Chapter One: Introduction

1.1 Background

It is well recognised by water resource managers, water authorities, utilities and regulators that end-product compliance monitoring of treated drinking water against numerical water quality guidelines does not provide timely information in the event of a water quality issue, is technically challenging and increasingly expensive (Sinclair and Rizak 2004). Perhaps more crucially, sole reliance on compliance monitoring has proved to be unreliable in preventing microbial and chemical contamination events even in sophisticated and well-operated water supply systems (see for example Hrudey and Hrudey 2007). Consequently, water authorities and utilities are increasingly looking to adopt quality management systems to achieve a comprehensive, integrated approach for managing water contamination risks across all stages of water supply – from catchment to consumer (Davidson et al. 2005; Hamilton et al. 2006).

The Australian Drinking Water Guidelines (ADWG), developed by the National Health and Medical Research Council (NHMRC) and the Natural Resources Management Ministerial Council (NRMMC), is an example of a quality management systems approach to drinking water quality management. First issued in 1980 as national guidelines and initially also a prescriptive, numerically based end-of-product set of standards, the Australian Drinking Water Guidelines co-evolved with the World Health Organisation (WHO) Guidelines for Drinking Water Quality through to its current (2011) edition. Fundamental to the contemporary ADWG is the Framework for the Management of Drinking Water Quality, which sets out a structured and systematic preventative management approach that encompasses all steps in water production utilising elements of HACCP (Hazard analysis and critical control points)/ ISO 22000, ISO 9001 and AS/NZS 4360 (Havelaar 1994; Rizak et al. 2003; Sinclair and Rizak 2004; NHMRC, NRMMC 2011).

At its core the ADWG (2011) includes a set of guiding principles considered vital to ensuring safe drinking water quality. The guiding principles are:

- The greatest risk to consumers of drinking water is pathogenic microorganisms. Protection of water sources and treatment are of paramount importance and must never be compromised;
- The drinking water system must have, and continuously maintain, robust multiple barriers appropriate to the level of potential contamination facing the raw water supply;
- Any sudden or extreme change in water quality, flow or environmental conditions (e.g. extreme rainfall or flooding) should arouse suspicion that drinking water might become contaminated;
- System operators must be able to respond quickly and effectively to adverse monitoring signals.
- System operators must maintain a personal sense of responsibility and dedication to providing consumers with safe water, and should never ignore a customer complaint about water quality; and
- Ensuring drinking water safety and quality requires the application of a considered risk management approach.

The ADWG Framework also contains 12 Elements that are considered good practice for management of drinking water supplies. The 12 Elements are:

1. Commitment to drinking water quality management
2. Assessment of the drinking water supply system
3. Preventative measures for drinking water supply system

4. Operation procedures and process control
5. Verification of drinking water quality
6. Management of incidents and emergencies
7. Employee awareness and training
8. Community involvement and awareness
9. Research and development
10. Documenting and reporting
11. Evaluation and audit
12. Review and continual improvement

It is important to recognize that the ADWG (2011) have not necessarily been designed to act as mandatory standards, although they are referred to directly in water supply-related legislation in most Australian states. Nevertheless, they have become emblematic of best-practice in drinking water quality management and are widely adopted by producers of drinking water throughout Australia.

Applying the ADWG Framework to source water catchments

The concept of ecosystem services, where human populations derive benefits such as crop pollination, raw materials, climate regulation etc. from nature/natural systems, is firmly established (Costanza et al. 1997; de Groot et al. 2002). As succinctly stated by Davies and Mazumder (2003), "nowhere does the link between human health and the environment manifest itself more strongly than our reliance on fresh clean drinking water". However, with the vast majority of Australia's population living in urban areas with reliable access to reticulated water (ABS 2006; AWA 2013), and, given recent advances in water treatment technology (including desalination and purified recycled water (see for example Shannon et al. 2008)) both society at large and those charged with operating drinking water treatment facilities could be forgiven for a fading consciousness of the direct links between the hydrologic cycle, the condition of a source water catchment (that is, a watershed that provides raw water to water treatment facilities) and safety of potable water to point of supply to homes and business.

Incidents such as the Sydney water crisis of 1998 and similar instances in the developed world are a sharp reminder that even where modern water treatment facilities are in operation serious public health incidents are possible, particularly where unmitigated water quality hazards are present in a source water catchment (Angulo et al. 1997; Stein 2000, Hrudey et al. 2003; Kuusi et al. 2005). The management systems approach and the ADWG Framework for the Management of Drinking Water Quality were developed in direct response to these types of incidents, and as such represent a judicious opportunity to rediscover, highlight and address the authentic links between the condition of the catchment and the condition of drinking water.

