormwater Harvesting System

2.2. Monash University Stormwater Harvesting System

The Monash University site is located in the south west corner of the university's Clayton Campus in Melbourne. There are four distinct catchment components, a 2.1 ha sports oval, a 0.4 ha section of road, 0.45 ha of car park (part of the top of a multistory car park) and 0.0225 ha of roof catchment (Figure 5). All of these areas drain into the storage pond, via three inlets. The majority of the catchment (the sports oval and road) enters the pond at its northern end. The car park catchment flows through sedimentations tanks and a biofilter before entering the pond on it's western side. The small roof area drains straight into the eastern side of the pond. Stormwater is pumped out of the pond via a floating off take pipe, mixed with potable water in the balancing tanks, and then used to irrigate the oval.

Figure 5: The Monash University Stormwater Harvesting System (Source: modified from Google Earth)

It is not known when the pond was initially constructed, or for what purpose, although it is thought to be over 20 years old, collecting runoff from the road and sports oval. In 1996, the pond was drained and a clay liner installed to prevent flooding of the South East Flats, which had been attributed to seepage losses from the pond. In 2002, the Monash University Water Conservation Committee investigated establishing a stormwater harvesting scheme at the Clayton Campus. The University at the time was carrying out a major upgrade of the main sports oval that involved new drainage and automatic sprinkler systems. The close proximity of the storage pond and the recent upgrade of the main sports oval provided a great opportunity to economically establish a stormwater harvesting system for open space irrigation (Figure 6).

Road section of catchment ***Car park section of catchment***

Biofilter ***Storage pond***

Water meters at the balancing stores ***Balancing stores***

Sports Oval

Figure 6: Photos of the Monash University Stormwater Harvesting System

The Water Conversation Committee's design objectives were to reduce potable water usage within Monash University's Clayton Campus, support Monash University's water conservation strategy, and meet Melbourne Water's stormwater discharge requirements. The civil design component of the system was carried out by members of the Water Conservation Committee whereas mechanical and electrical services were outsourced. By late 2002, the system was operating.

In 2003, the Water Conversation Committee decided to increase the catchment size by capturing stormwater runoff from the recently constructed multi-story car park adjacent to the pond. To treat stormwater runoff from the multi-story car park, a treatment train consisting of sedimentation tanks and a biofilter was installed. The storage capacity of the pond was increased by 0.4 ML (to 2.6 ML) in 2006 by raising the height of the outlet by 300mm.

For this project the key features of interest are:

- a biofilter as the main treatment barrier, in addition to a sedimentation basin and storage pond (biofilters are an important emerging stormwater treatment technology);
- a multi story car park as part of its catchment, presenting different contamination hazards within the harvesting system; and
- a moderate level of operation and maintenance by university ground staff.

2.3. *Altona Green Stormwater Harvesting System*

The Altona Green Stormwater Harvesting System was the outcome of a collaboration between Hobsons Bay City Council and the Altona Green Primary School. In 2003, an area of vacant land adjacent to the primary school was redeveloped, creating a new residential development comprising of 20 house lots and Skipper Drive, which runs along the perimeter of the two sports ovals (Figure 7). Hobsons Bay City Council engaged Hyder Consulting to do the conceptual design, while the detailed design was carried out by Roger Milne and Associates.

The stormwater from the residential properties, road and ovals flows into the combined grass swale and biofilter system, which is in turn pumped into the underground store via an inlet pit. The stormwater then is pumped from the outlet pit to irrigate the two sports ovals using a sprinkler system. The total catchment area is 6.3 ha, the majority of which was the two sports ovals. The underground storage capacity is 0.4 ML (Figure 8).

There were a wide range of design objectives for the Altona Green system, covering biodiversity, amenity and water dimensions. The specific water objectives were to reduce potable water usage within the Hobsons Bay area, comply with Melbourne Water's best practice guidelines for pollutant removal targets, reduced the discharge of stormwater discharge from the site and provide flood protection.

For this project the key features of interest are:

- an underground store (c.f. Royal Park and Monash that have open storage ponds) which will potentially have advantages and disadvantages from a water quality point of view;
- it is indicative of the type of small scale infill residential development that will increasingly occur in cities which are wishing to limit urban sprawl;
- minimal treatment pre-storage; and
- minimal operation and maintenance.

Signage for Altona Green Park ***Catchment and grass swale***

Inlet pit ***Grass covering the underground store***

Water meters and potable back up ***Outlet pit***

Sports Oval

Figure 7: Photos of the Altona Green Stormwater Harvesting System

Figure 8: The Altona Green Stormwater Harvesting System (Source: modified from Google Earth)

It can be seen from the above aerial photo that many of the house blocks are yet to be built on, reducing the imperviousness of the catchment, relative to the design estimates, and thereby reducing the amount of runoff produced relative to the expected volumes.

2.4. Climate conditions for the three sites

The three sites are also geographically spread across Melbourne, resulting in differing climatic conditions at each site (Table 1).

Melbourne was in drought during the entire monitoring period with rainfall at each of the sites being well below historical averages, and pan evaporation being greater than historical averages, as shown in Table 2 and Figure 9 to Figure 11. This resulted in considerably less runoff than would be expected under more average climate conditions.

Table 1: Historical average rainfall and pan evaporation patterns for the three sites[1]

		Monthly mean												Annual mean
Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Altona Green	Mean rainfall, mm	38	42	38	46	46	42	42	46	51	56	50	47	545
	Rainfall coefficient of variation (c.v.)	0.72	1.01	0.87	0.68	0.54	0.48	0.47	0.42	0.53	0.51	0.59	0.61	0.22
	Pan evaporation, mm	200	168	139	89	58	41	48	65	86	123	150	185	1352
Royal Park	Mean rainfall, mm	48	49	46	57	56	47	48	53	59	65	60	58	646
	Rainfall coefficient of variation (c.v.)	0.76	0.91	0.81	0.65	0.52	0.48	0.45	0.42	0.51	0.51	0.61	0.61	0.21
	Pan evaporation, mm	191	162	130	82	53	38	42	60	80	117	142	177	1275
Monash	Mean rainfall, mm	53	55	56	73	78	68	65	74	75	81	74	71	824
	Rainfall coefficient of variation (c.v.)	0.66	0.86	0.72	0.56	0.49	0.43	0.41	0.42	0.48	0.46	0.55	0.59	0.20
	Pan evaporation, mm	179	153	122	77	49	35	40	57	76	108	131	162	1192

1: Data sourced from Silo using Data Drill (www.nrw.qld.gov.au/silo/datadrill/) for the period 1908 to 2007

Table 2: Rainfall and evaporation patterns during the monitoring period[1], mm/month

Location		Dec ‘06	Jan ‘07	Feb ‘07	Mar ‘07	Apr ‘07	May ‘07	Jun ‘07	Jul ‘07	Aug ‘07	Sep ‘07	Oct ‘07	Nov ‘07	Dec ‘07	Jan ‘08	Feb ‘08	Mar ‘08	Apr ‘08	May ‘08	Jun ‘08	Equivalent ann. ave[2]
Altona Green	Rainfall	16	32	20	32	29	36	24	50	8	9	14	71	46	10	19	34	12	46	10	327
	Pan evap.	214	212	179	163	95	83	40	50	81	102	154	161	201	216	152	172	90	50	50	1557
Royal Park	Rainfall	14	34	19	39	26	42	42	58	19	26	16	62	79	26	36	44	-	-	-	437
	Pan evap.	207	210	174	160	91	77	36	45	77	98	153	158	200	210	149	169	-	-	-	1661
Monash	Rainfall	41	23	18	41	22	60	72	86	31	35	29	84	160	15	33	60	-	-	-	608
	Pan evap.	193	194	166	145	82	68	32	43	69	87	135	146	182	195	136	159	-	-	-	1524

1: Data sourced from Silo using Data Drill (www.nrw.qld.gov.au/silo/datadrill/), except for Altona Green rainfall for the period 1/8/07 to 30/06/08 which was sourced from Melbourne Water (www.melbournewater.com.au/content/rivers_and_creeks/rainfall_and_river_level_data), 2: the equivalent annual average rainfall is calculated on the basis of the rainfall monitoring data presented in this table.

