APPENDIX 9

GROUNDWATER REPLENISHMENT SCHEME RISK ASSESSMENT

Perth Groundwater Replenishment Scheme – Stage 2A

Risk Assessment Report

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AWRP	Advanced Water Recycling Plant	A multiple treatment process consisting of ultrafiltration, reverse osmosis, ultraviolet disinfection to produce water for groundwater replenishment
CCP	Critical Control Point	An activity, procedure or process where control can be applied that is essential for operating the treatment process to ensure recycled water meets water quality guidelines.
DEC	Department of Environment and Conservation	Responsible for the protection of the environment.
DoH	Department of Health	Responsible for the protection of human health.
DoW	Department of Water	Responsible for the protection of water resources, including public drinking water sources.
EVs	Environmental Values	The term applied to particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health.
GL	Gigalitres	One billion litres.
GW-TRG	Groundwater Technical Reference Group	Team of hydrogeological experts from the CSIRO, DoW, Curtin University, Rockwater Pty Ltd and the Water Corporation formed to progress the groundwater objectives of the Trial, and to assess the feasibility and potential hazards of future GWR schemes based on available hydrogeological, water quality and geophysical data generated from the Trial and Yarragadee investigations.
GWR	Groundwater Replenishment	Is the process by which secondary treated wastewater undergoes advanced treatment to produce recycled water which meets Australian guidelines for drinking water prior to being recharged to an aquifer for later use as a drinking water source.
GWR MoU	Memorandum of Understanding between the Department of Health and the Water Corporation for the Groundwater Replenishment Trial	In the context of groundwater replenishment it refers to the agreement between the Department of Health and Water Corporation outlining the requirements for a groundwater replenishment scheme; i.e. water quality guidelines, operational performance and reporting requirements and communications protocols.
GWRT	Groundwater Replenishment Trial	Successfully completed by Water Corporation in December 2012 at Beenyup, it provided information to allow assessment and progress of a large GWR Scheme.
	Inherent Risk	The risk in the absence of mitigations.
IWSS	Integrated Water Supply Scheme	The system of pipes and pumps which supplies drinking water to the Perth Metropolitan area, Mandurah and the Goldfields pipeline.
LOR	Limit of Reporting	The lowest limit at which the laboratory will report a quantitative result for a parameter: chemical, microbiological or radiological. Multiple LOR's may be applicable for analytes due to changes in methods.

ML	Megalitres	One million litres.
PAHs	Poly Aromatic Hydrocarbons	
	Residual Risk	The risk after mitigations have been applied.
	Risk	A measure of the likelihood of identified hazards causing harm to the receiving environment in a specified timeframe with a severity measured by the consequence (risk = likelihood x consequence)
RMZ	Recharge Management Zone	Defines the minimum distance between recharge of recycled water and the boundary where groundwater quality meets guidelines and the environmental values protected and provides an adequate source of drinking water. A distance of 250m has been defined for the confined aquifers at the Beenyup site.
RWQI	Recycled Water Quality Indicator	Chemicals or pathogens that best represent a larger group of chemicals or microbiological hazards identified by the *Recycled Water Quality Parameters*. The RWQI have been specified by the Department of Health (DoH) and are set out in the GWRT MoU Schedule 1.
RWQP	Recycled Water Quality Parameter	Refers to the water quality parameters to be measured in recycled water, as defined by the DoH and set out in the *GWRT MoU* Schedule 1. Analysis of these parameters will allow assessment of the recycled water against the *Water Quality Guidelines.*
RO	Reverse Osmosis	Second treatment step in the advanced water recycling process.
UV	Ultraviolet Disinfection	Third treatment step in the advanced water recycling process.
	Water Quality Guidelines	Compliance with the water quality guidelines set by the DoH represents protection of human health and the Environmental Values. Water quality guidelines are defined in the GWRT MoU Schedule 1 and described in Table 6-1.
WRMOS	Water Resource Management Operation Strategy	A requirement from DoW whereby a licensee commits to a management strategy for a given water resource.
WWTP	Wastewater Treatment Plant	A treatment process which immediately precedes the Advanced Water Recycling Plant, providing secondary treatment to raw wastewater. In the context of GWRS it refers to the Beenyup WWTP, located in Craigie, Perth.

1 Executive Summary

The Groundwater Replenishment Trial was completed in December 2012, demonstrating that groundwater replenishment is a sustainable water source option for Perth. Based on the success of the Trial, Water Corporation is progressing the Perth Groundwater Replenishment Scheme (GWRS) at its Beenyup site in Perth's northern suburbs.

The Scheme will ultimately recharge up to 28 gigalitres per year (GL/yr) from an Advanced Water Recycling Plant (AWRP) to the Leederville and Yarragadee aquifers. The scheme will be staged to allow flexibility to meet future water supply demand.
Water Corporation is currently progressing approvals for Stages 1 and 2A in accordance with the GWR Regulatory Framework.

This report provides the outcomes of the risk assessment conducted Stage 2A (applicable also to Stage 1); recharging up to 14GL/yr to the Leederville or Yarragadee aquifer, or a combination of both, from the AWRP which sources treated wastewater from Beenyup Wastewater Treatment Plant (WWTP).

The Perth GWRS Stage 2A Risk Assessment will provide guidance to the designers of the Perth GWRS, support project referral to the Environmental Protection Authority and provide a basis for approvals from the Department of Health (DoH), Department of Environment and Conservation (DEC) and Department of Water (DoW) as outlined in the GWR Regulatory Framework.

The DoH, DEC and DoW have identified the Environmental Values (EV's) applicable to the Perth GWRS Stage 2A. They are Drinking Water, Primary Industry, Industrial Water and Cultural and Spiritual. The EVs consider the most conservative (worse case) scenario of recharging up to 14GL/year to each aquifer.

The DoH has defined 254 water quality guidelines that the recycled water must meet at the point of recharge and again at the boundary of the Recharge Management Zone (RMZ) in order to protect the Drinking Water EV, Primary Industries EV and Industrial Water EV. The Cultural and Spiritual EV cannot be protected with water quality guidelines and Water Corporation is continuing consultation with indigenous stakeholders.

Perth GWRS Stage 2A Risk Assessment applies the Wastewater Quality Framework, which adopts the risk management approach described in the *Australian Guidelines for Recycled Water: Managing Health and Environmental Risk (Phase 1)*.

Two separate risk assessments were undertaken using data provided by the Trial and additional investigations conducted for the Yarragadee aquifer. The scope of each assessment is described in the following table.

Table 1-1: Scope of the Risk Assessments

Risk Assessment	Scope	Assessed(1):
Treatment Process Risk Assessment	- Wastewater Catchment - WWTP - AWRP	Hazards – assessed the risk of not meeting water quality guidelines at the point of recharge. Barrier Failures – considers operational reliability to identify and assess the risk of potential failures within the treatment process.
Aquifer Risk Assessment	- Leederville aquifer - Yarragadee aquifer	Hazards – assessed the risk of not meeting water quality guidelines at the boundary of Recharge Management Zone (250m from recharge bore). Recharge efficiency – considers operational issues that may affect production or recharge.

(1) Risks were assessed using the Water Corporation's Risk Assessment Criteria

The Treatment Process Hazard Risk Assessment considered if the water would meet all 254 water quality guidelines after secondary treatment to assign an inherent risk and again after the AWRP to assign a residual risk at the point of recharge. Each chemical and microbiological parameter with a water quality guideline is considered a "hazard" in the context of this risk assessment. Maximum concentrations of each hazard detected during the Trial were used in the assessment.

In summary, the assessment identified:

- 122 hazards (parameters with guideline values) which were absent or below 10% of the water quality guideline were assigned a low risk rating and not assessed further.
- 132 hazards (parameters with guideline values) were assigned an inherent risk of low, moderate, high or extreme after secondary treatment and assessed further.

The Trial AWRP has demonstrated consistent and reliable removal of these hazards to well below water quality guidelines, resulting in a residual risk of low for all parameters. Therefore the risk of recharging water that does not meet the water quality guidelines is low.

The Treatment Process Barrier Failure Risk Assessment considered potential operational failures in the wastewater catchment, WWTP or AWRP to assign an inherent risk. Available mitigations were then considered in order to assign a residual risk.
34 potential barrier failures were identified, which can be summarised as:

- Illegal dumping of substances into the wastewater catchment.
- Events which may occur in the WWTP which may reduce the effectiveness of the wastewater treatment process and may compromise AWRP feed water quality.
- Failure of the ultrafiltration, reverse osmosis systems and ultra violet disinfection systems.
- Integrity of the process control system.

In addition, the three water quality events that were experienced during the Trial were considered in detail to ensure that similar failures could not reoccur.

The Trial has demonstrated that online monitoring of WWTP and AWRP critical control points resulting in automatic diversion if water quality requirements are not met is an adequate mitigation against potential barrier failures. Therefore the residual risk of a barrier failure impacting recycled water quality was assessed as low.

The Aquifer Risk Assessment considered if the groundwater quality in either the Leederville or Yarragadee aquifer would meet all 254 water quality guidelines at the boundary of the RMZ to assign an inherent risk. The assessment also considered operational issues which may affect recharge efficiency. Mitigations were considered in order to assign a residual risk.

20 potential hazards to the Leederville aquifer and 26 to the Yarragadee aquifer were identified. Mitigations were identified for all potential hazards. With these mitigations in place, the risk of not meeting the water quality guidelines at the boundary of the RMZ or occurrence of significant operational issues impacting recharge efficiency is low.

The Risk Assessment has demonstrated that the Perth GWRS Stages 1 and 2A is a low risk, and an AWRP recharging up to 14GL/yr of recycled water to the Leederville or Yarragadee aquifer can be undertaken in a manner which protects the identified EVs of the receiving aquifer.

2 Purpose

This report presents the outcomes of the Perth Groundwater Replenishment Scheme (GWRS) – Stage 2A Risk Assessment, concluding that with appropriate mitigations, the risks are low.

It was prepared in accordance with the requirements of the GWR Regulatory Framework (IAWG, 2012) and will provide guidance to the designers of the Perth GWRS, support project referral to the Environmental Protection Authority and provide a basis for approvals from the Department of Health (DoH), Department of Environment and Conservation (DEC) and Department of Water (DoW) as outlined in the GWR Regulatory Framework.

3 Scope

The risks associated with the Perth GWRS consider the Beenyup wastewater catchment, the Beenyup Wastewater Treatment Plant (WWTP), an Advanced Water Recycling Plant (AWRP) and the recharge aquifers; the Leederville aquifer and Yarragadee aquifer.

This Risk Assessment identified and assessed potential risks of recharging up to 14 gigalitres per year (GL/yr) from an AWRP to replenish the Leederville and Yarragadee aquifers using recharge bores located at the Beenyup site.

The Risk Assessment was conducted in two parts and documented in detail in the following reports:

- *Perth GWRS Stage 2A - Treatment Process Risk Assessment Report*, (provided in Appendix 2:) considering potential hazards and mitigations which may occur in the wastewater catchment, WWTP and AWRP to the point of recharge;
- *Perth GWRS Stage 2A - Aquifer Risk Assessment Report* (provided in Appendix 3:) considering potential hazards and mitigations within both aquifers to the boundary of the Recharge Management Zone (RMZ); a radial boundary 250m from the point of recharge.

This Report summarises the outcomes of these two risk assessments. References are made throughout this Report to the two supporting reports (described above) to allow the reader to obtain detailed information if required.

4 Introduction

Groundwater Replenishment (GWR) is the process by which secondary treated wastewater undergoes advanced treatment to produce water which meets Australian guidelines for drinking water prior to being recharged to an aquifer for later use as a drinking water source.

The Water Corporation completed the Groundwater Replenishment Trial in December 2012. During the Trial more than 2.5GL of recycled water was recharged into the confined Leederville aquifer at the Beenyup site in Craigie. The Trial was used to build knowledge of the technical, health, environmental and social issues associated with GWR in Perth.

Based on the success of the Trial, Water Corporation is progressing approvals for a 28GL/year AWRP at the Beenyup site (including recharge at offsite bores). Delivery of the Perth GWRS will be staged to allow flexibility to meet future water demand of the Integrated Water Supply Scheme (IWSS). The stages for delivery are described in Table 4-1.

To maintain supply in a drying climate, Water Corporation is considering accelerating the delivery of Stage 2 of the Perth GWRS. Given potential delays in construction and approvals, Water Corporation has reviewed the scope of Stage 2 and may progress its delivery in two parts; Stage 2A and 2B, also described in Table 4-1.

Table 4-1: Stages of the 28 GL/yr Perth GWRS

Stage	Activity
1	Construct a 7GL/yr AWRP at the Beenyup site. Recharge via the existing Leederville aquifer recharge bore and one new Yarragadee aquifer recharge bore located at the Beenyup site.
2A	Construct an additional 7GL/yr AWRP at the Beenyup site (to provide a total of 14GL/yr recycled water). Maximise recharge to Leederville and Yarragadee aquifer recharge bores. **Note:** Whilst maximum recharge rates for each bore can be estimated, this will not be confirmed until they can be tested under pumping and recharge conditions.
2B	Construct a pipeline and two new Leederville aquifer recharge bores (if required) located off the Beenyup site, to the east of Lake Joondalup to recharge the additional water produced by the Stage 2A AWRP.
3	Construct an additional 14GL/yr AWRP at the Beenyup site (to provide a total of 28GL/yr recycled water). Extend pipeline and construct two additional Leederville aquifer recharge bores and two additional Yarragadee aquifer recharge bores to recharge the additional water.

Water Corporation will be seeking approvals for Stage 2A in parallel with Stage 1, allowing Stage 2A to be expedited if necessary.

Approvals for Stage 2B will be progressed with Stage 3 and will be commenced in sufficient time to meet forecast demand. Figure 4-1 illustrates the staging options of the 28GL/yr Perth GWRS including acceleration of GWRS Stage 2.

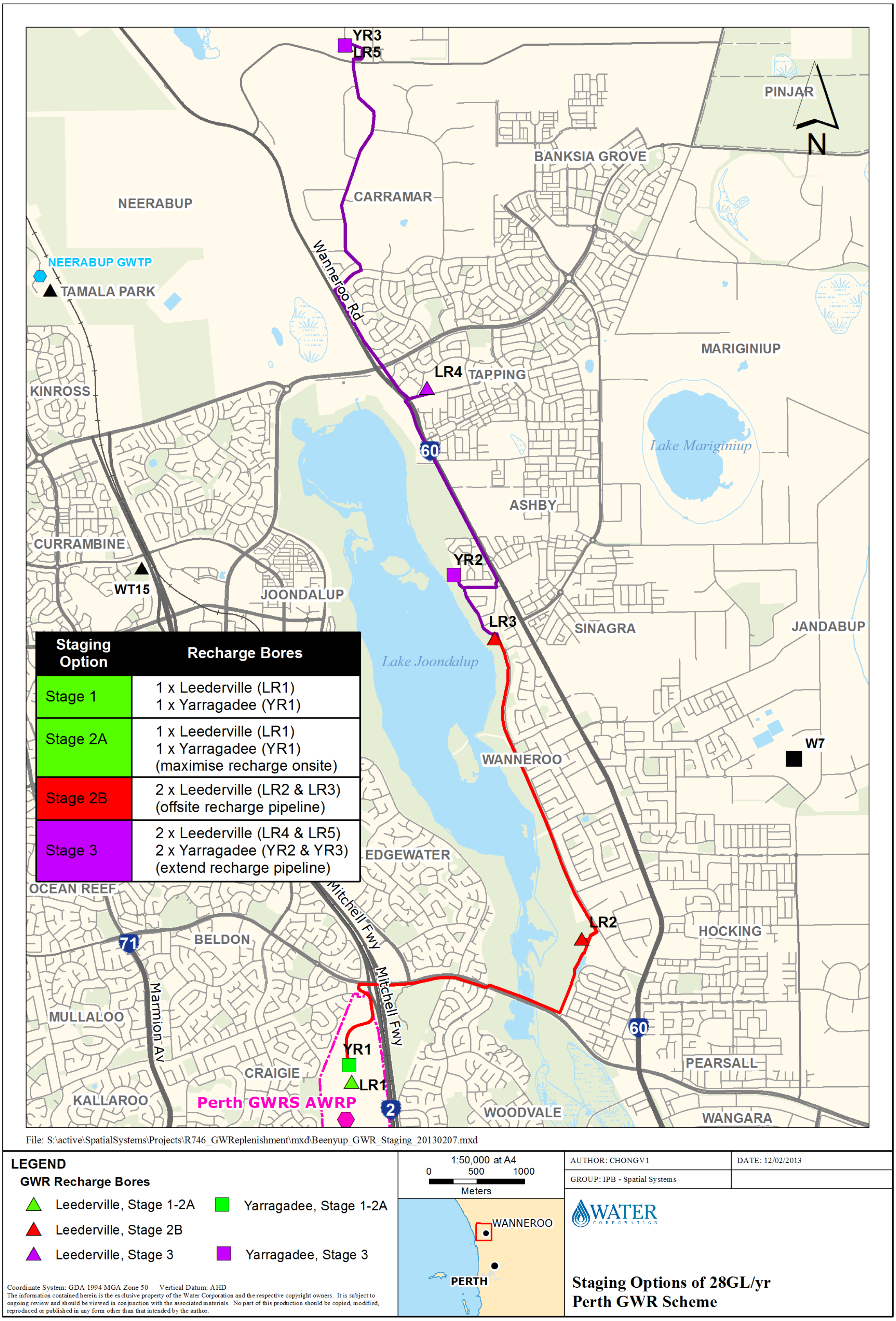

Figure 4-1: Staging of 28 GL/yr Perth GWRS

Water Corporation is progressing approvals in accordance with the GWR Regulatory Framework. An overview of the GWR Regulatory Framework (IAWG, 2012) is provided in Figure 4-2.

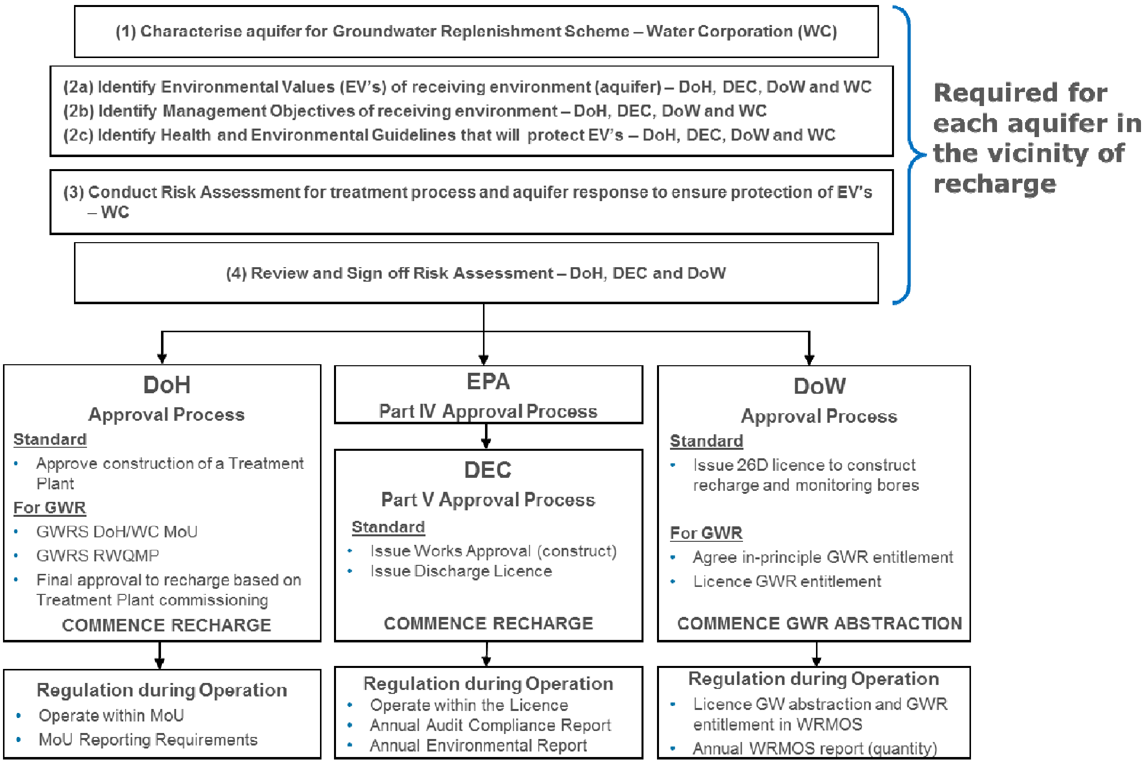

Figure 4-2: Groundwater Replenishment Regulatory Framework

Information from the Leederville aquifer was provided by the Trial, while investigations to characterise the Yarragadee aquifer commenced in August 2011.

This information was used to define the Environmental Values (EVs) and water quality guidelines applicable to recharging up to 14 GL/yr into the Leederville and Yarragadee aquifers at the Beenyup site and to identify and assess the potential risks of the Perth GWRS. This is described in more detail in Section 6.1 of this Report.

5 Risk Assessment Process

Water Corporation ensures that the recycled water quality continuously meets water quality guidelines by applying the Wastewater Quality Framework, which adopts the risk management approach described in the *Australian Guidelines for Recycled Water: Managing Health and Environmental Risks (Phase 1)* (NRMMC-EPHC-AHMC, 2006).

Additional technical information to conduct these risk assessments was provided by the *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Augmentation of Drinking Water Supplies* (NRMMC-EPHC-NHRMC, 2008) and the *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge* (NRMMC-EPHC- NHRMC, 2009).

The Water Corporation conducted the treatment process and aquifer response risk assessments separately to allow detailed discussion of the risks with the most appropriate expertise. The risk assessments followed the same process and applied Water Corporations' *Corporate Risk Assessment Criteria* to assess and assign risks. This criterion is provided in Appendix 1:.

Each risk assessment sought to:

- Assess all available information.
- Identify potential hazards and hazardous events.
- Assign an inherent risk based on the likelihood and the consequence of the hazard or hazardous event occurring.
- Identify mitigations to reduce the inherent risk to an acceptable level.
- Assign a residual risk rating.
- If necessary, identify further investigation required to better assess the risk in the future.

The Perth GWRS Stage 2A Risk Assessment will be reviewed at key milestones in project development (as illustrated in Figure 5-1); after detailed design to validate the design, after commissioning to ensure the process performs as designed and risks remain at acceptable levels, and then regularly during the operational phase of the Scheme. There will be additional reviews if there is a change to the water quality guidelines.

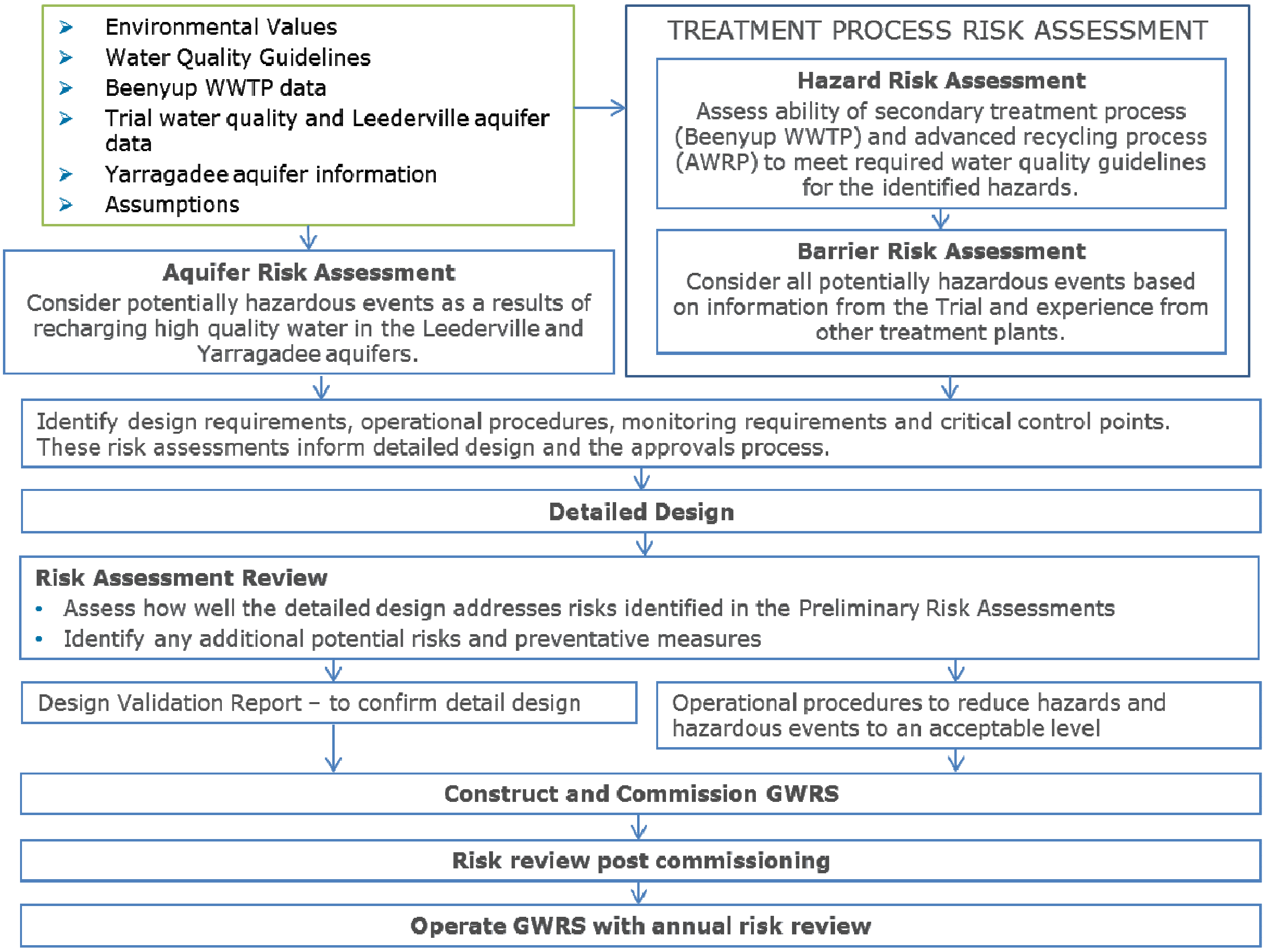

Figure 5-1: Risk Assessment Flow Chart

5.1 Treatment Process Risk Assessment Process

The Treatment Process Risk Assessment used the *2012 Groundwater Replenishment Trial Risk Assessment* (undertaken in December 2012) as a basis, determining the transferability of the identified risks to the Perth GWRS Stage 2A scope as well as identifying any new risks which may have resulted from an increase in the size of the AWRP required for Stage 2A.

There have been no changes to the water quality guidelines or new parameters identified as part of the environment scan process since December 2012, therefore no new risks were required to be considered from these sources.

Three planning workshops; one each for the wastewater catchment, WWTP and AWRP were conducted prior to the main workshop to review existing hazards and identify potential new hazards. This allowed time for further information to be gathered prior to the main workshop if required.

The Treatment Process Risk Assessment Workshop was facilitated by the Water Corporation on the 7 March 2013 and attended by Water Corporation staff with expertise in industrial waste discharges, wastewater treatment, advanced water recycling treatment and as well as technical peer reviewers MWH Global, Australia who provided technical expertise in wastewater and advanced water treatment processes.

Following the standard process, the Treatment Process Risk Assessment was delivered in two parts:

- Hazard Risk Assessment.
- Barrier Failure Risk Assessment.

5.1.1 Hazard assessment

Considers the ability of the treatment process to reduce hazards (defined as chemical or microbiological parameters with guidelines) to below water quality guidelines at the point of recharge. It considers hazards under normal operating conditions, with trained operators who are following robust procedures and a WWTP and AWRP that are operating to required criteria. Hazards are considered low risk if the recycled water at the point of recharge meets the water quality guidelines, thus protecting the EV's.

There are three steps in a hazard risk assessment:

1. **Preliminary screening of Beenyup WWTP secondary treated wastewater** Determine the extent to which the 254 hazards (parameters with a guideline value) in Beenyup WWTP treated wastewater meets the water quality guidelines.

   If the hazard was consistently absent or less than 10% of the water quality guideline in the treated wastewater, it was assigned a low risk rating and not considered further.

   If the hazard met the following criteria it was assessed in Step 2:

   - Below 10% but present in pre-Trial sampling, or had experienced a change to the water quality guideline or Limit of Reporting (LOR) during the Trial.
   - Present in concentrations above 10% of the water quality guideline.

2. **Inherent risk assessment of Beenyup WWTP secondary treated wastewater**

   An inherent risk is defined as the risk of the hazard in the absence of any action to control or mitigate the risk. It considers all hazards which were not screened out in the previous step, assigning inherent risks as follows:

   - Low: < 10% of the water quality guideline.
   - Moderate: between 10% and 100% of the water quality guideline.
   - High: > 100% of the water quality guideline.
   - Extreme: significantly greater than the water quality guideline.

3. **Residual risk assessment following the advanced treatment process**

   A residual risk is defined as the risk remaining after consideration of new or existing mitigations. Residual risks of low, moderate, high or extreme were assigned based on the application of the mitigations. Mitigations can be in the treatment design or the application of an operational procedure.

5.1.2 Barrier Failure Risk Assessment

The Barrier Failure Risk Assessment identified potential failures within the treatment process; the Beenyup wastewater catchment, WWTP and AWRP by reviewing the operational reliability of each process.

The assessment assumed that the treatment process was being operated with the management systems and processes used during the Trial, i.e. the critical control points (CCPs), process control points and supporting processes including work instructions, operation, maintenance and instrument calibration procedures and operator training. The Trial's management systems and processes were assessed as robust by an independent audit conducted in early 2013.

An inherent risk of low, moderate, high or extreme was assigned to each of these potential barrier failures based on the likelihood and consequence of the event.

A residual risk of low, moderate, high or extreme was then assigned to each of the potential barrier failures based on application of the mitigations identified during the Trial or new mitigations required for design improvements which will be applied to the Scheme.

5.2 Aquifer Risk Assessment Process

The Aquifer Risk Assessment considers any processes which may occur as a result of recharging 14GL/yr of recycled water into the Leederville aquifer or as a result of recharging 14GL/yr of recycled water to the Yarragadee aquifer which may result in the following:

- Cause an exceedance of the water quality guidelines at the boundary of the Recharge Management Zone (RMZ)[1] (Groundwater TRG, 2012).
- Affect recharge efficiency (operational consideration only, does not affect water quality).

The process was very similar to the Treatment Process Risk Assessments, involving two steps;

1. Assign an inherent risk of low, moderate, high or extreme for the potential hazards based on the likelihood and consequence.

2. Assign a residual risk of low, moderate, high or extreme for the potential hazards based on application of the mitigations identified for the:
    - Leederville aquifer based on Trial research data.
    - Yarragadee aquifer based on Trial research data and additional investigations.
    - AWRP and WWTP Treatment processes based on the Trial or additional mitigations identified as potential AWRP design improvements.

The Aquifer Risk Assessment Workshop was facilitated by the Water Corporation on 14 March 2013. Workshop participants included technical specialists from DoW, Water Corporation, CSIRO and Curtin University and hydrogeological consultants, Rockwater. Participants at this workshop have been involved with the Trial and have contributed extensively to the current understanding of GWR into the confined aquifers in Perth.

The risk assessment outcomes were also peer reviewed by Dr Peter Dillon, from CSIRO, who has extensive experience in Managed Aquifer Recharge (including guideline development).

[1] The RMZ is the same for the Leederville aquifer and Yarragadee aquifer; located a radial distance of 250m from the point of recharge. Detail on the RMZ can be found in Section 5.5 of Appendix 3: Aquifer Risk Assessment Report.

6 Inputs to the Risk Assessment

6.1 Environmental Values and Water Quality Guidelines

In February 2013 DoH, DEC and DoW identified the Environmental Values (EV's) and water quality guidelines applicable to the Perth GWRS Stage 2A recharging the Leederville aquifer and Yarragadee aquifer at the Beenyup site. The EVs take into account the most conservative scenario of recharging up to 14GL/year to each aquifer.

This has been summarised in Table 6-1:

Table 6-1: The identified EV's and water quality guidelines for GWRS Stage 2A

Environmental Value	Water Quality Guidelines for Leederville and Yarragadee aquifer – GWRS Stage 2A
Drinking Water	Recycled Water Quality Indicators (18 parameters) Recycled Water Quality Parameters (292 parameters to assess 254 water quality guidelines)[2] *As defined by the Memorandum of Understanding (MoU) between the Department of Health and Water Corporation for the Groundwater Replenishment Trial 2010* (DoH & Water Corporation, 2010)
Primary Industries	As per Drinking Water EV
Industrial Water	As per Drinking Water EV
Cultural and Spiritual	Consultation with Indigenous Community

The DEC, DoW and DoH determined that the management objective of the identified EV's is to "maintain for current and future use" (DEC, DoH, DoW and Water Corporation, 2013).

The DoH then identified the water quality guidelines that the recycled water must meet to protect human health and the identified EVs (completing Step 2 of the GWR Regulatory Framework). These are provided in Table 6-1.

The Aquifer Risk Assessment also considered six (6) additional parameters that were included in the Trial's AWRP DEC discharge licence. While these have not been identified as water quality guidelines for Perth GWRS Stage 2A, they are still applicable to the 1.5GL AWRP, therefore the conservative approach was taken to assess potential hazards against these guidelines.

[2] 46 of the 292 MoU RWQPs contribute to the calculation of "combined toxic equivalence" for PAHs and Dioxins. Only a few of these RWQPs have a relevant individual guideline value to report against.

6.2 Groundwater Replenishment Trial

The Trial AWRP operated for 3 years, recharging for 2 years between November 2010 and December 2012. The Trial provided data that was used in the evaluation of risks of the Perth GWRS Stage 2A, via:

- 4100 recycled water quality results, providing a minimum of 6 data points for each of the 254 parameters (hazards) used in the Treatment Process Hazard Risk Assessment.
- Critical Control Point (CCP) performance data and over 8,000 operational sampling results used in the Treatment Process' Barrier Failure Risk Assessment.
- Documentation of all technical issues that arose during design, construction and operation used in the Treatment Process Risk Assessments and Aquifer Risk Assessment.
- Comprehensive research data from the Leederville aquifer, including over 52,300 water quality results. This data can be used in both the Leederville and Yarragadee Aquifer Risk Assessments.
- Modelling tools assessed or developed during the Trial for use in predicting aquifer response were used in both the Leederville and Yarragadee Aquifer Risk Assessments.

6.3 Yarragadee aquifer investigations

Water Corporation and the Groundwater Technical Reference Group conducted a preliminary risk assessment of the Yarragadee aquifer in August 2011 which identified investigative works required (Water Corporation, 2011). Data from these investigations was used in this Yarragadee risk assessment.

6.4 Risk Assessment Assumptions

A number of assumptions were made to provide context for both the Treatment Process Risk Assessment and Aquifer Risk Assessment.

Section 4.4 of the Treatment Process Risk Assessment and Section 5.6 of the Aquifer Risk Assessment provides the detailed assumptions, however the most significant assumptions are as follows:

- The treatment process for the Perth GWRS AWRP will remain the same as the Trial AWRP with UF, RO, degasser & UV at 200mJ/cm2.
- The treatment process will include pre-formed chloramination and the AWRP will be designed to minimise disinfection by-product formation.
- The Perth GWRS will be operated using the same management systems and processes used in the Trial and are documented in the GWRT Recycled Water Quality Management Plan (Water Corporation, 2010).
- Two recharge bores – one into the Leederville aquifer (existing recharge bore), one into the Yarragadee aquifer at the Beenyup site
- Recharge will be up to 14GL/yr into the Leederville aquifer or Yarragadee aquifer via a single recharge bore in each (or a combination of both to a total of 14GL/yr)
- Monitoring will occur 60m from each recharge bore. This distance will provide sufficient early warning and the ability to implement mitigating strategies before the potential hazard reaches the boundary of the RMZ.

7 Scheme Description

Figure 7-1 provides an overview of the Perth GWRS.

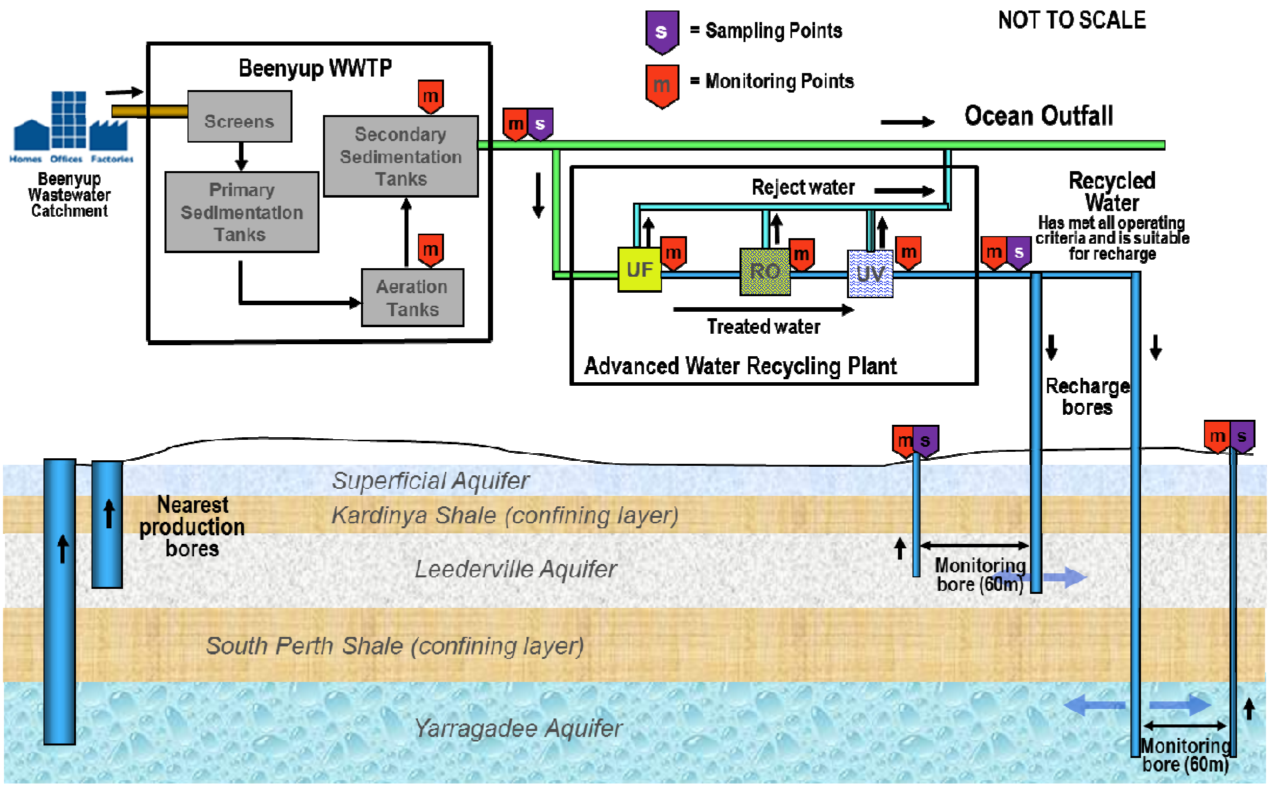

Figure 7-1: Overview of Perth Groundwater Replenishment Scheme

The following section summarises the components of the scheme. Please refer to Section 6 of the Treatment Process Risk Assessment Report for more detail on the Beenyup wastewater catchment, WWTP and AWRP or Section 6 of the Aquifer Risk Assessment Report for the Leederville aquifer and Yarragadee aquifer.

7.1 Source Water – Beenyup Wastewater Catchment

The majority of wastewater collected in the Beenyup wastewater catchment is sourced from households with approximately 2% of the total wastewater flow to Beenyup WWTP contributed by industrial waste customers.

All discharges to the wastewater collection system must meet Water Corporation's industrial waste acceptance criteria which limits or prohibits substances which may compromise the wastewater collection and treatment infrastructure, treatment processes, reuse options, environmental discharges or health and safety of staff.

7.2 Beenyup Wastewater Treatment Plant (WWTP)

The Beenyup WWTP treats approximately 120 megalitres a day (ML/d) of wastewater to a secondary standard using an activated sludge treatment process. The main treatment process units include screens, grit removal, activated sludge aeration tanks, secondary sedimentation tanks, and sludge digestion.

7.3 Advanced Water Recycling Plant (AWRP)

The Trial AWRP has successfully demonstrated that the ultrafiltration, reverse osmosis, ultra violet disinfection treatment process sufficiently treats treated wastewater to produce recycled water that consistently and reliably meets the water quality guidelines. Perth GWRS Stage 2A ARWP will use the same technology utilised in the Trial AWRP to produce approximately 14GL/yr (up to 40ML/day) recycled water.

7.4 Leederville and Yarragadee Aquifers at Beenyup

The Leederville aquifer is a confined aquifer composed of interbedded sandstone, siltstone and shale. The Leederville aquifer recharge interval, consisting of mainly quartz sandstone, with thin siltstone and shale beds is approximately 120-220m below ground level (Water Corporation, 2009).

The Yarragadee aquifer occurs from the base of the South Perth Shale and comprises the Gage Formation and the Yarragadee formation, consisting of alternating sandstones, siltstone and shales (Rockwater, 2013). The Yarragadee aquifer recharge interval is approximately between 380m to 750m below ground level.

8 Treatment Process Risk Assessment

The following section summarises the treatment process risk assessment. Further detail can be found in Appendix 2:

8.1 Hazard Risk Assessment Outcomes

The risk, that is likelihood and consequence, of all 254 chemical or microbiological parameters with water quality guidelines (defined as hazards) being below water quality guidelines at the point of recharge was assessed using the process described in Section 5.1.1.

The outcomes of the Preliminary screening are provided in Table 8-1.

The 132 hazards that passed the screening were assessed in detail. The outcomes of the inherent and residual risk assessment for these hazards are provided in Table 8-2.

Table 8-1: Outcomes of Hazard Assessment – Preliminary Screening

Number of Hazards	Assessment	Further action
122	Absent or below 10% of the water quality guideline - assigned a low risk rating	Not considered further
21	Below 10% but present in pre-Trial sampling, or had experienced a change to the water quality guideline or LOR during the Trial - assigned a low inherent risk rating	Considered in inherent risk assessment
111	Above 10% of the water quality guideline - assigned a moderate, high or extreme inherent risk rating	Considered in inherent risk assessment

Table 8-2: Outcomes of Hazard Assessment – Inherent and Residual Risk Assessment

Stage of Assessment	Low Risk	Moderate Risk (between 10-100% of the guideline)	High Risk (> 100% of the guideline)	Extreme Risk (significantly higher than the guideline)
Inherent Risk Assessment	21	86	21	4
Residual Risk Assessment	132	0	0	0

The extreme inherent risks assigned were the 4 pathogen indicators; MS2 coliphage, somatic coliphage, TTC/*E.coli* and *Clostridium perfringens* spores. This is not surprising as while some pathogen removal from the WWTP is expected (1 log), this is not sufficient to reduce pathogens to below the water quality guidelines.

The Trial has demonstrated by routine sampling of the ultrafiltration process and by challenge testing of the reverse osmosis process, that the AWRP is extremely effective in removing pathogens to below the water quality guidelines and meet the treatment performance requirements for log reduction of pathogens. This has resulted in a residual risk rating of low for the pathogen hazards.

All remaining parameter groups were chemicals, for example nutrients, inorganic ions, hormones, pesticides, which were spread across low, moderate and high inherent risk rankings. Again the Trial AWRP has demonstrated consistent and reliable removal of these hazards to well below water quality guidelines, resulting in a residual risk of low.

There were 28 hazards included in the inherent risk assessment for which the analytical method limit of reporting (LOR) was above the water quality guideline and an additional four (4) which still required development of the analytical method. Reducing the LOR to below the water quality guideline was actively pursued during the Trial.

The DoH has advised that they are satisfied that all 32 hazards were sufficiently low risk to ensure safety to human health and the Drinking Water Resource EV. Therefore all hazards were assigned a low residual risk. DoH also advised that further work should be conducted by Water Corporation as follows as described in Table 8-3.

Table 8-3: Further work required for method development

Number of Hazards	Assessment	Further action required
22	Existing LOR is above the water quality guideline.(1)	Review available methods annually.
6	Existing LOR is above the water quality guideline.	Continue to work with laboratory to pursue method development.
4	Require development of the analytical method.	Continue to work with laboratory to pursue method development.

(1) Note LOR generally close to water quality guideline.

One design improvement has been recommended as a result of the Trial. Pre-formation of chloramines to replace the current chloramination dosing system is expected to improve management of membrane biofouling. The existing chloramination process doses ammonia and hypochlorite separately into the feed water and requires careful management to minimise the formation of disinfection by-products throughout the treatment process. Pre-formation of chloramines is likely to result in better management of ammonia and disinfection by-products in recycled water and therefore the residual risk for both was assigned as low. These hazards will be reviewed in detail in the risk assessment which follows detailed design.

8.2 Barrier Risk Assessment Outcomes

The barrier failure assessment considered potential barrier failures within the treatment process – including the Beenyup wastewater catchment, WWTP and AWRP. The outcomes of the inherent and residual risk assessment are provided in Table 8-4.

Table 8-4: Outcomes of Barrier Failure Risk Assessment

Barrier	Low Risk	Moderate Risk	High Risk	Extreme Risk
Inherent Risk Assessment				
Catchment	5	1	2	0
WWTP	5	3	5	0
AWRP	4	5	4	0
Total	**14**	**9**	**11**	**0**
Residual Risk Assessment				
Catchment	8	0	0	0
WWTP	13	0	0	0
AWRP	13	0	0	0
Total	**34**	**0**	**0**	**0**

Potential barrier failures included:

- Illegal dumping of substances into the wastewater catchment.
- Events such as power loss and a reduction in the number of treatment tanks which may compromise the effectiveness of the wastewater treatment process affecting AWRP feed water quality.
- Failure of the ultrafiltration, reverse osmosis systems and ultra violet disinfection systems.
- Integrity of the process control system.

In addition, the three water quality events that were experienced during the Trial were considered in detail to ensure that similar failures could not reoccur.

Suitable mitigations were identified for all potential failures.

The CCPs located within the WWTP and AWRP were assessed as adequate to mitigate illegal dumping and other barrier failures identified in the wastewater catchment. This is because they are suitable indicators of treatment efficiency as well as indicators of increased organic loading, and will result in diversion or shutdown when CCPs are breached. They will be supported by improved procedures for monitoring and responding to discharges in the catchment.

Mitigations for potential WWTP and AWRP failures were also considered adequate as the CCPs were suitable indicators of treatment process efficiency. Additional mitigations that have been implemented to prevent recurrence of the three Trial water quality events were also assessed as adequate.

9 Aquifer Risk Assessment

The following section summarises the aquifer risk assessment. The detailed assessment can be found in Appendix 3:.

20 potential hazards in the Leederville and 26 potential hazards in the Yarragadee were identified and assessed. The hazards could be grouped as follows:

- Risks from drilling and bore construction materials.
- Risks resulting in bore clogging or reduced aquifer permeability.
- Risks to water quality guidelines at the RMZ boundary.
- Risks of poor aquifer performance.
- Risks to geothermal bores (Yarragadee aquifer only).

They are further described in the sections below.

9.1 Leederville Aquifer Risk Assessment Outcome

The inherent and residual risk ranking for the Leederville aquifer are summarised in Table 9-1.

Table 9-1: Inherent and Residual Risk Assessment for the Leederville aquifer

Stage of Assessment	Low Risk	Moderate Risk	High Risk	Extreme Risk
Inherent Risk Assessment	15	4	1	0
Residual Risk Assessment	20	0	0	0

Details of the moderate and high inherent risks are discussed below. With appropriate mitigations in place, the residual risks were assigned as low.

9.1.1 Risks from drilling and bore construction materials

The recharge of low ionic strength recycled water could cause corrosion of the recharge bore screen if inadequate materials are used in the construction. This resulted in a high inherent risk ranking. Well established mitigations are available, such as the use of fibre reinforced epoxy casing (FRP), stainless steel screens and pH adjustment of the recycled water. With these mitigations in place, the residual risk of screen corrosion is low.

9.1.2 Risks resulting in bore clogging or reduced aquifer permeability

Air bubbles entrained in recycled water caused by water cascading into the recharge bore may become trapped in the aquifer and plug the formation pores, resulting in an increase in water levels (hydraulic head). This does not affect water quality, but does impact recharge efficiency as recharge must stop while the bore is being redeveloped. As a result this potential risk was assigned an inherent risk of moderate. The Trial has demonstrated air-entrainment can be readily mitigated through appropriate design of the recharge bore infrastructure. Therefore by maintaining the current design and operational procedures of the Leederville recharge bore, this risk is mitigated to low.

Microbiological clogging can occur when bacteria introduced during drilling, during bore maintenance, or if indigenous bacteria undergo increased growth due to change in conditions. Again this does not affect water quality, but impacts on recharge efficiency resulting in a reduction in the recharge capacity. As a result it was assigned an inherent risk of moderate.

Managing nutrient concentrations in the recycled water and applying good hygiene practices during maintenance and drilling are adequate mitigations to reduce the residual risk to low.

9.1.3 Risks to Water Quality Guidelines at the RMZ boundary

All 58,200 groundwater quality results collected from the 22 monitoring bores (20 located within the Leederville aquifer) during the Trial's recharge period met water quality guidelines, providing a strong indication that the risk of not meeting the water quality guidelines at the boundary is low.

The mobilisation of phosphorus and/or fluoride as a result of the dissolution of the naturally occurring mineral, crandallite may occur in the Leederville aquifer due to chemical reactions between the recycled water and aquifer material. This was observed during the Trial, although phosphorus and fluoride concentrations remained below water quality guidelines[3]. Trial data also demonstrated that phosphorus and fluoride concentrations decreased after an initial peak following breakthrough. Therefore the risk of mobilisation of phosphorus and fluoride was assigned a moderate inherent risk due to the 'possible' likelihood of the event occurring, but given that the concentrations remained below water quality guidelines and will continue to decrease after an initial peak, the residual risk was low.

9.2 Yarragadee Aquifer Risk Assessment Outcome

The inherent and residual risk ranking for the Yarragadee aquifer are summarised in Table 9-2.

Table 9-2: Inherent and Residual Risk Assessment for the Yarragadee aquifer

Stage of Assessment	Low Risk	Moderate Risk	High Risk	Extreme Risk
Inherent Risk Assessment	16	8	2	0
Residual Risk Assessment	26	0	0	0

Details of the moderate and high inherent risks are discussed below. With appropriate mitigations in place, the residual risks were assigned as low.

9.2.1 Risks from drilling and bore construction

There are a number of potential mechanisms for bore failure caused by poor construction practices resulting in assigning a moderate inherent risk. Mitigations such as appropriate bore design and engaging experienced and competent drilling companies can adequately manage these risks as demonstrated with previous bores. These mitigations will be applied to construction of all Water Corporation bores. Therefore the residual risk was assessed as low.

Similar to the Leederville aquifer (see section 9.1.1), recharging low ionic strength recycled water could cause corrosion of the recharge bore screen if inadequate materials are used in construction. This has resulted in assigning an inherent risk of high. Use of appropriate construction materials and pH adjustment of the recycled water, if required, will reduce the residual risk to low.

[3] Phosphorus is not a Perth GWRS Scheme water quality guideline, however it currently remains on the 1.5GL AWRP DEC discharge licence. Therefore a conservative approach was taken and the risk of phosphorus not meeting the existing guideline at the RZM boundary was considered.

9.2.2 Risks resulting in bore clogging or reduced aquifer permeability

The Yarragadee aquifer has similar aquifer mineralogy to the Leederville aquifer with the presence of silt and clays, in particular kaolinite that can break down and release fine particles which clog up the aquifer pore spaces. This does not compromise water quality, but can affect recharge efficiency, resulting in assigning a moderate inherent risk. Preliminary investigations of a core of the Yarragadee observed that recharge rates can influence potential for clogging. Mitigations that are available to reduce the risk of aquifer clogging include appropriate design of recharge bore, stepped flow recharge rates, redevelopment if clogging of the recharge bore were to occur and pH adjustment of recycled water. With appropriate mitigations in place, the residual risk was assigned as low.

Similar to the Leederville aquifer, the risk of air-entrainment during recharge caused by cascading water plugging the pores in the aquifer was identified in the Yarragadee aquifer (see section 9.1.2) and was also assigned a moderate inherent risk due to the consequence of extended down time to redevelop the bore. This risk can be adequately mitigated by using the same design as the Leederville recharge bore, reducing the residual risk to low.

9.2.3 Risks to Water Quality Guidelines at the RMZ boundary

Preliminary results from the Yarragadee core collected at the Beenyup site indicate similar mineralogy to the Leederville aquifer. Therefore a similar geochemical response to the recharge of recycled water to the Leederville aquifer would be expected.

The risk of geochemical reactions causing a change in which groundwater pH will exceed the water quality guidelines (6.0 – 8.5) was assigned a moderate inherent risk. Reactive transport modelling for pH in the Leederville aquifer suggests that the pH will not drop below 6.2. Given that the Yarragadee appears to be less reactive than the Leederville it can be assumed that a significant decrease in pH is also unlikely. Monitoring will occur in the Yarragadee to confirm the model. If the model is inconclusive, then amending the buffering capacity of the recycled water will adequately mitigate the risk. Therefore, the residual risk assigned is low.

The inherent risk of metal mobilisation in the Yarragadee due to a decrease in pH was assessed as moderate. Further interpretation of Beenyup Yarragadee investigation data will allow this risk to be further understood. Amending the buffering capacity of the recycled water is known to be an adequate mitigation should the Yarragadee aquifer not provide sufficient buffering capacity. Therefore the residual risk has been assigned as low.

9.2.4 Risks to geothermal bores

A deep geothermal abstraction/reinjection bore constructed as part of the Craigie Leisure Centres swimming pool heating system is located approximately one kilometre to the south of the Beenyup site. Recharging the Leederville aquifer at the Beenyup site will increase pressures, possibly resulting in a change of pumping costs for the Craigie Leisure Centre. The Centre will be contacted by the Water Corporation to discuss the GWRS Scheme. The risk has been reviewed as a social risk and has been assessed as low.

In summary, the outcome of the Aquifer Risk Assessment has determined that with appropriate mitigations such as using appropriate materials in construction, mitigations by design and implementing operational procedures the residual risks are low.

10 Conclusion

Water Corporation has commenced the approvals process for the Perth GWRS Stage 2A in accordance with the GWR Regulatory Framework.

A detailed risk assessment of the treatment process has been conducted for the GWR Scheme; the wastewater catchment, WWTP, AWRP and Leederville and Yarragadee aquifers.

The Treatment Process Risk Assessment has determined, given the adequate mitigations, the risk of not meeting all 254 water quality guidelines at the point of recharge is low. It also determined that mitigations can adequately address all potential barrier failures which may occur in the wastewater catchment, WWTP or AWRP, also resulting in a residual risk of low.

The Aquifer Risk Assessment identified 20 potential hazards to the Leederville aquifer and 26 to the Yarragadee aquifer. These risks could also be adequately mitigated. Therefore the risk to the Leederville and Yarragadee aquifers as a result of recharging up to 14GL/yr of recycled water is low.

The Risk Assessment is an iterative process and there will be risk assessment reviews following detailed design, commissioning and operation of Stage 2A.

11 References

DEC, DoH, DoW and Water Corporation. (2013). *Perth Groundwater Replenishment Scheme - Environmental Values for the Leederville Aquifer and the Yarragadee Aquifer at the Beenyup Site.*

DoH & Water Corporation. (2010). *Memorandum of Understanding between the Department of Health and Water Corporation for the Groundwater Replenishment Trial*. Western Australia.

Groundwater TRG. (2012). *GWR Management Zone and Monitoring Requirements.*

IAWG. (2012). *Groundwater Replenishment Regulatory Framework.* Perth.

NRMMC-EPHC- NHRMC. (2009). *Australian Guidelines for Water Recycling: Managed Aquifer Recharge (Phase 2)*. Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra.

NRMMC-EPHC-AHMC. (2006). *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)*. Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and Australian Health Ministers' Conference, Canberra.

NRMMC-EPHC-NHRMC. (2008). *Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies (Phase 2)*. Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Resuearch Council, Canberra.

Rockwater. (2013). *Beenyup Groundwater Replenishment Scheme. BNYP YMB 1/12 Yarragadee monitoring bore completion report.*

Water Corporation. (2009). *Site Characterisation Report - Groundwater Replenishment Trial.*

Water Corporation. (2010). *Recycled Water Quality Management Plan Groundwater Replenishment Trial*. Western Australia.

Water Corporation. (2011). *Yarragadee Aquifer Preliminary Risk Assessment.*

Appendix 1: Risk Assessment Criteria Tables

CONSEQUENCE RATING

Rank	Financial	People & Public	Environmental	Service Interruption / Customer Impact	Reputation	Compliance	Descriptor
1	Less than $1M	Injuries or illness not requiring medical attention, or Minor first aid Injury	No lasting effect on the environment or social amenity, and/or Recovery– less than 1 week, and/or Cosmetic remediation	Brief loss of local services, and No measurable operational impact.	Low public awareness, no media coverage, possible localised impact on trust and credibility, and/or Inconsequential complaints from the community, and/or No government/ministerial involvement.	Licence or regulatory limit exceedance, informal approach with no formal action or no Regulator involvement.	Insignificant
2	$1M - $10M	Injury requiring medical treatment(no alternative duties), or Localised illnesses requiring medical attention	Short term or low-level long-term impact on the environment or social amenity, and/or Recovery – 1 week to several months, and/or Easy remediation	Localised operations or service interruption, and Temporary, short term service cessation (<6 hours)	Limited local media coverage, localised impact on trust and credibility with Minor Stakeholders, and/or Random substantiated complaints from the community, and/or Local member of parliament enquiry.	Non-compliance or breach of regulation – Formal direction by a Regulator or administrative / Statutory body with administrative or minor operational impacts	Minor
3	$10M - $100M	Middle to long term injury (able to return to work), or Long term condition, or Localised illnesses requiring hospitalisation	Long term impact on the environment or social amenity, and/or Recovery – several months to several years, and/or Challenging remediation	Wide-spread customer impacts – entire regional centre or country scheme, multiple metropolitan suburbs, and Temporary loss of operations and services (<24 hours)	Local and state-wide media coverage, impacts on trust and credibility with Minor and Major Stakeholder, and/or Coordinated communication of community concerns and complaints, and/or Parliamentary question / Ministerial directive.	Non-compliance or breach of regulation – Formal direction by a Regulator or administrative / Statutory body with threat of prosecution or localised public undertakings Loss of accreditations (e.g. Environmental, OH&S)	Moderate
4	$100M - $500M	Permanent disabling injuries, or Widespread illness requiring hospitalisation, or Single death	Extensive, long term impact on the environment or social amenity, and/or Recovery – several years to several decades, and/or Uncertain reversibility of remediation	Widespread degradation of operations or services, and Sustained service cessation (>24 hours)	State-wide and National media coverage, impacts on trust and credibility with Significant and Major Stakeholders, and/or Sustained community outrage, and/or Government Department Investigation.	Non-compliance or breach of regulation – Formal direction a Regulator or administrative / Statutory body with significant operational constraints/restriction and/or public undertaking Criminal / quasi-criminal charges for Water Corporation and/or personnel Loss of multiple/significant abstraction licence	Major
5	Greater than $500M	Multiple deaths	Significant extensive impact on the environment or social amenity, and/or Impacts are irreversible and/or permanent.	Significant widespread degradation of operations or services, and Long, sustained, loss of operations or services	Extensive National and/or some International media coverage, and/or Impacts on trust and credibility with all Corporate stakeholder categories, and/or Sustained community outrage.	Non-compliance resulting in cancellation or loss of operating licence. Loss of significant or major licence	Catastrophic

LIKLIHOOD RATING

Rank	Descriptor	Frequency	Description
A	**Almost Certain**	Will occur more than once a year Multiple times in a year	The event is expected or known to occur often
B	**Likely**	Once per year Once in a year or so	Known to re-occur approximately annually
C	**Possible**	Will occur once every 5 years Once in 5 years or multiple times over 10 years	The event should occur at some time Is sporadic, but not uncommon
D	**Unlikely**	Will occur once in 10 years Could occur once in 10 years or multiple times over 20 years	The event could occur at some time, usually requires combination of circumstances to occur
E	**Rare**	Will occur once every 30 years Once in 30 years or less frequent	The event may occur in exceptional circumstances Not likely to occur, but it's not impossible

CONTROL EFFECTIVENESS RATING

Rank	Descriptor	Description
O	**Optimal**	The control is designed and operating effectively and consistently Improvements to the control are not feasible or are unnecessary
A	**Adequate**	Control is designed to be effective The control is operating effectively Errors in control application can result in isolated cases of inconsistencies Improvements should be made if feasible
I	**Improvement Required**	The control is not designed and/or operating effectively Improvements are required

CONSEQUENCES	LEVEL OF RISK				
5 Catastrophic	H	H	E	E	E
4 Major	M	H	H	E	E
3 Moderate	L	M	H	H	H
2 Minor	L	L	M	H	H
1 Insignificant	L	L	L	M	M
	E Rare	D Unlikely	C Possible	B Likely	A Almost Certain
	LIKELIHOOD				

Appendix 2: Treatment Process Risk Assessment Report

Perth Groundwater Replenishment Scheme – Stage 2A

Treatment Process
Risk Assessment Report

April 2013

watercorporation.com.au

WATER CORPORATION

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Revision History

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2	Danielle Higgs	25/3/13	All workshop participants	3/4/13
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Endorsement

This report is endorsed as complete.

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Acronyms and Definitions

AGWR	Australian Guidelines for Water Recycling	A suite of guidelines that provide a reference for the supply, use and regulation of recycled water schemes.
AWRP	Advanced Water Recycling Plant	A multiple treatment process consisting of ultrafiltration, reverse osmosis, ultraviolet disinfection to produce water for groundwater replenishment
BOD	Biochemical Oxygen Demand	Amount of dissolved oxygen needed by aerobic biological organisms in a wastewater treatment plant to break down organic material present in a given water sample at certain temperature over a specific time period.
	Chloramination	Use of chloramines (compounds formed by the reaction of hypochlorous acid or aqueous chlorine with ammonia) as a means of disinfection to manage biofouling through the treatment process.
CCP	Critical Control Point	An activity, procedure or process where control can be applied that is essential for operating the treatment process to ensure recycled water meets water quality guidelines.
DEC	Department of Environment and Conservation	Responsible for the protection of the environment.
DoH	Department of Health	Responsible for the protection of human health.
DoW	Department of Water	Responsible for the protection of water resources, including public drinking water sources.
EC	Electrical Conductivity	A measure of how well a material accommodates an electrical charge. It provides an estimate of total dissolved salts in the water.
EVs	Environmental Values	The term applied to particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health.
GL	Gigalitres	One billion litres.
GWR	Groundwater Replenishment	Groundwater replenishment (GWR) is the process by which secondary treated wastewater undergoes advanced treatment to produce recycled water which meets Australian guidelines for drinking water prior to being recharged to an aquifer for later use as a drinking water source.
GWRT	Groundwater Replenishment Trial	Successfully completed by Water Corporation in December 2012 at Beenyup, it provided information to allow assessment and progress of a large GWR Scheme.
	Hazard	A biological, chemical, physical or radiological agent that has the potential to cause harm. In the context of this assessment it also represents each of the 254 *Recycled Water Quality Parameters* which have *water quality guideline* values.
	Inherent Risk	The risk of a hazard (RWQP) not meeting the *water quality guideline* after secondary wastewater treatment, therefore in the absence of advanced water treatment.
IWSS	Integrated Water Supply Scheme	The system of pipes and pumps which supplies drinking water to the Perth Metropolitan area, Mandurah and the Goldfields pipeline.

kL	Kilolitre	One thousand litres.
LOR	Limit of Reporting	The lowest limit at which the laboratory will report a quantitative result for a parameter: chemical, microbiological or radiological. Multiple LOR's may be applicable for analytes due to changes in methods.
ML	Megalitres	One million litres.
NDMA	*N*-Nitrosodimethylamine	Disinfection by-product produced in the *Advanced Water Recycling Plant* and a *Recycled Water Quality Indicator* as defined by the DoH.
Perth GWRS	Perth Groundwater Replenishment Scheme	28GL/year scheme proposed to be constructed stages to allow for a flexible approach to meet water demand in the *IWSS*.
	Residual Risk	The risk of a hazard (RWQP) not meeting the *water quality guideline* remaining after consideration of the existing or new mitigations, including advanced water treatment.
	Risk	The likelihood of a hazard causing harm in exposed populations in a specified time frame, including the magnitude of that harm.
	Risk Assessment	The overall process of using available information to predict how often hazards or specified events may occur (likelihood) and the magnitude of their consequences.
	Risk Management	The systematic evaluation of the water supply system, the identification of hazards and hazardous events, the assessment of risks, and the development and implementation of preventive strategies to manage the risks.
RWQI	Recycled Water Quality Indicator	Chemicals or pathogens that best represent a larger group of chemicals or microbiological hazards identified by the Recycled Water Quality Parameters. The RWQI have been specified by the Department of Health (DoH) and are set out in the GWRT MoU Schedule 1.
RWQP	Recycled Water Quality Parameter	Refers to the water quality parameters to be measured in recycled water, as agreed with the Department of Health (DoH) and set out in the GWRT MoU Schedule 1. Analysis of these parameters will allow assessment of the recycled water against the *Water Quality Guidelines.*
RO	Reverse Osmosis	Second treatment step in the advanced water treatment process.
TOC	Total organic carbon	Is derived from natural organic matter (plants, animals) and many man made materials, and is considered a good indication of contamination.
UV	Ultraviolet Disinfection	Third treatment step in the advanced water treatment process.
	Water Quality Guidelines (also referred to as *Guideline value*)	Compliance with the water quality guidelines will represent protection of human health and the identified Environmental Values.
WRMOS	Water Resource Management Operation Strategy	A requirement from DoW whereby a licensee commits to a management strategy for a given water resource.
WWTP	Wastewater Treatment Plant	A treatment process which immediately precedes the Advanced Water Recycling Plant, providing secondary treatment to raw wastewater. In the context of the Perth GWRS it refers to the Beenyup WWTP, located in Craigie, Perth.

WATER CORPORATION

1 Executive Summary

Background

In December 2012 Water Corporation completed the Groundwater Replenishment Trial (GWRT), demonstrating that groundwater replenishment can provide a sustainable water source option for Western Australia. Based on the success of the Trial, Water Corporation is progressing approvals for the Perth Groundwater Replenishment Scheme (GWRS), developed in stages to meet future water supply demands.

Ultimately providing 28 gigalitres per year (GL/year) of recycled water for groundwater replenishment, approvals are currently being sought to progress Stage 2A. This involves a 14 GL/yr Advanced Water Recycling Plant (AWRP) located adjacent to the Beenyup Wastewater Treatment Plant (WWTP) and the recharge of up to 14 GL/year of recycled water into the confined Leederville and Yarragadee aquifers.

Purpose of this risk assessment

The purpose of this risk assessment is to demonstrate that the proposed treatment process and operational procedures produce recycled water that meets the water quality guidelines at the point of recharge. The scope of this risk assessment covers the Beenyup wastewater catchment, WWTP and AWRP. Together with the Perth GWRS Aquifer Risk Assessment, it addresses Step 3 of the GWR Regulatory Framework (Inter Agency Working Group, 2012).

Inputs to this risk assessment

The State regulating agencies for groundwater replenishment, the Department of Health (DoH), Department of Environment and Conservation (DEC) and Department of Water (DoW) identified four environmental values (EVs) relevant to the Leederville and Yarragadee aquifers in the vicinity of recharge:

1. Drinking water resource
2. Industrial water
3. Primary industry
4. Cultural and spiritual

All EVs identified must be protected and maintained for current and future use.

The Agencies confirmed that water quality guidelines which will protect the drinking water resources EV will also be adequate to protect the Industrial water and Primary industry EVs.

The DoH has defined 254 water quality guidelines required to protect human health and the drinking water resource EV. These are listed in *the Memorandum of Understanding between the Department of Health and the Water Corporation for the Groundwater Replenishment Trial* (referred to as the MoU).

The Trial provided a comprehensive data set which was then used to assess the risks to EVs identified for the Perth GWRS. In addition, six risk assessments were undertaken during the Trial, providing background to assess potential risks to the Perth GWRS.

A series of four workshops were held to develop this risk assessment. Experts in the areas of wastewater catchment management, wastewater treatment and advanced water treatment attended. In addition it underwent a technical peer review from MHW Global, Australia.

The risk assessment assumed the AWRP will have the same treatment process as the Trial, with the addition of pre-formation of monochloramine. This addition to the AWRP treatment process will be designed to minimise disinfection byproducts.

Hazard Risk Assessment

The hazard risk assessment considered if the water would meet the 254 water quality guidelines after secondary treatment (to assign an inherent risk) and again after the AWRP (to assign a residual risk). In the context of this risk assessment each guideline parameter is considered a "hazard". In summary:

- Preliminary screening - identified 143 hazards (parameters) whose maximum concentration in secondary treated wastewater (AWRP feed water) was less than 10% of the water quality guideline;
- Inherent risks - 111 hazards (parameters) were assigned an inherent risk of moderate, high or extreme after secondary treatment, based on maximum concentrations; and
- Residual risks - all 254 hazards (parameters) were assigned a low residual risk ranking after AWRP treatment.

There were a number of hazards for which the chemical analytical method limit of reporting (LOR) was not as low as the water quality guideline or not currently available. At the end of the Trial the DoH accepted all represented a low risk (i.e. a low risk to human health and the environmental values). These are summarised below:

- 22 had a LOR above the guideline, but the DoH does not require further method development at this time. The LOR will be reviewed annually;
- 6 had a LOR above the guideline and will require continued work to reduce the LOR under the direction of the DoH; and
- 4 did not have an analytical method available during the Trial but Water Corporation will continue to pursue method development under the direction of the DoH.

Barrier Failure Risk Assessment

The barrier failure risk assessment considered potential barrier failures within the treatment process; the Beenyup wastewater catchment, WWTP and AWRP. The assessment assumed that the treatment process was being operated with the same management system and operational procedures used during the Trial. These were assessed to be robust by an independent audit conducted in early 2013.

There were 14 low inherent risks, 9 moderate inherent risks and 11 high inherent risks identified. All 34 risks were assigned a low residual risk after mitigation. Mitigations included AWRP design, operational procedures and automatic diversion or shut down of the AWRP if water quality requirements are not met by online monitoring of critical control points.

The barrier assessment also addressed three water quality events (control system failures), which occurred during the Trial. None of these events posed a risk to public health or the environment. The reoccurrence of these types of events in a full scale AWRP will be mitigated by the implementation of the learning's from the Trial. Mitigations include alteration of commissioning requirements and validation procedures and the control system review process.

Conclusions

The Perth GWRS Stage 2A treatment process preliminary risk assessment has shown that all potential risks have been appropriately addressed to low. It is important to note this is an iterative process and there will be future risk assessments following detailed design and commissioning of Perth GWRS.

2 Purpose

The report documents the treatment process risk assessment for a 14GL/year AWRP to ensure the treatment processes and operational procedures produce recycled water that meets all water quality guidelines for human health and the identified environmental values (EVs)[1] at the point of recharge. Together with the Perth GWRS Aquifer Risk Assessment, it addresses Step 3 of the GWR Regulatory Framework (Inter Agency Working Group, 2012)[2], which is provided in Appendix 1.

The scope of this risk assessment covers the Beenyup wastewater catchment, WWTP and AWRP.

3 Introduction

Groundwater replenishment (GWR) is a process by which secondary treated wastewater undergoes advanced treatment to produce water which meets Australian Drinking Water Guidelines (ADWG), prior to being recharged to an aquifer for later use as a drinking water source.

The Water Corporation trialled GWR at the Beenyup WWTP site. The Trial recharged up to 1.5 GL/year from an AWRP to the Leederville aquifer and assessed the technical, health, environmental and social issues associated with GWR in Perth.

It was overseen by an Inter Agency Working Group (IAWG) consisting of the State's regulating agencies; the DoH, DoW, DEC and Water Corporation.

The Trial successfully demonstrated that groundwater replenishment can provide a sustainable water source option for Western Australia. Specifically, it:

- Demonstrated that the treatment process can consistently and reliably perform to meet the water quality guidelines that will protect human health and the EVs.
- Identified and documented all technical issues that arose during design, construction and operation to ensure that they are addressed in future GWR schemes.
- Demonstrated that "GWRT Recycled Water Quality Management Plan", applying the Water Corporation's Wastewater Quality Management Framework, is an effective mechanism for managing the systems and processes to produce water that always meets the water quality guidelines. This included applying the Corporate Risk Assessment Process to the design, commissioning and ongoing operation of the AWRP.
- Provided information for DoH, DoW, and DEC to develop the GWR Regulatory Framework.

Based on the success of the Trial, Water Corporation is progressing a 28GL/year AWRP at the Beenyup site (including recharge at offsite bores). Delivery will be in 3 stages; Stage 1 – 7GL/year, Stage 2 – 14GL/year and Stage 3 – 28GL/year. A staged delivery allows a flexible approach to meeting future water demand in the Integrated Water Supply Scheme (IWSS).

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[1] Environmental Values (EVs) are defined as the "particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and that require protection from the effects of pollution, waste discharges and deposits".
[2] The GWR Regulatory Framework defines the approvals pathway required to develop a GWR scheme, approve commencement of recharge and provide ongoing regulation.

To maintain supply against a background of a drying climate, Water Corporation is considering accelerating the delivery of Stage 2 of the Perth GWRS. Given potential delays in construction and approvals, Water Corporation has reviewed the scope of Stage 2 and will progress its delivery in two parts, Stage 2A and 2B as described in Table 3-1.

Table 3-1: Stages of the 28 GL/year Perth GWRS

Stage	Activity
1	Construct a 7GL AWRP at the Beenyup site. Recharge via the existing Leederville aquifer recharge bore and one new Yarragadee aquifer recharge bore located at the Beenyup site.
2A	Construct an additional 7GL AWRP at the Beenyup site (to provide a total of 14GL recycled water). Maximise recharge to Leederville and Yarragadee aquifer recharge bores. **Note:** Whilst maximum recharge rates for each bore can be estimated, this will not be confirmed until they can be tested under pumping and recharge conditions.
2B	Construct a pipeline and two new Leederville aquifer recharge bores (if required) located off the Beenyup site, to the east of Lake Joondalup to recharge the additional 7GL produced by the Stage 2A AWRP.
3	Construct an additional 14GL AWRP at the Beenyup site (to provide a total of 28GL recycled water). Extend pipeline and construct two additional Leederville aquifer recharge bores and two additional Yarragadee aquifer recharge bores to recharge the additional water.

Figure 3-1 illustrates the location of the proposed scheme. Figure 3-2 illustrates the staging options of a 28GL/year scheme.

The Water Corporation has commenced the approval process for the Perth GWRS Stage 2A, following the GWR Regulatory Framework. The DEC, DoW and DoH identified the environmental values relevant to the Leederville and Yarragadee aquifer at the recharge site.

The DoH then identified the 254 water quality guidelines that the recycled water must meet at the point of recharge in order to protect human health and the identified EVs (completing Step 2 of the GWR Regulatory Framework). These guidelines are listed in the *Memorandum of Understanding between the Department of Health and Water Corporation for the Groundwater Replenishment Trial 2010 (MoU).*

A risk assessment was undertaken on 7 March 2013 to evaluate the adequacy of the treatment process, including the wastewater catchment management procedures, to produce 14GL/year of recycled water which meets the water quality guidelines at the point of recharge. It considered the scenario of the treatment process working optimally (the hazard risk assessment) and also potential failures of the process (barrier risk assessment).

This Treatment Process Risk Assessment Report provides the outcomes of the risk assessment. Together with the Aquifer Risk Assessment (Water Corporation, 2013), it addresses Step 3 of the GWR Regulatory Framework.

Figure 3-1: Perth GWRS Stage 2A location map

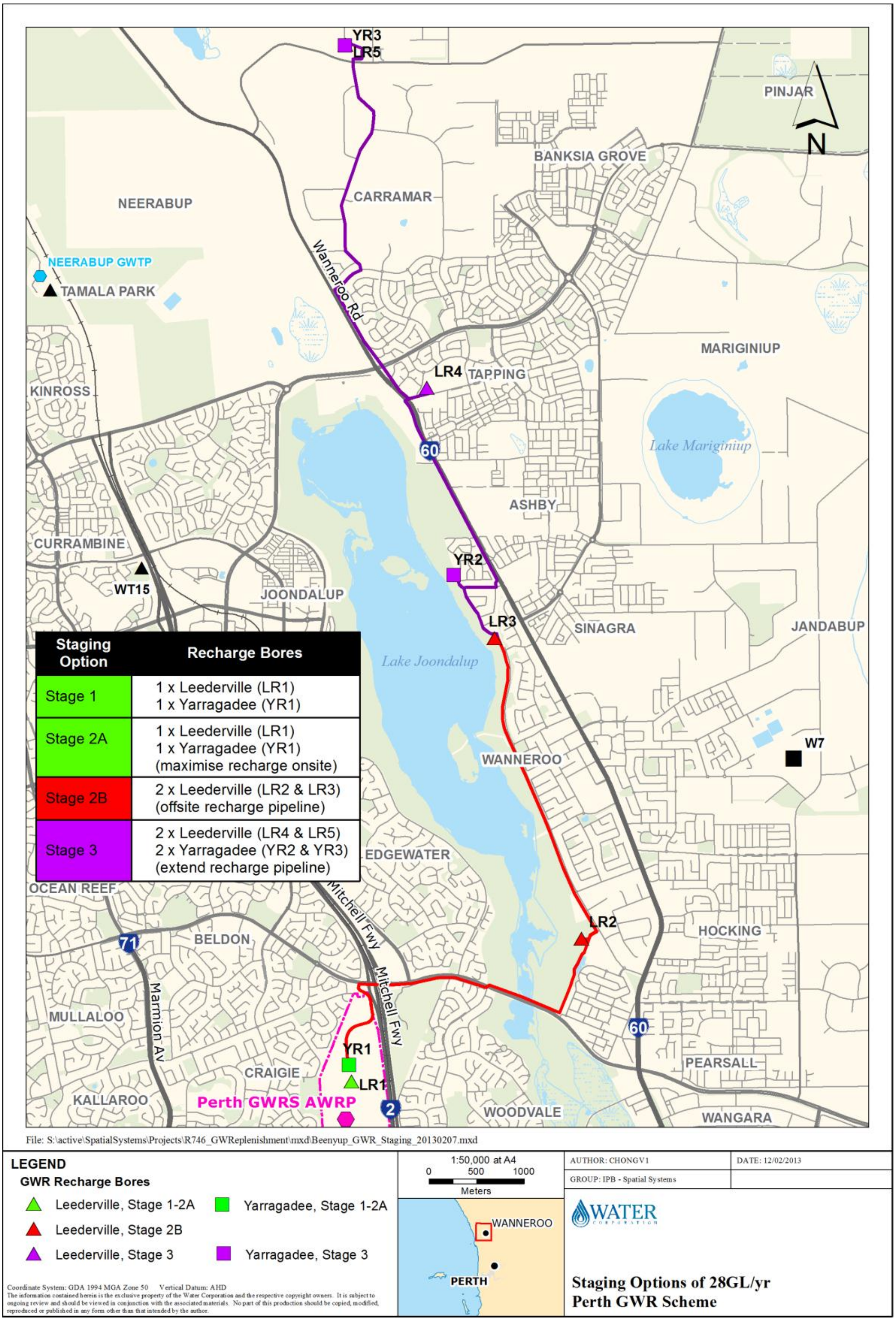


Figure 3-2: Staging options of 28GL/year Perth GWRS

4 Inputs to this Risk Assessment

4.1 Environmental values

In February 2013 the DoH, DEC and DoW identified the Environmental Values (EV's) and water quality guidelines applicable the Perth GWRS Stage 2A recharging the Leederville aquifer and Yarragadee aquifer at the Beenyup site. The EVs take into account the most conservative scenario of recharging up to 14GL/year to each aquifer. This has been summarised in Table 4-1.

Table 4-1: EV's and water quality guidelines applicable to Perth GWRS Stage 2A

Environmental Value	Water Quality Guidelines for Leederville and Yarragadee aquifer – Perth GWRS Stage 2A
Drinking Water	Recycled Water Quality Indicators (18 parameters) Recycled Water Quality Parameters (292 parameters to assess 254 water quality guidelines)[3] *As defined by the MoU*
Primary Industries	As per Drinking Water EV
Industrial Water	As per Drinking Water EV
Cultural and Spiritual	Consultation with Indigenous Community

The DEC, DoW and DoH determined that the management objective of the identified EV's is to "maintain for current and future use".

The DoH has set the water quality guidelines which protect the EVs. They are the 18 Recycled Water Quality Indicators (RWQI), 292 RWQPs and 254 water quality guidelines, listed in the GWRT MoU (2010) at the point of recharge. It is expected that by meeting these water quality guidelines at the point of recharge the EVs will be maintained for current and future uses.

The RWQPs and RWQIs may change periodically following an assessment of the water quality guidelines by the DoH. In this situation the hazard risk assessment will be reviewed with respect to the new guidelines.

4.2 Trial performance

The Trial AWRP operated for 3 years, recharging for 2 years between November 2010 and December 2012. The Trial recharged more than 2.5GL of recycled water to the Leederville aquifer.

The Trial provided three types of information critical to the assessment of potential risks to future GWR schemes at the Beenyup site. They were:

- Recycled water quality results;
- Critical Control Point (CCP) performance data and operational water quality results collected before and after ultra-filtration (UF), reverse osmosis (RO), ultra violet disinfection (UV); and

[3] 46 of the 292 MoU RWQPs contribute to the calculation of "combined toxic equivalence" for Polycyclic Aromatic Hydrocarbons (PAHs) and Dioxins. Only a few of these RWQPs have a relevant individual guideline values to report against.

- Documentation of all technical issues that arose during design, construction and operation.

The Trial's AWRP was required to comply with the 254 water quality guidelines and 18 RWQI defined in the GWRT MoU, and six chemical and physical parameters defined by DEC in the AWRP Discharge licence at the point of recharge. Note the additional DEC parameters are not a requirement for Perth GWRS Stage 2A.

Sampling frequency of RWQPs and RWQIs was based on risk and determined in consultation with the DoH. In general, each RWQP was sampled at least 6 times throughout the Trial recharge period. Some were sampled in excess of 40 times, including sampling undertaken during commissioning of the AWRP prior to recharge.

Over 4,100 recycled water samples were collected and all water quality guidelines. An additional 8,000 operational samples were collected throughout the AWRP to monitor efficacy of the treatment process. The following table outlines the results obtained during the GWR Trial.

Table 4-2: AWRP Performance against operational criteria

Recharge Period	No. of Recycled Water Results	No. of Operational Sampling Results	% of Recycled parameters that meet water quality guidelines	
			Health Guidelines	DEC Guidelines
Nov 10 – April 11	836	1,519	100	100
May 2011 – Jan 12	1,916	3,435	100	100
Feb 12 – Jul 12	1,006	1,832	100	100
Aug 12 – Oct 12	266	716	100	100
Nov 12 – Dec 12	169	529	100	100
Total	4,193 *	8,031 *		

Note: * Additional results have been recorded since the last GWRT Final Report, April 2013 (Water Corporation)

The process operated within the 13 CCPs for more than 99.93% of the time, i.e. there were three water quality events. These three events involved a control system issue – elevated pH (March 2012), dissolved oxygen levels in feed water (March 2012) and TOC analyser (August 2012). Detailed investigations occurred after each event and corrective actions were implemented. Each event has been considered in this barrier risk assessment.

None of these events posed a risk to the environment or public health and our regulators accepted our approach allowing recharge to continue on each occasion.

A number of technical issues were identified during the Trial relating to design, commissioning and operation. These were fixed and then documented. Where relevant these have also been considered in the barrier assessment.

4.3 Recycled Water Quality Management Plan

The Trial was operated in accordance with the Process Control Table (PCT) and associated work instructions, operational procedures, checklists, calibration and maintenance plans described in the GWRT Recycled Water Quality Management Plan (RWQMP). The RWQMP operationalizes the 12 elements from the wastewater quality framework as adapted from the *National Water Quality Management Strategy - Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)* and *Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies (Phase 2).*

The Perth GWRS Stage 2A risk assessment was undertaken assuming the same supporting processes outlined in the GWRT RWQMP. These supporting processes were assessed to be robust by an independent audit conducted in early 2013.

4.4 Risk assessment assumptions

The following assumptions were identified by participants of the workshop in order to progress the development of the risk assessment. These assumptions will need to be revisited during the risk assessment following detail design.

Table 4-3: Risk assessment assumptions

No.	Assumption
1	The Recycled Water Quality Management Plan and the Process Control Tables for the WWTP and AWRP will remain the same as shown in Appendix 7.
2	The treatment process for the Perth GWRS AWRP will remain the same as the Trial AWRP with UF, RO, degasser & UV disinfection at 200mJ/cm2.
3	The treatment process will include pre-formed monochloramine. The AWRP will be designed to minimise disinfection byproduct formation and excess ammonia.
4	Feed water into the AWRP will be continuous (to manage any negative impact of diurnal inflow and varying concentration loads from the WWTP).
5	The Beenyup WWTP bypass inlet to the ocean outlet pipeline will be located downstream of the AWRP intake on the ocean outlet pipeline, with hydraulic separation between the two.
6	Beenyup WWTP will continue to have Citech control system, whereas the new AWRP will have a different control system.
7	All waste streams from the Stage 1 and 2 AWRP will be disposed of via the ocean outlet downstream of the inlet to the AWRP with hydraulic separation between the two, and not returned to Beenyup WWTP.
8	Water efficiency measures in the wastewater catchment may increase the nutrient load concentration of inflow into the WWTP but this should not have an impact on the treatment process of the WWTP or the AWRP.

5 Risk Assessment Process

Water Corporation adopts the risk management approach set out in the *National Water Quality Management Strategy - Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)* and *Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies (Phase 2).*

This risk assessment involved three planning workshops to identify potential risks for the Beenyup wastewater catchment, WWTP and AWRP. The assessment used the GWRT Risk Assessments as a base and determined their transferability to GWRS Stage 2A as well as identifying any new risks.

The outcome of these planning workshops was to populate a draft Risk Assessment Table for review and discussion at the Treatment Process Risk Assessment workshop held on 7th March 2013.