The widespread adoption of the ADWG, inclusive of the guiding principles and 12 Elements, has meant water authorities and utilities across Australia have had to increase their focus on understanding, managing and protecting source water catchments. To illustrate, Element 1 (*Commitment to drinking water quality management*) provides a written example of a drinking water policy which sets out the importance of a commitment to drinking at the senior executive levels of a water supply business. This example in the ADWG Framework includes the explicit idea that a water supply business needs to manage water quality at all points along the delivery chain from catchment to consumer. Further, Element 2 (*Assessment of the drinking water supply system*) details the need to assess the entire water supply system, including catchments, groundwater systems, source waters, (raw water) storage reservoirs and intakes to understand and minimise risks to drinking water quality. Key to highlighting these ‘natural assets’ is the recognition that water quality can be impacted within each of these environments, and, because they are interrelated with each other and directly with treatment and distribution systems, integrated management is essential (NHMRC, NRMMC 2011).

The application of the risk assessment/risk management approach, a key aspect of Element 2, is pivotal to effective implementation of the ADWG. This approach enables potential hazards, their sources and hazardous events to be systematically identified across the water supply system, and the level of risk presented by each to be determined. In the context of the ADWG, a hazard is a biological, chemical, physical or radiological agent that has the potential to cause harm, a hazardous event is an incident or situation that can lead to the presence of a hazard, and the risk is the likelihood of identified hazards causing harm in exposed populations in a specified timeframe, including the severity of the consequences (NHMRC, NRMMC 2011). The ADWG states that it is important that risk management is inclusive and, therefore, needs to cover the whole system from catchment to consumer. Thus, proper execution of this cornerstone of the ADWG again sees natural assets highlighted as critical in provision of safe drinking water as authorities and utilities include catchments, aquifers, source waters, and storage reservoirs in their water quality risk assessments.

Catchments, aquifers, source waters, and storage reservoirs gain additional and deserved attention from water authorities and utilities on the role they play in the supply of safe drinking water through the application of Element 3 (*Preventative measures for the drinking water supply system*) and the detail in several of the ADWG guiding principles. Element 3 and the guiding principles promote the importance of the multiple barrier approach to minimise the likelihood of contaminants passing through the water supply system. That is, the failure of one barrier to mitigate a contamination event should be compensated by effective operation of the remaining barriers within the entire treatment system (NHMRC, NRMMC 2011). Although in the traditional sense multiple barriers were more likely to be viewed as various steps at a water treatment plant (e.g. filtration is one barrier, disinfection via chlorination another barrier), it is firmly recognised within Element 3 of the ADWG that source water catchments and other natural assets are the first and most fundamental barrier in the multiple barrier approach.

Element 9 (*Research and development*) of the ADWG focuses on research and development. Again, source water catchments and raw water reservoirs are highlighted in Element 9 as key components of the water supply systems where investigate studies and research monitoring are invaluable to achieve improvements in identification and characterisation of potential hazards. Improved understanding of the factors affecting water quality characteristics in source water catchments and raw water reservoirs allows water resource managers to plan and respond to them effectively to maintain a safe and secure drinking water supply.

1.2 Aims and objectives

This thesis sets out to firstly demonstrate how Element 2 (*Assessment of the drinking water supply system*) of the ADWG Framework can be applied to a source water catchment and raw water reservoir. Secondly, this thesis aims to address two crucial priority information gaps identified through the application of Element 2 and Element 3 (*Preventative measures for the drinking water supply system*) by undertaking investigative studies and research monitoring as per Element 9 (*Research and development*) of the Framework to improve understanding of catchment-based factors that can challenge water treatment and potentially affect the safety of drinking water at the point of supply.

Applying the Element 2 of ADWG to source water/raw water components of a water supply system

The widespread adoption of the ADWG has in turn seen the broad implementation of Element 2 of the framework. Central to Element 2 is the application of the specified risk assessment methodology to identify and document hazards to water quality, their sources and hazardous event for each component of a water supply system. However, while providers of potable water generally have a good understanding of water quality and how it changes as it is moved through treatment steps under process control in a hard asset (i.e. water treatment plant), water quality dynamics in the natural asset (i.e. source water catchment and raw water reservoir) are far more variable and can be less well understood. This can easily lead to a disproportionate focus on a water treatment plant, leaving the catchment and reservoir component as a critical blind spot in a comprehensive whole-of-system water quality risk assessment.