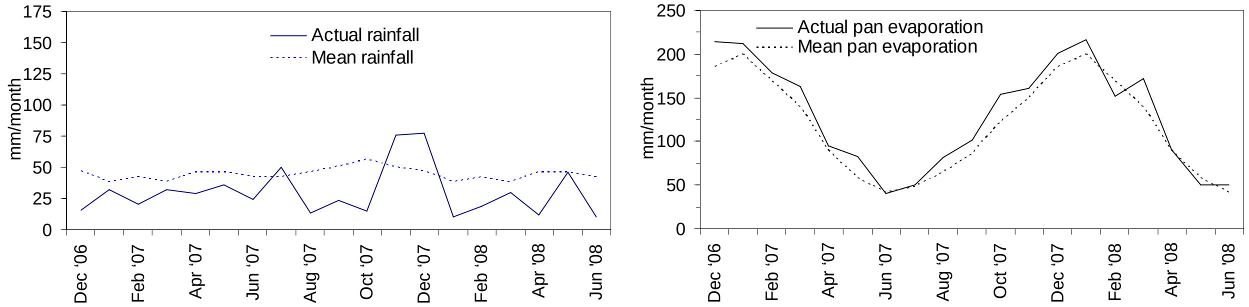


Figure 9: Comparison of actual and mean rainfall and pan evaporation – Altona site

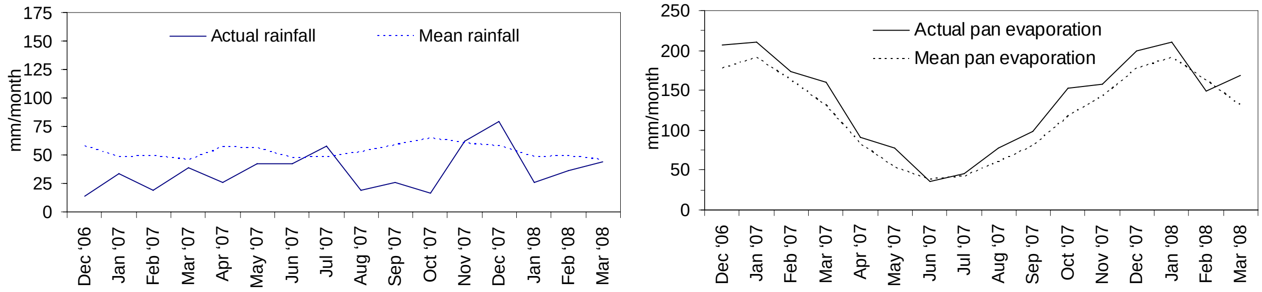


Figure 10: Comparison of actual and mean rainfall and pan evaporation – Royal Park site

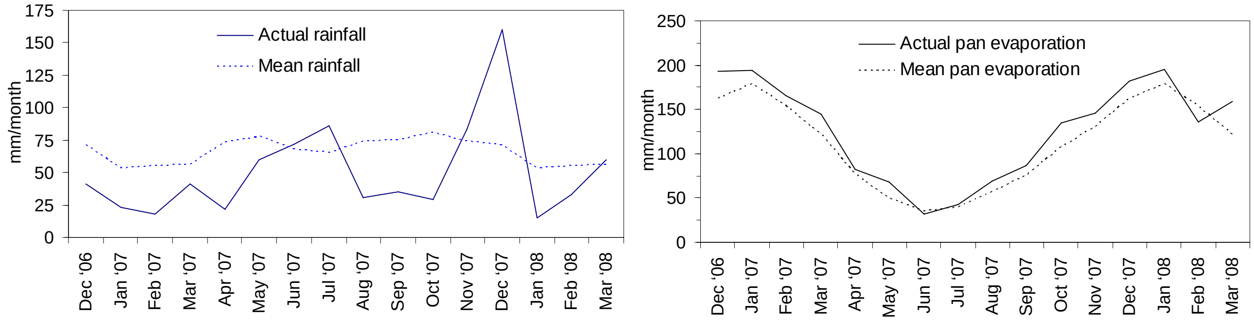


Figure 11: Comparison of actual and mean rainfall and pan evaporation – Monash site

3. Heavy Metals Review

During Stage 1 of the project an international literature review was conducted to critically summarise the state of knowledge about the short, medium and long-term human health and environmental impacts of the presence of heavy metals in stormwater used for recycling. The key aim of the review was to determine which heavy metals were of concern, thereby informing the detailed design of the monitoring regime. The full review is included in a separate report (Hatt et al. 2006).

Comparison of relevant data reported in the literature with water quality criteria indicated that concentrations of each of the heavy metals, and aluminium, in untreated stormwater are likely to exceed water quality criteria concentration limits for at least one water end use category.

Stormwater treatment via wetlands and ponds will most likely reduce the metals concentrations, although the performance of these treatment devices is highly variable depending on their design and operation. To date there has been a lack of research on the metals removal performance of the full range of WSUD type stormwater treatment measures. Therefore, at the time of undertaking the review, there was insufficient information available to design and operate a stormwater reuse system that performed reliably, providing an adequate level of metals removal.

It was recommended that the stormwater reuse system monitoring regime include metals as part of the suite of water quality parameters. The aims of this aspect of the performance monitoring and analysis were recommended to be:

- Determine the removal performance of the range of stormwater treatment devices contained within the three different stormwater reuse schemes;
- Determine if the stormwater that is delivered to the point of use meets the relevant fit-for-purpose water quality criteria; and
- Provide the required data for the subsequent reuse system performance assessment and the associated Quantitative Risk Assessment (Stage 2 Task 2).

4. Water Supply Performance Assessment

Water flow monitoring results were analysed to compare the observed water supply performance with design yields for each of the three study sites.

4.1. Royal Park

During the conceptual design phase of the Royal Park system, Ecological Engineering projected that the average annual stormwater yield of the system would be 74ML/y. When compared with the projected average annual demand of 95ML/y, the average annual volumetric reliability of the system was estimated to be 78%, with the yield constrained by the space available for the wetland and storage pond. Melbourne Water, based on this system yield estimate, granted the City of Melbourne approval for the water diversion with an annual cap of 74ML/y.

Water flux monitoring was undertaken over a 369 day period from January 2007 to January 2008. In the autumn of 2007, operators chose to limit irrigation in an effort to conserve available water, which suppressed the demand and influenced the overall yield evaluation. Indeed there was virtually no potable back up water used at the Royal Park site over the monitoring period, despite the fact that the period was considerably drier than the historical long term average with a total inflow from rainfall induced runoff ~33% lower than average, and a higher than average evaporative demand.

Irrigation demand modelling was therefore undertaken to estimate what the unrestricted demand would have been for the monitoring period. These calculations estimated the unrestricted demand to be 120ML, of which 77ML could have been supplied by harvested stormwater. More stormwater was available however the supply was limited by the annual diversion cap.

The modelling was then extended to investigate the dynamics of the system over the longer term. The 1998 to 2007 climate period was used, in line with current Melbourne Water practice. The modelling demonstrated that the highly seasonal pattern of demand, storage capacity in the pond, and the 74 ML/y stormwater diversion cap all limit the water supply performance of the system, however in five out of the ten years the usage of stormwater was limited by the diversion cap.

If the current storage capacity was doubled, without any change to the diversion limit or demand pattern, there would be a small increase in the average annual amount of stormwater harvested (~5%). Both doubling storage capacity and removing the diversion limit gives rise to somewhat larger increase in yield (~15%), but still rather modest given the cost of providing another 12 ML of storage.

If the diversion limit was removed, without any change to storage capacity or demand pattern, it was estimated that there would be a ~5% increase in the average annual amount of stormwater harvested, equivalent to doubling the storage capacity.

Therefore, it was concluded that re-negotiating the upper cap on annual diversion volumes should be considered in preference to increasing storage capacity. It is important that stormwater harvesting is not detrimental to the health of urban waterways. So it is suggested that the current simple maximum annual volume diversion conditions be replaced with a more flexible set of rules, which responds to climate conditions, enabling increasing harvesting in wetter years, when the environmental impact of increasing harvesting would be negligible.

4.2. Monash

During the conceptual design process, the university grounds staff determined that the irrigation demand would be in the range of 5.4 to 7.2 ML/year. Based on the established operational practice of using a 70:30 mix of treated stormwater and potable water, the demand for treated stormwater was estimated to be in the range of 3.8 to 5.0 ML/year.

The system was not designed with a specific potable water reduction target. Rather, Monash University's Water Conservation Committee and grounds staff were keen that the system provide as much potable supply substitution as possible (i.e. reliability was not a concern). The grounds staff operating the system stated that they didn't expected it to fully meet demand based on past experience.

Water flux monitoring was undertaken over a 365 day period from March 2007 to February 2008. Approximately 12.9 ML of water was used for open space irrigation during this period, of which 2.6 ML was harvested stormwater, representing 20% of the total amount used for irrigation.

Rainfall over the monitoring period was around 20% less than the long-term average with a higher than average evaporative demand, a higher demand was therefore expected. For comparison, modeling results estimated that for average rainfall conditions, an additional 1.1ML of stormwater may have been harvested, and the irrigation demand reduced to 7ML.

The water supply performance of this site was primarily limited by the lack of catchment inflows to the storage pond. An estimated 50-100% increase in catchment area would be necessary to enable the system to provide 70% of the open space irrigation requirements.

A second factor influencing the water supply performance of the system was the retention of water by the biofilter. Based on the monitored inflow and outflow data for the Monash Stormwater Harvesting System biofilter, it was estimated that one third of the inflow volume was retained (Hatt *et al.*, accepted). Therefore, in stormwater harvesting systems the use of biofilters as a treatment barrier may lead to a significant volume loss, which should be taken into consideration when evaluating the benefits and disadvantages relative to other treatment component options.

Monash University's Water Conservation Committee and grounds staff have been opportunistic in their development of this stormwater harvesting system, exploiting an existing pond as a water supply source. They have sought to increase the inflows to the pond, to improve both the reliability of the stormwater supply, and improve the quality of the water held in storage. The system in its current form will always struggle to provide a significant proportion of the open space irrigation demand.