The objective of the Treatment Process Risk Assessment workshop was to:

- Assess all available information;
- Identify potential hazards;
- Assign an inherent risk rating based on the likelihood and consequence of the hazard occurring;
- Identify mitigations to reduce the inherent risk to an acceptable level; and
- Assign a residual risk rating.

A rank of low, medium, high or extreme was given to the inherent and residual risks.

This workshop was facilitated by the Water Corporation and attended by Water Corporation staff with expertise in industrial waste discharges, wastewater treatment and advanced water treatment, as well as by technical peer reviewers MWH Global, Australia who provided technical expertise in wastewater and advanced water treatment processes. Appendix 2 contains a list of workshop attendees.

Figure 5-1 illustrates the risk assessment process and outlines how it is integral to the design, construction and commissioning of the AWRP and operation of the Perth GWRS Stage 2A. It is important to note that this is an iterative process and there will be future risk assessments following detailed design, construction, commissioning and throughout the operating life of the scheme.

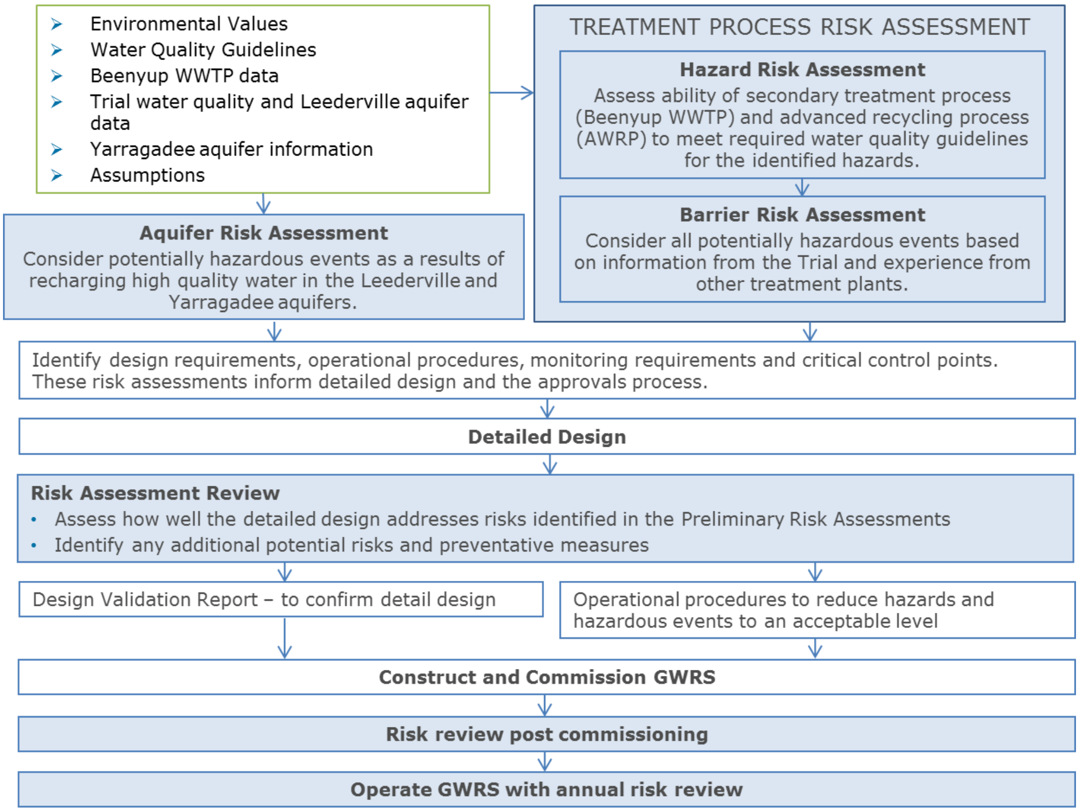


Figure 5-1: Risk Assessment Process

5.1 Hazard assessment of environmental values

The hazard assessment considers the ability of the treatment process to reduce hazards (defined as chemical or microbiological parameters with guidelines) to below the water quality guidelines. It considers hazards under normal operating conditions, with trained operators who are following robust procedures and a WWTP and AWRP that are operating to required criteria. Hazards are considered low risk if the recycled water at the point of recharge meets the water quality guidelines, thus protecting the EVs.

The hazard risk assessment involved:

1. Preliminary screening;
2. Inherent risk assessment; and
3. Residual risk assessment.

<u>Preliminary screening assessment of secondary wastewater treatment (after WWTP)</u>

Preliminary screening compared Beenyup secondary treated wastewater (GWR Trial feed water) collected during the Trial against the 254 water quality guidelines to determine:

1. Hazards that were either not present in Beenyup secondary treated wastewater or were consistently treated to less than 10% of the water quality guideline value; and
2. Hazards that may require further treatment in order to meet the water quality guideline.

The screening considered the maximum concentration measured in AWRP feed water in order to conduct a conservative assessment. Parameters which were consistently below 10% of the guideline in treated wastewater (AWRP feed water) were assigned a low risk and not considered further.

There were a number hazards screened as low risk which were considered in the inherent risk assessment. The reasons for this were:

- Detection above 10% of the guideline level in secondary treated wastewater during sampling which occurred prior to the Trial;
- The parameter's Limit of Reporting (LOR) changed over the course of the Trial;
- Guideline levels that have changed over the course of the Trial; or
- The parameter was detected in recycled water (e.g. disinfection byproducts).

Inherent risk assessment after secondary treatment (after WWTP)

An inherent risk is defined as the risk of a hazard in the absence of any action to control or mitigate the risk. It considers hazards that pass through the secondary treatment process (Beenyup WWTP) above 10% of the water quality guideline. In addition, a conservative approach was taken to include a number of parameters that were screened as low, as described above. The following criteria were assigned:

- Low inherent risk – parameters of interest, described above;
- Moderate inherent risk – when the maximum value is greater than 10% of guideline value but less than 100% of the guideline value;
- High inherent risk – when the maximum value is greater than the guideline value; and
- Extreme inherent risk – when the maximum value is significantly greater than the guideline value.

Residual Risk assessment after advanced treatment (after AWRP)

A residual risk is defined as the risk remaining after consideration of existing or new mitigations. Mitigations can be addressed in AWRP treatment design or the application of an operational procedure.

The adequacy of the advanced water treatment process to remove the remaining hazards was assessed based on data from the GWRT AWRP. The consequence was assigned using the definitions in Water Corporation's Consequence Rating Table for the Corporate Risk Matrix (Appendix 3). The likelihood was based on the frequency of data. The risk matrix was then used to determine the residual risk after advanced treatment at the point of recharge into the aquifer.

Figure 5-2 outlines the process for undertaking a hazard assessment.

Preliminary screening – after WWTP

Preliminary screening of Beenyup secondary wastewater (GWRT feedwater) against water quality guidelines to idenitify parameters that were not present or less than < 10% water quality guideline

Inherent Risk Assessment – after WWTP

Evaluate Beenyup WWTP secondary treated wastewater data and assign an **inherent risk** using the following criteria's:

- Low inherent risk – when maximum recorded value is < 10% of the guideline value
- Moderate inherent risk – when maximum recorded value is between 10% - 100% of the guideline value
- High inherent risk – maximum recorded value is greater than > 100% of the guideline value
- Extreme inherent risk – maximum recorded value is significantly greater than the guideline value

Residual Risk Assessment – after AWRP

Evaluate GWRT advanced water treatment process and identified **residual risk** using Water Corporation corporate risk matrix

Figure 5-2: Process for assessing risk to human health and environmental values

5.2 Barrier Failure Assessment

Barrier failure assessment identifies all potential failures in the system and then identifies preventative measures to either avoid the failure or avoid the impact of the failure. This process is outlined in the Figure 5-3.

Inherent Risk Assessment

Consider potential **barrier failures** or **hazardous events** and identify **inherent risks** in accordance with Water Corporation risk matrix. Scope covered the:

- Beenyup wastewater catchment
- Beenyup WWTP
- GWR AWRP

Residual Risk Assessment

1. Identify mitigations.
2. Reassess barrier failures or hazardous events with mitigations in place to assign a **residual risk** in accordance with Water Corporation risk matrix**.**
3. If barrier failures or hazardous events are adequately mitigated, **residual risk** is **LOW.**
4. If **residual risk** is Moderate, High or Extreme continue to identify additional mitigations until residual risk is **LOW**.

Figure 5-3: Barrier failure assessment process for human health and environmental values

The Barrier Risk Assessment considered the risk of hazardous events in the form of treatment failure modes by reviewing the operational reliability of each individual treatment process, or barrier. From this analysis, critical control points and process control points are identified. Supporting processes including work instructions, operation, maintenance and instrument calibration procedures and training requirements provide mitigations to be considered in assessment of the "residual risk" of the GWRS Stage 2A.

In addition, an aquifer assessment identifying and assessing potentially hazardous events as a result of recharging up to 14GL/year of recycled water into the Leederville and Yarragadee aquifers was conducted. This assessment will be documented in the *Aquifer Risk Assessment (Water Corporation, 2013)*.

6 Scheme Description

Figure 6-1 provides an overview of the scheme.

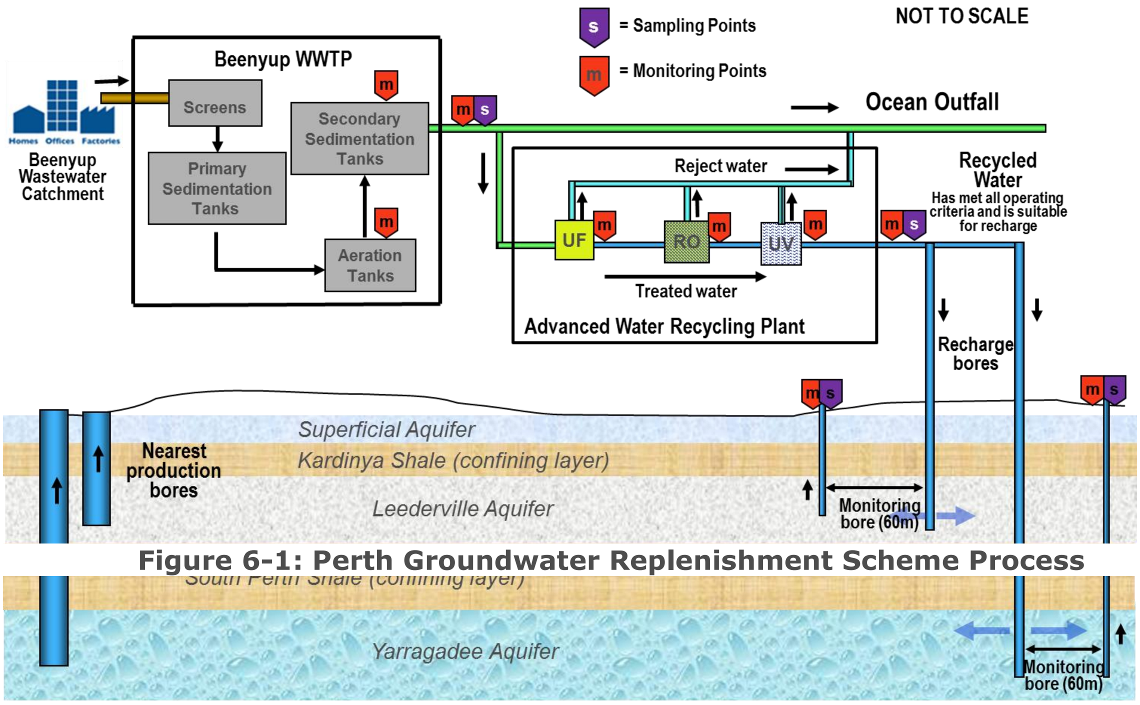


Figure 6-1: Perth Groundwater Replenishment Scheme Process

6.1 Source water – Beenyup Wastewater Catchment

Beenyup wastewater catchment extends from Burns Beach in the north, Scarborough Beach Rd in the south, and Ellenbrook and Midland in the east. The nominal population of the Beenyup wastewater catchment is 650,000. Figure 6-2 illustrates the Beenyup wastewater catchment.

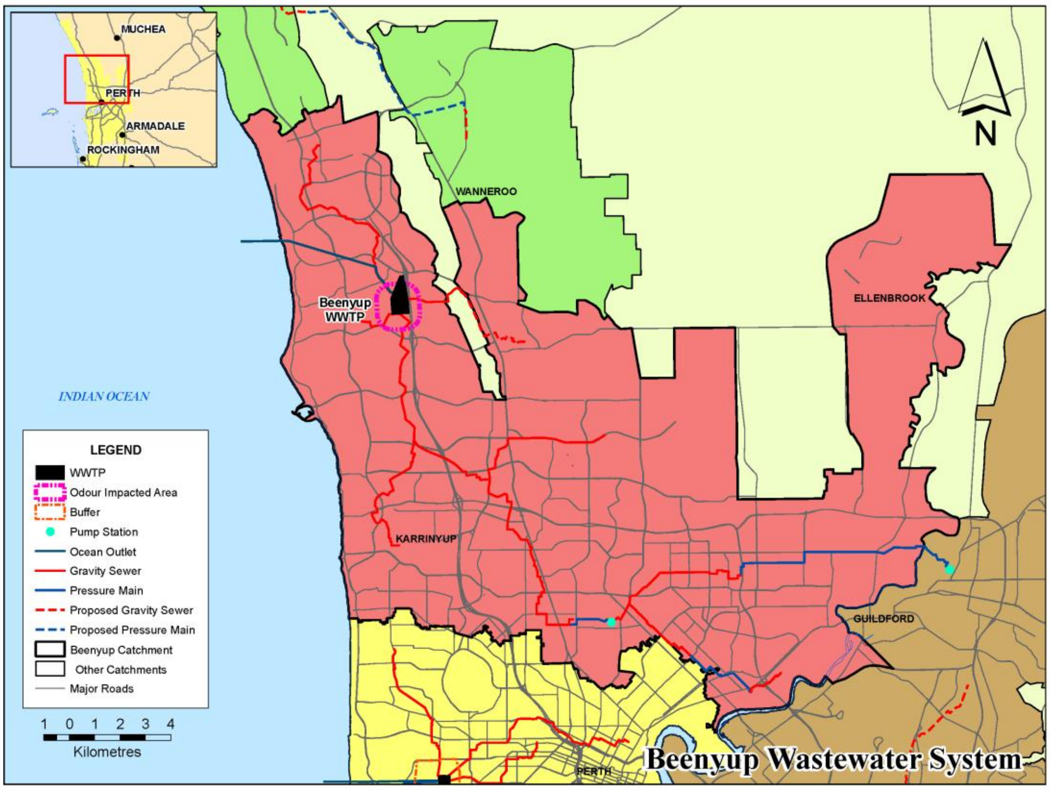


Figure 6-2: Beenyup wastewater catchment

The majority of wastewater collected in the Beenyup wastewater catchment is from households. Table 6-1 provides a breakdown of wastewater in the Beenyup catchment including from household, industrial and commercial customers. The largest of industrial and commercial customers are food producers and commercial laundries which contribute high volumes and biochemical oxygen demand (BOD) loads to the wastewater system.

Table 6-1: Household and industrial waste component of wastewater collected in the Beenyup catchment (2011-12)

Component	Volume Kilolitres per day	% of Beenyup WWTP inflow
Total inflow	127,000	100%
Domestic type wastewater	124,000	98%
Total hospital wastewater	73	0.06%
Non-medical hospital wastewater	60	0.05%
Medical hospital water	13	0.01%
Total industrial waste of all types – including hospitals	3,000	2%

All industrial waste discharges to the wastewater system must meet Water Corporation's industrial waste acceptance criteria. These criteria limit or prohibit substances that may negatively impact groundwater replenishment, as well as the Water Corporation's assets, the health and safety of Water Corporation staff, and other recycling of treated wastewater and biosolids.

Customers with high load discharges or with waste streams of concern are included in on-going surveillance programs. Any new industrial or commercial connections undergo a rigorous assessment prior to approval.

There is one large hospital and several smaller hospitals in the Beenyup catchment. The waste from these hospitals is highly regulated by the DoH and Water Corporation. Most clinical and related waste streams are prohibited from discharge to sewer under the DoH *Clinical and Related waste Management Policy.* Compliance with this policy is now a condition of a Water Corporation permit to discharge industrial waste. As a result, the predominant industrial wastewater discharge from hospitals is non-medical waste streams such as laundries and kitchens.

Industrial waste management is considered a barrier to ensure the reduction of contaminant loading to the wastewater collection system. It has been considered in this context in the barrier failure assessment.

6.2 Beenyup Wastewater Treatment Plant

The Beenyup WWTP treats wastewater to a secondary standard using an activated sludge treatment process. In 2011-12 the Beenyup WWTP treated on average 127,000 kilolitres per day and the WWTP has a capacity of 135,000 kilolitres per day.

The treatment plant consists of pre-treatment, primary treatment and secondary treatment processes, along with anaerobic sludge digestion. The following schematic (Figure 6-3) illustrates a simplified process overview of the Beenyup WWTP. Processes which are considered as treatment barriers (remove chemicals and pathogens) within the WWTP are highlighted blue.

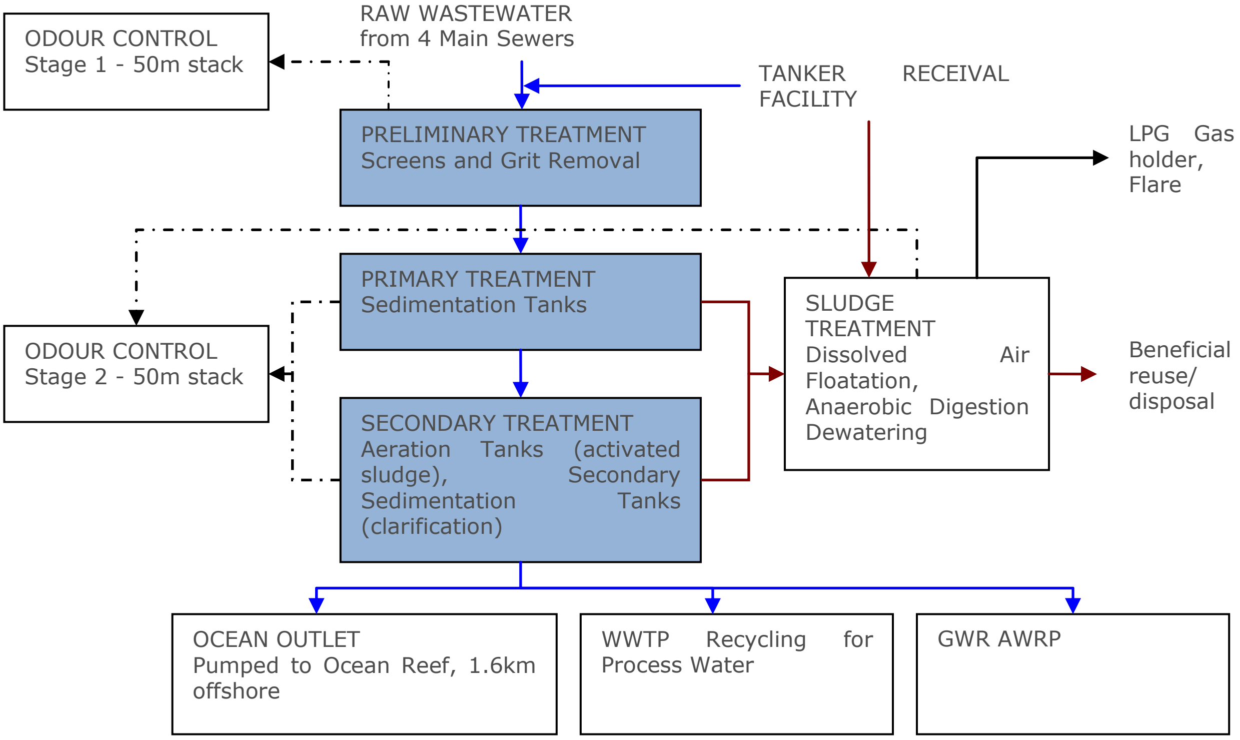


Figure 6-3: Beenyup WWTP process overview

6.3 Advanced Water Recycling Plant

The AWRP will produce up to 14 GL/yr (up to 38 mega litres per day). Figure 6-4 illustrates the proposed process for the 14GL/year AWRP. Processes which are considered as treatment barriers (remove chemicals and pathogens) are highlighted blue.

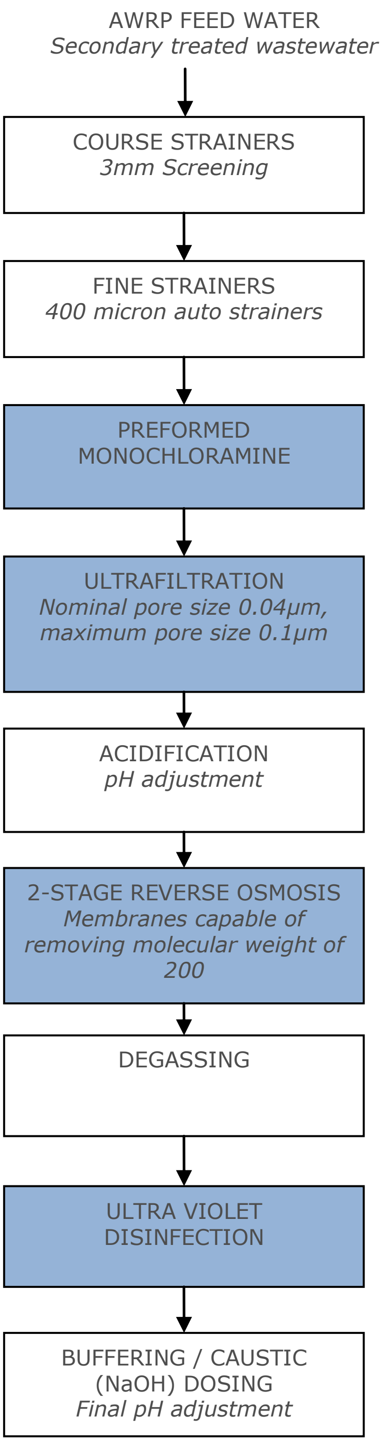


Figure 6-4: Proposed AWRP treatment process

7 Hazard risk assessment outcomes

The following figure summarises the hazards/RWQPs considered at each step during the hazard risk assessment.

Preliminary screening – after WWTP	– **254 hazards assessed (254 water quality guidelines)** – 143 hazards identified < 10% water quality guideline – 111 hazards > 10% guideline and considered in detailed inherent risk assessment
Inherent Risk Assessment – after WWTP	**132 hazards investigated in detail:** – Low inherent risk = maximum value is < 10% of the guideline = 143 (*21 considered in detail, 122 assigned low in preliminary screening and not considered further)* – Moderate inherent risk = maximum value is between 10% and 100% of the guideline value = 86 – High inherent risk = maximum value is greater than > 100% of the guideline value = 21 – Extreme inherent risk = maximum value is significantly greater than the guideline = 4
Residual Risk Assessment – after AWRP	**Residual risk low for all 254 guidelines:** – 22 have DoH approval that LOR sufficient to demonstrate safety – will be reviewed annually – 10 require further work to lower LOR or method development

Figure 7-1: Summary of hazard risk assessment outcomes

7.1 Preliminary Screening risk assessment

Preliminary screening considered the concentration of 254 hazards (chemical and microbiological parameters) against the water quality guidelines. The result of this screening was that 143 parameters were assigned a low risk. They were either not detected in the GWRT AWRP feed water or were consistently detected at less than 10% of the water quality guideline. 122 of these hazards were assigned a low residual risk and not considered further. Refer to Appendix 4 for the full list ruled out after preliminary screening.

7.2 Inherent risk assessment

The inherent risk assessment considered the 111 of the hazards that were above 10% of the water quality guideline in GWRT feed water. An additional 21 parameters that had a low risk ranking were also considered in the inherent risk assessment, for reasons outlined in

Section 5.1. Therefore a total of 132 out of 254 hazards were considered in the inherent risk assessment, which is summarised in Table 7-1.

Table 7-1: Summary of potential hazards after secondary wastewater treatment

Barrier	Low Risk [Max] < 10% Guideline	Moderate Risk 10% < [Max] < 100% Guideline	High Risk [Max] > 100% Guideline	Extreme Risk [Max] >> 100% Guideline
Secondary treatment – Beenyup WWTP	1 Inorganic Ions 1 Physical Parameters 1 Disinfection Byproducts 2 Hormones 2 Metals 3 Pesticides 7 Volatile Organic Compounds 1 Phenols 1 Iodinated Contrast Media 2 Radiation **21 in Total**	6 Inorganic Ions 1 Nutrients 1 Nitrosamines 19 Disinfection Byproducts 7 Hormones 7 Metals 15 Pesticides 12 Volatile Organic Compounds 5 Phenols 2 Chelating Agents 5 Pharmaceuticals 1 Iodinated Contrast Media 4 Other Organic Chemicals 1 Dioxins **86 in Total**	2 Inorganic Ions 2 Nutrients 2 Physical Parameters 7 Nitrosamines 1 Disinfection Byproducts 2 Pesticides 1 Volatile Organic Compounds 2 Polycyclic Aromatic Hydrocarbons 1 Chelating Agents 1 Other Organic Chemicals **21 in Total**	4 Pathogen Indicators **4 in Total**

7.3 Residual risk assessment

Table 7-2 summarises the residual risk after advanced water treatment, based on Trial data. This water quality is expected to be produced by a larger AWRP. It indicates the advanced water treatment process adequately reduces all 254 hazards to a low residual risk.

Table 7-2: Summary of all potential hazards after advanced water treatment

Barrier	Low Risk [Max] < 10% Guideline	Moderate Risk 10% GL < [Max] < 100% Guideline	High Risk [Max] > 100% Guideline	Extreme Risk [Max] >> 100% Guideline
Advanced water treatment – GWRT	11 Inorganic Ions 3 Nutrients 3 Physical Parameters 4 Pathogen Indicators 9 Nitrosamines 29 Disinfection Byproducts 13 Hormones 22 Metals 48 Pesticides 38 Volatile Organic Compounds 6 Polycyclic Aromatic Hydrocarbons 14 Phenols 5 Chelating Agents 29 Pharmaceuticals 5 Iodinated Contrast Media 2 Flame retardants 9 Other Organic Chemicals 2 Radiation 2 Dioxins **254 in Total**			

7.4 Discussion on results of hazard risk assessment

7.4.1 Pathogen indicators

There were 4 pathogen indicator water quality guidelines assessed – MS2 coliphage, somatic coliphage, TTC / *E Coli* and *Clostridium perfringens* spores. These four indicators represent all four pathogen groups: virus, bacteria, protozoa and helminths with respect to the AWRP treatment process.

The indicators MS2 coliphage and somatic coliphage were selected because they are small virus particles that provide a conservative measurement of the removal by ultrafiltration and reverse osmosis and they are consistently present in feed water.

The inherent risk for pathogen indicators was extreme because of the concentrations recorded in secondary treated wastewater.

All recycled water results for the pathogen indicators obtained during the Trial were below the water quality guidelines, demonstrating the effectiveness of the GWRT AWRP to consistently and reliably remove pathogens. This resulted in assigning a low residual risk to pathogens.

7.4.1 Polyaromatic Hydrocarbons

During the Trial a number of polyaromatic hydrocarbons (PAHs) were analysed. The water quality guideline to assess PAHs is an overall toxic equivalence (TEQ) of 0.01ug/L. This is determined by a calculation of 17 RWQPs, each multiplied by a toxic equivalence factor (TEF).

In March 2013 the GWRT Health Advisory Committee endorsed that a zero may be used in the calculation of TEQ if the concentration of a RWQP is less than the LOR. This assumes the concentration of the individual RWQP is zero. This will be used until the LOR of PAHs can be lowered in the future.

7.4.2 N-nitrosamines and Disinfection Byproducts

The Trial demonstrated all N-nitrosamines and disinfection byproducts to be below the current guideline limits in the recycled water during recharge.

The majority of N-nitrosodimethylamine (NDMA) results were below the guideline of 10ng/L during the Trial. There was a result of 17ng/L during commissioning. Further exceedances were prevented by optimising chloramination during the commissioning process to minimise NDMA formation, resulting in all results during recharge to be below guideline. In addition, the guideline has since increased in line with ADWG to 100ng/L as of January 2013.

N-nitrosomorpholine (NMOR) had a single detection of 3.1ng/L out of 25 samples and has a guideline of 5ng/L.

The only other disinfection byproduct detected was chlorate at 20ug/L, well below its guideline of 700ug/L.

Monitoring of the Trial demonstrated the treatment process and disinfection approach has effectively minimised formation of disinfection byproducts. Based on this experience, the likelihood of exceeding the water quality guidelines was assessed as “unlikely”.

Pre-formation of chloramines prior to the addition to feed water is recommended for implementation at the large scale AWRP to manage bio-fouling through the treatment process. This is based on extensive third party research. The impact of this change to the treatment process on formation of disinfection byproducts will be reviewed following detailed design.

7.4.3 Ammonia

The GWRT AWRP achieved chloramination of feed water by addition of ammonia and hypochlorite separately. Ammonia in recycled water has not exceeded the guideline during the Trial but maximum concentrations approached the guideline value.

The GWRS AWRP is planned to achieve chloramination with pre-formation of monochloramines and include better management of influent ammonia from the WWTP in order to minimise biofouling and disinfection byproduct formation. The GWRS will also implement continuous monitoring of feed water and diversion on excess ammonia as introduced during the Trial. The risk of exceeding the guideline is significantly lowered with these changes resulting in a low residual risk. This will be reviewed again following detailed design.

7.4.4 Parameters with LOR issues

Table 7-3 shows that for 32 hazards the limit of reporting (LOR) is either above the guideline level or currently there is no analytical method available. The DoH accepts that all represent a low risk to health and EVs.

Table 7-3: Summary of parameters with LOR or analytical issues

	Category	Guidelines	DoH approach
1	LOR > guideline but no further method development at this time *(LOR generally close to guideline)*	Tribromoacetonitrile Tribromoacetic acid Bromoacetic Acid (MBA) Bromochloroacetic acid Dichlorobromoacetic acid Dibromochloroacetic acid Monobromoacetonitrile Trichloroacetonitrile Monochloroacetonitrile Bromochloroacetonitrile 1,1-dichloropropanone Chloroacetone Chloropicrin Diuron 1,1,2-trichloroethane 1,2-dibromoethane 4-isopropyltoluene Chloroethane Hexachlorobutadiene 2-nitrophenol 2-propytoluene Dibromomethane **22 in Total**	DoH accepts the LOR is sufficient to demonstrate safety and no further method development required. LOR will be reviewed annually.
2	LOR > guideline, DoH require further method development	Amitraz Toltrazuril 2,6-di-tert-butylphenol Triclosan Benzidine 4-cumylphenol **6 in Total**	DoH accepts the LOR is sufficient to demonstrate safety, but require further method development.
3	No analysis to date, development ongoing under direction of DoH	Chlorantraniliprole Flupropanate Polihexanide Chlorophene **4 in total**	DoH accepts low risk but require analytical method development.
	Total	**32 in total**	

8 Barrier risk assessment outcomes

The barrier risk assessment considered the potential barrier failures within the Beenyup wastewater catchment, WWTP and AWRP. The identified hazardous events could have potential impact on water quality or infrastructure. There were 34 potential barrier failures identified.

Table 8-1 summarises the outcomes of the barrier risk assessment and describes the high inherent risks. After mitigations all these risks were reduced to low (Table 8-2). The full risk assessment table can be found in Appendix 6.

Table 8-1: Summary of barrier risk assessment – inherent risks

Barrier	Inherent Risk				Total
	Low	Moderate	High	Extreme	
Beenyup wastewater catchment	5	1	2 – Illegal toxic waste dumping resulting in contamination of recycled water – Reputation risk that trade waste could contaminate drinking water	0	8
Beenyup WWTP	5	3	5 – Bypass of WWTP impact AWRP feed water quality – Overloading treatment tanks during maintenance – Power failure – Blower failure – Solids carry over	0	13
AWRP	4	5	4 – Ultrafiltration membrane degradation – RO membrane degradation – UV effectiveness reduced – Monitoring system integrity failure	0	13
Total	14	9	11	0	34

Table 8-2: Summary of barrier risk assessment – residual risks

Barrier	Inherent Risk				Total
	Low	Moderate	High	Extreme	
Beenyup wastewater catchment	5+1+2	0	0	0	8
Beenyup WWTP	5+3+5	0	0	0	13
AWRP	4+5+4	0	0	0	13
Total	34	0	0	0	34

8.1 Beenyup wastewater catchment

There were two high inherent risks identified for the Beenyup wastewater catchment

8.1.1 Illegal toxic waste dumping resulting in contamination of recycled water

The impact of illegal dumping of chemical waste into the sewer system via access chambers was assigned a high inherent risk. It is considered possible as there were two events observed in 2010 which have been attributed to illegal dumping:

- An elevated simazine concentration was recorded in April 2010 of 110µg/L in feed water when the median is 6µg/L. The water quality guideline for simazine is 20µg/L and the GWRT recycled water was < 0.1µg/L. This illustrates the reverse osmosis treatment in the AWRP worked well.
- There was an elevated trend of total organic carbon (TOC) detected in the RO permeate in December 2010.

Appropriate CCPs with alert and violation limits will be set for critical process in the wastewater and advanced water treatment processes to ensure recycled water quality meets specification. This risk can be effectively mitigated to a low residual risk by operating the WWTP and AWRP in accordance with the CCPs outlined in the PCT (especially monitoring of organic carbon on the AWRP reverse osmosis permeate, which results in diversion).

Additional catchment management initiatives which will contribute toward reduced risk from inappropriate discharges and identifying the sources include:

- Protocols for documenting, communicating and responding to unusual discharge events within the catchment; and
- Development and deployment of portable continuous in-sewer monitors within the catchment.

Water Corporation will also continue to support the DEC waste tracking program.

8.1.2 Reputation risk from trade waste discharges

There is a risk that the community (and media) perceive that some trade waste discharges cannot be adequately removed by the AWRP and result in contamination of the recycled water. This is NOT a technical risk as water quality monitoring demonstrates that the AWRP reliably and consistently meets water quality guidelines.

This risk may be effectively controlled by robust trade waste management procedures for existing and new trade waste customers. This will be supported by monitoring the treatment process and recycled water quality. In addition, Water Corporation will continue with an environmental scan to identify any new chemicals of concern that may emerge over time. These procedures will be communicated as necessary.

8.2 Beenyup WWTP

There were five potential barrier failures identified within the WWTP assigned a high risk.

8.2.1 Bypass of primary or secondary treatment tanks

In exceptional circumstances it is possible for the primary or the secondary treatment tanks (aeration and clarification) to be bypassed during a large inflow event following high rainfall or during construction works. Bypassing either treatment process may result in reduced wastewater treatment efficiency and inadequately treated AWRP feed water.

Online turbidity and ammonia monitoring at the AWRP will result in automatic bypass of the AWRP if feed water does not meet the required quality described in the PCT.

8.2.2 Overloading secondary treatment aeration tanks during maintenance

It is possible that secondary treatment aeration tanks may become overloaded when other tanks are taken offline for maintenance. This may result in reduced wastewater treatment efficiency and inadequately treated AWRP feed water.

If more than one WWTP tank is offline, the PCT requires that flow will not enter the AWRP until this can be resolved.

Ammonia levels in the treated wastewater (AWRP feed water) are an adequate indicator of wastewater treatment performance. Therefore this risk is adequately mitigated by online ammonia and turbidity monitoring at the AWRP. This will result in automatic bypass of the AWRP if feed water does not meet the required quality described in the PCT.

With these mitigations in place, the residual risk is low.

8.2.3 Power failure impacting WWTP treatment

Each year the WWTP experiences approximately four major power failures. These are usually short in duration i.e. less than 10 minutes. There is no backup power for the WWTP so it is possible during a longer power failure may result in reduced wastewater treatment efficiency and inadequately treated AWRP feed water.

This risk is effectively mitigated to low because the AWRP is supplied from the same power source, therefore during a major power failure the AWRP will also be shut down. When the power failure is resolved the AWRP must be restarted manually by operators, who will ensure feed water is diverted until monitoring of CCPs indicates the feed water meets the required quality.

During the Trial there was a water quality event where there was partial power failure to the Beenyup WWTP but the AWRP remained operational. The lack of power resulted in a blower failure to the secondary treatment system causing dissolved oxygen (DO) concentrations that were lower than the set limit of 0.5mg/L.

There was also a failure of the DO monitoring system and WWTP/AWRP communication system.

After detailed investigation, the corrective action to prevent similar events occurring in the future was the installation of continuous ammonia monitoring of AWRP feed water and diversion upon reaching the CCP violation limit. This CCP would be applied to a large scale AWRP.

8.2.4 Blower failure impacting WWTP treatment

There are five blowers providing aeration in the secondary treatment aeration tanks. It is possible to maintain water quality with only three blowers online during peak daily flow. Any more than two (out of the five) blowers out of service may compromise the effectiveness of treatment process, therefore AWRP feed water quality.

This high risk can be effectively mitigated to a low residual risk by online ammonia monitoring at the AWRP, resulting in automatic bypass of the AWRP if feed water does not meet the required quality. There will also be additional operational measures such as online dissolved oxygen interlock and ammonia alarm CCP for AWRP operators.

8.2.5 Solids carry over from secondary sedimentation tanks

Each year it is almost certain that a WWTP secondary sedimentation tank will experience solids being carried over into the treated wastewater, therefore AWRP feed water. This represents a high risk to the AWRP but one which can be effectively mitigated.

Online turbidity and ammonia monitoring at the AWRP feed water will result in automatic bypass of the AWRP if feed water does not meet the required quality. In addition the WWTP PCT specifies that if more than one SST is offline the AWRP will shut down.

8.3 AWRP

There were four high inherent risks associated with the AWRP treatment process.

8.3.1 Ultrafiltration membrane degradation

It is possible the UF membranes may be damaged due to process malfunction, chemical degradation, wear and tear or defects. This risk can be effectively mitigated to low by daily integrity testing (pressure decay testing), automatic divert and online analysers including the critical control point of filtrate turbidity, regular back washes, and weekly silt density index tests.

8.3.2 Reverse Osmosis membrane degradation

The RO membranes may be damaged due to back pressure surges, oxidation degradation, instrument malfunction, cleaning chemicals, and general wear and tear.

This risk can be controlled by a number of measures that effectively mitigate the risk to low. There will be automatic shutdown/divert and alarms if water quality does not meet the critical control point criteria for TOC and conductivity at a number of locations.

8.3.3 Ineffective UV disinfection

There is a possible high risk of ineffective UV disinfection caused by either film build up inside the UV unit or lamp failure. This risk can be effectively mitigated by operating the AWRP within the CCPs, including online monitoring of UV intensity.

Regular maintenance and cleaning will also mitigate this risk.

8.3.4 Monitoring system failure

There is the likely risk that the monitoring system could experience failure due to inadequate instrument calibration or Programmable Logic Controller (PLC) issues. This can be effectively mitigated by a number of measures including design for shutdown of the AWRP when there has been a monitoring system failure; an appropriate calibration program; an effective PLC programme version control that is regularly backed up, especially prior to any modifications; and sufficient maintenance program of the monitoring system with redundancy (spares).

There were three GWRT events that involved instrumentation failure – treated water pH and dissolved oxygen in March 2012, and total organic carbon in August 2012. The reoccurrence of these types of control system failures are mitigated by the implementation of the learning’s from the GWRT events. Mitigations include alteration of commissioning requirements and validation procedures and the control system review process (e.g., performed by MWH Global Australia for the GWRT).

9 Conclusions

The Perth GWRS Stage 2A treatment process preliminary risk assessment has shown that all potential risks have been appropriately addressed to low. It is important to note this is an iterative process and there will be future risk assessments following detailed design and commissioning of Perth GWRS.

10 References

Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Augmentation of Drinking Water Supplies (2008).

Australian Guidelines for Water Recycling: Management Health and Environmental Risks (Phase 2), Managed Aquifer Recharge, July 2009

Beenyup WWTP Preliminary & Primary Treatment Process Control Table (Water Corporation)

Beenyup WWTP, L7882/1991/14, Annual Environmental Report, 01 July 2011 to 30 June 2012

Briefing Note: Calculation of Toxic Equivalence (TEQs) for PCBs and Dioxins, February 2013 (Water Corporation)

Draft Perth Groundwater Replenishment Scheme Basis for Design & Construction, February 2012 (Water Corporation)

Groundwater Replenishment Regulatory Framework, December 2012 (Water Corporation)

GWRT Beenyup AWRP Process Control Table (Water Corporation)

GWRT Final Report, April 2013 (Water Corporation)

GWRT Method Development Summary for DoH - October 2012 (Water Corporation)

GWRT Summary Report for DoH, March 2013 (Water Corporation)

Health and Environmental Risk Assessment Report – Review 1, Groundwater Replenishment Trial, April 2009 (Water Corporation)

Health and Environmental Risk Assessment Report – Review 2, Groundwater replenishment Trial, December 2010

Memorandum of Understanding (MoU) between the Department of Health and Water Corporation for the Groundwater Replenishment Trial 2010 (Department of Health and Water Corporation)

Risk Assessment Report, Groundwater Replenishment Trial, March 2008 (Water Corporation)

Risk Management Guidelines (Water Corporation)

Treating wastewater for potable reuse: removal of chemicals of concern advanced oxidation processes (Draft March 2013)

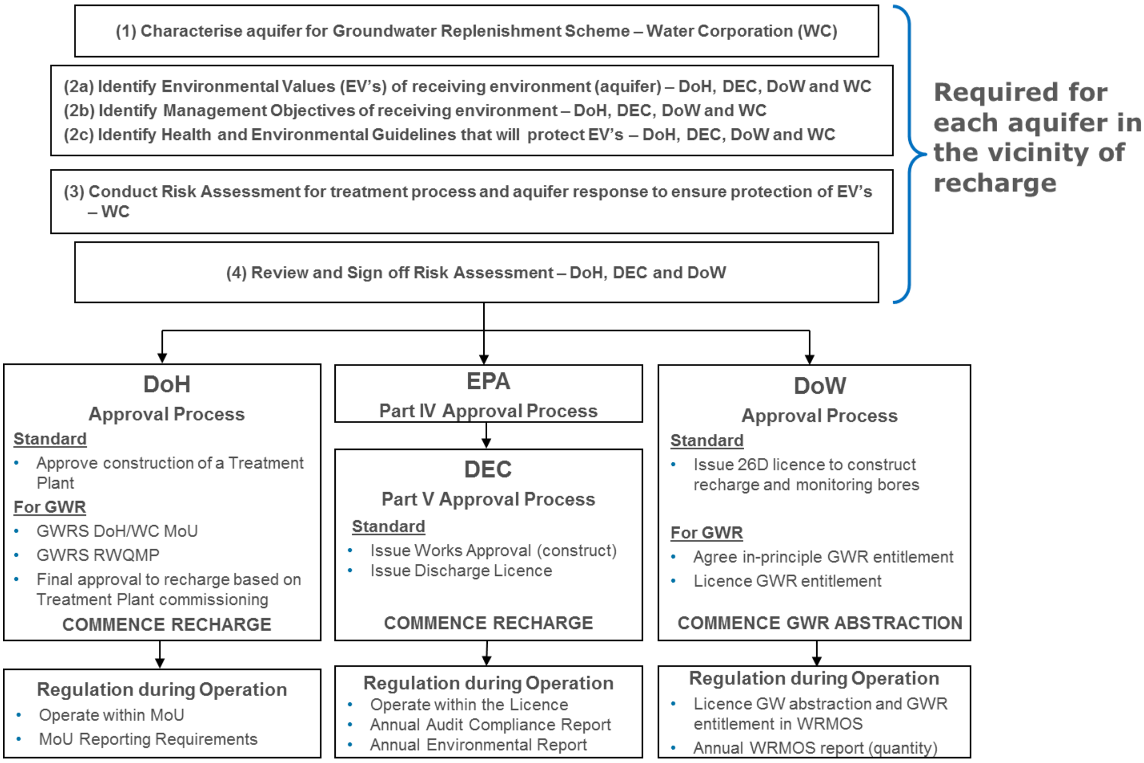
S389 Risk Assessment Criteria (Water Corporation)

Wastewater 2060, A Strategic Plan for the Perth-Peel Wastewater System, January 2010 (Water Corporation)

Yarragadee Aquifer, Preliminary Risk Assessment, August 2011 (Water Corporation)

Water Corporation, (2013). Perth Groundwater Replenishment Scheme – Stage 2A, Aquifer Risk Assessment Report (Leederville and Yarragadee Aquifers), March 2013. Water Corporation.

Appendix 1: Groundwater Replenishment Regulatory Framework



Appendix 2: Risk Assessment Workshop Attendee List

Attendee	Position	Signature
Daniel Bisgrove	GWRT Process Coordinator	—
Ben Boardman	Supervising Engineer, Water Treatment	
Iwona Burak	Supervising Engineer, Water Treatment	
Keith Cadee	General Manager Acquisition	
Sheena Clark	Process Technical Officer	
Mark Cocks	GWRT Process Coordinator	—
Eduardo Cosa	Process Technical Officer	
Peta Cruttenden	Supervisor Operations	
Margaret Domurad	Wastewater Operations Manager	—
Bradley Edwards	R & D	
Richard Forrest	Technical Services Manager	
Scott Garbin	Wastewater Quality Framework Coordinator	
Natasha Glass	Community Engagement	—
Kevin Guppy	Project Manager	—
Stacey Hamilton	Scientific Officer GWR	
Adam Henderson	GWRT Process Coordinator	—
Simon Higginson	Water Source Strategy Officer	
Danielle Higgs	Water Source Strategy Advisor	
Rod Holme	Wastewater Quality Manager	
Tran Huynh	Water Source Strategy Advisor	
Solonge Italiano	Customer Communications Officer	—
Stephen Jerkovic	Supervisor Investigations	
Peter Marchesani	Program Manager	—
Michael Martin	Principal Hydrogeologist	—
Glen Mcgregor	GWRT Plant Manager	
Arvi Rengasamy	Plant Manager	
Peter Spencer	Treatment Manager, Drinking Water Quality Branch	
Cameron Staib	Technical Expert	
Rino Trolio	Manager Wastewater Quality Branch	
Nick Turner	Principal Engineer, IWSS Source Planning	
Peter Wilmot	Industrial Waste Consultant	
Palenque Blair	Senior Environmental Engineer	Palenque Blair
Sarah Carroll	Project Manager	PMB.

Appendix 3: Water Corporation Risk Assessment Criteria Tables

Table 0-1: Consequence rating

Rank	Financial	People & Public	Environmental	Service Interruption / Customer Impact	Reputation	Compliance	Descriptor
1	Less than $1M	Injuries or illness not requiring medical attention, or Minor first aid Injury	No lasting effect on the environment or social amenity, and/or Recovery– less than 1 week, and/or Cosmetic remediation	Brief loss of local services, and No measurable operational impact.	Low public awareness, no media coverage, possible localised impact on trust and credibility, and/or Inconsequential complaints from the community, and/or No government/ministerial involvement.	Licence or regulatory limit exceedance, informal approach with no formal action or no Regulator involvement.	Insignificant
2	$1M - $10M	Injury requiring medical treatment(no alternative duties), or Localised illnesses requiring medical attention	Short term or low-level long-term impact on the environment or social amenity, and/or Recovery – 1 week to several months, and/or Easy remediation	Localised operations or service interruption, and Temporary, short term service cessation (<6 hours)	Limited local media coverage, localised impact on trust and credibility with Minor Stakeholders, and/or Random substantiated complaints from the community, and/or Local member of parliament enquiry.	Non-compliance or breach of regulation – Formal direction by a Regulator or administrative / Statutory body with administrative or minor operational impacts	Minor
3	$10M - $100M	Middle to long term injury (able to return to work), or Long term condition, or Localised illnesses requiring hospitalisation	Long term impact on the environment or social amenity, and/or Recovery – several months to several years, and/or Challenging remediation	Wide-spread customer impacts – entire regional centre or country scheme, multiple metropolitan suburbs, and Temporary loss of operations and services (<24 hours)	Local and state-wide media coverage, impacts on trust and credibility with Minor and Major Stakeholder, and/or Coordinated communication of community concerns and complaints, and/or Parliamentary question / Ministerial directive.	Non-compliance or breach of regulation – Formal direction by a Regulator or administrative / Statutory body with threat of prosecution or localised public undertakings Loss of accreditations (e.g. Environmental, OH&S)	Moderate
4	$100M - $500M	Permanent disabling injuries, or Widespread illness requiring hospitalisation, or Single death	Extensive, long term impact on the environment or social amenity, and/or Recovery – several years to several decades, and/or Uncertain reversibility of remediation	Widespread degradation of operations or services, and Sustained service cessation (>24 hours)	State-wide and National media coverage, impacts on trust and credibility with Significant and Major Stakeholders, and/or Sustained community outrage, and/or Government Department Investigation.	Non-compliance or breach of regulation – Formal direction a Regulator or administrative / Statutory body with significant operational constraints/restriction and/or public undertaking Criminal / quasi-criminal charges for Water Corporation and/or personnel Loss of multiple/significant abstraction licence	Major
5	Greater than $500M	Multiple deaths	Significant extensive impact on the environment or social amenity, and/or Impacts are irreversible and/or permanent.	Significant widespread degradation of operations or services, and Long, sustained, loss of operations or services	Extensive National and/or some International media coverage, and/or Impacts on trust and credibility with all Corporate stakeholder categories, and/or Sustained community outrage.	Non-compliance resulting in cancellation or loss of operating licence. Loss of significant or major licence	Catastrophic

Rank	Descriptor	Frequency	Description
A	Almost Certain	Will occur more than once a year Multiple times in a year	The event is expected or known to occur often
B	Likely	Once per year Once in a year or so	Known to re-occur approximately annually
C	Possible	Will occur once every 5 years Once in 5 years or multiple times over 10 years	The event should occur at some time Is sporadic, but not uncommon
D	Unlikely	Will occur once in 10 years Could occur once in 10 years or multiple times over 20 years	The event could occur at some time, usually requires combination of circumstances to occur
E	Rare	Will occur once every 30 years Once in 30 years or less frequent	The event may occur in exceptional circumstances Not likely to occur, but it's not impossible

Table 0-2: Likelihood rating

Rank	Descriptor	Description
O	Optimal	The control is designed and operating effectively and consistently Improvements to the control are not feasible or are unnecessary
A	Adequate	Control is designed to be effective The control is operating effectively Errors in control application can result in isolated cases of inconsistencies Improvements should be made if feasible
I	Improvement Required	The control is not designed and/or operating effectively Improvements are required

Table 0-3: Control effectiveness rating

CONSEQUENCES	Level of Risk				
5 Catastrophic	H	H	E	E	E
4 Major	M	H	H	E	E
3 Moderate	L	M	H	H	H
2 Minor	L	L	M	H	H
1 Insignificant	L	L	L	M	M
	E Rare	D Unlikely	C Possible	B Likely	A Almost Certain
	LIKELIHOOD				

Table 0-4: Water Corporation risk matrix

Appendix 4: List of MoU RWQPs removed in preliminary screening

Table 0-1: MoU RWQPs either not detected or below 10% guideline value

MoU RWQPs that were either not present in GWRT feed water or [Max] < 10% GL so not considered further in the risk assessment					
Inorganic Ions (2 out of 11) Magnesium Maganese **Nutrients (0 out of 3)** **Physical parameters (0 out of 3)** **Pathogen Indicators (0 out of 4)** **N-nitrosamines (1 out of 9)** N-nitroso-diphenylamine (NDPhA) **Disinfection by-products: Trihalomethanes (5 out of 6)** Total THMs Chloroform Chlorodibromomethane Bromoform Bromochloromethane Dibromomethane **HAAs (3 out of 9)** Chloroacetic acid Trichloroacetic acid Dibromoacetic acid **HANs (0 out of 7)** **Other DBPs (0 out of 7)**	**Hormones (4 out of 13)** Equilenin Testosterone Androstenedione Etiocholanolone **Metals & Metalliods (13 out of 22)** Beryllium Boron Copper Lithium Molybdenum Selenium Tin Silver Strontium Thallium Uranium Vanadium Zinc **Pesticides (28 out of 48)** Amitrole Asulam Atrazine Azinphos-methyl Bifenthrin Chlorpyrifos ethyl DEET Diazinon	Dicamba Dichlorprop Diclofop methyl Dimethoate Ethion Fenitrothion Fenthion Fipronil Glyphosate AMPA Imidacloprid Malathion MCPA Molinate Piperonyl butoxide Profenofos Prometryn Propazine Propiconazole Terbutryn **Volatile Organic Compounds VoCs (18 out of 38)** 1,1,1-trichloroethane 1,2-dichlorobenzene 1,3-dichlorobenzene 1,2 dichloroethane 1,2-dichloroethene-cis&tr 1,2-dichloropropane 1,4-dichlorobenzene Carbon disulfide Chlorobenzene	Chloromethane Ethyl benzene Napthalene Styrene Toluene Trichlorobenzenes total Trichloroethylene total Trimethyl benzenes total Xylenes total **Polycyclic Aromatic Hydrocarbons (PAHs) (4 out of 17 parameters in total *and 6 guideline values*)** Anthracene Fluorene Phenanthrene Pyrene **Phenols (8 out of 14**) 2-chlorophenol 4-chlorophenol 2,4-dichlorophenol 2,6-dichlorophenol 2,4,6-trichlorophenol Bisphenol A Pentachlorophenol 4 n-Nonylphenol **Chelating agents (2 out of 5)** NTA ADA	**Pharmaceuticals (24 out of 29)** **Antibiotics** Azithromycin Clarithromycin Clindamycin Erythromycin Metronidazol Roxithromycin Sulfamethoxazole Trimethoprim Tylosin **Other Pharmaceuticals** Acetaminophen Bezafibrate Carbamazepine Clofibric acid Cyclophosphamide Diazepam Phenytoin Fluoxetine Gemfibrozil Ibuprofen Indometacine Morphine Naproxen Salicylic acid Warfarin	**Iodinated contrast media (3 of 5)** Iohexol Iopamidol Iopromide **Flame retardants (2 out of 2)** Tetrabromobisphenol A TCEP **Other Organics (4 out of 9)** 1,4-dioxane MTBE Musk ketone Galaxolide **Radionuclides (0 of 2)** **Dioxins, Furans & dioxin like PCBs (1 out of 29 parameters in total and *2 guideline values*)** Octadioxin **Total MoU guidelines screened out = 122**

Appendix 5: Hazard Risk Assessment

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process				Post AWRP Treatment SCREENING RISK		
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
Risk assessment process: Preliminary screening of 295 MoU parameters (note 295 RWQPs sampled to report on 255 guidelines). If not present in treated wastewater or less than 10% of GL value screened out. Inherent risk ranking: Low = [Max] < 10% GL; Moderate = 10% < [Max] 100%< GL; High = [Max] > 100% GL; Extreme [Max] >> GL Residual Risk ranking: Consequence rating based on Water Corporation risk matrix: Financial (Fi), People & Public (PP), Environmental (E), Service Interruption/Customer Impact (SI), Reputation (Re), Compliance (Co) # parameters have GL value that can not be demonstrated because of an insuffiently low limit of reporting. DoH agree that achievement of a result below LOR will be acceptable to demonstrate safety until the LOR is lowered below GL in future (if possible). ^ parameters marked do not have suitable analytical methods available but it is anticipated these may be developed over time. This is not required to be demonstarted to gain approval to discharge. **Hazard Assessment of Environmental Value: Endpoint 1: Drinking Water, Endpoint 2: Industrial Use** **Data Used for this RA is from 1/1/2010 - February 2013. n = number of data points during this period.** **ACRONYMS: LOR = Limit of Reporting, LOD = Limit of detection GL = Guideline, AGWR = Australian Guidelines for Water Recycling Phase 2: Augmentation of Drinking Water Supplies, DoH = Department of Health GWRT Memorandum of Understanding (Oct 2010), ADWG= Australian Drinking Water Guidelines, WHO = World Health Organisation Guidelines for drinking, MW = Molecular weight**															
	INORGANIC IONS	Based on Max concentration in secondary treated wastewater (AWRP feed water)								Based on Max In AWRP Product Water					
1	Sodium	**DOH GL = 180mg/L (Minimise where possible)** **GWRT:** Feed Max = 220 mg/L (Above GL) Feed Ave = 166 mg/L n = 58		- can aggravate conditions of hypertension and congestive heart failure - water provides small contribution to dietary intake	Secondary Treatment - Primary - Activated Sludge - Clarification	2	B	High	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 14.2mg/L Ave = 9.5mg/L n = 27	O	Co	2	E	Low
2	Aluminium (Al) (Filtered)	**DOH GL = 0.2mg/L** **GWRT:** Feed Max = 0.039mg/L (>10% of GL) Feed Ave = 0.021mg/L LOR = <0.005mg/L n = 8		- neurotoxicity Drinking water contributes <2% of average daily intake	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max =<0.005mg/L LOR= <0.005mg/L = <10% of GL n = 6	O	Co	2	E	Low
3	Iron (Fe)	**DOH GL = 0.3mg/L** **GWRT:** Feed Max (Filtered) = 0.075 mg/L (>10% of GL) Feed Ave (Filtered) = 0.04 mg/L n = 70 Feed Max (Unfiltered) = 0.14 mg/L (>10% GL) Feed Ave (Unfiltered) = 0.04 mg/L		Background groundwater concentrations also exceed GL	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max (Filtered) = <0.005 mg/L (<10% of GL) n = 28 Max (Unfiltered) = 0.01 mg/L (<10% of GL) n = 28	O	Co	2	E	Low
4	Chloride	**DOH GL = 250mg/L** **GWRT:** Feed Max = 270mg/L, (Above GL) Feed Ave = 209 mg/L n = 57		Not harmful unless there is insufficient fresh water available. Food is major source of chloride.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	B	High	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 9mg/L n = 27	O	Co	2	E	Low
5	Fluoride	**DoH GL = 1.5mg/L** **GWRT:** Feed Max = 1.0mg/L (>10% of GL) Feed Ave = 0.83mg/L n = 57 Note: below concentration added for health benefits to drinking water		Skeletal & Dental fluorosis with excessive long term intake. Acute symptoms of overdose include: vomiting, diarrhoea, skin rash, lethal at 14mg/kg body weight. Not carcinogenic. Fluoridated water is major source of daily intake	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 0.18mg/L (>10% of GL) Median = 0.1 mg/L n = 27	A	Co	2	D	Low
6	Iodide	**DOH GL = 0.1mg/L** **GWRT:** Feed Max = <0.02 mg/L (LOR >10% of GL) n = 57		Iodism - similar to sinus cold. Affects thyroid at >2mg/day. Not carcinogenic. Main exposure: food, pharmaceuticals, drinking water	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	Low	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.02mg/L LOR > 10% of GL n = 27	A	Co	2	D	Low
7	Sulfate	**DoH GL = 500mg/L** **GWRT:** Feed Max = 84.3 mg/L (>10% of GL) Feed Ave = 66.6 mg/L n = 70		Negative health impacts can include dehydration and diarrhoea	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 0.5mg/L (<10% of GL) n = 27	O	Co	2	E	Low
8	Cyanide	**DOH GL = 0.08mg/L** **GWRT:** Feed Max = <0.01mg/L (LOR > 10% of GL) n = 26		Low Dose: loss of consciousness, general weakness, giddiness, headaches, vertigo, perceived difficulty in breathing. High dose: coma with seizures, apnoea and cardiac arrest	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.01mg/L LOR > 10% of GL n = 8	A	Co	2	E	Low
9	Perchlorate #	**DoH GL = 6ug/L (0.06mg/L)** **GWRT:** Max = <0.02 mg/L n = 27 LOR = 0.5ug/L		Thyroid effects through inhibition of iodide uptake - takes months to cause adverse effects. Lethal dose is 250mg/kg body weight. Intake is primarily through food & beverages.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.02mg/L n = 9	U	Co	2	D	Low

Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	NUTRIENTS	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
10	Ammonia	**DOH GL = 0.5mg/L (from ADWG)** **GWRT:** Feed Max = 6mg/L (Above GL) Feed Mean = 0.4 mg/L n = 71		Metabolism effects above 1000mg/L ammonium chloride Attacks copper pipes & fittings above 0.5mg/L	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	**High**	Advanced Treatment including in line chloramination with NH3 dosing at 1mg/L and Cl: NH3 ratio = 4.2:1 & online ammonia monitoring Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 0.44mg/L Mean = 0.26mg/L n = 28	A	Co	2	D	**Low**
11	Nitrate	**DOH GL = 11mg/L as N** **GWRT:** Feed Max = 21mg/L (Above GL) Feed Mean = 13mg/L UF Filtrate Max = 20mg/L n = 60		- Blue baby syndrome (infants <6months)	Secondary Treatment - Primary - Activated Sludge - Clarification	4	C	**High**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 3.6mg/L Mean = 1.96mg/L n = 28	A	Co	2	D	**Low**
12	Nitrite	**DOH GL = 1 mg/L as N** **ADWG GL = 0.67mg/L as N** **GWRT:** Feed Max = 0.39mg/L Feed Mean = 0.1mg/L UF Filtrate Max = 0.03 (LOR <0.01) n = 71		- Blue baby syndrome (infants <6months)	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 0.05mg/L Mean = <0.01mg/L n = 28	A	Co	2	D	**Low**
	PHYSICAL PARAMETERS	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
13	Turbidity & suspended solids	**DOH GL = 5NTU** **GWRT:** Feed Max = 6.6NTU (Above GL) UF Filtrate = <0.5NTU n = 76		Can affect efficiency of disinfection, can harbour contaminants	Secondary Treatment - Primary - Activated Sludge - Clarification	3	B	**High**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = < 0.5 NTU n = 27	O	Co	2	E	**Low**
14	TDS (Total dissolved solids)	**DOH GL = 500mg/L,** **Aesthetic Guideline = 1000mg/L** **GWRT:** Feed Max = 760mg/L (Above GL) Feed Ave = 651mg/L (Above GL) UF Filtrate Max = 750mg/L (Above GL) n = 78		None	Secondary Treatment - Primary - Activated Sludge - Clarification	2	A	**High**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 50mg/L n = 27	O	Co	2	E	**Low**
15	pH	**DoH GL = 6.5 - 8.5**		Below or above guideline range can result in disease Note: This is mostly an aquifer preservation limit as the ADWG pH limit is for optimisation of chlorine disinfection.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** AWRP product water Max = 9 because of GWRT event, due to a programming issue. New AWRP will have only one programming page containing limits. Min = 6.5	A	Co	2	D	**Low**

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	PATHOGEN INDICATORS	See GWR Treatment Validation Report - Feb 2010													
16	MS2 coliphage	Indicator virus representative of Virus and Adenovirus as well as the other pathogen groups: Protozoa, Helminths and Bacteria with respect to treatment. MS2 is a small virus particle, so provides conservative measurement of removal by UF & RO. **DoH GL = < 1 pfu/L** Unsuitable for drinking: potential for 3 log/L **GWRT - Feed:** Max = 450 pfu/100mL (>10% of GL) Ave = 66 pfu/100mL n = 36 LOR 10 pfu/100mL **GWRT - UF Filtrate:** Max = 0.6 pfu/L (>10% of GL) Ave = 0.35 pfu/L (due to changes in LOR) n = 32 LOR 0.6 pfu/L (prev 0.3)		Gastroenteritis	Secondary Treatment - Primary - Activated Sludge - Clarification	4	A	Extreme	Advanced Treatment Process & Control Point monitoring Maintain operational protocols -	GWRT: All < LOR n=33 Max = <0.6 pfu/L Ave = 0.36 pfu/L (due to changes in LOR)	O	Re	3	E	Low
17	Somatic coliphage	Indicator virus representative of Virus and Adenovirus as well as the other pathogen groups: Protozoa, Helminths and Bacteria with respect to treatment. Is a small virus particle, so provides conservative measurement of removal by UF & RO. **DoH GL = < 1 pfu/L** **GWRT - Feed:** Max = 27,000 pfu/100mL (>10% of GL) Ave = 11,537 pfu/100mL n = 26 LOR 10 pfu/100mL		Indicated pathogen groups cause gastroenteritis & respiratory disease	Secondary Treatment - Primary - Activated Sludge - Clarification	4	A	Extreme	Advanced Treatment Process & Control Point monitoring Maintain operational protocols -	GWRT: All < LOR n=26 Max = <0.6 pfu/L Av = 0.34 pfu/L	O	Re	3	E	Low
18	TTC/E. Coli Note; TTC will be removed from the future MoU list (i.e. only considering E.Coli)	**DoH GL = < 1 cfu/100mL** Represents bacteria, protozoa and helminths with respect to treatment Unsuitable for drinking: potential for 6 log/L **GWRT - Feed:** Max = 150,000 cfu/100mL (>10% of GL) Ave = 47,441 cfu/100mL n = 36 LOR 1 cfu/100mL		Gastroenteritis	Secondary Treatment - Primary - Activated Sludge - Clarification	4	A	Extreme	Advanced Treatment Process & Control Point monitoring Maintain operational protocols -	GWRT: All < LOR n=29 Max = <1 Av = <1 LOR 1 cfu/100mL	O	Re	3	E	Low
19	Clostridium perfringens spores	Represents protozoa and Helminths **DoH GL = < 1 cfu/100mL** Unsuitable for drinking: 3 log/L (protozoa) and 4 log/L (helminth) **GWRT - Feed:** Max = 20,000 cfu/100mL (>10% of GL) Ave = 4,644 cfu/100mL n = 12 **LOR 1 cfu/100mL**		Gastroenteritis	Secondary Treatment - Primary - Activated Sludge - Clarification	4	A	Extreme	Advanced Treatment Process & Control Point monitoring Maintain operational protocols -	GWRT: n=6 Max = < 1 cfu/100mL LOR 1 cfu/100mL	O	Re	3	E	Low

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process				Post AWRP Treatment SCREENING RISK		
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	NITROSAMINES	Based on Max conc. Data post chlorination								Based on Max In Product Water					
20	N-nitrosodimethylamine (NDMA)	**DOH GL = 100ng/L post Trial, previously: 10 ng/L** **GWRT:** Feed Max = 28ng/L (>10% of GL) UF Filtrate Max = 35ng/L (>10% of GL) n = 106 Note: NDMA & Precursors exist in secondary treated wastewater. Chloramination may elevate levels above guidelines		"probable human carcinogen" Cancer?: 5.8 in a million	Secondary Treatment (Source Control) - Primary - Activated Sludge - Clarification	4	C	High	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 74 **GWRT:** Commissioning Max = 17ng/L, Max During Recharge = 4.8ng/L Median = 2.2ng/L n = 51 **Notes:** Shown significant removal after UV. UV degrades NDMA, however	A	Co	2	D	Low
21	N-nitrosoethylmethylamine (NEMA) #	**DoH GL = 2ng/L** **GWRT:** Feed Max = <10ng/L UF Filtrate Max = <2ng/L (At guideline) n = 49 Note: Before recharge commenced the LOR was reduced from 10ng/L down to 2ng/L. Results before recharge reported as <10ng/L		Probable human carcinogen – increased incidences of tumours of the liver and other sites in two rat strains. Inadequate evidence for humans.	Secondary Treatment - Primary - Activated Sludge - Clarification	4	C	High	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 88 **GWRT:** Max = <2ng/L LOR =<2ng/L n = 25	A	Co	2	D	Low
22	N-nitrosodiethylamine (NDEA)	**DOH GL = 10ng/L** **GWRT:** Feed Max = <2ng/L (LOR >10% of GL) UF Filtrate Max = <2ng/L (LOR >10% of GL) n = 49 Note: Before recharge commenced the LOR was reduced from 10ng/L down to 2ng/L. Results before recharge reported as <10ng/L LOR		- Cancer risk 2X10-6	Secondary Treatment - Primary - Activated Sludge - Clarification	4	C	High	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 102 **GWRT:** Max = <2ng/L Based on new LOR Now LOR = <2ng/L Old LOR = <10ng/L n = 25	A	Co	2	D	Low
23	N-nitrosodi-n-butylamine (NDBA) #	**DoH GL = 4ng/L** **GWRT:** Feed Max = 4.5ng/L UF Filtrate Max = <2ng/L (>10% of GL) n=51 Note: Before recharge commenced the LOR was reduced from 10ng/L down to 2ng/L. Results before recharge reported as <10ng/L		Probable human carcinogen – increased incidences of several tumour types (mainly in urinary bladder, but also in respiratory tract) in rats, mice and hamsters. No epidemiological data available	Secondary Treatment - Primary - Activated Sludge - Clarification	4	C	High	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 158 **GWRT:** Max = 3.2 ng/L Av = 2.05 ng/L LOR = 2 ng/L n = 26	A	Co	2	D	Low
24	N-nitrosopiperidine (NPIP) #	**DoH GL = 4ng/L** **GWRT:** Feed Max = <10ng/L UF Filtrate Max = <2ng/L (>10% of GL) n = 49 Note: Before recharge commenced the LOR was reduced from 10ng/L down to 2ng/L. Results before recharge reported as <10ng/L		Probable human carcinogen – carcinogenic in mice, rats, hamsters and monkeys and produces benign and malignant tumours. Carcinogenic in mice and hamsters after single dose administration. No data available for humans.	Secondary Treatment - Primary - Activated Sludge - Clarification	4	C	High	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 114 **GWRT:** Max = <2ng/L post recharge LOR =<2ng/L n = 25	A	Co	2	D	Low
25	N-nitroso-pyrrolidine (NPYR)	**DoH GL = 20ng/L** **GWRT:** Feed Max = <2 ng/L Feed Av = <2 ng/L UF Filtrate Max = <2 ng/L (10% of GL) n = 26 Note: Before recharge commenced the LOR was reduced from 10ng/L down to 2ng/L. Results before recharge reported as <10ng/L		Sufficient evidence of a carcinogenic effect in humans. Produces hepatocellular carcinoma in rats and increases the incidence of lung adenomas in mice following oral administration. No data available for humans.	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 100 **GWRT:** Max = <2 ng/L Av = <2 ng/L LOR = 2 ng/L n = 26	A	Co	2	D	Low
26	N-nitrosomorpholine (NMOR) #	**DoH GL = 5ng/L** **GWRT:** Feed Max = 39ng/L (Above GL) Median=5.1ng/L (>10% of GL) UF filtrate Max=8.7ng/L (Above GL) Median =3.9ng/L (>10% of GL) n = 31 Note: Before recharge commenced the LOR was reduced from 10ng/L down to 2ng/L. Results before recharge reported as <10ng/L		Carcinogenic NMOR can be created outside or within the human body from morpholine - present in some packaging, waxes, toiletries, rubber babies pacifiers/bottles	Secondary Treatment - Primary - Activated Sludge - Clarification	4	C	High	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 116 **GWRT:** Max = 3.1ng/L 24/25 samples were <LOR n = 25	A	Co	2	D	Low
27	N-nitrosodi-n-propylamine (NDPA) #	**DoH GL = 5ng/L** **GWRT:** Feed Max = 4.4ng/L (>10% of GL) UF Filtrate Max = <2ng/L (>10% of GL) n = 49 Note: Before recharge commenced the LOR was reduced from 10ng/L down to 2ng/L. Results before recharge reported as <10ng/L		Probable human carcinogen – increased tumour incidence at multiple sites in two rodent species and in monkeys. Produces benign and malignant tumours of the liver, kidney, oesophagus and respiratory tract. Inadequate evidence available for humans	Secondary Treatment - Primary - Activated Sludge - Clarification	4	C	High	CCPs on WWTP to minimise pre-cursor availability Advanced Treatment Designed to minimise chloramine contact time & finely controlled chloramine dosing pumps Process & Control Point monitoring Maintain operational protocols	MW = 130 **GWRT:** Max = <2ng/L LOR = <2ng/L n = 25	A	Co	2	D	Low

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	DISINFECTION BYPRODUCTS	Based on Max conc. In 2ndry WW & UF filtrate								Based on Max In Product Water					
	Trihalomethanes														
28	Bromodichloromethane	**DoH GL = 6 ug/L** (WHO GL = 60ug/L) **GWRT:** Feed Max = <1.0ug/L (LOR >10% of GL) UF Filtrate Max = 3.3ug/L (>10% of GL) n = 39		Possibly carcinogenic At high doses - fatal toxicity, carcinogenic in animals	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 163.8 **GWRT:** Max = <1ug/L (>10% of GL) n = 28	O	Co	2	E	Low
	HAAs														
29	Dichloroacetic acid	**DoH GL = 100ug/L** **GWRT:** Feed Max = <3.0ug/L UF Filtrate Max = 21 ug/L (>10% of GL) n = 26		Carcinogen, risk and dangerous for the environment		2	C	Moderate	Advanced Treatment - Degasser Process & Control Point monitoring Maintain operational protocols	MW = 129 **GWRT:** Max = <3ug/L LOR = <10% of GL n = 8	O	Co	2	E	Low
30	Bromoacetic Acid (MBA) #	**DoH GL = 0.35ug/L** **GWRT:** Feed Max = <2.0ug/L (LOR>GL) n = 26		DBP increased risk of cancer	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 139 **GWRT:** Max = <2ug/L LOR above GL n = 8 NB: DoH accepts 2 ug/L LOR is sufficient to demonstrate safety	A	Co	2	D	Low
31	Tribromoacetic acid #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <10ug/L (LOR>GL) n = 7 Note: Too unstable to accurately analyse at concentrations near to GL. ChemCentre experiments 2010 evidence. Very unlikely to occur at concentrations of concern		Increased risk of cancer, reproductive and development effects. Neurotoxic effects are significant at high doses.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 297 **GWRT:** Max = <10ug/L LOR above GL n = 7 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	Low
32	Bromochloroacetic acid #	**DoH GL = 0.7ug/L** **GWRT:** Feed Max = <2.0ug/L (LOR>GL) Feed Median <2 ug/L UF Filtrate Max = 8.1ug/L n = 26		Short term effects on the liver from ingestion in water with observed effects of hepatomegaly, glycogen accumulation and cytomegaly. Possible long term effects are increased number of stillborns (fewer live fetuses).	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 173 **GWRT:** Max = <2ug/L LOR Above GL n = 8 NB: DoH accepts 2 ug/L LOR is sufficient to demonstrate safety	A	Co	2	D	Low
33	Dichlorobromoacetic acid #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <2.0ug/L (LOR>GL) n = 26 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		Possible reproductive risk to men (shown to disrupt spermatogenisis in rodents at high doses.	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	High	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 208 **GWRT:** Max = <2ug/L LOR above GL n = 8 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	Low
34	Dibromochloroacetic acid #	**DoH GL = 0.7ug/L** **GWRT:** Feed Max <5ug/L (LOR> GL) n = 26		Reduced fertility, reproductive effects Potentially mutagenic	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 252 **GWRT:** Max = <5ug/L LOR above GL n = 8 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	Low

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	HANs														
35	Monochloroacetonitrile #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR > GL) LOR = <1 ug/L, > GL Level n = 27 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		The substance may cause effects on the cellular respiration.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 75.5 **GWRT:** Max = <1ug/L LOR Above GL n = 9 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
36	Dichloroacetonitrile	**DOH GL = 2 ug/L** **GWRT:** Feed Max = <1ug/L (LOR >10% of GL) n = 27		DNA damage, developmental toxicity	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment (Chloramination, Ultrafiltration (UF), Reverse Osmosis (RO), UV irradiation (UV), Stabilisation (Degas, NaOH)) Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 110 **GWRT:** Max = <1ug/L (>10% of GL) n = 9	A	Co	2	D	**Low**
37	Trichloroacetonitrile #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR > GL) n = 27 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		Unknown	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 144 **GWRT:** Max = <1ug/L LOR Above GL n = 9 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
38	Monobromoacetonitrile #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR > GL) UF Filtrate Max = 1.9ug/L (>GL), n = 27 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		Unknown	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 120 **GWRT:** Max = <1ug/L LOR Above GL n = 9 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
39	Dibromoacetic acid	**DoH GL = 60ug/L** **GWRT:** Feed Max = <1ug/L UF Filtrate Max = 16ug/L (>10% of GL) n = 26 Note: Formation during summer		Diarrohea and hair loss		2	C	Moderate	Advanced Treatment - Degasser Process & Control Point monitoring Maintain operational protocols	MW = 218 **GWRT:** Max = <1ug/L LOR = <10% of GL n = 8	O	Co	2	E	**Low**
40	Bromochloroacetonitrile (BCAN) #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR > GL) LOR =<1ug/L, >GL level n = 27 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		DNA damage, chronic cytotoxicity (mid-range toxicity compared to other HANs)	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 154 **GWRT:** Max = <1ug/L (> GL) n = 9 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
41	Tribromoacetonitrile ^	**DoH GL = 0.7ug/L** **Do not have suitable analytical method**		Very toxic. Hazardous decomposition products.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	Incomplete due to time constraints/ higher priorities. Analytical standard in hand but method development not attempted. DoH satisfied to not develop further.	A	Co	2	D	**Unknown**

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	Other DBPs														
42	Bromate	**DOH GL = 20 ug/L** **GWRT:** Feed Max = <10ug/L (LOR > 10%GL) n = 27		Probable human carcinogen, carcinogenic in animals	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 128 **GWRT** Max = <10ug/L, LOR > 10% of GL n = 9	O	Co	2	D	**Low**
43	Chlorate	**DoH GL = 700ug/L** **GWRT:** Feed Max = 30ug/L (<10% of GL) UF Filtrate Max = 320ug/L (>10% of GL) n = 27 Note: Was observed in NeWater plants associated with excessive time of storage of hypochlorite (dosed in chloramination)		Oxidative damage to red blood cells at high doses	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment - Degasser Process & Control Point monitoring Maintain operational protocols Design & Operational protocols: store hypochlorite for minimum time on site	MW = 83.4 **GWRT:** Max = 20ug/L Median = <10ug/L n = 9	O	Co	2	E	**Low**
44	Chlorite	**DoH GL = 300 ug/L** **GWRT:** Feed Max = <20ug/L (<10% of GL) UF Filtrate Max = 170ug/L (>10% of GL) n = 27		Minor - Affects red blood cells at high doses	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols Design & Operational protocols: store hypochlorite for minimum time on site	MW = 67 **GWRT:** Max = <20ug/L Median = <10ug/L n = 9	O	Co	2	E	**Low**
45	Chloral hydrate (Trichloroacetaldehyde)	**DoH GL = 20ug/L** GWRT: Feed Max = <2ug/L (<10% of GL) n = 53 Note: Identified in Singapore as a problem when other DBPs observed		Addictive, sedative, Liver damage Formed from chlorination of water containing natural organic matter.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment - Degasser Process & Control Point monitoring Maintain operational protocols	MW = 165 **GWRT:** Max = <2ug/L LOR <10% of GL n = 17	O	Co	2	E	**Low**
46	Chloroacetone #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1.0ug/L (LOR > GL) UF Filtrate Max = 2.2ug/L (>GL) n = 28 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		The signs and symptoms of acute exposure to chloroacetone are tearing of the eyes, coughing, and redness and blistering of the skin.	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment - Degasser Process & Control Point monitoring Maintain operational protocols	MW = 92 **GWRT:** Max = <1ug/L n = 11 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
47	1,1-dichloropropanone #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR > GL) n = 27 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety.		Liver toxicity	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment - Degasser Process & Control Point monitoring Maintain operational protocols	MW = 112 **GWRT:** Max = <1ug/L LOR above GL n = 10 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
48	Chloropicrin #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR > GL) n = 27 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety.		Safe Work Australia - harmful, risk, very toxic and irritant	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment - Degasser Process & Control Point monitoring Maintain operational protocols	MW = 164 **GWRT:** Max = <1ug/L LOR above GL n = 10 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	HORMONES	Based on Max concentration in secondary treated wastewater (AWRP feed water)								Based on Max In AWRP Product Water					
49	Estrone	**DOH GL = 30 ng/L** **GWRT:** Feed Max = 16ng/L (>10% of GL) Feed Median = 3.0ng/L n = 27		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 270 **GWRT:** Max = <1ng/L LOR < 10% of GL n = 9	O	Co	2	E	Low
50	Estriol	**DOH GL = 50ng/L** **GWRT:** Feed Max = <1ng/L (<10% of GL) n = 27		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 288 **GWRT:** Max = <1ng/L LOR < 10% of GL n = 9	O	Co	2	E	Low
51	Ethinyl estradiol	**DOH GL = 1.5 ng/L** **GWRT:** Feed Max = <1ng/L (LOR >10% of GL) n = 9		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 296 **GWRT:** Max = <1ng/L LOR > 10% of GL n = 9	A	Co	2	D	Low
52	17alpha estradiol	**DOH GL = 175ng/L** **GWRT:** Feed Max = <1ng/L (<10% of GL) n = 27		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	Low	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 272 **GWRT:** Max = <1ng/L LOR <10% of GL n = 9	O	Co	2	D	Low
53	17 beta estradiol	**DOH GL = 175ng/L** **GWRT:** Feed Max = <1ng/L (<10% of GL) n = 9		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	Low	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 272 **GWRT:** Max = <1ng/L LOR <10% of GL n = 9	O	Co	2	D	Low
54	Equilin	**DoH GL = 30ng/L** **GWRT:** Feed Max = 4.6ng/L (>10% of GL) (2 samples >LOR of 26 samples, LOR = <2ng/L) n = 26		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 268 **GWRT:** Max = <2ng/L LOR <10% of GL n = 8	O	Co	2	E	Low
55	Mestranol	**DoH GL = 2.5ng/L** **GWRT:** Feed Max = <2ng/L (>10% of GL) n = 26		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=310 **GWRT:** Max = <2ng/L LOR >10% of GL n = 8	O	Co	2	E	Low
56	Norethindrone	**DoH GL = 250ng/L** **GWRT:** Feed Max = <100ng/L (>10% of GL) n = 26		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=298 **GWRT:** Max = <100ng/L LOR >10% of GL n = 8	O	Co	2	E	Low
57	Progesterone	**DoH GL = 105ng/L** **GWRT:** Feed Max = <100ng/L (>10% of GL) n = 26		Impacts Endocrine system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=314.5 **GWRT:** Max = <100ng/L LOR >10% of GL n = 8	O	Co	2	E	Low

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	METALS	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
58	Antimony	**DOH GL = 3ug/L** **GWRT:** Feed Max = 0.3ug/L (10% of GL) Feed Ave = 0.3ug/L n = 8		- Increase in blood cholesterol - Decreased blood sugar	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.1ug/L LOR = <0.1ug/L = <10% of GL n = 6	O	Co	2	E	**Low**
59	Arsenic	**DOH GL = 7ug/L NEW ADWG =10 ugL** Feed Max = <1ug/L (>10% of GL) LOR = increased from <0.6ug/L to <1ug/L. n = 8		- Skin damage - Effect on circulatory system - Potential increase of cancer risk	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <1ug/L LOR = <1ug/L = >10% of GL n = 6	O	Co	2	E	**Low**
60	Barium (Ba)	**DOH GL = 700ug/L** **GWRT:** Feed Max = 150ug/L (>10% of GL) Feed Ave = 109ug/L n = 70		- Increased blood pressure - Increased risk of cardiovascular disease	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <2ug/L LOR = <2ug/L = <10% of GL n = 28	O	Co	2	E	**Low**
61	Cadmium (Cd)	**DOH GL = 2ug/L** **GWRT:** Feed Max = <0.1ug/L (<10% of GL) n = 8		- Kidney damage	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.1ug/L LOR = <0.1ug/L =<10% of GL n = 6	O	Co	2	E	**Low**
62	Cobalt	**DoH GL = 0.001 mg/L** **GWRT:** Feed Max =0.0004 mg/L (>10% of GL) Feed Ave = 0.0002 mg/L n = 8		- Liver or kidney damage	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max =<0.0001ug/L LOR = <0.0001ug/L = <10% of GL n = 6	O	Co	2	E	**Low**
63	Chromium (Cr)	**DOH GL = 0.05mg/L** **GWRT:** Feed Max = 0.001mg/L; <10% of GL Feed Ave = 0.0008mg/L n = 8		- Allergic dermatitis - hexavalent chromium - carcinogenic	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** LOR = <0.0005mg/L= <10% of GL n = 6	O	Co	2	E	**Low**
64	Lead (Pb)	**DOH GL = 0.01mg/L** **GWRT:** Feed Max (Filt.) = 0.0011 mg/L (<10% of GL) Feed Ave (Filt.) = 0.0007 mg/L n = 8 Feed Max (Unfilt.) = 0.0016 mg/L (>10% of GL) Feed Ave (Unfilt.) = 0.0010 mg/L		- Impact on physical and mental development (children) - Impact kidney function - Increased blood pressure	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.0001mg/L LOD = <0.0001mg/L =<10% of GL n = 6	O	Co	2	E	**Low**
65	Mercury (Hg)	**DOH GL = 1ug/L** **GWRT:** Feed Max = <0.1 ug/L (10% of GL) n = 8		- kidney failure at high concentrations - may be carcinogenic - mental disturbances & neurological disorder	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.1ug/L LOR = <0.1ug/L = 10% of GL n = 6	O	Co	2	E	**Low**
66	Nickel (Ni)	**DOH GL = 20ug/L** **GWRT:** Feed Max = 3 ug/L (10% of GL) Feed Ave = 1.5 ug/L n = 8		- kidney & blood disorders at high concentrations	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <1ug/L LOR = <1ug/L = <10% of GL n = 6	O	Co	2	E	**Low**