The leading aim of this thesis is to demonstrate how Element 2 of the ADWG framework can be applied specifically to a source water catchment/raw water reservoir to improve recognition and knowledge of water quality at this key juncture in the water supply system. This will be addressed in the three main steps consistent with the Elements of the ADWG. Firstly, a water supply system analysis will be undertaken for a source water catchment and associated raw water system in terms of its physical setting, natural environment and land-use changes over time, and a review of available literature and historical water quality information undertaken with particular focus on parameters relevant to drinking water quality management. Secondly, water quality data collected under a long-term ambient monitoring program will be collated, trended and interpreted, again with a focus on parameters relevant under the ADWG. Finally, water supply system analysis and data analysis will be used as primary resources to undertake a risk assessment workshop, as per the methodology set out in the ADWG. In the workshop, hazards and hazardous events will be assessed and rated firstly in terms of their inherent risk (i.e. in the absence of any preventative measures), then in terms of their residual risk (i.e. after consideration of existing preventative measures, for example development regulation by governments or Landcare run riparian zone re-establishment programs). From this, a water quality risk register for the source/raw water quality will be developed which clearly identifies the water quality hazards, the preventative measures for each hazard, and provides a (semi-) quantitative assessment of the risk to water quality of each hazard both with and without the preventative measures.

In addition to providing a clear identification of water quality risks in source water and the aquatic environment, the catchment characterisation, water quality data assimilation, and the finalised risk registers will be designed to highlight which catchment-based preventative measures are effective, and where attention should be focused for implementation of catchment management works to address unacceptable risks to water quality. Further, by collectively providing a comprehensive understanding of the risks to catchment water quality, these documents will also be designed to dovetail with any following risk assessment of the subsequent components of the drinking water supply system, i.e. the water treatment process. The water supply systems analysis, the water quality data analysis, and the finalised in-catchment water quality risk register constitutes Chapter Two of this thesis.

Improving quantification of water quality hazards identified in the risk assessment process

As discussed above, applying Element 2 of the ADWG to catchment systems enables risks to source water quality to be identified, prioritised, and better understood. However, it is unlikely that sufficient knowledge or data regarding each hazard will be available to ensure the risk assessment is fully quantitative, particularly given the complex water quality dynamics of natural aquatic environments. Hazard identification and risk assessment are predictive activities designed to be undertaken, in part, via group discussion and consensus. As such they will often include subjective judgements (NHMRC, NRMMC 2011).

An additional aim of this thesis is to demonstrate how investigative studies and research monitoring, as per Element 9 of the ADWG, can be applied to fill gaps in knowledge and enable the level of uncertainty in the risk assessment process to be reduced. This will be achieved by undertaking an investigative study to assess the microbial risk to water quality posed by cormorants roosting at a raw water intake of a reservoir. The studies undertaken to improve quantification of the microbial risk to water quality posed by cormorants, identified through the water quality risk assessment process, constitutes Chapter Three of this thesis.

Improving quantification of catchment-based preventative measures and their role as 'barriers' against hazards in source water catchments

The principle of the multi-barrier approach to ensuring the safety of drinking water essentially describes the need for a series of robust and independent barriers between water users and water-borne contaminants (O'Connor 2002; NHMRC, NRMMC 2011). Examples of common barriers in a water supply system include source water protection incorporating limitations on direct access of livestock to waterways, water treatment comprising of coagulation/flocculation/filtration and disinfection, and secure/closed water distribution systems with on-going maintenance. The strength of this approach is that a failure of one barrier is countered by the remaining barriers, minimising the likelihood of contaminants passing through the water supply system to points where they could cause harm to water users (NHMRC, NRMMC 2011).

Although it is well recognised that effective catchment management and source water protection provide the first barrier for the protection of water quality, it is equally true that water supply catchments are coming under increased pressure from changes in land use and other development (see for example Postel and Thompson 2005), which in turn typically has negative consequences for water quality (see for example Hansen and Ongerth 1991; Bunn et al. 1999; Michell et al. 2005; Roser and Ashbolt 2007; Leigh et al. 2010; Burford et al. 2012). Consequently, environmental restoration programs often undertaken to attempt to address land degradation and subsequent impacts on the aquatic environment such as declining water quality (Curtis and Lockwood 2000; Brooks and Lake 2007).