4.3. Altona Green

Design modelling of the Altona Green system conducting by Hyder Consulting, estimated that over the long term, stormwater harvesting could contribute 62.5% (2.5 ML/y) of the average annual irrigation demand of 4ML (Charlton 2006). As part of this initial work, an average of 7.8ML/y of stormwater runoff was estimated to flow into the storage inlet pit, indicating that the primary constraint to yield would be storage capacity.

The water flux of the system was monitored for a 366 day period from July 2007 to June 2008. The water level in the underground store was continuously monitored, providing a clear indication of how the water was actively used in the summer irrigation months, filled during late autumn and remained full until the following spring. Of the 5.2ML of water used for open space irrigation during the monitoring period, 33% was supplied by harvested stormwater. The amount of rainfall during the monitoring period was 30% below the long term average. As a consequence, an increase in irrigation demand and decrease in stormwater runoff would be expected. Indeed, the amount of irrigation water actually used in this twelve month period was 30% above the design estimate, which seemed reasonable given the low rainfall.

More surprisingly however, the stormwater inflows (into the inlet pit) were well below those assumed during the design process, even when the lower than average rainfall was considered. A linear relationship between rainfall and stormwater inflow was observed in the dataset. By quantifying and extrapolating this relationship, it was estimated that in an “average rainfall year” there would be in the order of 2.7 ML of stormwater inflow into the inlet pit, well below the 7.8 ML/y estimated by the designers. It appeared that the runoff coefficient of the residential and sports field components of the catchment along with the swale was in the order of 0.07, considerably lower than that assumed during the design process (catchment weighted average of 0.22).

Two factors were identified which may have led to the lower than expected stormwater flows into the inlet pit. Firstly, to date, not all of the residential catchment has been developed, and so this component would have been less impervious than assumed. Secondly, and perhaps more significantly, there appears to have been a significant amount of infiltration losses from the unlined swale. The design drawings expressly noted that there would be stormwater infiltration losses, although the design water balance calculations did not take these losses into account, leading to the over estimation of stormwater inflows. Therefore, as was noted previously regarding the use of biofilters at the Monash site, the use of unlined swales are likely to lead to a significant volume loss, which should be taken into consideration when evaluating the benefits and dis-benefits of using them as part of a stormwater harvesting system.

Monitoring the Altona Green system demonstrated that the key constraint on the system performance was the amount of stormwater inflow rather than storage capacity. Minimising losses in the collection and treatment components of the system during design and construction would have resulted in improved system performance.

4.4. Conclusions from the Water Supply Performance Analysis

The following provides a summary of the key lessons drawn from the water supply performance analysis of the three stormwater harvesting systems:

- There will be significant month-to-month and year to year variations in catchment runoff, stormwater inflows and irrigation demand for any stormwater harvesting system. Therefore, graphs of average system performance are indicative only, providing a general guide to system behaviour only.
- It is crucial that any predictive performance modelling conducted as part of the design process accounts for inter-annual variability in runoff and demand, as well as projected changes due to climate change, otherwise the modelling results will systematically over estimate system yield.
- Whilst storage capacity constraints are routinely put forward as the limiting factor in a stormwater harvesting system, in all three monitored sites storage was not the most important constraint. For example, in the case of the Monash and Altona Green sites, stormwater inflows to the store limited the harvesting potential of these systems. Furthermore, the 74 ML/y diversion cap limited the stormwater yield from the Royal Park system more than storage capacity.
- Employing stormwater treatment devices which intercept or lead to infiltration of a significant proportion of the catchment runoff can dramatically reduce stormwater inflows and therefore the benefits and disadvantages of their use should be weighed up during the design process. Measures to reduce stormwater runoff losses should also be considered.

5. Pathogen Removal Performance of Stormwater Treatment Systems

Quantifying pathogen removal across stormwater treatment barriers is important for undertaking Quantitative Microbial Risk Assessment, and for evaluating the potential human health risks associated with end use water. During treatment, the number of infectious pathogens in the water column may be reduced by physical removal and/or pathogen inactivation (including grazing by other biota). The objective of this component of the study was to quantify the pathogen removal performance of the key treatment barriers at each of the three sites. Pathogens are not present in consistently high enough concentrations in stormwater to warrant direct enumeration, therefore faecal indicator organisms were used as microbial surrogates to investigate treatment removal performance. The magnitude of removal depends not only on numerous environmental factors, but also on the characteristics of the individual microorganism in responding to environmental processes and stressors. Rather than focus only on bacterial indicators such as faecal coliforms or *E. coli* to estimate pathogen removal performance, it was important to give consideration to the between organism variability in removal by considering each of the microbial groups (bacteria, viruses and protozoa) separately.

In this study, the treatment barriers at each of the three sites were evaluated using monitoring results of native microbial surrogates (*E. coli* to represent the behaviour of enteric bacteria, somatic coliphages to represent the behaviour of enteric viruses, and *Clostridium perfringens* to represent the behaviour of parasitic protozoan oo/cysts) from samples collected under baseline conditions and following rainfall events. For the three barriers, Monash sedimentation basin, Monash biofilter and the Royal Park UV, challenge testing was also undertaken. For the Monash sedimentation basin and biofilter, high concentrations of microbial surrogates (*E. coli* to represent enteric bacteria, the coliphage MS2 to represent enteric viruses, and *Saccharomyces cerevisiae* (baker's yeast) to represent protozoan cysts) were introduced (spiked) into the system upstream of the treatment barrier, and then monitored before and after treatment. For the Royal Park UV system, MS2 coliphage was used to evaluate performance, with a spiking trial undertaken on site, and laboratory scale collimated beam tests. Full details of the monitoring results and data analysis are included in the separate data collection and analysis report (Mitchell *et al.*, 2008).

A summary of the treatment trains for each site is included here along with the key outcomes of the performance evaluation.

5.1. *Royal Park*

The key barriers at the Royal Park site are illustrated in Figure 12, and results are presented in the following sections.

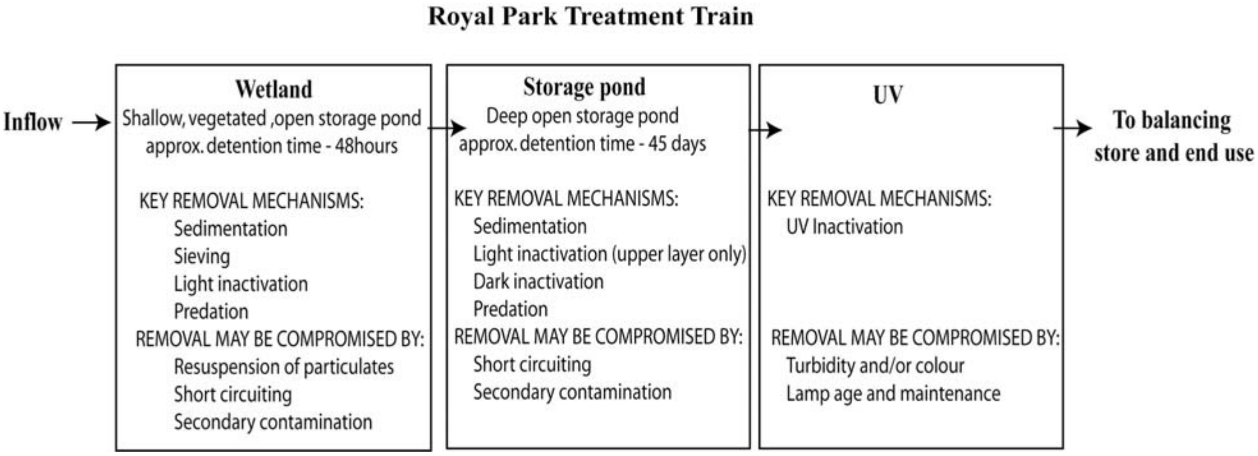


Figure 12: Royal Park treatment train

Royal Park Wetland: Average concentrations of all three native surrogate organisms were reduced by passage through the wetland, however during events, peaks in targeted bacteria and virus surrogate concentration were observed at the outflow. Indeed under event conditions, no viral reduction could be assumed. In contrast however, *C. perfringens* spore removal was observed to be higher during event conditions in comparison to background removal, this may have been real or apparent. *C. perfringens* spore removal may be enhanced during event conditions due to the higher proportion of settleable solids in the water column (Characklis et al. 2005), and the preferential attachment of *C. perfringens* to them. Alternatively, the apparent increase in removal performance may only be due to the lower inflow concentration during background conditions; the potential for removal may indeed be higher during background conditions, but it is not possible to demonstrate this with the native surrogate data. Following the pattern of *C. perfringens* removal, a higher log credit was assigned to *Cryptosporidium* under event conditions in comparison to background (Table 3).

Royal Park Storage Pond: It was not possible to statistically distinguish between the event and background datasets, and hence they were pooled. Variability in the inflow concentration of the native surrogates (around 3 orders of magnitude) meant that removal was difficult to demonstrate. Some reduction in the peak inflow concentration was observed for each of the organisms.

UV disinfection: Challenge study results confirmed the effective dose received by pathogens on passage through the UV unit. Based on this dose, reported pathogen sensitivities from the literature (Hijnen et al. 2006) were used to estimate the $\log_{10}$ reduction for each reference pathogen.