	HUMAN HEALTH HAZARD ASSESSMENT					INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	**Hazard/Compound**	**Description (GL and feed water concentration)**	**Cause (including background information)**	**Consequence**	**Existing Barriers**	**Consequence**	**Likelihood**	**Risk Level**	**AWRP Barriers**	**Comments re Barrier Effectiveness**	**Control Effectiveness Rating**	**Consequence Rating Basis**	**Consequence**	**Likelihood**	**Risk Level**
	PESTICIDES	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
67	2,4-D	**DOH GL = 30 ug/L** **GWRT:** Feed Max = <0.5ug/L (<10% of GL) n = 27		- kidney and thyroid effects - possibly carcinogenic	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <0.5ug/L LOR = <0.5ug/L = >10% of GL n = 9	O	Co	2	E	**Low**
68	Diuron	**DOH GL = 30 ug/L** **GWRT:** Feed Max = <10 ug/L (>10% of GL) LOR > 10% of Guideline n = 8		Safe Work Australia - Carcinogenic category 3, risk, harmful and dangerous for the environment	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW = 233 **GWRT:** Max = <10ug/L n = 6 DoH satisfied with LOR	A	Co	2	E	**Low**
69	Fenamiphos	**DOH GL = 0.3ug/L** **GWRT:** Feed Max = <0.05ug/L (>10% of GL) n = 8		Safe Work Australia - irritant, risk and dangerous for the environment	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW = 303 **GWRT:** Max = <0.05ug/L LOR = <0.05 = >10% of GL n = 6	A	Co	2	E	**Low**
70	Fluometuron	**DOH GL = 50ug/L** **GWRT:** Feed Max = <10ug/L (>10% of GL) LOR > 10% of Guideline n = 8		Moderately toxic to humans by ingestion and slightly toxic by dermal absorption	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**MW = 232** **GWRT:** Max = <10ug/L n = 6 DoH satisfied with LOR	A	Co	2	E	**Low**
71	Metolachlor	**DOH GL = 300ug/L** **GWRT:** Feed Max = <0.10ug/L (<10% of GL) n = 27		- low oral acute toxicity - at high levels: cramps, convulsions, diarrhoea, liver damage…. - NOT mutagenic or carcinogenic	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW = 284 **GWRT:** Max = <0.1ug/L n=9	A	Co	2	E	**Low**
72	Simazine	**DOH GL = 20ug/L** **GWRT:** Feed Max = 110 ug/L (Above Guideline) Feed Median = 6 ug/L (> 10% of GL) n= 28		- Problems with blood - Possible carcinogen - potential increased risk of ovarian cancer	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	**High**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols Maintain catchment review for simazine	MW = 201 **GWRT:** Max = < 0.1ug/L n = 9	O	Co	2	E	**Low**
73	Thiophanate-methyl	**DOH GL = 5ug/L** **GWRT:** Feed Max = <5ug/L (LOR at Guideline) n = 26 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		- low acute toxicity - growth retardation, liver and thyroid effects - possible human carcinogen, liver tumours - not stable or persistent in the environment	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	**High**	Advanced Treatment (Chloramination, Ultrafiltration (UF), Reverse Osmosis (RO), UV irradiation (UV), Stabilisation (Degas, NaOH)) Process & Control Point monitoring Maintain operational protocols	MW = 342 **GWRT:** Max = <5ug/L LOR = <5ug/L = Guideline n = 8	A	Co	2	D	**Low**
74	Triclopyr	**DOH GL = 10 ug/L** **GWRT:** Feed Max = 4.8 ug/L (>10% of GL) n = 27		- slightly toxic orally - some impacts on reproduction, kidneys	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = <1ug/L n = 9	O	Co	2	E	**Low**
75	Triclosan #	**DoH GL = 0.35ug/L** **GWRT:** Feed Max = <1 ug/L (>10% of GL) Feed Av = <1 ug/L n = 6 LOR = 1ug/L		Triclosan is readily absorbed in humans from food and drinking water. 9% absorption when applied on the skin through consumer products containing triclosan. It is metabolised by the liver. - not considered to be a skin sensitiser or irritant - probable human carcinogen - endocrine disrupter but no effects on reproductive performance were noted	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW=289 **GWRT:** Max = <1 ug/L LOR = 1 ug/L n = 6 NB: DoH currently accept that LOR is sufficiently low to demonstrate safety but require more work to lower LOR with additional monitoring & risk review	O	Co	2	D	**Low**
76	Trifluralin	**DoH GL = 50ug/L** **GWRT:** Feed Max = 0.39ug/L (<10% of GL) Feed Ave = 0.045 ug/L n = 27		- mild effects on liver - low purity Trifluralin may contain nitroso contaminants: mutagenic - little body adsorption, accumulates in fat	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW = 335 **GWRT:** Max = <1ng/L LOR = <1ng/L = <10% of GL n = 9	O	Co	2	D	**Low**
77	Amitraz ^ changed to # over course of GWRT	**DoH GL = 9ug/L** **GWRT - Feed:** Max = <20 ug/L Av = <20 ug/L n = 6 LOR = 20ug/L		Safe Work Australia - harmful, risk and dangerous for the environment	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW = 293 **GWRT:** Max = <20ug/L = <LOR n=6 LOR>GL NB: DoH currently accept that LOR is sufficiently low to demonstrate safety but require more work to lower LOR with additional monitoring & risk review	A	Co	2	D	**Low**

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process				Post AWRP Treatment SCREENING RISK		
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	PESTICIDES	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
78	Chlorantraniliprole ^	**DoH GL = 5500ug/L**		Studies results - exhibits minimal mammalian toxicity after long-term exposure	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate		No analytical methods available, development ongoing under direction of DoH	A	Co	2	D	**Unknown**
79	Flupropanate ^	**DoH GL = 9ug/L**		APVMA - chemical Nominated for Review (Priority 4) - Assessed as having moderate potential to cause harm	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate		No analytical methods available, development ongoing under direction of DoH	A	Co	2	D	**Unknown**
80	Metam sodium (MITC = methylisothiocyanate) ^	**DoH GL = 1.4ug/L** **GWRT - Feed:** Max = <1 ug/L Av = <1 ug/L n = 6		Safe Work Australia - toxic risk, carcinogen and dangerous for the environment for MITC and harmful, risk, carcinogen and harmful for metam sodium	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced treatment	**GWRT:** Max = <1 ug/L n=6	A	Co	2	D	**Low**
81	Polihexanide ^	**DoH GL = 700ug/L**		Potential carcinogen in high concentrations	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate		No analytical methods available, development ongoing under direction of DoH	A	Co	2	D	**Unknown**
82	Pyrasulfotole ^ changed to # over course of GWRT	**DoH GL = 40ug/L** **GWRT - Feed:** Max = <5 ug/L Av = <5 ug/L n = 2		Safe Work Australia - Reproductive risk category 3, harmful and irritant	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced treatment	**GWRT:** Max =< 5ug/L = LOR n=2	A	Co	2	D	**Low**
83	Pyroxsulam ^ changed to # over course of GWRT	**DoH GL = 3500ug/L** **GWRT - Feed:** Max = 1 ug/L Av = <1 ug/L n = 6		Eye, skin and respiratory irritation, and skin sensitisation	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced treatment	**GWRT:** Max =< 1ug/L = LOR n=7	A	Co	2	D	**Low**
84	Spirotetramat ^ changed to # over course of GWRT	**DoH GL = 3500ug/L** **GWRT - Feed:** Max = <1 ug/L Av = <1 ug/L n = 2		Safe Work Australia - Reproductive risk category 3 and irritant	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced treatment	**GWRT:** Max = <1ug/L = LOR n=2	A	Co	2	D	**Low**
85	Terbuthylazine ^ changed to # over course of GWRT	**DoH GL = 10ug/L** **GWRT - Feed:** Max = <1 ug/L Av = <1 ug/L n = 6		Safe Work Australia - harmful	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced treatment	**GWRT:** Max = < 1ug/L = LOR n=6	A	Co	2	D	**Low**
86	Toltrazuril ^ changed to # over course of GWRT	**DoH GL = 4ug/L** **GWRT - Feed:** Max = <100 ug/L Av = <100 ug/L n = 6 LOR = 100ug/L		Damages intracellular development stages	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW = 425 **GWRT:** Max = <100ug/L = <LOR n=6 LOR>GL NB: DoH currently accept that LOR is sufficiently low to demonstrate safety	O	Co	2	D	**Low**

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	VOCs - Volatile	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
87	1,1,2-trichloro-1,2,2-trifluoroethane	**DoH GL = 4000ug/L** **GWRT - Feed:** Max = <1 ug/L Av = <1 ug/L n = 6		Classified as a hazardous substance by Safe Work Australia	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max = 1.3ug/L n=8	A	Co	2	D	Low
88	1,1,2-trichloroethane #	**DoH GL = 0.6 ug/L** **GWRT:** Feed Max = <1ug/L (LOR above GL) n = 12		Liver, kidney or immune system problems	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=133 **GWRT:** Max = <1ug/L LOR Above GL n = 17 NB: DoH satisfied that LOR is	A	Co	2	D	Low
89	1,1-dichloroethane	**DoH GL = 5 ug/L** **GWRT:** Feed Max = <1ug/L (>10% of GL) n = 12		solvent	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	Low	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=99, **GWRT:** Max = <1ug/L LOR >10% of GL n = 17	A	Co	2	D	Low
90	1,2-dichloroethane	**DoH GL = 3 ug/L** **GWRT:** Feed Max = <1ug/L (>10% of GL) n = 12		probable human carcinogen, solvent	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	Low	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=99 **GWRT:** Max = <1ug/L LOR >10% of GL n = 17	A	Co	2	D	Low
91	Dibromomethane	**DoH GL = 0.7ug/L** **GWRT:** Feed Max = <1 n = 17 LOR = 1ug/L		probable human carcinogen, solvent	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 172 **GWRT:** Max = <1ug/L LOR above GL n = 28 NB: DoH accepts 1 ug/L LOR is sufficient to demonstrate safety	A	Co	2	D	Low
92	1,2-dibromoethane #	**DoH GL = 0.4 ug/L** **ADWG= 1ug/L** **GWRT:** Feed Max = <1ug/L (Above GL) n = 12		Safe Work Australia - Carcinogenic category 2, risk, toxic, irritant and dangerous to the envionment	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=188 **GWRT:** Max = <1ug/L LOR Above GL n = 17 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	Low
93	2-propytoluene ^	**DoH GL = 0.7ug/L**		Possible link with pancreatic cancer	Secondary Treatment - Primary - Activated Sludge - Clarification	3	D	Moderate		Incomplete due to time constraints/ higher priorities. Not yet attempted, still need to source analytical standard. DoH satisfied to not develop further.	A	Co	2	D	Unknown
94	4-isopropyltoluene #	**DOH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR above GL) n = 12		May cause skin irritation and be harmful if swallowed	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=134 **GWRT:** Max = <1ug/L LOR Above GL n = 17 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	Low

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	VOCs - Volatile	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
95	Acrylamide	**DoH GL = 0.2 ug/L** **GWRT:** Feed Max = <0.05 ug/L (>10% GL) n = 5		carcinogen	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 71 **GWRT:** Max = <0.05ug/L LOR>10% of GL n = 6	A	Co	2	D	**Low**
96	Benzene	**DoH GL = 1 ug/L** **GWRT:** Feed Max = <1ug/L (LOR at GL) n = 12		Liver, neurological & reproductive effects	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	**High**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 78 **GWRT:** Max = <1ug/L LOR = GL, n = 17 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
97	Bromomethane	**DoH GL = 5 ug/L** **GWRT:** Feed Max = <1ug/L (>10% of GL) n = 12		Neurological effects	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=95 **GWRT:** Max =<1ug/L LOR >10% of GL n = 17	A	Co	2	D	**Low**
98	Carbon tetrachloride	**DoH GL = 3 ug/L** **GWRT:** Feed Max = <1ug/L (>10% of GL) n = 12		affects nervous system, liver, ubiquitous air pollutant	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=154 **GWRT:** Max = <1ug/L LOR >10% of GL n = 17	A	Co	2	D	**Low**
99	Chloroethane #	**DoH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR above GL) n = 12 LOR = 1ug/L		possible carcinogen, effects similar to alcohol	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=64.5 **GWRT:** Max = <1ug/L LOR Above GL n = 17 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
100	Dichlorodifluoromethane	**DoH GL = 700ug/L** **GWRT - Feed:** Max = <1 ug/L Av = <1 ug/L n = 6 LOR = 1 ug/L		Used as an active ingredient in prescription medicines or excipient ingredient for export only for over the counter and prescription medicines, and devices	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max < 1ug/L < LOR n=30	A	Co	2	D	**Low**

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process				Post AWRP Treatment SCREENING RISK		
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	VOCs - Volatile	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
101	Dichloromethane (methylene chloride)	**DOH GL = 4 ug/L** **GWRT:** Feed Max = 4.1ug/L (>10% of GL) Feed Median = 1.6ug/L (>10% of GL) LOR = <1ug/L, > 10% of GL n = 12 Note: ubiquitous in the lab so assigned		Least toxic of the chlorohydrocarbons Volatile - most toxicity studies on inhalation effects - very slightly carcinogenic Metabolised by the body to carbon monoxide	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	**GWRT:** Commissioning max = 12ug/L, Max During recharge = 1.6ug/L Median = <1ug/L n = 15 Note: lab analysis uncertainty	A	Co	2	D	**Low**
102	Hexachlorobutadiene #	**DOH GL = 0.7 ug/L** **GWRT:** Feed Max = <1ug/L (LOR above GL) n = 12 Note: DoH satisfied that LOR is sufficiently low to demonstrate safety		- Kidney Toxicant - Possible Carcinogen	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW = 261 **GWRT:** Max = <1ug/L LOR above GL n = 17 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	**Low**
103	Hexachloroethane ^ changed to # over course of GWRT	**DoH GL = 3ug/L** **Feed Max = No results** **n = No results** **LOR = 1ug/L** Note: As this is a volutile organic, retrospective samples were not able to be analysed as the method was developed towards the end of the Trial.		Considered to be quite toxic by skin adsorption. The primary effect is depression of the central nervous system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	MW= 237 **GWRT:** Max = No results n = No results Note: As this is a volutile organic, retrospective samples were not able to be analysed as the method was developed towards the end of the Trial.	A	Co	2	D	**Unknown**
104	N-butyl benzene	**DoH GL = 7 ug/L** **GWRT:** Feed Max = <1ug/L (>10% of GL) n = 12		Can cause significant irritation	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=134 **GWRT:** Max = <1ug/L LOR >10% of GL n = 17	O	Co	2	D	**Low**
105	tert-butyl benzene	**DoH GL = 7 ug/L** **GWRT:** Feed Max = <1ug/L (>10% of GL) n = 12		May cause gastrointestinal irritation with nausea, vomiting and diarrhea. The toxicological properties of this substance have not been fully investigated	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	**Low**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	MW=134 **GWRT:** Max = <1ug/L LOR>10% of GL n = 17	A	Co	2	D	**Low**
106	Tetrachloroethene (perchloroethylene)	**DOH GL = 50 ug/L** **GWRT:** GWRT Feed Max = <1ug/L (<10% of GL) n = 12		- Depression of central nervous system - Some evidence of liver and Kidney toxicity at higher dose - Possible Carcinogen	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	**Moderate**	Advanced Treatment Process & Control Point monitoring - Degasser Maintain operational protocols	**GWRT:** Max = <1ug/L n = 17	O	Co	2	E	**Low**

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process			Post AWRP Treatment SCREENING RISK			
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	Polycyclic Aromatic Hydrocarbons (PAHs)	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
107	PAHs (total TEQ) #	**DoH GL = 0.01 ug/L (TEQ = 0.01 ug/L)** TEQ from 17 parameters. All <LOR, but LORs such that guideline cannot be shown to be met. TEQ > 0.01 ug/L		- Mutagenic, highly carcinogenic - Primary exposure through smoke, burnt food	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	High	Advanced Treatment Process & Control Point monitoring Operational protocols	MW's = 128-278 All <LOR, TEQ > 0.01 ug/L. No change to TEQ, individual parameters with GLs are low risk, apart from BaP noted below Briefing note with agreement from DoH to assign to < LOR (Doc #8584946)	A	Co	2	D	Low
108	Benzo (a) Pyrene	**DoH GL =0.01ug/L** **GWRT:** Feed Max = <0.1ug/L (LOR at GL level) 2 LORs : 0.1 ug/L and 0.01 ug/L n = 30		- Mutagenic, highly carcinogenic - Primary exposure through smoke, burnt food	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	High	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 252 **GWRT:** Max = <0.1ug/L Median = <0.01 ug/L Note: Variable LOR (0.01 ug/L and 0.1 ug/L) n = 14 (9 x <0.01, 5 x <0.1)	A	Co	2	D	Low
	PHENOLS	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
109	4-cumylphenol #	**DoH GL = 0.35ug/L** **GWRT:** Feed Max = <10ug/L (Above GL) n = 7		No acute toxicity information is available	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW= 212 **GWRT:** Max = < 10ug/L LOR above GL n = 7 NB: DoH currently accept that LOR is sufficiently low to demonstrate safety but require more work to lower LOR with additional monitoring & risk review	U	Co	2	D	Low
110	2-phenylphenol ^ changed to # over course of GWRT	**DoH GL = 20ug/L**		Safe Work Australia - irritant, risk and dangerous for the environment	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max < 1 ug/L < LOR n=7	A	Co	2	D	Low
111	4-nitrophenol	**DoH GL = 30ug/L** **GWRT - Feed:** Max = <1 ug/L Av = <1 ug/L n = 6 LOR = 1 ug/L		Causes headaches, drowsiness, nausea, and cyanosis	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	Low	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max < 1 ug/L < LOR n=8	A	Co	2	D	Low
112	2-nitrophenol #	**DoH GL = 0.7ug/L** **GWRT:** Feed Max = <1ug/L (LOR above GL) n = 8		Moderate toxicity potential	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=139 **GWRT:** Max = <1ug/L LOR above GL n = 6 NB: DoH satisfied that LOR is sufficiently low to demonstrate safety	A	Co	2	D	Low
113	2,6-di-tert-butylphenol ^ changed to # over course of GWRT	**DoH GL = 0.014 ug/L** **GWRT - Feed:** Max = <10 ug/L (LOR > GL) Av = <10 ug/L n = 6 LOR = 10ug/L		May cause liver damage. Causes gastrointestinal tract irritation	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 206 GWRT: Max <10ug/L = LOR n=7 NB: DoH currently accept that LOR is sufficiently low to demonstrate safety but require more work to lower LOR with additional monitoring & risk review					
114	4-tert-octylphenol	**DoH GL = 50 ug/L** **GWRT:** Feed Max = <10ug/L (LOR >10% of GL) n = 7		Safe Work Australia - irritant, risk and dangerous for the environment	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=206 **GWRT:** Max = <10ug/L LOR >10% of GL n = 7	A	Co	2	D	Low

HUMAN HEALTH HAZARD ASSESSMENT						INHERENT RISK Post 2ndry Treated Wastewater Screening			Recycled Water Treatment Process				Post AWRP Treatment SCREENING RISK		
Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	CHELATING AGENTS	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
115	Ethylenediamine Tetraacetic Acid (EDTA)	**DOH GL = 250 ug/L** **GWRT:** Feed Max = 0.62mg/L (Above GL) UF Filtrate Max = 0.65mg/L (Above GL) n = 83		- chelating agent, does not accumulate in the body - can mobilise heavy metals in environment (metal complexing agent) - prevents Zinc adsorption in gastrointestinal tract	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	High	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 292 **GWRT:** Max = <10ug/L LOR <10% n = 34	O	Co	2	E	Low
116	DTPA (diethylenetrinitrilopentaacetic acid)	**DoH GL = 20ug/L** **AGWR GL = 5ug/L** **GWRT:** Feed Max = <2ug/L (<10% of GL) n = 6		- chelating agent - used to clean poisons (including radioactive contamination) from the body	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 393 **GWRT:** Max = <2ug/L LOR <10% of GL n = 6 Post-RO Median =<1.5ug/L (LOD)	O	Co	2	D	Low
117	1,3-Propylenedinitrilotetraacetic Acid (PDTA)	**DoH GL = 20ug/L** **AGWR GL = 0.7ug/L** **GWRT:** Feed Max = 3ug/L (>10% of GL) n = 24		- chelating agent - does not degrade as easily as other chelating agents	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 483 **GWRT:** Max = <1ug/L LOR < 10% of GL n = 6	O	Co	2	D	Low
	PHARMACEUTICALS	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
	Antibiotics														
118	Amoxicillin # ^	**DoH GL = 1.5ug/L** **GWRT:** Feed Max = <1ug/L (LOD >10% of GL) All data < LOR n = 6		Common side effects: Diarrhoea, Nausea, Vomiting, Fatigue. May cause severe allergic reactions	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 419 **GWRT:** Max = <1ug/L LOR >10% of GL n = 6	A	Co	2	E	Low
	Other Pharmaceuticals														
119	Alprazolam ^ changed to # over course of GWRT	**DoH GL = 0.25ug/L** **GWRT:** Feed Max = <0.05ug/L n = 8 LOR = 0.05ug/L		Alprazolam is used to treat anxiety disorders and panic disorder. Serious side effects include shortness or breath and seizures	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=309 **GWRT:** Max = <0.05ug/L n = 6	O	Co	2	E	Low
120	Atorvastatin (Lipitor)	**DoH GL = 5ug/L** **GWRT:** Feed Max = <1.0ug/L (LOR = 10% GL) n = 8 Note: LOR reduced from 1ug/L to 0.5ug/L prior to recharge.		Used to treat high cholesterol. Side effects include muscle soreness and fever	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	[illegible] **GWRT:** Max = <1ug/L LOR = 10% of GL n = 6 LOR reduced from 1ug/L to 0.5ug/L prior to recharge.	O	Co	2	E	Low
121	Diclofenac	**DoH GL = 1.8ug/L** **GWRT:** Feed Max = 0.66ug/L (>10% of GL) Median = 0.34ug/L n = 94		Non-steroidal anti-inflammatory, some damage to kidney at high doses	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 296 **GWRT:** Max = <50ng/L LOR <10% of GL n = 33	O	Co	2	E	Low
122	Isophosphamide ^ changed to # over course of GWRT	**DoH GL = 3.5ug/L** **LOR = 1ug/L**		May cause nausea and vomiting	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max < 1ug/L n =8	A	Co	2	D	Low

Ref	Hazard/Compound	Description (GL and feed water concentration)	Cause (including background information)	Consequence	Existing Barriers	Consequence	Likelihood	Risk Level	AWRP Barriers	Comments re Barrier Effectiveness	Control Effectiveness Rating	Consequence Rating Basis	Consequence	Likelihood	Risk Level
	Iodinated Contrast Media	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
123	Diatrizoic acid (Amidotrizoic acid)	**DoH GL = 360 ug/L** **AGWR GL =0.35ug/L** **GWRT:** Feed Max = <100ug/L (LOR >10% of GL) n = 23 Note: LOR reduced from 100ug/L to 50ug/L prior to recharge.		Iodinated contrast media used for imaging of the kidneys, gastrointestinal & urinary tract	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW = 614 **GWRT:** Max = <50ug/L LOR > 10% of GL n = 6	A	Co	2	E	**Low**
124	Iodipamide	**DoH GL = 540ug/L** **GWRT - Feed:** Max = <50 ug/L Av = <50 ug/L n = 6 LOR = 50 ug/L		Iodinated contrast media used for imaging of the kidneys, gastrointestinal & urinary tract. Serious adverse reactions that include death, convulsions, cerebral hemorrhage, coma, paralysis, arachnoiditis, acute renal failure, cardiac arrest, seizures, rhabdomyolysis, hyperthermia, and brain edema	Secondary Treatment - Primary - Activated Sludge - Clarification	2	D	Low	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** Max <50ug/L = LOR n=7	A	Co	2	D	**Low**
	OTHER ORGANIC CHEMICALS	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
125	Benzidine #	**DoH GL = 0.2ng/L** **GWRT:** Feed Max = <1ug/L (LOR Above GL) n = 8 LOR = 1ug/L		carcinogenic. Used in production of dyes & in test for cyanide & previously blood. Largely withdrawn from use. Biodegradable in soil at low concentrations, also adsorbs particularly at low pH	Secondary Treatment - Primary - Activated Sludge - Clarification	3	C	High	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=184 **GWRT:** Max =<1ug/L LOR above GL n = 6 NB: DoH currently accept that LOR is sufficiently low to demonstrate safety	U	Co	2	D	**Low**
126	Formaldehyde	**DoH GL = 500ug/L** **GWRT:** Feed Max = 98ug/L (>10% of GL) n = 8		Safe Work Australia - Carcinogenic risk category 3, toxic and carcinogen	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=30 **GWRT:** Max =<50ug/L (>10% of GL) n = 10 LOR = 50ug/L (10% of GL)	A	Co	2	D	**Low**
127	Benzotriazole ^	**DoH GL = 20ug/L**		May be toxic to the nervous system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	GWRT: Max < 1ug/L <LOR n= 7 MW = 119	A	Co	2	D	**Low**
128	Tolyltriazole ^ changed to # over course of GWRT	**DoH GL = 20ug/L** **GWRT:** Feed Max = 4.9ug/L (>10% of GL) n = 7		May be toxic to the nervous system	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Operational protocols	MW=133 **GWRT:** Max = <1ug/L <LOR n = 7	A	Co	2	E	**Low**
129	Chlorophene ^	**DoH GL = 0.35ug/L**		Chlorophene is used as a germicide in formulating disinfectant and sanitizer products. End applications include soaps, anionic detergents, cosmetics and aerosol spray products. Some evidence of toxicity	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	No analytical methods available, development ongoing under direction of DoH	A	Co	2	D	**Unknown**
	RADIATION	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
130	Radionuclides - gross alpha particle activity	**DoH GL = 0.5Bq/L = 500mBq/L** Even though both radiation parameters are well below the GL it has been included as they provide the trigger to investigate other radioactive parameters.		Associated with risk of cancer		3	E	Low		GWRT: Max = 40mBq/L n=12	O	Re	3	E	**Low**
131	Radionuclides gross beta particle activity	**DoH GL = 0.5Bq/L = 500mBq/L**		Associated with risk of cancer		3	E	Low		GWRT: Max = 70mBq/L n=12	O	Re	3	E	**Low**
	DIOXINS, FURANS & DIOXIN-LIKE PCBs	**Based on Max concentration in secondary treated wastewater (AWRP feed water)**								**Based on Max In AWRP Product Water**					
132	Dioxins & PCBs	**DoH GL = 16 pg Toxic Equivalence/L** **WWTP:** TEQ ≈ 4 pg/L (All <LOR)		- Reproductive difficulties - Increased risk of cancer	Secondary Treatment - Primary - Activated Sludge - Clarification	2	C	Moderate	Advanced Treatment Process & Control Point monitoring Maintain operational protocols	**GWRT:** TEQ ≈ 4 pg/L	A	Co	2	D	**Low**

Appendix 6: Barrier Risk Assessment

Barrier Failure Assessment						Risk to AWRP INHERENT RISK						Post Mitigation RESIDUAL RISK		
Ref	**Description (Failure mode or process upset)**	**Hazard/Compound**	**End Point**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**INHERENT Risk Level**	**Mitigation**	**Controls**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**RESIDUAL Risk Level**
ACRONYMS: AWRP = Advance Water Recycling Plant; CoC - Chemicals of concern; CCP = Critical Control Point; CIP = Clean in Place; DAFT = Dissolved Air Floatation Tank; DEC = Department of Environment and Conservation; GLV = Guideline Value; IAWG = Inter Agency Working Group; PCT = Process Control Table; PDT = Pressure Decay Test; PLC = Programmable Logic Controller; PST = Primary Sedimentation Tank; RO = Reverse Osmosis; SDI = Silt Density Index; SST = Secondary Sedimentation Tanks; TOC = Total Organic Carbon; TW = Trade waste; UF = Ultra Filtration; WC = Water Corporation; WI = Work Instruction; WWTP = Wastewater Treatment Plant														
A	**Barrier assessment for trade waste in wastewater catchment Risk assignment determined using the Water Corporation Risk Matrix**													
A1	Illegal toxic waste dumping to sewer access chambers results in contamination in recycled water	Potentially dumped: Metals (unlikely) Organics Pesticides Small organics (unlikely) Radioactivity (unlikely)	Soils Human Health	Contamination of product water due to: Increased contaminant load to AWRP, could overload RO. OR dumped chemical not well removed by RO	One elevated TOC event occurred Christmas 2010, possibly from this type of event. Corrective actions occurred (Doc#4364847). One elevated feed Simazine event occurred in April 2010 (~100ug/L but was removed by RO) most likely due to a "dumping" event (Doc #5468002 & 5306236). Sensitivity of the UF filtrate TOC would be unlikely to detect this change in concentration (i.e. 100ug/L change in ~8000ug/L TOC background). But it is a big catchment therefore there is dilution Parameters more likely to be dumped are less likely to pass through treatment	3	C	**High**	CCP and PCTs of WWTP and AWRP (will result in diversion on excessive RO permeate TOC reading) Support periodic review of DEC waste tracking program (will deter people dumping illegally) Implement response & communications protocols during unusual discharge events	PCP: online TOC - pre/post UF CCP: online TOC - post-RO	TOC - Unknown expect Adequate	2	D	**Low**
A2	Illegal toxic dumping to sewer access chambers results in failure of secondary treatment process	Potentially dumped: Metals Organics Pesticides Microbiological	Human Health	Contamination of product water due to reduced efficiency 'Failure' of activated sludge process (loss of nitrification) resulting in inadequately treated AWRP feed water - chemicals, pathogens, suspended solids	Unlikely - big catchment thus dilution Affects digestors (for a couple of months, e.g. toluene), once in 20+ yrs	3	E	**Low**	CCP and PCTs of WWTP and AWRP (will result in diversion on excessive RO permeate TOC reading) Support periodic review of DEC waste tracking program (will deter people dumping illegally) Implement response & communications protocols during unusual discharge event Catchment surveillance procedures Develop & implement AWRP procedures for response to failure of WWTP When WWTP process under-performing, alarms visible & actioned at AWRP	CCP: online Turbidity - AWRP inlet PCP: online DO - WWTP alarmed at AWRP auto-divert PCP: Treatment Capacity CCPs with auto-divert in place PCP: online TOC - pre UF CCP: online TOC - post-RO CCP: on-line Ammonia in AWRP feed	Adequate	2	D	**Low**
A3	Illegal discharge and changes in catchment discharge from fixed connections results in contamination of recycled water	Potentially dumped: Metals Organics Pesticides	Human Health	Contamination of product water	Rare - big catchment thus dilution Parameters more likely to be dumped are less likely to pass through treatment	3	D	**Moderate**	CCP and PCTs of WWTP and AWRP (will result in diversion) Environment scan - changes in catchment discharge (including domestic) Raising awareness of appropriate behaviours (ie tenants) Catchment surveillance procedures Implement response & communications protocols during unusual discharge events Ensure we don't install uncontrolled influent access spots e.g. for Ports in Beenyup catchment (eg, Bennett Ave Coogee for Woodman Pt WWTP) Ongoing communication with trade waste customers who potentially store CoCs (fact sheet).	PCP: online TOC - pre UF CCP: online TOC - post-RO	TOC - Unknown expect Adequate	2	E	**Low**
A4	Illegal discharge from fixed connections results in failure of secondary treatment process	Potentially dumped: Metals Organics Pesticides	Human Health	Contamination of product water Reduced efficiency "failure" of activated sludge process resulting in contamination	Rare - big catchment thus dilution Affects digestors (for a couple of months, e.g. toluene), once in 20+ yrs	3	E	**Low**	CCP and PCTs of WWTP and AWRP (will result in diversion when excessive TOC reading) When WWTP process under-performing, alarms visible & actioned at AWRP Implement response & communications protocols during unusual discharge event Environment scan - changes in catchment discharge (including domestic) Raising awareness of appropriate behaviours (ie tenants) Catchment surveillance procedures Ongoing communication with trade waste customers who potentially store CoCs (fact sheet)	CCP: online Turbidity - AWRP inlet PCP: online DO - WWTP alarmed at AWRP PCP: Treatment Capacity CCPs with auto-divert in place PCP: online TOC - pre UF CCP: online TOC - post-RO CCP: on-line Ammonia in AWRP feed	Adequate	2	E	**Low**

Barrier Failure Assessment						Risk to AWRP INHERENT RISK						Post Mitigation RESIDUAL RISK		
Ref	Description (Failure mode or process upset)	Hazard/Compound	End Point	Consequence	Likelihood	Consequence	Likelihood	INHERENT Risk Level	Mitigation	Controls	Control Effectiveness Rating	Consequence	Likelihood	RESIDUAL Risk Level
ACRONYMS: AWRP = Advance Water Recycling Plant; CoC - Chemicals of concern; CCP = Critical Control Point; CIP = Clean in Place; DAFT = Dissolved Air Floatation Tank; DEC = Department of Environment and Conservation; GLV = Guideline Value; IAWG = Inter Agency Working Group; PCT = Process Control Table; PDT = Pressure Decay Test; PLC = Programmable Logic Controller; PST = Primary Sedimentation Tank; RO = Reverse Osmosis; SDI = Silt Density Index; SST = Secondary Sedimentation Tanks; TOC = Total Organic Carbon; TW = Trade waste; UF = Ultra Filtration; WC = Water Corporation; WI = Work Instruction; WWTP = Wastewater Treatment Plant														
A	**Barrier assessment for trade waste in wastewater catchment** **Risk assignment determined using the Water Corporation Risk Matrix**													
A5	Major industries (managed customers) discharging in excess of TW acceptance criteria impacting product water quality	Potentially discharged: BOD Metals Organics	Human Health	Increased BOD, Contamination	Rare: Few large industries in Beenyup catchment, with well-characterised wastewater & well-defined licencing process	2	E	**Low**	CCP and PCTs of WWTP and AWRP (will result in diversion when excessive TOC reading) When WWTP process under-performing, alarms visible & actioned at AWRP Implement response & communications protocols during unusual discharge event Active surveillance of TW customers Industrial waste licencing criteria met (including chemical acceptance criteria) Embed basic response plans for relevant managed customers	PCP: online TOC - pre UF CCP: online TOC - post-RO	Adequate	2	E	**Low**
A6	Major industries (managed customers) discharging in excess of TW acceptance criteria resulting in WWTP process inefficiency (e.g. process issue in Brownes WWTP)	Potentially discharged: BOD (only current) Possible future: Metals Organics	Human Health	Reduced efficiency of activated sludge process resulting in contamination Increased ammonia levels resulting from higher BOD	Rare: Dependent on operation/efficiency of Industries on-site treatment	2	E	**Low**	CCP and PCTs of WWTP and AWRP (will result in diversion when excessive TOC reading) When WWTP process under-performing, alarms visible & actioned at AWRP Implement response & communications protocols during unusual discharge event Active surveillance of TW customers Industrial waste licencing criteria met Embed basic response plans for relevant managed customers Ongoing communication with trade waste customers who potentially store CoCs (fact sheet)	CCP: online Turbidity - AWRP inlet PCP: online DO - WWTP alarmed at AWRP PCP: Treatment Capacity CCPs with auto-divert in place PCP: online TOC - pre UF CCP: online TOC - post-RO CCP: on-line Ammonia in AWRP feed	Adequate	2	E	**Low**
A7	Major industries (managed customers) discharging an excess of contaminants not covered by criteria impacting product water quality - TW	Organics Pharmaceuticals Hormones VOCs	Human Health	Managed customers discharge unduly adds load to treatment processes for removal of hazards Reputational risks if WC dont understand the wastewater characteristics of businesses discharging to BYP catchment e.g. hospitals	Unlikely as indicated by catchment review Few large industries in Beenyup catchment, with well-characterised WW & well-defined licencing process Only one large hospital within catchment	2	D	**Low**	CCP and PCTs of WWTP and AWRP (will result in diversion) WC procedures in managing TW customers Treatment process (WWTP & AWRP) adequately reduces all hazards to below GLV Reviewed Managed customers wastewater characteristics against agreed water quality parameters (contaminants of concern) Reviewed waste produced by hospitals Ongoing review with managed customers (eg, hospitals) Ongoing communication with trade waste customers who potentially store CoCs (fact sheet)	PCP: online TOC - pre UF CCP: online TOC - post-RO Standard Comms for Big customers - Comms complete and on-going	Optimal	2	E	**Low**
A8	Reputational risk associated with legal discharge from Trade Waste (TW) or non-TW customers who are perceived to have discharges that will contaminate a drinking water source	Anything: Organic chemicals microbiological	Reputational Human Health	Serious reputational risks if WC doesn't understand the types of businesses discharging to BYP catchment	Possible	4	C	**High**	Robust TW management process and access to monitoring data of CoCs Implement "environment scan" procedure for appropriate Water Corp staff and Project partners Including NICNAS reviews, GWR validation outcomes ID'ed customers of concern: eg, hospitals in catchment review All new customers or chemicals get an assessment	Need to have a technical assessment for all discharges that may be 'a concern' Need to be able to communicate on how hospital wastes are handled (details as well - Radiation, pharmaceuticals, infectious pathogens, blood) Update fact sheet on Hospital wastes and distribute to appropriate spokes people.		3	E	**Low**

Barrier Failure Assessment						Risk to AWRP INHERENT RISK						Post Mitigation RESIDUAL RISK		
Ref	Description (Failure mode or process upset)	Hazard/Compound	End Point	Consequence	Likelihood	Consequence	Likelihood	INHERENT Risk Level	Mitigation	Controls	Control Effectiveness Rating	Consequence	Likelihood	RESIDUAL Risk Level
ACRONYMS: AWRP = Advance Water Recycling Plant; CoC - Chemicals of concern; CCP = Critical Control Point; CIP = Clean in Place; DAFT = Dissolved Air Floatation Tank; DEC = Department of Environment and Conservation; GLV = Guideline Value; IAWG = Inter Agency Working Group; PCT = Process Control Table; PDT = Pressure Decay Test; PLC = Programmable Logic Controller; PST = Primary Sedimentation Tank; RO = Reverse Osmosis; SDI = Silt Density Index; SST = Secondary Sedimentation Tanks; TOC = Total Organic Carbon; TW = Trade waste; UF = Ultra Filtration; WC = Water Corporation; WI = Work Instruction; WWTP = Wastewater Treatment Plant														
B	**Barrier assessment for Beenyup WWTP** **Risk assignment determined using the Water Corporation Risk Matrix**													
B1	Failure of plant screening resulting in 'screenings' influent to AWRP	solids (rags)	Infrastructure	Blockage reduced inflow quality - "rags"	Power backup, alarms Screens actually need to be removed to fail, or flow bypass: at inlet or at individual screens WWTP Screens were bypassed in April 2010	2	E	**Low**	AWRP screening prior to membranes Schedule maintenance during summer / periods of low flow Communication between sites when/if screens removed or bypassed to allow more frequent backwashing of AWRP incoming screens Primary treatment can assist in settling and removing rags	Screens at inlet of AWRP CCP: Feed turbidity Pressure differential over screens monitoring	Adequate	2	E	**Low**
B2	Bypass options 1&2: Partial bypass of PST or failure of PST to Aeration Tanks OR Bypass options 3, 4 & 5: Partial bypass of aeration tanks affecting secondary wastewater quality (see Bypass Options flow chart, Doc#1776113)	solids (rags) chemicals	Infrastructure Human Health	Poor secondary WW quality	More likely in winter, 30mins possible during high flow period wet weather AND during construction works No secondary bypass in 2012	3	C	**High**	Monitoring and operating to Beenyup and AWRP CCPs and PCTs Comms link between AWRP & WWTP during Bypass Calibrated level indicator in primary effluent channel Improve Primary Effluent Discharge Channel capacity to minimise secondary treatment bypass - end 2013 Locate offtake for GWR upstream of secondary process bypass (mitigates full bypass only) AWRP screening	CCPs for WWTP identified in WWTP & GWRT PCTs: WWTP CCP: DO; PCP: suspended solids; AWRP CCP: influent turbidity AWRP PCP: online DO AWRP PCP: <=1 WWTP secondary tank offline at any one time, or shut down AWRP	Optimal	1	E	**Low**
B3	Loss of nitrification for long enough periods in activated sludge process	Ammonium	Plants Human Health	Toxicity (45 mg/L, upper band limit) (This is the upper limit for raw WW) Increased biofouling within AWRP (i.e.membranes)	Major cause is loss of power or blowers and loss of nitrifying bacteria population	3	D	**Moderate**	AWRP treatment	AWRP CCP: turbidity, online ammonia (very accurate and reliable)	Adequate	2	E	**Low**
									Installation of on-line ammonia analyser at AWRP inlet Monitoring CCPs in WWTP in Beenyup WWTP PCT Monitoring CCPs in WWTP in AWRP PCT (including ammonia) Automated Diversion - pre AWRP on low DO only, high ammonia and turbidity Comms link & protocol between AWRP & WWTP Continuous monitoring of water quality (not composite sample)	CCPs for WWTP identified in WWTP & GWR PCTs WWTP - CCP: DO with divert; PCP: suspended solids AWRP CCP: influent turbidity, on-line ammonia AWRP PCP: online DO RO working as defined by: CCP: online conductivity, TOC	Optimal	1	E	**Low**
B4	Loss of healthy microbiological community (aeration) in activated sludge process	pharmaceuticals & trace organics microbiological	Human Health	Contamination - higher feed concs into AWRP (Nitrification/denitrification process provides a bio-monitor on feed water quality - marker for source control issues)	Major cause is loss of power or blowers and loss of nitrifying bacteria population	3	D	**Moderate**	Monitoring and operating to CCPs in WWTP in Beenyup WWTP PCT (Doc#614274) Monitoring and operating to CCPs in WWTP in AWRP PCT TOC online monitoring at AWRP Diffusers on regular replacement program	WWTP CCP: DO, alarmed as PCP at AWRP and auto diversion AWRP CCP: on-line ammonia - AWRP inlet AWRP PCP: online DO RO working as defined by: CCP: online conductivity, TOC on permeate	Optimal	1	E	**Low**
B5	Overloading of treatment tanks (Aeration and/or Secondary SSTs) during maintenance	pharmaceuticals & trace organics microbiological	Human Health	Contamination through insufficient treatment	Likely (however during planned maintenance only one tank taken offline at a time)	3	B	**High**	Online monitoring at AWRP (ammonia) PCT specifies CCP of <=1 WWTP tank offline at any one time, or shut down AWRP Effective comms WI between sites	AWRP CCP: online Turbidity, ammonia - AWRP inlet AWRP PCP: online TOC - pre UF and online DO CCP: online TOC - post-RO WWTP CCP: on-line DO measurement in aeration tanks and	Adequate	1	E	**Low**

Barrier Failure Assessment						Risk to AWRP INHERENT RISK						Post Mitigation RESIDUAL RISK		
Ref	**Description (Failure mode or process upset)**	**Hazard/Compound**	**End Point**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**INHERENT Risk Level**	**Mitigation**	**Controls**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**RESIDUAL Risk Level**
ACRONYMS: AWRP = Advance Water Recycling Plant; CoC - Chemicals of concern; CCP = Critical Control Point; CIP = Clean in Place; DAFT = Dissolved Air Floatation Tank; DEC = Department of Environment and Conservation; GLV = Guideline Value; IAWG = Inter Agency Working Group; PCT = Process Control Table; PDT = Pressure Decay Test; PLC = Programmable Logic Controller; PST = Primary Sedimentation Tank; RO = Reverse Osmosis; SDI = Silt Density Index; SST = Secondary Sedimentation Tanks; TOC = Total Organic Carbon; TW = Trade waste; UF = Ultra Filtration; WC = Water Corporation; WI = Work Instruction; WWTP = Wastewater Treatment Plant														
B	**Barrier assessment for Beenyup WWTP Risk assignment determined using the Water Corporation Risk Matrix**													
B6	Power failure impact on activated sludge treatment - no backup power	Phosphorus	(Human Health) Environment Infrastructure	Loss of nitrification/ denitrification Significant P release that can cause membrane scaling - primarily an Infrastructure risk	8hrs blackout max to date, Possible but usually short <10mins, 3-4x per year No major power failures in past year but partial failure resulted in GWRT incident in March 2012 Need to consider power maintenance as well	3	C	**High**	AWRP will be shutdown during power failure If partial failure CCP of online ammonia will pick up DO issue On re-start: Pump to waste and monitor inlet S1 (AWRP Turbidity + ammonia & WWTP DO) initially following power failure WI (for AWRP) to indicate procedure following a power failure. Specific to time (i.e. >6hrs to ensure feed water has had full WW treatment & hydraulic retention time in WWTP & protecting against chem/micro hazards) Use TOC in AWRP to confirm if have started too early	WWTP CCP: online DO on WWTP aeration tanks AWRP CCP: online ammonia and TOC (post-RO) AWRP PCP: online TOC - pre UF and online DO Time (monitoring & control process to be defined - manual or automatic)	Adequate	3	E	**Low**
B7	Blower failure	solids (infrastructure)	Human Health Environment	Loss of nitrification	Have 5, can have max 2 out at one time, need min of 3 blowers for sufficient aeration during daily peak flow	3	C	**High**	Implement AWRP procedures for response to failure of WWTP Online DO interlock and ammonia alarm for AWRP operators	WWTP CCP DO alarm visible at AWRP plant and interlock in place Online NH3 diversion	Optimal	1	E	**Low**
B8	Solids carried over from secondary sedimentation tanks (Clarifiers upset)	solids chemicals microbiological	Human Health Infrastructure	Contamination - solids carry over	Clarifier upset: 2 - 3 day turbidity increase in inflow, at least 15x per year = 12% of time Reduced frequency for 2009/10 ~ 6x per year this last year Reduced frequency and duration for 2010/11 (2-6hrs)	2	A	**High**	Operate WWTP in accordance with WWTP PCT (Aqua#614274) Continuous turbidity & ammonia monitoring of AWRP feed: CCP resulting in auto AWRP bypass PCT specifies CCP of <=1 WWTP SST offline at any one time, or shut down AWRP	SVI & Solids loading weekly on Secondary WWTP PCT AWRP CCP: online Turbidity - AWRP inlet PCP: online TOC - pre UF CCP: online TOC - post-RO	Optimal	1	D	**Low**
B9	Poor quality feedwater from centrifuges and/or DAF tanks causing overload	Metals Organics Nutrients Pesticides Solids	Human Health	Contamination of feed water to AWRP	Occurs very infrequently Fines removed in secondary treatment	2	C	**Moderate**	WWTP and sludge handling to operate to PCT AWRP to operate to the PCT (turbidity & ammonia monitoring on influent and TOC on RO) Monitor quality of centrate and DAFT underflow on a scheduled basis (weekly) Potential separate discharge to outfall	AWRP CCP: online Turbidity, online ammonia - AWRP inlet PCP: online TOC - pre UF CCP: online TOC - post-RO WWTP CCP: on-line DO measurement in aeration tanks, ammonia in aeration tanks	Optimal	1	E	**Low**
B10	Skimmings carried over from PSTs and passed through secondary treatment process	Oil and Grease	Infrastructure	Damage to UF	Unlikely Bulk oil & grease will be removed by PSTs and inlet screens, remainder will be well treated by secondary treatment process Skimming scraper breakdown, inadequate removal of new SSTs (no scrapers)	2	D	**Low**	Design of AWRP sufficient, Oil & grease removed in PSTs (skimmings scrapers), SSTs (foam harvesters) & not taken up by AWRP influent pumps Submerged pump in AWRP wet well (oil & grease float)	Not required	Optimal	2	E	**Low**
B11	Contamination of WWTP influent by AWRP reject - including backflush water, RO concentrate,-water treatment byproducts, purge water & bypass at feed	Chemicals	WWTP	Microbiological treatment processes - digestion, activated sludge, settleability of solids Hydraulic load (particularly of bypass) overloads WWTP	Unlikely as all reject will go to outfall for future plants, Assess through Reject water monitoring Experience indicates no issues over last 30 months Biocide (DBNPA) due to be used on ROs in 12/13FY	2	E	**Low**	AWRP reject water will be directed to a neutralisation tank for treatment prior to discharge to ocean outfall (meeting DEC licence)	Not relevant under planned design	Optimal	2	E	**Low**
B12	Sludge treatment interruptions causes overloading Primary tanks and potential to impact secondary treatment	solids	Human Health	Overloading primary and carrying over to secondary treatment increasing solids loading - lack of wasting of Activated Sludge for 2 days would cause solids carry over	Problem occurred during commissioning upgraded sludge treatment system Have not had an issue since system was fully commissioned	2	D	**Low**	AWRP Turbidity & WWTP DO monitoring as PCPs WWTP-AWRP Communications protocol on events in WWTP (on DO exceedance and early warning) Auto diversion on DO PCP for AWRP	AWRP CCP: Turbidity AWRP PCP: online DO Overloading aeration tanks mitigations WWTP CCP: DO	Optimal	2	E	**Low**
B13	Upgrade of WWTP resulting in reduced secondary treatment capacity	Organics and solids	Human Health	WWTP effluent of lower quality	Upgrade of aeration tanks 16 and 17 will result in 25% reduction in secondary treatment capacity for up to 2 months. This work may start in 2014	1	C	**Low**	AWRP plant not in operation when influent does not meet quality requirements (monitored by ammonia, turbidity and DO)	CCP: online Turbidity, online ammonia- AWRP inlet, online TOC - post-RO PCP: online TOC - pre UF and online DO WWTP CCP: on-line DO measurement in aeration tanks and automatic diversion	Optimal	1	C	**Low**

Barrier Failure Assessment						Risk to AWRP INHERENT RISK						Post Mitigation RESIDUAL RISK		
Ref	Description (Failure mode or process upset)	Hazard/Compound	End Point	Consequence	Likelihood	Consequence	Likelihood	INHERENT Risk Level	Mitigation	Controls	Control Effectiveness Rating	Consequence	Likelihood	RESIDUAL Risk Level
ACRONYMS: AWRP = Advance Water Recycling Plant; CoC - Chemicals of concern; CCP = Critical Control Point; CIP = Clean in Place; DAFT = Dissolved Air Floatation Tank; DEC = Department of Environment and Conservation; GLV = Guideline Value; IAWG = Inter Agency Working Group; PCT = Process Control Table; PDT = Pressure Decay Test; PLC = Programmable Logic Controller; PST = Primary Sedimentation Tank; RO = Reverse Osmosis; SDI = Silt Density Index; SST = Secondary Sedimentation Tanks; TOC = Total Organic Carbon; TW = Trade waste; UF = Ultra Filtration; WC = Water Corporation; WI = Work Instruction; WWTP = Wastewater Treatment Plant														
C	Barrier assessment for GWRT AWRP Risk assignment determined using the Water Corporation Risk Matrix													
C1	RO membrane degradation - Accellerated biofouling through loss of chloramination (hypo dosing failure)	Microbiological (biofouling leading to membrane damage)	Infrastructure	Biological fouling of membranes Chloramination not designed for pathogen removal Biofouling of membranes observed - long term (days) loss of chloramination causes irreversible fouling	Hypo dosing failure is possible	2	C	Moderate	Interlock to stop raw water pumping if hypochlorite dosing ceases Only running membranes on hypo-dosed water: Membrane treatment will stop when dosing stops & water in feed tank runs out Design for finely controlled hypo dosing pumps Duty-standby on dosing system (I.e. redundancy) Chloramine online analysers - with frequent maintenance & lab verification Maintenance servicing of dosing system	Interlock on hypo dosing system chloramine analyser on RO feed	Optimal	2	D	Low
C2	Ultra Filtration Membrane degradation - damage or loss of membrane integrity (fibres or seals broken)	solids Organic chemicals Microbiological	Human Health	Contamination (loss of LRV for pathogens)	Due to: - Process malfunction - PDT process failure blowers, air process - chemical attack (all membranes at once) - CIP/ MW strength, etc - wear and tear (lifetime) (only observed cause - hard shell amoebae) - Defects (slippy fibres)	4	C	High	Pressure integrity testing (PDT daily) - PDT is used to verify the integrity of the UF membranes On-line analysers and CCP - filtrate turbidity Instrument calibration - high priority with Maintenance supplier & Ops Monitor delta pressure & flow across membranes (includes alarms) Clean in place, Maintenance washes daily, back-washes Backwash sequence to prevent back pressure on membranes SDI tests done weekly on RO feed - also confirms suitable UF operation (online turbidity better indication)	On-line analysers: interlocks CCP: turbidity Instrument calibration Pressure integrity testing (PDT daily) & system inspection Monitor delta pressure across membranes (alarms with action)	Optimal	2	E	Low
C3	RO membrane degradation - damage or loss of membrane integrity (membrane or seals damaged)	Organic chemicals Microbiological	Human Health	Contamination Loss of micro LRV	Due to: - Back pressure surge (happened in GWRT commissioning) - oxidative attack - irreversible fouling (chemical or biological) - instrument malfunction - wear & tear - CIP chemicals (e.g. caustic)	4	C	High	Auto RO shutdown or divert on limit exceedance of CCPs and PCT (pre or post-RO) (i.e. correct UF operation & RO operation required to pass water on to UV) Online meters & alarms identifying adequate treatment: conductivity, TOC, Online salt passage Instruments protecting RO (feed): pH, ORP (RO feed will be automated on alarm to prevent Cl2 oxn), monoCl, filtrate turbidity Instrument calibration Antiscalant dosing and pH correction (sulphuric acid) Manual SDI check (weekly) of RO feed water Clean in Place (CIP) High pressure safegards inplace (normal operation & CIPs); CIP discharge pump pressure; RO cartridge filt DP; bursting discs; CIP valve sequencing; DP across stages/trains (alarmed) Use vessel probing/profiling to manage membrane integrity (including membrane mapping) Use pH and ORP to investigate whether UF CIP solution is passing onto RO - extra UF flush to prevent this Suitable CIP procedures to prevent CIP solution entering treated water Effective CIP system, e.g. CIP heating, biocide	Online meters & alarms: CCPs: conductivity, TOC, (autodivert if outside criteria) Feed interlocks (auto-diverts): pH, ORP, monochloramine, Turbidity Monitor delta pressure across stage 1 & 2 membranes (alarms & interlocks)	Optimal	2	E	Low
C4	UV effectiveness reduced	Microbiological	Human Health	Loss of barrier (loss of virus LRV)	Effectiveness due to film buildup; lamp failure Note: 7 minutes lag time for effective treatment after GWRT start up	4	C	High	Use WC Corporate design standard Online monitoring of UV intensity (indicates film or scaling), power and flow with alarms Maintenance - regular cleaning program in place with standards recommended by manufactures and sensor cleaning Chloramine, UF, RO operation Transmissivity weekly monitoring	CCP - continuous monitoring of UV intensity, flow	Optimal	2	D	Low

Barrier Failure Assessment						Risk to AWRP INHERENT RISK						Post Mitigation RESIDUAL RISK		
Ref	Description (Failure mode or process upset)	Hazard/Compound	End Point	Consequence	Likelihood	Consequence	Likelihood	INHERENT Risk Level	Mitigation	Controls	Control Effectiveness Rating	Consequence	Likelihood	RESIDUAL Risk Level
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C	**Barrier assessment for GWRT AWRP** **Risk assignment determined using the Water Corporation Risk Matrix**													
C5	Discharging AWRP reject stream to ocean outlet - neutralisation treatment tank fails	Organic chemicals Microbiological	Human Health Environment	Discharge of effluent that breaches DEC licence	Unlikely to affect ocean outfall until using full flow of Beenyup	2	D	Low	AWRP PCT Alarm on neutralisation treatment tank Dilution in WWTP final effluent that will not have an impact on human health or environment	Unnecessary for 14GL plant	Adequate	1	D	Low
C6	Impact on UV effectiveness if degassing is removed to address aquifer buffering	Microbiological	Human Health	UV effectiveness reduced	Unlikely	2	D	Low	Current plan to design is to include degassing in AWRP treatment train Only need to consider if degassing is not included in design but AWRP CCPs and PCT will cover	AWRP CCPs and PCT		1	D	Low
C7	Monitoring system integrity failure due to: - Inadequate calibration program of monitoring devices or PLC issues or monitoring instruments not reinstalled after maintenance	TOC, conductivity, turbidity, pH	Infrastructure Human Health Plants	destroy membranes recharging out of spec water NB: Uncertainty causing major inconvenience, regulatory risk (causing shutdown) but not actual risk necessarily	Likely, need to plan for it - i.e. a robust maintenance & calibration program required for all instruments e.g. TOC instrument GWRT incident pH analyser March 2012 and TOC analyser August 2012	3	B	High	Design for shutdown for appropriate failures Appropriate calibration program - Monitored by Ops/Plant Manager Instrument verification/management required Effective use and management of PLC programme version control (Regularly backup and prior to any modification) Audit procedures Appropriate maintenance program with sufficient spares Critical control points to manage redundancy issues WWTP DO probe calibration process includes regular accuracy check - 3x weekly Instrumentation appropriately commissioned including alert and violation limits	Shutdown on CCP instrument or Communications failures except for PDT reading faulty - this now usually fixed Approval of PCT Management System QA/QC Process	Optimal	3	E	Low
C8	Re-introduction of solids post-RO causing clogging of recharge bore	Clogging of bore-aquifer interface due to solids introduction post-RO	Physical clogging of injection bore	Clogging of bore aquifer interface	Rare: only treatments post-RO are: UV disinfection, degassing, and NaOH dosing	2	D	Low	Limited opportunity for solids introduction in treatment process post-RO. Strainer on NaOH dosing line Manual daily turbidity sampling of product water at headworks Degasser filters checked for integrity	Strainers of NaOH dosing line Operations Protocol: manual sampling post-tank pre-injection bore - on commencement of recharge	Optimal	2	E	Low
C9	Contamination of product water post treatment (product water tank, pipework, pumps)	chemical, microbiological	Human health	Borefield contamination	Rare: Not seen to date	3	D	Moderate	Maintenance procedures to ensure lines are flushed after maintenance Approved chemical suppliers Procurement/ contract process ensures quality suppliers (Same as for Drinking Water) Lines and bore headworks are flushed Monitoring program to be developed		Optimal	2	E	Low
C10	Cross contamination between WWTP and AWRP and recharge bore - maintenance - sampling	microbiological	Human Health	Sample contamination giving false positive results Confusion & uncertainty, Loss of credibility	Use of common tools Insufficient QA on sampling	2	C	Moderate	Operator training, culture, adequate procedures including: Maintenance protocols in WI Disposable items are changed (e.g. gloves) and tools disinfected QA/QC for sampling including change of gloves, sampling order (clean to dirty)	Management System QA/QC Process, Work Instructions (#?) Maintenance Plan	Adequate	2	E	Low

Barrier Failure Assessment						Risk to AWRP INHERENT RISK						Post Mitigation RESIDUAL RISK		
Ref	Description (Failure mode or process upset)	Hazard/Compound	End Point	Consequence	Likelihood	Consequence	Likelihood	INHERENT Risk Level	Mitigation	Controls	Control Effectiveness Rating	Consequence	Likelihood	RESIDUAL Risk Level
ACRONYMS: AWRP = Advance Water Recycling Plant; CoC - Chemicals of concern; CCP = Critical Control Point; CIP = Clean in Place; DAFT = Dissolved Air Floatation Tank; DEC = Department of Environment and Conservation; GLV = Guideline Value; IAWG = Inter Agency Working Group; PCT = Process Control Table; PDT = Pressure Decay Test; PLC = Programmable Logic Controller; PST = Primary Sedimentation Tank; RO = Reverse Osmosis; SDI = Silt Density Index; SST = Secondary Sedimentation Tanks; TOC = Total Organic Carbon; TW = Trade waste; UF = Ultra Filtration; WC = Water Corporation; WI = Work Instruction; WWTP = Wastewater Treatment Plant														
C	Barrier assessment for GWRT AWRP Risk assignment determined using the Water Corporation Risk Matrix													
C11	Misalignment of WWTP upgrade/maintenance & secondary treatment operations with AWRP	Organics and solids	Infrastructure	Out of spec influent Project Risk - get a failure/shutdown of AWRP Delays, reputation	Most likely during daily peak flow	2	C	Moderate	WWTP and AWRP PCTs Regular communication between AWRP Ops and Beenyup Ops team during Operation GWRT Ops, WWTP Ops liaison meetings Ensure any large maintenance items picked up in Comms between GWR Ops & WWTP Ops Outside working hours Ops Centre monitors CCP ammonia and turbidity	Not applicable	Adequate	2	D	Low
C12	Failure of Beenyup Ops to acknowledge AWRP & change operational procedures accordingly	Project Risk	Project Risk	Inability to run AWRP smoothly	Note that Operations relationships	3	E	Low	Regular communication between Beenyup operators and AWRP Ops - meetings Cultural change from running an effective ocean discharge WWTP to a drinking water production plant All Operators AWRP & WWTP co-located for enhanced communication Rotate WWTP staff into AWRP to encourage Communication	Not applicable	Unknown	3	E	Low
C13	Communications between WWTP and AWRP operating systems - WWTP Citech, new AWRP will be SCADA/SCX6	System failure	Infrastructure Human Health	destroy membranes recharging out of spec water NB: Uncertainty causing major inconvenience, regulatory risk (causing shutdown) but not actual risk necessarily	Possible because upgrade of WWTP operating system not planned for short-medium term	2	C	Moderate	AWRP PCT Design for shutdown for appropriate failures Appropriate calibration and maintenance programs for all instruments (including spares) Instrument verification/management required ongoing (look for partial failures) Effective use and management of PLC programme version control (Regular backup and prior to any modifications) Critical control points to manage redundancy issues WWTP DO probe calibration process includes regular accuracy check - 3x weekly	Shutdown on CCP instrument or Communications failures Approval of PCT Management System QA/QC Process	Optimal	3	E	Low

Appendix 7: Process Control Tables for Beenyup WWTP and GWRT

WATER CORPORATION ABN 28 003 434 917 Doc ID 614274	***BEENYUP*** ***WASTEWATER TREATMENT PLANT*** ***Preliminary & Primary Treatment Process Control Table***	**Version Date** 23/06/2012 **Next Review Date** 23/08/2013	**Custodian** *Manager, Wastewater Process Expertise* **Accountabilities Framework** Level 1 – Manage Wastewater Quality Level 2 – Manage WWQ System Analysis and Operations

Endorsement

This Wastewater Treatment Process Control Table is endorsed for implementation.

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Process	Asset	Monitoring point	Functional Location Number	Parameter	WWQMS Sample Group		Frequency	Target/Limits	Alert Limit Low	Alert Limit High	Violation Limit Low	Violation Limit High	Corrective actions	Reference
Preliminary Treatment	Screening and Grit Plant Post Grit Liquid Waste Tanker Receiving Facility 2, 3Primary Sedimentation Tanks (PSTs)1	Step Screens		Mod 1&2 (Step Screens 1-3) Flow				Average: <868 L/s Peak: <1910 L/s Design Capacity: 800 L/s/screen (2duty, 1 standby)					Check and adjust flow splitting.	PM-#2893291-Beenyup WWTP - Operating Manual Pre-treatment
				Mod 3&4 (Step Screens 4,5) Flow				Average: <868 L/s Peak: <1910 L/s Design Capacity: 1500 L/s/screen (1 duty, 1 standby)					Check and adjust flow splitting.	PM-#2893291-Beenyup WWTP - Operating Manual Pre-treatment
		Grit Tanks		Mod 1&2 (Grit Tanks 1-4) Capacity				208 L/s/tank (3duty, 1 standby)						PM-#2893291-Beenyup WWTP - Operating Manual Pre-treatment
				Mod 3&4 (Grit Tanks 5-8) Capacity				417 L/s/tank (3duty, 1 standby)						PM-#2893291-Beenyup WWTP - Operating Manual Pre-treatment
		Grit Washer		Grit Washer 1 Capacity				15 L/sec						
				Grit Washer 2 (New) Capacity				30 L/sec						
		Grit (SP Beenyup WWTP De-watered Grit)	S1001127	Moisture	-	IL	Monthly	<10 %					Investigate possible causes. Potential causes include: - solids loading too high - grit removal time is too long (reset the times)	PM-#2893291-Beenyup WWTP - Operating Manual Pre-treatment
				Total Organic Carbon	-	IL	Monthly	5 %					Investigate possible causes. Potential causes include: - insufficient upflow - upflow distributing unit is clogged - solenoid valve problem - peaks of high solids - impulse time of grit removal screw is too long - grit removal time is too long (reset the times)	PM-#2893291-Beenyup WWTP - Operating Manual Pre-treatment
		Sample Point - Raw Influent	S1001081	pH	Ops	IL	Daily	6.5-8.0	6.5	8.0	-	-	Report variations > 15% to the plant manager. Investigate possible cause of high influent concentrations with Trade Waste Officer or Industrial Waste. If variation outside the range or a trend of concern occurs, contact the Process Specialist.	Typical levels for influent. S100 – Standards for Wastewater Monitoring. WWTP Operations Analytical Schedule ** Loaded to external lab as individual analyte. Alert Limits based on ±15% approx
				Suspended Solids (SS)				290-350 mg/L	240	400	-	-		
				BOD			Weekly	290-350 mg/L	240	400	-	-		
				Kjeldahl Nitrogen (TKN)				60~75 mg/L	50	90	-	-		
				Ammonium-N (NH_4^+-N)				40~55 mg/L	30	70	-	-		
				Total Nitrogen (TN)				60~75 mg/L	50	90	-	-		
				Total Phosphorus (TP)				10~15 mg/L	5	20	-	-		
				COD			2 - weekly	600-750 mg/L	500	850	-	-		

Process	Asset Screening and Grit Plant	Monitoring point	Functional Location Number	Parameter	WWQMS Sample Group		Frequency	Target/Limits	Alert Limit		Violation Limit		Corrective actions	Reference
									Low	High	Low	High		
				Metals (As, Cd, Cr, Cu, Pb, Hg, Ni, Se, CN, Zn)		M1	Quarterly	Record	-	-	-	-		
				Sulphate		**		Record	-	-	-	-		
				Oil and Grease		PC5		Record	-	-	-	-		
		Tanker		Volume			Each Delivery	m3						
Primary Treatment		Module 1 (PST 2-4) Module 2 (PST 5-8) Module 3 (PST 9, 10)		Flow -Mod 1&2 (PSTs 2-8)				Ave.: <11ML/d/tank Peak: <17 ML/d/tank Design, Average2: 14 ML/d/tank Design Peak2: 22.4 ML/d/tank (TBC)						W2WA Basis of Design Memorandum (50/50 flow split between Mod 1&2 and Mod 3 and based on inflow of 150 ML/d)
				Flow - Mod 3 (PSTs 9 & 10)				Ave.: <38 ML/d/tank Peak: <60 ML/d/tank Design, Average2: 35.4 ML/d/tank Design Peak2: 56.7 ML/d/tank (TBC)						W2WA Basis of Design Memorandum (50/50 flow split between Mod 1&2 and Mod 3 and based on inflow of 150 ML/d)
		Primary Influent		Settling Test			Weekly	5 – 25 mL/L		25				Target and Alert values to be reviewed at next PCT review.
				Sludge Blanket Level (Mod 1&2)										Sludge blanket level is required by S100 but cannot currently be determined.
				Sludge Blanket Level (Mod 3)										
				2, 4Surface loading rate (Mod 1&2)			Weekly	Average:31 m3/m2/d Peak:49.6 m3/m2/d Design:41 m3/m2/d		41			Check totalised flow into plant	Beenyup Pre-Primary Basis of design Memorandum; O&M Manual ** No flow meter available to determine individual Loading rates**
				2, 4Surface loading rate (Mod 3)			Weekly	Average:43 m3/m2/d Peak:68.8 m3/m2/d Design:41 m3/m2/d		43				
				2, 4Detention time (Mod 1&2)			Weekly	Average: >1.9 h Design: 1.5 h	1.5				Check totalised flow into plant	Beenyup Pre-Primary Basis of design Memorandum ** No flow meter available to determine individual detention times **
				2, 4Detention time (Mod 3)			Weekly	Average: >1.9 h Design: 1.5 h						
		Auto Sampler - Primary Effluent	S1001082	pH	Ops	IL	Daily	7.5-8.0	7.0	8.0	-	-		Metcalf & Eddy (Chap 7.9) Optimal nitrification rates at pH 7.5~8.0 SS: 60% removal BOD: 40% removal Nutrient levels in Primary Effluent should be similar to Raw Wastewater. Alert Limits based on ±15% approx.
				Suspended Solids (SS)	Ops	IL	Daily	<140 mg/L	-	170	-	-		
				BOD	Ops	IL	Weekly	170~240 mg/L	-	280	-	-		
				COD	Ops	IL	2 - Weekly	300~500 mg/L	-	600	-	-		
				Kjeldahl Nitrogen (TKN)	Ops	IL	Weekly	60~75 mg/L	-	90	-	-		
				Ammonium (NH4+-N)	Ops	IL	Weekly	40~55 mg/L	-	65	-	-		
				Total Nitrogen (TN)	Ops	IL	Weekly	60~75 mg/L	-	90	-	-		
				Total Phosphorus (TP)	Ops	IL		10~15 mg/L	-	20	-	-		
				Alkalinity as CaCO3	Ops	IL		>280mg/L	280	-	-	-		
				Settling Test (Effluent)	Ops	IL		<0.2 mL/L		0.5				

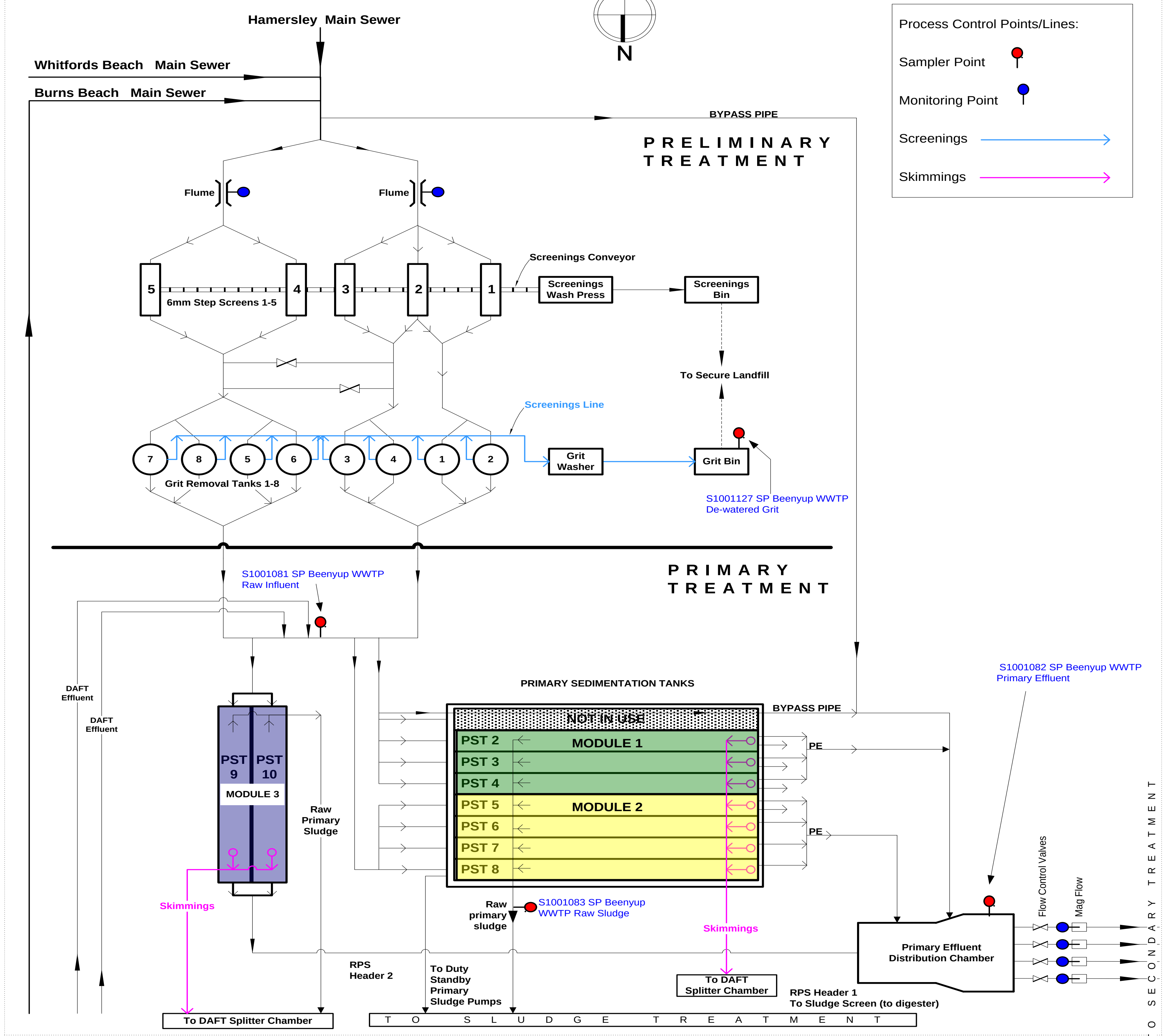
Process	**Asset** Screening and Grit Plant	**Monitoring point**	**Functional Location Number**	**Parameter**	**WWQMS Sample Group**		**Frequency**	**Target/Limits**	**Alert Limit** Low	High	**Violation Limit** Low	High	**Corrective actions**	**Reference**
		Primary Sludge	S1001083 Primary Raw Sludge	% Total Solids		IL	2/Week	3 – 4 % w/v	3.0%	4.5%			Adjust raw sludge removal rates to achieve nominal value within target range.	O&M Manual 2005, PST, Chapter 12 Module 1&2 : 1duty 1 standby pumps servicing PST 3~6, (when PST 2,7, 8 are online, current pump will service PST2~5; new pumps duty standby will service PST 6,7,8) Module 3: 1 designated pump for each PST Current sludge draw-off based on %total solids. Increase pumping when %total solids>4%. Sampling conducted from a single tank. Tank selected on an ad-hoc basis.
				% Volatile Solids		IL	2/Week	> 85 %						
				Primary Raw Sludge Production (Mass Load) (m^3/d)			Daily	See Form 007					Check % of total solids of Raw Sludge to determine Solids Removal Rate	O&M Manual PST Volume 3 Chapter 6 Form 007 PM-#2263600 To be updated once works completed in 2010.
				Primary Raw Sludge Production (Flow rate) (average)			Daily	See Form 006					Check current flows against long term targets.	Based on 3.7% Total Solids Form 006 PM-#2263586 To be updated once works completed in 2010.
				Raw sludge Pump Capacity/ Rate- Max (Modules 1 & 2)			Daily	8 L/s	6 L/s	8 L/s			Check sludge scrapers are operational Check raw sludge draw off valves are operating correctly Check raw sludge pumps Check % total solids of raw sludge	Form 007 PM-#2263600
				Raw sludge Pump Capacity/ Rate- Max (Module 3)			Daily	11 L/s	9 L/s	11L/s				
				% Solids Removal			Weekly	40~60%					Check raw sludge pumps and skimmings removal	

Ops – Operational Requirement *Reg – Regulatory Requirement* *Alert Limits – Operational Alert Limits* *Violation Limits – Regulatory Alert Limits (Note: Limit may not exist for regulatory requirement)*

[1] Existing PSTs: PST 3-10; PST 2 to be recommissioned (Jan 10);
[2] Based on 150MLD (including recommissioning of PST 2); 50/50 flow split between Mod 1&2 and Mod 3
[3] Recommissioning of PST 2 scheduled to be done by Jan 2010
[4] PST Dimensions (per tank) - Mod 1&2: L: 36m; W: 9.5m; D: 2.5m (average)
Mod 3: L: 72m; W: 12m; D: 2.75m (average)

Beenyup WWTP – Preliminary / Primary Treatment Schematic (FL S001-001-003)

Environmental Licence Beenyup WWTP L195-91



PCT improvement items

Item to be improved	Additional detail on action	Date identified	Date to action by (if req'd)	Position to action item (if req'd)
-	-	-	-	-

PROCESS CONTROL TABLE (Critical Control Points are highlighted in yellow)

Process	Asset	Monitoring Point	Functional Location No.	Parameter	WWQMS / Lab Sample Group		Frequency	Targets	Alert Limit		Violation Limit		Corrective Actions	Reference
									Low	High	Low	High		
Beenyup Wastewater Treatment Plant	Secondary Treatment	Aeration Tanks Module 1,2,3&4		Dissolved Oxygen	n/a	n/a	Continuous	*1.5 – 3.0 mg/l*	<0.5* for >4hrs	-	<0.5* for >6hr	-	ALERT and VIOLATION – if D.O. in last zone is below 0.5 for 4 hours in 2 or more of the 9 aeration tanks, divert the flow.	PM-#614257-Beenyup WWTP Secondary Treatment Process Control Table Change Requests: PM-#4409652, PM-6296095
		SST Effluent Module 1,2,3&4		Suspended Solids	n/a	n/a	Daily	*5.0 – 30.0 mg/l*	-	30.0	-	50.0	Alert and Violation – Monitor turbidity and if turbidity exceed target level, refer to actions for turbidity.	PM-#614257-Beenyup WWTP Secondary Treatment Process Control Table
		Aeration Tanks Module 1,2,3&4		Treatment Capacity Off-line	n/a	n/a	Continuous	< 11%	-	-	-	11.0	Violation - If more than 1 in 9 aeration tanks (11%) are off-line then divert flow until aeration tank(s) is/ are back in service	PM-#614257-Beenyup WWTP Secondary Treatment Process Control Table PM-#4409652
		SST Effluent Module 1,2,3&4		Treatment Capacity Off-line	n/a	n/a	Daily	< 2 SSTs per module offline by manual diversion	-	1	-	2	Violation - If more than 1 SST per module is off-line then divert flow until SSTs are back in service	PM-#614257-Beenyup WWTP Secondary Treatment Process Control Table PM-#4409652
		SST Effluent Module 1,2,3&4		Ammonia			Weekly	0.5 – 4.0 mg/l	-	5.0	-	7.5	Refer to Beenyup Secondary Treatment Process Control Table for corrective actions.	PM-#614257-Beenyup WWTP Secondary Treatment Process Control Table
Raw Water	Raw Water Pump Station & Coarse Screens	Raw Water	*FIT03103*	Flow	n/a	n/a	continuous	3.50 – 7.5 ML/d	–	–	–	–	Information only	W2WA PFD JO07-60-0.3 Rev 4
			AIT 03131	Turbidity	n/a	n/a	continuous	0 - 10 NTU	–	20.0	–	30.0	Alert - investigate Violation – Raw Water dump valve opens	Pilot Plant
			AIT 25122	Total Organic Carbon, TOC (UV_{abs} correlation)	n/a	n/a	continuous	5 – 100 mg/L	–	–	–	–	Information only	Pilot Plant
			AIT25123	Ammonia	n/a	n/a	continuous	0.0 – 4.0 mg/L	–	5.0	–	7.5	Information only	Pilot Plant
		Coarse screens	*PDS03110 PDS03111*	Differential Pressure	n/a	n/a	continuous	0.1 Bar	–	–	–	–	Alert – Initiate clean/backwash Violation – Take unit out of service	Vendor (Absolute Filters)
Chemical Dosing	Pre-MF Hypo Dose	Dose Point on MF Feed	FIT05201	Flow Meter	n/a	n/a	continuous	8 – 18 L/hr	–	–	–	–	Flow will depend on dose set point. Information only	Commissioning Report (W2W)
	Pre-MF Ammonia Dose	Dose Point on MF Feed	FIT06201	Flow Meter	n/a	n/a	continuous	1.5 – 2.5 L/hr	–	–	–	–	Flow will depend on dose set point. Information only	Commissioning Report (W2W)
Membrane Filtration	MF	MF Feed	*AIT25127*	Total Chlorine	n/a	n/a	continuous	2 – 3 ppm	–	3.5	-	4	Shutdown of sodium hypochlorite dosing, and shutdown MF units	KWRP experience
			AIT25128	ORP	n/a	n/a	continuous	200 – 570 mV	–	580	-	590	Shutdown of sodium hypochlorite dosing, and shutdown MF units	KWRP experience
			PIT04102	Pressure	n/a	n/a	continuous	120 – 160 kPa	–	–	–	–	MF Feed Pumps are started and stopped and ramped up and down to maintain the pressure set point in the header.	Commissioning Report (W2W)

GWRT Advanced Water Recycling Plant Process Control Table

Process	Asset	Monitoring Point	Functional Location No.	Parameter	WWQMS / Lab Sample Group		Frequency	Targets	Alert Limit		Violation Limit		Corrective Actions	Reference
									Low	High	Low	High		
		Autostrainers	*PDS04121*	Differential Pressure	n/a	n/a	continuous	0.7 Bar	–	–	–	–	High dP triggers strainer backwash. Backwash is also initiated after preset time, if high differential pressure does not occur.	Vendor (Filtomat)
Membrane Filtration	MF	MF 1-3	*PIT10114, PIT10214, PIT10314*	Trans-Membrane Pressure, TMP	n/a	n/a	continuous	< 100 kPa	–	–	–	–	High TMP triggers maintenance wash or CIP	Vendor (Siemens-Memcor)
			FE10110, FE10120, FE10130	Flux	n/a	n/a	continuous	< 88.4 lmh	–	–	–	–		Vendor (Siemens-Memcor)
		MF Skid		Pressure Decay Test, PDT	n/a	n/a	daily	< 5.0 kPa/min	–	5.0	–	7.0	Alert – Failed test results in detailed investigation of other performance data (refer PCT) Violation – Failed test results in unit being taken out of service	WTPE advice, Pre-Commissioning Validation Report (W2W)
				Log Reduction Value	n/a	n/a	daily	> 4 log (bacteria/crypto) – as calculated by the integrity test	–	–	–	–		Vendor (Siemens-Memcor)
				Feed Fouling Index	n/a	n/a	continuous	<10	–	–	–	–		Commissioning Report (W2W)
		MF Filtrate	*AIT25304*	Turbidity	n/a	n/a	continuous	< 0.08 NTU	–	0.10 (Exceeds for >5 minutes)	–	0.15 (Exceeds for >5 minutes)	Alert – Initiate pressure decay test Violation – Take unit our of service	Pre-Commissioning Validation Report (W2W)
			AIT25306	Particle Counter	n/a	n/a	continuous	*1000 /mL for particle size 2-5 µm*	–	–	–	–	Information only	Commissioning Report (W2W)
			AIT25303	Total Organic Carbon, TOC	n/a	n/a	continuous	*0.5 – 10 mg/L*	–	–	–	–		Pilot Plant Data, Commissioning Report (W2W)
			AIT25302	Phosphate	n/a	n/a	continuous	3.1 – 17.5 mg/L (as P)	–	–	–	–		WTPE – Vendor (Koch)
				RO metals suite Calcium Iron Zinc Copper Manganese Aluminium Silica (reactive) Silica (colloidal) Silicone			weekly – monthly	 < 5 mg/L <0.05 mg/L <0.05 mg/L <0.05 mg/L <0.02 mg/L <0.05 mg/L <10 mg/L <0.1 mg/L 0 mg/L	–	–	–	–	Review anti-scalent strategy	WTPE – Vendor (Koch)
			AIT25301	pH	n/a	n/a	continuous	5.8 - 6.6	–	–	–	–		Commissioning Report (W2W)
			AIT25305	Chloramine	n/a	n/a	continuous	1.5 – 3.0 mg/L	–	–	–	–	chloramine tolerance of 60,000 ppm hours @ 25°C	Commissioning Report (W2W) Vendor (Koch)
		MF CIP	*AIT22204*	pH	n/a	n/a	continuous	1.5 - 12	–	–	–	–		Commissioning Report (W2W)
			AIT22205	Conductivity	n/a	n/a	continuous	< 1500 µS/cm	–	–	–	–		Commissioning Report (W2W)
Chemical Dosing	Sulphuric Acid	Dose Point on MF filtrate	FIT07302	Flow	n/a	n/a	continuous	7 – 13 L/hr	–	–	–	–		Commissioning Report (W2W)
Reverse Osmosis Reverse Osmosis	RO Feed Tanks & RO Feed Pumps	RO Train 1 & 2 Feed	*AIT25507*	ORP	n/a	n/a	continuous	200 – 570 mV	–	580	–	590	Violation – open feed water dump valve and shutdown RO train.	Commissioning Report (W2W)
			AIT25505	Chloramine	n/a	n/a	continuous	1) >25 °C - 3.0 mg/L 2) 20-25 °C - 2.5 mg/L 3) <20 °C - 2.0 mg/L	1.2	1) 3.3 mg/L 2) 2.8 mg/L 3) 2.3 mg/L	1.0	1) 3.5 mg/L 2) 3.0 mg/L 3) 2.5 mg/L	Violation – open feed water dump valve and shutdown RO train.	Commissioning Report (W2W), PM#4386820
			AIT25503	Conductivity	n/a	n/a	continuous	800-1500 µS/cm	–	–	–	–		Commissioning Report (W2W)

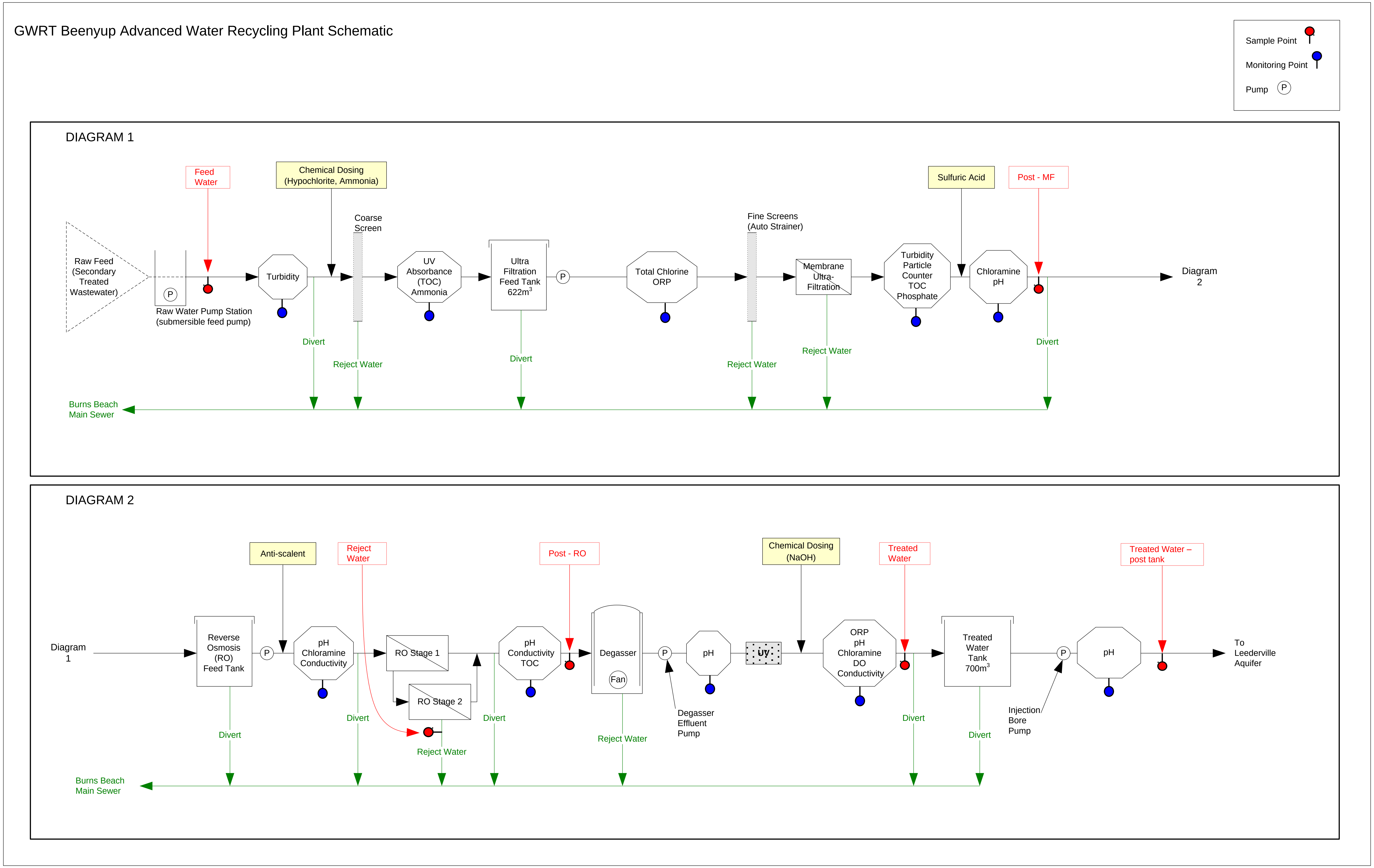
GWRT Advanced Water Recycling Plant Process Control Table

Process	Asset	Monitoring Point	Functional Location No.	Parameter	WWQMS / Lab Sample Group		Frequency	Targets	Alert Limit		Violation Limit		Corrective Actions	Reference
									Low	High	Low	High		
			AIT25502	pH	n/a	n/a	continuous	5.8-6.6	–	6.8	–	6.9	Violation – open feed water dump valve and shutdown RO train.	Commissioning Report (W2W)
	RO Train 1	RO Train 1 Stage 1 Reject	*AIT11321*	Conductivity	n/a	n/a	continuous	1500 - 3500 µS/cm for normal production	–	–	–	–		Commissioning Report (W2W)
		RO Train 1 Stage 2 Reject	*AIT11327*	Conductivity	n/a	n/a	continuous	2800 - 5500 µS/cm for normal production	–	–	–	–		Commissioning Report (W2W)
		RO Train 1 Stage 1 Permeate	*AIT11323*	Conductivity	n/a	n/a	continuous	10-50 µS/cm	–	50	–	75	Information only	Commissioning Report (W2W)
		RO Train 1 Stage 2 Permeate	*AIT11324*	Conductivity	n/a	n/a	continuous	20-75 µS/cm	–	75	–	100	Information only	Commissioning Report (W2W)
		RO Train 1 Combined Stages Permeate	*AIT11308*	Conductivity	n/a	n/a	continuous	20-75 µS/cm	–	75	–	100	Alert – Investigate Violation – divert water to waste via train waste valve	WTPE advice, Pre-Commissioning Validation Report (W2W
		RO Train 1 Stage 2 Reject	*AIT11326*	pH	n/a	n/a	continuous	6.0 - 7.0 for normal operation 1.5-12 for CIP						Commissioning Report (W2W)
		RO Train 1 Stage 1 & 2		Differential pressure across each Stage	n/a	n/a	continuous	Greater than startup baseline plus 20%	–		–		Perform CIP	Vendor (Koch)
	RO Train 2	RO Train 2 Stage 1 Reject	*AIT11421*	Conductivity	n/a	n/a	continuous	1500 - 3500 µS/cm for normal production	–	–	–	–		Commissioning Report (W2W)
		RO Train 2 Stage 2 Reject	*AIT11327*	Conductivity	n/a	n/a	continuous	2800 - 5500 µS/cm for normal production	–	–	–	–		Commissioning Report (W2W)
		RO Train 2 Stage 1 Permeate	*AIT11423*	Conductivity	n/a	n/a	continuous	10 – 50 µS/cm	–	50	–	75	Information only	Commissioning Report (W2W)
		RO Train 2 Stage 2 Permeate	*AIT11424*	Conductivity	n/a	n/a	continuous	20 – 75 µS/cm	–	75	–	100	Information only	Commissioning Report (W2W)
		RO Train 2 Combined Stages Permeate	*AIT11408*	Conductivity	n/a	n/a	continuous	20-75 µS/cm	–	75	–	100	Alert – Investigate Violation – divert water to waste via train waste valve.	WTPE advice, Pre-Commissioning Validation Report (W2W
		RO Train 2 Stage 2 Reject	*AIT11426*	pH	n/a	n/a	continuous	6.0 - 7.0 for normal operation 1.5-12 for CIP						Commissioning Report (W2W)
		RO Train 1 Stage 1 & 2		Differential pressure across each Stage	n/a	n/a	continuous	Greater than startup baseline plus 20%	–		–		Perform CIP	Vendor (Koch)
	Combined RO Train 1 & 2 Permeate	Combined RO Train 1 & 2 Permeate	*AIT25606*	pH	n/a	n/a	continuous	4.7-6.6						Commissioning Report (W2W)
		Combined RO Train 1 & 2 permeate	*AIT25605*	Conductivity	n/a	n/a	continuous	20-75 µS/cm	–	75	–	100	Alert – Investigate Violation – divert water to waste	WTPE advice Pre-Commissioning Validation Report (W2W
		Combined RO Train 1 & 2 Permeate	*AIT25604*	Total Organic Carbon, TOC	n/a	n/a	continuous	0 - 50 µg/L	–	75	–	150	Alert – Investigate Violation – divert water to waste	Commissioning Validation
		Combined RO Train 1 & 2 Permeate	*TIT11510*	Temperature	n/a	n/a	continuous	20 - 33 °C	–	–	–	–		Commissioning Report (W2W)
	RO CIP	RO CIP	*AIT24310*	pH	n/a	n/a	intermittent	2.5 – 4 (acidic CIP)						Commissioning Report (W2W)

GWRT Advanced Water Recycling Plant Process Control Table

Process	Asset	Monitoring Point	Functional Location No.	Parameter	WWQMS / Lab Sample Group		Frequency	Targets	Alert Limit		Violation Limit		Corrective Actions	Reference
									Low	High	Low	High		
								9 – 11 (basic CIP)						Commissioning Report (W2W)
				Temperature	n/a	n/a	intermittent	< 45 °C	–		–			Commissioning Report (W2W)
								< 45 °C	–		–			Commissioning Report (W2W)
		Cartridge on RO CIP	PDIS24305	Differential pressure and feed pressure	n/a	n/a	continuous	70 kPa	–		–			Vendor (Koch)
Degasser	Degasser	Degasser influent	*AIT25606*	pH	n/a	n/a	continuous	4.7-6.6						Commissioning Report (W2W)
UV	UV	UV feed	*FIT19201*	Flow	n/a	n/a	continuous	83 - 209 m^3/hr	–	214 (Exceeds for >2 minutes)	–	220 (Exceeds for >2 minutes)	Alert – investigate unit. Violation – take UV unit out of service (via UV PLC)	Commissioning Report (W2W)
				UV Transmittance (@253.7 nm)			weekly	> 94.4 %		–	94.4	–	Violation - Check UV intensity value. Check present power ratio/ballast % trend.	Vendor data (ITT-Wedeco)
			AIT19202	pH	n/a	n/a	continuous	4.7-6.6					For monitoring only	Commissioning Report (W2W)
			UV19010 UV19020 UV19310 UV19320	Intensity	n/a	n/a	continuous	77 W/m^2	74	–	70	–	Alert – Investigate units Violation – if up to 2 UV unis in violation, shutdown 1 RO train. If 3 or more UV units in violation, shutdown both RO trains.	Commissioning Report (W2W)
				Present Power Ratio	n/a	n/a	continuous	50-100%		100 (Equals for >30 min)			Alert – Check for decline in UV intensity; complete manual UVT reading of RO permeate. If the low UVT Alert limit is exceeded AND UV intensity is in Alert (but not yet violation), consider diversion of treated water to waste	Vendor (ITT Wedeco)
Treated Water	Treated Water	Treated Water	*AIT25706*	ORP	n/a	n/a	continuous	*50 – 590 mV*	–	–	–		Information only	Trial EV's
			AIT25702	pH	n/a	n/a	continuous	*7*	6.5 (Below for >5 minutes)	8.0 (Exceeds for >5 min)	6.0 (Below for >5 min)	8.5 (Exceeds for >5 min)	Violation – divert water to waste	Trial EV's - ADWG, Change Request PM#5285893
			AIT25705	Chloramine	n/a	n/a	continuous	*0.1-2.0 mg/L*	–	–	–	–		Trial EV's - ADWG
			AIT25704	DO	n/a	n/a	continuous	*< 10 mg/L*	–	–	–	–		Trial EV's
			AIT25703	Conductivity	n/a	n/a	continuous	*20-150* µS/cm	–	200	–	250	Violation – divert water to waste	Trial EV's - ADWG
Treated Water (post treated water tank)	Treated Water	Treated Water	*AIT25806*	pH	n/a	n/a	continuous	*7*	6.5	8.0	6.0	8.5	Violation – shutdown injection pumps	Change Request PM#5285893

GWRT Advanced Water Recycling Plant Process Control Table



Appendix 3: Aquifer Process Risk Assessment Report

Perth Groundwater Replenishment Scheme – Stage 2A

Aquifer Risk Assessment Report (Leederville and Yarragadee Aquifers)

April 2013

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Acknowledgement

The preparation of this document was undertaken by Simon Higginson and Michael Martin. Appreciation is extended to researchers from the CSIRO (Bradley Patterson, Henning Prommer, Laura Wendling, Mike Donn, Saeed Torkzaban and Maneesha Ginige), who assisted in characterising the Yarragadee aquifer and modelling, Rockwater Pty Ltd (Karen Johnston, Hanna Stokes) for logging the Yarragadee cored hole and preparation of the bore completion report and Curtin University (Brett Harris) who conducted the site seismic and dispersion assessment work.