The final aim of this thesis is to determine if any improvements to source water quality can be quantified by applying an intervention preventative measure to mitigate a source of contamination and assess its effectiveness as an in-catchment barrier against microbial hazards. This will be achieved by undertaking an investigative study to determine the magnitude of microbial pollution contributed to a stream by a herd of dairy cattle, and to what extent microbial pollution was moderated by on-ground catchment remediation work designed to limit cattle access to the stream. The investigative study undertaken to quantify improvement in microbial water quality realised by applying on-ground in catchment interventions forms Chapter Four of this thesis.

The fifth and final chapter of this thesis comprises a synthesis. The synthesis reiterates the applicability of the ADWG Framework to source waters, and re-examines how Elements 2, 3 and 9 were applied to a source water catchment in south-east Queensland to understand the supply system, assess risks to source water quality, improve certainty in risk ratings, and to quantify to what extent a particular hazard can be moderated by on-ground remediation. Specifically, chapter five synthesises the empirical findings of Chapters two, three and four, highlights the implications for water resource management arising from this study, and discusses the study’s limitations and applicability of its outcomes. Finally, recommendations for future research are discussed in the synthesis chapter.

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Chapter two: Assessment of the drinking water supply system.

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Chapter three: Reassessing the risk of microbial contamination from roosting cormorants in source water supply reservoirs

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Abbreviated title: Cormorants and microbial risk to water quality.

Chapter 4: Cattle-derived microbial input to source water catchments: an experimental assessment of stream crossing modification

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Chapter five: Synthesis

5.1 Introduction

The Australian Drinking Water Guidelines (ADWG) Framework for the Management of Drinking Water Quality (the Framework) (NHMRC, NRMMC 2011) promotes a structured and systematic preventative management approach to assure safety of drinking water at point of supply. Amongst its guiding principles and 12 key Elements is the clear recognition that source water catchments (= watershed that provides raw water to water treatment facilities) are a critical component of the supply system. For example, it is acknowledged in Element 2 (*Assessment of the drinking water supply system*) of the Framework that effective water quality management requires an understanding of the water supply system from catchment to consumer, and, in Element 3 (*Preventative measures for drinking water quality management*) that catchment management and source water protection provide the first barrier for the protection of drinking water quality. In addition, Element 9 (*Research and development*) highlights the importance of investigative studies and research monitoring to increase understanding of the source/raw water component of the supply system to improve characterisation of water quality hazards and to fill gaps in knowledge related to identified risks.

This thesis set out to demonstrate how the Framework is directly applicable to source water systems by applying Element 2 and undertaking a water supply analysis for Lake Baroon and the Baroon catchment in south east Queensland, combined with water quality data to identify hazards and hazardous events. This information was used to undertake a water quality risk assessment for the source/raw water. The study also sought to practically demonstrate the process of applying Element 9 to improve the certainty in rating the risk of a particular hazardous event arising from the Baroon risk assessment, and, to quantify to what extent a particular hazard can be moderated by on-ground catchment remediation work as a preventative measure/in-catchment barrier. This practical demonstration of Element 9 was achieved by answering these questions:

1. Do birds roosting on intake infrastructure at source water reservoirs pose an extreme risk of microbial contamination to the water supply system through direct deposition of faecal matter to the aquatic environment?
2. Was the installation of the bridging structure on a dairy farm an effective management intervention for reducing livestock-derived microbial and suspended solids inputs to a source water catchment?

5.2 Empirical findings

The main empirical findings of this broader study are chapter specific and are detailed within the chapters: Assessment of the Lake Baroon source water catchment: water supply system analysis, assessment of water quality data, and hazard identification and risk assessment (Chapter two); Reassessing the risk of microbial contamination from roosting cormorants in source water supply reservoirs (Chapter three); and, Reducing cattle-derived microbial inputs in source water catchments through modifying on-farm stream crossings (Chapter four). This section will synthesize the empirical findings of these chapters to highlight main findings that can be used in turn to revisit and update the risk register developed in Chapter two and hence demonstrate the practicality and value of implementing the ADWG Framework to source water catchments.