A summary of the $\log_{10}$ credits assigned to each of the treatment barriers at Royal Park is reported in Table 3. The lowest overall removal credit was noted for the human enteric viruses, given poor physical removal during events, and resistance to UV inactivation. While the monitoring data provided no evidence for assigning a removal credit to the viruses under background conditions, this was believed to be excessively conservative. Based on data reported in the literature, some removal would be expected under low flow conditions and a conservative value of 0.3 was selected to represent this. More data is required to support the selection of this assumed value.

Due to the presence of waterfowl on both the wetland and storage ponds at Royal Park, the use of native surrogate data for the evaluation of treatment performance was compromised. In particular, the treatment removal for bacterial pathogens based on *E. coli* was likely to be underestimated. Also, low inflow concentrations during background conditions may have led to an underestimate of removal performance.

Table 3: Log_{10} reduction credits for the Royal Park treatment train under event and background conditions

	Wetland		Storage Pond	UV disinfection	**OVERALL**	
	Background	Event			Background	Event
Salmonella	0.5	0.3	0.5	2.7	3.7	3.5
Campylobacter	0.5	0.3	0.5	4.6	5.6	5.4
Rotavirus	0.3	0	0.1	0.53	0.93	0.63
Adenovirus	0.3	0	0.1	0.13	0.53	0.23
Cryptosporidium	0.5	1.5	1	2.3	3.8	4.8

5.2. Monash University Site

The key barriers at the Monash site are illustrated in Figure 13 and results are presented in the following sections.

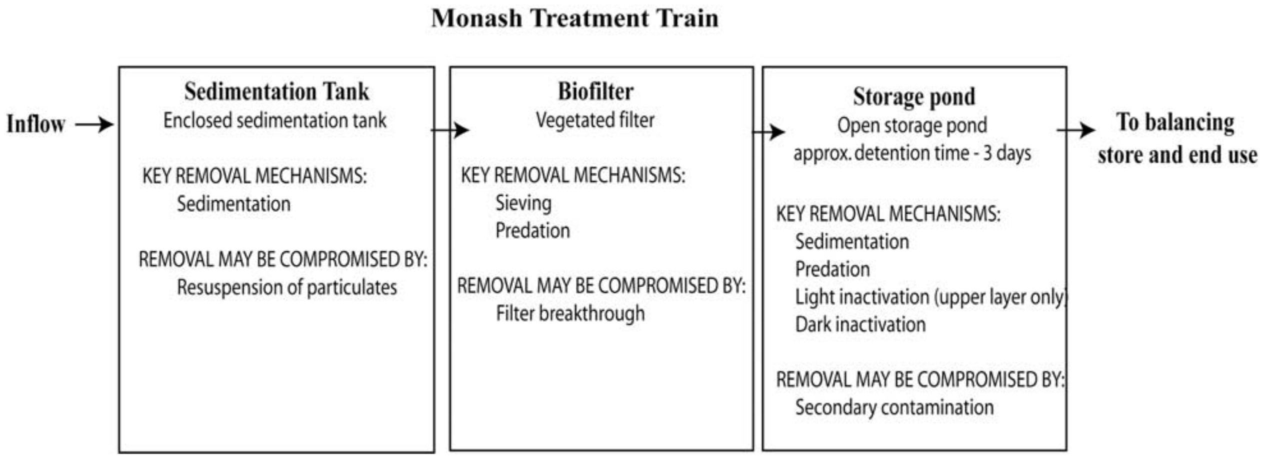


Figure 13: Monash treatment train

Sedimentation Tank: Challenged testing was undertaken on the Monash sedimentation tanks using *E. coli*, baker's yeast and MS2 coliphage, to evaluate their potential removal performance. The overall removal was highest for MS2 coliphage, followed by *E. coli* and then yeast. Viruses are very small (0.02-0.08 µm) in comparison to bacteria (about 1 µm) and protozoa (several microns) and hence viral removal by sedimentation is expected to be negligible, unless there is significant interaction with sedimenting particulates). The high removal observed in this study could be explained by sorption of viruses to solid particles that settle more easily.

Monash Biofilter: In addition to monitoring the native *E. coli* at the inflow and outflow to the Biofilter, two replicate challenge tests were performed using spiked concentrations of *E. coli*, yeast and MS2 coliphage. Highest removal was estimated for yeast, followed by *E. coli* and then MS2. A full description of the methods applied in performing the challenge test are contained in the previous report: "Quantifying Stormwater Recycling Risks and Benefits: 2nd Quarterly Monitoring Report".

Storage Pond: The *E. coli* concentration at the inflow water was very low, however the samples collected from the pond showed a greater variability and much higher peaks in concentration (up to 1000 MPN.100mL^{-1}). This increase in the concentration of faecal indicator bacteria in the pond was expected to be due to the presence of waterfowl. Waterfowl excrete large numbers of *E. coli* with their faeces leading to secondary contamination of the open water storage. One sample from the pond was analysed for *C. perfringens* and somatic coliphages, neither were detected.

A summary of the $\log_{10}$ credits assigned to each of the treatment barriers at the Monash site based on the results of the challenge tests and monitoring data, are reported in Table 4. For both the sedimentation tanks and the biofilter, the variability in the outflow concentration was significant, and log credits were applied conservatively as the minimum average removal estimated for each of the challenge test runs. Greater information regarding the removal performance of these barriers may be obtained by a higher level statistical analysis of the same challenge test data. Unfortunately this detailed level of process modelling was beyond the scope of the current project. No evaluation of the storage pond removal performance was possible since the native surrogate concentration in the biofilter outflow was negligible, however inactivation by light and dark processes would be expected. The magnitude of removal would depend on residence time and the level of solar radiation. Given the low level of faecal contamination from the catchment, the most significant aspect for consideration with the Monash storage pond was the potentially for secondary contamination.

Table 4: Log_{10} reduction credits for the Monash treatment train

	Sedimentation tank	Biofilter	Storage pond	**OVERALL**
Campylobacter	1.4	1.4	-	2.8
Salmonella	1.4	1.4	-	2.8
Rotavirus	1.1	1.2	0*	2.3
Adenovirus	1.1	1.2	0*	2.3
Cryptosporidium	1.4	1.7	0*	3.1

*Some dark and light inactivation in the storage pond would be expected, but this cannot be quantified with the current dataset

5.3. Altona Green

The two key components of the Altona Green treatment train are illustrated in Figure 14, the grass swale filter and the underground storage. The grass swale filter was not expected to provide any consistent pathogen reduction, and therefore the focus of the Altona Green treatment train was on the performance of the underground storage tank.

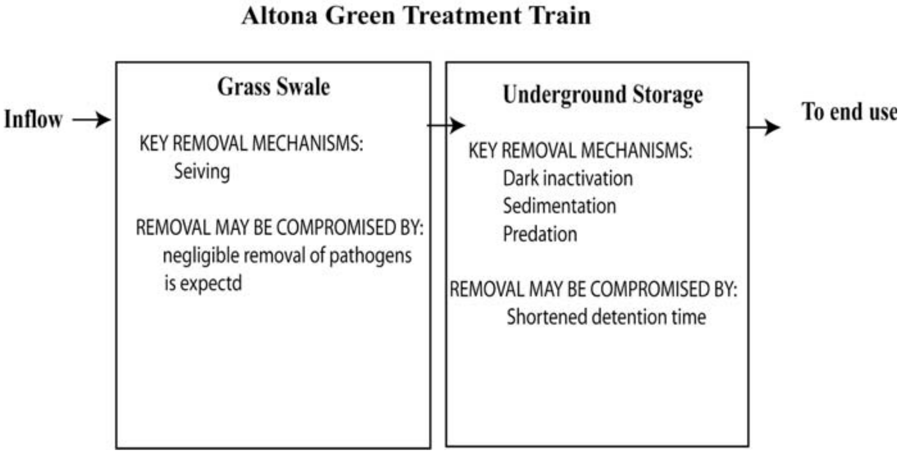


Figure 14: Altona Green treatment train

The primary mechanisms of pathogen removal in underground storage were sedimentation and dark inactivation. Since dark inactivation processes can be very slow, long detention times would be necessary to achieve significant inactivation. A comparison of *E. coli* concentration at the inflow and outflow of the underground storage tank at Altonta Green site indicates some reduction in concentration. An average $\log_{10}$ reduction in the *E. coli* concentration of 0.61 was observed from the data including a decline in the peak concentration (850 MPN. 100mL $^{-1}$ in comparison to 240 MPN.100mL^{-1}). It is important however to note that the outflow sample size was considerably smaller than the inflow (n=8 in comparison to 39) and therefore it may be a product of the sampling regime that greater variability was captured at the inflow. A $\log_{10}$ credit of 0.6 was applied for bacteria pathogens, however no estimate could be made for viruses or protozoa.