Revision History

Version	Prepared By	Date Issued	Issued to	Comments Received
1	Simon Higginson, Michael Martin	25/03/2013	All workshop participants, GW - TRG	05/04/2013
2	Simon Higginson	15/04/2013	Published	

Endorsement

This report is endorsed as complete.

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WATER CORPORATION

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ADWG	Australian Drinking Water Guidelines	The ADWG have been developed by National Health and Medical Research Council (NHMRC) in collaboration with the Natural Resource Management Ministerial Council (NRMMC). The ADWG incorporates the Framework for the Management of Drinking Water Quality and provides the Australian community and the water supply industry with guidance on what constitutes good quality drinking water.
AWRP	Advanced Water Recycling Plant	A multiple treatment process consisting of ultrafiltration, reverse osmosis, ultraviolet disinfection to produce water for Groundwater Replenishment
DBP	Disinfection-by-Product	A range of organic and inorganic products resulting from the reaction of disinfection oxidants in a water system. The number and nature of by-products vary with disinfectant employed and quality of the water prior to disinfection
DEC	Department of Environment and Conservation	Responsible for the protection of the environment.
DoH	Department of Health	Responsible for the protection of human health.
DoW	Department of Water	Responsible for the protection of water resources, including public drinking water sources.
EV's	Environmental Values	The term applied to particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health.
GL	Gigalitres (1 billion litres)	One billion litres.
GW-TRG	Groundwater Replenishment Groundwater Technical Reference Group	Team of hydrogeological experts from the CSIRO, Department of Water, Curtin University, Rockwater Pty Ltd and the Water Corporation formed to progress the groundwater objectives of the Trial, and to assess the feasibility and potential hazards of GWR from available hydrogeological, water quality and geophysical data generated from the Trial and Yarragadee investigations
GWR	Groundwater Replenishment	Groundwater replenishment (GWR) is the process by which secondary treated wastewater undergoes advanced treatment to produce recycled water which meets Australian guidelines for drinking water prior to being recharged to an aquifer for later use as a drinking water source.
GWR MoU	Memorandum of Understanding between the Department of Health and the Water Corporation for the Groundwater Replenishment Trial	In the context of groundwater replenishment it refers to the agreement between the Department of Health and Water Corporation outlining the requirements for a groundwater replenishment scheme; i.e. water quality guidelines, operational performance and reporting requirements and communications protocols.
GWRT	Groundwater Replenishment Trial	Successfully completed by Water Corporation in December 2012 at Beenyup, it provided information to allow assessment and progress of a large GWR Scheme.
	Guideline	The concentration or measure of a water quality characteristic that, based on present knowledge, either does not result in any significant risk to the health of the consumer (health-related guideline value), or is associated with good quality water (aesthetic guideline value).
IAWG	Inter-Agency Working Group	Consisting of representatives from the Departments of Health, Environment and Conservation, Water and the Water Corporation, was formed to oversee the GWR Trial with the intention of developing policy and regulation for groundwater replenishment.
	Inherent Risk[1]	Risk in the absence of preventative measures or mitigations

[1] Definitions provided by the *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)* (NRMMC and EPHC, 2006)

IWSS	Integrated Water Supply Scheme	The system of pipes and pumps which supplies drinking water to the Perth Metropolitan area, Mandurah and the Goldfields pipeline.
LOR	Limit of Reporting	The lowest limit at which the laboratory will report a quantitative result for a parameter: chemical, microbiological or radiological. Multiple LOR's may be applicable for analytes due to changes in methods.
mbgl	Metres below ground level	This is an indicative value which should not be used for any design, construction etc. purpose
ML	Megalitres	One million litres.
	Mitigated Risk[1]	Risk after consideration of existing and proposed preventative measures or mitigations
	Mitigation	Any planned design, operational procedure or action that is used to prevent hazards from occurring or reduced them to an acceptable level
PRAMS	Perth Regional Aquifer Modelling System	A groundwater model jointly developed by the Water Corporation and the Department of Water (formerly the Waters and Rivers commission) to assist with groundwater resource management
	Risk[1]	A measure of the likelihood of identified hazards causing harm in exposed populations or receiving environments in a specified timeframe with a severity measured by the consequence (risk = likelihood x consequence)
RMZ	Recharge Management Zone	Defines the minimum distance between recharge of recycled water and the boundary where groundwater quality meets guidelines and the environmental values protected and provides an adequate source of drinking water. A distance of 250m has been defined for the confined aquifers at the Beenyup site.
RO	Reverse Osmosis	Second treatment step in the advanced water treatment process.
RWQI	Recycled Water Quality Indicator	Chemicals or pathogens that best represent a larger group of chemicals or microbiological hazards identified by the Recycled Water Quality Parameters. The RWQI have been specified by the Department of Health (DoH) and are set out in the GWRT MoU Schedule 1.
RWQP	Recycled Water Quality Parameter	Refers to the water quality parameters to be measured in recycled water, as agreed with the Department of Health (DoH) and set out in the GWRT MoU Schedule 1. Analysis of these parameters will allow assessment of the recycled water against the Water Quality Guidelines.
UF	Ultrafiltration	First treatment step in the advanced water treatment process.
UV	Ultraviolet Disinfection	Third treatment step in the advanced water treatment process.
	Water Quality Guidelines	Compliance with the water quality guidelines set by the DoH and DEC will represent protection of human health and the Environmental Values. Water quality guidelines that are relevant to protecting human health and the health-related Environmental Values are set out in the GWRT MoU Schedule 1. *Referred to as guidelines in this document*.
WWTP	Wastewater Treatment Plant	A treatment process which immediately precedes the Advanced Water Recycling Plant, providing secondary treatment to raw wastewater. In the context of the GWRS it refers to the Beenyup WWTP, located in Craigie, Perth.
yr	Year	

1 Executive Summary

The Water Corporation completed a three year Groundwater Replenishment Trial (GWRT) in December 2012, during which more than 2.5GL of recycled water was recharged into the confined Leederville aquifer at the Beenyup site in Craigie. The Trial was used to build knowledge of the technical, health, environmental and social issues associated with Groundwater Replenishment (GWR) in Perth.

Given the success of the Trial, the Water Corporation is progressing approvals for the Perth Groundwater Replenishment Scheme (GWRS), developed in stages to meet future water supply demands. The proposed scheme will recharge up to 28GL/yr into the confined Leederville and Yarragadee aquifers. Approvals are being sought to progress Stage 2A (Table 3.1).

The scope of this risk assessment covers recharging up to 14GL/yr into the Leederville aquifer or Yarragadee aquifer (or a combination of both up to a total of 14GL/yr) at the Beenyup GWR site.

The Water Corporation adopts the risk management approach defined in the *Australian Guideline for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge* (NRMMC, EPHC, NHRMC, 2009), assessing risks to the Environmental Values (EV's) of the aquifers as defined by the Department of Health, Department of Water, Department of Environment and Conservation. They are;

- Drinking water resource – current and future use
- Industrial water
- Primary industry
- Cultural and spiritual

The water quality guidelines identified to protect these EV's are the recycled water quality indicators (RWQI) and recycled water quality parameters (RWQP) as identified in the Memorandum of Understanding between the Department of Health and the Water Corporation for the Groundwater Replenishment Trial (GWR MoU) (DoH & Water Corporation, 2010).

The risk assessment was undertaken by the GWR – Groundwater Technical Reference Group for the Trial and incorporated experts in hydrogeology, geochemistry, geophysics, groundwater quality, groundwater modelling, managed aquifer recharge, wastewater treatment and advanced water treatment. The risk assessment process was peer reviewed by Dr Peter Dillon, managed aquifer recharge expert from the CSIRO and principle author of the *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge* (NRMMC, EPHC, NHRMC, 2009).

A total of 46 potential hazards, likelihoods, consequences and potential mitigations were identified and assessed for both aquifers (Leederville aquifer – 20, Yarragadee aquifer - 26), in the following groups;

- Risks from drilling and bore construction
- Risks resulting in bore clogging or reduced aquifer permeability
- Risks to human and environmental health
- Risks of poor aquifer performance
- Risks to geothermal bores (Yarragadee aquifer only)

All potential hazards were assessed as low risk with adequate mitigations in place.

Therefore the risk to the both aquifers as a result of recharging up to 14GL/yr of recycled water is low.

The outcomes of this risk assessment will feed into the detailed design of the Perth GWRS Stages 1 and 2A.

The risk assessment process is iterative one, and identified risks, mitigations and information obtained as a result of further investigations will be re-assessed following detailed design, construction, commissioning, changes in water quality guidelines, and annually during operation of the Perth GWRS Stages 1 and 2A.

2 Purpose

This report documents the aquifer risk assessment for recharging up to 14GL/yr into the confined aquifers at the Beenyup site, to ensure the processes and procedures continue to meet recycled water quality guidelines at the boundary of the Recharge Management Zone (RMZ). Together with the Treatment Process Risk Assessment (Water Corporation, 2013c), it addresses Step 3 of the GWR Regulatory Framework (Appendix A)(IAWG, 2012)[2].

The scope of this risk assessment covers recharging up to 14GL/yr recycled water into the Leederville and Yarragadee aquifers (or a combination of both to total 14GL/yr) at the Beenyup site.

3 Introduction

Groundwater Replenishment (GWR) is the process by which secondary treated wastewater undergoes advanced treatment to produce water which meets the Australian drinking water guidelines (ADWG) prior to being recharged to an aquifer for later use as a drinking water source.

Water Corporation's three year Groundwater Replenishment Trial has successfully demonstrated that groundwater replenishment can provide a sustainable water source option for Western Australia. Specifically it:

- Demonstrated that the treatment process can consistently and reliably perform to meet the recycled water quality guidelines to protect human health and the environment.
- Identified and documented all technical issues that arose during design, construction, and operation to ensure that they are addressed in the design and operation of future GWRS, including risk assessments.
- Demonstrated that "GWRT Recycled Water Quality Management Plan", applying the Wastewater Quality Management Framework, is an effective mechanism for managing the systems and processes to produce water that always meets the recycled water quality guidelines. This included applying the Corporate Risk Assessment Process to the design, commissioning and ongoing operation of the AWRP.
- Provided information for the regulators of groundwater replenishment; the Department of Health (DoH), Department of Water (DoW) and Department of Environment and Conservation (DEC) to develop the GWR Regulatory Framework

Based on the success of the Trial, the Water Corporation is progressing with developing a 28 gigalitres (GL) per year (yr) GWRS at the Beenyup site (Table 3.1). Delivery will be in 3 stages; Stage 1 - 7GL/yr, Stage 2 - 14GL/yr and Stage 3 - 28GL/yr as detailed in Table 3.1. A staged delivery allows a flexible approach to meet water demand in the Integrated Water Supply Scheme (IWSS).

In order to maintain supply against a background of a drying climate, the Water Corporation is considering accelerating the delivery of Stage 2 of the Perth GWRS. Given potential delays in construction and approvals, the Water Corporation has reviewed the scope of Stage 2 and will progress its delivery in two parts, Stage 2A (Figure 3.2) and 2B:

[2] GWR Regulatory Framework – defines the approvals pathway for how a groundwater replenishment scheme will be assessed, regulated and operated.

Stage 2A – Construct an additional 7GL/yr AWRP at the Beenyup site (to provide a total of 14GL/yr recycled water). Maximise recharge to Leederville (screened ~120-220mbgl) and Yarragadee (screened ~ 389-443, 460-487, 605-676 and 690-744mbgl) aquifer recharge bores.
Note: Whilst maximum recharge rates for each bore can be estimated, this will not be confirmed until they can be tested under pumping and recharge conditions.

Stage 2B – Construct a pipeline and two new Leederville aquifer recharge bores (if required) located off the Beenyup site, to the east of Lake Joondalup to recharge the additional 7GL/yr produced by the Stage 2A AWRP.

The Water Corporation has commenced the approval process for Stage 2A, following Steps 1 – 4 of the GWR Regulatory Framework.

The Water Corporation commenced investigations to characterise the Yarragadee aquifer (Step 1) and some of this information was used by the Departments of Health (DoH), Environment and Conservation (DEC) and Water (DoW) to identify the Environmental Values (EV's)[3] and water quality guidelines that the recycled water must meet at the point of recharge and at the boundary of the RMZ (completing Step 2 of the GWR Framework).

An Aquifer Risk Assessment was undertaken on the 14th March 2013 to evaluate the risks of recharging up to 14GL/yr recycled water into the Leederville and Yarragadee aquifers at the Beenyup site.

This report provides outcomes of the Aquifer Risk Assessment. Together with the Treatment Process Risk Assessment Report (Water Corporation, 2013c), it addresses Step 3 of the GWR Regulatory Framework (Appendix A).

Table 3.1: Stages of the 28GL/yr Perth GWRS

Stage	Activity
1	Construct a 7GL/yr AWRP at the Beenyup site. Recharge via the existing Leederville aquifer recharge bore and one new Yarragadee aquifer recharge bore located at the Beenyup site.
2A	Construct an additional 7GL/yr AWRP at the Beenyup site (to provide a total of 14GL/yr recycled water). Maximise recharge to Leederville and Yarragadee aquifer recharge bores. **Note:** Whilst maximum recharge rates for each bore can be estimated, this will not be confirmed until they can be tested under pumping and recharge conditions.
2B	Construct a pipeline and two new Leederville aquifer recharge bores (if required) located off the Beenyup site, to the east of Lake Joondalup to recharge the additional 7GL/yr produced by the Stage 2A AWRP.
3	Construct an additional 14GL/yr AWRP at the Beenyup site (to provide a total of 28GL/yr recycled water). Extend pipeline and construct two additional Leederville aquifer recharge bores and two additional Yarragadee aquifer recharge bores to recharge the additional water.

[3] Environmental Values (EV's) - The term applied to particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health.

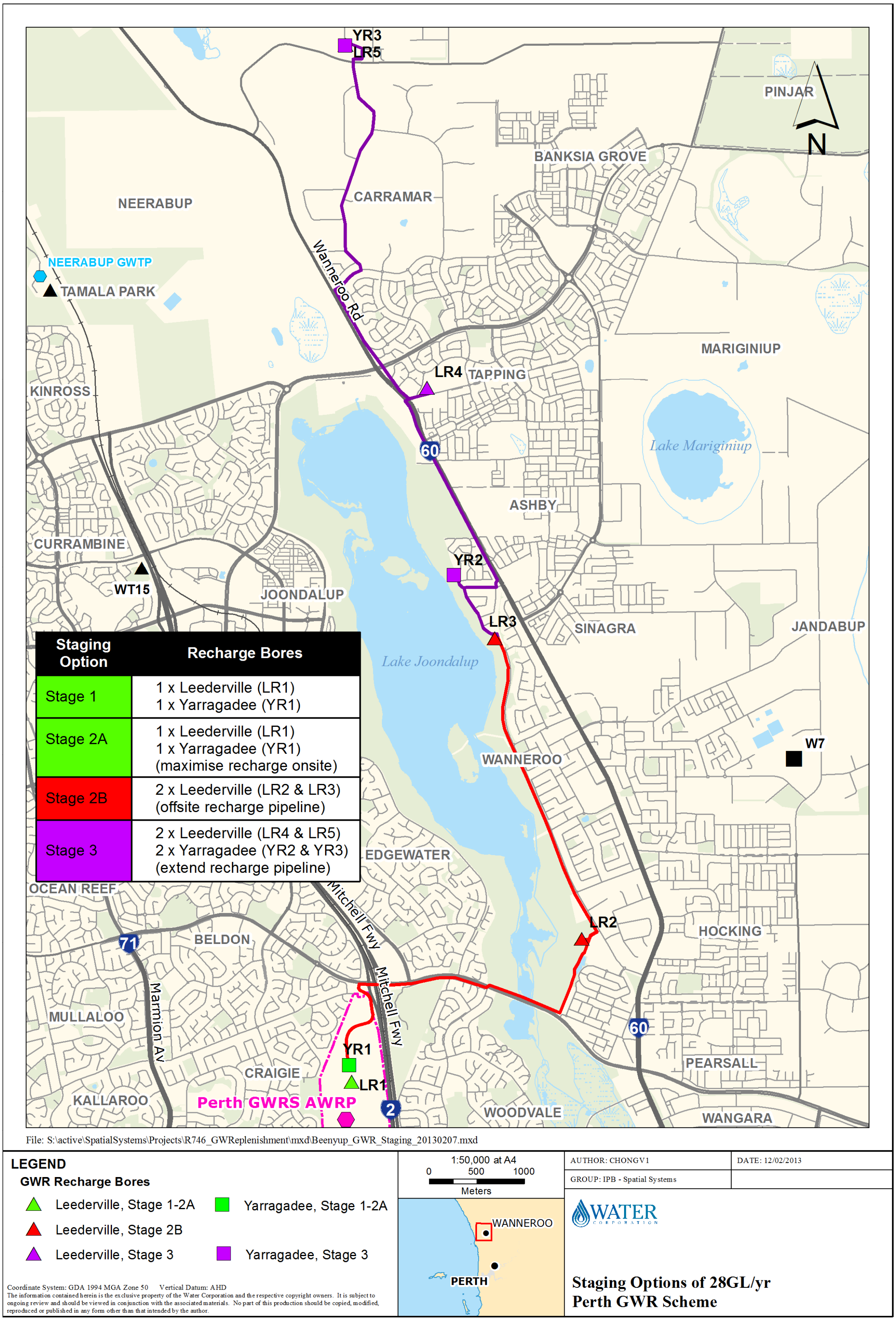


Figure 3.1: Staging Options of 28 GL/yr GWRS including acceleration of Stage 2

Figure 3.2: Perth GWRS Stage 2A - location map

4 Risk Assessment Process

Water Corporation ensures that the recycled water quality continuously meets water quality guidelines by applying the Wastewater Quality Framework, which adopts the risk management approach described in the *Australian Guidelines for Recycled Water: Managing Health and Environmental Risks (Phase 1)* (NRMMC, EPHC, AHMC, 2006). The aquifer risk assessment process was guided by the *Australia Guidelines for Water Recycling; Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge* (NRMMC, EPHC, NHRMC, 2009) (referred to from here as the MAR guidelines). These guidelines recognise that the level of some risks cannot be fully understood before a managed aquifer recharge (or groundwater replenishment) scheme is implemented due to uncertainties in aquifer processes. However with adequate system characterisation and assessment it is possible to adopt preventative measures and operational procedures which will allow the scheme to be implemented without compromising the environmental values of the aquifer (NRMMC, EPHC, NHRMC, 2009).

The risk management approach assesses risks to the environmental values of the aquifer system. It involves conducting a risk assessment workshop to:

- Assess all available information.
- Identify potential hazards.
- Assign an inherent risk based on the likelihood and consequence of the risk occurring.
- Identify mitigations to reduce the inherent risk to an acceptable level.
- Assign a residual risk.

A rank of low medium, high or extreme is given to the inherent risk and mitigated risk. Water Corporation's risk assessment criteria are available in Appendix G.

In some cases further investigation may be required to improve the understanding of either the consequence or likelihood of a hazard or investigate an alternative mitigation to reduce the risk to an acceptable level.

The workshop was facilitated by the Water Corporation on the 14th March 2013. Workshop participants included technical specialists and researchers from the Department of Water, Water Corporation, CSIRO, Curtin University and Rockwater Hydrogeological Consultants. The participants have been involved with the Trial and contributed significantly to the current understanding of managed aquifer recharge, including groundwater replenishment to confined aquifers in Perth. The risk assessment process was peer reviewed by Dr Peter Dillon, managed aquifer recharge expert from the CSIRO and principle author of the MAR guidelines. Appendix H provides a list of workshop attendees.

Figure 4.1 illustrates the GWR risks assessment process and outlines how it is integral to the design, construction and commissioning of a GWR Scheme and operation of the Perth GWRS Stage 2A. It is important to note that this is an iterative process and there will be future risk assessments following detailed design, construction, commissioning, changes to water quality guidelines and throughout the operating life of the scheme.

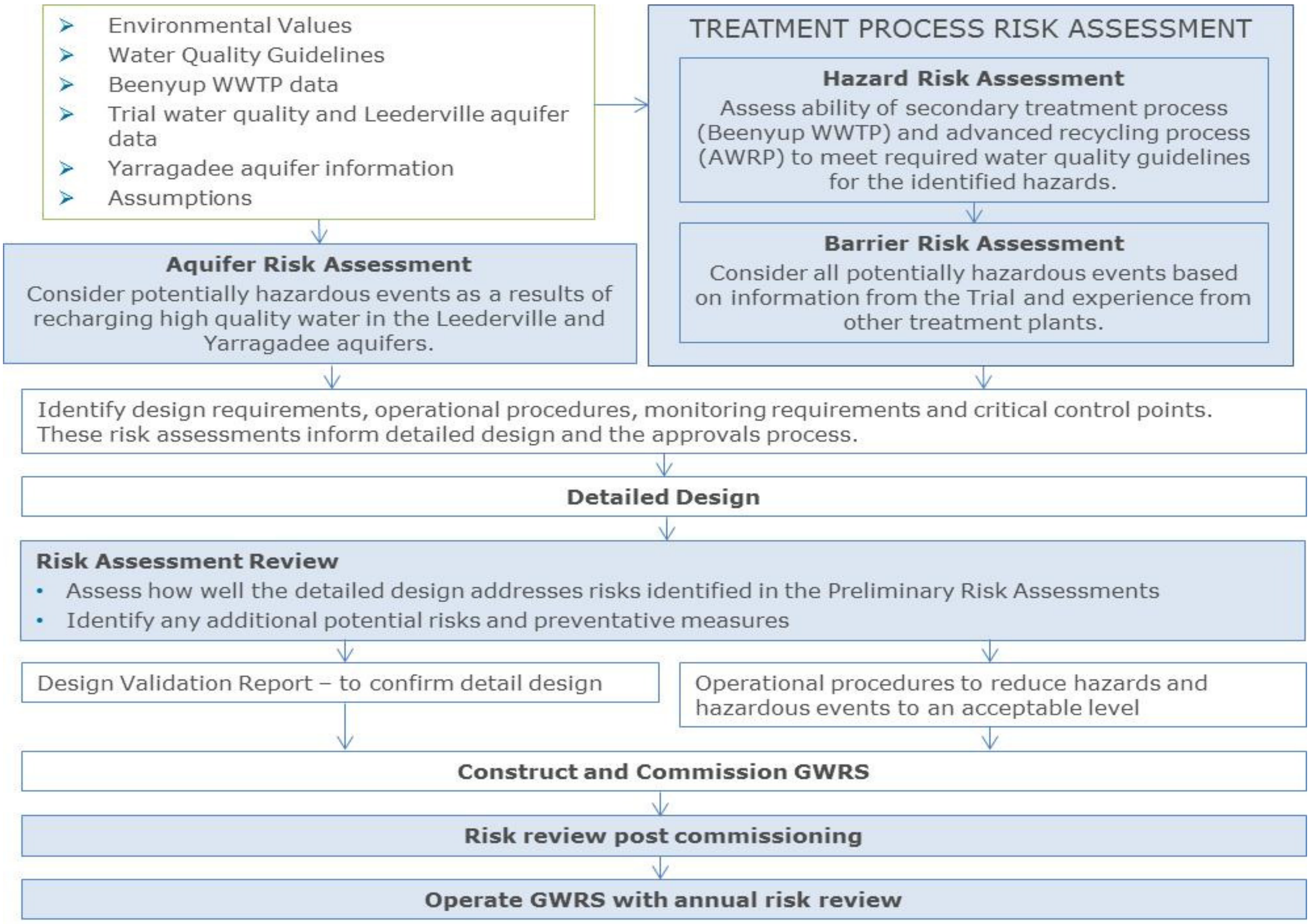


Figure 4.1: Risk Assessment Process

5 Inputs to the Risk Assessment

5.1 Environmental Values and Water Quality Guidelines

In February 2013, the DoH, DEC and DoW established the relevant Environmental Values (EV's) and water quality guidelines applicable the Perth GWRS Stage 2A recharging the Leederville aquifer and Yarragadee aquifer at the Beenyup site. The EV's take into account the most conservative scenario of recharging up to 14GL/yr to each aquifer. This has been summarised in Table 5.1:

Table 5.1: The identified EV's and water quality guidelines for GWRS Stage 2A

Environmental Value	Water Quality Guidelines for Leederville and Yarragadee aquifer – GWRS Stage 2A
Drinking Water	Recycled Water Quality Indicators (18 parameters) Recycled Water Quality Parameters (292 parameters to assess 254 water quality guidelines) [4] *As defined by the Memorandum of Understanding (MoU) between the Department of Health and Water Corporation for the Groundwater Replenishment Trial 2010* Note: these guidelines are referred to in this document as 'water quality guidelines or guidelines'
Primary Industries	As per Drinking Water EV
Industrial Water	As per Drinking Water EV
Cultural and Spiritual	Consultation with Indigenous Community

The DEC, DoW and DoH determined that the management objective of the identified EV's is to "maintain for current and future use".

The DoH has set the water quality guidelines which protect the EV's. They are the 18 Recycled Water Quality Indicators (RWQI), 292 Recycled Water Quality Parameters (RWQP), and 254 water quality guidelines, as outlined in the GWRT MoU (2010) at the point of recharge. It is expected that by meeting these guidelines at the point of recharge the EV's will be maintained for current and future uses.

The RWQP and RWQI may change periodically following an assessment of the guidelines by the DoH. In this situation the hazard risk assessment will be reviewed with respect to the new guidelines.

5.2 Groundwater Replenishment Trial

The Trial has provided a detailed understanding of the Leederville aquifer response to recharge to allow for planning of a larger GWR scheme into the Leederville. Some of this knowledge is transferable to potential recharge of the Yarragadee aquifer.

The Trial has provided information critical to the assessment of risks to the Leederville aquifer for future GWR schemes at the Beenyup site. They are:

[4] 46 of the 292 MoU RWQPs contribute to the calculation of "combined toxic equivalence" for PAHs and Dioxins. Only a few of these RWQPs have a relevant individual guideline values to report against.

- The addition of recycled water to groundwater has lowered the high level of some naturally occurring chemicals, resulting in improved groundwater quality;
- Movement of the recycled water through the Leederville aquifer is variable; and
- Recharge increases pressure in the Leederville aquifer, reducing the downward flow of water from the Superficial aquifer, however this pressure is not sufficient to allow upward movement of the recycled water into the Superficial aquifer

Groundwater salinity is significantly reduced as the recycled water passes through the aquifer generally, approaching the salinity of the recycled water. In some instances salinity stabilized slightly higher, indicating a greater degree of mixing or more geochemical reactions in some layers. Groundwater chemistry has exhibited a shift from background sodium-chloride type water towards sodium-bicarbonate type water consistent with recycled water chemistry, with pyrite oxidation and carbonate dissolution as the predominant geochemical reactions.

Movement of the recycled water through the Leederville aquifer is variable, with water in different layers moving at different speeds this has been demonstrated by recycled water being detected 180 metres west from the recharge bore in all depths of the monitoring layers but only in the deepest layer at 240 metres north.

At the end of the Trial, more than 2.5GL of recycled water had been recharged to the Leederville aquifer. Over the course of the Trial, groundwater quality monitoring took place (at five locations) from 22 monitoring bores. Over 58,200 groundwater samples have been collected and all results meet health and environmental guideline values, except for some naturally occurring metals and major ions (e.g. iron and chloride) which were above guideline levels in the ambient groundwater.

Outcomes of the Trial have also included the development of tools and models for the assessment of large scale GWR into both the Leederville and Yarragadee aquifers.

5.3 Modelling

The capability of the Perth Regional Aquifer Modelling System (PRAMS), (Davidson and Yu, 2006) to evaluate regional scale aquifer response to a GWR scheme (Water Corporation, 2012b) was assessed as part of the GWR Trial. A suite of models has been developed and utilised to evaluate the approach and transfer from the Trial scale to a full scale GWR scheme (Table 5.2).

Numerical models are MODFLOW-based applications, selected because of their general acceptance and well documented and reliable simulation tools. An analytic model was developed to predict travel times of upward flow at a site scale, and is applicable for a range of potential recharge rates (Appendix D). The model provides a conservative prediction of travel time as it does not take into account lateral flow due to spreading, regional through flow in the overlying sediments or head reduction due to abstraction.

Table 5.2: Groundwater models, designation and description

Model designation, platform	Variant	Description	Reference
GWRTM4.0.	Flow, tracer, chloride, reactive transport	MODFLOW, MT3DMS, and PHT3D: High resolution model grid in lateral and vertical direction to describe local-scale GWRT processes.	Water Corporation (2012b)
GWRTSL1.0	Flow, solute transport	MODFLOW, Single layer model with a vertical extent corresponding to the thickness of the recharge zone. Grid discretisation in lateral direction as in GWRTM4.0	Water Corporation (2012b) CyMod (2013)
PRAMSOL3.4R	Flow, solute transport	As for PRAMSOL3.4 with refined grid about to the GWRT site	Water Corporation (2012b) CyMod (2013)
PRAMSOL3.4	Flow, solute transport	MODFLOW, MT3DMS: retaining grid and layering of PRAMS3.4.	Water Corporation (2012b) CyMod (2013)
PRAMS3.4_PMPATH	Particle Tracking	Standard MODFLOW module	CyMod (2013)
YAR_LOC1.0	Solute and Temperature transport	Local scale MODFLOW and MT3DMS model refined grid of Yarragadee aquifer	Appendix B
YAR_GAS1.0	Batch geochemical model	PHREEQC model of geochemical evolution and potential gas production/release	Appendix B
V_Flow	Analytic (spreadsheet) model.	Based on first principles to estimate effective vertical hydraulic conductivity and travel times from site strata and head information. Assumes no lateral flow or additional pumping.	Appendix D

5.4 Yarragadee Investigations

In August 2011 a preliminary risk assessment of GWR into the Yarragadee aquifer was held, which allowed a detailed assessment of the technical feasibility of recharging the Yarragadee at the Beenyup site, and identified a work plan and timelines to further assess risks and develop a GWR scheme. This information is detailed in the Yarragadee Aquifer Preliminary Risk Assessment Report, August 2011.

An outcome of the Preliminary Yarragadee Risk Assessment included a work plan to collect the required information to address the likelihood and potential mitigations of some identified risks. This involved collecting samples of the Yarragadee aquifer material at the Beenyup site (cored and cuttings), and allowing the aquifer material to be subjected to a range of experiments, site based geophysics, water quality sampling of nearby Yarragadee bores, and a range of modelling scenarios (Section 5.3). Reports created by research partners and consultants addressing items of the work plan are available in;

CyMod Systems Pty Ltd, (2013). *Impact of recharge on water quality in the Leederville and Yarragadee aquifer using the Perth regional aquifer model solute transport PRAMSOL3.4*. Prepared for the Water Corporation. February 2013. Draft distributed to GW-TRG 26/03/2013

Patterson, B., Prommer, H., Wendling, L., Donn, M., Ginige, M. (Appendix B). *Characterisation and quantification of water quality evolution during recharge of recycled water into the Yarragadee aquifer*. Draft CSIRO technical report. Distributed to GW-TRG 26/03/2013, Modelling Section distributed 01/03/2013

Rockwater, (2013). *Beenyup groundwater replenishment scheme. BNYP YMB 1/12 Yarragadee monitoring bore completion report*. Report for the Water Corporation of Western Australia. February 2013. Draft distributed to GW-TRG 01/03/2013

Harris, B., (Appendix C). Curtin Report. Draft technical report for the Water Corporation. Seismic for risk mitigation paper distributed to GW-TRG 01/03/2013

5.5 Recharge Management Zone

The Trial's regulators determined that the RMZ boundary for the confined aquifers at the Beenyup site should be located a radial distance of 250m from the recharge bore.

To confirm that EV's remain protected at the RZM boundary, the Water Corporation will conduct groundwater monitoring within the RMZ at 60m from the Leederville and Yarragadee recharge bores. This distance will provide sufficient early warning and the ability to implement mitigating strategies before the potential hazard reaches the boundary of the RMZ (Groundwater TRG, 2012).

5.6 Risk assessment assumptions

The following assumptions were identified by workshop participants (Table 5.3) in order the progress the development of the risk assessment. These assumptions will be revisited during the risk assessment following detailed design of the future AWRP.

Table 5.3: Aquifer Risk Assessment assumptions

No.	Assumption
1	The treatment process for the Perth GWRS AWRP will remain the same as the Trial AWRP with UF, RO, degasser & UV at 200mJ/cm2, producing the same quality recycled water
2	Recharge will be up to 14GL/yr into the Leederville aquifer or Yarragadee aquifer via a single recharge bore in each (or a combination of both to a total of 14GL/yr)
3	Recharge rates will be stepped, (similar to the Trial), but individual steps may be greater
4	Two recharge bores – one into the Leederville aquifer (existing recharge bore), one into the Yarragadee aquifer at the Beenyup site
5	Monitoring bores will be screened to match the recharge intervals
6	Monitoring at 60m from the recharge bore as representative of water quality within the RMZ boundary. This distance will provide sufficient early warning and the ability to implement mitigating strategies before the potential hazard reaches the boundary of the RMZ (Note – additional research monitoring being conducted within the Leederville aquifer 2013 - 2014)

6 Site Description

The development of the Perth GWRS includes construction of an Advanced Water Recycling Plant (AWRP) using the same technology utilised in the Trial. Secondary treated wastewater from the Beenyup WWTP will undergo advanced treatment by ultra-filtration (UF) followed by reverse osmosis (RO) and ultra violet (UV) treatment. Recycled water that has met all treatment performance requirements will then be recharged into the Leederville and Yarragadee aquifers. An illustration of the GWR process is provided in Figure 6.1.

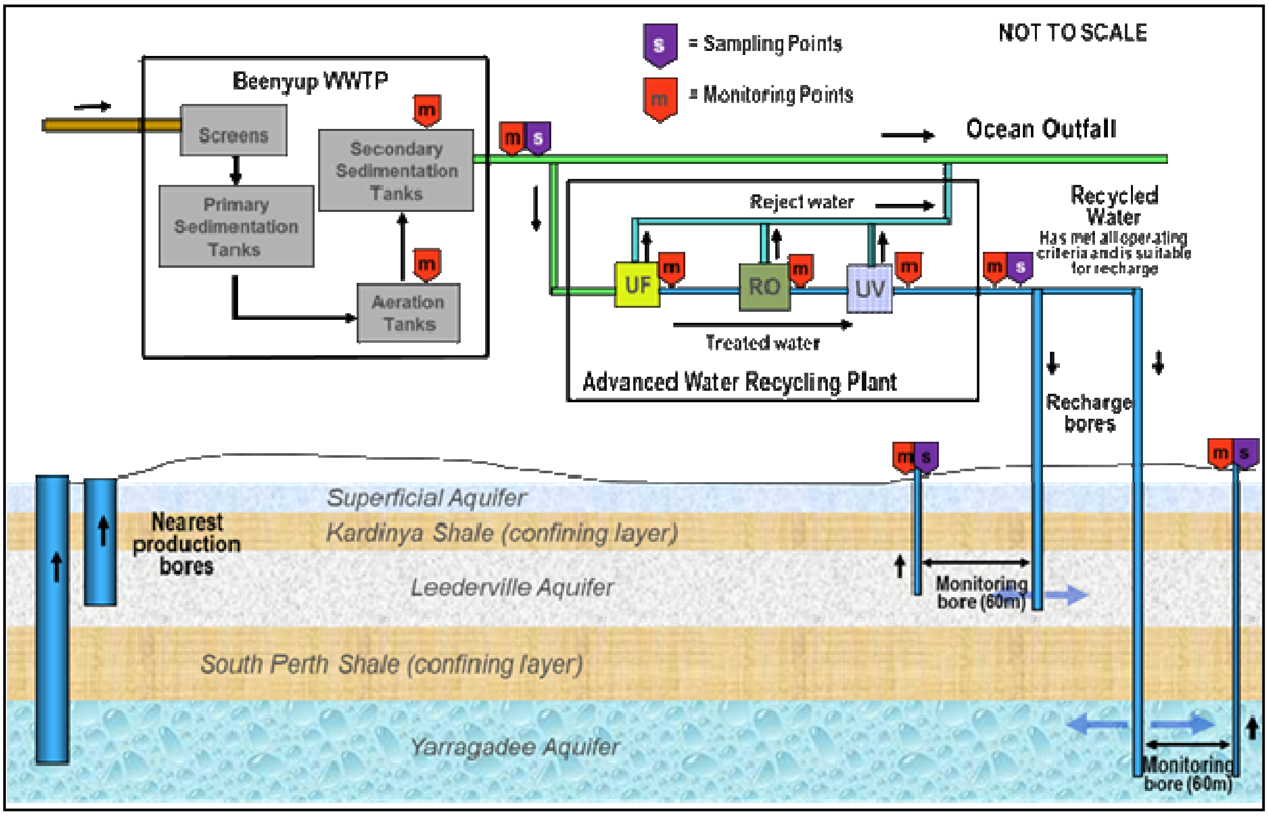


Figure 6.1: Perth Groundwater Replenishment Scheme Process

The results from the Site Characterisation Report (Water Corporation, 2009a) show the Superficial aquifer, Mirrabooka aquifer, Leederville aquifer and the Yarragadee aquifer are present at the Beenyup site and typically representative of the aquifer systems found within the Gnangara groundwater system.

The Leederville Formation forms a major confined aquifer composed of interbedded sandstone, siltstone and shale. The recharge interval within the Leederville Formation consists mainly of thick beds of moderately to well sorted, fine to coarse grained quartz sandstone, with thin siltstone and shale beds. A less permeable zone containing a greater proportion of siltstone and shale occurs between about 175m and 190m depth; this has been informally designated "intra-formational siltstones", separating upper and lower high permeability zones within the recharge interval. The Leederville Formation is unconformably overlain by the Osborne Formation and conformably overlies the South Perth Shale which provides a good confining layer between the Leederville and Yarragadee aquifers at the Beenyup site.

The Leederville recharge interval is approximately 120-220mbgl.

The Yarragadee aquifer occurs from the base of the South Perth Shale and comprises the Gage Formation and the Yarragadee formation, consisting of alternating sandstones, siltstone and shales (Rockwater, 2013). The Yarragadee Formation sandstones (~390mbgl - >750mbgl) are generally over 30m thick and consists of interbedded very fine to very coarse grained quartz sand, with occasional thin shale/siltstone intervals, with grain size generally increasing with depth.

The Yarragadee recharge interval is ~ 389-443, 460-487, 605-676 and 690 -744mbgl.

The stratigraphy at the Beenyup site was characterised from the lithology description, geophysical logs and palynological studies is summarised in Table 6.1. More detailed descriptions of site geology and hydrogeology are available in the Site Characterisation Report (Water Corporation. 2009a) and Yarragadee aquifer drilling investigation (Rockwater, 2013).

Table 6.1: Hydro-stratigraphic summary for the Beenyup site

Summary Depth (m) From	To	Description	Geological Unit	Hydrogeology
0	20	Sand, medium to coarse grained quartz and limestone grains	Tamala Limestone	Superficial aquifer
20	50	Limestone	Tamala Limestone	Superficial aquifer
Unconformity				
50	65	Sandstone, silty, medium to coarse grained quartz and glauconite with silt and shale beds.	Osborne Formation	Mirrabooka aquifer Kardinya Shale aquitard
Unconformity				
65	95	Sandstone, fine to coarse grained, moderately sorted, sub-rounded quartz with thin dark grey siltstone beds	Leederville Formation (undifferentiated)	Leederville aquifer
95	125	Siltstone and shale	Leederville Formation	aquitard
125	175	Sandstone, fine to coarse grained quartz with thin siltstone and mudstone beds	Leederville Formation: Wanneroo Member	Leederville aquifer
175	190	Siltstone, mudstone and poorly sorted sandstone.	Leederville Formation: Wanneroo Member	Intra-formational siltstone
190	225	Sandstone, fine to coarse grained quartz with thin siltstone and mudstone beds	Leederville Formation Wanneroo Member	Leederville aquifer
225	260	Siltstone and mudstone	Leederville Formation: Mariginiup Member	aquitard
260	320	Siltstone and mudstone	South Perth Shale	aquitard
Unconformity				
320	390	Sandstone and siltstone	Gage Formation	Yarragadee aquifer
390	>750	Sandstone and siltstone	Yarragadee Formation	Yarragadee aquifer

Note: yellow shading highlights the recharge zone for the Leederville bore.
After (Water Corporation, 2012b)

7 Leederville Aquifer Risk Assessment

7.1 Risks from drilling and bore construction

7.1.1 Risk of screen corrosion

The recharge of low ionic strength of recycled water could cause corrosion of the recharge bore screen if inadequate materials are used and rated as inherently high risk. This could result in recharge bore screen failure impacting the capability to recharge.

Mitigations were identified during detailed design by the use of appropriate materials of fibre reinforced epoxy casing (FRP) and stainless steel screens (Water Corporation, 2009a) and pH adjustment after RO. When a maintenance opportunity arises requiring the down hole valve and recharge bore infrastructure to be removed a camera log of the recharge bore and screens will be conducted to confirm the condition of the recharge bore screens. With the mitigation of FRP casing and stainless steel screens, the risk of screen corrosion was considered low.

7.1.2 Risks of deteriorating recharge bore integrity

The risk to recharge bore infrastructure due to over-pressurising the recharge bore, resulting in failure of the bore casing or headwork's causing injury to by-standers was assessed. Adequate drilling techniques were used during construction, design criteria and work instructions ensured appropriate materials and fitting were utilised and will be used for any maintenance. Based on recharge response during the Trial, the estimated head for a recharge rate of 14GL/yr would be 21m above ground level. This is well below the minimum design specification of 150m above ground level for the headworks infrastructure. Continuous monitoring of bore pressures and flow ensure the maximum allowed pressure is not reached. The mitigated risk to recharge bore integrity has been assessed as low

7.2 Risks resulting in bore clogging and reduced aquifer permeability

7.2.1 Suspended solids – Introduction via recycled water

The potential for physical clogging of the recharge bore-aquifer interface due to the introduction of solids in the recycled water is limited due to the nature of the treatment process after reverse osmosis. Although NaOH dosing to correct the pH to a target of 7 and intrusive maintenance after the reverse osmosis trains does present an opportunity to introduce solids into the recycled water.

Current mitigations include:

- the use of a strainer on the NaOH dosing line to minimise the risk of impurities/solids in the NaOH entering the recycled water
- AWRP operations and maintenance staff have specific work instructions regarding maintenance after the reverse osmosis trains, including the flushing/cleaning of lines, fittings and instruments prior to being brought back into service.
- Daily manual turbidity checks are carried out by AWRP operations on the treated water to verify the quality of the recycled water.

Monitoring data (presented in Table 7.1) demonstrate that these mitigations have been effective to date. Therefore the risk of clogging due to the introduction of solids was assessed at an inherent risk of low and a mitigated risk of low.

If alkalinity buffering is required to be included in the treatment process, there are a number of robust mitigations, including appropriate design and continuous monitoring of turbidity, which may be implemented to mitigate this risk. If there is a change in the AWRP (including alkalinity buffering) this risk will require re-assessment.

Table 7.1: Recycled Water Quality Data (Solids and Turbidity)

Parameter	Units	Average	StDev	Max	Min	n
Total Suspended Solids	mg/L	1.2	0.6	4	<1	30
Turbidity	NTU	<0.5	0	<0.5	<0.5	30
AWRP Daily Turbidity	NTU	0.01	0.02	0.12	0.00	706

7.2.2 Mobilisation of fines

Mobilisation of colloids has been observed in the Trial as total aluminium increases from interaction between the low ionic strength recycled water and kaolinte clay present in the Leederville aquifer. Colloidal mobilisation has the potential to clog aquifer pores.

The conceptual model assumes the mobile colloids would be exhausted and flushed as the recycled water passes through, reflected in reducing concentrations after an initial peak around the time of breakthrough of the recycled water. This appears to be occurring through observed site data (Figure 7.1 - Figure 7.3). Utilising stepped flow recharge rates will assist in minimising colloidal mobilisation and verification monitoring of pressure and water quality at the 60N site will be ongoing through a GWR scheme. While there is the potential for the mobilisation of colloids, and this has been observed as increases in total aluminium, the risk assessment workshop agreed that this mobilisation is not high enough to cause clogging and has been assessed as low.

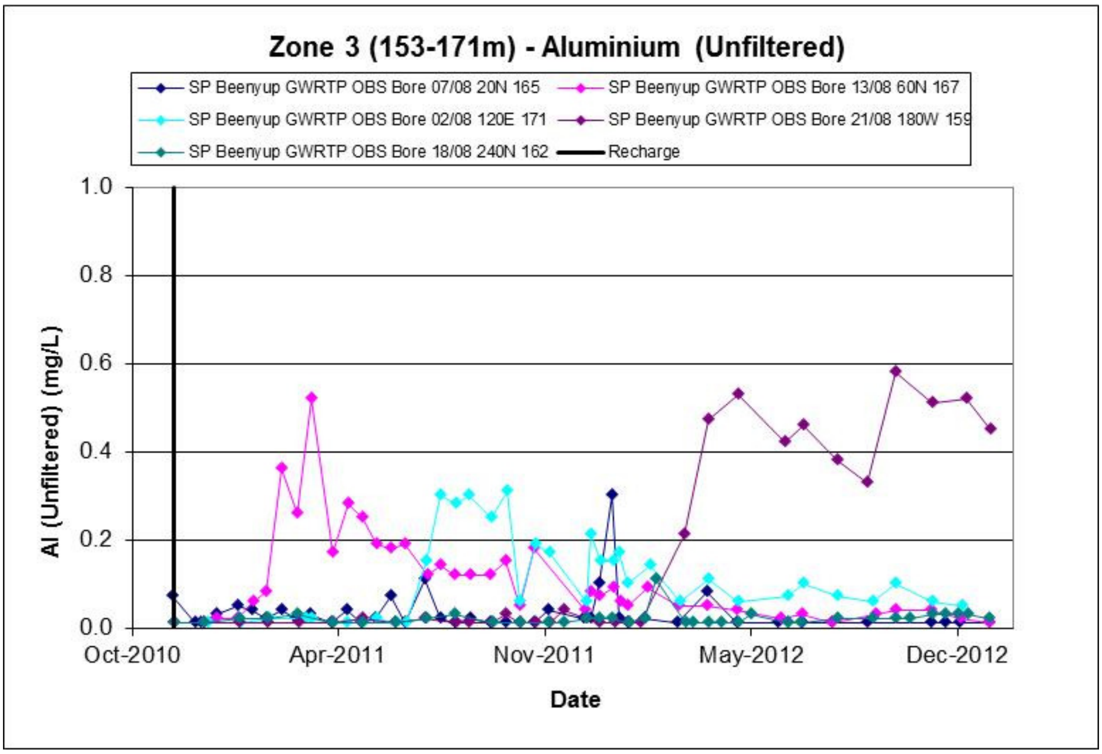


Figure 7.1: Aluminium (Unfiltered) - Zone 3 (153-171m)

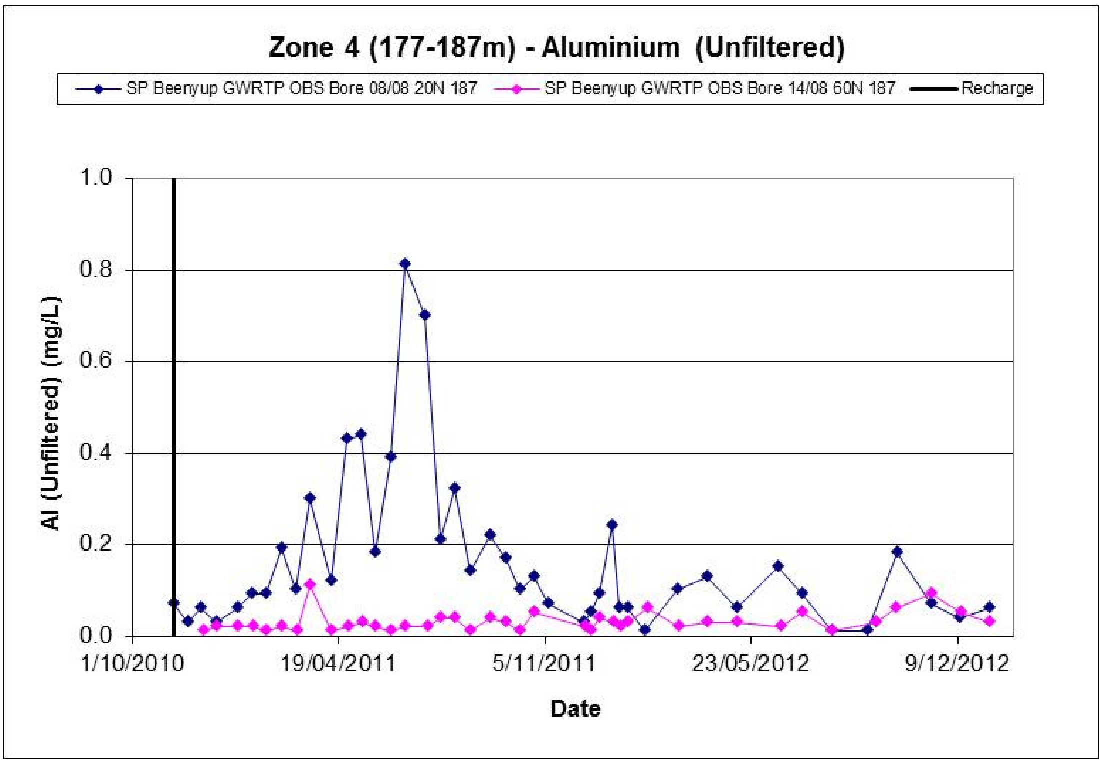


Figure 7.2: Aluminium (Unfiltered) - Zone 4 (177-187m)

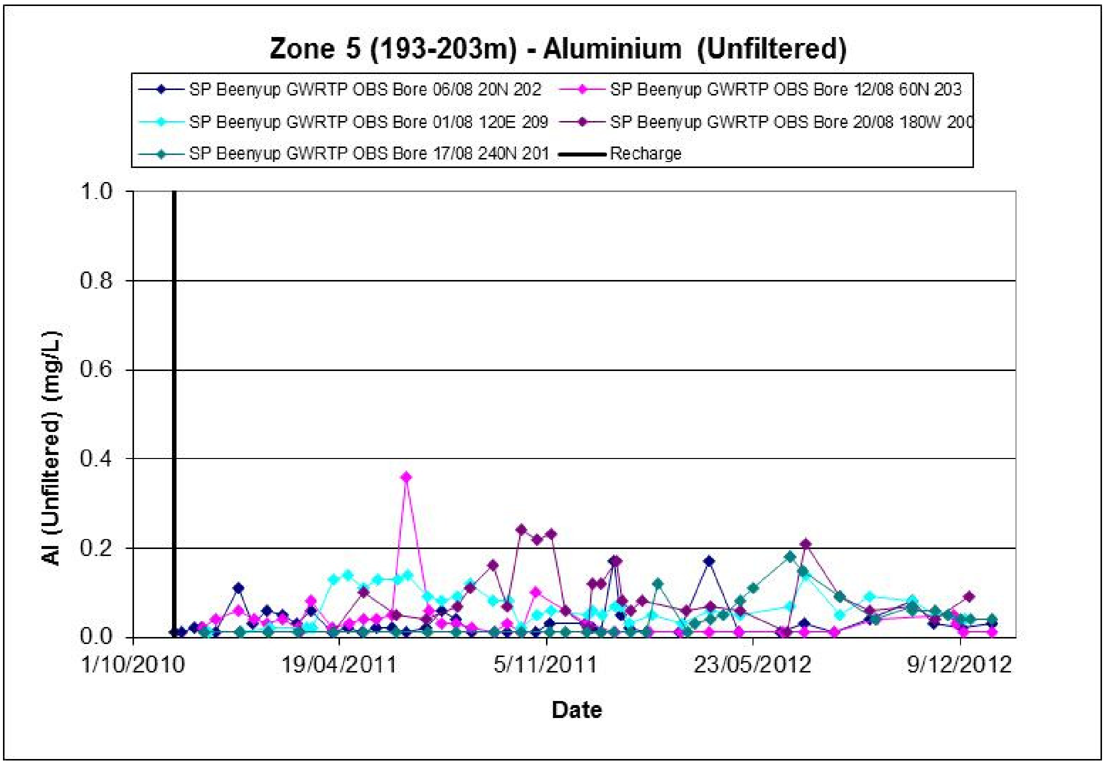


Figure 7.3: Aluminium (Unfiltered) - Zone 5 (193-203m)

7.2.3 Air entrainment – cascading water

Air-entrainment during recharge can be caused by cascading water into the bore, resulting in reduced bore efficiency as air bubbles become trapped in the aquifer and plug the formation pores. This often results in a significant and rapid increase in resistance to flow and a sudden increase in water levels (hydraulic head), particularly on start-up of the bore. This has been assigned an inherent risk of moderate, due to a likelihood rating of possible and consequence of minor, based on down time required to redevelop the bore.

The Trial has demonstrated that the risk of air-entrainment is readily mitigated with appropriate recharge bore infrastructure (through use of a down hole valve), which allows a positive recharge head to be maintained via an recharge line installed below the resting water level. The current target for recharge is 200kPa, with alerts set at 90kPa and 320kPa and violations set at 85kPa and 350kPa. If a violation level were to be reached, recharge would shutdown, mitigating the risk of cascading water. Therefore through the current design and operation of the recharge bore, this risk is mitigated to low.

7.2.4 Microbiological clogging

Microbiological clogging can occur when bacteria introduced during drilling or via bore infrastructure or indigenous bacteria undergo increase growth due to a change in conditions. An accumulation of impermeable slimes and a mat of dead cells can build up in and around the bore screens and lead to clogging and reduction of the recharge capacity of the bore. The degree of biological growth is directly related to the amount of assimiliable organic carbon (AOC) and nutrients present. This was rated as a moderate inherent risk.

Through the Trial, the AWRP has consistently produced water with very low microbiological contact (<LOR), dissolved organic carbon (DOC) (average - <1mg/L), AOC (average - 0.082mg/L) and total nitrogen (average: TN - 2.34mg/L, NO3 as N – 2mg/L, NH3 as N 0.26mg/L). Nitrate concentrations were generally below limit of reporting (<0.01mg/L) in the Leederville aquifer during baseline monitoring (Water Corporation, 2010). Groundwater monitoring indicates that denitrification is occurring in the aquifer. Nitrate levels at the 20N site are below those of the recycled water, but follow a similar trend to the recycled water (Figure 7.4). However, nitrate has only been detected in three bores at the 60N site at concentrations significantly below that of recycled water, indicating denitrification is occurring (Figure 7.5). Denitrification within the Leederville aquifer is consistent with laboratory experiments using sediment from the Leederville site in large-scale (non-sterile) columns (Patterson et al, 2010) and reactive transport modelling data (Water Corporation, 2012b).

The 2011 Leederville Aquifer Risk Assessment recommended additional characterisation of microbiological population in the Leederville aquifer, for comparison with populations prior to recharge commencing (Water Corporation, 2012a). Sampling of nine monitoring bores located at the 20N, 60N and 240N sites occurred in April 2012 (BNYP06/08 20N 202, BNYP07/08 20N 165, BNYP08/08 20N 187, BNYP09/08 20N 94, BNYP10/08 20N 147, BNYP11/08 20N 129, BNYP15/08 60N 146, BNYP18/08 240N 162, BNYP19/08 240N 151). Initial results indicate an average 30 times increase in native microbial cell numbers at bores that have had recycled water breakthrough, however with a reduced microbial diversity (Ginige, et al, in prep).

Between the 30th April and 1st May 2012, the recharge bore down hole valve and equipment was removed to allow for maintenance. After the equipment was reinstalled, the rate of clogging increased, indicating that a bacteria source may have been introduced at the surface. Future disinfection procedures will be put in place to ensure microbiological and chemical contaminants are not introduced to the recharge bore infrastructure when removed for maintenance.

Clogging monitoring will be ongoing throughout a GWR Scheme, and mitigations could include;

- AWRP operation to limit concentration of nutrients and organic carbon to limit biomass growth
- Disinfection of DHV and equipment after maintenance
- Understand clogging and bore remediation (camera log of screens, sample, backwash/airlift)

Through mitigation, the residual risk of microbiological clogging has been rated as low.

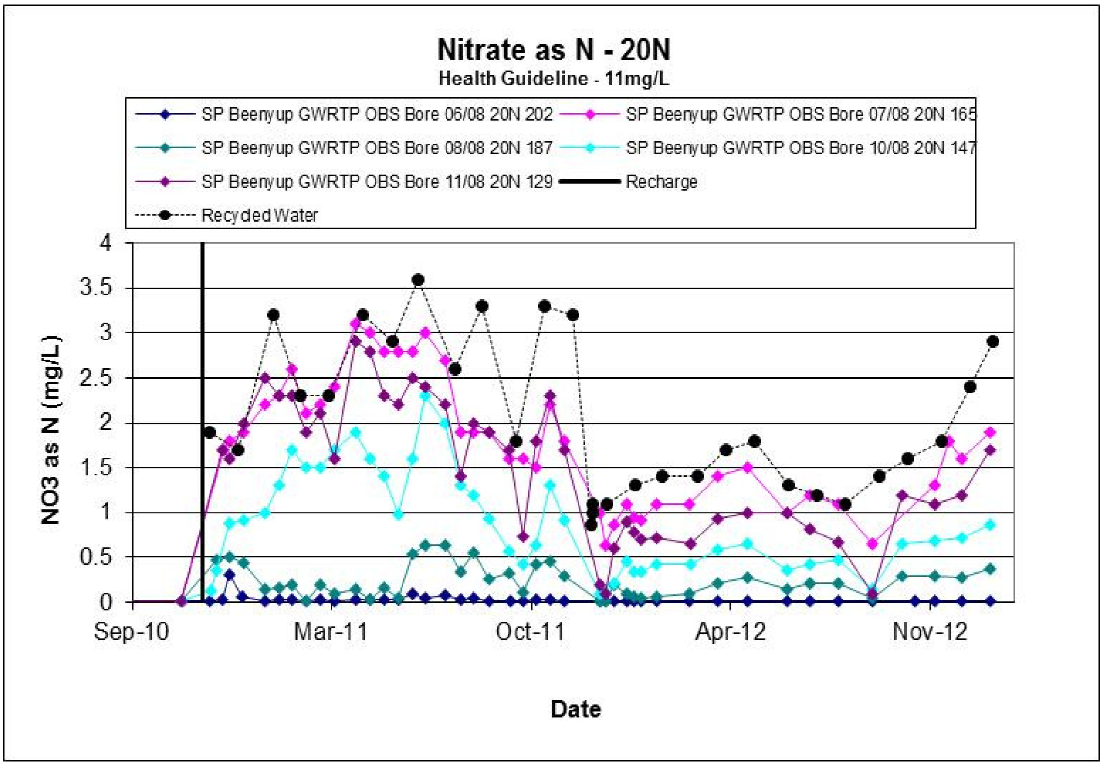


Figure 7.4: Nitrate as N - 20N Site

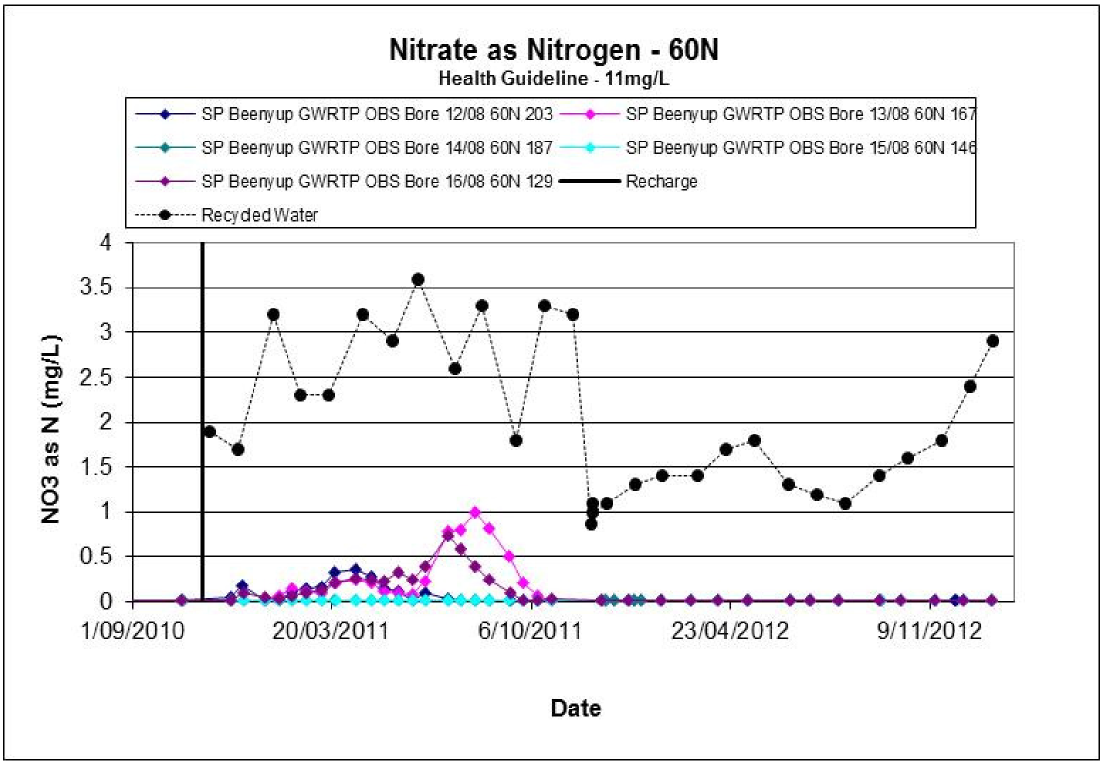


Figure 7.5: Nitrate as N - 60N Site

7.2.5 Geochemical Clogging

Geochemical clogging can occur when minerals are precipitated as a result of reactions between the ambient groundwater and/or the aquifer matrix with the recharge water. The GWRT Groundwater Report 2011 (Water Corporation, 2012a) identified that aluminium and iron-hydroxides may precipitate in zones where aerobic and/or denitrifying conditions prevailed.

Clogging monitoring through the Trial indicated that the limited clogging that occurred was likely due to changes in microbiological populations (Section 7.2.4). Clogging monitoring will be ongoing through a GWR Scheme, and if significant geochemical clogging were to occur the corrective action could include the construction of a new recharge bore onsite. The inherent risk and mitigated risk of geochemical clogging has been assessed as low.

7.2.6 Scaling

Scaling of the recharge bore screens due to bio-geochemical reactions does not pose an issue to water quality, but is an operational issue impacting the efficiency of pumping into the aquifer.

It was rated as a low inherent risk and was not observed during the Trial.

Data obtained during the Trial informing the reassessment of this risk includes:

- Water quality results which confirm that the recycled water has very low ionic strength, very low TDS and low bicarbonate concentrations, and there is limited capacity for precipitates to clog.
- Monitoring of pressure in the aquifer during the two years of operation of the Trial recharge bore has not indicated a significant increase in pressure.

Based on this information, the workshop concluded that it is unlikely that scaling will be observed when recharge from the Perth GWRS commences whilst utilising the same treatment process used in the Trial.

Pressure will continue to be monitored as part of a GWR Scheme to confirm this assessment. If detected, then bore maintenance/remediation may be triggered (e.g. backwashing/airlifting).

This risk will need to be considered at future recharge sites or if significant changes are made to the AWRP process (i.e. increasing buffering capacity of the recycled water). Potential mitigation strategies include reducing exit velocities of the recycled water through the screens, particularly at new recharge bores (i.e., longer and/or large diameter screens), regular recharge bore maintenance including options such as camera logging, airlifting and backwashing.

7.3 Risks to human and environmental health

7.3.1 pH change

Potential loss of buffering capacity within the aquifer could result in a drop in pH creating a situation where metals could potentially mobilise. The inherent risk of a pH change outside of guidelines (6.0 - 8.5) was rated as low due to longer term buffering reactions (e.g. feldspar buffering) likely to continue to become greater in buffering the water more than 60m from the recharge bore. Geochemical modelling (Appendix B) indicates that the buffering capacity of the aquifer and recycled water is likely to prevent pH dropping below 6.2 at more than 60m from the recharge bore. Research monitoring after the conclusion of the Trial at the 20N site (Water Corporation, 2013b) will monitor for changes in aquifer conditions and trends in buffering until 2014. Monitoring will be on going at the 60N site within the RMZ to confirm the pH is within guideline and that additional metals are not being mobilised as a result of decreased pH. The risk of a pH change outside of guideline is assessed as low with the mitigating actions of reactive transport modelling to determine the likely long term change in pH and on-going verification monitoring.

7.3.2 Mobilisation of chemicals

Geochemical reactions will occur as a result of the recharge of recycled water to the Leederville aquifer, there is a risk that metals could be mobilised above water quality guideline levels. The predominant geochemical reactions identified in the Leederville aquifer include pyrite oxidation, sediment organic matter (SOM) mineralisation, trace carbonate (siderite) dissolution and aluminosilicate (feldspar) weathering (Water Corporation, 2012b). The oxidation of pyrite and SOM by introduced oxygen and nitrate in the recycled water, has the potential to create acidity which can result in a decrease in groundwater pH and potentially mobilise trace metals.

The pH in two bores at the 20N site (BNYP07/08 20N 165 and BNYP11/08 20N 129) decreased to a pH of 6.5 in mid-2012 (Figure 7.6), coinciding with this decrease, cobalt concentrations increased above limit of reporting (LOR), but remained below the water quality guideline. Recent data (until Jan 2013) indicates pH has stabilised at 6.4, after a decrease down to 6.3 and cobalt levels are now at 0.0006mg/L and 0.0004mg/L in relation to a guideline of 0.001mg/L (Figure 7.14). Pyrite has been identified as the source of the cobalt (Descourvieres, 2010). It is likely that the cobalt released during pyrite oxidation is rapidly re-adsorbed (e.g. onto neo-formed iron oxides) while pH remained buffered at greater than 6.5 and is only mobilised once the pH decreases below a critical level (Appendix B). This was modelled in the simplified 2D reactive transport model, which showed the maximum cobalt concentrations would be in the order of 0.0003mg/L to 0.0006mg/L, below the guideline of 0.001mg/L. The simplified 2D model did not incorporate buffering from slow reacting aluminosilicates, which would likely mitigate pH declines and therefore cobalt release at a greater distance from the recharge bore (Appendix B). Given the buffering capacity of the aquifer to maintain cobalt concentrations within guideline levels and on-going verification monitoring within the RMZ, the mitigated risk of cobalt mobilising in concentrations which will exceed the water quality guideline at the RMZ boundary has been assessed as low.

Six metals were assessed in the final GWRT Leederville aquifer risk assessment (Water Corporation, 2013a) that could potentially mobilise above baseline concentrations. These were arsenic (Figure 7.7 - Figure 7.9), barium (Figure 7.10 - Figure 7.11), boron (Figure 7.12 - Figure 7.13), iron, manganese and strontium (Figure 7.26 - Figure 7.27). Assessment for the probability of exceeding the Recycled Water Quality Parameter (RWQP) was assessed for all metals and determined an inherent risk of low. This is due to the natural buffering capacity of the aquifer assisting on maintaining pH neutral and reducing conditions, with any metals release likely to re-sorb or precipitate back onto the aquifer matrix.

Iron and manganese (Figure 7.21) are both naturally occurring in the Leederville aquifer, with baseline concentrations of iron greater than guideline values (Figure 7.19 - Figure 7.20). After an initial decrease in concentrations on breakthrough of the recycled water, iron and manganese (Figure 7.21) concentrations have increased in some bores towards baseline concentrations. Current groundwater treatment plants have been designed to reduce iron and manganese concentrations to below guideline levels prior to distribution through the IWSS. These metals were again re-assessed as an inherent risk and mitigated risk of low.

Mobilisation of phosphorus (predominantly as soluble reactive phosphate) has been observed in most Leederville monitoring bores on breakthrough of the recycled water to concentrations above baseline conditions (Figure 7.22, Figure 7.23). Total phosphorus does not have a water quality guideline, however it currently remains on the 1.5GL AWRP DEC discharge licence, therefore a conservative approach was taken and the risk of phosphorus not meeting the existing guideline at the RMZ boundary was considered. This increase has been associated with the dissolution of crandallite ($CaAl_3(PO_4)_2.(OH)_5.(H_2O)$). An inherent risk of moderate was assigned in the 2012 Leederville Aquifer Risk Assessment (Water Corporation, 2013a), given that a transient spike could exceed the environment target (2.1mg/L) and limit (2.3mg/L) set for total phosphorus. The transient increases in phosphorus have occurred at different times within different layers at each site reflecting differential dissolution of crandallite and migration from the recharge bore. Average aquifer concentrations (multiple discrete aquifer intervals at each site) have been below environmental targets and limits (Figure 7.24, Figure 7.25). Phosphorus concentrations within a discrete layer at any point away from the recharge bore will successively decline after an initial peak, and is expected to decrease below background levels. The current mitigation is monitoring at the operational site located within the RMZ (Groundwater TRG, 2012), and research monitoring planned for 2013-2014 of the 20N and 240N sites to understand the water quality evolution near the recharge bore and at the boundary of the RMZ (Water Corporation, 2013b). The mitigated risk of an average aquifer concentration of phosphorus exceeding an environmental limit has been assessed as low.

Concentrations of naturally occurring fluoride vary in the Gnangara groundwater system, with some concentrations greater than the guideline of 1.5mg/L occurring in some groundwater sources (Water Corporation, 2012d). Groundwater sources in the Perth region are blended and further fluoride added if required to provide an average concentration of 0.9mg/L as agreed with the DoH. Fluoride mobilisation has been observed in bores (Figure 7.15, Figure 7.16) that have had phosphorus mobilised. This increase may be associated with the dissolution of the mineral crandallite, where F^- can replace the OH^- in the crystal structure (Water Corporation, 2012b). A moderate inherent risk was assigned to fluoride exceeding the guideline. The transient increases in fluoride have occurred at different times within different layers at each site reflecting differential dissolution of crandallite and migration from the recharge bore. Average aquifer concentrations (multiple discrete aquifer intervals at each site) have been below guideline levels (Figure 7.17, Figure 7.18). Fluoride concentrations within a discrete layer at any point away from the recharge bore will successively decline after an initial peak. The current mitigation is monitoring at the operational site located within the RMZ (Groundwater TRG, 2012) (RMZ), and research monitoring planned for 2013-2014 of the 20N and 240N sites to understand the water quality evolution near the recharge bore and at the boundary of the RMZ (Water Corporation, 2013b). The mitigated risk of an aquifer average concentration of fluoride exceeding the guideline has been assessed as low.

A potential mitigation to the mobilisation of metals and other chemicals could be to increase the alkalinity of the recycled water to increase the buffering capacity, mitigating all metals mobilisation risks to low. There are a number of ways that buffering capacity can be increased, with varying impacts to downstream processes. Preliminary research indicates that by reducing or removing the degassing process and correcting pH to 7.5 (currently via sodium hydroxide dosing) after reverse osmosis, could potentially increase the buffering capacity of the recycled water (alkalinity – 44mg/L, bicarbonate – 53mg/L). All amendments to design should be reviewed.