In Chapter two, the hazards to source water quality in the Lake Baroon and the Baroon catchment were characterised as biological (pathogenic bacteria, protozoa and viruses), chemical (metals, hydrocarbons, pesticides and pharmaceuticals), and physical (dissolved solids and turbidity). Key hazardous events include rainfall/runoff events, failure at local sewage treatment plant, pastoral grazing, intensive animal production, birds roosting on reservoir raw water intake structures and livestock with direct access to catchment tributaries. The ADWG (2011) defines risk as the likelihood of identified hazards causing harm in exposed population in a specified timeframe, including severity of consequences. Accordingly, following the risk assessment methodology/process contained in the ADWG, pathogenic bacteria were rated as posing an extreme risk to human health, pathogenic protozoa and viruses as posing a high risk to human health, and, cyanotoxins as posing a medium risk to human health. Other catchment water quality hazards, such as heavy metals, nitrate, hydrocarbons and pharmaceuticals were rated as posing a low risk to human health.

As highlighted in Chapter two, the risk assessment process endorsed in the ADWG (2011) involves undertaking a collaborative workshop whereby a level of risk is estimated by identifying the likelihood of the occurrence and evaluating the severity of the consequences if the hazard were to occur. While there was clear consensus among workshop participants at the Baroon risk assessment on rating the water quality risk of pathogenic bacteria as extreme, there was disagreement on the importance of native birds roosting on raw water intake infrastructure as a key hazardous event that can lead to the presence of a microbial pollution in source/raw waters. This presented a key knowledge gap and an opportunity to undertake research monitoring as per Element 9 of the ADWG to enable the level of risk posed by birds roosting on intake structures to be more fully quantified. Chapter three describes how populations of little black cormorants (*Phalocrocorax sulcirostris*) were surveyed at three intake structures across two reservoirs; and up to 3.9 x 10^{14} *E. coli* organisms were estimated to be produced per day by the largest population. While cormorants were present at intake sites and absent from reference sites, concentrations of *E. coli* were not significantly higher in water at intake sites compared with reference sites. Further, no significant relationship was detected between cormorant numbers and water column concentrations of *E. coli*. Results suggest that inputs from across the broader catchment dominate microbial pollution in the two study reservoirs, and inputs attributable to roosting cormorants are minor when compared to other sources.

Preventative measures are any planned action, activity or process that is used to prevent hazards from occurring or reduce them to acceptable levels (NHMRC, NRMMC 2011). The ADWG (2011) clearly states that preventive measures should be applied from catchment to consumer in accordance with the multiple barrier approach (Element 3). However, unlike in the water treatment component of the supply system where the efficacy of a preventative measure is relatively easy to determine (e.g. the reduction of microbes achieved through UV disinfection) it can be difficult to quantify the effectiveness of preventative measures applied to source water catchments. To illustrate, an additional outcome of the Baroon catchment risk assessment (as per Chapter two) was a highlighting of the lack of clarity regarding the effectiveness of in-catchment preventative measures to mitigate livestock-derived microbial pollution. This presented another key knowledge gap and a further opportunity to undertake an investigative study as per Element 9 of the ADWG. The installation of the bridging structure on a dairy farm as a management intervention for reducing livestock-derived microbial and suspended solids inputs to a source water catchment was investigated in Chapter four. Here we detected a positive relationship between antecedent hydrology and total suspended solids (TSS), but not between antecedent hydrology and concentrations of faecal indicator bacteria. Although there was no consistent significant effect on concentrations of faecal indicator bacteria or TSS attributable to the installation of the bridging structure, post-hoc pairwise tests detected significant longitudinal increases in concentrations between up- and downstream reaches in the control reach after crossing modification, but not the treatment reach. This study shows stream bridging as an alternative to a ford crossing reduces the point source impact posed by dairy cattle habitually fording waterways. However, the results also suggest that the water quality benefit to the upper Lake Baroon catchment may be overwhelmed by chronic microbiological and suspended solids pollution arising from the diffuse source impact presented by the same cattle as they range across the property to graze. Therefore, while installation of the bridging structure was effective in reducing cattle-derived point source pollution, cattle-derived diffuse source pollution is not ameliorated by this best intervention/change in farm management practice alone.

The empirical findings of Chapters three and four present an opportunity to revisit the risk register presented in Chapter two, and consequently illustrate the inbuilt continual improvement/adaptive management philosophy of the ADWG Framework. That is, knowledge gaps identified through the assessment of the drinking water supply system (Element 2) are addressed through the application of research and development (Element 9), which in turn improves the assessment of the drinking water supply system.