5.4. Conclusions from Pathogen Removal Performance Assessment

- Removal performance of stormwater treatment barriers varies between different microbial groups. When evaluating a treatment barrier it is therefore important to select a range of microbial surrogates that represent the behaviour of the human enteric pathogens of interest.
- In order to evaluate treatment removal performance, data must be available at both the inflow and the outflow of the treatment unit. Native microbial surrogates are often not present in high enough concentrations to adequately quantify removal performance, since outflow concentrations often report a high number of non-detects. Challenge testing (full-scale spiking trials) can overcome this limitation with the artificial introduction of a very high inflow concentration.
- Native microbial surrogate counts in stormwater samples are highly variable, often implying a concentration variation of several orders of magnitude. This variability complicates quantifying treatment removal performance. Challenge testing (full-scale spiking trials) can overcome this limitation by allowing the treatment process to be challenged with a relatively constant inflow concentration.
- Secondary faecal contamination of open storages is a critical consideration when evaluating treatment removal performance using native surrogates. Waterfowl excrete large numbers of *E. coli* in their faeces, and multiplication of other microbial surrogates is possible, leading to a potential underestimation of the treatment removal performance.

- Performance of stormwater treatment barriers varies between low flow and event conditions; and even over the course of a single event. Comparison of average inflow and outflow concentrations is unlikely to capture the variability in removal performance. Quantification of removal performance under different scenarios and events is therefore important for any subsequent risk assessment.
- Microbial datasets are complex to analyse consisting of relatively few counts, of high variability. While a relatively simple, traditional analysis approach is possible, more information may be gleaned from the implementation of tailored approaches suitable to the individual datasets.

6. Treatment System Performance: Other Water Quality Parameters

6.1. Royal Park

6.1.1. Royal Park Wetland

The wetland provided a reduction in the average concentration of the majority of the pollutants, with comparable outlet flow concentrations during wet and dry weather. A notable exception was electrical conductivity, which was higher in the outlet flows in comparison to the inlet.

The flow weighted wet weather site mean concentration (SMC) and dry weather concentration (DWC) were calculated for Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN) at the inlet and outlet of the wetland (Table 5).

Table 5: Calculated Wet and Dry Weather Concentrations for Selected Pollutants – Royal Park Wetland Inflow and Outflow, mg/L

		Total Suspended Solids	Total Phosphorus	Total Nitrogen
Inflow	Wet weather site mean concentration	22.1	0.15	1.4
	Dry weather concentration	9.1	0.13	1.1
Outflow	Wet weather site mean concentration	11.2	0.13	1.0
	Dry weather concentration	8.0	0.11	0.8

Comparison between the observed wetland outflow concentrations of TSS, TP and TN with those predicted during the conceptual design of the system, indicated that removal of TSS was similar to predicted under dry conditions and poorer than predicted following rainfall events; TP removal was poorer than predicted under both dry and wet conditions; and TN removal was better than predicted under both dry and wet conditions.

6.1.2. Royal Park Storage Pond

The open storage pond was effective in providing further treatment, with the mean concentration of all of the of water quality parameters (except pH) falling in comparison to the wetland outlet (which is also the pond inlet). The water from Royal Park storage pond also overflows into Moonee Ponds Creek, so it is noteworthy that the TSS, TN and TP were all well below the environmental flow target values.

6.2. Altona Green

The primary role of the Altona Green underground storage tank is storage, although some pollutant removal is expected, mainly due to sedimentation processes. During the monitoring period, a significant amount of potable water (around double the stormwater inflow volumes) flowed into the underground store, which would have influenced pollutant levels through dilution. This potable substitution was not accounted for in the treatment evaluation. Nevertheless, comparison of inlet and outlet water quality results showed that the stormwater quality either remained unchanged or improved, depending on the particular parameter, with the notable exceptions of lead and electrical conductivity. There was a marked reduction in turbidity, TSS, aluminium and iron levels and a modest reduction in TN, TP, chromium, manganese, nickel and zinc concentrations. The sample size at the outlet was much smaller (14-20, compared with 78-84 at the inlet) which may have biased this result.

6.3. Monash

6.3.1. Monash biofilter

The Monash biofilter treated the runoff from the multistorey car park after it had passed through the sedimentation tanks. Analysis of monitoring data indicated that the biofilter was effective in reducing the concentration of TSS in stormwater, while there were small reductions in pH and turbidity. The mean metals concentrations at the inlet were below those recommended for long term agricultural irrigation (ANZECC and ARMCANZ, 2000), as were the outlet concentrations, except in the case of iron, which fell between the short-term and long-term irrigation guideline levels. The biofilter reduced the concentration of aluminium, copper, iron, lead and zinc, although the concentrations of manganese and nickel increased modestly. The TP and TN concentrations also increased, although they remained below those recommended for long-term agricultural irrigation (ANZECC and ARMCANZ, 2000).

The treatment performance of the Monash biofilter has been extensively studied by Belinda Hatt, as part of her Ph.D. research. In Hatt *et al.* (2009), it was reported that the concentrations of sediment and heavy metals were consistently reduced by the biofilter, whereas nitrogen concentrations were largely unchanged, and phosphorus concentrations increased. The latter was attributed to leaching of dissolved phosphorus from the filter media. Hatt *et al.* (2009) also provides extensive details about the configuration of the biofilter and filter media.

7. End Use Water Quality Assessment

The purpose of a stormwater harvesting system treatment train is to produce stormwater which is of suitable water quality for the specific use(s) that the system supplies. The end use water quality monitoring undertaken as part of this study was used to compare the water quality from each site with the appropriate guidelines.

7.1.1. Royal Park

The Royal Park system was the most intensively sampled due to its continual operation throughout the monitoring period. Post treatment, the stormwater met the water quality objectives for long-term agricultural irrigation (ANZECC/ARMCANZ, 2000) and municipal use (NRMMC-EPHC-AHMC, 2008) for all but two cases: the mean iron (Fe) concentration of 0.38 $mg.L^{-1}$ was approaching double the long-term agricultural irrigation guideline value of 0.2 $mg.L^{-1}$; and the 95th percentile turbidity level of 11 NTU was marginally above the municipal use guideline value of 10 NTU. It is important to note though that mean Fe concentration was well below the short-term (20 year) value of 10 $mg.L^{-1}$. Also, the turbidity levels in the draft guideline are being debated, as a UV unit for example may still be able to provide adequate disinfection if it is specifically designed to handle turbidity levels in this range.

The salinity of the stormwater, as indicated by its electrical conductivity, would be suitable for all but the most sensitive plants, or in situations where the soils have low permeability. Further information on this topic can be found in Section 4.2.4 of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC/ARMCANZ, 2000).

7.1.2. Altona Green

The Altona Green system provided irrigation water that exceeded several of the water quality objectives for long-term agricultural irrigation (ANZECC/ARMCANZ, 2000) and municipal use (NRMMC-EPHC-AHMC, 2008). The mean iron (Fe) concentration of 2.1 $mg.L^{-1}$ was higher than the long-term agricultural irrigation guideline value of 0.2 $mg.L^{-1}$. Although, as is the case for Royal Park, the mean Fe concentration was well below the short term (20 year) value of 10 $mg.L^{-1}$. The 95th percentile and maximum turbidity levels were above the municipal use guideline objectives, as was the median *E. coli* level.

The turbidity levels can influence the performance of disinfection, however at this site there was no disinfection step within the treatment train, and therefore, in themselves, these high turbidity levels were not of concern. But, if a disinfection unit such as UV was installed, it is likely that the turbidity levels would need to be managed to ensure that adequate disinfection was achieved.

The exceedence of the guideline median *E. coli* level (<10 $MPN.100mL^{-1}$) by the monitoring results (median *E. coli* level of 31 $MPN.100mL^{-1}$) was not surprising given the absence of any real microbiological barriers at this site. As identified in the QMRA, while the level of faecal contamination from the catchment was low, the underground storage did not provide effective opportunity for microbial reduction leading to the persistence of microbial surrogates in the end use water. Microbiological treatment at this site may therefore be considered inadequate.

7.1.3. Monash

In comparison to the other two sites, the Monash site met turbidity and *E. coli* objectives for municipal use, although fewer samples were taken due the lengthy periods that no stormwater was harvested. The irrigation water did exceed the Total Phosphorus and iron water quality objectives for long-term agricultural irrigation, although both were well below the short-term levels.

7.2. Non-Potable Residential End Uses

All three sites produced water, which if it was to be used for non-potable residential end uses without further treatment, may cause aesthetic problems due to the iron and manganese levels. At concentrations higher than 0.3 $mg.L^{-1}$, iron gives water a brownish colour and can leave stains, such as in laundry items (NHMRC and NRMMC, 2004). Manganese, at concentrations as low as 0.02 $mg.L^{-1}$, will coat pipes than can subsequently slough off (NHMRC and NRMMC, 2004), leading to stains on plumbing fixtures and laundry items, however as the end-use under consideration was irrigation, staining was not considered to be a limitation to use.

8. Quantitative Microbial Risk Assessment

Quantitative Microbial Risk Assessment (QMRA) is a widely adopted tool for investigating, evaluating and managing microbial risks associated with water systems. The process of implementing QMRA requires quantifying pathogen concentration in the source water, removal during treatment, through to potential exposure during water use. An overview of each of the three systems is illustrated in Figure 15.