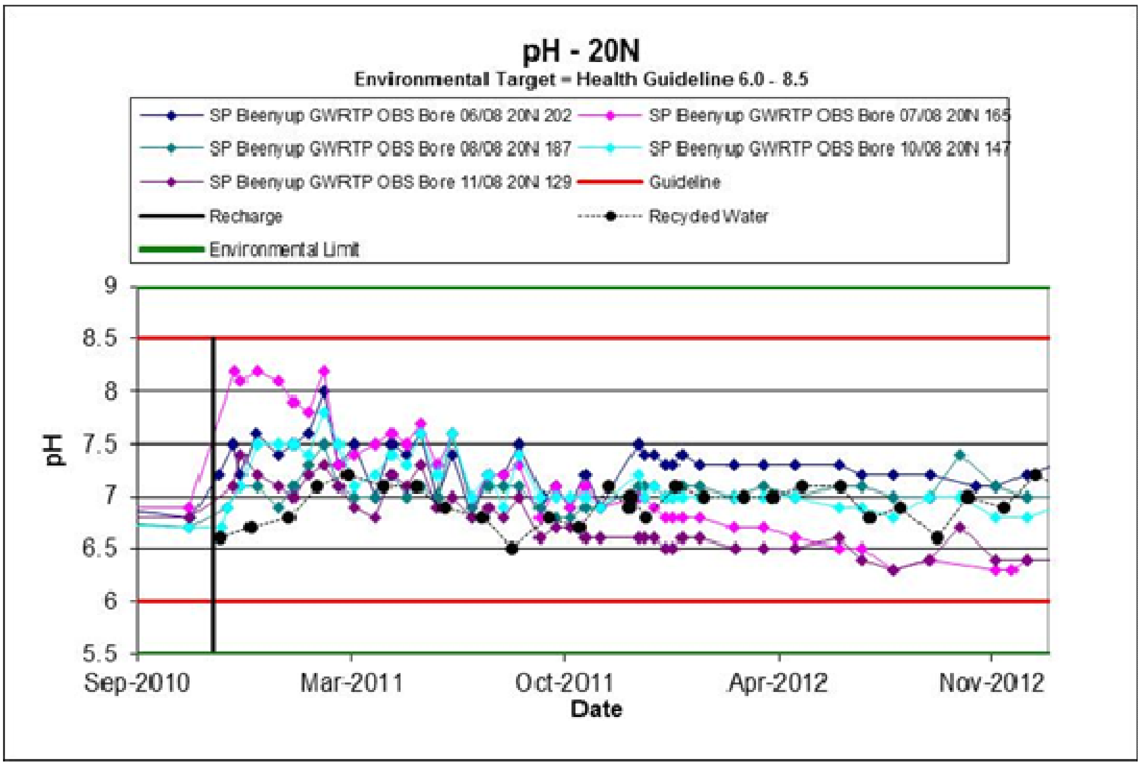


Figure 7.6: pH - 20N Site

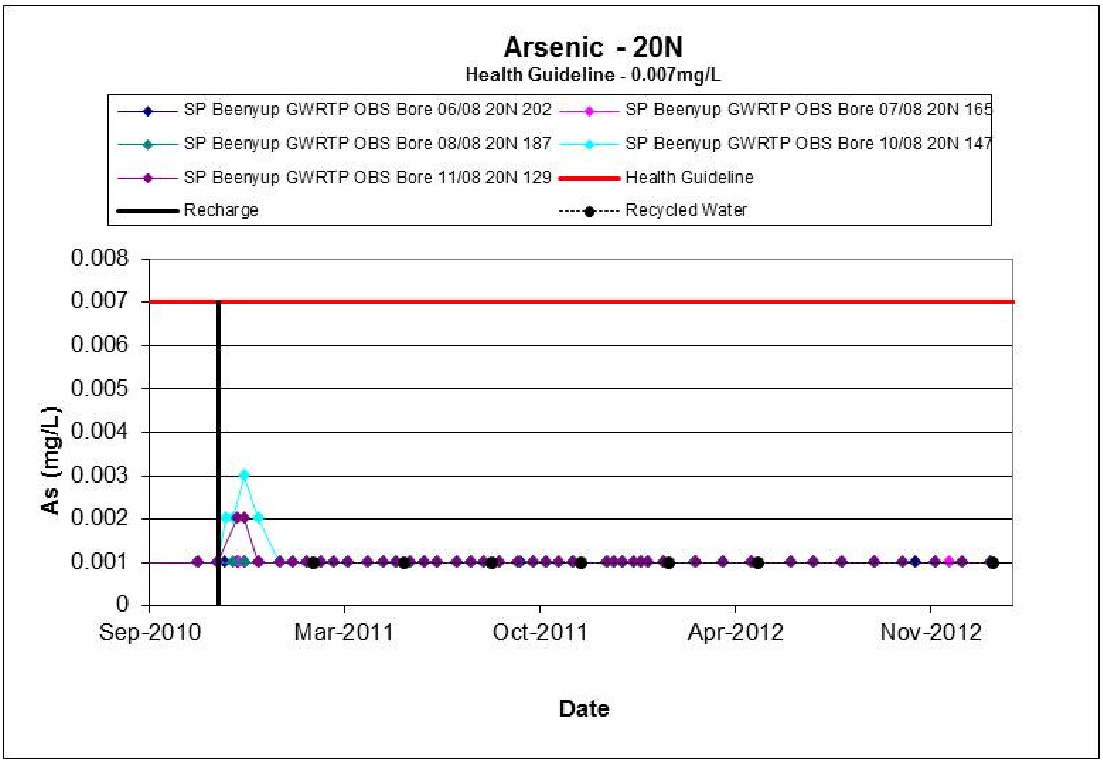


Figure 7.7: Arsenic - 20N Site

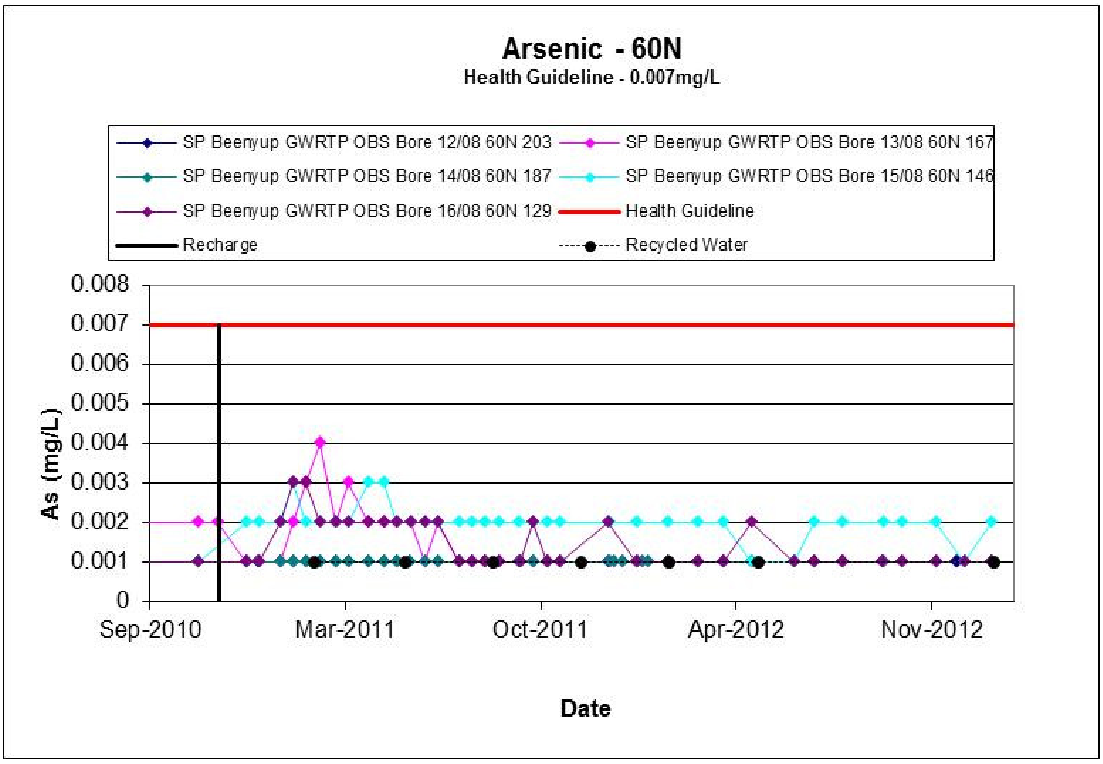


Figure 7.8: Arsenic - 60N Site

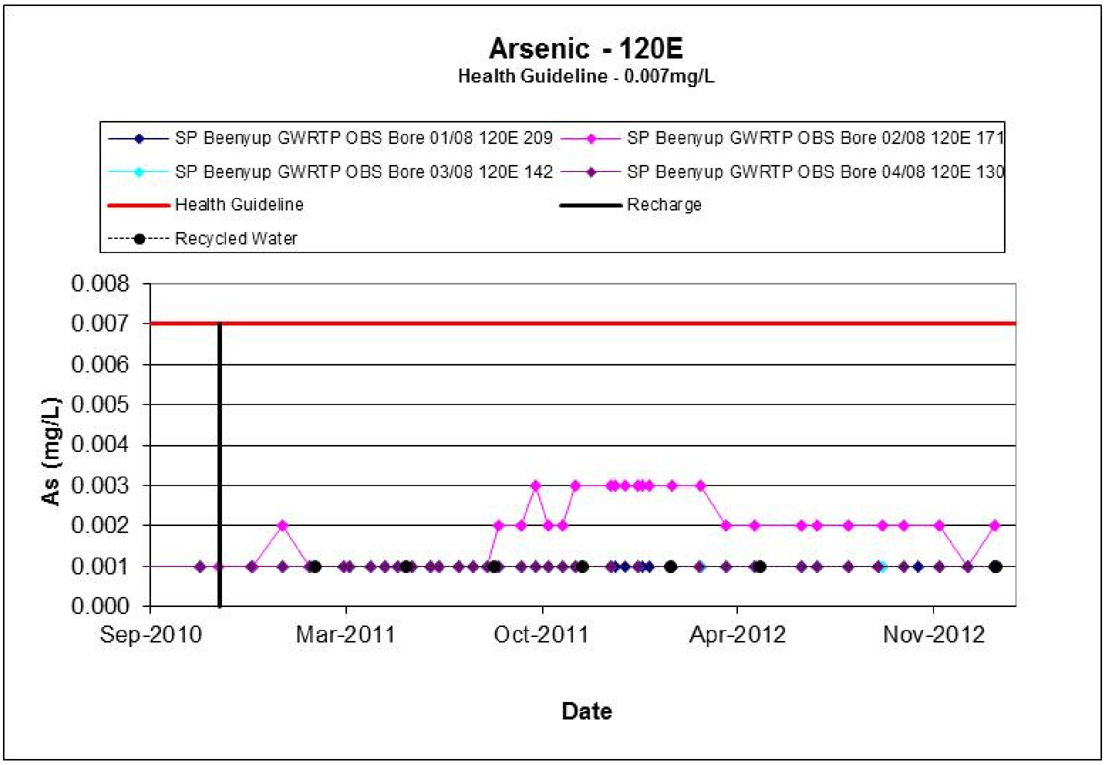


Figure 7.9: Arsenic - 120E Site

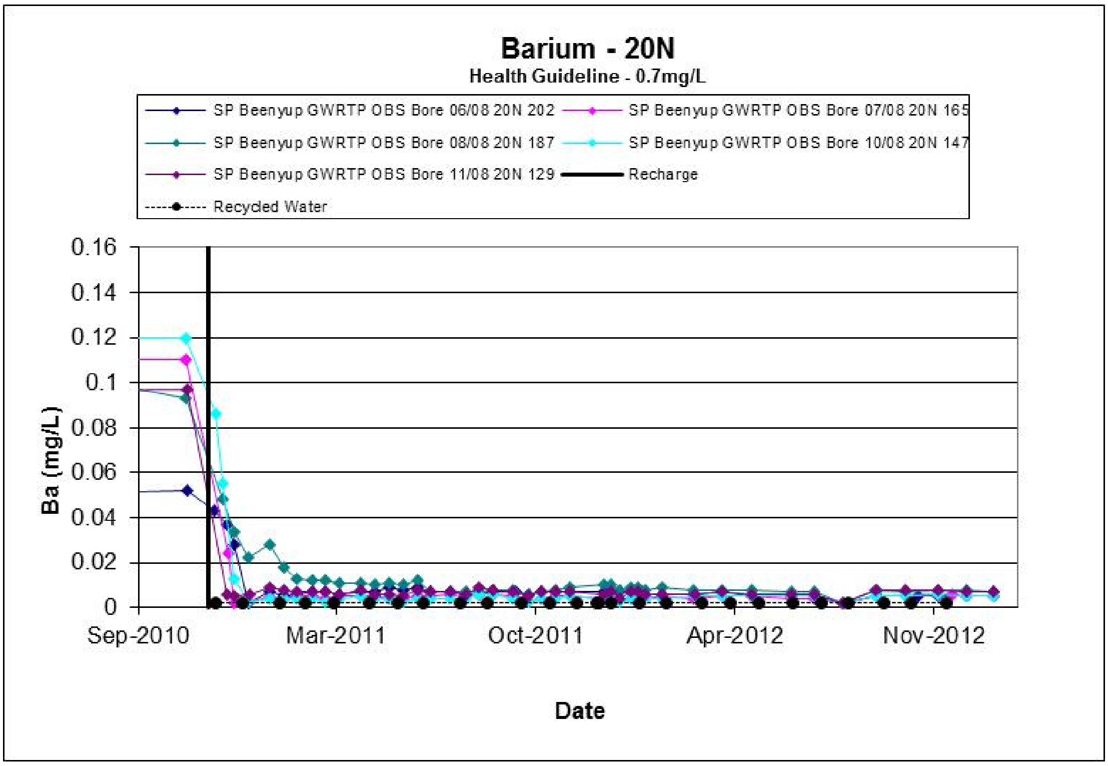


Figure 7.10: Barium - 20N Site

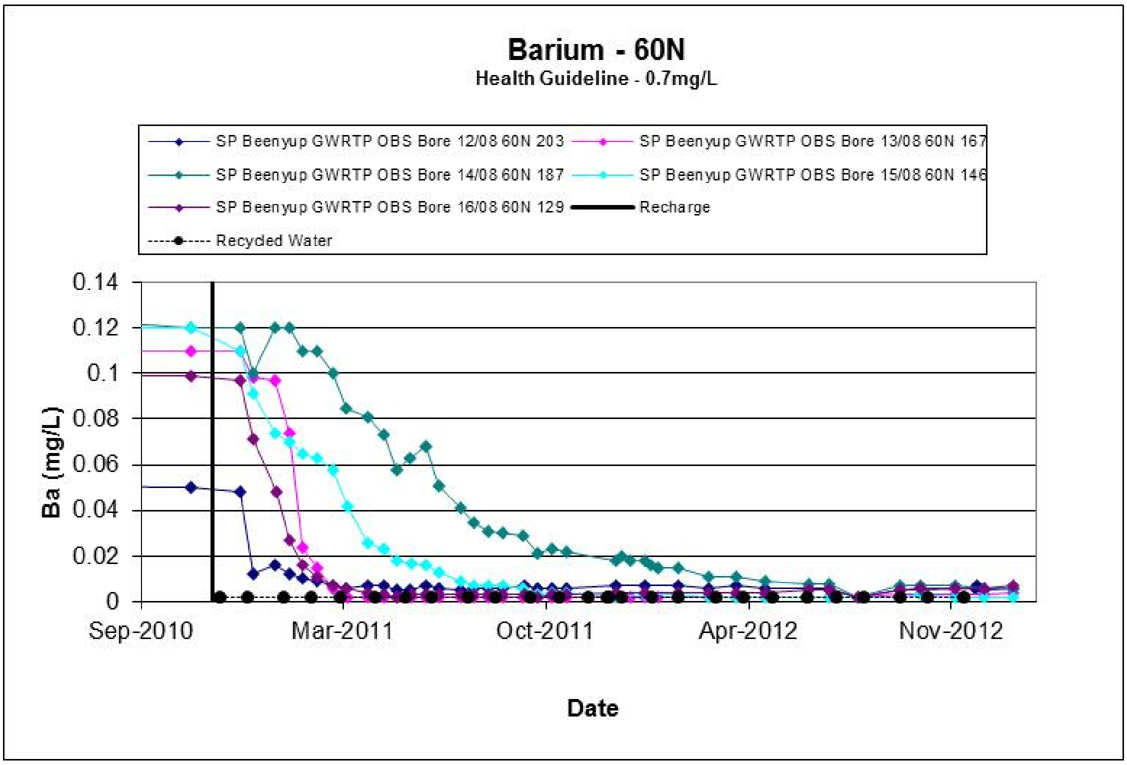


Figure 7.11: Barium - 60N Site

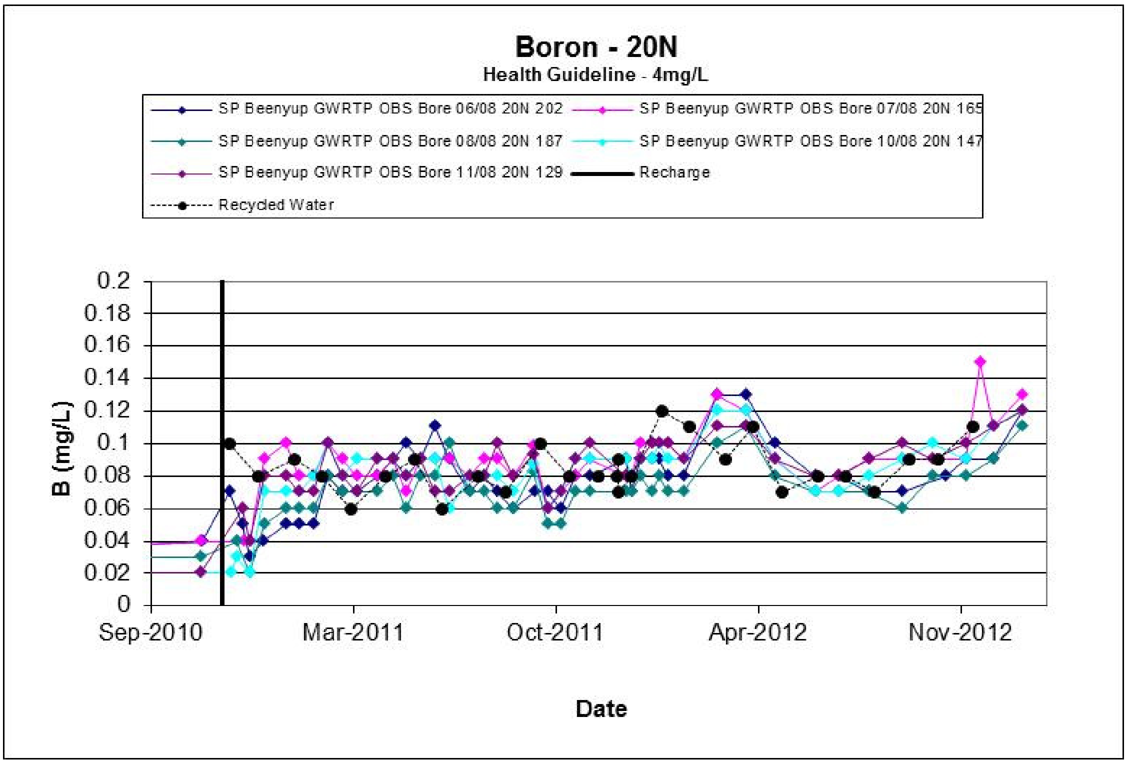


Figure 7.12: Boron - 20N Site

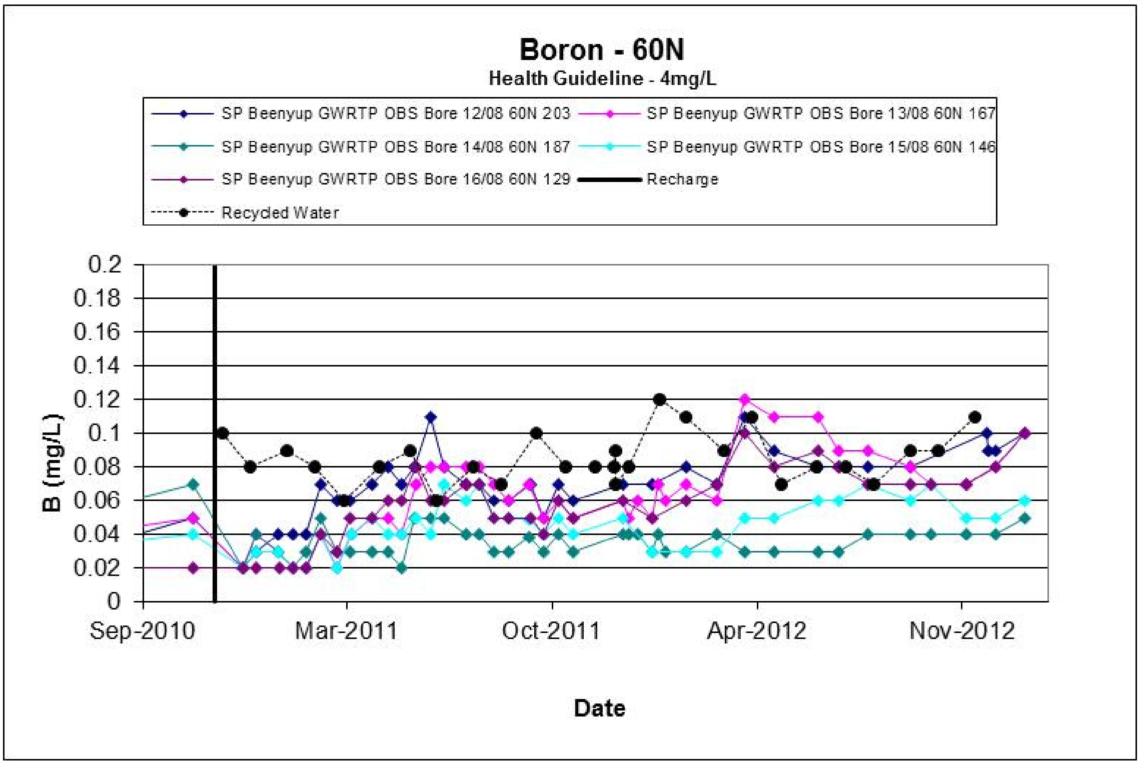


Figure 7.13: Boron - 60N Site

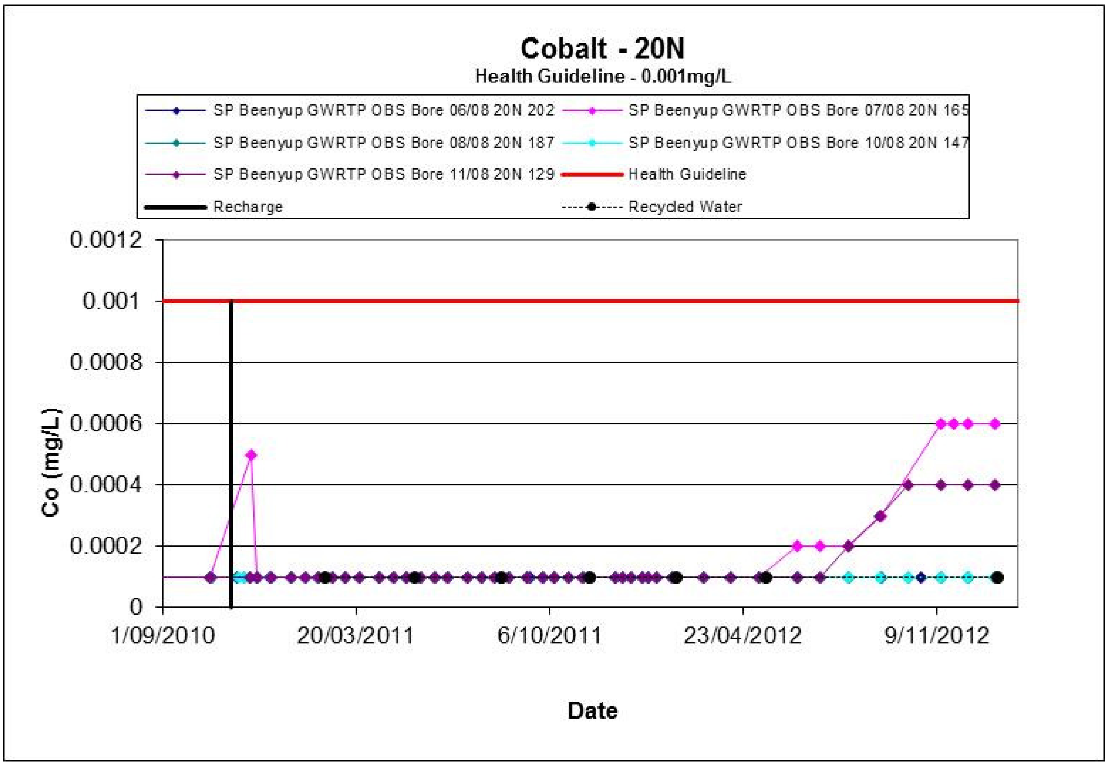


Figure 7.14: Cobalt - 20N Site

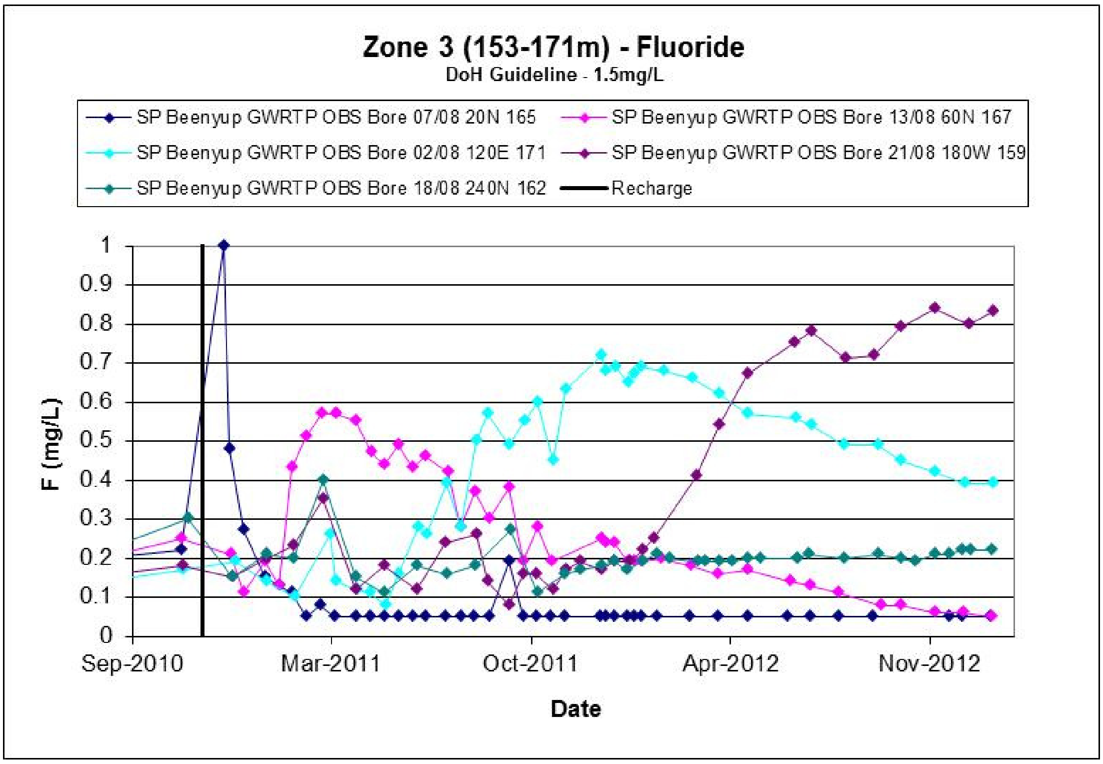


Figure 7.15: Fluoride - Zone 3 (153-171m)

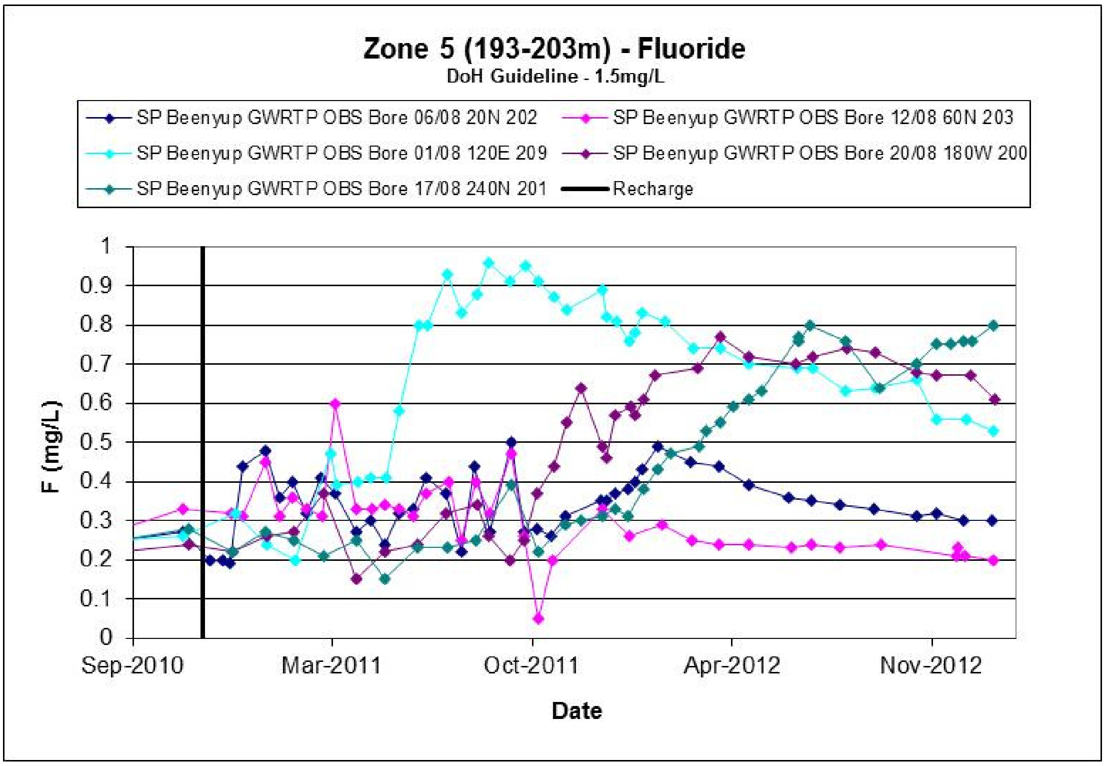


Figure 7.16: Fluoride - Zone 5 (193-203m)

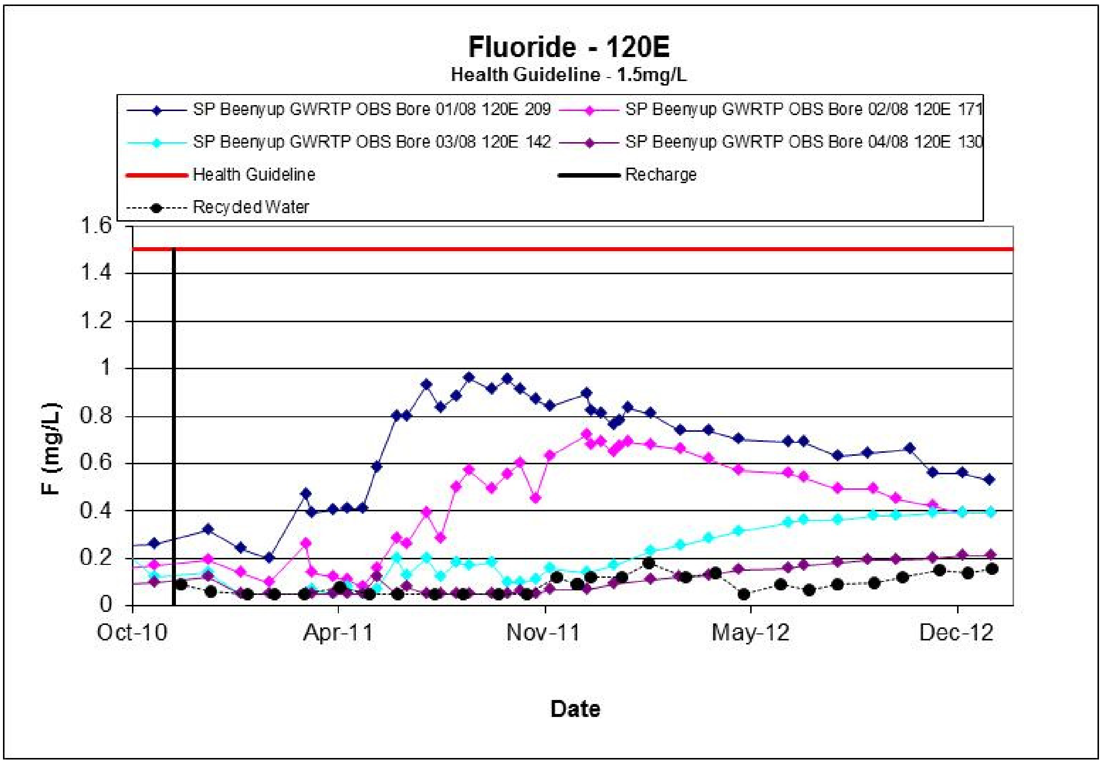


Figure 7.17: Fluoride - 120E Site

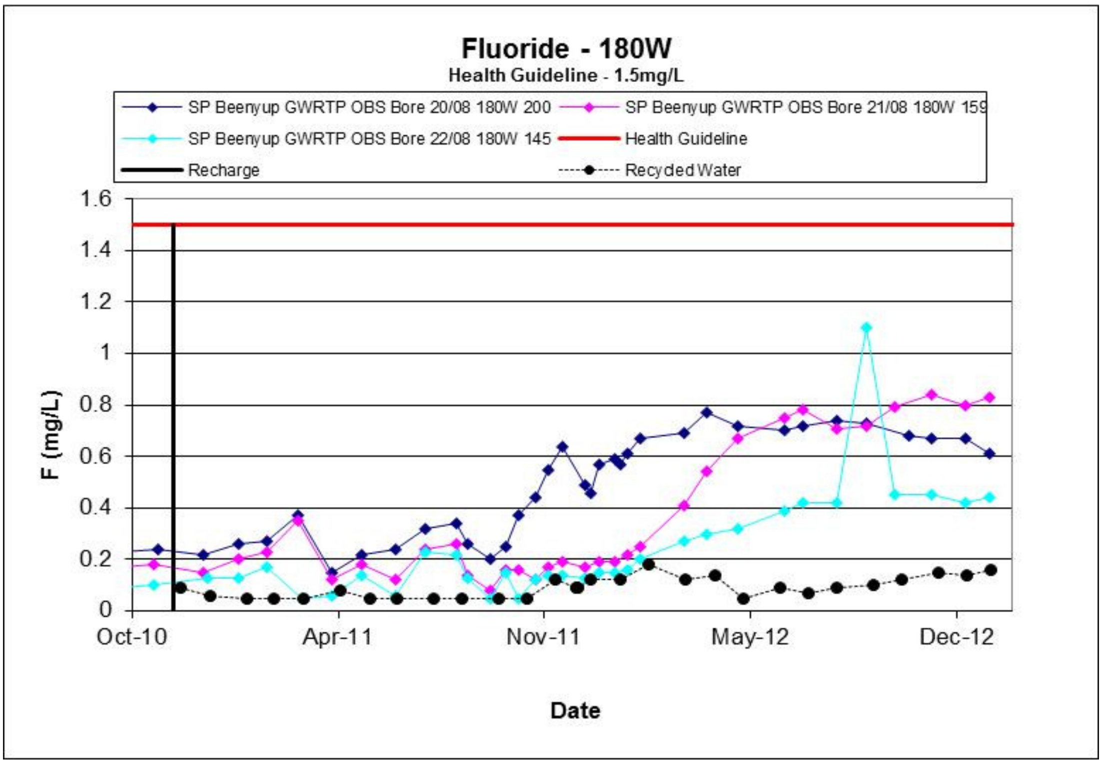


Figure 7.18: Fluoride - 180W Site

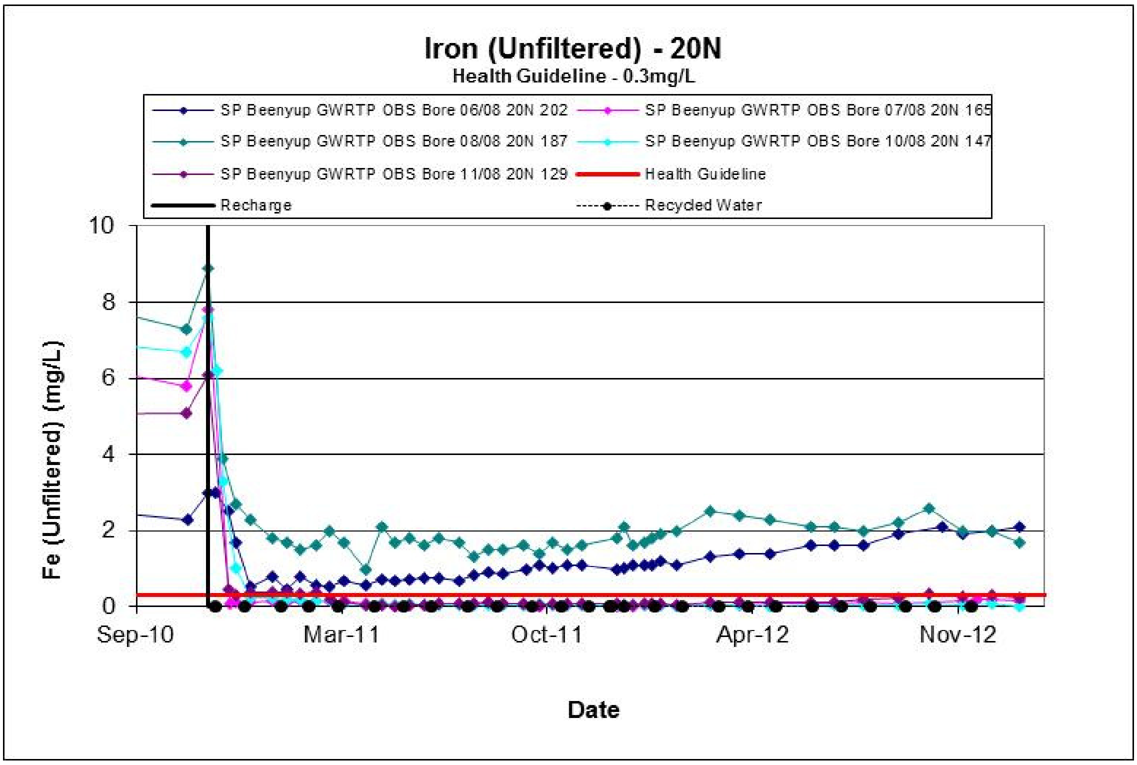


Figure 7.19: Iron (Unfiltered) - 20N Site

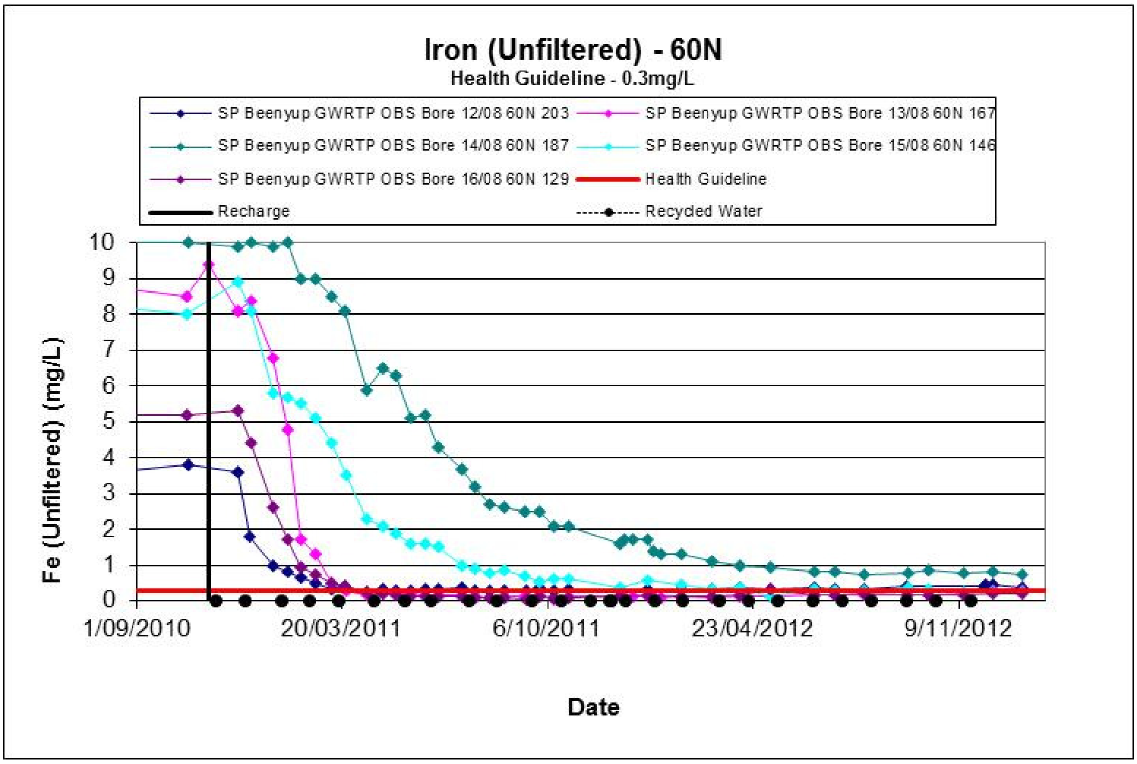


Figure 7.20: Iron (Unfiltered) - 60N Site

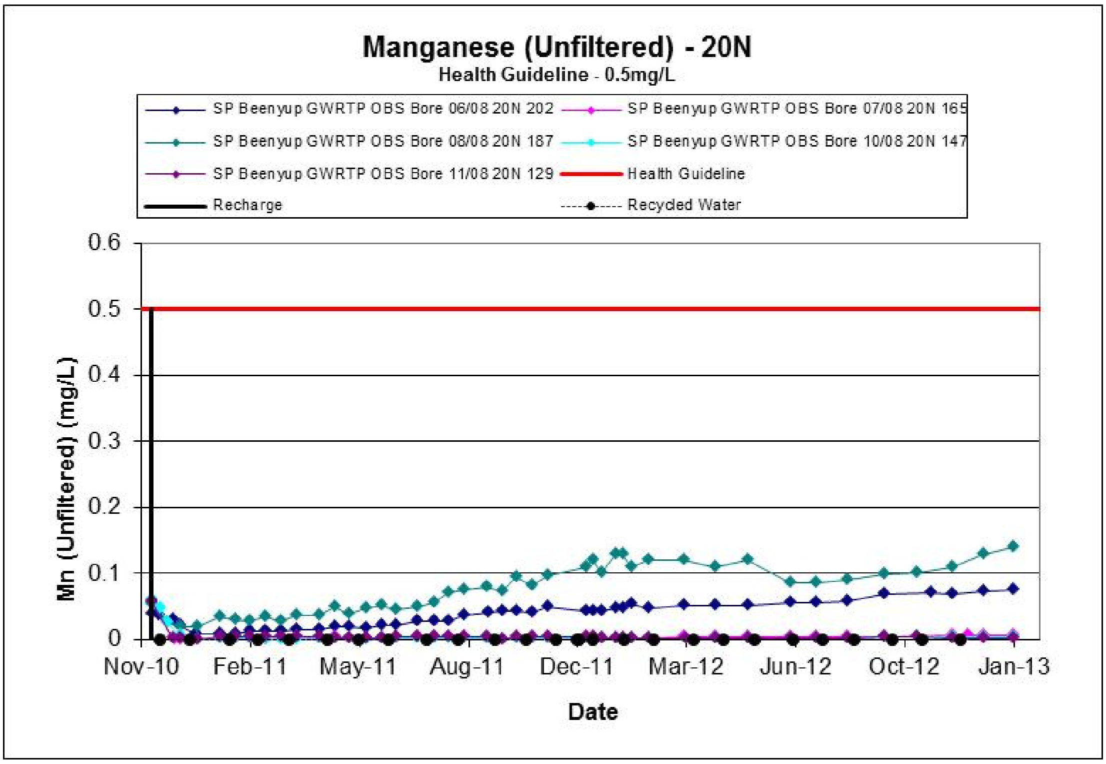


Figure 7.21: Manganese (Unfiltered) - 20N Site

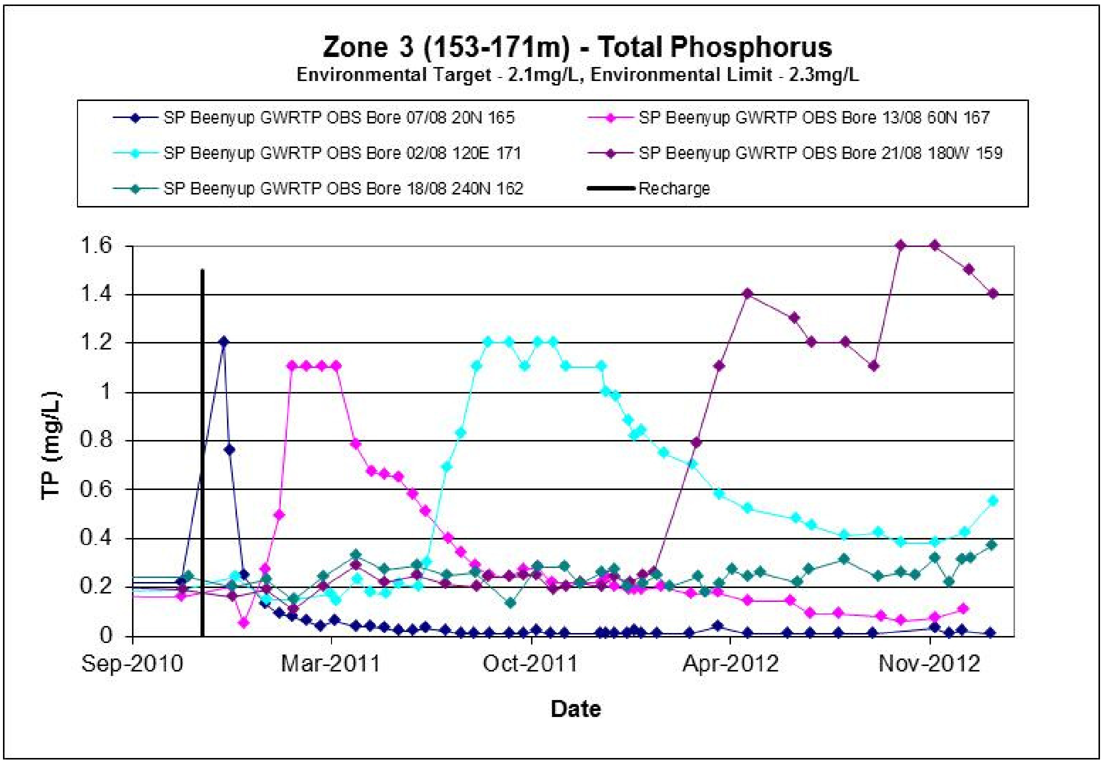


Figure 7.22: Total Phosphorus - Zone 3 (153-171m)

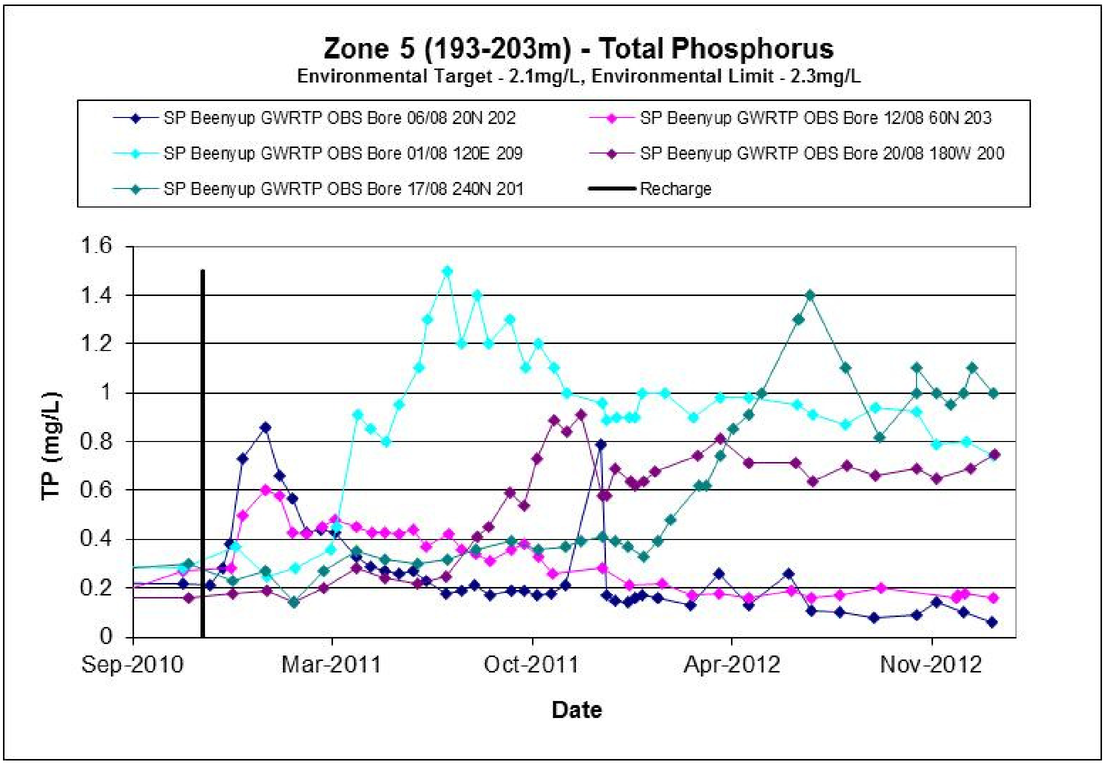


Figure 7.23: Total Phosphorus - Zone 5 (193-203m)

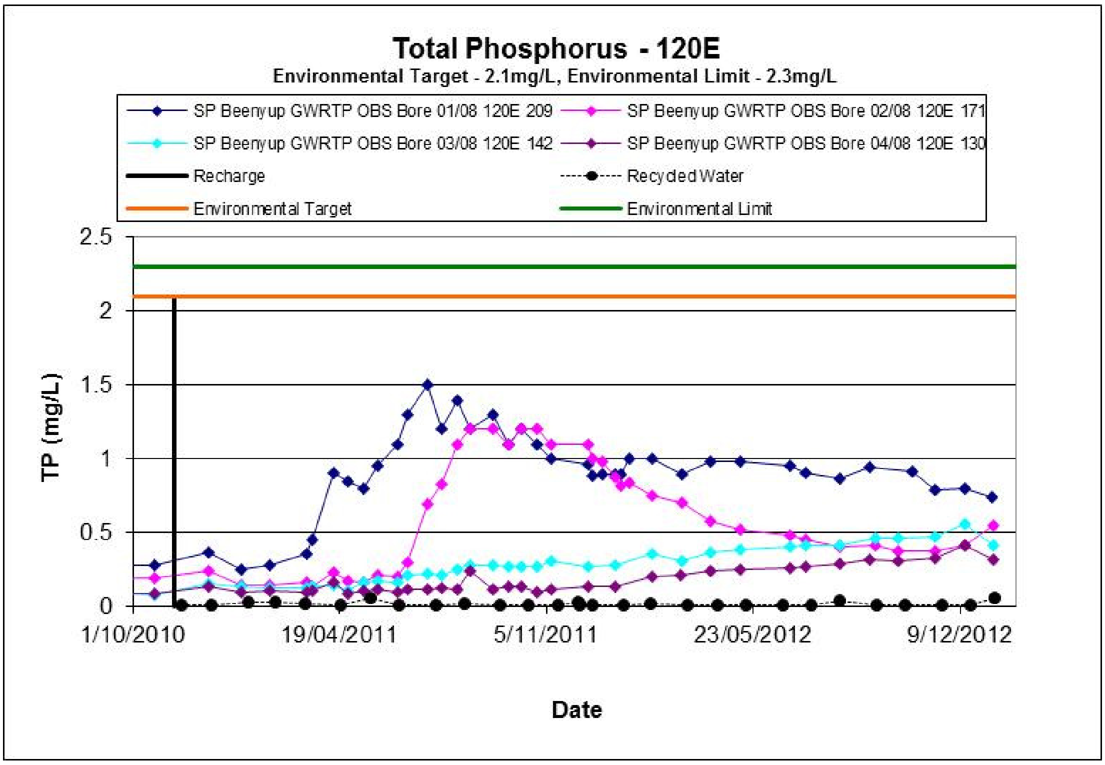


Figure 7.24: Total Phosphorus - 120E Site

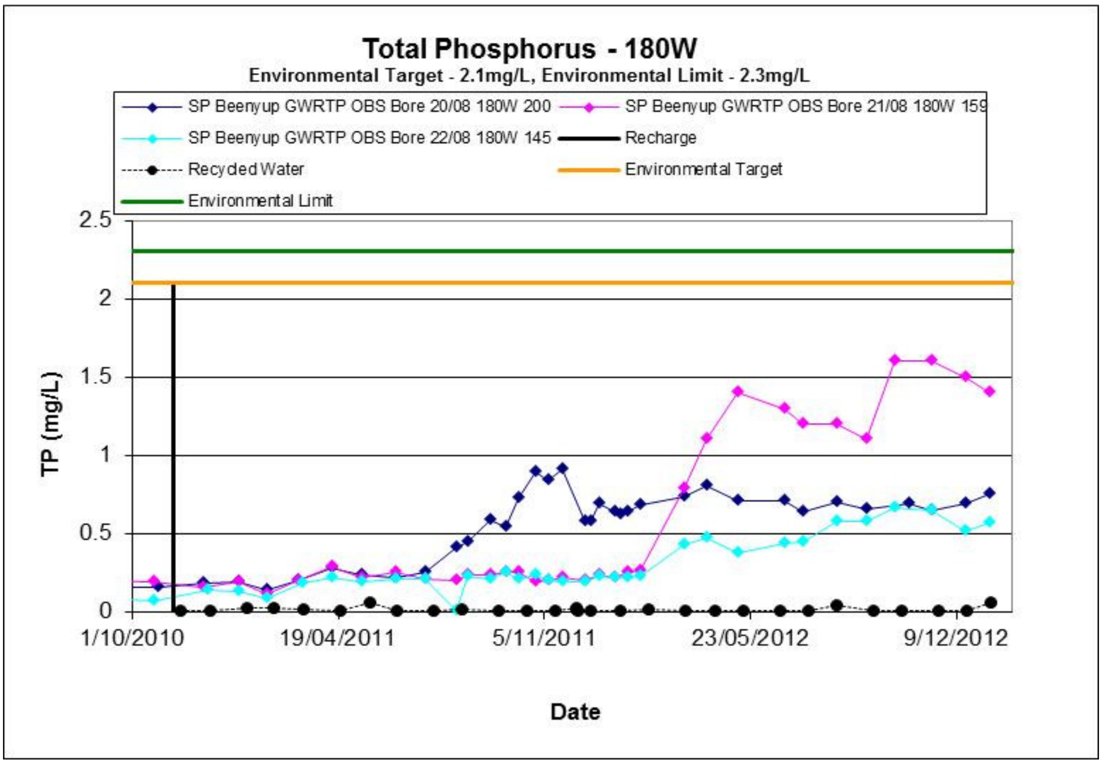


Figure 7.25: Total Phosphorus - 180W Site

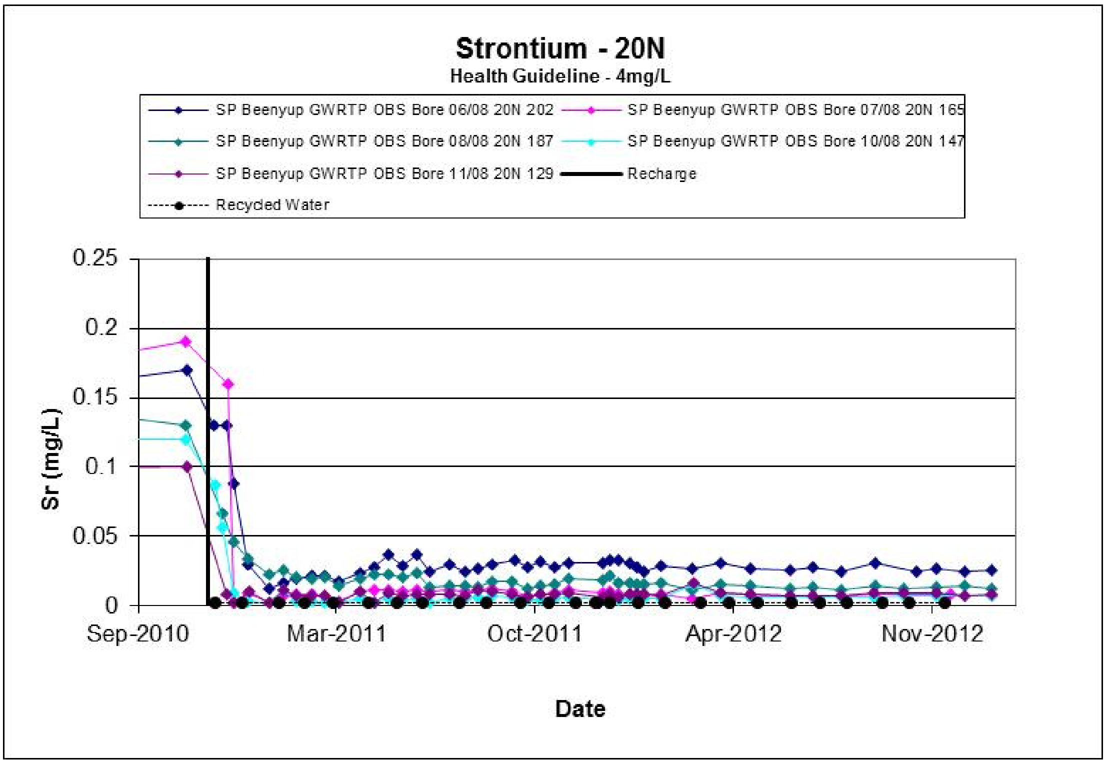


Figure 7.26: Strontium - 20N Site

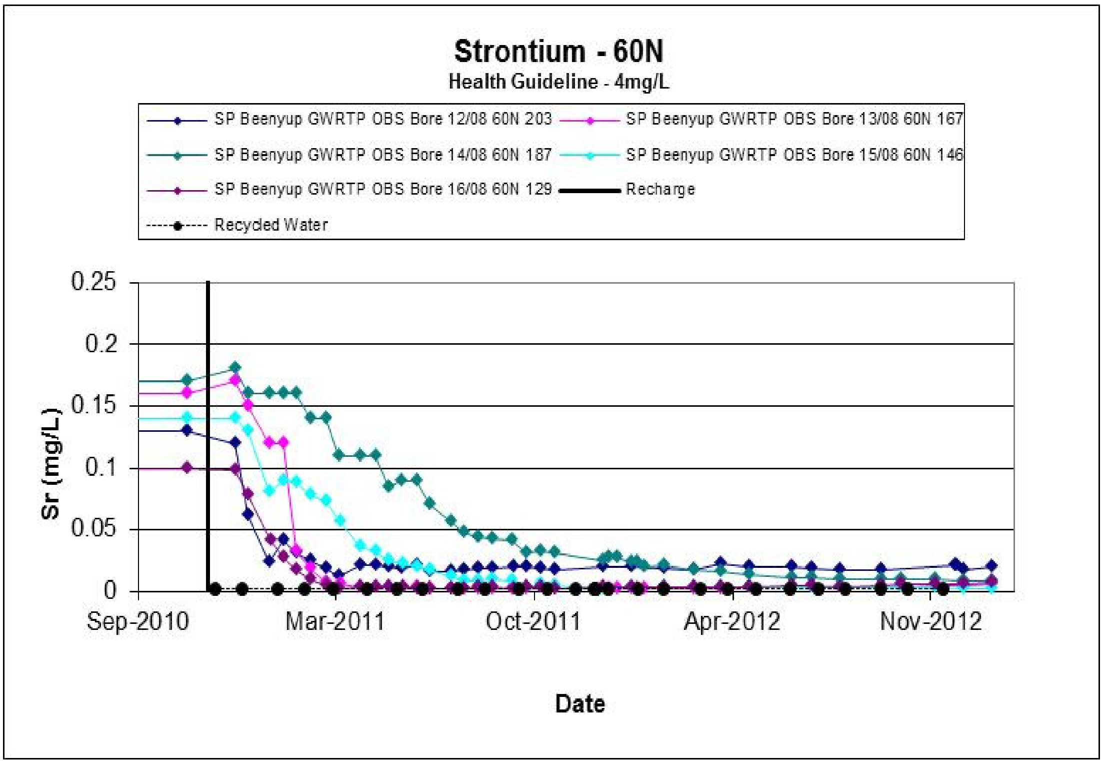


Figure 7.27: Strontium - 60N Site

7.3.3 Recycled water quality

Approximately 300 chemical, microbiological and physical parameters have guidelines set by regulators to protect human and environmental health. These guidelines must be met in the recycled water prior to recharge to an aquifer. There is potential for low level trace organic compounds to be present in the recycled water after treatment, particularly disinfection-by-products (DBPs). The current design and operation of the AWRP is to minimise formation of DBPs. In addition, groundwater research indicates that microbiological communities present in the aquifer contribute to the degradation of these compounds.

To verify the safety of the recycled water, 18 RWQI which are representative of the 292 RWQP were monitored. When these RWQI are below water quality guidelines, these provide confidence that the represented group of RWQP are also below guideline levels.

Analysis of recycled water during the Trial indicates concentrations of DBPs and other trace organics in the recycled water were close to or below LOR (Table 7.2). These low concentrations have made it difficult to detect trace organic compounds in the Leederville aquifer (Water Corporation, 2012b).

Trials results to date also indicate that microbiological communities naturally present in the Leederville aquifer have the ability to biodegrade trace organics and nutrients (Patterson et al, 2010, Water Corporation, 2012b).

Given the AWRP's ability to reduce organic and inorganic chemicals to below guideline concentrations and the potential of the Leederville aquifer to biodegrade, the mitigated risk from recharging trace organic and inorganic compounds was assessed as low.

Table 7.2: GWRT Recycled Water Quality Indicators Summary (10th November 2012 – 31st December 2013)

Indicator	Group Represented	Unit	GWRT Guideline	LOR	Ave	StDev	Max	Min	N
MS2 coliphage	Microbial pathogens	pfu/L	<1	0.6	<0.6	0	<0.6	-	31
Gross alpha activity	Radioactivity	mBq/L	500	10	15	6	27	<10	10
Gross beta activity (minus K40)		mBq/L	500	10	55	24	<71	<10	10
Boron	Metals and metalloids	mg/L	4	0.02	0.09	0.02	0.12	0.05	29
Nitrate	Inorganic anions	mg/L	11	0.01	1.99	0.84	3.6	0.87	29
NDMA	Nitrosamines	ng/L	10	1	1.8	0.97	4.8	<1	29
Chlorate	Inorganic DBPs	mg/L	0.7	0.01	<0.01	0	0.01	<0.01	10
Chloroform	DBPs	µg/L	200	0.05	0.38	0.19	0.83	0.17	29
Carbamazepine	Pharmaceuticals and personal care products	µg/L	100	0.05	<0.05	0	<0.05	-	29
Diclofenac		µg/L	1.8	0.05	<0.05	0	<0.05	-	29
Estrone	Hormones	µg/L	30	1	<1	0	<1	-	9
Trifluralin	Pesticides and herbicides	ng/L	50,000	1	<1	0	<1	-	9
2,4,6-trichlorophenol	Phenols	µg/L	20	1	<1	0	<1	-	7
1,4-dioxane	Neutral organic compounds	µg/L	50	0.1	<0.1	0	<0.1	-	29
1.4-dichlorobenzene	Volatile organics	µg/L	40	0.05	0.12	0.08	0.41	<0.05	29
EDTA	Complexing agents	µg/L	250	10	<10	0	<10	-	29
Fluorene	Polycyclic aromatic hydrocarbons	µg/L	140	0.1	<0.1	0	<0.1	-	7
Octadioxin	Dioxins, furans & dioxin-like PCBs	pg/L	100ng/L	2	4.6	3.38	10	<2	8

7.4 Risk of poor aquifer response

7.4.1 Hydrogeological Barriers

Extended pump testing as part of the Trial (Rockwater 2011a, (Water Corporation 2012a) confirmed the presence of a hydrogeological barrier in the Leederville aquifer, believed to be caused by the Kings Park Formation. This is accounted for in current build up estimates and PRAMS models.

As part of assessing head build up for recharge at 14GL/yr, it was observed that scaled extrapolated head build up was greater than theoretical predictions at distance from the recharge bore (Appendix D). While this may be partly attributable to the extrapolation and scaling approach, it may indicate the presence of other boundaries, possibly due to aquifer heterogeneity or faulting. Pressure will be monitored in the recharge bore and monitoring bores of a GWR Scheme and used to evaluate if there an increased recharge head due to a hydraulic barrier.

7.4.2 Integrity of the confining layer

Damage to the confining (aquitard) layers due to over-pressurising the Leederville aquifer resulting in upward leakage of the recycled water was identified as a low inherent risk in the 2012 Leederville Aquifer Risk Assessment. The MAR guidelines provide a conservative maximum recharge pressure that the aquitard could tolerate, derived by calculating (1.5 x depth of overburden to base of the aquitard). Therefore a maximum recharge head would be 180m above the surface at the Beenyup site. The AWRP is currently recharging at a pressure of 200kPa, and heads in the aquifer have been at a maximum of 11m below ground level (9mAHD, Figure 7.28).

Modelling of head rises as a result of recharging 14GL/yr is included in Appendix D. The head build up after 10 years for a range of recharge rates was determined from scaling and extrapolation of the late time (post boundary effect), extended pumping test results (Rockwater 2011a, Water Corporation 2012a), and are shown in Table D-3 (Appendix D). Recharging up to 14GL/yr into the Leederville aquifer at the Beenyup site would result in an increase in head to 21m above ground level, well below the 180m maximum based on the MAR guidelines, and has been assessed as a low mitigated risk.

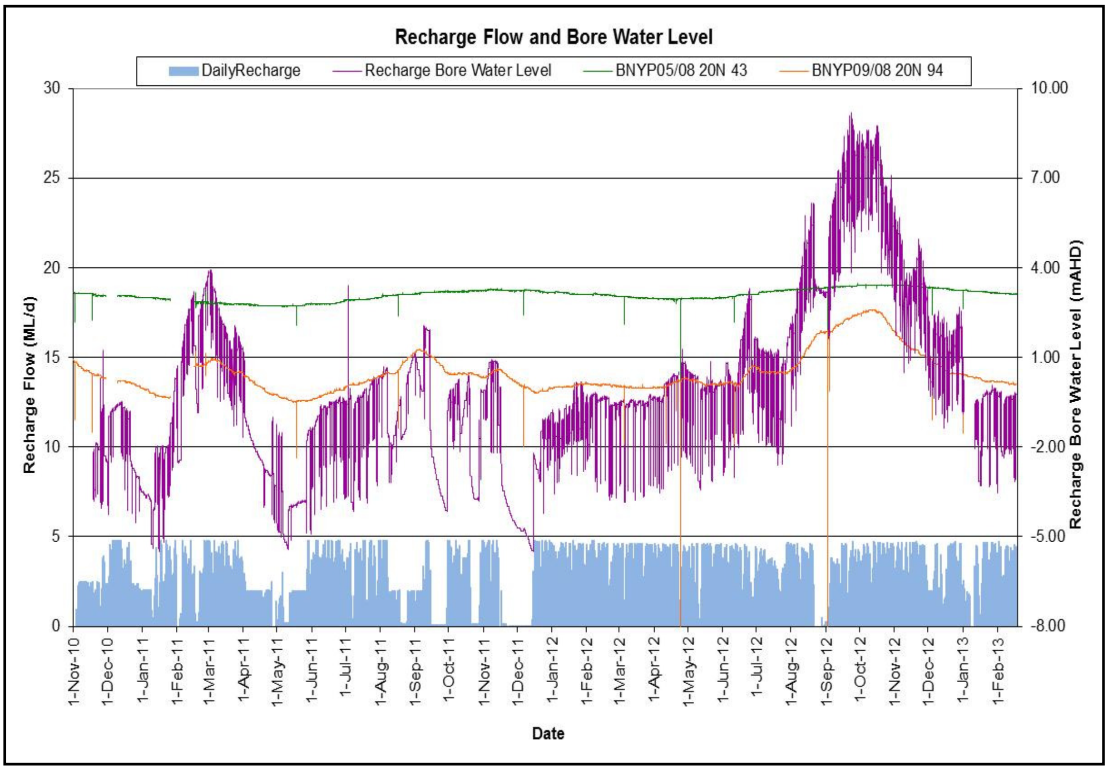


Figure 7.28: Potentiometric heads, water level and recharge volumes

7.4.3 Risk of leakage to the overlying aquifer

The travel times for recycled water to reach the Superficial aquifer was predicted by applying the recharge scenarios to the analytic model presented in Appendix D. Results of the travel times resulting from the recharge rates are summarised in Table 7.3.

Table 7.3: Estimated travel times for recycled water recharged at the Beenyup site to move to the base of the Superficial aquifer

GWR Scheme	Recharge (GL/yr)	ML/d	Travel Time (years)
Stage 1	3.5	9.6	1500
	7	19.2	600
Stage 2A	10	27.4	440
	14	38.4	250

While there is a possibility for upward flow further from the recharge bore, this is mitigated by the reduced head with distance from the bore, the horizontal travel time within the aquifer, and the extent and thickness of sediments overlying the recharge zone. At a distance of 500m (1 PRAMS grid cell) from the recharge bore, the estimated vertical travel time would increase to 700 years at a recharge rate of 14GL/yr (Appendix D).

A 3D visualisation of the steady state solute transport based on PRAMS3.4 PMPATH for recharge at 14GL/yr to the Leederville aquifer is shown in Figure 7.29. This indicates that recharged water does not move out of the Leederville aquifer. This result is consistent with the long travel times predicted for upward flow at a site scale, and highlights the conservative nature of the analytic approach which does not include lateral flow in the overlying sediments. No mitigating actions are required, as the confining layer separating the Leederville and Superficial aquifers is sufficient to prevent the recycled water from moving upward.

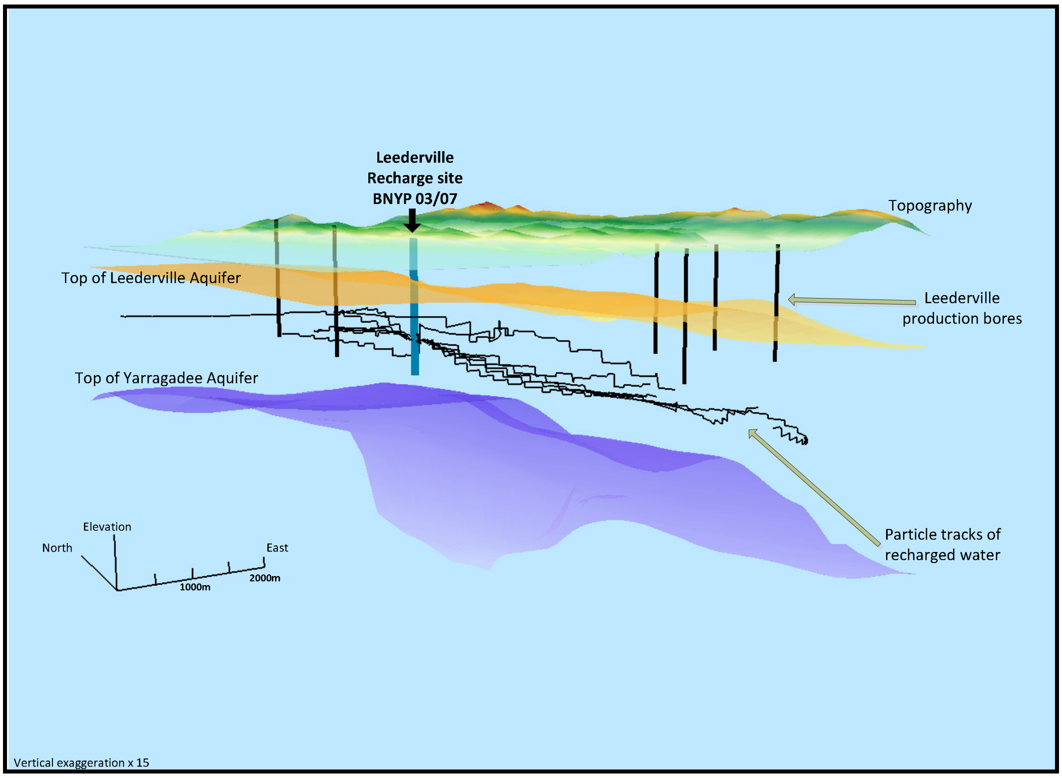


Figure 7.29: Steady state flow of recycled water in the Leederville aquifer

7.4.4 Risks of aquifer dissolution

The potential of aquifer dissolution due to mixing of recycled water with the native groundwater and aquifer was assessed with two end points; impacts to aquifer integrity by increased permeability and a human health end point due to the recycled water travelling to nearby abstraction bore faster. The inherent risk of both was assessed as low due to the Leederville aquifer being predominantly silica based with low levels of carbonates, and the pH of the groundwater is unlikely to increase to levels that may cause dissolution of silicates. Carbonates, such as calcite and siderite, are more soluble minerals compared to silica based minerals (Water Corporation, 2012a). The low levels of carbonates (Water Corporation, 2009a) indicate significant aquifer dissolution is unlikely to occur. Total dissolved solids (TDS) and bicarbonate concentrations are used as surrogates of aquifer dissolution. Concentrations of TDS to date are only slightly higher than recycled water concentrations indicating that major dissolution is not occurring (Figure 7.30– Figure 7.32).

Bicarbonate and pH monitoring are included in the GWR 1.5GL Scheme Aquifer Monitoring Plan (Water Corporation, 2013b). Monitoring pH will provide an indication of a change in aquifer conditions that may allow for the potential for aquifer dissolution. These parameters will be used as indicators of aquifer dissolution, along with the monitoring of aquifer pressure. The mitigated risk of aquifer dissolution has been assessed as low.

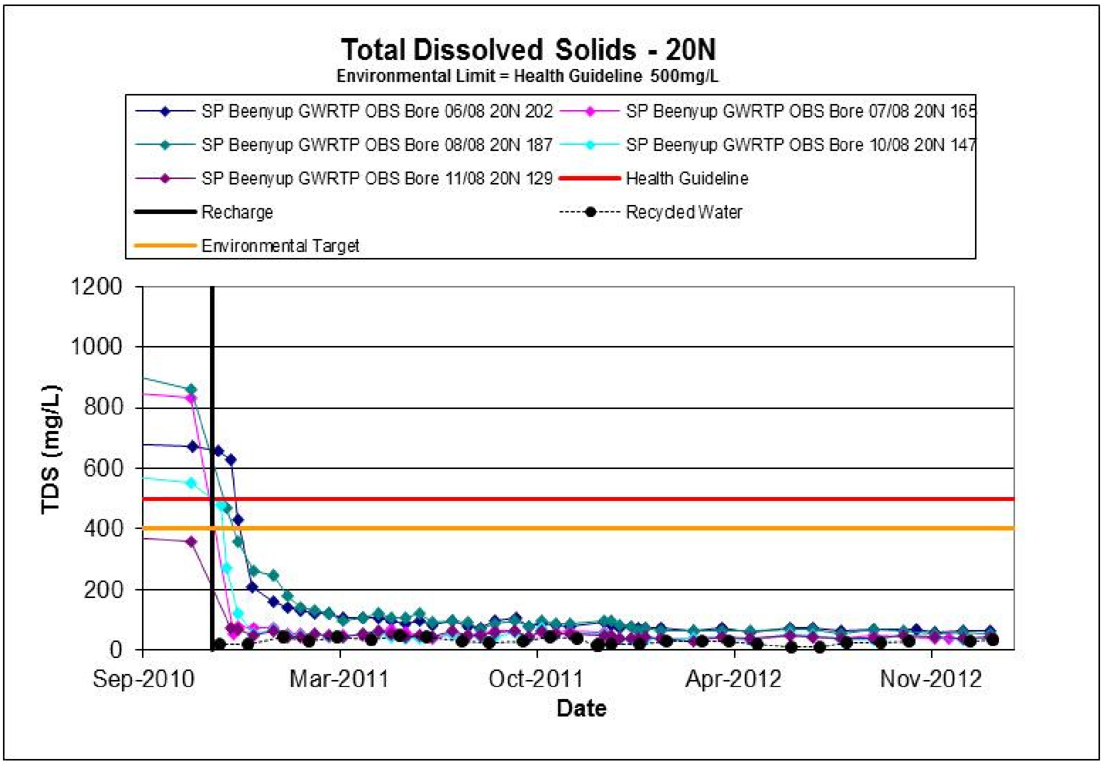


Figure 7.30: Total Dissolved Solids - 20N Site

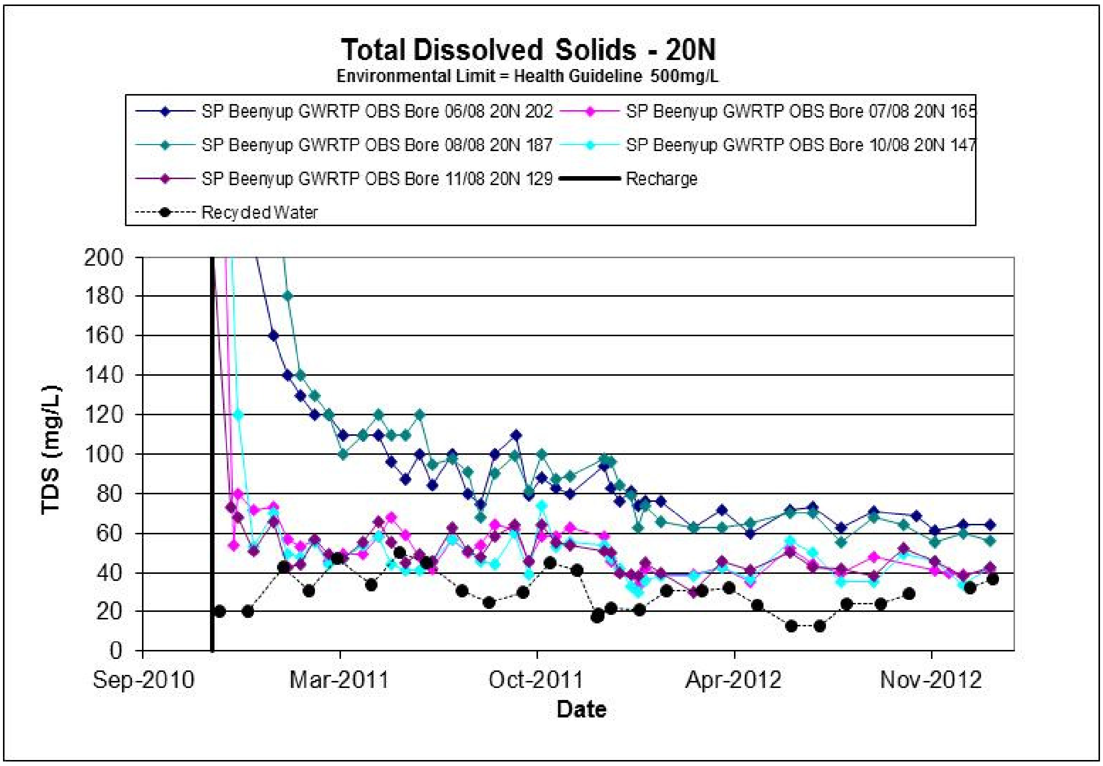


Figure 7.31: Total Dissolved Solids - 20N Site - refined mg/L axis

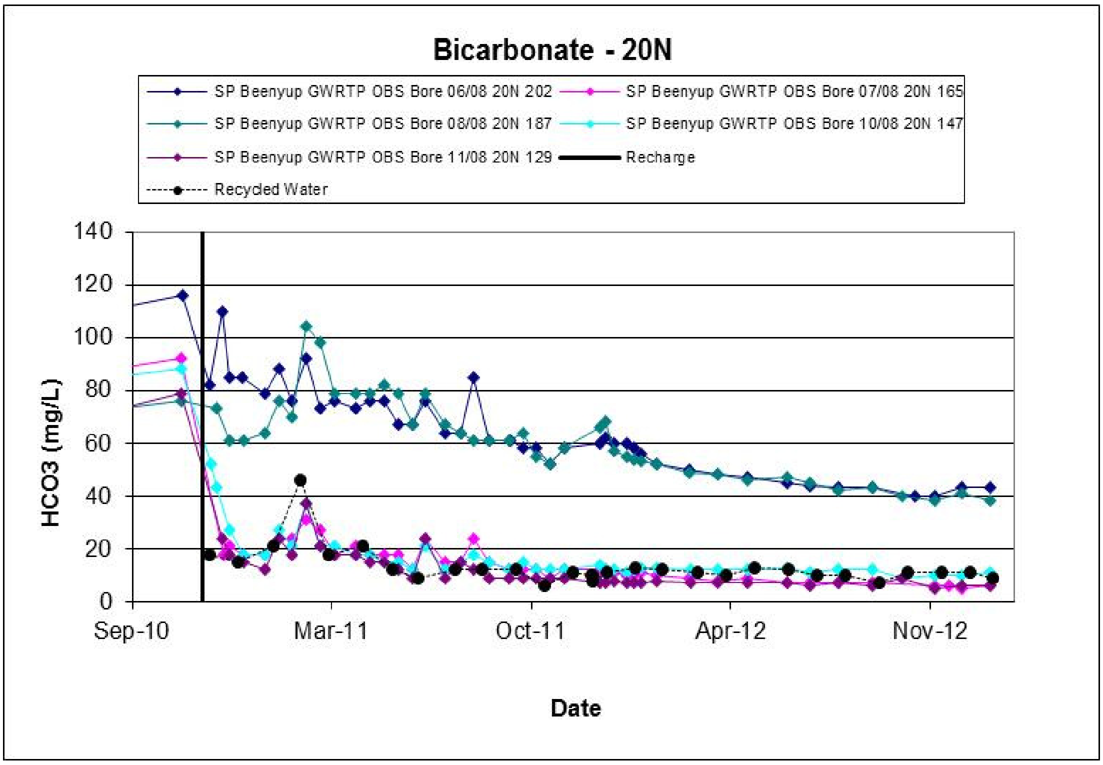


Figure 7.32: Bicarbonate - 20N Site

8 Yarragadee Aquifer Risk Assessment

8.1 Risks from drilling and bore construction

Potential risks resulting from drilling and bore construction are associated with encountering adverse geological conditions, i.e., cavernous limestone and/or swelling clays, and construction problems such as loss of the casing string, packer failure and failure to adequately seal the bore annulus (Rockwater, 2011b).

The inherent risks were assessed as low or moderate without mitigation, and can all be adequately controlled by ensuring appropriate bore design and engaging experienced and competent drilling companies with support from drilling mud specialists. The mitigation strategies are well understood and proven in Western Australia and have been successfully used in the Leederville and Yarragadee aquifers. Key site-specific mitigation strategies include:

- Pre-collar karstic Superficial formations to reduce the risk of bore collapse during drilling;
- Ensuring a drilling mud engineer is available and on site to oversee mud quality, and mitigate risks associated with swelling clays, reaction with carbonaceous material (esp. coal) and bore construction;
- Engaging drilling contractors with proven experience in deep water-bore drilling and well documented process controls;
- Providing suitable recharge bore construction design plans which will avoid the risk of packer failure and cementing of screens.
- Running a cement bond or suitable sonic log upon completion to confirm a complete annular seal.

Drilling and construction of the Yarragadee monitoring bore (YMB-01/12) commenced in September 2012, details of drilling, lithology and construction details are available in the *Yarragadee Monitoring Bore Completion Report* (Rockwater, 2013). The Superficial aquifer precollar was drilled utilising dual rotary drilling to a depth of 59.7mbgl and a Leederville aquifer precollar due to planned coring, utilising mud rotary drilling to a depth of 275mbgl. The hole was then drilled to a depth of 652mbgl using diamond core drilling methods to provide material for the required characterisation experiments. The hole was then reamed using mud rotary drilling methods to convert the hole to a monitoring bore, and drilled down to a final depth of 751mbgl. The bore was then constructed using FRP blank and slotted casing.

Given the listed mitigations, the risks associated with drilling and constructing a bore in the Yarragadee aquifer have been assessed as low.

8.1.1 Risk of screen corrosion

The recharge of low alkalinity recycled water could cause a decrease in pH when mixing with the groundwater and aquifer material resulting in corrosion of the recharge bore screen if inadequate materials are used. This could result in recharge bore screen failure impacting capability to recharge.

Due to the low alkalinity of the recycled water this was previously rated as a high inherent risk in the Leederville Aquifer Risk Assessment. Mitigations were identified during detailed design by the use of appropriate materials of fibre reinforced casing (FRP) and stainless steel screens (Water Corporation, 2009b). When a maintenance opportunity arises requiring the down hole valve and recharge bore infrastructure to be removed from the Leederville aquifer recharge bore (BNYP03/07) a camera log of the recharge bore and screens will be conducted to confirm the condition of the recharge bore screens. With the mitigation of FRP casing and stainless steel screen, the risk of corrosion was considered low.

These leanings from the Trial on using appropriate casing material such as FRP and stainless steel are transferable to the construction of Yarragadee recharge and monitoring bores.

8.1.2 Risks of deteriorating recharge bore integrity

The risk to recharge bore infrastructure due to over-pressurising the recharge bore, resulting in failure of the bore casing or headwork's causing injury to by-standers was assessed. Through adequate drilling techniques, design criteria and work instructions, this will ensure appropriate materials and fittings are utilised in construction and maintenance. Currently, the lowest design limit is for headworks, which has a pressure rating of 150m head of water above ground level, (to be confirmed at time of construction). Continuous monitoring of bore pressure and flow results in shutdown if set limits are reached, ensuring the maximum allowed pressure is not exceeded. With appropriate design, construction and monitoring, this risk is mitigated to low.

8.2 Risks resulting in bore clogging and reduced aquifer permeability

8.2.1 Suspended Solids – Introduction via recycled water

Clogging may be caused by suspended solids that have been introduced from the recycled water. Recycled water from the AWRP is essentially free of suspended solids, but they are potentially introduced when chemicals are added at the end of the treatment process. This risk was mitigated at the Trial's AWRP by:

- Excluding alkalinity buffering from the treatment process;
- Placing strainers on the chemical dosing lines;
- Providing work instructions for cleaning and flushing pipes and fittings after maintenance;
- Providing the pipework to flush headworks; and
- Undertaking regular turbidity sampling of recycled water.

The AWRP demonstrated through verification monitoring (Table 7.1) that these current mitigations are appropriate. Monitoring in the Leederville aquifer as part of the Trial has shown that only minor clogging has occurred to date and unlikely due to introduced suspended solids. Therefore the risk of clogging due to the introduction of solids was assessed at an inherent risk of low and a mitigated risk of low.

If alkalinity buffering is required to be included in the treatment process, there are a number of robust mitigations, including appropriate design and continuous monitoring of turbidity, which may be implemented to mitigate this risk. If there is a change in the AWRP process (including alkalinity buffering) this risk will require re-assessment.

8.2.2 Mobilisation of fines

The potential for mobilisation of fines within the Yarragadee aquifer may be similar to that in the Leederville aquifer (Section 7.2.2), given similar aquifer mineralogy with the presence of silt and clays, in particular kaolinite. However, there are potential differences in particle distribution and mineral types, with the presence of aquifer fines reported throughout the "poorly sorted" sandstones in core samples.

As recommended from the Preliminary Yarragadee Risk Assessment (Water Corporation, 2012c) dispersion tests have been conducted on Yarragadee core from the Beenyup site (Appendix C). This involved passing water from the AWRP through core plugs at successively increasing flow rates (7mL/min, 14mL/min, 36mL/min, 50mL/min and 100mL/min). Approximately 182 samples were taken during each full test (i.e. for each plug).

Turbidity has been recovered for the first ten 14mL water sample (i.e. 14mL vials) collected at each step change in flow rate, and results are presented in Appendix C. A significant number of tests remain to be completed however the preliminary results are adequate for the Yarragadee aquifer risk assessment. This risk will be further reviewed at future risk assessments.

At low rates of flow small particles are mobilized at an almost continuous rate. At much higher rates small particles (colloid sized particles as inferred form turbidity) tend to be mobilized as a pulse. Another important conclusion is that there is significant difference in small particle mobilization from samples that look very similar to the naked eye. For example core plug from 554.7m depth has an order of magnitude lower turbidity for most flow rates compared to the plug from 640.6m depth. However on closer inspection, the sample from 554.7m is relatively clean compared to 640.6m which is very poorly sorted. Additional work is being undertaken to assess the size and chemistry of particles mobilized at various stages of the flow through test for each plug sample.

Additional investigations may involve recharging the Yarragadee aquifer utilising the current AWRP, to test recharge conditions at a field scale. It is likely that mobile colloids would be exhausted and flushed as the recycled water passes through. Possible mitigations include appropriate design of the recharge bore (larger diameter and longer screens), stepped flow recharge rates, redevelopment if clogging of the bore were to occur, and potential amendment for the recycled water to increase the ionic strength, however this would require the physical clogging (suspended solids) risk to be reviewed. As this risk can be managed through design, operation and monitoring, it has been assessed as a mitigated risk of low.

8.2.3 Air entrainment – cascading water

Air-entrainment during recharge can be caused by cascading water into the bore, resulting in reduced bore efficiency as air bubbles become trapped in the aquifer and plug the formation pores. This often results in a significant and rapid increase in resistance to flow and a sudden increase in water levels (hydraulic head), particularly on start-up of the bore.

The inherent risk was assessed as moderate. The Trial demonstrated that the risk of air-entrainment is readily mitigated with appropriate recharge bore infrastructure, such as a down hole valve, which allows a positive recharge head to be maintained via an recharge line installed below the resting water level. With this mitigation in place the mitigated risk was assessed as low.

8.2.4 Air entrainment – dissolved gases

Air-entrainment during recharge can also be caused by the release of dissolved gasses from the recharge water or the groundwater in the aquifer usually as a result of changes to pressure and/or temperature. These released air bubbles may have the potential to clog aquifer pores, reducing the permeability of the aquifer and recharge efficiency.

Geochemical modelling utilising PHREEQC (Appendix B), and using available water quality, pressure and temperature data from the Yarragadee aquifer show that the contact of aerobic recharge water with sediment-bound organic matter and decomposition (mineralisation) of the organic matter leads the formation of CO_2 gas in the aquifer. The results illustrate that CO_2 gas formation at 40ºC is increased compared to the simulation for 25ºC, however the effect is far outweighed by the increased pressure at depths where the groundwater temperature is 40ºC. Under the pressure prevailing at 500m depth, no gas was formed in the simulations. The results indicate that gas formation at the depth of the Yarragadee recharge interval is unlikely. This has been assessed as a low risk and no further assessment is required.

8.2.5 Microbiological clogging

Microbiological clogging can occur when bacteria in the recharged water, introduced during drilling or indigenous to the aquifer undergo increased growth in modified conditions. An accumulation of impermeable slimes and a mat of dead cells can build up in and around the bore screens and lead to clogging and reduction of the recharge capacity of the bore. The degree of biological growth is directly related to the amount of assimiliable organic carbon and nutrients present.

The Trial has determined that the treatment process produces recycled water with a very low microbial content (less than the limit of detection) and dissolved organic carbon (less than 1mg/L), therefore the inherent risk associated with microbial clogging resulting from bacteria introduced via the recycled water is low.

The risks of introduced bacteria as a result of the drilling process are mitigated by standard drilling practice of disinfection of the bores as part of the bore development process. The risk of introducing bacteria via the drilling and bore construction process was considered to be low.

Sampling the Leederville aquifer prior to commencing recharge found that the groundwater microbial communities are likely to reflect dominant sediment communities present in the aquifer (Water Corporation, 2012). Groundwater samples from three nearby Yarragadee production bores (G17, W7 and WT97) were collected and analysed for microbiology communities using the same primers developed for the Leederville aquifer (Appendix B). The results indicate low numbers of bacteria in the Yarragadee aquifer samples compared to the Leederville aquifer.