5.3 Implications for water resource management

This study has highlighted that the ADWG Framework for the Management of Drinking Water Quality can be effectively and meaningfully applied to source water catchments and raw water reservoirs. The capacity for the Framework to be applied to the source/raw water component of the drinking water supply system comes directly out of the intent of the ADWG (i.e. it is explicit in the document), and, from the principles of continual improvement and adaptive management built into the ADWG.

Adaptive management refers to a systemic process for continual improvement in management policies and practices by learning from the outcomes of implemented management strategies (Pahl-Wostl 2007). Adaptive management is inherent to the ADWG by being embedded throughout the Framework, but particularly in Elements 2 and 9.

Application of these Elements to the source/raw water component of the drinking water supply system as shown in this thesis demonstrates how participatory assessment and an improved understanding of the factors affecting water quality characteristics in source/raw waters allows water resource managers plan and respond to effectively to maintain a safe and secure drinking water supply. Accordingly, the implications of this study to water resource management is a full adoption of the ADWG Framework will enable water authorities and utilities to achieve a comprehensive, integrated approach for managing water contamination risks across all stages of water supply – from catchment to consumer.

5.4 Limitations of this study

This study has offered an evaluative perspective on the practical application of the ADWG framework to source water catchments, inclusive of research which sought to fill knowledge gaps regarding the rating of a particular risk to water quality and to quantify the water quality benefit of implementing a catchment based on-farm best management practice. The study was conducted in a sub-tropical region of Queensland (Australia) in a water supply system servicing numerous major population centres, with the two in-field experiments undertaken at the reservoir and reach scale respectively. As a consequence there are a number of limitations which need to be considered.

Firstly, given the resources necessary to implement a quality management system such as the ADWG Framework that is inclusive of a data driven catchment water quality risk assessment, there may be limitations on how applicable or transferable this process may be to water supply systems in developing nations given the resources required. Indeed, there may be limits on the application and transferability of the ADWG Framework within developed nations such as Australia, where small utilities or regional/remote municipalities may not have the financial capacity or in-house expertise to fully execute the process.

Secondly, the results of the in-field experiment investigating birds roosting on intake infrastructure and their risk of microbial contamination to the water supply system was limited in terms of its applicability to other source water reservoirs. That is, the study focused on only one species, the little black cormorant, and the size of the populations roosting at the two source water reservoirs were small. Other studies have shown birds in large populations were responsible for input of microbial contamination causing a degradation of water quality (e.g. Benton et al. 1983; Klimaszky 2012). This study has not necessarily shed light on the 'carrying capacity' at which populations of cormorants roosting on reservoirs will become a significant hazardous process, nor has this study fully explored how the risk profile may differ if a population was transient or was made up of species whose average daily faecal coliform production rates were greater than for cormorants.

Thirdly, the in-field experiment examining the installation of the bridging structure and an on-farm intervention to reduce livestock-derived microbial and suspended solids inputs may be limited by its inapplicability beyond the farm/reach scale. Kay et al. (2012) highlight that in their experience the adoption of on-farm interventions to address livestock-derived faecal contamination of waterways has generally been confined to small areas of land within broader catchments. This, according to Kay et al. (2012) has meant that data collected characterizing rates and efficacy of attenuation associated with in-catchment interventions to reduce livestock-derived fecal contamination is exceedingly site dependent and precludes meaningful empirical investigation of catchment-scale microbial fluxes. As such, results from study investigating the installation of the bridging structure on a dairy farm to reduce livestock-derived microbial and suspended solids inputs undertaken as part of this thesis may be limited in their transferability to other systems.

While there are limitations across the three main components of this thesis, the overall benefits of applying the ADWG process are still clearly evident in each component. To illustrate, although there may be some constrains regarding the transferability of the ADWG Framework or similar quality management systems to developing nations, there has been 'buy-in' on water safety plans for drinking water supplies in countries such as Bangladesh, Uganda and others (see Edgar et al. 2010). Further, while there may be some restrictions on applicability of quality management systems even in developed nations where small utilities or regional/remote municipalities may not have the financial capacity or in-house expertise to fully execute them, the ADWG (2011) has a chapter specifically dedicated to the application of the Framework to small water supplies. Hence, the transferability of the Framework/quality management systems does not hinge on resourcing or the availability of particular because at the centre of these systems is a preventative approach which can be applied inexpensively and following a stepwise process.