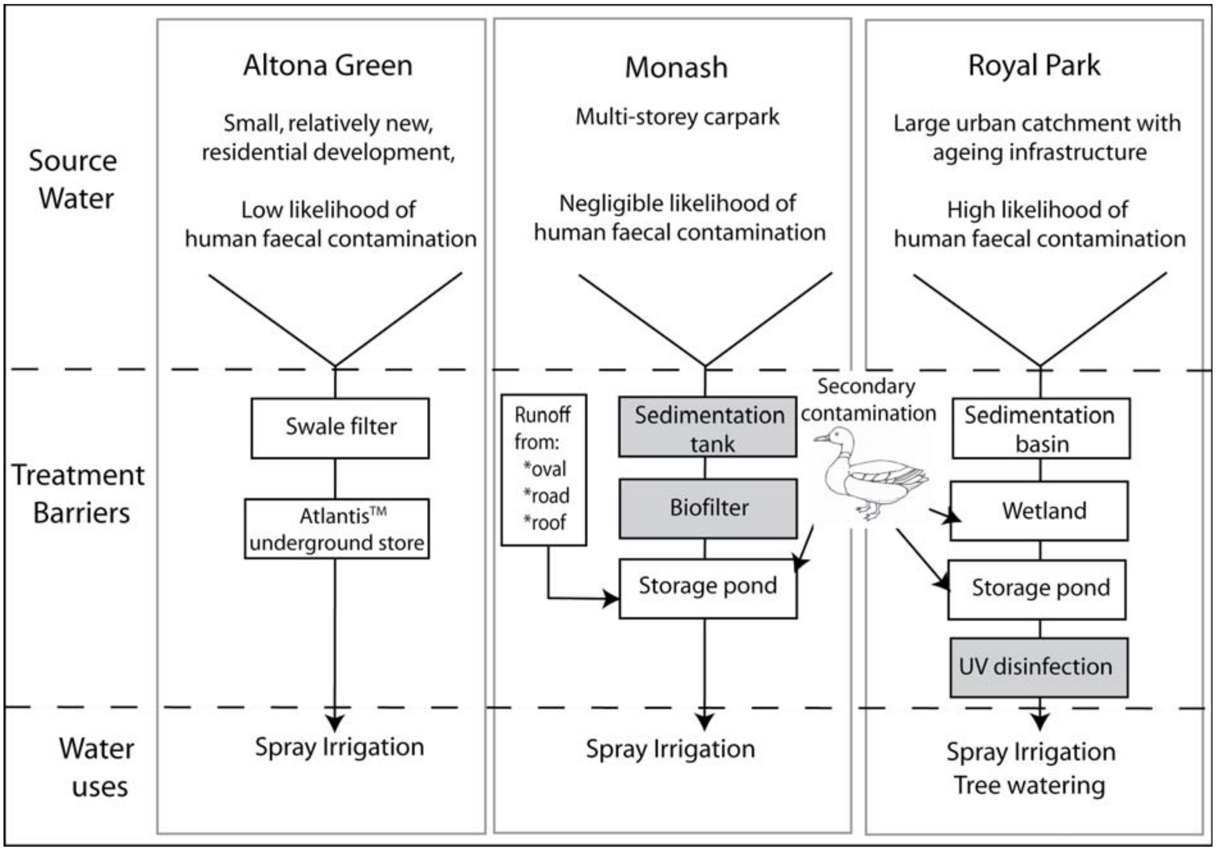


Figure 15: Schematic illustration of QMRA model framework for each of the three sites

The steps involved in implementing the QMRA were as follows:

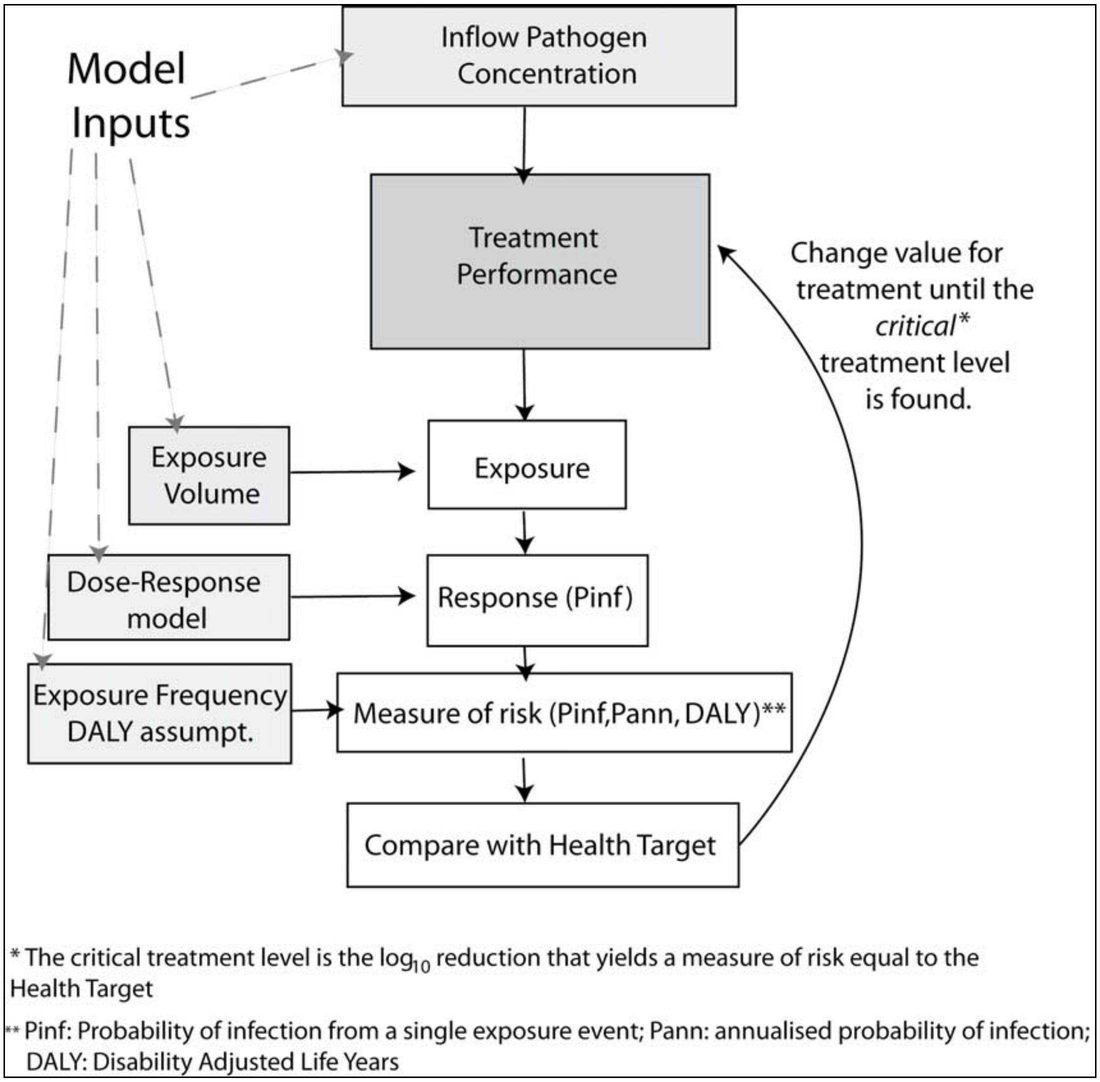
1. **Hazard identification and selection of reference pathogens:** Initially reference pathogens were selected to represent the key microbial groups. Five reference pathogens were selected; two bacterial, two viral and one parasitic protozoan (see Table 6).

Table 6: Selection of reference pathogens for QMRA

Pathogen Group	Reference Pathogen	Relevance to the study population
Bacteria	*Campylobacter jejuni*	Recognised waterborne bacterial pathogen. Avian sources may be important contributors to human incidence of infection.
	Salmonella enterica	Recognised waterborne bacterial pathogen. Waterfowl can be reservoirs of *Salmonella.*
Viruses	Adenovirus 2	Important cause of gastroenteritis and respiratory infections in the population. Relatively resistant to UV disinfection.
	Rotavirus	Important cause of gastroenteritis in children and the elderly. Highly infectious.
Parasitic Protozoa	*Cryptosporidium parvum*	One of the most important waterborne pathogens in developed countries. Environmentally resistant.
Helminths	None	Not considered endemic in developed countries. Waterborne transmission unlikely to be important for these organisms, and if present, more readily controlled by processes for the above microbial groups.

2. **Exposure Assessment:**
    a. **Estimation of inflow pathogen concentration:** The concentration of each reference pathogen in the inflow water was estimated for each site. This concentration estimate was based on the monitoring of native faecal indicator organisms, and numerical modelling.
    b. **Estimation of treatment barrier performance:** The performance of each treatment barrier for removing pathogenic organisms was quantified in section 5. These results were implemented in the QMRA.
    c. **Exposure volumes:** The amount of water an individual may consume depends on the type of use, and the level of contact with the water. Consideration was given to the water usage at each site, with a range of potential exposure scenarios investigated.
3. **Dose-response assessment:** Based on the estimated pathogen concentration, and the exposure scenarios, the probability of infection was quantified using published dose-response relationships.
4. **Risk characterisation:** Risk estimates were compared with health targets to evaluate the suitability of water for current uses.