For all three samples, while some diversity was observed, less than 20% of the bacterial groups could be identified. Considering the potential differences (e.g. lithology geochemistry and temperature) between the Leederville and Yarragadee aquifers, some differences in the microbial diversities could be expected. The bacterial community Burkholderiales was detected in all Leederville and Yarragadee groundwater samples, suggesting that this bacterial community is widespread in both the Leederville and Yarragadee aquifers.

Similar conditions with regard to microbial growth are likely to prevail in both the Leederville and Yarragadee aquifers. Mitigations include constructing an AWRP that limits concentration of nutrients and organic carbon, to limit biomass growth, disinfection recharge bore equipment prior to installation and after maintenance, and if clogging were to be detected through pressure monitoring, determine the cause of clogging and redevelop through processes such as backwashing or airlift the bore. The mitigated risk of microbiological clogging has been assessed as low.

8.2.6 Geochemical clogging

Geochemical clogging can occur when minerals are precipitated as a result of reactions occurring in response to a change in the existing geochemical equilibrium between the ambient groundwater and/or the aquifer matrix with the recharged recycled water. Due to the relatively low iron content of most aquifer materials and slow siderite dissolution kinetics, precipitation of iron minerals such as ferric oxides, hydroxides and oxyhydroxides is unlikely (Appendix B).

Initial geochemical modelling was based on Yarragadee groundwater samples from Water Corporation production bores WT97, W7, G17 and G7 taken 13/12/2012. This indicates that carbonate, sulphate, iron precipitation is unlikely (Appendix B). After two years of recharge into the Leederville aquifer, no geochemical precipitation causing clogging has been detected. Clogging monitoring will be ongoing through a GWR Scheme, and if significant were to occur the mitigation could include the construction of a new recharge bore onsite. The inherent and mitigated risk of geochemical clogging has been assessed as low.

8.2.7 Scaling

Clogging of the bore-aquifer interface could occur as a result of scaling. Scaling has not been seen in the Leederville recharge bore to date, and given this is dependent primarily on the quality of the recycled water; the information should be directly transferable (Section 7.2.6). Therefore the inherent risk of scaling was assessed as low without mitigation.

This risk will require reassessment if significant changes are made to the AWRP process (i.e. increasing buffering capacity of the recycled water). Potential mitigation strategies could include; reducing exit velocities of the recycled water through the screens (through longer or larger diameter screens), and through regular recharge bore maintenance including options such as camera logging, airlifting and backwashing.

8.3 Risks to human and environmental health

8.3.1 Mobilisation of chemicals

Geochemical reactions will occur as a result of the recharge of recycled water to the Yarragadee aquifer, there is a risk that metals could be mobilised above guideline levels. The predominant geochemical reactions identified in the Leederville aquifer relate to the oxidation of pyrite and organic matter, weathering of aluminosilicates (feldspars), dissolution of trace carbonate minerals and cation exchange reactions. As a result of the oxidation of pyrite and organic matter oxygen levels have generally remained low. There has been an initial increase in pH in the Leederville aquifer on breakthrough of recycled water, however with extended contact time, pH has decreased towards baseline levels. Mobilisation of metals, in particular aluminium (Al) (associated with the mobilisation of kaolinite clay), arsenic (As), iron (Fe), manganese (Mn) , cobalt (Co) and trace levels of other heavy metals have been observed in concentrations above baseline, although under guideline limits set by the DoH and DEC (Section 7.3.2).

Based on preliminary mineralogy results from samples of the Yarragadee at the Beenyup site (Appendix B), mineralogy is similar to that of the Leederville aquifer, predominantly quartz (SiO_2), with substantial kaolinite and feldspar minerals (Figure 8.1). Trace pyrite, siderite and almandine garnet were also detected in most cores. Therefore a similar geochemical response to the recharge of recycled water to the Leederville aquifer would be expected. Pyrite and SOM are present in smaller amounts compared to the Leederville aquifer, and the oxygenation zone will likely develop further through the aquifer. As carbonates are in trace amounts, only siderite in detectable concentrations, there is potentially less buffering capacity in the aquifer. Other minerals may be present and contribute to buffering as was found in the Leederville aquifer, but remain less than limits of detection by XRD.

Total trace element content of the core samples indicated cadmium, chromium, nickel, antimony and zinc were greater than interim sedimentary quality guidelines low trigger values (ISQG) (ANZECC/ARMCANZ, 2000). On average more than 80% of the cobalt, copper, nickel and zinc were acid-extractable and may be susceptible to mobilisation as a result of aquifer dissolution.

Respirometer results (Appendix B) showed trace metal release from the Yarragadee sediments, on average was less than those measured in the Leederville sediments. Nickel, cadmium, manganese and lead released into the supernatant solution during the respirometer tests were greater than water quality guidelines while cobalt, nickel and zinc concentrations are highly correlated with final pH, suggesting that the release of these metals may relate to pyrite oxidation (Appendix B).

The risk of geochemical reactions causing a change in pH to outside water quality guidelines (6.0 - 8.5) was assessed as an inherent risk of moderate, given the uncertainty of the reactivity and buffering capacity of the Yarragadee aquifer. Further interpretation and assessment of the data generated from the Beenyup Yarragadee investigation will be conducted through 2013 to determine the potential for acidity to be created and the buffering capacity of the aquifer material. The current prediction from the reactive transport model is for pH to decline no lower than 6.2 (Section 7.3.2 and Appendix B) in the Leederville aquifer, and given that the Yarragadee appears to be less reactive and additional pH buffering may be provided through slow reacting aluminosilicates, it is unlikely that pH will decrease below this level in the Yarragadee aquifer. If the additional research does not give conclusive answers, then amendment of the recycled water to increase the buffering capacity should be considered. This risk has been assessed after mitigation as low, as increasing the buffering capacity of the recycled water is known to be an adequate mitigation should the Yarragadee aquifer not provide sufficient buffering capacity.

The inherent risk of metal mobilisation, particularly cobalt, cadmium, copper, nickel and zinc due to a decrease in pH was assessed as moderate. Further interpretation of the Beenyup Yarragadee investigation data through mineralogy characterisation and respirometer experiments of sediments from the cored hole will allow this risk to be further understood. Additional investigations may involve recharging the Yarragadee aquifer utilising the current AWRP to test water quality changes resulting from recharge at a field scale. Understanding of the geochemical process that may occur may be achieved through sampling of the 60mS monitoring bore and the recharge bore. Increasing the pH buffering capacity of the recycled water is known to be an adequate mitigation should the Yarragadee aquifer not provide sufficient buffering capacity. The mitigated risk of metal mobilisation occurring beyond the RMZ above guideline levels has been assessed as low.

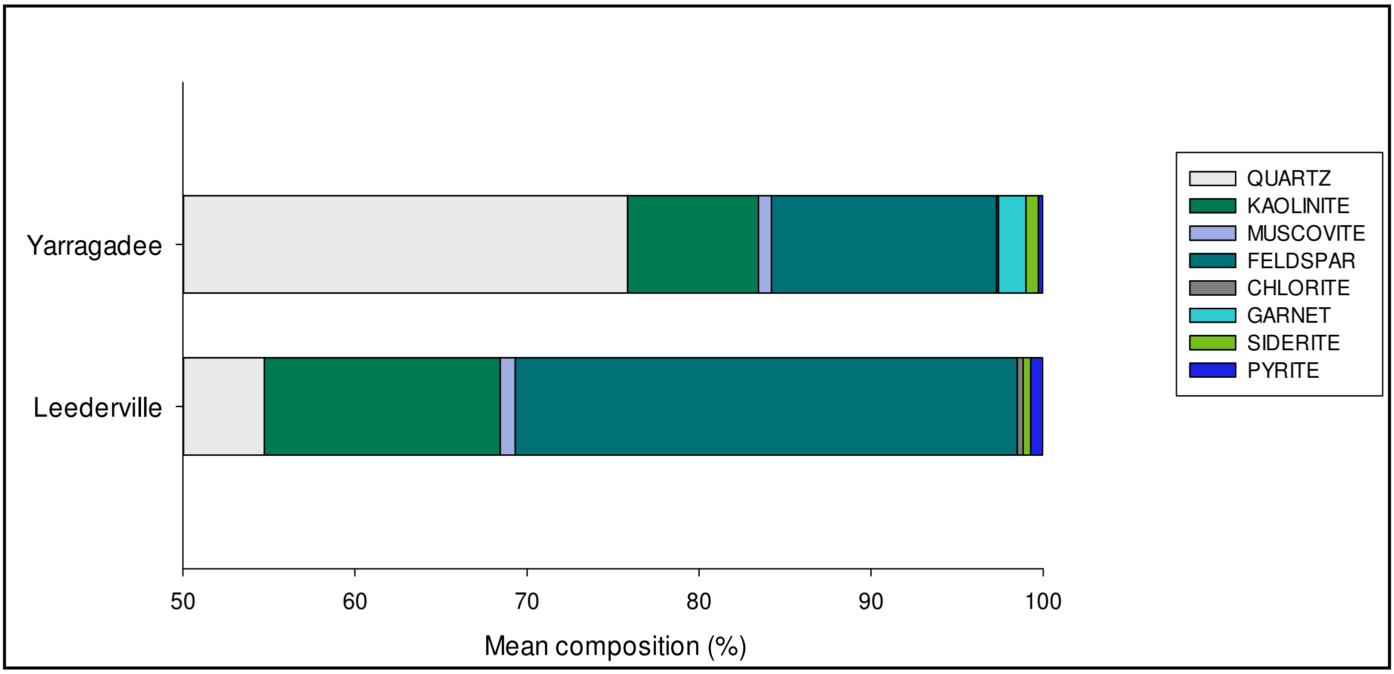


Figure 8.1: Mean mineralogical composition of Yarragadee (n=23) and Leederville (n=42) aquifer sediments (from Wilfert, 2009)

8.3.2 Recycled water quality

Approximately 300 chemical, microbiological and physical parameters have guidelines set by regulators to protect human and environmental health. These guidelines must be met in the recycled water prior to recharge to an aquifer. There is potential for low level trace organic compounds to be present in the recycled water after treatment, particularly disinfection-by-products (DBPs). The current design and operation of the AWRP is to minimise formation of DBPs. To verify the safety of the recycled water, 18 RWQI (Table 7.2) which are representative of the 292 RWQP were monitored. When these RWQI are below water quality guidelines, these provide confidence that the represented group of RWQP are also below guideline levels.

The Water Corporation had a two part approach to mitigating this potential risk in the Trial:

1. Improve the design and operation of the AWRP to minimise formation of disinfection by-products; and to
2. Assess the capacity of the Leederville aquifer to reduce these compounds.

Treatment process - The Trial has demonstrated that the improvements to AWRP design and operational procedures have been very effective in minimising formation of disinfection by-products. Recycled water concentrations are well below the guideline values and are often close to, or below, the Limit of Reporting. This makes it extremely difficult to monitor the presence of the compound in the aquifer.

Aquifer response - Results to date indicate that microbiological populations in the aquifer can have a beneficial impact on water quality through biodegradation processes that remove or break down organic chemicals and reduce concentrations of trace metals and nutrients. Results have also indicated that processes affecting biogeochemical reactions are largely redox dependent (relating to the presence or absence of oxygen in the aquifer).

The Preliminary Yarragadee Aquifer Risk Assessment (Water Corporation, 2012c) provided an initial risk ranking as low. However it was recognised that given the potential difference in redox conditions, the results from the Leederville aquifer, in particular the early and near recharge bore results may not be transferable to the Yarragadee aquifer. Therefore, further investigation would be necessary to understand the Yarragadee aquifer's biodegradation processes if this was required as mitigation. Given the successful design and operation of the AWRP in reducing organic and inorganic chemical to below guideline levels prior to recharge, this is considered to be not required at this stage. The mitigated risk through appropriate design and operation of an AWRP is rated as low.

8.4 Risks of poor aquifer response

8.4.1 Hydrogeological barriers

The risk of drilling into a low permeability barrier (fault) was identified in the Yarragadee Background Report (Rockwater, 2011b) and assessed as low in the Preliminary Yarragadee Risk Assessment (Water Corporation, 2012c). A review of existing seismic and a limited seismic survey, which was conducted as a part of the Yarragadee investigations, confirmed the absence of faults or hydraulic barriers beneath the site (Appendix C).

As part of further investigations for the GWR scheme, an extended seismic survey has been commissioned to investigate the location of proposed faults in the Yarragadee aquifer with the potential to act as hydrogeological barriers. In addition, extended pump testing during commissioning of the Yarragadee recharge bore is planned, and will be analysed to determine if boundary effects are apparent. The risk of a hydraulic barrier impacting recharge efficiency at the Beenyup site has been assessed as low.

8.4.2 Integrity of the confining layer

The 2011 Yarragadee Risk Assessment identified a low risk of damage to the confining layer. Based on drilling at the Beenyup site the confining layer is approximately 115m thick, with the base at ~320mbgl. Using the MAR guidelines the maximum recharge head (1.5 x depth of overburden to base of aquitard) would be 480m above the surface.

Estimated head rise as a result of recharging 14GL/yr is included in Appendix D. Recharging up to 14GL/yr into the Yarragadee aquifer at the Beenyup site would result in an increase in head to 56m above ground level, well below the maximum based on the MAR guidelines, and has been assessed as a low mitigated risk.

8.4.3 Risk of leakage to the overlying aquifer

In considering upward flow from the Yarragadee aquifer into the Superficial aquifer, the TRG advised of the thick and extensive nature of the low permeability sediments that overlie the Yarragadee aquifer. Travel time from the top of the Yarragadee aquifer to the base of the Leederville aquifer at a recharge rate of 14GL/yr would be more than 1000 years (Appendix D).

Under current conditions with no recharge to the Leederville aquifer, there is a downward head within the Leederville aquifer (Water Corporation, 2009a) and therefore no potential for upward flow. Water recharged to the Yarragadee aquifer would not reach the Superficial aquifer.

The steady state flow path based on PRAMS3.4 PMPATH for recharge at 14GL/yr to the Yarragadee aquifer is shown in Figure 8.2, and confirms that recharged water does not leave the Yarragadee aquifer. The risk of recycled water moving vertically has been assessed as low, and will not require future assessment at the Beenyup site when recharging up to 14GL/yr into the Yarragadee.

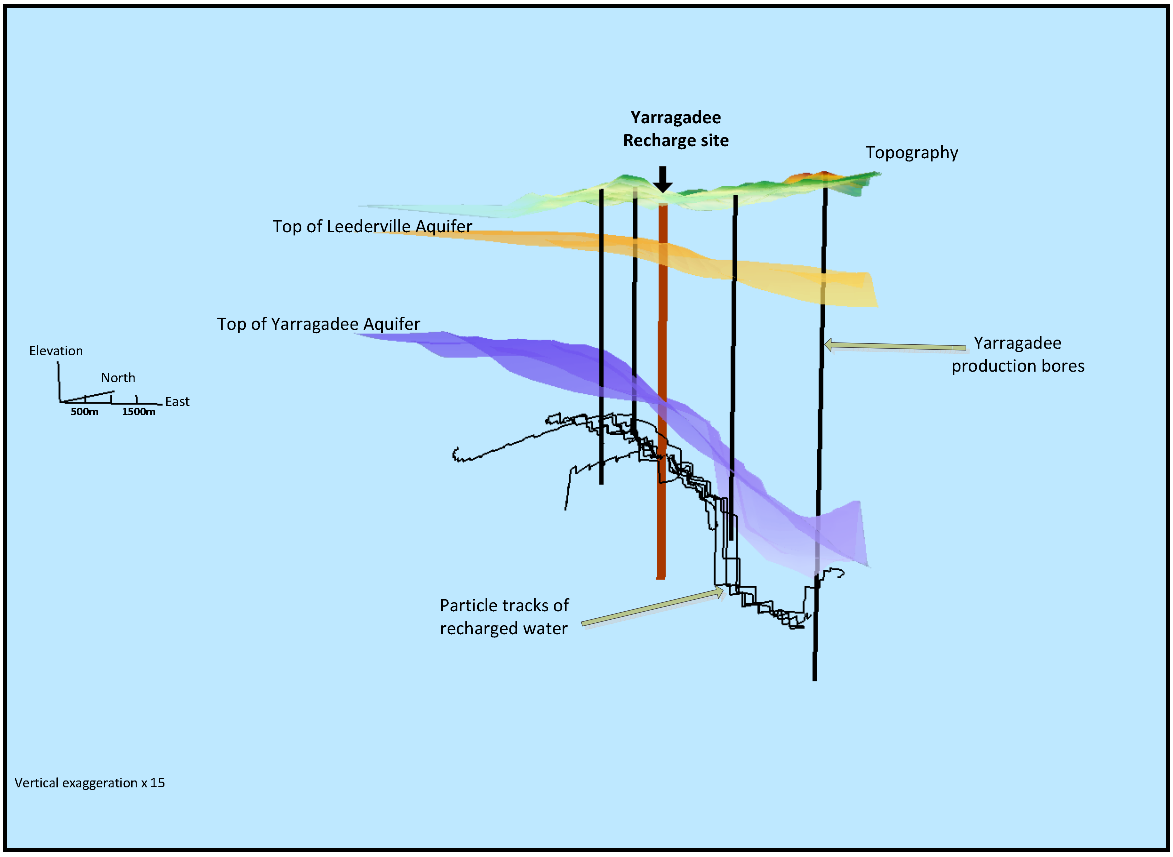


Figure 8.2: Flow path for recharge at 14GL/yr to the Yarragadee aquifer

8.4.4 Risks of aquifer dissolution

Mineralogy data from samples collected from the hole drilled into the Yarragadee aquifer at the Beenyup site indicate that mineralogy is similar to the Leederville aquifer (Figure 8.1), with silica (SiO_2) as the dominant mineral, with trace levels of siderite ($FeCO_3$) and no detections of calcite ($CaCO_3$). Carbonates such as siderite and calcite are more soluble minerals compared to silica, indicating significant aquifer dissolution is unlikely, as assessed in the Leederville aquifer and the pH of the groundwater is unlikely to increase to levels that may cause dissolution of silicates (Section 7.4.4). Pressure and water quality monitoring will be conducted as part of a GWR Scheme to confirm if aquifer dissolution were to occur, and the mitigated risk has been assessed as low.

8.5 Risk of impact to local geothermal bores

8.5.1 Risk from change in temperature

A deep geothermal bore is located approximately one kilometre to the south of the Beenyup Site at the Craigie Leisure Centre. Further details regarding this bore and operation are provided in the Yarragadee Background Report (Rockwater, 2011, Section 5.4). Local scale heat transport modelling was undertaken to determine the Yarragadee aquifer response at a recharge rate of 38.4ML/d (14GL/yr), and results are shown in Appendix B.

The simulation results (Figure 8.3) indicate a 2°C temperature decrease after 40 years and a 6°C decrease after about 70 years. Utilising longer screens in the recharge bore will distribute the recycled water over a larger surface area, however discussion with Craigie Leisure Centre will be required in the future. This risk has been reviewed as a social and reputational risk, and has been assessed as low.

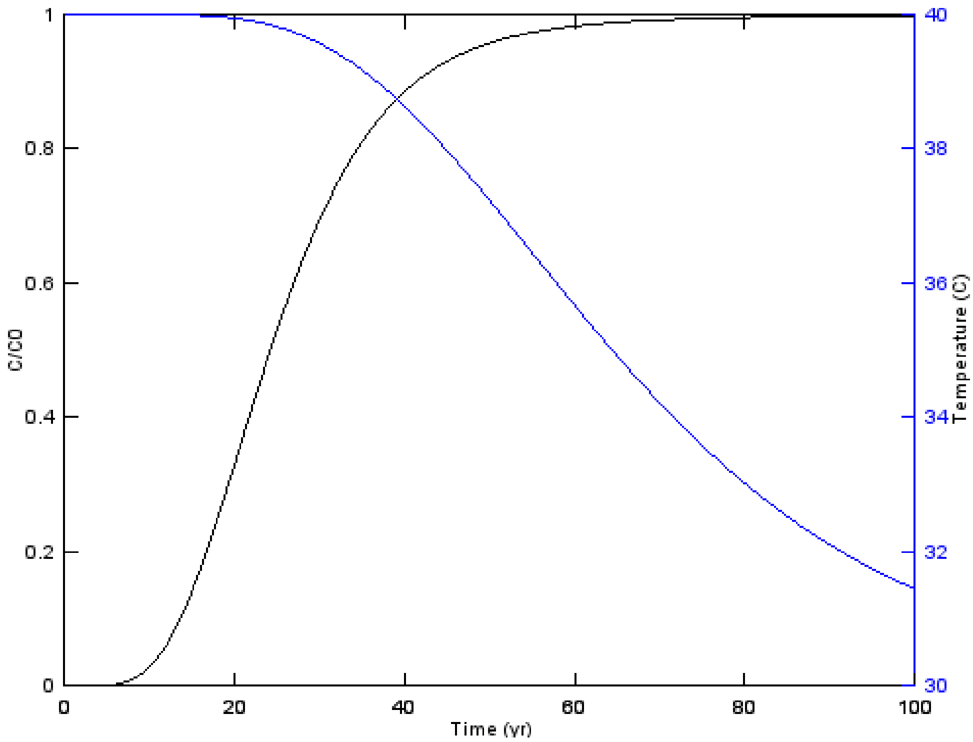


Figure 8.3: Simulated solute and temperature breakthrough curves at 1000m radial distance from the Yarragadee recharge bore at 14GL/yr.

8.5.2 Risk from change in pressure

The most likely impact on the geothermal bores due to pressure is an increase in re- injection costs resulting from increased potentiometric head pressures in the aquifer. The inherent risk was assessed as high. There is little that can be done to mitigate an increase in potentiometric heads due to recharge. Numerical modelling will be conducted utilising the PRAMS model to assess potential changes to the head pressures at Craigie. The leisure centre will be contacted by the Water Corporation to discuss the Yarragadee GWR project and inform the operators of the potential impacts. This risk has been reviewed as a social and reputational risk, and has been assessed as low.

9 Conclusions

Information to undertake a risk assessment of the Leederville and Yarragadee aquifers has been provided through (i) characterisation of both the Leederville and Yarragadee aquifers at the Beenyup site; (ii) existing information available on the Yarragadee aquifer; (iii) research and observed and modelled water quality changes within the Leederville aquifer due to recharge; and (iv) two years of successful operation of the AWRP and recharge bore.

The assessment identified 20 potential hazards to the Leederville aquifer and 26 to the Yarragadee aquifer, which can be summarised in the following groups;

- Risks from drilling and bore construction
- Risks resulting in bore clogging or reduced aquifer permeability
- Risks to human and environmental health
- Risks of poor aquifer performance
- Risks to geothermal bores (Yarragadee aquifer only)

Mitigations through design and operations, including monitoring are available for all potential hazards.

Therefore the risk to the both aquifers as a result of recharging up to 14GL/yr of recycled water is low.

The outcomes of this risk assessment will feed into the detailed design of the Perth GWRS Stages 1 and 2A.

The risk assessment process is iterative, and identified risks, mitigations and information obtained as a result of further investigations will be re-assessed following detailed design, commissioning and annually during operation of the Perth GWRS Stages 1 and 2A.

10 References

Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ). (2000). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Canberra, ACT, Australia. http://www.environment.gov.au/water/publications/quality/pubs/nwqms-guidelines-4-vol1.pdf

CyMod Systems Pty Ltd, (2013). *Impact of recharge on water quality in the Leederville and Yarragadee aquifer using the Perth Regional Aquifer Model Solute Transport PRAMSOL3.4*. Prepared for the Water Corporation. February 2013.

Davidson, W.A., & Yu, X, 2006, *Perth regional aquifer modelling system (PRAMS) model development: Hydrogeology and groundwater modelling*, Western Australia. http://www.water.wa.gov.au/PublicationStore/first/71802.pdf

Department of Health (DoH), (2010), *Characterising Treated Wastewater for drinking purposes following reverse osmosis treatment*, Department of Health, 2010. http://www.public.health.wa.gov.au/3/1117/2/groundwater_replenishment_trial.pm

Descourvieres, C., Hartog, N., Patterson, B. M., Oldham, C., & Prommer, H. (2010). *Geochemical controls on sediment reactivity and buffering processes in a heterogeneous aquifer*. Applied Geochemistry, 25(2), 261-275. http://www.sciencedirect.com/science/article/pii/S0883292709003242

DoH & Water Corporation, (2010). *Memorandum of Understanding between the Department of Health and Water Corporation for the Groundwater Replenishment Trial*. Western Australia.

Groundwater TRG. (2012). *GWR Management Zone and Monitoring Requirements.*

Ginige, M.P., Kaksonen, A.H., Morris, C., Shackleton, M., Patterson, B.M, (in Prep.). *Bacterial community and groundwater quality changes in an anaerobic aquifer during groundwater recharge with aerobic recycled water*.

National Health and Medical Research Council (NHMRC), (2004). *Australian Drinking Water Guidelines. National Water Quality Management Strategy 6*. National Health and Medical Research Council, National Resource Management Ministerial Council, Canberra. http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh34_adwg_11_06.pdf

NHMRC and NMMRC, (2011). *Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy*. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra.

Natural Resource Ministerial Management Council, Environment Protection and Heritage Council, Australian Health Ministers' Conference (2006). *National Water Quality Management Strategy Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)*, Natural Resource Ministerial Management Council, Environment Protection and Heritage Council, Australian Health Ministers' Conference, Canberra. http://www.ephc.gov.au/sites/default/files/WQ_AGWR_GL__ADWS_Corrected_Final_%20200809.pdf

Natural Resource Ministerial Management Council, Environment Protection and Heritage Council, National Health and Medical Research Council (2008). *National Water Quality Management Strategy Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) – Augmentation of Drinking Water Supplies*, Environment Protection and Heritage Council and

National Health and Medical Research Council and Natural Resource Ministerial Management Council, Canberra.
http://www.ephc.gov.au/sites/default/files/WQ_AGWR_GL__ADWS_Corrected_Final_%20200809.pdf

NRMMC, EPHC, NHRMC. (2009). *Australian Guidelines for Water Recycling: Managed Aquifer Recharge (Phase 2)*. Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra.
http://www.ephc.gov.au/sites/default/files/WQ_AGWR_GL__Managed_Aquifer_Recharge_Final_200907.pdf

Parkhurst, D.L., and Appelo, C.A.J., 1999, *User's guide to PHREEQC (Version 2) -- A computer program for speciation, reaction-path, advective-transport and inverse geochemical calculations*: U.S. Geological Survey Water-Resources Investigations Report 99-4259, p. 143.

Patterson, B.M., Shackleton, M., Furness, A.J., Pearce, J., Descourvieres, C., Linge, K.L., Busetti, F., Spadek, T., (2010). *Fate of nine recycled water trace organic contaminants and metal(loids) during managed aquifer recharge into a anaerobic aquifer: Column studies*. Water Research 44, 1471-1481.
http://www.sciencedirect.com/science/article/pii/S0043135409007179

Rockwater, (2008). *Groundwater Replenishment Trial. Site Evaluation Report – Aquifer Assessment*, Rockwater Pty Ltd for Water Corporation, WA, Perth. February 2008.
http://www.watercorporation.com.au/_files/PublicationsRegister/2/GWRT_Site_Eval_Aquifer_Assessment_Full_Report.pdf

Rockwater, (2011a). *Beenyup Groundwater Replenishment Trial Report on Extended Pumping Test at Recharge Bore 3/07*. Rockwater Pty Ltd for Water Corporation, WA, Perth. March 2011.
http://www.watercorporation.com.au/_files/PublicationsRegister/2/GWRT_extended_pumping_test_March2011.pdf

Rockwater, (2011b). *Background Report for the Preliminary Risk Assessment for Groundwater Replenishment of the Yarragadee Aquifer*. Rockwater Pty Ltd for the Water Corporation, WA, Perth. October 2011.

Rockwater, (2013). *Beenyup Groundwater Replenishment Scheme. BNYP YMB 1/12 Yarragadee Monitoring Bore Completion Report*. Report for the Water Corporation of Western Australia. February 2013.

Water Corporation, (2008). *Risk Assessment Report. Groundwater Replenishment Trial*, March 2010, Water Corporation

Water Corporation, (2009a). *Site Characterisation Report. Groundwater Replenishment Trial*, Water Corporation.
http://www.watercorporation.com.au/_files/PublicationsRegister/2/GWRT_SCR_Final%20Report_highres.pdf

Water Corporation, (2009b). *Health and Environmental Risk Assessment Report – Review 1*. April 2009, Water Corporation.

Water Corporation, (2010). *Baseline Groundwater Quality Results Report, Groundwater Replenishment Trial*, Water Corporation.
http://www.watercorporation.com.au/_files/Groundwater_Baseline_Water_Quality_Results_Report_Final_Nov2010.pdf

Water Corporation, (2011). *Health and Environmental Risk Assessment Report – Review 2*. December 2010, Water Corporation.

Water Corporation, (2012a). *Groundwater Report 2011. Groundwater Replenishment Trial*, Water Corporation. http://www.watercorporation.com.au/_files/InfrastructureProjects/GWRT_Groundwater_Report_2011.pdf

Water Corporation, (2012b). *Groundwater Report 2012. Groundwater Replenishment Trial*, Water Corporation. http://www.watercorporation.com.au/_files/Water_Recycling/GWRT_Groundwater_Report_2012.pdf

Water Corporation, (2012c). *Yarragadee Aquifer – Preliminary Risk Assessment. August 2011*, Water Corporation.

Water Corporation, (2012d). Drinking Water Quality Annual Report 2011-2012, Water Corporation. http://www.watercorporation.com.au/_files/PublicationsRegister/13/DWQ_Annual_Report_2011_12.pdf

Water Corporation, (2013a). *Leederville Aquifer Risk Assessment 2012 Report – Groundwater Replenishment Trial*, Water Corporation.

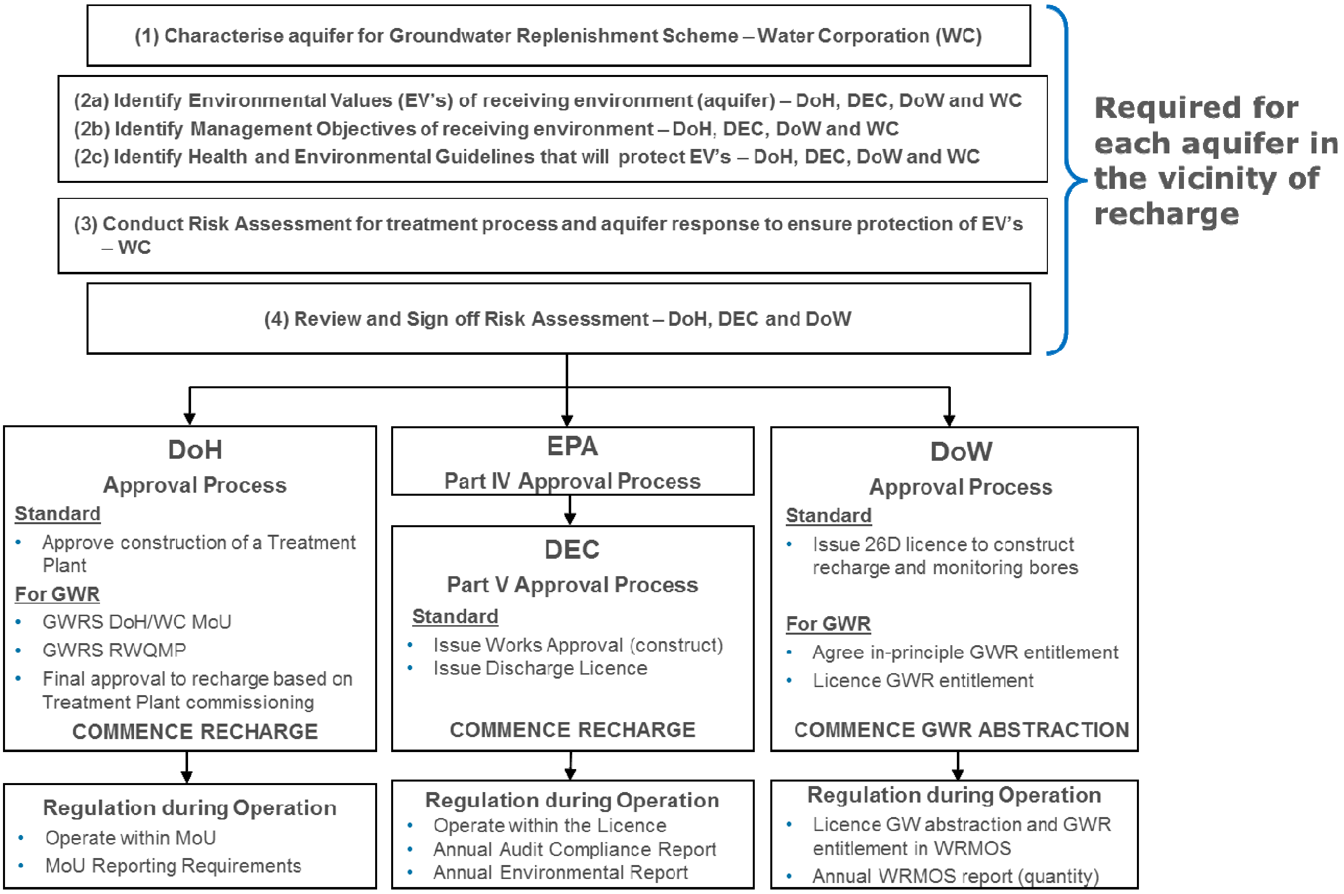
Water Corporation, (2013b). *Groundwater Replenishment - Principles of Sampling and Monitoring the Leederville Aquifer – GWR 1.5*, Water Corporation.

Water Corporation, (2013c). *Perth Groundwater Replenishment Scheme – Stage 2A - Treatment Process Risk Assessment Report*. March 2013, Water Corporation.

Wilfert, L., (2009). *Experimental identification and quantification of reductive processes to anticipate water quality changes during aerobic water injection into an anaerobic aquifer*. Master Thesis. Duisburg, 3 November 2009. University of Duisburg – Essen.

Appendices

Appendix A – Groundwater Replenishment Regulatory Framework



Appendix B – Draft CSIRO Report

Characterisation and quantification of water quality evolution during recharge of recycled water into the Yarragadee aquifer

Bradley Patterson, Henning Prommer, Laura Wendling, Mike Donn and Maneesha Ginige - CSIRO

1. Summary

Analysis of ambient groundwater quality indicated that the Yarragadee groundwaters are anoxic, with nitrate below detection and low sulphate concentrations, suggesting sulphate reducing conditions. Results of hydrogeochemical analyses showed that none of the parameters measured exceeded health-based Australian drinking water guidelines (ADWGs; NHMRC, 2011). Zinc within the Yarragadee groundwaters was present at concentrations within the Australian groundwater investigation level range for freshwater aquatic ecosystems, but well below the aesthetic ADWG value (NEPC, 1999; NHMRC, 2011).

Results from geochemical modelling of Yarragadee groundwaters were consistent with the observed low aqueous major and trace element concentrations, as well as with observed aquifer lithology and mineralogy. There was also good agreement between the observed mineral assemblage within Yarragadee sediments and the controlling mineral phases identified via modelling of bore water geochemistry.

The Yarragadee aquifer core samples were largely classified as sandstone with substantial silt in some samples (sandstone/siltstone and silty sandstone. As compared to sediments from the Gage formation (approximately 327-356 mBGL) which exhibited fine to very fine grain size and contained lignite, the examined core samples from the Yarragadee formation (373 to 652 mBGL) generally exhibited a wider range of grain sizes and more angular quartz, as well as visible mica, pyrite, bands of clay/silt or shale, organic matter (OM) or heavy mineral deposits, and/or lignitic zones. Pyritic nodules and traces of pyrite (Fe_2S) were noted in a number of Yarragadee aquifer core samples. Together, quartz and kaolinite accounted for approximately 70-90% of the total mineral content of each Yarragadee core sample. The remainder of the mineral phase was primarily feldspar minerals, and monoclinic orthoclase ($KAlSi_3O_8$) was generally two to three times more enriched than triclinic microcline ($KAlSi_3O_8$). Mineralogical analysis indicated minor to trace muscovite mica ($KAl_2(Si_3Al)O_{10}(OH,F)_2$) in most of the core samples, and several Yarragadee core samples contained trace pyrite (isometric crystalline FeS_2) and/or marcasite (orthorhombic crystalline FeS_2). The occurrence of minor to trace quantities of siderite ($FeCO_3$) increased with depth between approximately 530 and 750 mBGL, whilst the almandine garnet ($Fe_3Al_2(SiO_4)$) was detected at depths below approximately 600 mBGL. Calcite ($CaCO_3$) was below detection.

Compared to the Leederville aquifer sediments 120-220 mBGL, the Yarragadee aquifer sediments examined contained more quartz, but less kaolinite and total feldspar. Siderite within Yarragadee aquifer was slightly greater but not statistically significant. Calcite and/or dolomite were less than analytical detection levels. Based on mineral composition that showed higher quartz content and limited acid buffering minerals, the Yarragadee aquifer materials examined are expected to exhibit a lower or similar acid buffering capacity compared to the previously investigated Leederville 120-220 mBGL aquifer sediments.

Major elemental composition analysis by XRF confirmed mineralogical analyses, showing that 68-94 wt. % of the samples was accounted for by SiO_2. Across all core samples, Al was the next most abundant element (as Al_2O_3), followed by K (as K_2O) and Fe (as Fe_2O_3). Calcium, Mg, Mn, Na, P and Ti (as oxides) each comprised <1% in the Yarragadee aquifer core samples analysed. Correlation analyses indicated that the SiO_2 content of core samples was strongly correlated with quartz content whereas Al_2O_3 content was strongly correlated with total clay (e.g. kaolinite, muscovite, chlorite and sepiolite) content. Iron as quantified by XRF (Fe_2O_3) was largely accounted for by siderite, whilst S (as SO_3) was strongly correlated with the pyrite/marcasite content of core samples The Na and K

content of core samples can be primarily attributed to the presence of clay and feldspar minerals within the sandstone matrices.

The total trace element content of the Yarragadee aquifer core samples examined was generally low, with the mean total trace element content equivalent to <0.2% by mass (0.16 ± 0.06% w/w). Trace elements of potential concern based on total content in the Yarragadee core samples included Cd, Cr, Ni and Sb. The Cd content of many of the Yarragadee aquifer core samples examined was clearly greater than Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ, 2000) ISQG-low (trigger value) recommended sediment quality guideline values. Nine of the 28 Yarragadee core samples examined exhibited <2 mg/kg Cd; however, the ISQG-low trigger value is 1.5 mg Cd/kg (ANZECC/ARMCANZ, 2000). Similarly, most of the Yarragadee aquifer core samples contained Sb at concentrations in excess of ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guideline values, whilst the Sb content of the remaining seven samples was less than the 6 mg/kg limit of detection but may have been greater than the 2 mg/kg ISQG-low trigger value.

Several core samples contained Cr at concentrations greater than ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines, and the concentration of Ni within one core sample exceeded the ISQG-low trigger value. Another Yarragadee core sample exhibited Cd in excess of ANZECC/ARMCANZ (2000) ISQG-high recommended sediment quality values.

Acid-extractable metal concentrations were low, with only the acid-extractable Ni content of a single Yarragadee aquifer core sample YarMAR exceeding ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines. On average, more than 80% of the Co, Cu, Ni and Zn measured within the Yarragadee aquifer core samples using XRF were acid-extractable. In contrast, comparison between total contents and acid-extractable quantities indicated an average of <10% of total Ba, Be and Cd in Yarragadee samples were extracted from the sediments via acidification. Acid digest analysis results indicated that Co, Cu and Ni within the Yarragadee aquifer sediments are susceptible to mobilisation as a result of partial acid dissolution of aquifer materials.

In general, the mean major ion composition of the Yarragadee aquifer sediments examined was similar to previously investigated Leederville aquifer sediments. Similarly, mean trace element content of the Yarragadee aquifer sediments did not differ significantly from that of the more shallow (120-220 mBGL) Leederville sediments. The mean total organic carbon (TOC) and chromium reducible sulphur contents within the Yarragadee aquifer sediments examined were similar to or lower than that previously measured for Leederville 120-220 mBGL sediments. This is potentially indicative of a lower net acid generation potential for the Yarragadee aquifer sediments compared to the Leederville sediments.

The lower Cr-reducible S content of the Yarragadee cores may suggest lower potential for acid generation from pyrite oxidation, but may result in a greater migration rate of the oxygenation zone during recharge of aerobic recycled water.

The measured reductive capacity (MRC) determined by the incubation experiments showed a wide range of total O_2 consumption (1.5 to 96.9 µmol O_2/g), with the average MRC of 22.3 µmol O_2/g for the Yarragadee aquifer sediments. The lower MRC of the Yarragadee sediments, compared to the Leederville sediments (120-220 mBGL) of 163 µmol O_2/g is consistent with the mineralogical and geochemical characterisation.

Respirometer experiments showed trace metal release from the Yarragadee sediments, on average was less than those measured for the Leederville sediments with the exception of Pb). The range of trace metal concentrations released from the Yarragadee sediments were also similar or less than those observed for the Leederville sediments.

Microbial cell numbers in the groundwater of Yarragadee aquifer showed bacterial cell counts between 1 and 10 cells/mL, with the highest observed in groundwater collected from bore G17. The groundwater of bores W7 and WT97 showed negligible number of cells. These cell numbers at all three locations were very low compared to an average cell number of 2.6E+03 ± 1.5E+03 cells/mL detected in the Leederville aquifer. Low bacterial numbers were also confirmed using DNA extraction and amplification techniques.

Using the primers designed from Leederville core material, less than 20 % of the bacterial groups could be identified in the Yarragadee groundwaters. Considering the potential differences (e.g. lithology geochemistry and temperature) between the Leederville and Yarragadee aquifers, some differences in the microbial diversities could be expected. The bacterial community *Burkholderiales* (belonging to class *Betaproteobacteria*), was detected in all Leederville and Yarragadee groundwater samples, suggesting that this bacterial community was widespread in both the Leederville and Yarragadee aquifers.

2. Introduction

Over the past 5 years the Water Corporation has planned and undertaken a comprehensive groundwater replenishment trial in the Leederville aquifer at a site located near the Beenyup wastewater treatment plant. The aim of the trial was to identify and assess potential hazards and to develop strategies for managing the associated risks in a way that would be consistent with the NWQMS Phase 2 Guidelines for water recycling: managing health and environmental risks, including: Managed Aquifer Recharge and Augmentation of Drinking Water Supplies.

Current planning by the Water Corporation envisages extending and applying groundwater replenishment to the Yarragadee aquifer. Compared to the comprehensive understanding of the fluid flow and geochemical processes developed for the Leederville aquifer, much less is currently known for the Yarragadee aquifer. Therefore several new research activities were proposed by the GWRT Technical Reference Group (TRG) in order to reduce this knowledge gap, and improve the risk assessment and risk mitigation for recharge to the Yarragadee aquifer.

The time-frame for reporting these new activities extends over ~2years. Initial research has focused on activities to ensure that critical data for design of the treatment process for a full scheme is delivered by April 2013. This preliminary report focuses on providing a preliminary assessment of the risk of (i) metals release, (ii) colloid dispersion and clogging, and (iii) evaluation of buffering capacity of the Yarragadee aquifer and implications. A more complete assessment will be reported by December 2013.

3. Groundwater Geochemistry

3.1 Methodology

3.1.1 Groundwater sampling and analysis

Yarragadee aquifer groundwater samples from bores WT97, W7, G17 and G7 were collected on 13 December 2012 and submitted to the ChemCentre (Perth, WA) for comprehensive hydrogeochemical analysis, including: pH, electrical conductivity (EC), dissolved organic carbon (DOC) and total organic carbon (TOC), total dissolved solids (TDS) at 180°C, total suspended solids (TSS), turbidity, bicarbonate alkalinity (HCO_3^- as mg $CaCO_3$/L), Ag, Al, As(III), As(V), total As, B, Ba, Be, Br, Ca, Cd, Cl, Co, Cr, Cu, F, Fe, inorganic Hg, K, La, Li, Mg, Mn, Mo, Na, Ni, Pb, SO_4^{2-}, Sb, Se, Si, Sn, Sr, Tl, U, V, Zn, NH_3-N, NO_2-N, NO_x-N, total N, soluble reactive P (SRP) and total P.

3.1.2 Geochemical modelling

Interpretation of groundwater geochemistry was carried out on Yarragadee aquifer bore waters WT97, W7, G17 and G7 collected 13 December 2012 to examine aqueous speciation and mineral eqilibria. Speciation calculation for the major ions (Na, K, Ca, Mg, Cl, HCO_3, SO_4) and Fe, Al and Mn chemistry was undertaken using the geochemical model PHREEQC (Parkhurst and Appelo, 1999). The PHREEQC calculations were used to determine the saturation index (SI) of critical mineral phases, in particular, those of Al, Fe and Mn minerals. The SI for a given mineral is defined as: SI = log IAP/K_{sp} where IAP is the ion activity product of the chemical species in the reaction, and K_{sp} is the solubility product for the designated mineral. All log K_{sp} values were sourced from the PHREEQC database. For modelling purposes, where the concentration of a given element was less than detection limits the concentration was assumed to equal one-half of the limit of detection. Mineral dissolution reactions and solubility products used to calculate saturation indices are given in Table 1.

Table 1 - Minerals, reactions and Log Ksp (at 25℃) used in PHREEQC calculations

Mineral	Reaction	Log K
$Al(OH)_{3(am)}$	$Al(OH)_3 + 3 H^+ \rightarrow Al^{3+} + 3 H_2O$	10.8
Albite	$NaAlSi_3O_8 + 8 H_2O \rightarrow Na^+ + Al(OH)_4^- + 3 H_4SiO_4$	-18.002
Alunite	$KAl_3(SO_4)_2(OH)_6 \rightarrow K^+ + 3 Al^{3+} + 2 SO_4^{2-} + 6 H_2O$	-1.35
Anhydrite	$CaSO_4 \rightarrow Ca^{2+} + SO_4^{2-}$	-4.36
Anorthite	$CaAl_2Si_2O_8 + 8 H_2O \rightarrow Ca^{2+} + 2 Al(OH)_4^- + 2 H_4SiO_4$	-19.714
Aragonite	$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$	-8.336
Ca-Montmorillonite	$Ca_{0.165}Al_{2.33}Si_{3.67}O_{10}(OH)_2 + 12 H_2O \rightarrow 0.165 Ca^{2+} + 2.33 Al(OH)_4 + 3.67 H_4SiO_4 + 2H^+$	-45.03
Calcite	$CaCO_3 + 2 H^+ \rightarrow Ca^{2+} + H_2CO_3$	-8.48
Chalcedony	$SiO_2 + 2 H_2O \rightarrow H_4SiO_4$	-3.55
Chlorite	$Mg_5Al_2Si_3O_{10}(OH)_8 + 16 H^+ \rightarrow 5 Mg^{2+} + 2 Al^{3+} + 3 H_4SiO_4 + 6 H_2O$	68.38
Chrysotile	$Mg_2Si_2O_5(OH)_4 + 6 H^+ \rightarrow H_2O + 2 H_4SiO_4 + 3 Mg^{2+}$	32.2
Dolomite	$CaMg(CO_3)_2 + 4 H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2 H_2CO_3$	-17.09
Ferrihydrite	$Fe(OH)_3 + 3 H^+ \rightarrow Fe^{3+} + 3 H_2O$	4.89
FeS (ppt)	$FeS + H^+ \rightarrow Fe^{2+} + HS^-$	-3.915
Gibbsite	$Al(OH)_3 + 3 H^+ \rightarrow Al^{3+} + 3 H_2O$	8.77
Goethite	$FeOOH + 3 H^+ \rightarrow Fe^{3+} + 2 H_2O$	0.50
Gypsum	$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2 H_2O$	-4.58
Halite	$NaCl \rightarrow Na^+ + Cl^-$	1.582
Hausmannite	$Mn_3O_4 + 8 H^+ + 2 e^- \rightarrow 3 Mn^{2+} + 4 H_2O$	61.03
Hematite	$Fe_2O_3 + 6 H^+ \rightarrow 2 Fe^{3+} + 3 H_2O$	-4.01
Illite	$K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2 + 11.2 H_2O \rightarrow 0.6 K^+ + 0.25 Mg^{2+} + 2.3 Al(OH)_4 + 3.5 H_4SiO_4 + 1.2 H^+$	-40.27
K-Jarosite	$KFe_3(SO_4)_2(OH)_6 + 6 H^+ \rightarrow K^+ + 3 Fe^{3+} + 2 SO_4^{2-} + 6 H_2O$	-14.80
K-Feldspar	$KAlSi_3O_8 + 8H_2O \rightarrow K^+ + Al(OH)_4^- + 3 H_4SiO_4$	-20.573
K-Mica	$KAl_3Si_3O_{10}(OH)_2 + 10 H^+ \rightarrow K^+ + 3 Al^{3+} + 3 H_4SiO_4$	12.703
Jurbanite	$AlOHSO_4 + H^+ \rightarrow Al^{3+} + SO_4^{2-} + H_2O$	-3.23
Kaolinite	$Al_2Si_2O_5(OH)_4 + 6 H^+ \rightarrow H_2O + 2 H_4SiO_4 + 2 Al^{3+}$	7.44
Makinawite	$FeS + H^+ \rightarrow Fe^{2+} + HS^-$	-4.648
Manganite	$MnOOH + 3 H^+ + e^- \rightarrow Mn^{2+} + 2 H_2O$	25.34
Melanterite	$FeSO_4 \cdot 7H_2O \rightarrow 7 H_2O + Fe^{2+} + SO_4^{2-}$	-2.209
Pyrite	$FeS_2 + 2 H^+ + 2 e^- \rightarrow Fe^{2+} + 2 HS^-$	-18.479
Pyrochroite	$Mn(OH)_2 + 2 H^+ \rightarrow Mn^{2+} + 2 H_2O$	15.2
Pyrolusite	$MnO_2 \cdot H_2O + 4 H^+ + 2e^- \rightarrow Mn^{2+} + 3 H_2O$	41.38

Mineral	Reaction	Log K
Quartz	$SiO_2 + 2 H_2O \rightarrow H_4SiO_4$	-3.98
Rhodochrosite	$MnCO_3 \rightarrow Mn^{2+} + CO_3^{2-}$	-11.13
Sepiolite	$Mg_2Si_3O_{7.5}OH \cdot 3H_2O + 4 H^+ + 0.5 H_2O \rightarrow 2 Mg^{2+} + 3 H_4SiO_4$	15.76
Siderite	$FeCO_3 \rightarrow Fe^{2+} + CO_3^{2-}$	-10.89
SiO2(am)	$SiO_2 + 2 H_2O \rightarrow H_4SiO_4$	-2.71
Talc	$Mg_3Si_4O_{10}(OH)_2 + 4 H_2O + 6 H^+ \rightarrow 3 Mg^{2+} + 4 H_4SiO_4$	21.399

3.2 Ambient groundwater quality

Concentrations of major and trace ions in WT97, W7, G17 and G7 Yarragadee aquifer bore waters collected on 13 December 2012 were generally low and within Australian drinking water guidelines (ADWGs; Table 2). None of the measured parameters of Yarragadee aquifer bore waters exceeded health-based Australian drinking water guidelines (NHMRC, 2011). Only the total Fe, Na, and TDS contents of groundwater from bore G7 were greater than recommended aesthetic ADWG values.

Table 2 - Physico-chemical characteristics of Yarragadee bore waters collected 13/12/2012 and guideline values where applicable (NHMRC, 2011).

Parameter	Units	ADWG	WT97	W7	G17	G7
pH	N/A	6.5-8.5[a]	8.0	8.1	7.9	8.0
ECond	mS/m		47.7	33.4	76.5	123
Ag	mg/L	0.1[h], 0.0001[b]	<0.0001	<0.0001	<0.0001	<0.0001
Al	mg/L		<0.005	<0.005	<0.005	<0.005
Al_total	mg/L	0.2[a], 0.1[b]	0.02	<0.01	0.03	0.02
As(III)	mg/L		<0.001	<0.001	<0.001	<0.001
As(V)	mg/L		<0.001	<0.001	<0.001	<0.001
Total As	mg/L	0.01[h], 0.05[b]	<0.001	<0.001	<0.001	<0.001
B	mg/L	4.0[h]	0.12	0.08	0.16	0.26
Ba	mg/L	2.0[h]	0.91	0.8	0.73	0.22
Be	mg/L	0.004[b], 0.06[h]	<0.0001	<0.0001	<0.0001	<0.0001
Br	mg/L		0.19	0.11	0.42	0.71
Ca	mg/L		9.1	7.3	9.9	7.1
Cd	mg/L	0.002[h] 0.0002-0.002[b]	<0.0001	<0.0001	<0.0001	<0.0001
Cl	mg/L	250[a]	63	35	113	232
Co	mg/L		<0.0001	<0.0001	<0.0001	<0.0001
Cr	mg/L	0.01[b], 0.05[h,c]	<0.0005	<0.0005	<0.0005	<0.0005
Total Cr	mg/L		<0.001	<0.001	<0.001	<0.001

Cu	mg/L	1.0[a], 2.0[h] 0.002-0.005[b]	<0.0001	0.0001	<0.0001	<0.0001
F	mg/L	1.5[h]	0.33	0.22	0.48	0.92
Fe	mg/L		<0.005	0.013	0.027	0.01
Total Fe	mg/L	0.3[a], 1.0[b]	<0.01	0.01	0.03	0.01
HCO_3	mg $CaCO_3$/L	200[a,d]	171	139	190	**284**
Hg	mg/L	0.001[h], 0.0001[b]	<0.0001	<0.0001	<0.0001	<0.0001
K	mg/L		8.5	5.6	11	7.3
La	mg/L		0.0003	0.0003	0.0003	<0.0001
Li	mg/L		0.0027	0.0017	0.0047	0.0079
Mg	mg/L		5.9	2.9	6.8	3.5
Mn	mg/L		0.002	0.004	0.012	0.007
Total Mn	mg/L	0.1[a], 0.5[h]	0.002	0.005	0.013	0.008
Mo	mg/L	0.05[h]	<0.001	<0.001	<0.001	0.002
NH_3-N	mg/L	0.5[a]	0.38	0.33	0.42	0.35
NO_2-N	mg/L	3.0[h]	<0.01	<0.01	<0.01	<0.01
NO_x-N	mg/L	50[e]	<0.01	<0.01	<0.01	<0.01
TKN	mg/L		0.38	0.33	0.5	0.38
Total N	mg/L		0.38	0.33	0.5	0.38
Na	mg/L	180[a]	66.4	47.5	112	**206**
Ni	mg/L	0.02[h] 0.015-0.15[b]	<0.001	<0.001	<0.001	<0.001
SRP	mg/L		0.04	0.01	0.01	0.01
Total P	mg/L		0.06	0.04	0.04	0.03
Pb	mg/L		<0.0001	0.0001	<0.0001	<0.0001
Pb_total	mg/L	0.01[h] 0.001-0.005[b]	<0.0005	<0.0005	<0.0005	<0.0005
SO_4	mg/L	500[h], 250[a]	1.2	<0.1	6.9	14.3
Sb	mg/L	0.03[b], 0.003[h]	<0.0001	<0.0001	<0.0001	<0.0001
Se	mg/L	0.005[b], 0.01[h]	<0.001	<0.001	<0.001	<0.001
Si	mg/L	80[a]	22	21	18	21
Sn	mg/L		<0.0001	<0.0001	<0.0001	<0.0001

Sr	mg/L		0.1	0.077	0.13	0.092
Tl	mg/L	0.004[b]	<0.0001	<0.0001	<0.0001	<0.0001
U	mg/L	0.017[h]	<0.0001	<0.0001	<0.0001	<0.0001
V	mg/L		<0.0001	<0.0001	<0.0001	<0.0001
Zn	mg/L	3.0[a], 0.005-0.05[b]	**0.006**	**0.02**	**0.007**	**0.006**
DOC	mg/L		1.3	1.7	1.3	1.8
TOC	mg/L		1.3	1.7	1.3	1.7
TDS(180°C)	mg/L	600[a]	270	180	400	**660**
TSS	mg/L		<1	<1	<1	<1
Turbidity	NTU	5[a]	<0.5	<0.5	<0.5	<0.5

[a] Australian drinking water aesthetic guideline value (NHMRC, 2011)
[b] Australian groundwater investigation level for freshwater aquatic ecosystems (NEPC, 1999)
[c] Australian drinking water guideline value for chromium as Cr^{6+} (NHMRC, 2011)
[d] Australian drinking water guideline for hardness as $CaCO_3$ (NHMRC, 2011)
[e] Australian drinking water guideline for nitrate (NHMRC, 2011)
[h] Australian drinking water health-based guideline value (NHMRC, 2011)

3.3 Major ion chemistry

The Yarragadee aquifer bore waters samples on 13 December 2012 contained relatively low concentrations of major cations, with the exception of Na in water from bore G7 which exceeded the aesthetic ADWG (Figure 2, Figure 3). Concentrations of the major anions F^- and SO_4^{2-} were similarly low in Yarragadee aquifer bore waters samples on 13 December 2012 (Figure 4); however, the Cl^- concentration in water from bore G7 was near the aesthetic ADWG and HCO_3^- (expressed as mg $CaCO_3$/L) exceeded the aesthetic ADWG for hardness (as $CaCO_3$).

3.4 Redox status

Results of hydrogeochemical analyses indicate that the Yarragadee aquifer bore waters are anoxic. The primary redox-sensitive species in groundwater are SO_4^{2-}, HS^-, Fe^{2+}, Mn^{2+}, NH_4^+, NO_2^-, NO_3^-, CH_4(g), N_2O(g) and O_2(g). Although dissolved oxygen and oxidative-reductive potential were not measured for the Yarragadee aquifer bore water samples WT97, W7, G17 and G7 collected on 13 December 2012, the composition of N species is indicative of reducing conditions. Oxidised forms of N, NO_2-N and NO_x-N, were not detected in any of the bore waters whilst the reduced form of N, NH_3-N, accounted for 84-100% of the measured total N (Table 2). In addition, dissolved Fe^{2+} and Mn^{2+} were approximately equal to total Fe and total Mn, respectively, suggesting negligible Fe or Mn oxidation. With nitrate below detection, low sulphate and increased HCO_3^- concentrations in the groundwater, the results suggest that (slow) sulphate reduction in conjunction with organic matter oxidation dominates the redox conditions within the Yarragadee aquifer.

3.5 Metals

With the exception of Zn, concentrations of all metals/metalloids in the Yarragadee aquifer bore water samples WT97, W7, G17 and G7 collected on 13 December 2012 were less than ADWG values and less than Australian groundwater investigation level range for freshwater aquatic ecosystems (Table 2). Zinc within the Yarragadee bore waters examined was present at concentrations within the Australian groundwater investigation level range for freshwater aquatic ecosystems, but well below the aesthetic ADWG value (NEPC, 1999; NHMRC, 2011).

3.6 Mineral saturation indices

Geochemical modelling using PHREEQC was carried out for bore waters from the Yarragadee aquifer (Table 2). Because hydrogeochemical analyses indicated that the Yarragadee bore waters were anoxic, the bore waters were assumed to be in equilibrium with respect to pyrite (FeS_2).

On average, relatively few mineral phases approached or exceeded theoretical saturation in the Yarragadee aquifer bore WT97, W7, G17 and G7 waters collected 13/12/2012 (Figure 1). Table 3 shows the calculated saturation indices (SI) for a range of mineral phases potentially influencing the concentrations of dissolved ions in the Yarragadee aquifer bore water samples. Where the SI for a given mineral phase is between -0.5 and 0.5, the solution is likely to be in thermodynamic equilibrium with respect to that solid phase. A positive SI value (SI >0) indicates that the solution is supersaturated with respect to a given solid phase, and that the solid (mineral) may precipitate as a secondary phase. A negative SI value (SI <0) indicates that a given mineral phase is undersaturated with respect to the solution, not stable, and may dissolve if the undersaturated mineral phase is present in solid material which is in contact with the solution.

3.6.1 Aluminium minerals

Aqueous geochemistry of the Al_2O_3-SO_3-H_2O system is complex due to the large number of stable and metastable minerals that may form over a wide range of pH and sulphate concentrations. Gibbsite ($Al(OH)_3$) and kaolinite ($Al_2Si_2O_5(OH)_4$), both of which exhibit oversaturation in the Yarragadee bore waters, usually control Al concentrations in natural waters due to their low solubilities (Hem, 1970). Non-crystalline Al hydroxide ($Al(OH)_3(am)$) is least soluble between pH *ca.* 5-7, and crystalline $Al(OH)_3$ in the form of gibbsite extends Al hydroxide insolubility over a wider pH range. Alumina initially precipitated as an amorphous Al hydroxide will develop a more ordered structure with time to become the mineral gibbsite. In the Yarragadee aquifer bore waters examined, amorphous Al hydroxide was undersaturated whereas gibbsite was either oversaturated or approaching saturation (Table 3).

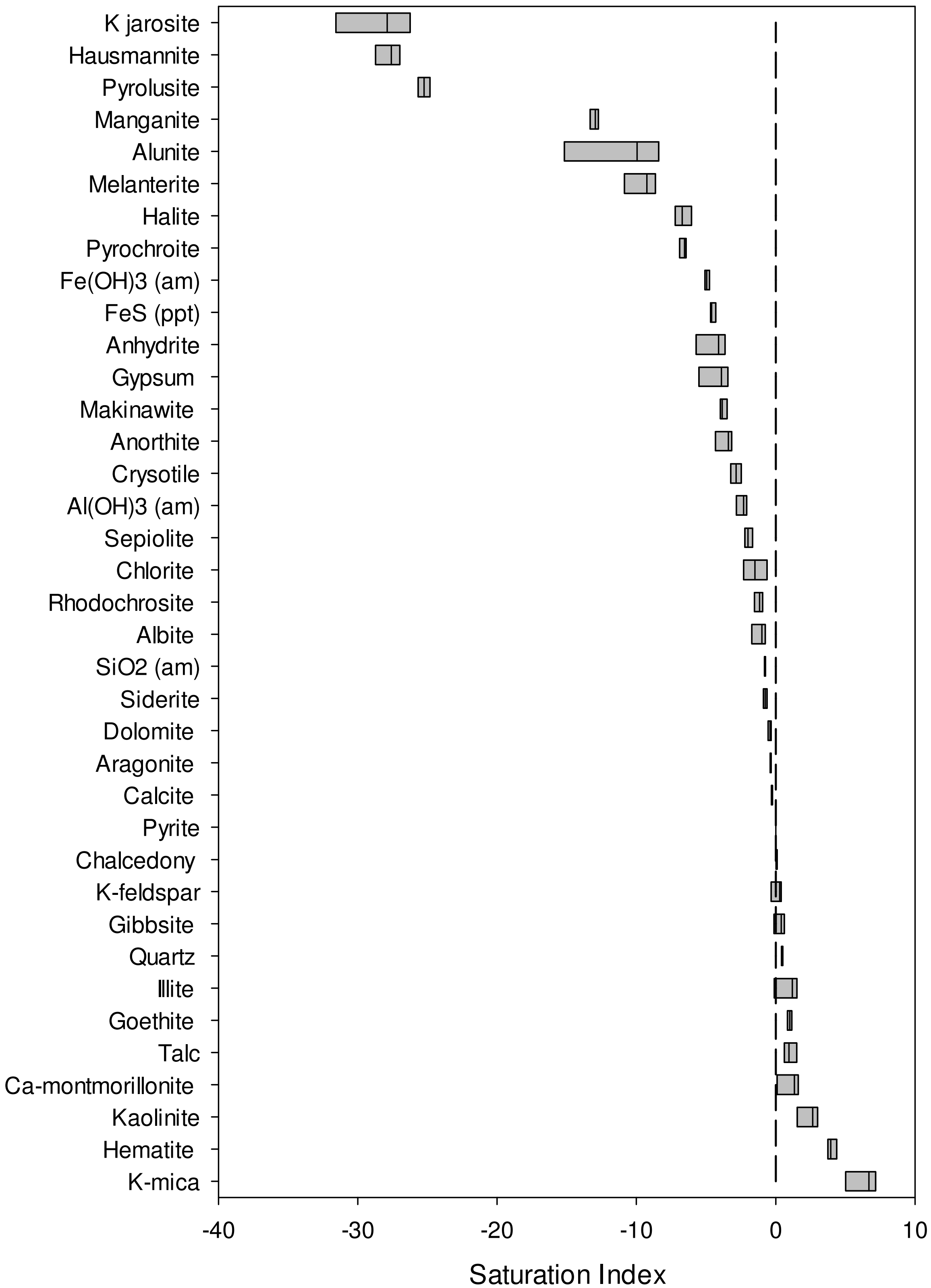


Figure 1 - Mean mineral saturation in Yarragadee aquifer bore waters WT97, W7, G17 and G7 collected 13/12/2012 (*n*=4)

The presence of sulphate along with Al in aqueous solutions can result in the neoformation of other, less soluble minerals such as alunite ($KAl_3(SO_4)_2(OH)_6$), which was highly undersaturated in the Yarragadee bore waters examined. Alunite has been identified as a mineral phase likely to control Al solubility in sulphate-rich natural waters (Adams and Hajek, 1978). Alunite undersaturation in the Yarragadee bore waters can likely be attributed to the low sulphate concentration of the waters examined.

At alkaline pH, gibbsite and alunite are theoretically the most stable minerals; however, because the formation of crystalline basic Al sulphate minerals is kinetically controlled precipitation of amorphous/less crystalline minerals is possible even when alunite or gibbsite is theoretically a more stable mineral phase (Nordstrom, 1982). Geochemical modelling showed that both alunite and amorphous Al hydroxide were undersaturated in the Yarragadee aquifer bore water samples whilst gibbsite was oversaturated in all bore waters (Table 3). Nevertheless, amorphous Al hydroxide was the mineral phase most likely controlling Al solubility in the Yarragadee aquifer bore waters examined. With time, precipitated amorphous Al hydroxide will be transformed to the more crystalline mineral gibbsite, which in the presence of dissolved Si may in turn be transformed to kaolinite.

Gibbsite is a final weathering product in the aluminosilicate mineral weathering process. In the context of Yarragadee aquifer bore waters, weathering of feldspar minerals via hydrolysis will result in kaolinite formation. Kaolinite can subsequently be transformed into gibbsite by weathering. When a portion of the kaolinite is transformed to gibbsite and the solution becomes saturated with respect to gibbsite, kaolinite and gibbsite minerals will exist together in equilibrium. In a mineral formation sequence, free hydrated aluminium oxides, e.g. gibbsite, will generally silicify spontaneously in sedimentary environments to form kaolinite. Based on kaolinite/gibbsite equilibrium reactions, gibbsite is stable relative to kaolinite only where dissolved Si activities are very low (Curtis and Spears, 1971). In the Yarragadee aquifer sediments, with time precipitated gibbsite in the presence of soluble Si will likely be altered to form kaolinite and more complex secondary aluminosilicate minerals during mineral diagenesis.

3.6.2 Iron minerals

Hematite and goethite, which were oversaturated in the Yarragadee aquifer bore waters (Figure 1, Table 3), are the minerals widely believed to define the energetic and thermodynamic minimum of the Fe_2O_3-H_2O system (Mazjlan et al., 2004). Whilst hematite formation is favoured in the pH range 6 to 9, goethite forms preferentially at higher and lower pH. Evidence of this preferential formation is apparent in the current examination, wherein the Yarragadee aquifer bore waters at pH *ca.* 8 exhibited substantially greater hematite saturation compared to goethite. Under oxidised conditions, the poorly crystalline, metastable hydrated Fe oxide ferrihydrite ($Fe(OH)_3$) forms via the rapid hydrolysis of Fe^{3+} salts or rapid oxidation of solubilised Fe^{2+}, and is the precursor of more crystalline iron oxides such as goethite ($FeOOH$) and hematite (Fe_2O_3). Under anoxic conditions such as those in the Yarragadee aquifer, however, ferrihydrite remains undersaturated (e.g. Figure 1).

3.6.3 Carbonate/Sulphate minerals

Modelling showed that precipitation of carbonate minerals such as calcite ($CaCO_3$), aragonite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) or siderite ($FeCO_3$) was unlikely in the Yarragadee aquifer as the bore waters examined were slightly undersaturated with respect to each of these minerals (Table 3).

Sulphate concentrations in the Yarragadee aquifer bore waters were low, and were likely controlled by sulphate reduction in the absence of oxygen. Due to the low sulphate concentration within Yarragadee bore waters, the Ca sulphate minerals gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite exhibited a substantially greater degree of undersaturation than the carbonate minerals in all Yarragadee bore waters examined (Figure 1, Table 3).

3.6.4 Clay minerals

Although quartz was theoretically oversaturated in all Yarragadee bore waters examined (Table 3), precipitation of crystalline quartz from solution is unlikely. Crystalline quartz (SiO_2) is much less soluble than either chalcedony or amorphous silica; thus, a solution in equilibrium with amorphous silica or chalcedony will be oversaturated with respect to crystalline quartz. Because quartz dissolution and crystallization occur extremely slowly at low (ambient) temperatures, the concentration of dissolved Si in solution is largely determined by the solubility of amorphous silica. Although the Yarragadee bore waters were undersaturated with respect to amorphous silica and oversaturated with respect to crystalline quartz (Table 3) the mineral chalcedony, which exhibited approximately equilibrium saturation with respect to solution, likely controlled Si concentrations in the Yarragadee bore waters. Chalcedony may precipitate from slightly saturated solutions via the assembly of short-chain linear polymers using bridging silica monomers (Heaney, 1993).

Nucleation and growth (neoformation) of complex aluminosilicate minerals is frequently observed during physical and chemical weathering of primary minerals at the earth's surface. The high degree of isomorphic substitution observed in the structure of clay minerals, sometimes referred to as phyllosilicate, layer silicate or aluminosilicate minerals, provides clear evidence of the precipitation of solid-solutions during water-rock interactions. Soluble Al-Si complexes may comprise as much as 95% of inorganic mononuclear Al in natural waters and are key to the formation of new mineral phases during interactions between minerals and water (Browne and Driscoll, 1994). Aluminium and Si both exhibit high solubility in aqueous solution at alkaline pH; however, when both ions are present, Al and Si co-precipitate as aluminosilicate minerals in the pH range of 4 to 11, effectively lowering the relative solubility of both ions. Kaolinite has a low solubility in aqueous solution and may form via the crystallisation of amorphous hydrous oxides of Si and Al. All Yarragadee bore waters were oversaturated with respect to kaolinite ($Al_2Si_2O_5(OH)_4$; Table 3). At low temperature (e.g. 25°C), kaolinite has been shown to form in solutions that are oversaturated with respect to kaolinite after 3-4 years (Kittrick, 1970).

Where alkaline and alkaline earth ions (Na, K, Ca, Mg) are present with Si the formation of smectitic clays (e.g. montmorillonite) and possibly hydrated micaceous clay minerals (e.g. illite) is thermodynamically favourable, but kinetically slow. Where the dissolved Si concentration is relatively high, as in Yarragadee aquifer waters, polymerisation of silicic acid in solution inhibits the formation of clay minerals (Harder, 1972). Montmorillonite formation is favoured where Si concentration and hydrogen ion activity are low. At pH 10 montmorillonite and talc may form with as little as 10 mg/L Mg in solution and Mg may be co-precipitated with Al-hydroxide under neutral conditions; however, at lower Mg concentrations and/or higher hydrogen ion concentration (lower pH) Mg/Al hydroxide precipitates will remain amorphous (Harder, 1972). In the Yarragadee aquifer bore waters, Ca montmorillonite ($Ca_{0.165}Al_{2.33}Si_{3.67}O_{10}(OH)_2$) and illite ($K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2$; Table 3) were theoretically oversaturated with respect to solution in all bore waters examined. All Yarragadee bore waters also exhibited theoretical oversaturation with respect to K-mica and all samples were either approaching saturation or oversaturated with respect to K-feldspar (Table 3). Like kaolinite, these mineral phases are kinetically slow to form but likely to substantially influence the ionic composition of Yarragadee aquifer waters due to the age of the water.

Secondary minerals such as kaolinite, montmorillonite, and illite may also form as a result of primary mineral weathering. In particular, kaolinite forms via weathering of aluminosilicate primary minerals; thus, feldspar minerals commonly form kaolinite and/or montmorillonite clay minerals as a result of physical or chemical weathering processes. Similarly, illite forms due to the weathering of K- and Al-rich parent materials, such as muscovite mica and feldspar. The observed theoretical oversaturation of aluminosilicate minerals K-feldspar, K-mica, kaolinite, illite and Ca-montmorillonite is likely due to weathering of feldspar and mica parent materials within the Yarragadee aquifer.

The Mg phyllosilicate mineral talc ($Mg_3Si_4O_{10}(OH)_2$) was theoretically oversaturated in all the Yarragadee bore waters examined (Figure 1, Table 3). Talc usually forms as a weathering product of ferromagnesian minerals (e.g. olivine, pyroxene, amphibole) in high temperature and pressure environments. With time, talc may in turn weather to form chlorite ($Mg_5Al_2Si_3O_{10}(OH)_8$) which approached theoretical saturation only in the WT97 bore water from the Yarragadee aquifer. In siliceous calcite-dolomite sediments talc has been shown to form as a result of dolomite weathering, where dolomite and quartz react at relatively low temperature and low CO_2 partial pressure to form talc and calcite (Puhan and Hoffer, 1973). Alternatively, talc may precipitate from solution along with trioctahedral smectite minerals, although talc precipitation is strongly influenced by pH and generally occurs at pH>9 (Khouri et al., 1982).

3.6.5 Summary

Results from geochemical modelling of Yarragadee bore waters are consistent with the observed low aqueous major and trace element concentrations, as well as with observed aquifer lithology (Section 5.2) and mineralogy (Section 5.3). There is good agreement between the observed mineral assemblage within Yarragadee sediments (Section 5.3) and the controlling mineral phases identified via modelling of bore water geochemistry.

Table 3 - Saturation indices (SI) for Yarragadee bore waters. Saturated minerals and those within ± 0.5 SI for each are shown in bold text.

Mineral	WT97	W7	G17	G7	Mean ± SD
$Al(OH)_3$ (am)	-2.3	-3.0	-2.0	-2.3	-2.4 ± 0.4
Albite $NaAlSi_3O_8$	-1.1	-1.9	-0.9	-0.7	-1.2 ± 0.5
Alunite $KAl_3(SO_4)_2(OH)_6$	-10.9	-16.6	-8.2	-9.0	-11.2 ± 3.8
Ammonia NH_3 (g)	-7.8	-7.7	-7.8	-7.8	-7.8 ± 0.0
Anhydrite $CaSO_4$	-4.5	-6.1	-3.7	-3.6	-4.5 ± 1.2
Anorthite $CaAl_2Si_2O_8$	-3.3	-4.6	-3.1	-3.5	-3.6 ± 0.7
Aragonite $CaCO_3$	**-0.4**	**-0.4**	**-0.4**	**-0.3**	**-0.4 ± 0.0**
Ca-montmorillonite $Ca_{0.165}Al_{2.33}Si_{3.67}O_{10}(OH)_2$	**1.4**	**-0.3**	**1.7**	**1.3**	**1.0 ± 0.9**
Calcite $CaCO_3$	**-0.3**	**-0.3**	**-0.3**	**-0.2**	**-0.3 ± 0.1**
Methane CH_4 (g)	-7.2	-5.5	-8.2	-8.1	-7.3 ± 1.3
Chalcedony SiO_2	**0.1**	**0.1**	**0.0**	**0.1**	**0.1 ± 0.1**
Chlorite $Mg_5Al_2Si_3O_{10}(OH)_8$	**-0.5**	-2.4	-1.0	-2.0	-1.5 ± 0.9
Crysotile $Mg_3Si_2O_5$	-2.4	-2.7	-3.0	-3.3	-2.9 ± 0.4
Carbon dioxide CO_2 (g)	-2.8	-3.0	-2.6	-2.6	-2.8 ± 0.2
Dolomite $CaMg(CO_3)_2$	**-0.3**	-0.6	**-0.4**	**-0.4**	**-0.4 ± 0.1**
Ferrihydrite $Fe(OH)_3$ (am)	-5.1	-5.0	-4.7	-4.9	-4.9 ± 0.2
FeS (ppt)	-4.6	-4.2	-4.6	-4.7	-4.5 ± 0.2
Gibbsite $Al(OH)_3$	**0.4**	**-0.3**	**0.7**	**0.4**	**0.3 ± 0.4**
Goethite FeOOH	**0.8**	**1.0**	**1.2**	**1.0**	**1.0 ± 0.2**
Gypsum $CaSO_4{\cdot}2H_2O$	-4.3	-5.9	-3.5	-3.4	-4.3 ± 1.2
Hydrogen gas H_2 (g)	-7.5	-7.1	-7.8	-7.8	-7.6 ± 0.3
Gaseous water H_2O (g)	-1.5	-1.5	-1.5	-1.5	-1.5 ± 0.0
Hydrogen sulphide H_2S (g)	-9.6	-9.6	-9.9	-9.8	-9.7 ± 0.1
Halite NaCl	-6.9	-7.3	-6.5	-5.9	-6.7 ± 0.6
Hausmannite Mn_3O_4	-29.0	-27.9	-26.9	-27.3	-27.8 ± 0.9
Hematite Fe_2O_3	**3.7**	**3.9**	**4.5**	**4.0**	**4.0 ± 0.3**
Illite	**1.3**	**-0.5**	**1.6**	**1.1**	**0.9 ± 0.9**

$K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2$					
K jarosite $KFe_3(SO_4)_2(OH)_6$	-29.1	-32.4	-26.1	-26.7	-28.6 ± 0.9
K-feldspar $KAlSi_3O_8$	**0.4**	**-0.5**	**0.4**	**0.2**	**0.1 ± 0.4**
K-mica $KAl_3Si_3O_{10}(OH)_2$	**6.8**	**4.5**	**7.3**	**6.6**	**6.3 ± 1.2**
Kaolinite $Al_2Si_2O_5(OH)_4$	**2.7**	**1.2**	**3.1**	**2.6**	**2.4 ± 0.8**
Makinawite FeS	-3.8	-3.4	-3.9	-4.0	-3.8 ± 0.3
Manganite MnOOH	-13.4	-13.1	-12.7	-12.8	-13.0 ± 0.3
Melanterite $FeSO_4 \cdot 7H_2O$	-9.8	-11.2	-8.6	-8.7	-9.6 ± 1.2
Nitrogen gas N_2 (g)	-3.4	-3.5	-3.5	-3.5	-3.5 ± 0.1
Oxygen O_2 (g)	-68.1	-69.0	-67.5	-67.5	-68.0 ± 0.7
Pyrite FeS_2	**0.0**	**0.0**	**0.0**	**0.0**	**0.0 ± 0.0**
Pyrochroite $Mn(OH)_2$	-7.0	-6.5	-6.4	-6.6	-6.6 ± 0.3
Pyrolusite $MnO_2 \cdot H_2O$	-25.7	-25.6	-24.8	-24.9	-25.3 ± 0.5
Quartz SiO_2	0.5	0.5	0.4	0.5	0.5 ± 0.1
Rhodochrosite $MnCO_3$	-1.6	-1.3	-0.9	-1.0	-1.2 ± 0.3
Sepiolite $Mg_2Si_3O_{7.5}OH \cdot 3H_2O$	-1.6	-1.8	-2.2	-2.2	-2.0 ± 0.3
Siderite $FeCO_3$	-0.9	-0.8	-0.6	-0.7	-0.8 ± 0.1
SiO_2 (am)	-0.7	-0.8	-0.8	-0.8	-0.8 ± 0.1
Sulfur	-8.0	-8.4	-7.9	-7.8	-8.0 ± 0.3
Talc $Mg_3Si_4O_{10}(OH)_2$	1.6	1.2	0.7	0.6	1.0 ± 0.5

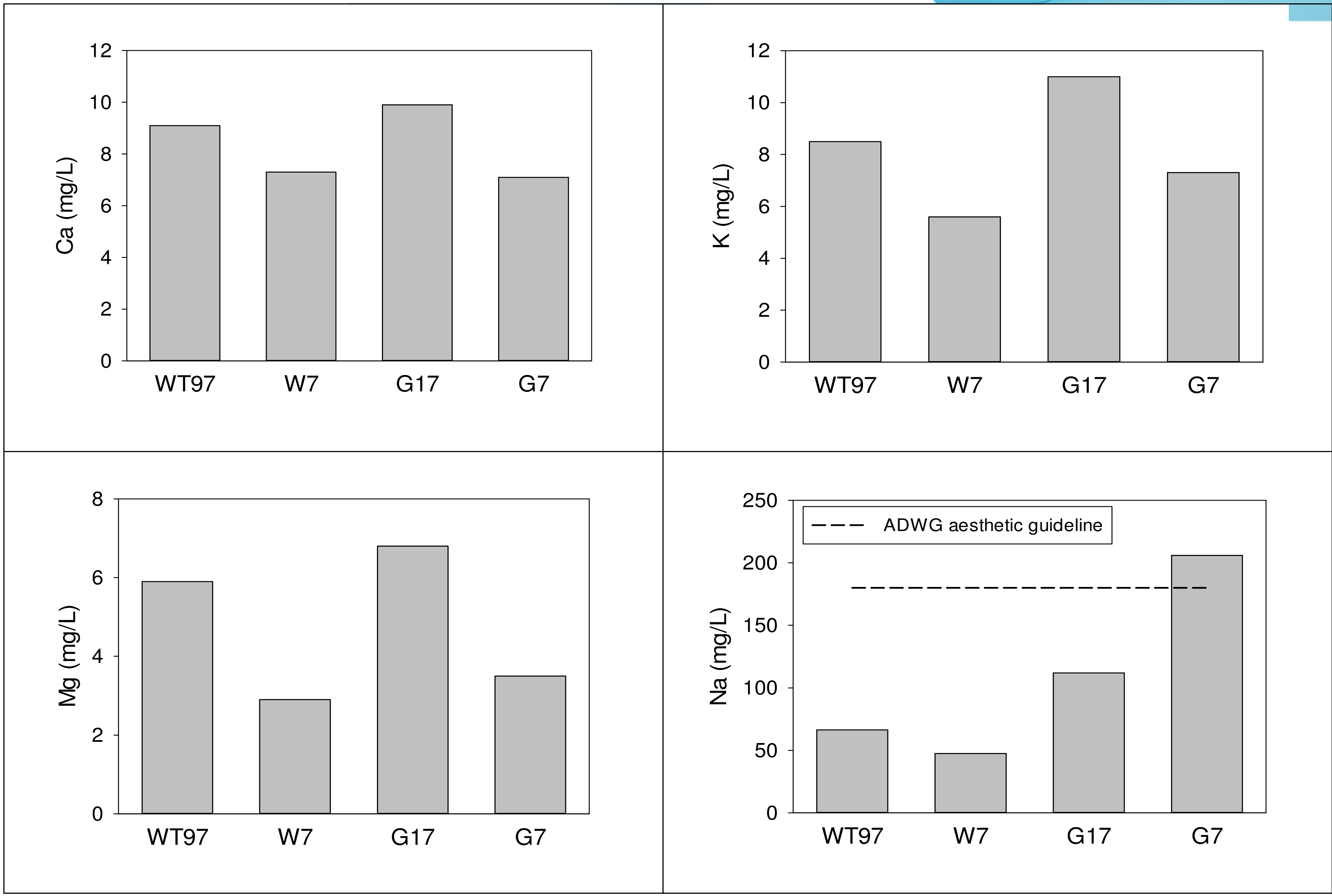


Figure 2 – Concentrations of major cations - Ca, K, Mg, Na in Yarragadee bore water samples (13/12/12)

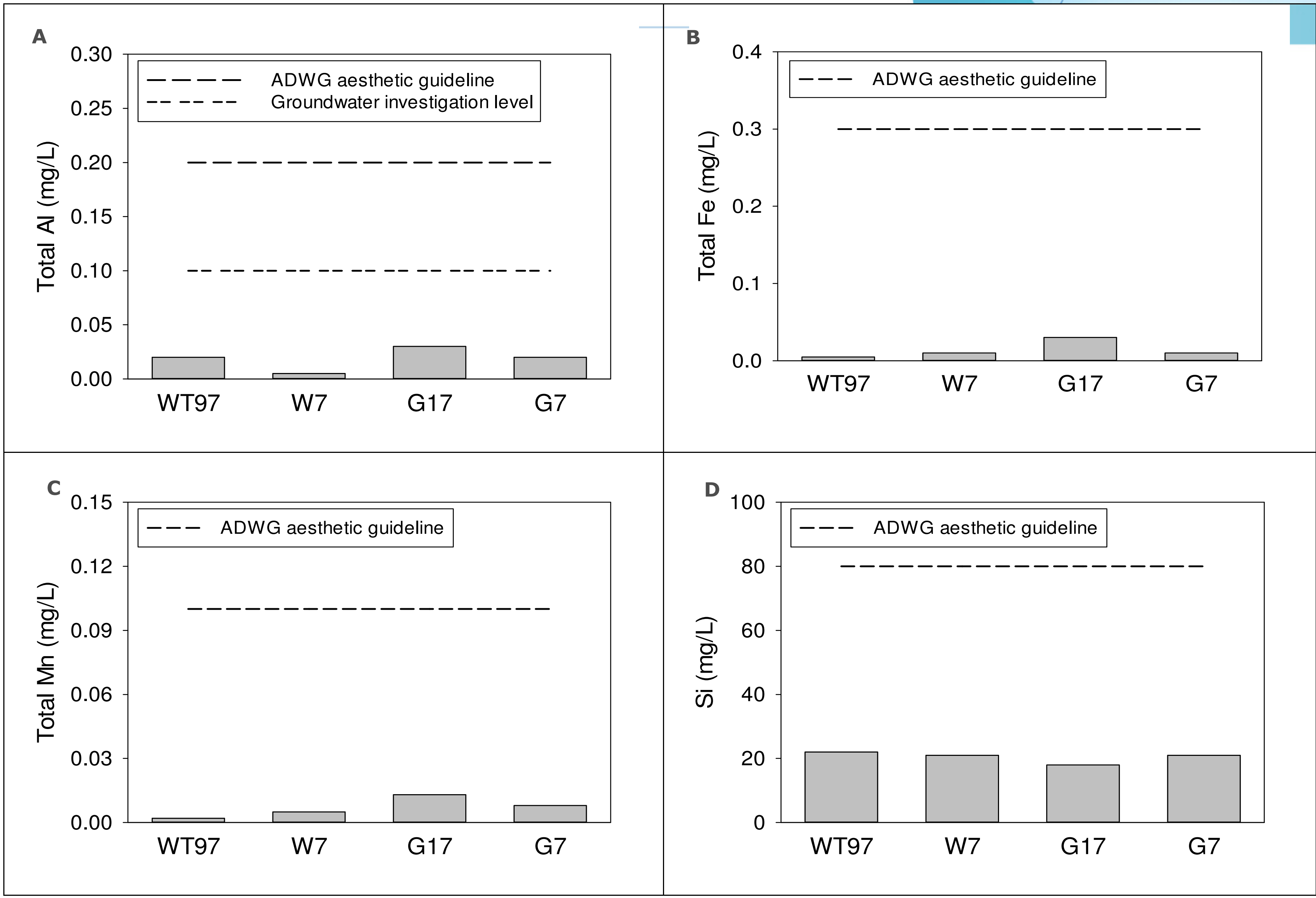


Figure 3 – Concentration of major cations – Al, Total Fe, Total Mn, Si in Yarragadee bore water samples (13/12/12)

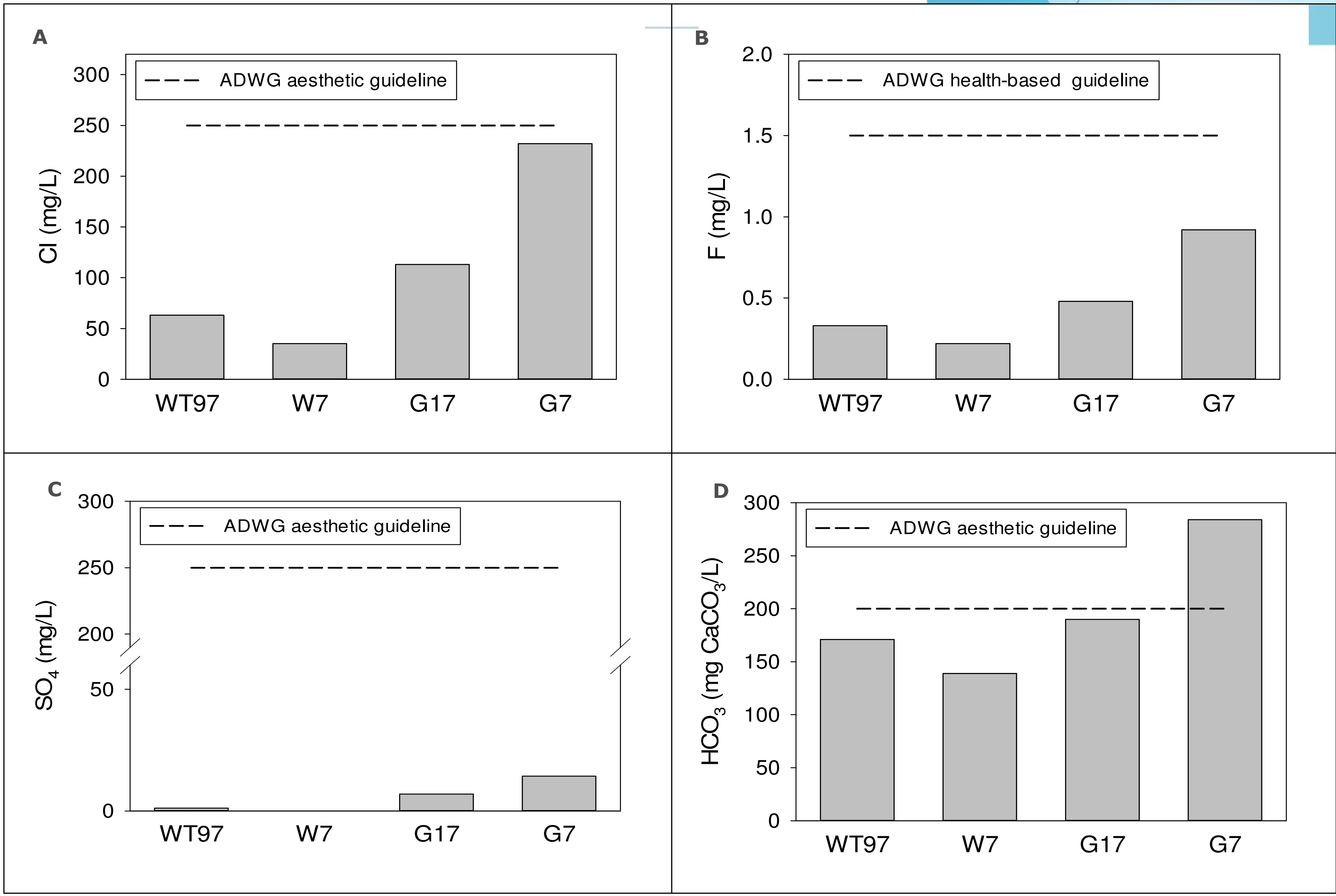


Figure 4 – Concentration of major anions – Cl, F, SO_4, HCO_3 (as $CaCO_3$) in Yarragadee bore water samples (13/12/12)

4. Groundwater microbiology

4.1 Materials and methods

Groundwater samples from three bores of Yarragadee (G17, W7 and WT97) were collected into 20 L sterile carboy container (Nalgene) and transferred to the laboratory for storage at 4°C prior to processing. The microbiology of the collected water samples was carried out using flow cytometry and quantitative PCR (qPCR). qPCR was carried out using the same primers that were used to screed the microorganisms of the Leederville aquifer.