Similarly, although the experiment investigating birds roosting on intake infrastructure focused on only one species and the size of the study populations were small, the general approach used is transferable to any reservoir and any given suite of bird species, and more importantly the study provides a worked example of the type of simple study that can further knowledge of hazards and strengthen the risk assessment approach as per Elements 2 and 9 of the Framework. Likewise, despite authors such as Kay et al. (2012) questioning the validity of small (reach) scale experiments in understanding the effectiveness of in-catchment interventions to attenuate live-stock derived pathogens within catchments, others such as Winter et al. (2011) suggest that there is limited evidence to suggest that the effects of changes in land measurement can be distinguished at the catchment scale, and, that management and measurement at the farm and reach scale is crucial to water quality outcomes. Winter et al. (2011) advise that integrated research across scales is needed for effective management of microbial pollution in source water catchments. Thus, studies such as that examining the installation of the bridging structure to reduce livestock-derived microbial and suspended solids inputs as undertaken in this thesis are relevant to effective management and planning of water resources.

5.5 Recommendations for future research

As stated in the ADWG (2011), there will always be uncertainty associated with hazard identification and risk assessment. While variability can only be better understood (e.g. by improved characterisation of a hazard), uncertainty due to lack of knowledge can be reduced through better measurement and research (NHMRC, NRMMC 2011). A central theme of this thesis is application of Element 9 of the ADWG to identify knowledge gaps and reduce uncertainty in the source water component of the water supply system. While two knowledge gaps arising from applying Elements 2 and 3 were addressed in Chapters three and four of this thesis, there is a clear need for more case studies at the local level to further develop the understanding of the risk profile of the Baroon catchment and how this impacts on the quality of drinking water at point of supply.

As discussed in Chapter three, water sampling based on faecal indicator bacteria alone is unlikely to provide the level of information required to understand temporal and spatial variability in microbial concentrations, or on the relative contribution of pathogen sources, in heavily degraded source water catchments. Accordingly, it is recommended that future investigative studies and research focus on the application of tools such as microbial source tracking (MST) in source water catchments. Microbial source tracking is a relatively new and developing approach that aims to identify the origins of faecal pollution in water (Roslev and Bukh 2011). The underlying assumption is that characteristics in, or associated with, faecal pollution can be used to identify the faeces type and source (Field and Samadpour 2007). Therefore MST not only detects faecal pollution, but provides information about the source, which can be used by water authorities to improve management of water quality and therefore minimise public health risk (Stratton et al. 2009), based on the premise that a human faecal contamination events are likely to be of a higher risk to human health.

Element 3 of the ADWG unequivocally affirms that, because water quality hazards occur throughout the water supply system, preventative measures should be comprehensive from catchment to consumer. Further, Element 3 states that preventative measures should be applied as close to the source as possible, with a focus on prevention in catchments rather than sole reliance on downstream control. Indubitably the application of preventative measures to source water catchments is imperative. However, how many/what combination of preventative measures constitutes an in-catchment barrier (as prescribed by the multi-barrier approach) and how exactly the efficacy of in-catchment barriers is validated are areas where further understanding is needed, framed within the ADWG process. Therefore, exploring these questions in the Baroon catchment is recommended for future research. For example, questions around optimal combinations or preventative measures and their ultimate value as a barrier within the water supply system can be answered by quantifying impacts of different combinations of on-farm interventions to address diffuse microbial pollution at the farm/reach scale, then undertaking the same experiments at multiple sites to validate if the equivalent effects will apply across the catchment.

5.6 Conclusion

It is well recognised that quality management systems that set out a structured and systematic preventative management approach that encompasses all steps in water production is the most effective means of assuring the safety of water at point of supply. While ADWG Framework or similar are widely applied to drinking water supply systems in Australia, the application of key Elements, such as Element 2 and 3, to source water component of the water supply system can be challenging.

This study has offered an evaluative perspective on the application of Element 2 of the ADWG Framework to source water catchments and associated raw water reservoirs, and provided practical demonstration of how execute an assessment of this critical component of the drinking water supply system. Additionally, this study has provided a practical demonstration of the process of applying Element 9 to improve the certainty in rating the risk of a particular hazardous event in a raw water reservoir, and to evaluate to what extent microbial pollution was an in-catchment intervention as preventative measure/barrier to microbial hazards. Ultimately, this study has reemphasised the authentic links between the condition of the catchment and the condition of drinking water, and the need for a structured, systematic and adaptive approach to managing water quality.

5.7 References

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