The QMRA framework was also applied to evaluate the level of treatment necessary at each site sites in order to meet the desired health target, the approach is illustrated in Figure 15. For the estimated pathogen inflow concentration and the required health targets, the treatment performance required of the given treatment train could be calculated and compared with the assigned $\log_{10}$ credits from the treatment evaluation.



* The critical treatment level is the $\log_{10}$ reduction that yields a measure of risk equal to the Health Target

** Pinf: Probability of infection from a single exposure event; Pann: annualised probability of infection; DALY: Disability Adjusted Life Years

Figure 16: Process for calculating critical treatment performance within a QMRA framework.

A considerable limitation to undertaking the QMRA was that very little data is available regarding the concentration of human pathogens in urban stormwater. Direct enumeration of human pathogens from environmental samples has many limitations. In particular, analytical methods are costly and often lack the sensitivity to detect pathogens at low concentrations. In addition, pathogen concentrations in stormwater are expected to be highly variable, with long periods of low or zero concentration, and short-term peaks of potentially high pathogen concentration. Without a thorough understanding of catchment pathogen sources and the events that drive pathogen mobilisation, a negative pathogen result from an environmental sample provides little comfort regarding overall system health risks. With this in mind, the microbial analyses in this project focussed on faecal indicator and surrogate organisms. In comparison to human pathogens, both faecal indicator and surrogate organisms are more easily identified by laboratory analysis in terms of cost, sensitivity and recovery (method performance); providing the opportunity to obtain a greater number of datapoints, each with a higher degree of accuracy, that may be used to resolve many important questions regarding the processes that drive pathogen occurrence and fate. There is no doubt that translating the results from indicators and surrogates to human pathogens has many uncertainties, and there is a great need for more data on actual pathogen numbers in urban stormwater. In the context of the current study, given the overall lack of knowledge regarding microbial risks associated with each system, a larger dataset focussing on the role of events in the mobilisation of faecal material and the performance of treatment barriers using indicator and surrogate data was chosen to inform the initial QMRA.

8.1. Royal Park

Analysis of monitoring results demonstrated that faecal indicator organisms, and by implication faecal material, were consistently present in the water at the inflow to the Royal Park system under both low flow and event conditions. The level of contamination increased during and following rainfall events (with approximately 2 orders of magnitude higher concentration of *E. coli*, and 1 order of magnitude higher of *C. perfringens* spores and somatic coliphages), however there was no apparent relationship between event size and the concentration of faecal indicator organisms in the water column; similar elevated concentrations were reported for events from “small” to “large”. A log-normal distribution was fitted to the reported concentrations of *E. coli*, somatic coliphages and *Clostridium perfringens* spores under event and background conditions at the Royal Park inlet. The human health implications of this level of faecal contamination were investigated by separately assuming two potential faecal sources:

1. **Human:** Municipal human sewage is the highest risk faecal source and was a likely contributor at the Royal Park site. Pathogen concentration in raw sewage was estimated by epidemiological modelling (Ashbolt et al. 2006), which relied on information regarding the prevalence, duration and severity of gastroenteric infections. The magnitude of dilution and inactivation acting on the raw sewage was estimated using the faecal indicator results at the inlet and following the approach outlined by Mitchell *et al.* (2008).
2. **Avian**: The wetland and storage ponds at the Royal Park site are a habitat for waterfowl, which were undoubtedly contributing to the load of faecal indicator organisms. The potential for an outbreak involving human infectious *Salmonella* or *Camplylobacter* spp. amongst waterfowl would lead to the excretion of high numbers of infectious organisms and hence, a likely health risk. This (most likely) rare event was investigated as a single scenario in the QMR*A. To estim*ate *pathogen conc*entration in the storage pond during an avian outbreak, hypothetically infected birds were assumed to excrete pathogens at a similar density to *E. coli*, an assumption supported by the literature (Doyle 1991; Wallace et al. 1998).

Overview of Results

When human faecal contamination was assumed to be present, human enteric viral risks dominated due to their high concentration in sewage, poor physical removal under event conditions and resistance to UV inactivation. Comparison of the annualised probability of infection estimates with the 10^{-4} benchmark (Regli et al. 1991; Asano et al. 1992) indicated that viral pathogens were the primary concern; for all exposure scenarios, the median probability of infection exceeded the benchmark. While acknowledging that conservative assumptions were applied in the QMRA, a risk management plan that includes investigations for the possible presence of sewage in the Royal Park influent is warranted. Critical treatment limits were estimated for both background and event pathogen concentrations for a range of exposure scenarios.

Table 7: Critical treatment level required for representative exposure volume and frequency for Royal Park assuming human faecal source (Bold indicates that treatment requirement exceeds estimate from monitoring and challenge test data)

		Log $_{10}$ Reductions Required to meet Health Target (Median)				
	Exposure Frequency	*Salmonella*	*Campylobacter*	Adenovirus	Rotavirus	*Cryptosporidium*
Royal Park: ***EVENT CONDITIONS***						
Aerosol (0.1mL)	Weekly	-	2.0	**3.0**	**2.4**	2.1
Ingestion (1mL)	Weekly	-	3.0	**4.0**	**3.4**	3.1
Ingestion (1mL)	Daily	-	**3.8**	**4.9**	**4.3**	3.9
Accidental (100mL)	Single Event	-	3.3	**4.3**	**3.7**	2.3
Royal Park: ***BACKGROUND CONDITIONS***						
Aerosol (0.1mL)	Weekly	-	0.3	**2.2**	**1.5**	0.7
Ingestion (1mL)	Weekly	-	1.3	**3.2**	**2.5**	1.7
Ingestion (1mL)	Daily	-	2.1	**4.0**	**3.4**	2.6
Accidental (100mL)	Single Event	-	1.5	**3.5**	**2.8**	1.0

For the avian source scenario, the probability of infection was marginally exceeded by the 1.0 mL weekly and daily exposure for *Campylobacter,* marginally exceeded by 100 mL accidental exposure for *Salmonella* and clearly exceeded for the 100 mL accidental exposure for *Campylobacter*. Given the conservative assumptions regarding the concentration of pathogens, and the rare event that was being investigated, the UV disinfection appears to provide an adequate barrier. The high risk for 100 mL exposure needs to be moderated by the consideration that two rare events are being considered simultaneously (avian outbreak and accidental ingestion) and hence the significance of exceeding the 10^{-4} infection risk benchmark is reduced.

8.2. Monash

Stormwater collected at the Monash site was not expected to have any human faecal contamination as the catchment was the well confined top story of a multi-storey car park, and therefore a highly unlikely event would be necessary to result in human faecal contamination (e.g. changing or disposal of a used baby nappy. Additional runoff also fed the storage pond directly (bypassing the sedimentation tank and biofilter) from the sporting oval, roads and roofs. Indicator concentrations at the inflow to the Monash biofilter during events were very low, indicating a low level of faecal contamination. A peak concentration of *E. coli* following an event of 1300 MPN.100mL^{-1} was assumed to be of animal origin, most likely avian. Very low numbers of *C. perfringens* and no somatic coliphage were identified.

Of greater potential concern was the presence of waterfowl inhabiting the storage pond. Any faecal material from the car park catchment had two protective barriers: the sedimentation tank; and the biofilter. Secondary contamination by waterfowl into the pond however, was direct without any treatment barriers. For the purposes of the QMRA, the sedimentation tank and biofilter were therefore not considered.

E. coli concentration in the pond was used to estimate the *Salmonella* and *Campylobacter* concentration in pond water. Using the same approach as adopted for the Royal Park site, a scenario was considered whereby waterfowl were assumed to become infected with a human infectious strain of *Salmonella* or *Campylobacter*. In this event, excretion patterns were assumed to be similar to *E. coli*. Given the size of the dataset, rather than attempt to characterise the distribution of *E. coli*, the peak *E. coli* concentration (1000 MPN.100mL^{-1}) was used as a conservative input for the QMRA. The impact of a single exposure during the avian outbreak scenario of 0.1 mL (representing aerosols), and 100 mL (representing accidental ingestion) was modelled.

Overview of Results

The risk of infection from *Campylobacter* in the event of an avian outbreak following a single exposure to irrigation water exceeded annual health targets. Risk of infection from *Salmonella* was lower, and only exceeded the target for accidental consumption of 100 mL, requiring the combined occurrence of two rare events. Given the measured density of faecal indicator bacteria in the pond water, and the absence of any treatment barriers between the pond and exposure, should the waterfowl become infected with a human infectious strain of *Campylobacter*, a real public health risk would result. Consideration therefore needs to be given to the likelihood of such an event, and whether additional risk management is required. To the author's knowledge, an approach for incorporating such events into an overall QMRA has not been presented in the literature.

8.3. Altona Green

While the Altona Green catchment is residential urban, human faecal contamination of stormwater was anticipated to be unlikely given the smaller size and younger age of the catchment. Review of the background surrogate data supports the assumption that a human source of the faecal material was very unlikely as, *C. perfringens* spores numbers were relatively low with almost complete absence of somatic coliphage.