4.1.1 Flow cytometry

The bacteria of the three water samples were stained using 5 µL/mL SYBR® Gold (1:100 dilution in DMSO; Cat. No. S11494, Invitrogen, Australia Pty. Ltd.) and the stained samples were incubated in the dark for 15 min prior to measurement. A Cell Lab Quanta™ SC (Beckman Coulter®, USA) flow-cytometer fitted with a 488 nm solid state laser was used for counting. SYBR® Gold has excitation/emission maxima at 495/537 nm respectively. FL1 channel (525 nm) was used to collect the green fluorescence and also was used as the trigger. The data collected were processed using Cell Lab Quanta Analysis software (Beckman Coulter®). Samples were measured in triplicate, and epifluorescence microscopy was used to confirm the bacterial nature of stained particles.

4.1.2 qPCR

The three water samples were concentrated by a hollow fibre ultrafiltration system (HFUFS), using Hemoflow HF80S dialysis filters (Fresenius Medical Care, Lexington, MA, USA) as previously described by Hill et al. (2005). The samples were concentrated to approximately 100 mL and further concentration of samples was carried out by filtering through 0.22 µm filters (Polycarbonate membrane, Cat No. GTBP02500, Millipore, UK) to recover biomass. Subsequently DNA was extracted using the Fast DNA® spin kit for soil (Cat No. 6560-200, MP Biomedicals LLC, France) following manufacturer's instructions. Using the primers (Table 4) designed for the Leederville study, the abundance of specific groups of microorganisms was then estimated using qPCR.

The thermocycler conditions used during qPCR for all primer pairs included an initial denaturation step at 95°C for 15 min followed by 50 cycles of denaturation at 95°C for 60 sec, annealing at 60°C for 60 sec and an elongation at 72°C for 45 sec. An iQ5 real-time PCR detection system (Bio-Rad) was used for all qPCR and IQ SYBR green supermix (Bio-Rad) was used in all reactions following manufacturers' instructions. Plasmids carrying the respective cloned genes used as standards for calibration of the assay are also given in Table 4. A negative control (1 to 5 base mismatches, Table 4) and a negative control with no template DNA was also included in each qPCR run. qPCR of dissimilatory sulfite reductase (*dsr*B) genes of sulfate reducing prokaryotes (SRP) was carried out using primers DSR1F (5'- ACS CAC TGG AAR CAC G -3') and RH3-dsr-R (5'- GTG GAR CCR TGC ATG TT -3') and the primer sequences are modifications of Ben-Dov et al.(2007). A PCR amplified product of *dsr*B gene was used as standard for calibration of the assay and the thermocycler conditions used were similar to those of Ben-Dov et al.(2007). All qPCRs were performed in triplicate and at the end of each assay, a single band of expected size was observed using agarose gel electrophoresis. Additionally, the specificity of each qPCR reaction was confirmed by comparing melting curve analysis of the sample and its respective reference clone-derived PCR product. Data analysis was carried out using IQTM software (version 5.2).

4.2 Results and discussion

Microbial cell numbers in the groundwater of Yarragadee were estimated using flow cytometry. As shown in Figure 5, all three samples showed bacterial cell counts between 1 and 10 cells/mL, with the highest observed in groundwater collected from bore G17. The groundwater of bores W7 and WT97 showed negligible number of cells. These cell numbers at all three locations were very low compared to an average cell number of 2.6E+03 ± 1.5E+03 cells/mL detected in the Leederville aquifer. When DNA was extracted from concentrated groundwater samples of G17, W7 and WT97 no visible band was observed on gel electrophoresis. This confirms the very low abundance of bacteria in all three groundwater samples and is consistent with the flow cytometric measurements. Although a DNA band was not visible upon extraction, when a polymerase chain reaction (PCR) was carried out on the DNA samples, PCR amplification was observed. This observation confirmed the presence of low numbers of bacteria in groundwater of the Yarragadee aquifer. Note: more than 95% of bacteria are found attached to particle surfaces (Harvey et al., 1984), and a reduced abundance of microorganisms in Yarragadee groundwater compared to Leederville groundwater does not necessarily reflect a reduced abundance of bacteria in the Yarragadee aquifer.

Using the primers (Table 4) designed from Leederville core material, the abundance of each specific group of microorganisms was then estimated for groundwater samples using qPCR. For all three samples, while some diversity was observed (Figure 5), less than 20 % of the bacterial groups could be identified. Differences in bacterial communities between Yarragadee and Leederville aquifers would likely contribute the incomplete diversity coverage. Considering the potential differences (e.g. lithology geochemistry and temperature) between the Leederville and Yarragadee aquifers, some differences in the microbial diversities could be expected. The bacterial community *Burkholderiales* (belonging to class *Betaproteobacteria*), was detected in all Leederville and Yarragadee groundwater samples, suggesting that this bacterial community was widespread in both the Leederville and Yarragadee aquifers.

Table 4 – Oligonucleotide primers used in this study

Forward Primer	Reverse Primer	Product Length	Positive Control	Negative Control	Target Bacterial Order
SHEW590f 5'(TGTTAAGCGAGATGTGAA)3'	SHEW647r 5'(CCTCTACAAGACTCTAGTTC)3'	77	KC166793	KC166742	*Alteromonadales*
ACHRO939f 5'(CGGTGGATGATGTGGATT)3'	ACHRO1018r 5'(TTCTCTTGCGAGCACTTC)3'	99	KC166742	KC166857	*Burkholderiales*
PSE638f 5'(ATAACTGCTTGGCTAGAG)3'	PSE702r 5'(TGGTGTTCCTTCCTATATC)3'	83	KC166823	KC166751	*Pseudomonadales*
PSE413f 5'(AAGGTCTTCGGATTGTAA)3'	PSE484r1 5'(TGCTTATTCTGTCGGTAA)3'	89	KC166751	KC166823	*Pseudomonadales*
PSE413f 5'(AAGGTCTTCGGATTGTAA)3'	PSE484r2 5'(GTGCTTATTCTGTTGGTAA)3'	90	KC166835	KC166748	*Pseudomonadales*
BEE1069f 5'(TCGTGTCGTGAGATGTTG)3'	BEE1127r 5'(ATTAGAGTGCCCTTTCGTAG)3'	78	KC166857	KC166847	*Burkholderiales*
BEE940f 5'(GGTGGATGATGTGGTTTA)3'	BEE1029r 5'(CTGTGTTACGGTTCTCTT)3'	109	KC166847	KC166840	*Burkholderiales*
Thau935f 5'(CAAGCGGTGGATGATGTG)3'	Thau996r 5'(TCAGCAAGGTTCCAGACA)3'	79	KC166840	KC166850	*Rhodocyclales*
Agro402f 5'(CGTGAGTGATGAAGGTCTTA)3'	Agro484r 5'(GGCTTCTTCTCCGACTAC)3'	75	KC166729	KC166835	*Rhizobiales*
Bee642f 5'(CTGGCTATCTTGAGTATGG)3'	Bee702r 5'(TGGTGTTCTTCCGAATATC)3'	79	KC166768	KC166741	*Caulobacterales*
Bee636f 5'(TTGATACTGACTGTCTTGAG)3'	Bee697r 5'(GTTCTTCCGAATATCTACGA)3'	81	KC166741	KC166782	*Caulobacterales*
Flavo674f 5'(AATATGTAGTGTAGCGGTGAA)3'	Flavo745r 5'(GTCCATCAGCGTCAATCA)3'	90	KC166702	KC166782	*Flavobacteriales*
Blasto144f '5'(TGGGATAACTCCAAGAAAT)3'	Blasto193r 5'(AGCCGATAAATCTTTCCA)3'	81	KC166745	KC166835	*Actinomycetales*
27f 5'(GAGTTTGATCCTGGCTCAG)3'	EUB338r 5'(GCTGCCTCCCGTAGGAGT)3'	312	Q629738	N/A	*All bacteria*

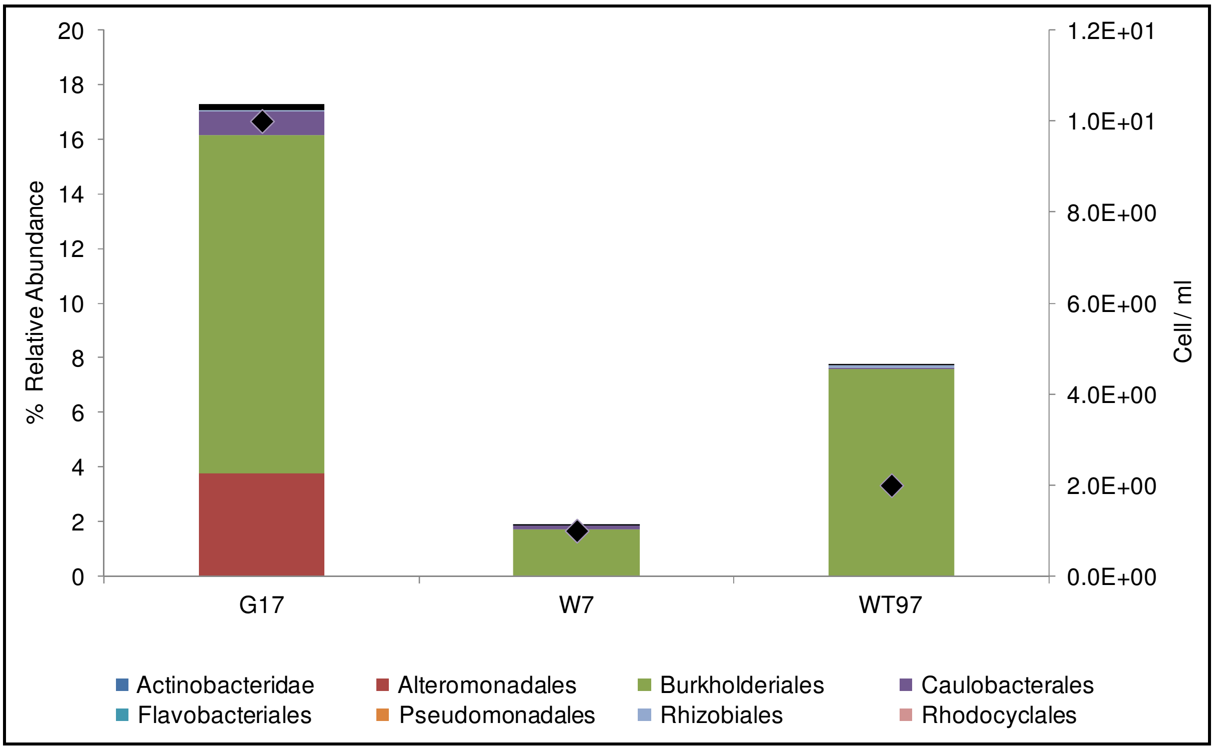


Figure 5 - The Abundance of the 16S rRNA gene copy number of identified bacterial order relative to the total bacterial copy numbers determined using qPCR and flow-cytometric cell counts in groundwater. (% relative abundance = (copy numbers of 16S rRNA gene targeted by specific primer / 16S rRNA gene copy numbers of all bacterial in sample) * 100).

5. Sediment characterisation

5.1 Methodology

5.1.1 Particle size analysis

The particle size distribution of sub-samples from Yarragadee aquifer cores was analysed by the CSIRO Particle Analysis Service (Waterford, WA) using laser diffraction (0.02-500 μm) and wet sieving (500-10000 μm). Water was used as dispersant and 10 mL Calgon solution as an additive. Each sample was sonicated for 20 min in an ultrasonic bath prior to analysis. Core texture was assessed according to the U.S. Department of Agriculture's soil textural class framework (USDA-NRCS, 2002).

5.1.2 Mineralogical analysis

The mineralogical composition of the Yarragadee aquifer core samples was determined using quantitative X-ray diffraction (XRD). All samples were analysed by the CSIRO Mineralogical and Geochemical Services Centre (Urrbrae, SA). For quantitative XRD analysis, *ca.* 1.5 g subsamples of each material were ground to <10 μm for 10 min in a McCrone micronizing mill under ethanol. The resulting slurries were oven dried at 60°C then mixed with a mortar and pestle before being pressed into stainless steel sample holders for XRD analysis. X-ray diffraction spectra were recorded with a PANalytical X'Pert Pro Multi-purpose Diffractometer using Fe filtered Co Kα radiation, variable divergence slit, 1° anti-scatter slit and fast X'Celerator Si strip detector. The diffraction patterns were recorded in steps of 0.017° 2Θ with a 0.5 s counting time per step. Quantitative analysis was performed on the XRD data using the commercial package TOPAS from Bruker AXS. The results were normalised to 100% and thus do not include estimates of unidentified or amorphous materials.

5.1.3 Geochemical analysis

The major elemental composition of each Yarragadee aquifer core sample was quantified as element by fusion X-ray fluorescence (XRF) at the CSIRO Mineralogical and Geochemical Service Centre. Oven-dried (105°C), ground 1 g sub-samples of each material were weighed with 4 g of 12-22 lithium borate flux. The mixtures were fused at 1050°C in a Pt/Au crucible for 20 min then poured into a heated Pt/Au mould. The melt was cooled over a compressed air stream and the resulting glass disks were analysed on a PANalytical AXios Advanced wavelength dispersive XRF system using the CSIRO Mineralogical and Geochemical Services in-house Silicates program. For pressed powder XRF analysis of trace elements in residues, 4 g of each oven-dried sample (105°C) was mixed with 1 g of Licowax binder. The mixtures were pressed in a 32 mm die at 12 t pressure and the resulting pellets were analysed on a PANalytical AXios Advanced wavelength dispersive XRF system using the CSIRO Mineralogical and Geochemical Services in-house Powders program.

Sample electrical conductivity (EC), pH, acid-digestible metal and total organic carbon (TOC) contents, cation exchange capacity (CEC), and ammonium oxalate-extractable Al, Fe, Mn and Si were determined by the ChemCentre (Perth, WA). The electrical conductivity (EC) and pH of each Yarragadee aquifer core sample were determined in a 1:5 (solid:liquid, w/w) aqueous extract using Milli-Q water. Acid-digestible metals in core samples, including Ag, As, B, Ba, Be, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, se, Sn, V, and Zn, were quantified using mixed nitric/hydrochloric acid digestion followed by inductively-coupled plasma-atomic emission spectrometry (ICP-AES) analysis of digest solutions. The TOC in each sample was determined using combustion analysis. Ammonium oxalate-extractable Al, Fe, Mn and Si were assessed at pH 3.25 to quantify Al, Fe, Mn and Si within poorly-crystalline mineral phases. The cation exchange capacity (CEC) of each Yarragadee aquifer core sample was determined using 1 M NH_4Cl.

Chromium-reducible S analysis was performed for each core sample by ALS Group (Perth, WA).

5.2 Lithology and particle size distribution

The Yarragadee aquifer core samples were largely classified as sandstone with substantial silt in some samples (sandstone/siltstone and silty sandstone), and one shale sample (Table 5 and Figure 6 - Figure 9). Core samples YarMAR01, 03 and 04 from the Gage formation (approximately 327-356 mBGL) exhibited fine to very fine grain size and contained lignite. Core samples from the Yarragadee formation (373 to 652 mBGL) generally exhibited a wider range of grain sizes and more angular quartz, as well as visible mica, pyrite, bands of clay/silt or shale, organic matter (OM) or heavy mineral deposits, and/or lignitic zones. Pyritic nodules and traces of pyrite (Fe_2S) were noted in a number of samples, including: YarMAR06 (throughout 389.6-396.6 mBGL), YarMAR08 (pyritic nodules at 456.6, 456.8 and 457.2 mBGL), YarMAR04 (pyrite cement at 528.9 and 530.0 mBGL), YarMAR21 (pyrite nodules 585.7-594.8 mBGL), and YarMAR26 (pyrite observed at 634.6 and 637.8 mBGL). Some pyrite nodules isolated from core sample YarMAR04 are shown in Figure 9.

Textural class analysis showed that the core samples examined were relatively coarse-textured and based on particle size distribution were classified as sand, loamy sand or sandy loam (Table 6, Figure 10). Consistent with lithological descriptions (Table 5), several Yarragadee aquifer core samples contained gravels, defined as particles >2 mm in diameter. Only the YarMAR06 sample contained sufficient gravel (>15%) to be classified as “gravelly”. Clay (particles <2 µm in diameter) contents ranged from <1 to 3.5 volume % (Table 6).

Table 5 - Lithology description of Yarragadee aquifer (YarMAR) core samples

No.	Date collected	Sample Depth (m)	Geological Description			
		From	Core Depth	Stratigraphy	Lithology	Description
01	20/11/2012	327.4-327.7	327.0 – 336.0	GAGE FORMATION	SANDSTONE	Dark grey, slightly silty, well sorted, very fine to fine grained, sub-rounded quartz sand, weakly to moderately consolidated. Minor mica, lignite and heavy minerals. Silt content decreasing with depth with intervals of clean light grey, fine grained sand.
02	21/11/2012	336.9-337.2	336.0 – 337.9	GAGE FORMATION	SANDSTONE	Light to dark grey, well sorted, very fine to fine grained, sub-rounded quartz sand. Traces of mica and heavy minerals, soft and weakly consolidated.
03	21/11/2012	341.8-342.1	341.5 – 343.0	GAGE FORMATION	SANDSTONE	Light to dark grey, well sorted, very fine to fine grained, sub-rounded quartz sand. Traces of mica and heavy minerals, hard and moderately consolidated, traces of lignite.
04	23/11/2012	356.1-356.9	356.1 – 357.8	GAGE FORMATION	SANDSTONE/ SILTSTONE	Grey to dark grey, moderately sorted, fine to very fine grained, sub-rounded quartz sand, minor gravel up to pebble size (8 mm). Gravel component increased from 356.8 m, sub-angular to sub-rounded. Moderate to well consolidated, weakly consolidated at 357.7 m. Lignitic at 357.1 m.
05	29/11/2012	373.5-374.2	371.9 – 374.2		SILTY SANDSTONE	Dark grey, silty, poorly sorted, very fine to very coarse grained, sub-angular, moderately to weakly consolidated quartz sand. Slightly micaceous, trace lignite.

No.	Date collected	Sample Depth (m)	Geological Description			
		From	Core Depth	Stratigraphy	Lithology	Description
06	2/12/2012	390.1-391.3	389.6 – 396.6		SANDSTONE	Light grey, fine to granule size, poorly sorted, sub-rounded to sub-angular, very well consolidated quartz sand. Significant orange tinting, traces of heavy metals, pyritic nodules and traces of pyrite throughout. Very coarse at 391.9 m. Stratified grains are coarse from 392.5 m to gravel size at 393.0 m. Sandstone well cemented in some parts. Very thin (1-2 cm) interlayered beds of fine and course sandstone with siltstone.
07	3/12/2012	423.1-424.1	418.1 – 427.7		SANDSTONE	Light grey, fine to medium grained, well sorted, sub-rounded to sub-angular quartz sand. Well consolidated. Very silty band between 418.2 and 418.3 m, dark grey and very micaceous. Minor tinted quartz and heavy minerals throughout, micaceous at top of interval. Dark brown, hard shale band between 419.5 and 419.7 m. Occasional small lenses of clay/silt (0.5 cm) at 421.1 and 425.7 m. Rich in black heavy minerals and red quartz at 427.1 m. Minor core losses.
08	4/12/2012	459.1-460.1	449.1 – 461.3		SANDSTONE	Grey, very fine to fine grained, well sorted, sub-angular. Moderately to well consolidated. Occasional micaceous bands and horizontal deposits of heavy minerals (or organic matter?). Minor heavy minerals and tinted quartz throughout. Pyritic nodules at 456.6 m, 456.8 m, 457.2 m. Some very coarse grains between 456.5 and 456.7 m. Dark brown, hard siltstone between 457.5 and 457.6 m.

No.	Date collected	Sample Depth (m)	Geological Description			
		From	Core Depth	Stratigraphy	Lithology	Description
09	5/12/2012	476.8-477.9	473.8 – 477.9		SANDSTONE	Grey, fine to medium grained, moderately to well sorted. Horizontal zones of lignite and occasional silt. Some coarse to very coarse grain patches.
10	5/12/2012	489.7-490.8	488.8-491.9		SANDSTONE	Light grey, very fine to fine grained, well sorted, sub-angular, well consolidated quartz sand. Micaceous and minor heavy minerals. Silty in zones.
11	6/12/2012	500.6-501.8	498.7 – 511.0		SANDSTONE	Light grey, fine to medium grained, moderately sorted, sub-angular, well consolidated quartz sand. Micaceous and minor heavy minerals. Silty in zones. Some coarse grained patches.
12	6/12/2012	509.9-511.0	498.7 – 511.0		SANDSTONE	Light grey, fine to medium grained, moderately sorted, sub-angular, well consolidated quartz sand. Micaceous and minor heavy minerals. Silty in zones. Some coarse grained patches.
13	6/12/2012	520.1-521.3	520.0 – 523.7		SILTY SANDSTONE	Light to dark grey, very fine to fine grained, sub-angular to angular, well sorted, moderately to well consolidated. Approx. 70% quartz sand. Less silty from 522.0 m, micaceous and traces of lignite.
14	7/12/2012	531.0-532.3	528.2 – 533.8		SANDSTONE	Grey, fine to medium grained, well sorted, well consolidated, minor silt. Minor core loss. Dark grey (?silt) banding. Very micaceous in silt bands, pyrite cement at 528.9, 530.0.

No.	Date collected	Sample Depth (m)	Geological Description			
		From	Core Depth	Stratigraphy	Lithology	Description
15	7/12/2012	540.1-541.3	539.1 – 541.9		SANDSTONE/ SILTSTONE	Grey/dark grey, alternating sandstone/siltstone. Sand is well sorted, very fine to fine grained and well consolidated.
16	7/12/2012	549.2-550.6	547.9 – 550.95		SANDSTONE	Light to dark grey, well sorted, very fine to fine grained, sub-angular, well consolidated quartz sand. Lignitic and micaceous. Very lignitic between 547.9 and 548.1 m. Small 1 cm scale pockets of silts. 5 cm siltstone (as per 545.6 – 545.7) at 549.0 m.
17	7/12/2012	555.8-557.0	555.8 – 557.0		SANDSTONE	Light grey, poorly sorted, coarser grained.
18	8/12/2012	562.6-563.2	557.8 – 563.2		SHALE	Dark grey, very minor sand, hard, well consolidated, micaceous, pyrite cemented at 558.6, 558.8, 559.2, 559.6 m. Sandy zones (<10 cm), very fine to fine grained sand. Some cement at 560.2. Minor core loss.
19	8/12/2012	573.2-574.1	571.9 –574.1		SANDSTONE	Grey, well to moderately sorted, fine to medium grained, sub-rounded to sub-angular, well consolidated. Some lignite.
20	9/12/2012	582.8-583.8	582 .0 – 584.1		SANDSTONE	Light grey, well sorted, fine to medium grained, occasional coarse grains, sub-angular, moderately to well consolidated quartz sand. Lignitic in very fine bands. Micaceous. Very fine to silty between 582.0 – 582.05 and 582.45 – 582.6 m.

No.	Date collected	Sample Depth (m)	Geological Description			
		From	Core Depth	Stratigraphy	Lithology	Description
21	9/12/2012	592.15-593.1	585.7 – 594.8		SILTY SANDSTONE	Light to dark grey, well sorted, very fine to fine grained, sub-angular, well consolidated, silty quartz sand. Occasional very coarse grains. Lignitic, pyritic nodules, tinted quartz and micaceous. Very lignitic in bands between 585.7 and 585.9 m. Siltstone and sandstone in horizontal bands, but with a majority of sand. Some medium to coarse sand at 590.7, 593.3 m. Less silty from 593 m.
22	9/12/2012	599.2-600.0	598.0 – 600.1		SANDSTONE	Light to dark grey, very fine to fine grained, majority of fine, sub-angular, well consolidated quartz sand. Some siltstone bands (0.5 to 2 cm). Micaceous, lignitic, tinted quartz. Some coarse to very coarse grained at 589.1 m. Very lignitic between 598.6 – 598.7 m.
23	9/12/2012	611.0-612.0	610.6 – 612.1		SANDSTONE	Grey, moderately sorted, very fine to medium grained, sub-rounded to sub-angular, well consolidated. Lignitic, micaceous in zones, some silts, some coarse grained bands.
24	10/12/2012	621.1-622.4	618.1 – 622.7		SANDSTONE	Grey, moderately to well sorted, fine to medium grained, sub-rounded to sub-angular, well consolidated. Lignitic, micaceous in zones.
25	10/12/2012	625.95-627.1	624.1 – 630.5		SANDSTONE	Light grey, well sorted, very fine to fine grained, sub-angular, well consolidated quartz sand. Lignitic, tinted quartz, slightly micaceous. Very lignitic between 624.1 and 624.3 m. Some very coarse to granule size sand at 627.2 m.

No.	Date collected	Sample Depth (m)	Geological Description			
		From	Core Depth	Stratigraphy	Lithology	Description
26	11/12/2012	634.9-636.2	630.5 – 638.7		SANDSTONE	Light grey, well sorted, fine to medium grained, sub-angular to sub-rounded, well consolidated. Garnet\tinted quartz-rich at 632.6 m, 632.9 m, 633.6 m, 633.7 m, 637.1 m, 637.4 m and 637.9 – 638.7 m. Pyrite at 634.6 m and 637.8 m. Very lignitic 635.0 – 635.1 m. Some coarse grains from 638.1 m, pebble size gravel at 638.5 m.
27	11/12/2012	641.0-642.1	638.7 – 642.1		SANDSTONE	As 630.5 – 638.7, but fine to coarse grained, poorly sorted, some very coarse grained, some silt at 639.2 m, garnet\tinted quartz-rich at 639.1 m.
28	11/12/2012	650.0-652.2	648.9 – 650.0		SANDSTONE	As 630.5 – 638.7, but fine to coarse grained, poorly sorted, some finer grained zones.
29	Week of 15/01/2013	655-661				Drilling spoils
30	Week of 15/01/2013	670-673				Drilling spoils
31	Week of 15/01/2013	685-688				Drilling spoils
32	Week of 15/01/2013	697-700				Drilling spoils
33	Week of 15/01/2013	709-712				Drilling spoils

No.	Date collected	Sample Depth (m)	Geological Description			
		From	Core Depth	Stratigraphy	Lithology	Description
34	Week of 15/01/2013	721-724				Drilling spoils
35	Week of 15/01/2013	733-736				Drilling spoils
36	Week of 15/01/2013	745-748				Drilling spoils

Figure 6 - Yarragadee aquifer core samples. Top (from left): YarMAR01, YarMAR04, YarMAR06. Bottom (from left): YarMAR07, YarMAR08, YarMAR09.

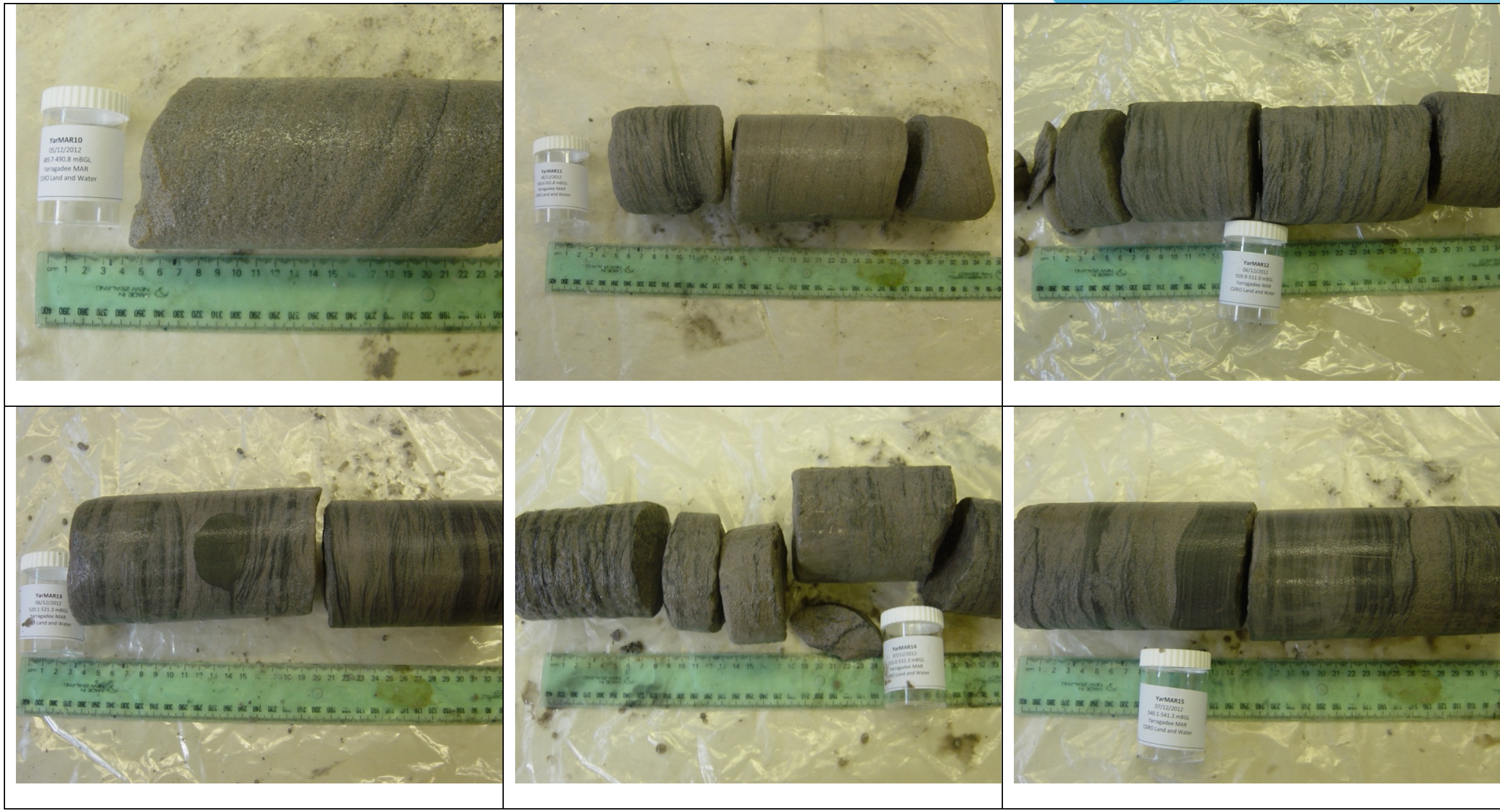


Figure 7 - Yarragadee aquifer core samples. Top (from left): YarMAR10, YarMAR11, YarMAR12. Bottom (from left): YarMAR13, YarMAR14, YarMAR15.

Figure 8 - Yarragadee aquifer core samples. Top (from left): YarMAR16, YarMAR17, YarMAR18. Bottom (from left): YarMAR19, YarMAR20, YarMAR21.

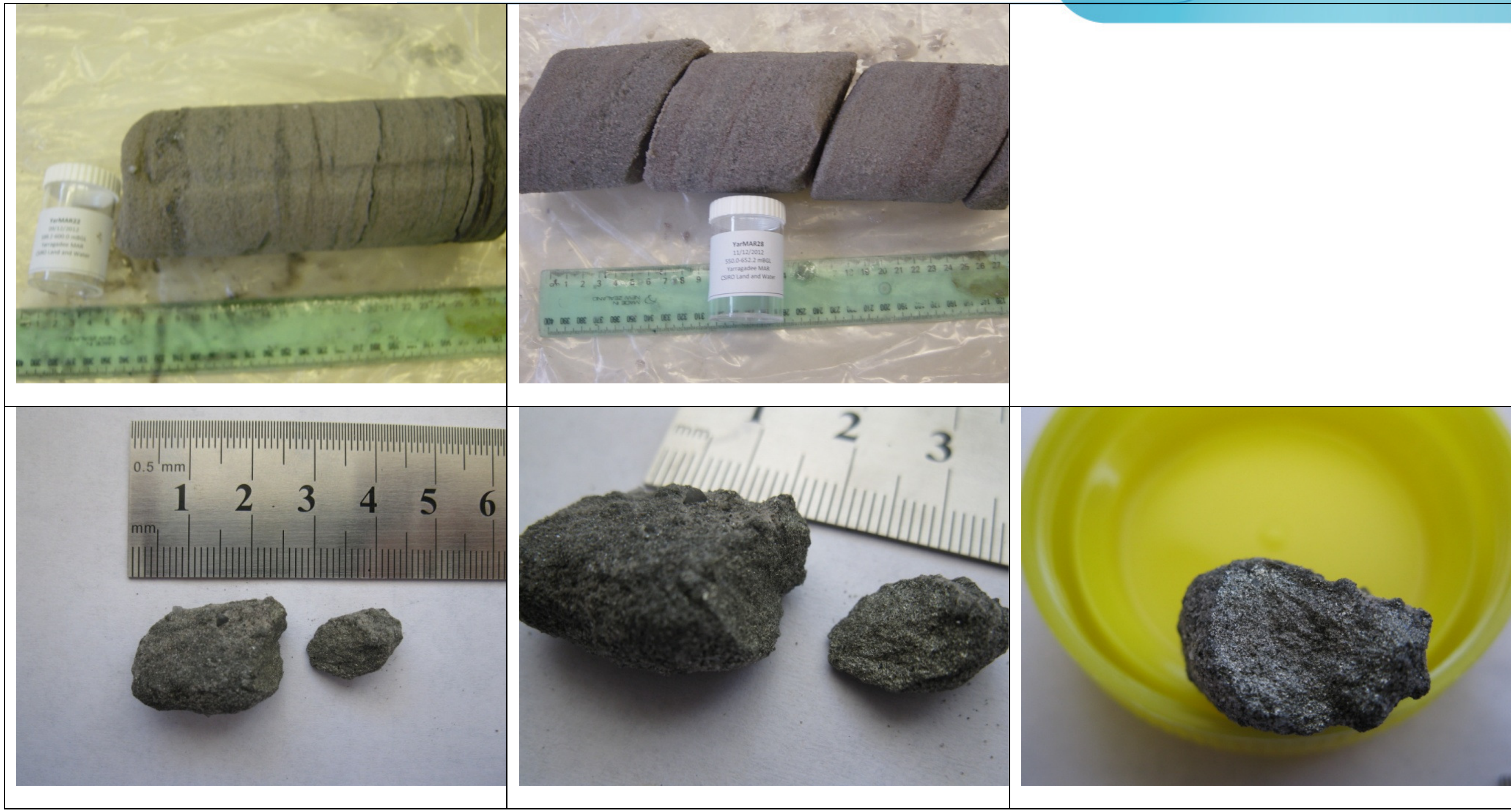


Figure 9 - Yarragadee aquifer core samples (top) and pyrite nodules (bottom). Top (from left): YarMAR22, YarMAR28. Bottom (from left): pyrite nodules found within YarMAR04 core sample during sample processing prior to use in respirometer experiment.

Table 6 – Particle size distribution (vol. %) and textural class of Yarragadee aquifer core samples.

	Mean sample depth (mBGL)	Clay <2.0 µm	Silt 2-63 µm	Fine sand 63-252 µm	Medium sand 252-500 µm	Coarse sand 500-2000 µm	Gravel >2000 µm	Textural class[a]
YarMAR01	331.5	2.07	14.73	59.30	20.10	2.40	1.40	Loamy sand
YarMAR04	356.5	2.34	18.14	61.90	14.91	2.30	0.40	Loamy sand
YarMAR06	390.7	1.89	11.00	12.03	9.08	42.70	23.30	Gravelly loamy sand
YarMAR07	423.6	3.50	14.22	19.45	48.13	6.10	8.60	Loamy sand
YarMAR08	459.6	2.57	16.36	37.61	18.16	15.80	9.50	Loamy sand
YarMAR09	477.35	1.76	9.92	26.35	30.57	28.40	3.00	Sand
YarMAR10	490.25	3.08	37.64	35.49	11.28	12.50	0.00	Sandy loam
YarMAR11	501.2	2.38	43.44	40.82	6.86	6.50	0.00	Sandy loam
YarMAR12	510.45	1.82	34.88	45.35	6.45	6.60	4.90	Sandy loam
YarMAR13	520.7	2.92	45.28	47.78	0.31	3.70	0.00	Sandy loam
YarMAR14	531.65	2.42	24.50	45.75	19.33	7.20	0.80	Sandy loam / loamy sand
YarMAR15	540.7	3.31	41.21	39.18	5.71	10.60	0.00	Sandy loam
YarMAR16	549.9	3.32	21.60	48.18	15.79	11.10	0.00	Loamy sand
YarMAR17	556.4	0.78	6.17	16.90	24.04	37.80	14.30	Sand
YarMAR18	562.9	3.89	51.34	29.50	3.27	12.00	0.00	Silt loam

YarMAR19	573.65	2.29	16.04	21.70	16.27	38.80	4.90	Loamy sand
YarMAR20	583.5	2.20	22.66	47.31	14.43	13.40	0.00	Loamy sand
YarMAR21	592.63	3.49	54.50	34.02	0.89	7.10	0.00	Silt loam
YarMAR22	599.6	2.98	21.05	42.75	21.31	10.40	1.50	Loamy sand
YarMAR28	651.1	1.22	11.28	12.11	41.09	34.20	0.10	Sand
YarMAR29	658	2.69	23.64	8.65	17.03	47.40	0.60	Loamy sand
YarMAR30	671.5	2.75	18.75	7.70	34.20	36.60	0.00	Loamy sand
YarMAR31	686.5	3.00	22.74	29.44	32.82	9.50	2.50	Loamy sand
YarMAR32	698.5	2.18	13.00	12.07	13.04	59.70	0.00	Loamy sand
YarMAR33	710.5	2.56	17.02	23.39	33.43	23.60	0.00	Loamy sand
YarMAR34	722.5	3.20	20.86	13.95	17.29	44.70	0.00	Loamy sand
YarMAR35	734.5	3.50	23.90	12.31	16.60	43.60	0.10	Sandy loam / loamy sand
YarMAR36	746.5	3.22	19.80	15.85	20.03	41.10	0.00	Loamy sand

[a] *Soil textural class (U.S. Department of Agriculture, http://soils.usda.gov/technical/aids/investigations/texture/).*

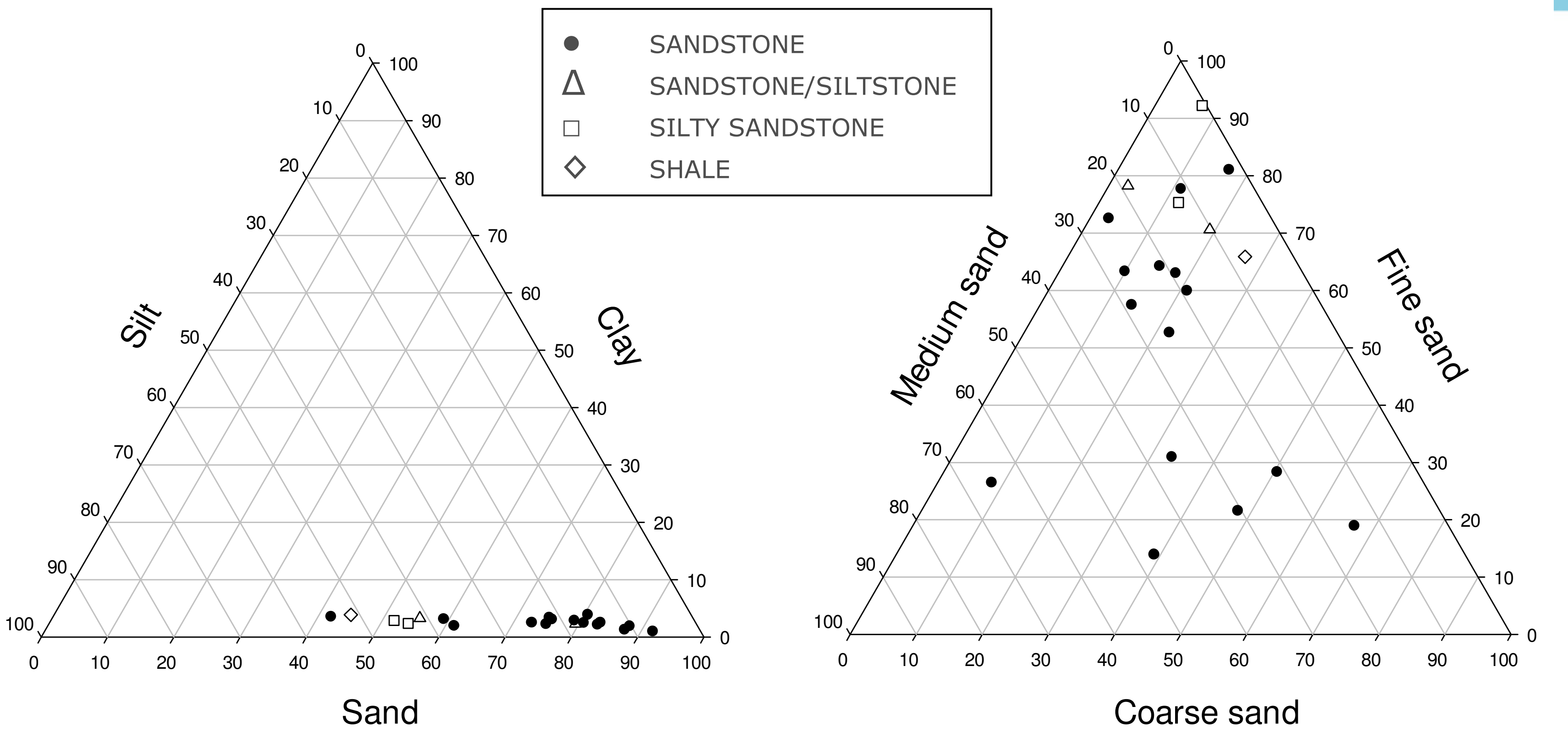


Figure 10 - Ternary diagrams of particle size distribution of Yarragadee aquifer core samples 01-28 normalised without gravel (left), and the textural distribution of sands in Yarragadee aquifer core samples (right).

5.3 Mineralology

Sandstones are sediments comprised of the transported or washed residues originating from the weathering of parent rocks (Pettijohn, 1963). Thus, sandstones contain the relatively more chemically inert and mechanically more durable minerals as compared to parent rocks. The bulk composition of sandstone is a function of the parent material composition, nature and duration of weathering and diagenic processes, and the degree of biochemical (such as shell debris) and other contamination (Morton and Hallsworth, 1999; Pettijohn, 1963).

Quantitative XRD analysis of Yarragadee aquifer core samples showed that quartz (SiO_2) was the dominant mineral, with substantial kaolinite ($Al_4Si_4O_{10}(OH)_8$) and feldspar minerals (Table 7). Together, quartz and kaolinite accounted for approximately 70-90% of the total mineral content of each core sample. The remainder of the mineral phase was primarily feldspar minerals, and monoclinic orthoclase ($KAlSi_3O_8$) was generally two to three times more enriched than triclinic microcline ($KAlSi_3O_8$). Consistent with the descriptions of core lithology, XRD analysis indicated minor-trace muscovite mica ($KAl_2(Si_3Al)O_{10}(OH,F)_2$) in most of the core samples and several samples contained trace pyrite (isometric crystalline FeS_2) and/or marcasite (orthorhombic crystalline FeS_2). Most of the Yarragadee aquifer core samples between approximately 530 and 750 mBGL showed minor-trace siderite ($FeCO_3$), whilst core samples between *ca.* 600 and 750 mBGL contained minor amounts of almandine garnet ($Fe_3Al_2(SiO_4)$).

Mineralogical analyses detected sylvite (KCl) within samples from approximately 670 to 750 mBGL. This is most likely an artefact of the sample collection process. Drilling fluids/muds frequently contain KCl to prevent hydration of clays and shales during drilling. As the Yarragadee samples from 658 to approximately 750 mBGL were not intact cores but were drilling spoils, the material may have been contacted by drilling fluids/mud to a greater extent than the intact cores collected at lesser depths.

Preliminary mineralogical analysis of five Yarragadee core samples from a North Perth site (Beatty Park) showed trace calcite ($CaCO_3$); however, calcite was not detected in any of the subsequent analyses. With the exception of $CaCO_3$ and CaO contents, mineralogical and geochemical results of preliminary analyses were similar to subsequent XRD and XRF results reported herein (see Appendix 1, Tables A1 and A2).

On average, the Yarragadee aquifer sediment cores examined contained 0.3±0.2% pyrite/marcasite, compared to 0.7±0.5% pyrite in the Leederville aquifer (Wilfert, 2009). The mean concentration of siderite within Yarragadee aquifer sediments, 0.7±1.2%, was slightly greater than the 0.5±1.2% detected in the Leederville aquifer sediments 120-220 mBGL, but the difference was not statistically significant. Calcite and/or dolomite ($CaMg(CO_3)_2$) may be present within Yarragadee aquifer sediments at concentrations less than analytical detection limits, similar to the Leederville aquifer and potentially indicative of a limited acid buffering capacity of the Yarragadee aquifer.

Compared to the Leederville aquifer sediments 120-220 mBGL (Wilfert, 2009), the Yarragadee aquifer sediments examined contained on average more quartz, with 54.7±19.2% and 75.8±12.4% mean quartz content in the Leederville and Yarragadee sediments, respectively. The Yarragadee aquifer sediments exhibited concomitant lesser mean kaolinite (10.6±17.3% versus 7.6±7.6%, respectively) and total feldspar (29.2±7.2%versus 13.8±5.6%, respectively) mineral contents (Figure 11). However, when comparing average mineral contents it should be considered that the averaging process includes samples from aquifer units (layers) that have very different hydraulic conductivities. A refined assessment that will still need to be made in the next step will need to compare the mineralogy of the most permeable aquifer sections, where most of the mineral reactions with the injectant are likely to take place.

Quartz and potassium and sodium feldspar minerals exhibit low acid buffering capacity, and soils or sediments derived from these parent materials are susceptible to acidification (Hodson et al., 1998). The release of exchangeable base cations such as Ca^{2+}, Mg^{2+} and K^+ buffer the acidification of soils and sediments via mineral weathering. The primary minerals (parent materials) in Yarragadee aquifer sediments include quartz, feldspar, and muscovite. Plagioclase feldspar and muscovite mineral dissolution can buffer acidification to some extent, dependent upon mineral dissolution kinetics. Previous studies have shown that acid buffering capacity in sandstone aquifers is largely associated with their clay content (e.g. Probst et al. 1999); however, kaolinite, the predominant clay mineral within the Yarragadee aquifer sediment core samples, has relatively little acid buffering capacity. Based on mineral composition, the Yarragadee aquifer materials examined herein may be expected to exhibit a lesser or similar acid buffering capacity compared to the Leederville 120-220 mBGL aquifer sediments.

In the Yarragadee aquifer, siderite dissolution may also buffer acidification through the reaction:

$$FeCO_{3(s)} + H^+_{(aq)} \rightarrow Fe^{2+}_{(aq)} + HCO_3^-{}_{(aq)}$$

In the absence of oxygen, siderite dissolution generates bicarbonate alkalinity and results in Fe^{2+} release to aqueous solution.

Divalent Fe released during siderite dissolution may be oxidised to Fe^{3+} in the presence of oxygen, consuming additional protons via:

$$Fe^{2+}_{(aq)} + 0.25\ O_{2(g)} + H^+_{(aq)} \rightarrow Fe^{3+}_{(aq)} + 0.5\ H_2O$$

The subsequent hydrolysis of $Fe^{3+}_{(aq)}$, however, results in the release of substantial acidity:

$$Fe^{3+}_{(aq)} + 3\ H_2O \rightarrow Fe^{3+}(OH)_{3(s)} + 3\ H^+_{(aq)}$$

Thus, in the presence of oxygen siderite has no net neutralising capacity. Examination of the preceding reactions indicates that siderite dissolution can neutralise acidity only in the absence of oxygen. Based on the oxygen removal rates observed for the Leederville groundwater replenishment trial this might be a realistic scenario (siderite dissolution in the absence of oxygen) as the oxygen removal in the Yarragadee by pyrite and SOM will presumably also occur rather rapidly, despite the somewhat lower average pyrite concentrations. However, Younger (2004) suggests that even in the absence of oxygen, siderite dissolution provides only localised acid neutralisation. Thus, the contribution of siderite to acid buffering capacity is somewhat ambiguous and is largely dependent upon oxygen concentration. This aspect will require further investigation.

Table 7 – Mineralogical compostion (wt. %) of Yarragadee aquifer core sub-samples

	Mean sample depth (mBGL)	Quartz SiO_2	Kaolinite $Al_4Si_4O_{10}(OH)_8$	Orthoclase (monoclinic K feldspar) $KAlSi_3O_8$	Microcline (triclinic K feldspar) $KAlSi_3O_8$	Albite (Plagioclase feldspar) $NaAlSi_3O_8$	Pyrite FeS_2 (isometric)	Marcasite FeS_2 (orthorhombic)	Muscovite $KAl_2(Si_3Al)O_{10}(OH,F)_2$	Chlorite $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2\cdot($ $Mg,Fe)_3(OH)_6$	Sepiolite $Mg_4Si_6O_{15}(OH)_2\cdot 6(H_2O)$	Siderite $FeCO_3$	Garnet (Almandine) $Fe_3Al_2(SiO_4)_3$	Sylvite KCl	Total
YarMAR01	331.5	81.2	1.9	9.9	6.4		0.5		<0.5						99.9
YarMAR04	356.5	74.9	4.2	12.4	7.4		0.7		<0.5						99.6
YarMAR06	390.7	88.9	1.3	5.1	4.2		0.5								100.0
YarMAR07	423.6	85.9	3.0	7.4	3.8										100.1
YarMAR08	459.6	77.4	7.4	9.5	5.0				0.7						100.0
YarMAR09	477.35	83.0	4.4	7.7	4.3		<0.5		<0.5						99.4
YarMAR10	490.25	76.8	8.8	8.6	4.6		<0.5		1.0						99.8
YarMAR11	501.2	70.6	12.8	10.0	4.9		<0.5		1.7	<1					100.0
YarMAR12	510.45	68.3	14.3	10.2	5.2		<0.5		1.9						99.9
YarMAR13	520.7	55.5	20.3	15.8	6.1				2.2	<1	<1				99.9
YarMAR14	531.65	67.8	12.3	12.8	5.3				1.2			0.6			100.0
YarMAR15	540.7	57.4	16.9	14.0	5.5		<0.5		2.0	<1		4.1			99.9
YarMAR16	549.9	70.5	9.1	14.2	5.6				0.6						100.0

YarMAR17	556.4	89.6	1.6	5.5	3.0				<0.5						99.7
YarMAR18	562.9	49.7	26.9	12.7	4.8				3.1	<1		2.8			100.0
YarMAR19	573.65	83.5	4.0	8.1	3.8		<0.5	0.5							99.9
YarMAR20	583.5	55.9	17.9	16.5	5.8				1.8	<1		2.1			100.0
YarMAR21	592.63	50.2	23.0	16.6	5.4				2.7	<1	<1	2.0			99.9
YarMAR22	599.6	71.8	9.2	11.9	4.4		<0.5		0.5				2.2		100.0
YarMAR28	651.1	85.3	2.2	5.8	3.0		<0.5						3.6		99.9
YarMAR29	658	87.3	2.0	3.2	2.5	0.9	1.0						3.1		100.0
YarMAR30	671.5	89.5	1.1	3.3	2.5	0.8	0.2						2.5	0.2	100.1
YarMAR31	686.5	80.0	1.6	5.5	2.9		0.3		0.2			0.4	9.0	0.2	100.1
YarMAR32	698.5	87.7	0.7	2.4	1.9		0.2					0.2	6.5	0.2	99.8
YarMAR33	710.5	85.1	1.0	4.6	2.6	0.4	0.3					1.3	4.6	0.2	100.1
YarMAR34	722.5	84.5	2.5	4.1	2.6	0.4	0.6					1.5	3.7	0.1	100.0
YarMAR35	734.5	83.3	1.6	3.5	2.5	0.5	0.4		0.2			3.1	4.6	0.1	99.8
YarMAR36	746.5	84.0	1.5	3.6	2.4	0.4	0.3		0.2			2.4	5.0	0.2	100.0

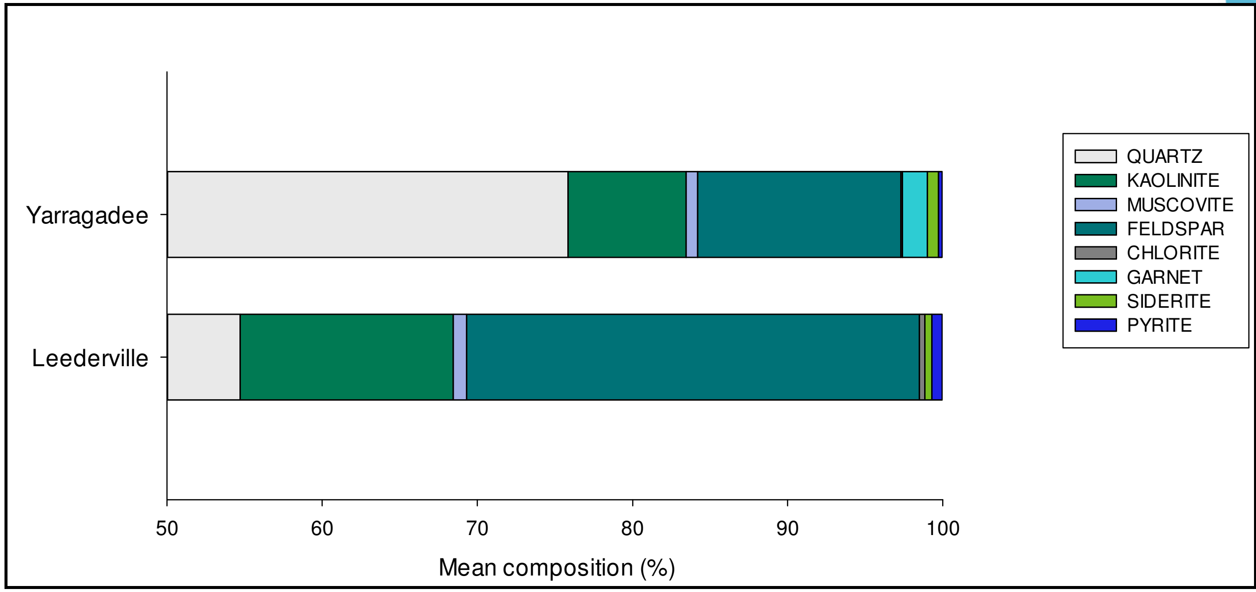


Figure 11 – Mean mineralogical composition of Yarragadee (*n*=28) and Leederville (*n*=42; from Wilfert, 2009) aquifer sediments

5.4 Geocehmistry

Whole-rock elemental concentrations provide important additional information for aquifer characterisation. Major elemental composition analysis by XRF confirmed mineralogical analyses, showing that 68-94 wt. % of the samples was accounted for by SiO_2 (Table 8). Across all core samples, Al was the next most abundant element (as Al_2O_3), followed by K (as K_2O) and Fe (as Fe_2O_3). Calcium, Mg, Mn, Na, P and Ti (as oxides) each comprised <1% in the Yarragadee aquifer core samples analysed. The uppermost three core samples examined, YarMAR01, 04 and 06, along with YarMAR19 contained the greatest quantity of S (as SO_3, Table 8). This result is consistent with mineralogical analyses showing highest concentration of the S minerals pyrite/marcasite in YarMAR01, 04, 06, and 19 (Table 7). Figure 12 shows a depth profile of the Yarragadee aquifer sediments, including lithology, stratigraphy, mineralogy and major elements with depth.

The loss on ignition (LOI) at 1050°C determined as the difference between 100% and the sum of major elements ranged from approximately nil to >6%. Sequential LOI is a technique widely used to estimate the organic and carbonate content of soils and sediments. In the sequential process, organic matter (OM) is oxidised to CO_2 and ash at 500-550°C, then CO_2 is evolved from carbonate at 900-1000°C leaving oxides. Temperature control is essential for accurate OM determination, as loss of volatile salts, structural water and inorganic C may also occur depending on the ignition temperature (Dean, 1974; Sutherland, 1998). Across all samples, the LOI at 1050°C was strongly correlated (r=0.95) with total clay mineral content as determined by quantitative XRD; however, the LOI at 1050°C was poorly correlated (r=0.21) with the siderite content of the samples.

Simple correlation analyses showed that the SiO_2 content of core samples was strongly correlated (r=0.99) with quartz content whereas Al_2O_3 content was strongly correlated (r=0.99) with total clay (e.g. kaolinite, muscovite, chlorite and sepiolite) content. A few core samples contained major Fe_2O_3 or CaO; contents of all other major elements in the core samples examined were minor. Iron as quantified by XRF (Fe_2O_3) was largely (r=0.88) accounted for by siderite, whilst S (as SO_3) was strongly correlated (r=0.86) with the pyrite/marcasite content of core samples The Na and K content of core samples can be primarily attributed to the presence of clay and feldspar minerals within the sandstone matrices.

Table 8 - Major elemental composition (wt. %, as oxides) and Cl content (mg/kg) of Yarragadee aquifer core sub-samples.

	Mean sample depth (mBGL)	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MnO	CaO	MgO	Na_2O	K_2O	P_2O_5	SO_3	Cl	Sum %
YarMAR01	331.5	89.26	5.03	0.61	0.80	0.01	0.04	0.13	0.18	2.36	0.03	0.55	<0.01	99.00
YarMAR04	356.5	86.31	6.50	0.67	1.04	0.01	0.06	0.18	0.18	2.74	0.04	0.44	<0.01	98.15
YarMAR06	390.7	94.17	2.68	0.09	0.78	0.01	0.03	0.09	0.12	1.28	0.02	0.72	<0.01	99.98
YarMAR07	423.6	91.69	4.39	0.18	0.51	0.01	0.10	0.19	0.15	1.53	0.02	0.07	<0.01	98.83
YarMAR08	459.6	86.09	7.27	0.70	0.86	0.02	0.14	0.29	0.16	2.18	0.05	0.11	<0.01	97.88
YarMAR09	477.35	90.29	4.99	0.44	0.64	0.02	0.10	0.19	0.14	1.67	0.03	0.13	<0.01	98.64
YarMAR10	490.25	86.48	7.67	0.35	0.64	0.01	0.06	0.26	0.14	2.02	0.03	0.10	<0.01	97.77
YarMAR11	501.2	80.40	10.51	0.80	1.42	0.02	0.10	0.51	0.16	2.31	0.05	0.18	<0.01	96.46
YarMAR12	510.45	79.41	11.54	0.69	1.47	0.02	0.08	0.54	0.15	2.44	0.04	0.16	<0.01	95.54
YarMAR13	520.7	74.94	13.66	0.70	1.93	0.02	0.11	0.75	0.20	3.48	0.05	0.08	<0.01	95.91
YarMAR14	531.65	80.46	9.31	0.62	1.68	0.03	0.13	0.40	0.18	2.66	0.05	0.08	<0.01	95.59
YarMAR15	540.7	73.76	12.11	0.81	4.32	0.05	0.14	0.58	0.19	2.98	0.06	0.24	<0.01	95.24
YarMAR16	549.9	85.33	8.19	0.32	0.59	0.01	0.08	0.20	0.21	2.90	0.04	0.14	<0.01	98.00
YarMAR17	556.4	92.60	2.81	0.25	0.53	0.01	0.10	0.17	0.11	1.15	0.02	0.06	<0.01	97.81
YarMAR18	562.9	67.94	16.27	0.89	4.02	0.04	0.17	0.85	0.18	2.84	0.06	0.15	<0.01	93.41

YarMAR19	573.65	90.92	4.33	0.23	1.08	0.01	0.08	0.18	0.13	1.70	0.03	0.74	<0.01	99.43
YarMAR20	583.5	74.37	13.03	0.57	2.90	0.03	0.11	0.54	0.21	3.32	0.05	0.13	<0.01	95.26
YarMAR21	592.63	68.48	15.75	0.88	3.87	0.04	0.16	0.95	0.21	3.34	0.06	0.14	<0.01	93.87
YarMAR22	599.6	84.70	7.79	0.81	1.42	0.03	0.19	0.35	0.17	2.36	0.05	0.15	<0.01	98.02
YarMAR28	651.1	92.28	3.48	0.20	1.35	0.03	0.21	0.35	0.11	1.22	0.02	0.24	<0.01	99.49
YarMAR29	658	91.00	3.29	0.23	2.09	0.03	0.39	0.39	0.14	0.98	0.08	0.69	282	99.32
YarMAR30	671.5	93.9	2.40	0.21	1.16	0.02	0.18	0.29	0.13	1.02	0.03	0.33	965	99.76
YarMAR31	686.5	87.13	4.56	0.56	3.66	0.08	0.60	0.78	0.15	1.32	0.04	0.47	1272	99.48
YarMAR32	698.5	91.46	2.78	0.22	2.53	0.05	0.38	0.60	0.10	0.72	0.03	0.38	791	99.32
YarMAR33	710.5	90.37	2.99	0.38	2.78	0.07	0.35	0.50	0.13	1.17	0.04	0.52	1262	99.41
YarMAR34	722.5	89.22	3.55	0.32	2.93	0.05	0.31	0.44	0.13	1.16	0.04	0.69	1139	98.96
YarMAR35	734.5	88.63	3.23	0.25	3.72	0.09	0.34	0.65	0.12	1.05	0.04	0.63	1338	98.88
YarMAR36	746.5	89.24	3.21	0.32	3.41	0.07	0.33	0.56	0.13	1.07	0.03	0.41	1534	98.95

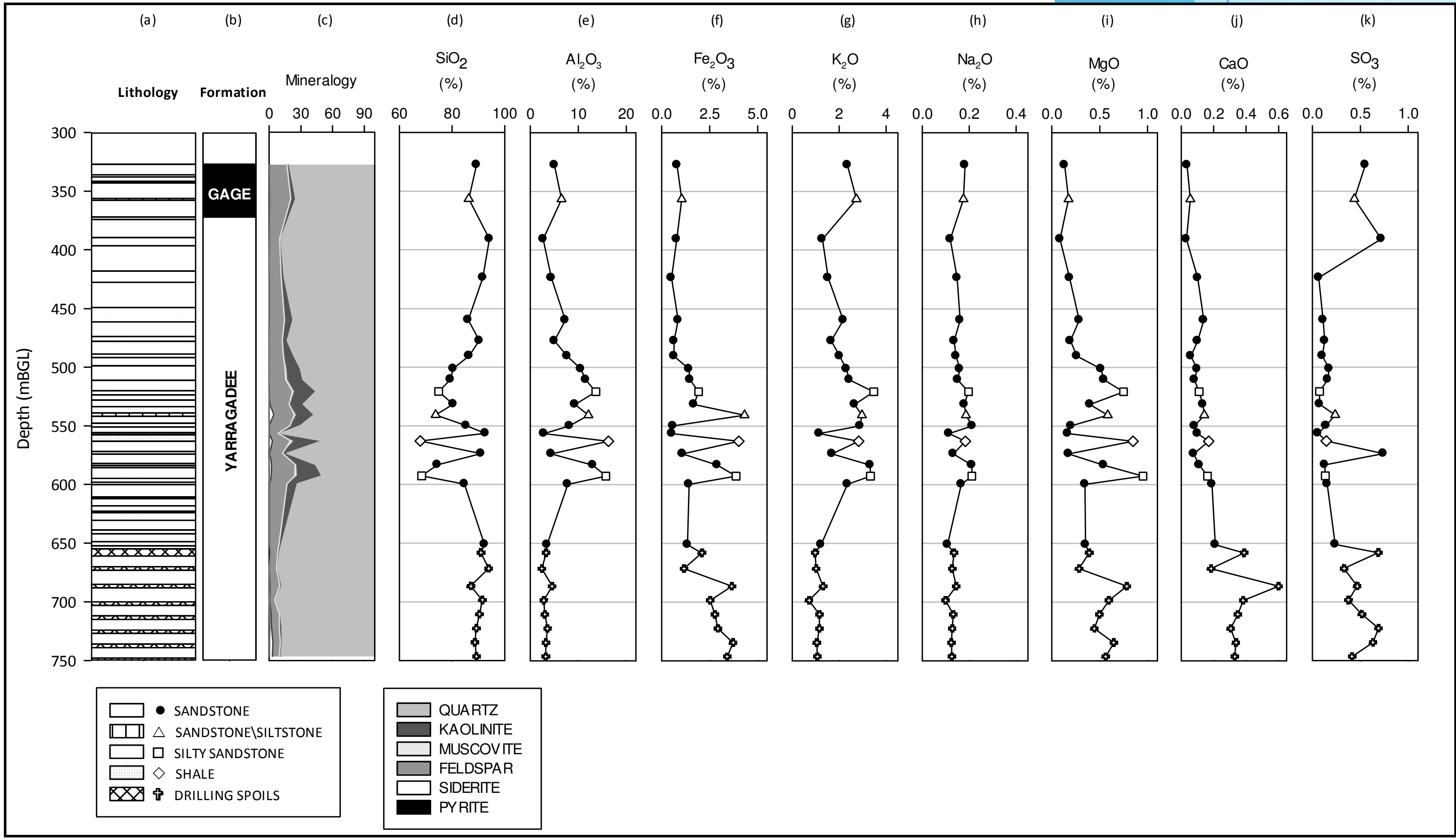


Figure 12 - Depth profiles of Yarragadee aquifer including (a) lithology, (b) stratigraphy, (c) mineralogy and (d-k) major elements (as oxides)

The total trace element content of the Yarragadee aquifer core samples examined was generally low (Table 9), with the mean total trace element content equivalent to <0.2% by mass (0.16 ± 0.06% w/w). Some trace elements readily substitute for major elements. For example, Sr readily substitutes for Ca in feldspar and clay minerals and Ti in some minerals is readily replaced by Nb (Preston et al., 1998). In addition, Rb or Cs may substitute for K and thus can be expected to be relatively more abundant in samples containing substantial feldspar and/or micaceous minerals such as muscovite. The Sr content of Yarragadee core samples was more strongly correlated to the feldspar content (r=0.97) than to the total clay mineral content (*r*=0.71). The Rb and K contents of core samples were strongly correlated (*r*=0.95) to one another and both Rb and K were strongly correlated (*r*=0.91 and *r*=0.99, respectively) with the feldspar mineral content of core samples.

Trace elements of potential concern based on total content in the Yarragadee core samples included Cd, Cr, Ni and Sb. The Cd content of many of the Yarragadee aquifer core samples examined was clearly greater than Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ, 2000) ISQG-low (trigger value) recommended sediment quality guideline values. Seven of the examined Yarragadee core samples exhibited <2 mg/kg Cd; however, the ISQG-low trigger value is 1.5 mg Cd/kg (ANZECC/ARMCANZ, 2000). Similarly, most of the Yarragadee aquifer core samples contained Sb at concentrations in excess of ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guideline values, whilst the Sb content of the remaining seven samples was less than the 6 mg/kg limit of detection but may have been greater than the 2 mg/kg ISQG-low trigger value.

Several core samples contained Cr at concentrations greater than ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines, including: YarMAR04 (*ca.* 356-357 mBGL, 185 ppm), YarMAR11 (*ca.* 501-502 mBGL, 291 ppm), YarMAR12 (*ca.* 510-511 mBGL, 99 ppm), YarMAR18 (*ca.* 363 mBGL, 85 ppm), YarMAR20 (*ca.* 583-584 mBGL, 102 ppm) and YarMAR21 (*ca.* 592-593 mBGL, 113 ppm) (Table 9). The YarMAR09 core sample (*ca.* 477-478 mBGL) exhibited 404 mg/kg Cd, in excess of ANZECC/ARMCANZ (2000) ISQG-high recommended sediment quality values. The concentration of Ni within core sample YarMAR21 (*ca.* 592-593 mBGL) was 30 mg/kg, greater than the 21 mg/kg ISQG-low trigger value (ANZECC/ARMCANZ, 2000).

Only the acid-extractable Ni content of sample YarMAR21 exceeded ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines (Table 10). On average, more than 80% of the Co, Cu, Ni and Zn measured within the Yarragadee aquifer core samples using XRF were acid-extractable. In contrast, comparison between total contents and acid-extractable quantities indicated an average of <10% of total Ba, Be and Cd in Yarragadee samples were extracted from the sediments via acidification (Figure 14). The differences in elemental composition obtained via XRF analyses and acid digestion are due to incomplete decomposition of minerals using an HCl-HNO_3 acid mixture. Microwave-assisted acid digestion of minerals, as by the U.S. EPA Method 3051A (2007) used herein, is a rapid sample digestion method which is not susceptible to losses of volatile metals; however, substantial variation has been reported in the efficiency of metals recovery from siliceous matrices using this technique (e.g. Chen and Ma, 2001; Church et al 1992; Totland et al., 1992). Results of acid digest analyses indicate that Co, Cu and Ni within the Yarragadee aquifer sediments are susceptible to mobilisation as a result of partial acid dissolution of aquifer materials.

Table 9 – Trace elemental composition (mg/kg) of Yarragadee aquifer core samples

	Mean sample depth (mBGL)	Ag	As	Ba	Bi	Br	Cd	Ce	Co	Cr	Cs
YarMAR01	331.5	<2	4	567	6	<1	<2	47	26	24	<7
YarMAR04	356.5	<2	4	697	5	<1	2[a]	52	25	185[a]	<7
YarMAR06	390.7	<2	3	318	6	<1	<2	<14	47	15	<7
YarMAR07	423.6	<2	2	419	7	<1	3[a]	26	33	27	<7
YarMAR08	459.6	<2	2	553	7	<1	2[a]	52	32	41	<7
YarMAR09	477.35	<2	4	425	5	<1	2[a]	20	43	404[b]	<7
YarMAR10	490.25	<2	2	517	4	<1	3[a]	16	31	46	<7
YarMAR11	501.2	<2	3	626	7	<1	3[a]	75	31	291[a]	8
YarMAR12	510.45	<2	2	643	5	<1	3[a]	47	28	99[a]	8
YarMAR13	520.7	<2	3	868	6	<1	<2	52	24	67	<7
YarMAR14	531.65	<2	2	753	4	<1	2[a]	50	24	59	<7
YarMAR15	540.7	<2	3	784	5	<1	<2	78	22	58	13
YarMAR16	549.9	<2	3	740	6	<1	<2	28	26	52	<7
YarMAR17	556.4	<2	3	316	5	<1	3[a]	18	39	28	<7
YarMAR18	562.9	<2	4	674	7	<1	4[a]	80	25	85[a]	8
YarMAR19	573.65	<2	2	428	6	<1	<2	<14	38	27	<7
YarMAR20	583.5	<2	3	872	5	<1	2[a]	44	27	102[a]	<7
YarMAR21	592.63	<2	2	868	6	<1	<2	68	28	113[a]	<7
YarMAR22	599.6	<2	2	676	6	<1	3[a]	59	29	52	<7
YarMAR28	651.1	<2	2	320	4	<1	2[a]	<14	44	29	<7
YarMAR29	658	<2	4	245	7	<1	2[a]	18	23	26	<7
YarMAR30	671.5	<2	1	225	4	<1	<2	<14	22	19	<7
YarMAR31	686.5	<2	2	369	6	<1	<2	53	34	46	<7
YarMAR32	698.5	<2	2	198	6	<1	3[a]	20	29	31	<7
YarMAR33	710.5	<2	2	300	7	<1	2[a]	17	25	30	<7
YarMAR34	722.5	<2	1	281	5	<1	3[a]	33	29	45	<7
YarMAR35	734.5	<2	3	249	8	<1	3[a]	24	30	30	<7
YarMAR36	746.5	<2	1	250	7	<1	2[a]	29	31	30	<7

[a] Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines.
[b] Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-high recommended sediment quality guidelines.

Table 9 (continued) – Trace elemental composition (mg/kg) of Yarragadee aquifer core samples

	Mean sample depth (mBGL)	Cu	Ga	Ge	Hf	Hg	I	La	Mn	Mo	Nb
YarMAR01	331.5	3	6	2	12	<12	<6	22	43	3	12
YarMAR04	356.5	5	9	2	13	<12	<6	32	63	2	13
YarMAR06	390.7	<1	4	2	<6	<12	7	<12	27	<1	3
YarMAR07	423.6	<1	6	2	<6	<12	<6	<12	67	<1	5
YarMAR08	459.6	3	10	2	14	<12	<6	21	102	2	14
YarMAR09	477.35	3	7	3	<6	<12	<6	12	93	2	9
YarMAR10	490.25	6	10	3	<6	<12	<6	<12	53	<1	8
YarMAR11	501.2	10	13	2	16	<12	<6	41	138	4	16
YarMAR12	510.45	10	15	3	10	<12	<6	25	123	<1	13
YarMAR13	520.7	7	17	2	8	<12	<6	31	130	<1	14
YarMAR14	531.65	6	11	2	11	<12	10	16	162	<1	13
YarMAR15	540.7	6	16	2	10	<12	<6	26	387	2	16
YarMAR16	549.9	2	10	2	<6	<12	<6	<12	50	<1	8
YarMAR17	556.4	2	4	6	<6	<12	9	<12	72	<1	5
YarMAR18	562.9	13	21	2	11	<12	<6	39	282	<1	19
YarMAR19	573.65	2	6	2	<6	<12	9	<12	73	<1	5
YarMAR20	583.5	5	18	2	<6	<12	12	16	218	<1	11
YarMAR21	592.63	10	19	2	11	<12	<6	18	275	<1	17
YarMAR22	599.6	2	9	2	16	<12	<6	31	177	1	14
YarMAR28	651.1	<1	5	2	<6	<12	6	<12	201	<1	5
YarMAR29	658	3	6	2	<7	<12	<6	19	160	<1	5
YarMAR30	671.5	<1	3	2	<7	<12	<6	<12	127	<1	4
YarMAR31	686.5	3	6	2	12	<12	<6	16	510	2	12

	Mean sample depth (mBGL)	Cu	Ga	Ge	Hf	Hg	I	La	Mn	Mo	Nb
YarMAR32	698.5	<1	4	2	9	<12	<6	<12	311	<1	5
YarMAR33	710.5	2	4	1	<7	<12	<6	<12	425	<1	7
YarMAR34	722.5	2	5	2	7	<12	<6	13	328	<1	6
YarMAR35	734.5	3	5	2	<7	<12	<6	<12	639	<1	5
YarMAR36	746.5	2	5	2	7	<12	<6	<12	484	<1	7

[a] Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines.

[b] Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-high recommended sediment quality guidelines.

Table 9 (continued) – Trace elemental composition (mg/kg) of Yarragadee aquifer core samples

	Mean sample depth (mBGL)	Nd	Ni	Pb	Rb	Sb	Sc	Se	Sm	Sn	Sr
YarMAR01	331.5	<8	<2	11	62	**7**[a]	<3	1	<8	4	69
YarMAR04	356.5	<8	5	14	75	**7**[a]	5	<1	<8	<3	80
YarMAR06	390.7	<8	<2	<2	34	**10**[a]	<3	<1	<8	<3	34
YarMAR07	423.6	<8	<2	6	39	**12**[a]	3	<1	<8	4	53
YarMAR08	459.6	<8	5	11	59	**8**[a]	5	<1	11	<3	68
YarMAR09	477.35	<8	8	5	43	<6	4	2	<8	<3	54
YarMAR10	490.25	<8	7	12	59	<6	5	1	<8	<3	58
YarMAR11	501.2	23	21	12	79	<6	8	<1	<8	<3	65
YarMAR12	510.45	10	18	12	84	<6	6	<1	<8	<3	65
YarMAR13	520.7	<8	18	15	102	**7**[a]	9	<1	13	<3	97
YarMAR14	531.65	<8	6	12	73	<6	3	<1	<8	<3	88
YarMAR15	540.7	14	14	16	87	**10**[a]	9	2	<8	<3	87
YarMAR16	549.9	<8	<2	10	71	<6	4	<1	<8	<3	99
YarMAR17	556.4	<8	<2	<2	28	**8**[a]	<3	2	<8	<3	38

	Mean sample depth (mBGL)	Nd	Ni	Pb	Rb	Sb	Sc	Se	Sm	Sn	Sr
YarMAR18	562.9	17	18	18	97	<6	10	<1	<8	<3	82
YarMAR19	573.65	<8	<2	4	42	**7**[a]	4	<1	<8	<3	53
YarMAR20	583.5	11	12	15	91	**8**[a]	8	<1	<8	<3	105
YarMAR21	592.63	15	**30**[a]	18	106	**9**[a]	10	<1	<8	<3	95
YarMAR22	599.6	12	5	13	59	**8**[a]	7	1	<8	4	84
YarMAR28	651.1	<8	<2	2	30	**7**[a]	5	<1	11	<3	37
YarMAR29	658	<8	<2	3	24	**9**[a]	4	<1	<8	13	32
YarMAR30	671.5	<8	<2	2	22	<6	3	<1	<8	<3	28
YarMAR31	686.5	<8	<2	4	30	<6	9	<1	<8	5	43
YarMAR32	698.5	<8	<2	<2	18	**10**[a]	6	<1	<8	<3	22
YarMAR33	710.5	<8	<2	2	26	**8**[a]	5	<1	<8	<3	37
YarMAR34	722.5	<8	3	4	28	**6**[a]	3	<1	<8	<3	35
YarMAR35	734.5	<8	<2	3	24	**13**[a]	4	<1	<8	<3	29
YarMAR36	746.5	<8	<2	3	23	**7**[a]	4	<1	<8	<3	30

[a] *Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines.*

[b] *Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-high recommended sediment quality guidelines.*

Table 9 (continued) – Trace elemental composition (mg/kg) of Yarragadee aquifer core samples

	Mean sample depth (mBGL)	Ta	Te	Th	Tl	U	V	Y	Yb	Zn	Zr
YarMAR01	331.5	<5	<6	32	6	8	39	12	<8	13	540
YarMAR04	356.5	9	<6	30	4	8	56	15	<8	20	490
YarMAR06	390.7	<5	<6	20	4	3	8	3	<8	<2	73
YarMAR07	423.6	<5	<6	21	4	5	20	4	<8	8	62
YarMAR08	459.6	<5	<6	32	5	6	51	17	<8	25	581

	Mean sample depth (mBGL)	Ta	Te	Th	Tl	U	V	Y	Yb	Zn	Zr
YarMAR09	477.35	<5	<6	25	3	4	55	8	<8	15	259
YarMAR10	490.25	<5	<6	24	3	7	34	6	<8	24	143
YarMAR11	501.2	<5	<6	39	3	8	82	20	<8	104	721
YarMAR12	510.45	<5	<6	28	4	7	67	13	<8	30	394
YarMAR13	520.7	<5	<6	28	<2	8	67	14	<8	75	284
YarMAR14	531.65	<5	<6	27	4	7	58	12	<8	38	316
YarMAR15	540.7	<5	<6	33	4	7	69	19	<8	54	516
YarMAR16	549.9	<5	<6	22	3	5	30	6	<8	86	131
YarMAR17	556.4	<5	<6	23	3	4	26	6	<8	3	174
YarMAR18	562.9	<5	<6	35	3	9	94	23	<8	123	316
YarMAR19	573.65	<5	<6	21	4	5	18	5	<8	5	132
YarMAR20	583.5	<5	<6	26	3	5	66	11	<8	77	190
YarMAR21	592.63	<5	<6	31	<2	9	98	19	<8	95	354
YarMAR22	599.6	<5	<6	33	6	8	50	18	<8	27	559
YarMAR28	651.1	<5	<6	20	4	5	22	8	<8	11	85
YarMAR29	658	<5	<6	24	5	6	22	9	<8	61	132
YarMAR30	671.5	<5	<6	23	4	6	16	7	<8	49	110
YarMAR31	686.5	<5	<6	33	2	6	45	23	<8	42	510
YarMAR32	698.5	<5	<6	25	4	2	21	14	<8	23	177
YarMAR33	710.5	<5	<6	26	4	5	28	12	<8	45	285
YarMAR34	722.5	<5	<6	26	5	6	31	11	<8	18	197
YarMAR35	734.5	<5	<6	23	5	6	25	11	<8	30	155
YarMAR36	746.5	<5	<6	26	4	6	25	12	<8	14	287

[a] *Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines.*

[b] *Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-high recommended sediment quality guidelines.*

Table 10 - Acid-extractable metal composition (mg/kg) of Yarragadee aquifer core samples

	Mean sample depth (mBGL)	Ag	As	B	Ba	Be	Cd	Co	Cr	Cu	Mn	Mo	Ni	Pb	Sb	Se	Sn	V	Zn
YarMAR01	331.5	<0.5	<1	<5	38	0.23	<0.05	19	5.1	2.3	12	0.6	4	3.2	<2	<2	<0.5	7	10
YarMAR04	356.5	<0.5	1	<5	79	0.57	0.12	16	7.3	4.1	23	<0.5	6	5.5	<2	3	1.3	10	18
YarMAR06	390.7	<0.5	<1	<5	17	<0.05	<0.05	39	2.1	0.5	4.5	<0.5	1	<0.5	<2	<2	<0.5	0.8	<5
YarMAR07	423.6	<0.5	<1	<5	28	0.06	<0.05	30	2.7	1.1	7.9	<0.5	2	1.1	<2	<2	1.1	1.4	6
YarMAR08	459.6	<0.5	<1	<5	43	0.16	<0.05	38	5.0	2.1	18	<0.5	7	2.6	<2	<2	<0.5	5.7	19
YarMAR09	477.35	<0.5	<1	<5	34	0.10	<0.05	22	3.8	2.4	10	<0.5	7	1.6	<2	<2	<0.5	3.5	11
YarMAR10	490.25	<0.5	<1	<5	83	0.20	<0.05	26	8.5	4.8	24	<0.5	10	4.3	<2	<2	<0.5	6.7	21
YarMAR11	501.2	<0.5	<1	<5	120	0.29	0.13	25	13	6.4	43	<0.5	13	5.1	<2	<2	<0.5	13	49
YarMAR12	510.45	<0.5	<1	<5	130	0.42	<0.05	32	17	8.1	61	<0.5	14	3.2	<2	3	<0.5	13	19
YarMAR13	520.7	<0.5	<1	<5	190	0.59	0.12	19	29	6.5	78	<0.5	19	5.7	<2	4	<0.5	25	71
YarMAR14	531.65	<0.5	<1	<5	130	0.81	0.15	17	21	5.0	88	<0.5	9	3.0	<2	3	<0.5	27	34

YarMAR15	540.7	<0.5	<1	<5	150	0.79	0.30	19	23	5.5	340	<0.5	15	8.6	<2	10	<0.5	22	51
YarMAR16	549.9	<0.5	<1	<5	36	0.18	<0.05	25	5.1	1.7	14	<0.5	4	1.0	<2	<2	<0.5	3.3	70
YarMAR17	556.4	<0.5	<1	<5	27	0.24	<0.05	31	8.3	1.7	12	<0.5	2	<0.5	<2	<2	<0.5	9.2	<5
YarMAR18	562.9	<0.5	<1	<5	160	1.0	0.42	18	21	14	180	<0.5	18	10	<2	6	<0.5	33	98
YarMAR19	573.65	<0.5	<1	<5	16	0.07	0.06	30	2.9	0.8	11	<0.5	13	1.9	<2	4	<0.5	1.9	<5
YarMAR20	583.5	<0.5	<1	<5	130	0.65	0.27	14	23	4.2	200	<0.5	14	6.6	<2	7	<0.5	28	72
YarMAR21	592.63	<0.5	<1	<5	200	1.0	0.23	21	37	9.1	180	<0.5	**26**[a]	6.7	<2	6	<0.5	33	79
YarMAR22	599.6	<0.5	<1	<5	43	0.17	<0.05	14	6	1.3	18	<0.5	12	2.2	<2	<2	<0.5	5	20
YarMAR28	651.1	<0.5	<1	<5	9	<0.05	<0.05	25	2.3	0.3	13	<0.5	3	<0.5	<2	<2	<0.5	1.6	<5

[a] *Concentration exceeds ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guidelines.*

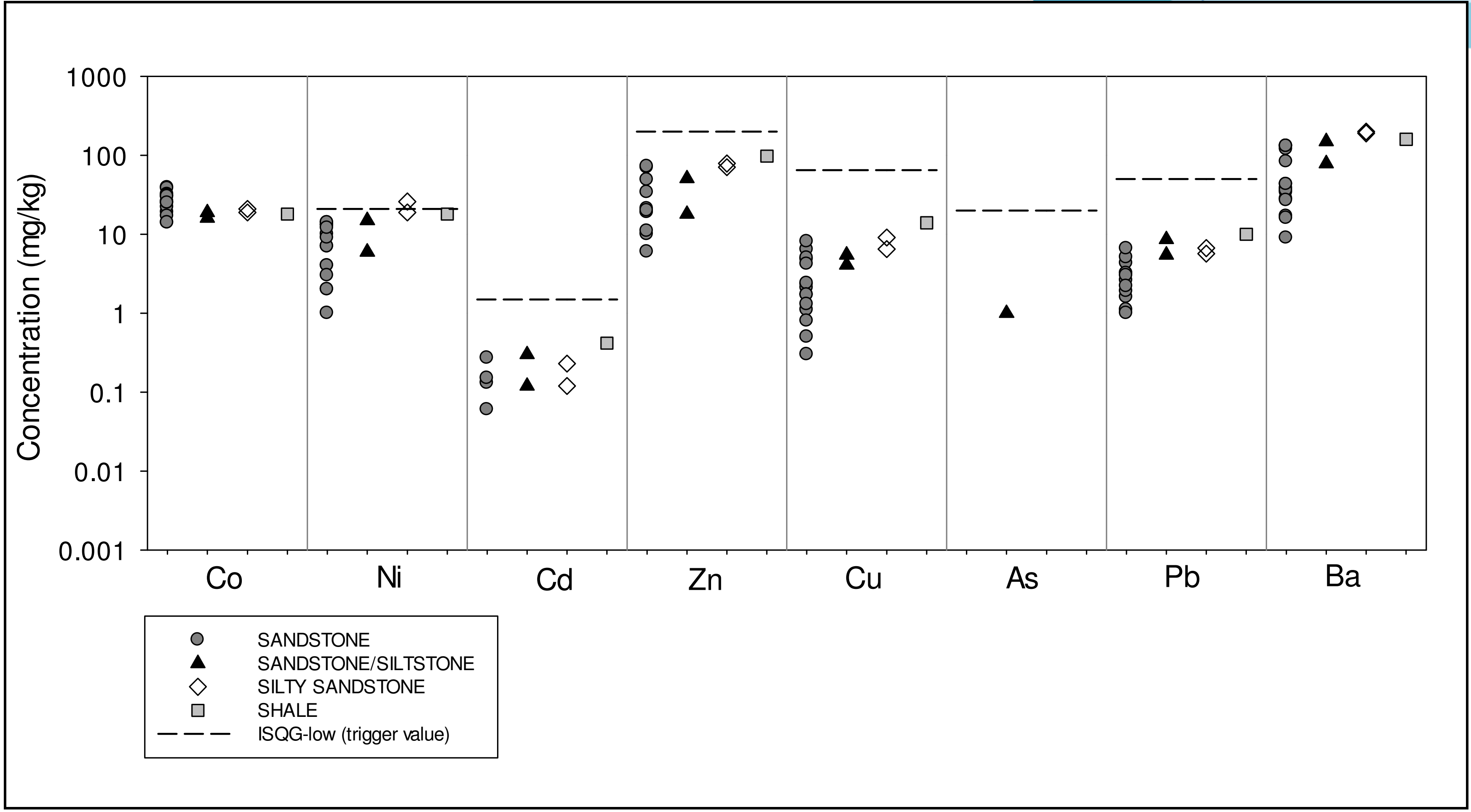


Figure 13 - Acid-extractable metals in Yarragadee aquifer sediments (in mg/kg) and interim sediment quality guideline trigger values (ISQG-low) where applicable.