The faecal indicators were assumed to be of animal origin with domestic pets and birds the most likely contributors in the urban context. Dogs and cats tend to excrete high numbers of *C. perfringens* and therefore given the low number at the inflow, the most likely faecal source was avian. The key zoonotic pathogens for consideration are the bacterial organisms *Salmonella* and *Campylobacter*. The concentration of *E. coli* at the inflow to the Altona Storage tank was used to estimate the concentration of *Salmonella* and *Campylobacter*. A normal distribution was fitted to the $\log_{10}$ transformed concentrations of *E. coli*.

In the case of an event, whereby the avian population in the catchment becomes infected with a human infectious strain of *Campylobacter* or *Salmonella*, as argued previously, the concentration of *E. coli* was assumed to provide a reasonable estimate of the distribution of the concentration of the bacterial pathogens at the inlet. The only treatment barrier between inflow and exposure was therefore the underground storage tank; with an overall reduction in bacterial pathogens assumed to be 0.6 $\log_{10}$.

Overview of Results

The probability of infection associated with exposure to *Campylobacter* in the event of an avian outbreak of human infectious *Campylobacter* exceeded the health targets. Probability of infection with *Salmonella* was considerably lower, only exceeding the health target for the accidental ingestion of 100 mL, requiring the combined occurrence of two rare events. Should the Altona system become challenged with faecal pathogens, the underground storage provides a very limited barrier for the protection of public health, and a risk to public health would result. The likelihood of this event occurring is not well known, however in order to reduce the estimated *Campylobacter* DALY to below the 1 microDALY benchmark under the assumptions of the current QMRA model, the avian outbreak scenario would need to be less likely than a 1 in 400 year event

Given the low risk of human faecal contamination from the catchment, the risk associated with viral infection was not calculated. Similarly, if the primary faecal contributors to the system are birds, then the excretion of infectious protozoa is also unlikely. Nevertheless, should an event be identified whereby these organisms are allowed to enter the Altona Green storage tank, little protection would be provided to public health.

8.4. Conclusions from Quantitative Microbial Risk Assessment

The lack of data on the distribution of faecal pathogens in urban stormwater is a significant limitation to undertaking QMRA. The occurrence of pathogens in stormwater is expected to vary temporally (with long periods of low or zero concentration and peaks of short duration) and spatially (depending on the faecal sources in the individual catchment). Both of these factors limit the effectiveness of traditional water quality monitoring programs since randomly collected water samples are very likely to miss pathogen concentration peaks. Monitoring programs need to be developed that focus on the expected sources of pathogens in the catchment, and quantify the events that mobilise them. The results presented in this study for faecal indicator concentration in urban stormwater demonstrate high variability of more than 3 orders of magnitude, add greater support to the expectation of high pathogen variability.

In this study a framework was presented for quantifying pathogen concentration in stormwater based on the faecal indicator concentration. This framework required quantitative information on the pathogen concentration in faecal source material including the frequency of infection in the contributing population. This approach has value for undertaking stormwater QMRA as it is potentially transferable between catchments and allows for the variability in concentration to be modelled. Catchment specific faecal indicator data could be collected and used to estimate pathogen concentration based on catchment sources.

Results from Royal Park demonstrate that when human faecal contamination is present, viral risks dominate. Viral infection is common in the Australian community. Virions are excreted in very high numbers by infected individuals. These may persist in the environment, are not easily removed by sedimentation or sieving, and can be resistant to UV.

Open storages that provide a habitat for waterfowl result in secondary faecal contamination and the potential for zoonotic transmission of infection. For transmission to occur, animals must be infected with a strain of pathogen that can cause infection in the human host. The frequency of the occurrence of these infections across species in urban catchments is not well known, and is no doubt constantly changing. If the system receives water contaminated with human faecal material, then the likelihood of waterfowl becoming infected with a human infectious pathogen may increase. When such an infection occurs, pathogen numbers and subsequent health risks can rise rapidly leading to increased probability of infection and DALY estimates well above health targets. This scenario could lead to a higher incidence of human infection and the potential for an outbreak with associated disease burden implications. In this study, the Monash site contained an open storage pond downstream of the key system treatment barriers. Hence, should secondary contamination occur at this site, there are no barriers to provide protection for human health.

A framework is needed to incorporate the likelihood and consequence of these, most likely rare, infection events into the QMRA so that rational decisions can be made to protect public health.

9. Conclusions

The overall project provided valuable insight for the improved design and management of stormwater harvesting and reuse projects. The data collection and analysis program demonstrated the value of monitoring the actual performance of system in comparison to design estimates along with the benefit of adopting a risk management approach to evaluating human health risks. The key conclusions and recommendations of the project are summarised below.

The water volume monitoring and analysis demonstrated that:

- Inter-annual variability in rainfall and subsequent harvest volumes; changes in catchment surface characteristics; and long-term trends such as climate change will all have an important impact on actual system yields. Long-term average projections are not sufficient to describe the yield and performance of stormwater harvesting systems.
- In this study, for all three monitored sites storage capacity was NOT the most important constraint to yield, dispelling a widely held view that this is the key limitation to stormwater recycling in Australia.
- Some stormwater treatment devices can dramatically reduce inflows and hence harvest volumes for full-scale systems. This loss needs to be accounted for in treatment train selection and system design.

The evaluation of treatment train performance demonstrated that:

- It is not sufficient to use one microbial surrogate (such as *E. coli*) to represent the behaviour of all microbial groups, as differences exist in the environmental behaviour of the different pathogen groups.
- Three limitations in using native surrogates: 1. Variability in the inflow concentration of native surrogate organisms (more than 3 orders of magnitude) often exceeded the overall removal of the treatment barrier making removal performance difficult to evaluate. 2. Native surrogates were often not present in high enough concentrations to adequately quantify removal performance with outflow concentrations often reported as a high number of non-detects. 3. Secondary faecal contamination of open storage ponds lead to an underestimation of removal performance. In the light of these uncertainties $\log_{10}$ credits had to be applied conservatively. Challenge testing (full-scale spiking trials) can overcome these limitations with the artificial introduction of a very high and consistent inflow concentration.
- Separate consideration of baseline and event conditions was important for evaluating treatment removal performance. Performance of stormwater treatment barriers varies between low flow and event conditions; and even over the course of a single event. Comparison of average inflow and outflow concentrations is unlikely to capture the variability in removal performance. Quantification of removal performance under different scenarios and events is therefore important for any subsequent risk assessment.

The end use water quality assessment indicated that all three sites produced water, which if it was to be used for non-potable residential end uses without further treatment, may cause aesthetic problems due to the iron and manganese levels. Exceedence of the median *E. coli* level (<10 *E. coli* MPN.100mL^{-1}) at the Altona Green site highlighted the need for a risk management approach to evaluating infectious pathogen risks as the human health implications of faecal indicator bacteria alone are unclear.

The Quantitative Microbial Risk Assessment concluded that:

- The lack of data on the distribution of faecal pathogens in urban stormwater is a significant limitation to undertaking QMRA. The monitoring results for the faecal indicator organisms under event and background conditions at the Royal Park site demonstrated a high variability in faecal contamination. The variability in the concentration of human infectious pathogens of faecal origin is expected to be even greater with long periods of low or zero concentration and peaks of short duration.
- The distribution of faecal pathogens in urban stormwater is likely to be site specific, dependent upon the individual catchment and faecal sources. A risk management approach is essential with monitoring programs focussed on the expected sources of pathogens in the catchment, and quantifying the events that mobilise them.
- Results from Royal Park demonstrate that if human faecal contamination were present, viral risks would dominate. Viral infection is common in the Australian community. Virions are excreted in very high numbers by infected individuals. These appear to persist in the environment, are not easily removed by sedimentation or sieving, and can be resistant to UV. The microbiological data collection program focussed only on faecal indicator organisms and surrogates. Based on these data it was not possible to identify the source(s) of faecal contamination, and hence the data provided no real evidence for or against the presence of human faecal contamination. The high counts for *Clostridium perfringens* were consistent with the presence of human faecal material - although other sources (including dogs) could account for these values. Review of the Royal Park drainage catchment indicated that human faecal discharges from cracked pipes and poor connections are likely as the area is a large, urban catchment with ageing infrastructure. In addition, sewage overflow events have been identified in the catchment including one notable event during the monitoring program. Therefore, a risk management plan that includes investigations for the possible presence of sewage is warranted.
- Open storages that provide a habitat for waterfowl result in secondary faecal contamination and the potential for zoonotic transmission of infection. For transmission to occur, animals must be infected with a strain of pathogen that can cause infection in the human host. The frequency of the occurrence of these infections across species in urban catchments is not well known, and is no doubt constantly changing. If the system receives water contaminated with human faecal material, then the likelihood of waterfowl becoming infected with a human infectious pathogen may increase. When such an infection occurs, pathogen numbers and subsequent health risks can rise rapidly leading to probability of infection and DALY estimates well above health targets. This scenario could lead to a higher incidence of human infection and the potential for an outbreak with further reaching disease burden implications. In this study, the Monash site contained an open storage pond downstream of the key system treatment barriers. Hence should secondary contamination occur at this site, there are no barriers to provide protection for human health. A framework is needed to incorporate the likelihood and consequence of these, most likely rare, infection events into the QMRA so that rational decisions can be made to protect public health.

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