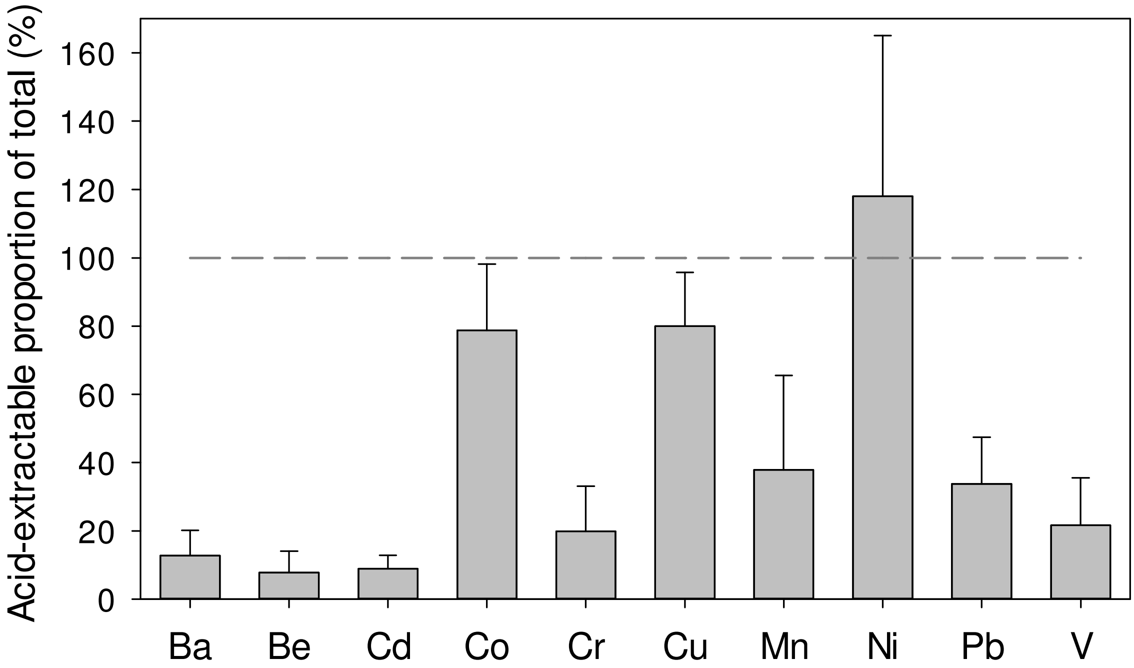


Figure 14 - Mean acid-extractable proportion of total metals in Yarragadee aquifer core samples (*n*=20) as measured using X-ray fluorescence.

Injection of water at a different oxidative-reductive potential (ORP) than existing groundwater has the potential to alter the aquifer's geochemical equilibrium conditions and processes such as dissolution and/or precipitation of minerals (e.g., sulphide minerals, Fe- and Mn-carbonates), organic matter mineralization, ion exchange and sorption processes. Injection of water containing dissolved oxygen will oxidise common reductants such as pyrite/marcasite, sedimentary organic matter (SOM) and/or siderite, resulting in a successive change from reducing to oxidizing conditions in the aquifer zones surrounding the injection well. Oxidation of pyrite has the potential to mobilise elements within the aquifer materials via acidification following depletion of buffering capacity or where kinetics of buffering reactions are slower than pyrite oxidation, which is the key acid-generating process.

Mineralogical analyses of core samples from the Yarragadee aquifer showed some zones with substantial pyrite/marcasite content, including: 0.5-0.7% pyrite in YarMAR01, 04 and 06 (approximately 327-397 mBGL); trace pyrite in YarMAR09-12, YarMAR15, 19, 22 and 28 (*ca.* 474-511, 540, 598-600 and 650 mBGL); and 0.54% marcasite within the YarMAR19 core sample from approximately 572-574 mBGL (Table 7). Siderite was detected in several core samples, including YarMAR14 (*ca.* 528-534 mBGL) which contained 0.6% siderite, 4.1% siderite in YarMAR15 (*ca.* 539-542 mBGL), as well as YarMAR18 (*ca.* 558-563 mBGL), YarMAR20 (*ca.* 582-584 mBGL) and YarMAR21 (ca. 586-595 mBGL) which contained 2.0-2.8% siderite (Table 7, Figure 12). Based on results of quantitative mineralogical analyses and LOI results, core samples likely potentially substantial SOM include: YarMAR11-15 and YarMAR20 (*ca.* 499-542 and 582-584 mBGL), which exhibited 3-5% LOI at 1050°C; and YarMAR18 and 21 (*ca.* 558-563 and 586-595 mBGL, respectively), which each had >6% LOI at 1050°C.

Siderite dissolution is possible in zones containing substantial siderite following injection of water with negligible Fe content; however, the rate of siderite dissolution under either oxic or anoxic conditions is extremely slow (Duckworth and Martin, 2004). In most areas, de novo precipitation of iron minerals such as ferric oxides, hydroxides and oxyhydroxides is unlikely to occur due to both the relatively low Fe content of most aquifer materials and slow siderite dissolution kinetics.

Although there are no Australian guidelines concerning the trace element content of aquifer materials, comparison of Yarragadee core sample trace element geochemistry data to Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ) sediment quality guidelines (2000) indicates that certain elements should be carefully monitored during and following injection of treated wastewaters in case of metal/metalloid mobilisation due to changes in aquifer geochemistry. In particular, Sb, Cd and Cr were frequently present in the Yarragadee core samples analysed at concentrations greater than ANZECC/ARMCANZ (2000) recommended sediment quality guidelines, whilst both total Ni and acid-extractable Ni in one sample exceeded the 21 mg/kg ISQG-low (trigger value) recommended sediment quality guideline value.

As illustrated in Figure 15, mean major ion composition of the Yarragadee aquifer sediments examined were generally similar to previously investigated Leederville aquifer sediments (120-220 mBGL; Wilfert, 2009). The lower SO_3 in the Yarragadee aquifer sediments was consistent with lower pyrite content within the Yarragadee sediments compared to the Leederville aquifer 120-220 mBGL sediments.

Similarly, mean trace element content of the Yarragadee aquifer sediments did not differ significantly from that of the more shallow (120-220 mBGL) Leederville sediments (Figure 16; Wilfert, 2009).

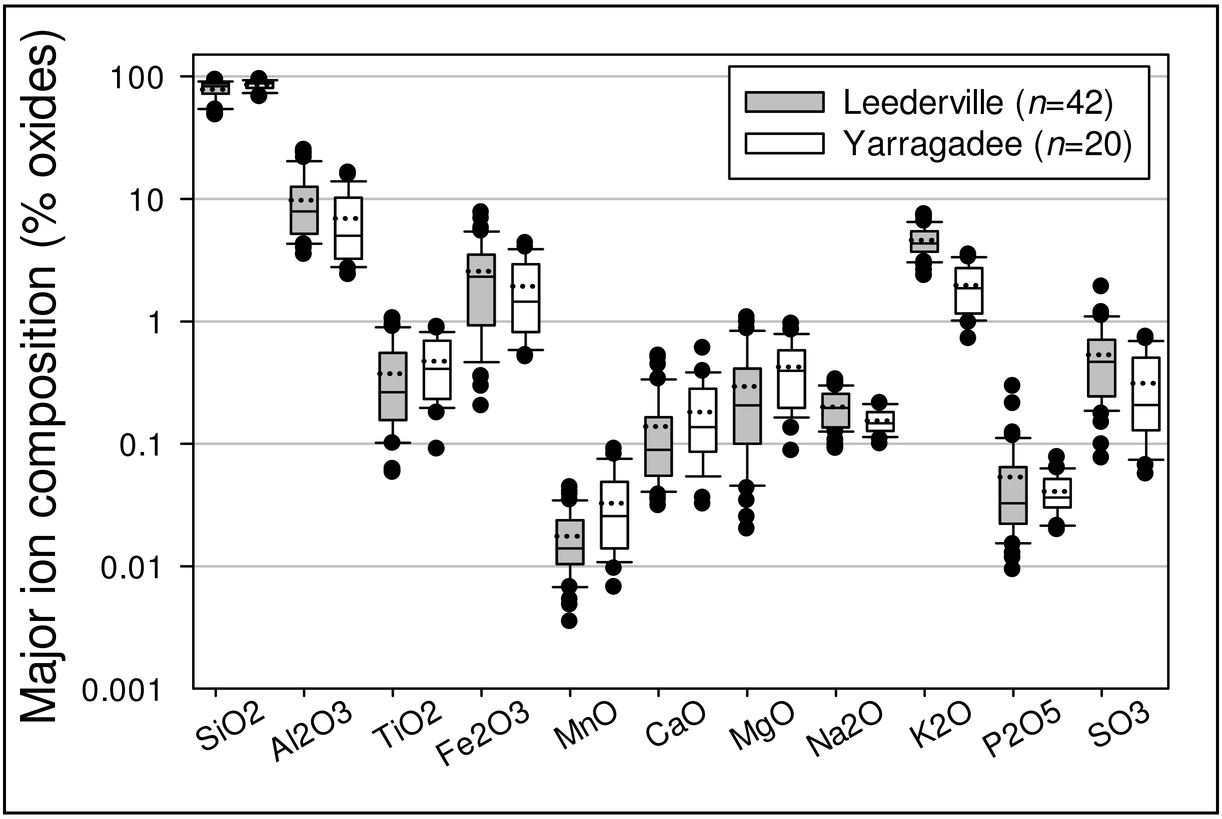


Figure 15 - Comparison of major ion contents (as oxides) in Leederville and Yarragadee aquifer sediments. Dotted lines represent means.

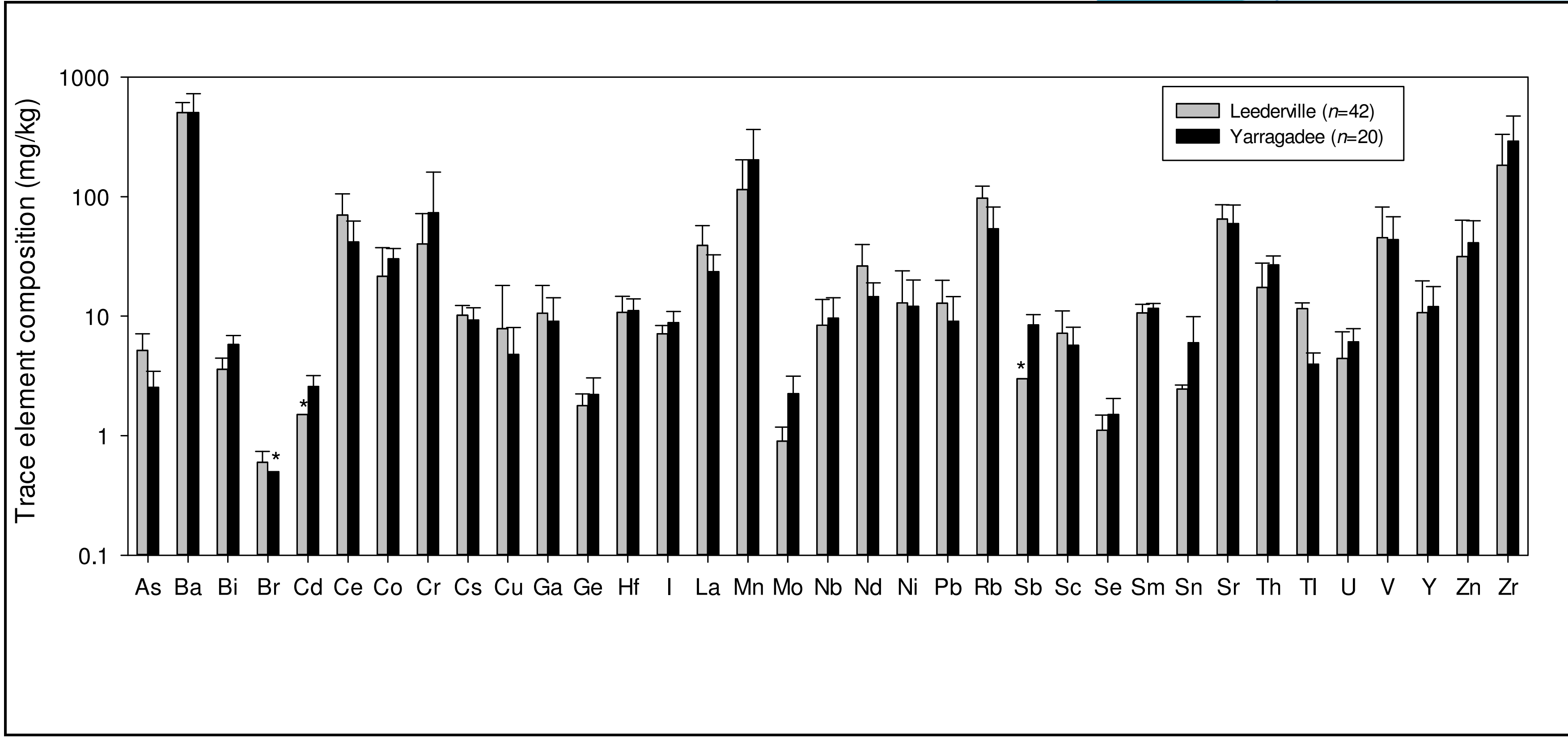


Figure 16 - Mean trace element composition (mg/kg) of Leederville and Yarragadee aquifer sediments. Error bars represent one standard deviation from the mean. Bars marked with '*' indicate all values were less than analytical detection limits and a value equal to half the limit of detection is shown for purposes of comparison.

5.5 Reactive capacity of sediments

The Cr-reducible S content of the Yarragadee aquifer core samples examined (Table 11) was strongly correlated with both the pyrite/marcasites content (r=0.81) and total S as SO_3 (r=0.71), whilst the pyrite/marcasites mineral content and total S as SO_3 exhibited a simple correlation coefficient of 0.86 across all Yarragadee core samples. Chromium-reducible S was greatest in the samples containing the greatest quantity of pyrite/marcasites (Figure 17). The CEC of Yarragadee core samples was correlated with both the total clay content (r=0.80) and the TOC content (r=0.79), suggesting that clays and sedimentary organic matter within the Yarragadee aquifer sediments are the primary sources of the CEC. Total organic carbon within Yarragadee aquifer core samples was also correlated with the LOI at 1050°C (r=0.77).

Table 11 - Electrical conductivity (EC), pH, cation exchange capacity (CEC) total organic carbon (TOC) content, and chromium-reducible sulphur content of Yarragadee aquifer core samples.

	Mean sample depth (mBGL)	pH	EC (mS/m)	CEC ($cmol_c$/kg)	TOC (%)	Cr-reducible S (%)
YarMAR01	331.5	4.5	31	2	0.25	0.206
YarMAR04	356.5	4.8	26	2	0.36	0.809
YarMAR06	390.7	9.2	5	1	0.05	0.134
YarMAR07	423.6	9.7	10	2	0.05	0.022
YarMAR08	459.6	8.9	8	2	0.08	0.026
YarMAR09	477.35	9.0	8	2	0.07	0.056
YarMAR10	490.25	8.5	9	2	0.06	0.027
YarMAR11	501.2	8.8	9	3	0.15	0.050
YarMAR12	510.45	6.9	7	2	0.08	0.047
YarMAR13	520.7	7.0	8	3	0.34	0.018
YarMAR14	531.65	7.1	6	3	1.14	0.019
YarMAR15	540.7	7.2	9	3	0.99	0.037
YarMAR16	549.9	9.2	13	2	0.06	0.045
YarMAR17	556.4	8.6	7	3	0.77	0.020

YarMAR18	562.9	7.2	10	5	0.98	0.036
YarMAR19	573.65	6.0	6	1	0.05	0.948
YarMAR20	583.5	7.0	8	3	0.70	0.045
YarMAR21	592.63	7.0	11	4	0.84	0.041
YarMAR22	599.6	6.9	7	1	0.06	0.048
YarMAR28	651.1	6.7	4	1	<0.05	0.068

Compared to 120-220 mBGL Leederville aquifer sediments (0.54±0.70%; Wilfert, 2009), the mean Cr-reducible S content of the Yarragadee aquifer sediments examined (0.14±0.26%) was lower. Similarly, the TOC content of Yarragadee aquifer sediments, 0.36±0.39%, was substantially lower than the 0.12±1.61% TOC in 120-220 mBGL Leederville aquifer sediments. This is indicative of a lower net acid generation potential for the Yarragadee aquifer sediments compared to the Leederville sediments.

Although only a negligible proportion of the total Si or total Al within the Yarragadee aquifer sediments examined was oxalate-extractable, approximately 1-22% of the total Fe as quantified by XRF was extractable by ammonium oxalate (Table 12). Similarly, a large proportion of the total Mn within the Yarragadee sediments was oxalate-extractable. At 1118±1977 mg/kg, the mean quantity of poorly crystalline or 'reactive' Fe (oxalate-extractable Fe) within Yarragadee aquifer sediments was substantially lesser than the 5090±5885 mg/kg oxalate-extractable Fe in 120-220 mBGL Leederville sediments. Given that the mean total Fe contents of Yarragadee and Leederville sediments were similar (Figure 15), a greater proportion of Fe within the Leederville aquifer sediments was poorly crystalline. Similarly, oxalate-extractable Al (generally <100 mg/kg) in the Yarragadee aquifer sediments examined was substantially less than that in 120-220 mBGL Leederville aquifer sediments (619±597 mg/kg; Wilfert, 2009). However, the mean quantity of oxalate-extractable Mn in Yarragadee sediments, 152±273 mg/kg, was greater than the 31±50 mg/kg mean observed in 120-220 mBGL Leederville sediments. Yarragadee aquifer sediments contained on average 266±179 mg/kg total Mn whilst the 120-220 mBGL Leederville sediments contained 176±102 mg/kg total Mn; thus, a greater proportion of Mn within the Yarragadee sediments was poorly crystalline and extractable using ammonium oxalate.

Table 12 - Ammonium-oxalate extractable Al, Fe, Mn and Si in Yarragadee aquifer core samples.

	Mean sample depth (mBGL)	Al (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Si (mg/kg)
YarMAR01	331.5	<100	280	16	13
YarMAR04	356.5	<100	290	23	20
YarMAR06	390.7	<100	45	5.6	9
YarMAR07	423.6	<100	97	12	20
YarMAR08	459.6	<100	86	15	19
YarMAR09	477.35	<100	110	13	18
YarMAR10	490.25	<100	84	9.4	25
YarMAR11	501.2	<100	120	15	23
YarMAR12	510.45	<100	110	7.8	22
YarMAR13	520.7	100	410	56	37
YarMAR14	531.65	<100	1300	210	28
YarMAR15	540.7	100	6600	910	48
YarMAR16	549.9	100	240	26	34
YarMAR17	556.4	<100	130	15	18
YarMAR18	562.9	150	5500	750	76
YarMAR19	573.65	<100	50	3.9	7.3
YarMAR20	583.5	100	3700	480	41
YarMAR21	592.63	120	3100	460	64
YarMAR22	599.6	<100	82	9.8	18
YarMAR28	651.1	<100	18	2.1	6.6

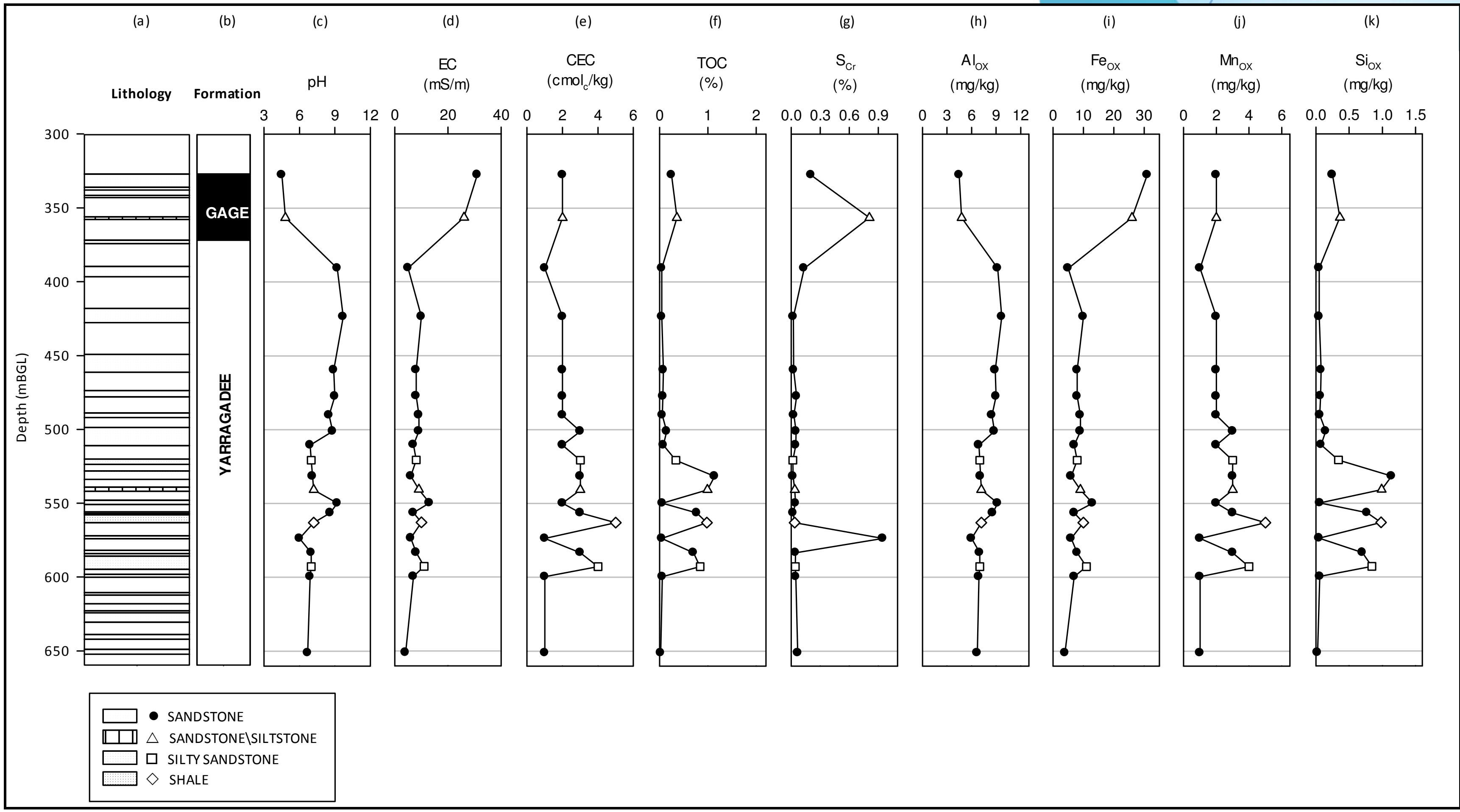


Figure 17 - Depth profile of Yarragadee aquifer showing (a) lithology, (b) stratigraphy, (c) pH, (d) electrical conductivity (EC, in mS/m), (e) cation exchange capacity (CEC, in cmolc/kg), (f) total organic carbon (TOC, in %), (g) chromium-reducible sulphur (SCr, in %), and oxalate-extractable Al, Fe, Mn, and Si (h-k, in mg/kg).

6. Sediment reactivity via respirometer tests

6.1 Materials and methods

Respirometer experiments were conducted for a selection of twenty core samples (Table 13) covering the rage of sediment types in the Gage and Yarragadee formations. The objective of these studies was to determine the amount, type and reactivity of the sedimentary reductants in the Yarragadee aquifer and investigate the relation between the oxygen reduction capacity and the sediment type through respirometer (laboratory incubation) tests. The methodology for the respirometer experiments was adapted from the procedure developed by Descourvieres et al. (2010b) for sediments from the Leederville aquifer (bore M345) and later used on the Leederville sediments from the Beenyup site (Wilfert 2009).

Core samples (30 cm long) collected during drilling were stored in Yarragadee groundwater in sealed aluminium tins and refrigerated (4^{o}C) until sub-sampling could take place. The consolidated sediment cores were broken up before sub-sampling for the respirometer experiment. These sub-samples were stored moist under anaerobic conditions (N_2/H_2 atmosphere) until they were required for the respirometer experiment. Larger aggregated particles were further broken down using a mortar and pestle (agate) in the anaerobic chamber before conducting the respirometer experiments.

Moist sediment samples of 22.5 g oven-dry equivalent were mixed with 150 mL nitrogen saturated ultrapure laboratory grade (MilliQ) water in 250 mL Duran bottles. Nineteen samples and a blank, consisting of 150 mL of MilliQ water, were prepared for the respirometer experiment. The samples and the blank were incubated at 25.4^{o}C ± 2^{o}C and connected to close circuit respirometer (Micro-Oxymax, Columbus Instruments) designed to detect low levels of oxygen (O_2) consumption and carbon dioxide (CO_2) production using electrochemical and infrared detection, respectively. The head space was initially equilibrated with atmospheric O_2 and CO_2 concentrations with the respirometer automatically refreshing the head-space with air if O_2 or CO_2 concentrations fell outside the measurement range (19.3 to 21.5% for O_2 and 0 to 1.0% for CO_2).

The samples were incubated for a period of 35 days and O_2 consumption and CO_2 production measured every 2.1 hrs. The sediment-water slurry was stirred using an orbital shaker (Thermocline Scientific) at 180 rpm to ensure a homogeneous chemical system and enhance oxygen diffusion between the head-space and the water phase.

Prior to and after the incubation, pH, EC and Eh were measured using a handheld pH, EC and Eh meter (WTW). Initial pH, EC and Eh were determined following mixing of 4.5 g oven-dry equivalent sediment with 30 mL end-over-end in a 50 mL centrifuge tube for 2 h. Final values were determined in aliquots of sediment suspensions taken from the incubation vessels. The sediment suspensions were centrifuged at 4,000 rpm for 30 min and the supernatants analysed for major ion and trace metal concentrations.

Table 13 - Samples selected for respirometer experiment and initial pH, electrical conductivity (EC) and redox potential (Eh) of sediment slurries.

	Sample No.	Lithology	Depth from (mBGL)	Depth to (mBGL)	pH	EC (mS/m)	Eh (mV)
1	YarMAR01	SANDSTONE	327.4	327.7	6.36	16.32	126
2	YarMAR04	SANDSTONE\SILTSTONE	356.1	356.9	9.02	3.95	111.6
3	YarMAR06	SANDSTONE	390.1	391.25	9.22	2.78	22.7
4	YarMAR07	SANDSTONE	423.1	424.1	9.79	6.33	37.1
5	YarMAR08	SANDSTONE	459.1	460.1	9.47	4.44	24.7
6	YarMAR09	SANDSTONE	476.8	477.85	9.58	4.80	71.7
7	YarMAR10	SANDSTONE	489.7	490.8	9.40	4.78	71.7
8	YarMAR11	SANDSTONE	500.6	501.8	9.50	4.98	76.7
9	YarMAR12	SANDSTONE	509.9	511	8.35	3.10	130.8
10	YarMAR13	SILTY SANDSTONE	520.1	521.3	8.25	3.17	132.4
11	YarMAR14	SANDSTONE	531	532.3	8.34	2.33	157.4
12	YarMAR15	SANDSTONE/SILTSTONE	540.1	541.3	8.34	2.87	167
13	YarMAR16	SANDSTONE	549.2	550.6	9.75	7.05	101.7
14	YarMAR17	SANDSTONE	555.8	557	9.35	3.35	105.7
15	YarMAR18	SHALE	562.6	563.2	8.48	2.74	134.6
16	YarMAR19	SANDSTONE	573.2	574.1	7.89	2.75	146.5
17	YarMAR20	SANDSTONE	582.8	583.8	8.29	2.84	151.5
18	YarMAR21	SILTY SANDSTONE	592.15	593.1	8.53	3.21	134.4
19	YarMAR22	SANDSTONE	599.2	600	8.59	2.80	131.7
20*	YarMAR28	SANDSTONE	650	652.2	8.26	1.87	141.2

** Not included in respirometer experiment*

6.2 Reductive capacity

The reductive capacity is a measure of the amount of O_2 consumed (in µmol O_2/g sediment) by reductants present in the aquifer sediments (Hartog et al., 2002; Descourvieres et al., 2010b). The potential reductive capacity (PRC_{tot}) is the theoretical maximum O_2 consumption in the absence of any kinetic and diffusion limitations based on the sediment geochemistry. The most common reductants in aquifer sediments are pyrite (FeS_2) and sedimentary organic matter (SOM) with the PRC_{tot} defined as:

$$PRC_{tot} = 3.75[FeS_2] + [TOC]$$

where [FeS_2] and [TOC] are the pyrite and total organic carbon concentrations (µg/g sediment) respectively, and [TOC] is assumed to be equivalent to the sediment organic matter concentration, [SOM]. The different coefficients (3.75 and 1) reflect the different stoichiometry of the respective reactions FeS_2 and TOC with O_2 (Table 14). The presence of reductants other than FeS_2 and TOC will result in the underestimation of PRC_{tot}. For example, the oxidation of siderite ($FeCO_3$,Table 14) may contribute to the PRC_{tot} for samples YarMAR14, YarMAR15, YarMAR18, YarMAR20 and YarMAR21 (0.6 to 4.1 %w/w, Table 7). As the addition of siderite contribution, 0.25[SID], to the PRC_{tot} increases it by between 1.3 and 9.5% for these samples, siderite was considered as a minor contributor in these samples.

Table 14 - Potential oxidation reactions in the Yarragadee aquifer and their theoretical $\Delta CO_2 : \Delta O_2$ stoichiometric ratios. (a) sediment organic matter oxidation, (b) pyrite oxidation unbuffered, (c) pyrite oxidation buffered by dolomite, and (d) siterite oxidation.

Reaction	$\Delta CO_2 : \Delta O_2$
(a) $CH_2O + O_2 \rightarrow CO_2 + H_2O$	1
(b) $FeS_2 + {}^{15}/_{4} O_2 + {}^{7}/_{2} H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$	0
(c) $FeS_2 + {}^{15}/_{4} O_2 + {}^{3}/_{2} H_2O + CaMg(CO_3)_2 \rightarrow Fe(OH)_3 + Ca^{2+} + Mg^{2+} + 2SO_4^{2-} + 2CO_2$	8/15
(d) $FeCO_3 + {}^{1}/_{4} O_2 + {}^{3}/_{2} H_2O \rightarrow Fe(OH)_3 + CO_2$	4

Sedimentary organic matter is the main contributor (>63%) to the PRC_{tot} for most samples the exceptions being YarMAR04, YarMAR06, YarMAR19 and YarMAR28 where pyrite was the major contributor (Figure 18). Pyrite may be present in small quantities in other samples as suggested by the Fe_{ex}:S_{Cr} ratios less than the pyrite ratio (Figure 18g)). Lower in the profile however the Fe_{ex}:S_{Cr} ratio is high (3.9-10.2) indicating that other Fe bearing minerals such as siderite are present in these samples.

Unlike the Leederville aquifer (Descourvieres et al. 2010b), there was no relationship between the pyrite (PRC_{py}) and SOM (PRC_{SOM}) contributions to the PRC_{tot} or between the PRC_{tot} and any particular particle size fraction. However, this may be related to the smaller sample size of the Yarragadee sediments (20) compared to the larger number of Leederville sediments (105) analysed by Descourvieres et al. (2010b).

The average PRC_{tot} for Yarragadee aquifer was 387 µmol O2/g. The PRCtot depth profile (Figure 18) showed two main reductive zones. One zone was 327.6 to 356.5 mBGL (Gage formation) and dominated by pyrite oxidation, while the second zone was 520.7 to 540.7 mBGL and dominated by SOM oxidation.

Table 15 - Potential and measured reductive capacity of Gage and Yarragadee sediments

Sample No.	Aquifer formation	Depth (ave) mBGL	PRC_{tot} µmol O_2/g	PRC_{SOM} % PRC_{tot}	PRC_{PY} % PRC_{tot}	PRC_{SID} % PRC_{tot}	MRC µmol O_2/g
YarMAR01	Gage	327.6	329	63	37	0	45
YarMAR04	Gage	356.5	773	39	61	0	110
YarMAR06	Yarragadee	390.7	120	35	65	0	2
YarMAR07	Yarragadee	423.6	54	76	24	0	13
YarMAR08	Yarragadee	459.6	82	81	19	0	10
YarMAR09	Yarragadee	477.3	91	64	36	0	9
YarMAR10	Yarragadee	490.3	66	76	24	0	11
YarMAR11	Yarragadee	501.2	154	81	19	0	19
YarMAR12	Yarragadee	510.5	94	71	29	0	14
YarMAR13	Yarragadee	520.7	294	96	4	0	16
YarMAR14	Yarragadee	531.7	973	98	1	1	22
YarMAR15	Yarragadee	540.7	934	88	2	10	24
YarMAR16	Yarragadee	549.9	76	66	34	0	7
YarMAR17	Yarragadee	556.4	653	98	2	0	31
YarMAR18	Yarragadee	562.9	897	91	2	7	24
YarMAR19	Yarragadee	573.7	596	7	93	0	8
YarMAR20	Yarragadee	583.3	654	89	4	7	18
YarMAR21	Yarragadee	592.6	767	91	3	6	27
YarMAR22	Yarragadee	599.6	78	64	36	0	11
YarMAR28	Yarragadee	651.1	61	34	66	0	NA

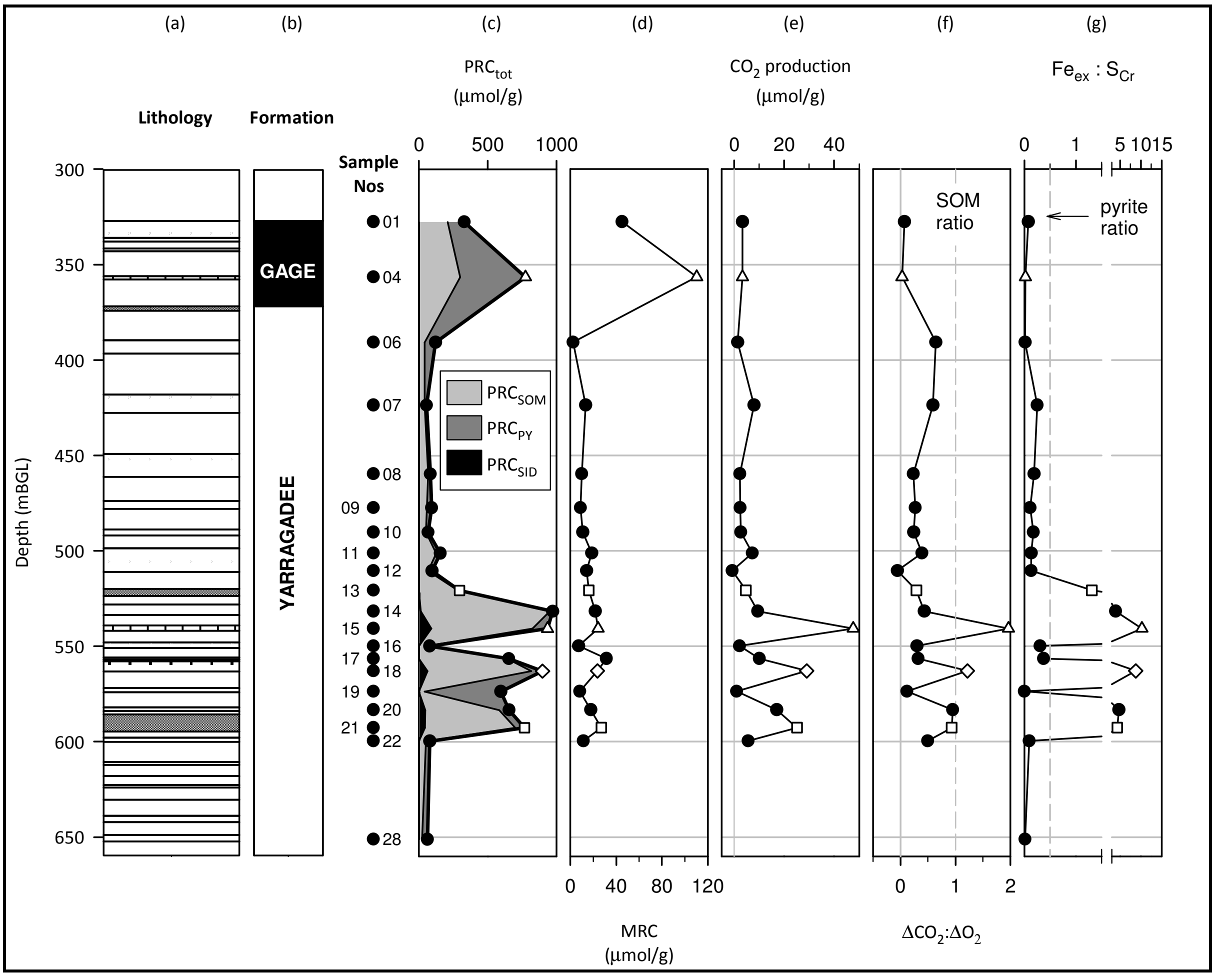


Figure 18 - Depth profiles of (a) lithology, (b) aquifer formation, (c) potential reductive capacity (PRC_{tot}) and the pyrite (PRC_{PY}), sediment organic matter (PRC_{SOM}) and siderite (PRC_{SID}) components, (d) measured reductive capacity (MRC), (e) CO_2 production, (f) $\Delta CO_2:\Delta O_2$ ratio, and (g) ratio of extractable Fe to Cr-reducible sulfur ($Fe_{ex}:S_{Cr}$).

6.3 Oxidation processes during incubation

The measured reductive capacity (MRC) determined by the incubation experiments showed a wide range of total O_2 consumption (1.5 to 96.9 µmol O_2/g) and CO_2 production (-0.6 to 40.6 µmol O_2/g; Figure 18). MRC ranged between 1% and 20% of the PRC_{tot} (Figure 19), with the average MRC of 22.3 µmol O_2/g ~9 % of the average PRC_{tot}. Generally a lower proportion of the PRC_{tot} has reacted in samples with a higher PRC_{tot}, indicating that although some samples have a greater reductive capacity the rate at which reactions take place were similar. Figure 20 shows the cumulative CO_2 production relative to the cumulative O_2 consumption along with the $\Delta CO_2:\Delta O_2$ for the reactions in Table 14. With the exception of YarMAR12 the slope of the measured data does not match that of any individual oxidation reaction. This suggests that multiple reactions simultaneously contribute to the MRC. Sample YarMAR12 is unique in that it appears that pyrite oxidation is the only contributor to the MRC in this sample suggesting that the SOM present has low reactivity potentially to its refractory nature.

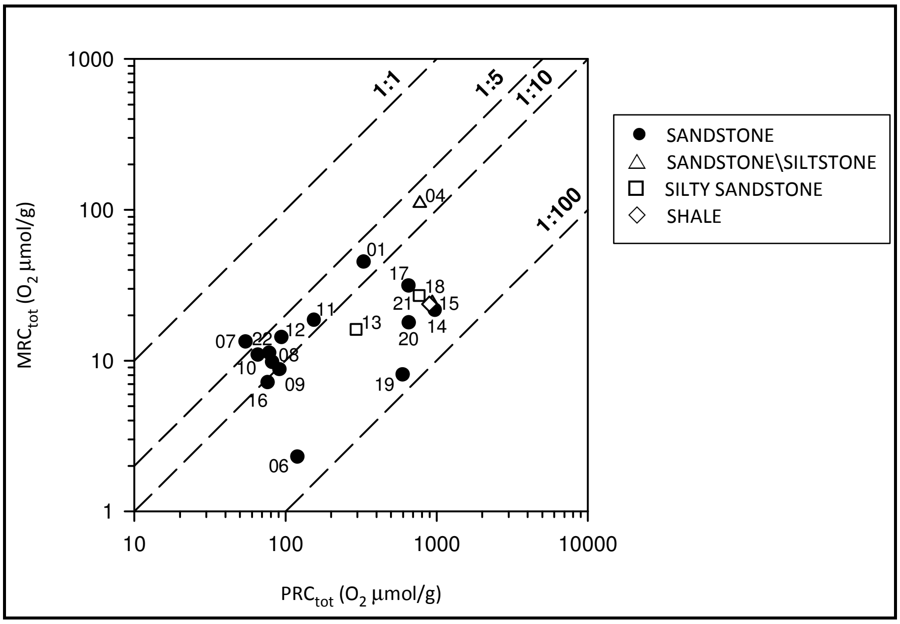


Figure 19 - Relationship between measured reductive capacity (MRC) and the potential reductive capacity (PRC_{tot}) showing 1:1, 1:5, 1:10 and 1:100 lines.

In all other samples CO_2 is produced to some extent (Figure 20) suggesting that SOM oxidation contributes to the MRC given that carbonate minerals aside from siderite (discussed below) were not detected (see section 5.3).

The greatest oxygen consumption was associated with the two Gage formation samples (YarMAR01 and YarMAR04, Figure 18 and Figure 20), which is largely related to the high pyrite content of these samples (0.5% and 0.7%, respectively). Since CO_2 production is low unbuffered pyrite oxidation is probably the main contributor to the MRC. The other samples with similar pyrite contents, YarMAR06 (0.5%) and YarMAR19 (0.5%), did not have appreciable MRC suggesting that the pyrite is less reactive perhaps due to Fe-hydroxide coatings on pyrite grains (Andersen et al. 2001).

The high siderite and SOM content of samples YarMAR14, YarMAR15, YarMAR18, YarMAR20 and YarMAR21 (Table 7) result in high O_2 consumption and CO_2 production (Figure 19 and Figure 20). With the exception of YarMAR14, which has the lowest siderite content, the final $\Delta CO_2:\Delta O_2$ is high (>0.9) close to or exceeding the ratio for SOM oxidation (Figure 18). These $\Delta CO_2:\Delta O_2$ are also high relative to the final values observed in most Leederville aquifer sediments (Descourvieres et al. 2010). The low initial slope he $\Delta CO_2:\Delta O_2$ relationship may indicate that siderite dissolution and oxidation was initially low in these samples. In the two samples containing siderite, Descourvieres et al. (2010) suggested that the oxidation of trace levels of pyrite and the associated pH reduction accelerated the dissolution and oxidation of siderite. Further analysis of the supernatant following the completion of the incubation experiment is required to determine whether this process is occurring in the Yarragadee sediments.

The net consumption of CO_2 (negative production values) was observed initially in a number of the sediment incubations (Figure 20). According to Descourvieres et al. (2010) this supports the presence of fast reacting carbonate minerals such as calcite ($CaCO_3$) that were potentially present at trace concentrations, i.e., below the XRD detection limit.

The importance of the different components to the MRC will be further investigated following analysis of the supernatant solutions upon completion of the incubation period of the respirometer experiments. This will enable the determination of the major contributors to the MRC based on the changes in solution geochemistry as a result of reactions with oxygen.

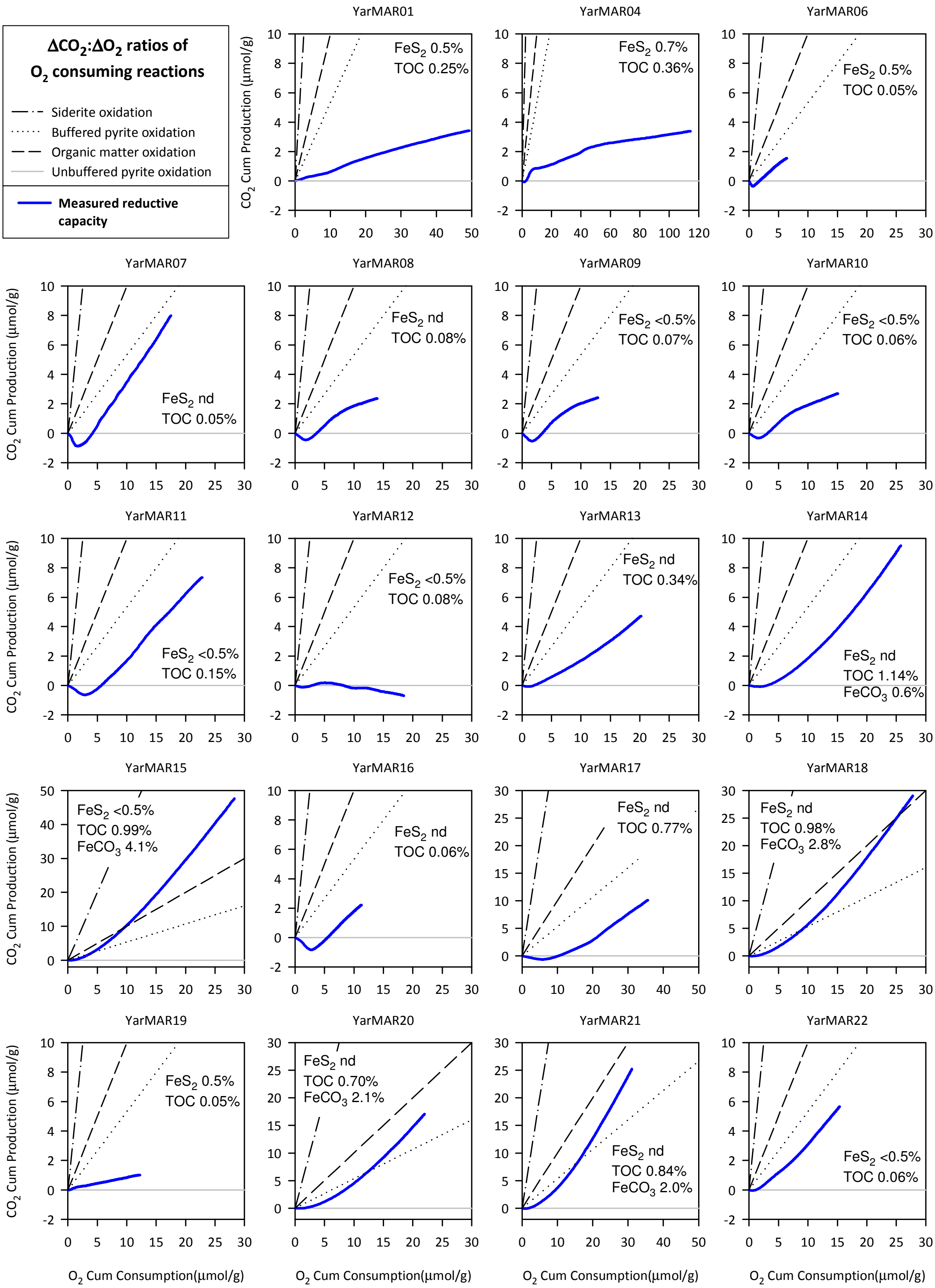


Figure 20 - Cumulative O_2 consumed and CO_2 produced every 2.1 h during sediment incubations and predicted ΔCO2:ΔO2 ratios for O_2 consuming reactions with minerals (pyrite – FeS_2 and siderite – $FeCO_3$) and organic matter present in the sediment. Note the x- and y-scales differs between graphs.

6.1 Buffering processes

The pH buffering processes will be analysed when the final supernatant concentrations from the respirometer experiment are analysed.

6.2 Trace metal release

The trace metals released into the supernatant solution following the incubation experiment were compared to the mean ambient groundwater concentrations and Australian Drinking Water Guidelines (ADWG) (Figure 21). Generally the supernatant concentrations exceeded the mean ambient groundwater concentrations, sometimes by several orders of magnitude. Most samples were less than the ADWG however a large number of samples (13) exceeded the ADWG health guidelines (NHMRC, NMMRC, 2011) for Ni and several samples for Cd, Mn and Pb. The two Gage formation samples (YarMAR01 and YarMAR04) generally show the greater metal release than the Yarragadee samples (except for Ba and Co; Table 16) potentially associated with the higher pyrite contents (Table 7).

The supernatant concentrations of Co, Ni and Zn are highly correlated with the final pH (r^2 = 0.67, 0.88 and 0.69 respectively, $p<0.001$) suggesting that the release of these metals may be related to pyrite oxidation.

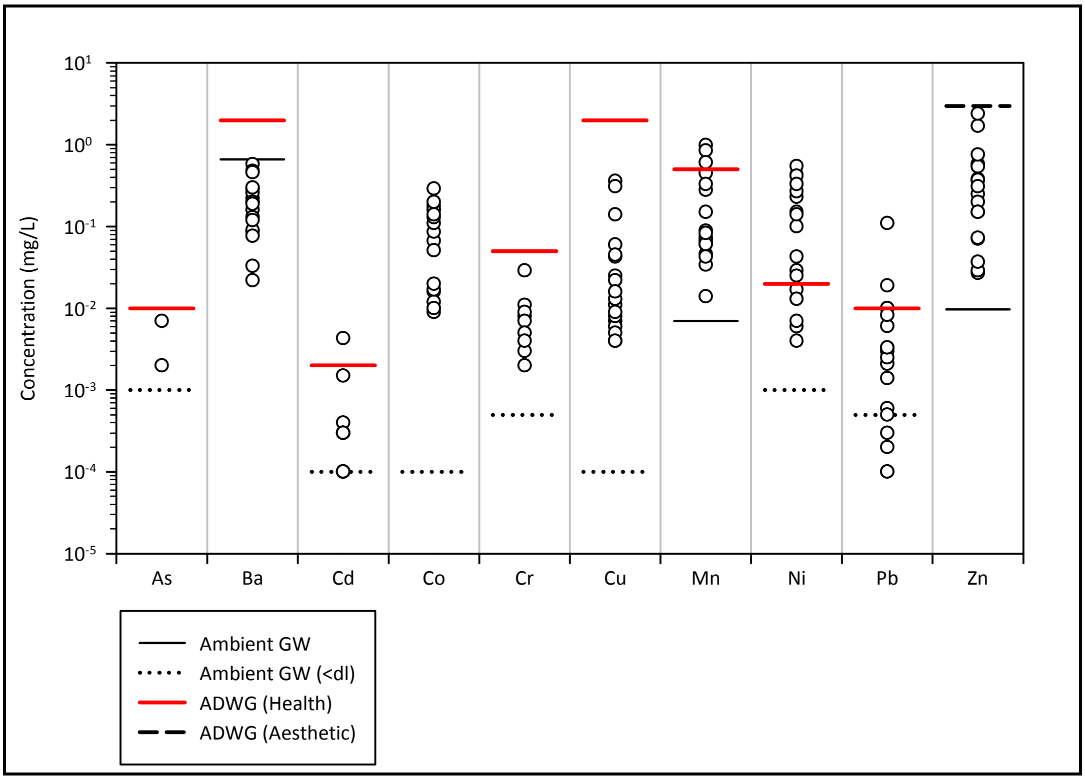


Figure 21 - Trace metal concentrations released from Yarragadee and Gage sediments into solution following incubation for 35 days. Samples where trace metal concentrations were less than detection limit were excluded. Comparison provided with the mean ambient groundwater concentrations and Australian Drinking Water Guidelines (NHMRC, NMMRC, 2011). Note there is no guideline value for cobalt (Co).

There is no Australian health-based guideline for Zn in drinking water, and few samples from the incubation experiment approached the aesthetic ADWG (NHMRC, NMMRC, 2011). However, the National Environment Protection Council framework for assessment of groundwater contamination, which is based on ANZECC Australian Water Quality Guidelines (1992) and the NHMRC/ARMCANZ Australian Drinking Water Quality Guidelines (1996), defines a groundwater investigation level of 0.005-0.05 mg/L Zn for freshwater ecosystems at the point of extraction (NEPC, 1999). Aqueous Zn concentrations in excess of the NEPC groundwater investigation level indicate that this element should be monitored to ensure that appropriate investigation and evaluation are undertaken where necessary to protect freshwater aquatic ecosystems.

Neither health- or aesthetic-based ADWGs are available for Co (NHMRC, NMMRC, 2011). While NEPC groundwater investigation levels are available (0.05-1.0 mg/L; NEPC, 1999) these are based on ANZECC Australian Water Quality Guidelines (1992) for Agricultural uses (irrigation and stock water) which should be taken in to account when using these guideline values. Approximately half of the samples exceed the lowest NEPC groundwater investigation level and indicate that this element should be monitored to ensure that appropriate investigation and evaluation are undertaken where necessary to protect freshwater aquatic ecosystems.

Table 16 - Supernatant trace metal concentrations released from Yarragadee and Gage sediments into solution following incubation for 35 days

Sample ID	Final pH	As	Ba	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
YarMAR01	2.802	0.002	0.033	0.0015	0.16	0.008	0.14	0.28	0.43	0.019	1.7
YarMAR04	2.430	0.007	0.022	0.0043	0.18	0.029	0.36	0.99	0.55	0.11	2.4
YarMAR06	5.736	<0.001	0.22	0.0001	0.01	<0.001	0.007	0.034	0.013	0.0014	0.37
YarMAR07	6.609	<0.001	0.58	0.0001	0.016	<0.001	0.025	0.046	0.017	0.01	0.25
YarMAR08	4.990	<0.001	0.48	0.0001	0.067	0.011	0.011	0.065	0.15	0.003	0.38
YarMAR09	4.672	<0.001	0.29	0.0001	0.16	0.003	0.022	0.074	0.23	0.0021	0.37
YarMAR10	4.664	<0.001	0.16	0.0004	0.2	<0.001	0.06	0.061	0.33	0.0025	0.58
YarMAR11	5.404	<0.001	0.46	0.0001	0.086	0.009	0.013	0.043	0.1	0.01	0.2
YarMAR12	3.844	<0.001	0.087	0.0003	0.29	0.002	0.31	0.069	0.42	0.0061	0.56
YarMAR13	4.938	<0.001	0.09	0.0003	0.11	<0.001	0.006	0.15	0.14	0.0002	0.31
YarMAR14	6.331	<0.001	0.29	<0.0001	0.009	0.007	0.004	0.089	0.006	0.0006	0.027
YarMAR15	6.835	<0.001	0.13	<0.0001	0.012	<0.001	0.004	0.85	0.013	0.0001	0.029
YarMAR16	7.134	<0.001	0.26	0.0001	0.017	0.005	0.016	0.061	0.029	0.0083	0.15
YarMAR17	6.563	<0.001	0.12	<0.0001	<0.005	0.004	0.008	0.014	0.004	0.0033	0.071
YarMAR18	7.349	<0.001	0.2	<0.0001	0.01	<0.001	0.005	0.45	0.007	0.0001	0.037
YarMAR19	3.483	<0.001	0.3	0.0003	0.13	<0.001	0.043	0.061	0.27	0.0033	0.54
YarMAR20	6.545	<0.001	0.2	<0.0001	0.02	<0.001	0.045	0.33	0.025	0.0003	0.15
YarMAR21	6.485	<0.001	0.077	<0.0001	0.051	<0.001	0.004	0.61	0.043	<0.0001	0.073
YarMAR22	4.264	<0.001	0.19	0.0003	0.14	<0.001	0.009	0.083	0.33	0.0005	0.76

Relative to both the total (XRF) and acid-extractable metal concentrations the proportion of trace metals released during incubation was low (<6.9% and <13.3%, respectively) for most metals (As, Ba, Cd, Co, Cr, Pb). However substantial proportions of Cu, Ni and Zn with up to 48%, 73% and 87% of the total trace metals released during incubation predominately related to the two Gage formation samples (YarMAR01 and YarMAR04) and those Yarragadee formation samples with a low final pH (<5) such as YarMAR12 and YarMAR19. As the trace metal release was related to pH, the oxidation of sulfide minerals and/or the dissolution carbonate minerals containing these trace metals may account for the high proportions released.

The observed concentrations of Cd and Ni in supernatants from incubation experiments greater than ADWGs is consistent with Yarragadee aquifer core sample geochemical assessment results (Section 5.4) wherein total Cd, Cr and Ni were identified as trace elements of potential concern based on total contents greater than ANZECC/ARMCANZ (2000) ISQG-low (trigger value) recommended sediment quality guideline values.

6.3 Assessment

6.3.1 Yarragadee and Leederville comparison

PRC Comparison

In this section the PRC of the Yarragadee and Leederville sediments will be compared. It is important to consider factors that may influence the comparison of the current study to previous investigations of the Leederville sediments. Firstly, the total number samples analysed differs, 20 samples for the Yarragadee/Gage formations and 42 for the Leederville formation (120-220 mBGL). Secondly the sampling density (samples per m depth) is much lower for the Yarragadee/Gage formations (sampled between 327-651 mBGL) than for the Leederville. As such the heterogeneity of the aquifer sediments in the Leederville may be better described than in the Yarragadee/Gage.

Taking this into account, the PRC_{tot} of the Yarragadee sediments (average PRC_{tot} 387 µmol O_2/g) is lower than the Leederville sediments (average PRC_{tot} 1354 µmol O_2/g) (Figure 22) with the range of PRC_{tot} determined for the Yarragadee also less than the average PRC_{tot} of the Leederville. The lower SOM and pyrite concentrations in the Yarragadee both contribute to the lower PRC_{tot}. While the SOM is the major contributor to the PRC_{tot} in both aquifer sediments, as a proportion of the PRC_{tot}, the average pyrite contribution in the Yarragadee sediments (28%) is lower than in the Leederville sediments (35%). The lower overall PRC_{tot} and pyrite contribution may potentially mean that metal release from the Yarragadee sediments is also lower than in the Leederville sediments.

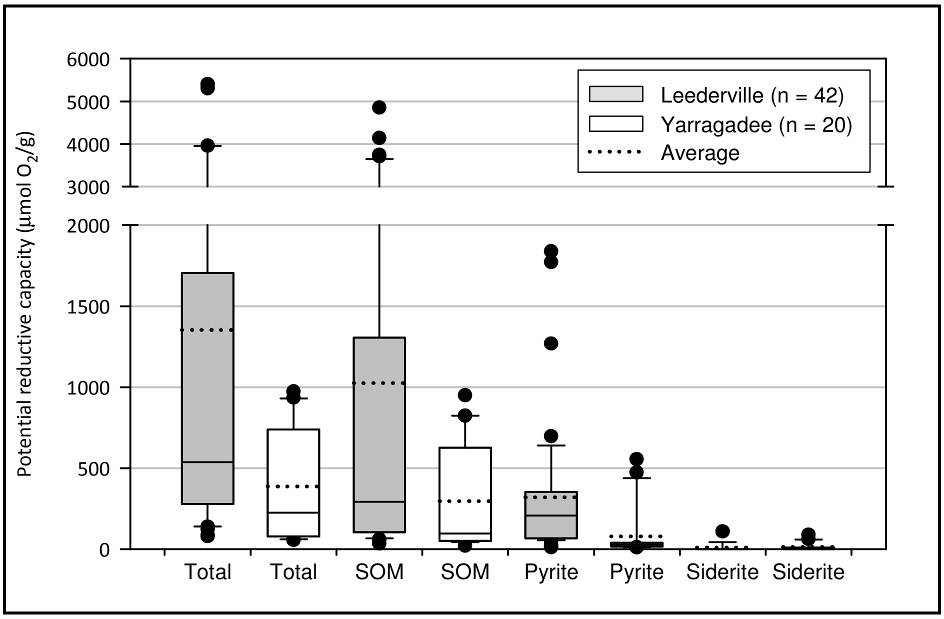


Figure 22 - Comparison of the potential reductive capacity, total and the sedimentary organic matter (SOM), pyrite and siderite components, between the Leederville sediments (120-220 mBGL) and Yarragadee/Gage sediments (327-651 mBGL).

MRC Comparison

In the Leederville (120-220 mBGL) the MRC was only determined for nine samples (Wilfert, 2009) compared to the nineteen Yarragadee/Gage samples analysed in the current study. The incubation periods of the two experiments were also different with the Leederville sediments incubated for a longer period (53 day) compared to the Yarragadee/Gage samples (35 days).

The proportion of MRC to PRC_{tot} for individual samples varied widely for both the Leederville and Yarragadee sediments (Figure 23). However, the Yarragadee on average showed a lower MRC relative to the PRC_{tot} of 9% compared to the Leederville of 31%. The longer duration of the Leederville incubation experiment may explain the overall greater oxygen consumption for the Leederville aquifer.

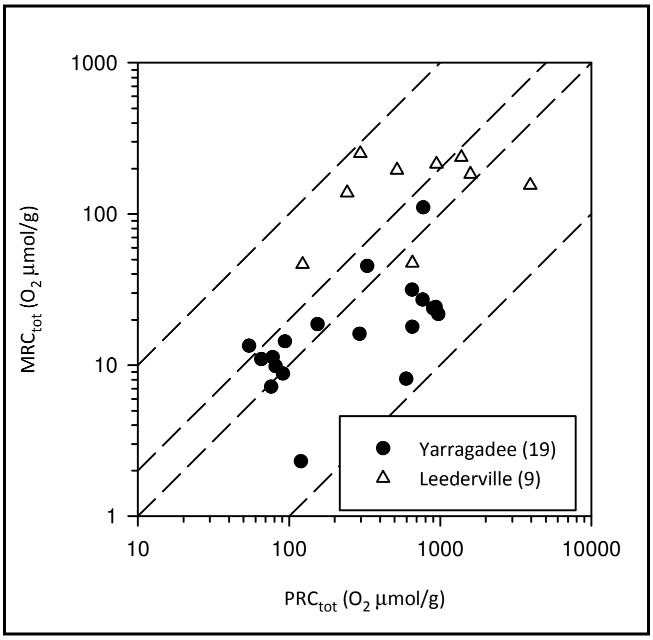


Figure 23 - Comparison of the relationship between measured reactive capacity (MRC) and the potential reactive capacity (PRC_{tot}) for the Leederville sediments (120-220 mBGL) and Yarragadee sediments. The MRC was determined after a 53 day and 35 day incubation periods, respectively.

Trace metal release

Trace metal release from the Yarragadee sediments, on average was less than those measured for the Leederville sediments with the exception of Pb (Figure 24). The range of trace metal concentrations released from the Yarragadee sediments were also similar or less than those observed for the Leederville sediments.

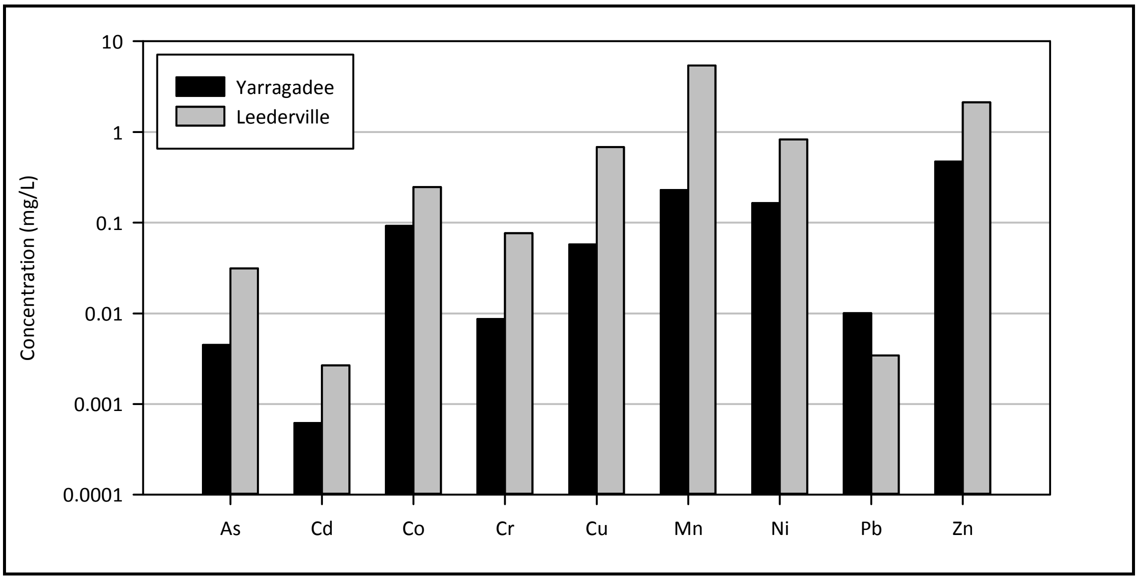


Figure 24 - Comparison of average trace metal release from the Yarragadee and Leederville sediments following incubation during respirometer experiments. Leederville data from Wilfert (2009)

7. Modelling

7.1 Assessment of local-scale temperature transport

7.1.1 Model setup

Local-scale solute and heat transport modelling was carried out to assess the anticipated temperature evolution in the Yarragadee aquifer in response to the injection of up to 38.4ML/day. For this purpose a local-scale numerical flow and solute/heat transport model was constructed using the standard models MODFLOW and MT3DMS, respectively.

Heat transport was simulated with MT3DMS by incorporating temperature as an additional model species into the solute transport model, as in previous MT3DMS heat transport applications by, for example, Ma et al. 2012, Vandenbohede et al., 2011, Vanderberg, 2011). Thermal energy uptake by the sediment was considered as a sorption process, but employing a thermal retardation term defined as

$$Kd = cs/cw*rhow$$

where cs is the specific heat capacity of the sediment, Kd is the thermal distribution term, and cw and rhow represent the specific heat capacity and density of water.

Heat conductive transport in MT3DMS was approximated by using a (compound-specific) thermal diffusion term (Dm) in analogy to the molecular diffusion for solutes defined as

$$Dm=ko/ntot*cw*rhow$$

where ntot is the total porosity, as for example discussed by Thorne et al., 2006. The value for the bulk thermal conductivity ko was defined as

$$ko=ntot*kw + (1-ntot)*kg$$

with ntot representing the total porosity and kg and kw representing the thermal conductivity of the solid and water phase respectively. Thermal dispersivity was assumed to be similar to solute dispersivity (e.g., de Marsily 1986, Vanderberg, 2011). The initial temperature distribution was for simplicity in this assessment assumed to be homogeneous and heat conduction from deeper aquifer sections was neglected

The local-scale model domain has a lateral extend of 5400m × 5400m, the model's top was set to 300mbgl and the bottom was set to 1000mbgl. The injection well was screened between 400mbgl and 700mbgl. The regional groundwater flow within the Yarragadee was assumed to be negligible relative to the flow induced by the injection. The estimated hydrodynamic dispersion was set to 10m. Note that longitudinal dispersion does not affect the average arrival/breakthrough time.

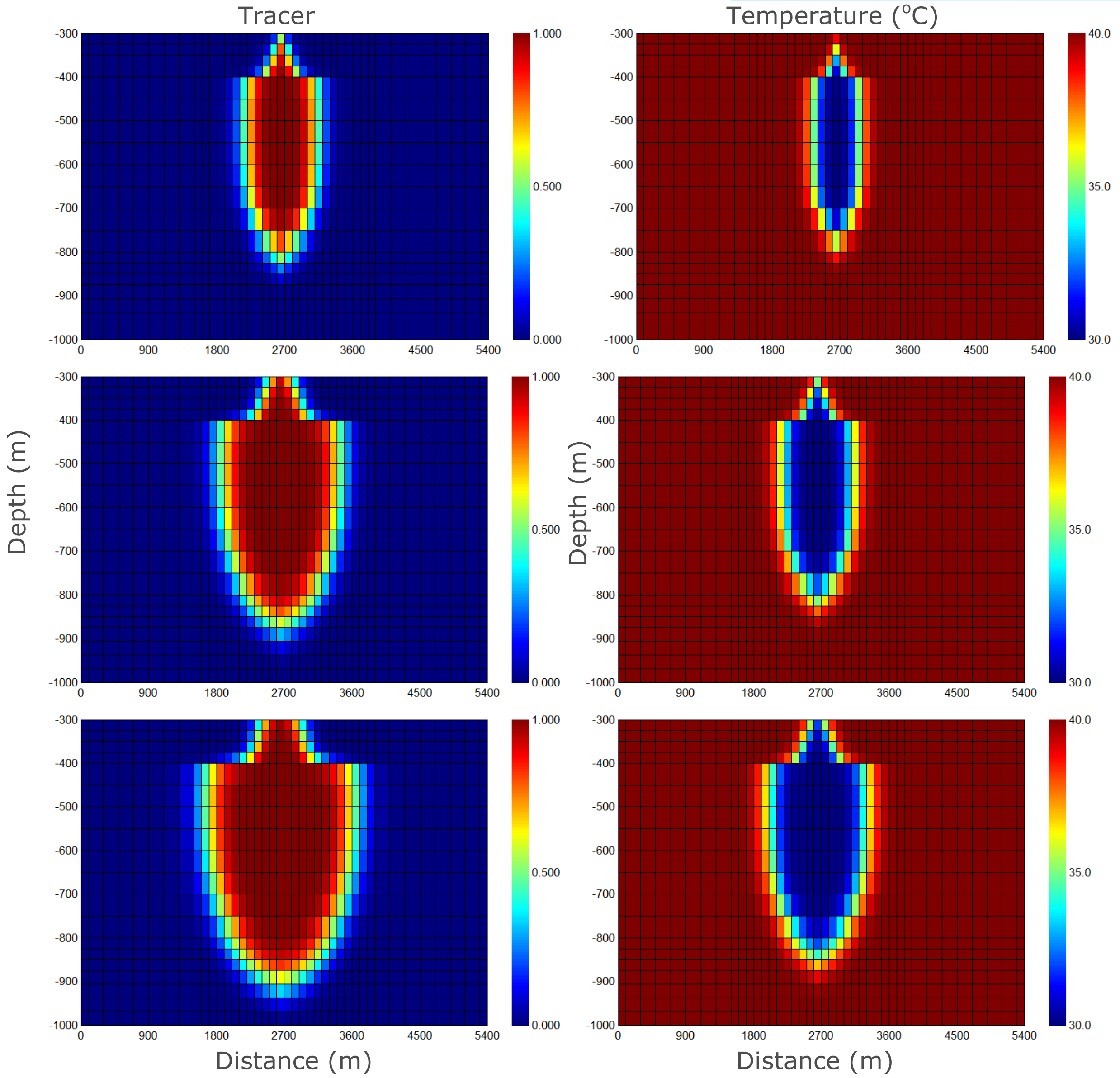


Figure 22 - Results of simulated solute (left) and temperature (right) transport after 4 (top), 10 (middle) and 20 years (bottom) simulation time along a vertical cross-section

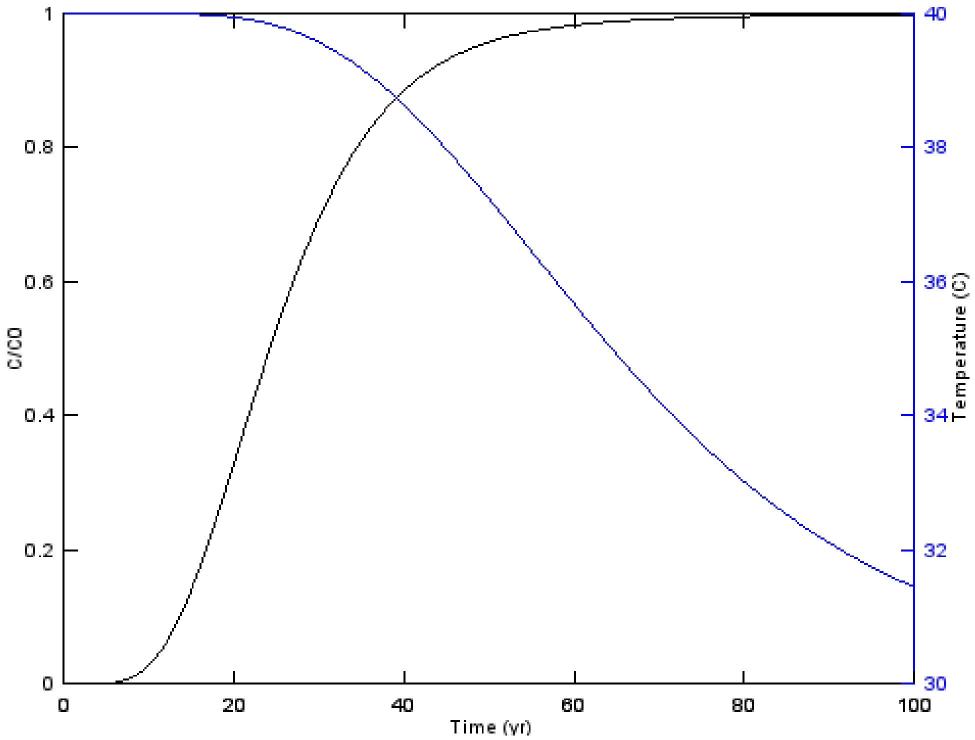


Figure 23 - Simulated solute and temperature breakthrough curves at 1000m radial distance from the Yarragadee injection well.

7.1.2 – Simulated solute and heat transport behaviour

A single scenario of solute and heat transport propagation was simulated for an injection rate of 38ML/day to assess the potential temperature changes at the Craigie geothermal bore. Figure 22 shows the predicted solute and temperature spreading and Figure 23 shows the predicted solute breakthrough curves at 1000m distance from the proposed Yarragadee injection well. The simulation results indicate that injectant breakthrough will occur after approximately 20-25 years while temperature transport is retarded due to heat uptake of the sediments, occurring after approximately 60 years.

7.2 Assessment of clogging potential by gas formation

7.2.1 Model set-up

Batch-type geochemical modelling with PHREEQC (Parkhurst and Appelo, 1999) was used to assess whether the increased temperatures at the depth of the Yarragadee injection and the associated lower solubilities (in water) could provide any potential for increased gas production and therefore an increased risk of clogging. This issue was addressed by simulating CO_2 (gas) production from organic matter decomposition at different temperatures and different pressures. Pyrite oxidation was neglected to provide a worst case scenario in terms of potential for CO_2 production. Methane production was excluded as potential reaction rates were considered too slow. The four simulated scenarios were:

1. GWRT-type RO water composition + organic matter decomposition at 25ºC and 1 atmosphere (near surface)
2. GWRT-type RO water composition + organic matter decomposition at 40ºC and 1 atmosphere (near surface)
3. GWRT-type RO water composition + organic matter decomposition at 25ºC and 50 atmospheres (500m depth)

4. GWRT-type RO water composition + organic matter decomposition at 40ºC and 50 atmospheres (500m depth)

The initial water composition used for the scenarios is listed in Table 14.

7.2.2 Model results

The model results show that, as defined in the conceptual model, the contact of aerobic injectant water with sediment-bound organic matter and the forced decomposition (mineralisation) of the organic matter leads the increase in inorganic carbon concentrations. Once a sufficiently high amount of organic matter is mineralised, this can lead to the formation of CO_2 gas. However, depending on the assumed temperatures and pressures, CO_2 gas formation will start for different amounts of organic matter decomposition (Table 15). The results illustrate that CO_2 gas formation at 40ºC is indeed increased compared to the simulation for 25ºC, the effect is far outweighed by the increased pressure that is expected at locations where the groundwater temperature is 40ºC. Under the pressure prevailing at 500m depth no gas was formed in the simulations. Therefore the results suggest that gas formation as a result of organic matter decomposition at the depth of the Yarragadee injection interval is unlikely to be of an increased risk compared to the GWRT trial injection into the Leederville aquifer.

Table 14 – Initial water composition assumed in the PHREEQC batch simulations (+ except for pH)

Aqueous component	Concentration (mg/L)$^{+}$
pH	6.6
pe	14
Ca	0.05
Cl	7
Fe	0.0025
Amm	0.21 as N
Alkalinity	18
K	0.9
Mn	0.0005
Mg	0.05
NO3	1.9
Na	8.40
P	0.01
O	7.90
Si	0.8 as SiO2
SO4	0.2

Table 15 - Results of PHREEQC batch simulations

	Temperature	Pressure	Mass of organic matter required to start CO_2 gas production (>1e-04 mol/L)
Scenario 1	25	1	1.30×10^{-2} mol/L
Scenario 2	40	1	1.05×10^{-2} mol/L
Scenario 3	25	50	$> 5 \times 10^{-2}$ mol/L (not produced in simulation)
Scenario 4	40	50	$> 5 \times 10^{-2}$ mol/L (not produced in simulation)

8. Assessment of the acid generation, buffering and cobalt mobilisation risks for GWR Stage 2A

8.1 Background

A meeting was held between the members of the GWR Technical Reference Group to consider the risk to human health and environmental end points of the observed slow decline in pH in the Leederville aquifer groundwater in response to over two years of recharge of ultra-purified water into the aquifer, and the subsequent mobilisation of cobalt in the groundwater.

The decline in pH to the end of the Trial (December 2012) only occurred in some of the 20 m observation bores, specifically over the last few months. It is known that the acidity is generated primarily by pyrite oxidation, and that generated acidity has been buffered by a combination of mineral reactions within the aquifer and to some extent also by HCO_3^- that is contained within the recharge water. The recent decrease in pH in the groundwater indicates that the aquifer source of the buffering that originally maintained a near neutral pH was successively consumed in the vicinity of the 20 m bore.

8.2 Geochemical review and modelling

Despite ongoing detailed geochemical transport modelling activities the exact source of buffering remains uncertain. Investigated hypotheses have included dissolution of a wide range of minerals, and specifically carbonates, including scenarios where only trace levels of calcite and/or siderite were present. The inclusion of each of these minerals into the 3D reactive transport model by CSIRO has failed to accurately reproduce the groundwater quality measured at the various GWRS monitoring locations. However, the results and simulations indicate that some other, as yet unidentified, buffering reaction has mitigated the effects of the acidity produced by pyrite oxidation.

Simplified 2D modelling using a proton (H^+) adsorption reaction as part of the ion exchange model has reproduced the observed pH trends at various distances. However, the required modification of the model input parameters and standard reaction constants need to be critically reviewed and checked for their validity.

From the work carried out to date and the discussions of the Technical Reference Group it was concluded that unidentified trace minerals are most likely to explain the observed buffering behaviour of the aquifer.

The uncertainty regarding the buffering mechanism in the aquifer limits the ability to tightly constrain the geochemical modelling predictions of the future hydrochemical behaviour. Nevertheless, the modelling can still be used in a sensible way to define a range of (worst) case scenarios. For example, the geochemical modelling indicated that even in a completely unbuffered system, the pH values would not fall below ~5.2 in the immediate vicinity of the recharge bore. With the currently simulated buffering mechanisms, and including the buffering capacity contained in the recharge water, the pH is predicted not to decrease below 6.2, i.e., only slightly lower than the currently observed value of 6.3.

Modelling also indicates that the decline in pH could be mitigated by the addition of HCO_3 to the recharged water: if HCO_3 concentrations were raised to 44 mg/L in the recycled water, the minimum groundwater pH would be 6.7, even in an otherwise unbuffered system. It was also noted that the simplified model did not consider the buffering capacity of the more slowly reacting minerals such as feldspars, which would contribute more significantly further away from the bore, where flow velocities are very slow, and the residence times of the recharged water are orders of magnitude greater than the residence times at 20N. The buffering from more slowly reacting minerals is likely to maintain groundwater pH at higher values than those now seen in the immediate vicinity of the recharge bore. This is consistent with the observed pH trend at the 60 m site, which shows a delayed and dampened pH trend compared to the 20 m site. It is also important to note that significant amounts of 'fast' buffering capacity, which has stabilised the pHs for almost 2 years even within the 20m radius is still available at larger distances and is unlikely to be depleted within the recharge management zone within the next tens of years.

Pyrite has previously been identified as the source of Cobalt (Co) in the aquifer (Descourvieres et al., 2010a, b). It is likely that the Co released during pyrite oxidation is rapidly re-adsorbed (for example onto the neo-formed iron oxides within the recharge zone) under buffered conditions, and is only mobilised once the pH decreases below a critical level. This was successfully modelled in the simplified 2D model, which showed the maximum Co concentrations would be in the order of 0.0003 to 0.0006 mg/L, which is consistent with the previously found results from respirometer tests (Descourvieres, et al, 2010b), and below the 0.001 mg/L drinking water guideline value.

While the modelling indicated peak concentrations increasing further from the recharge bore (although still remaining within the values noted above), the simplified model did not incorporate the buffering from the slower reacting silicates, which would mitigate Co release at greater distance from the recharge bore.

The information that is currently available suggests that the Yarragadee aquifer can be expected to behave geochemically in a similar manner to the Leederville, but will be overall less reactive. Cobalt was the only metal to be released during acid solubility tests, and although there is less buffering potential, the sediment analysis shows also that the pyrite concentrations in the Yarragadee are lower, thus overall generating less acidity.

References

Acero, P., C. Ayora, C. Torrentó and J.-M. Nieto. 2006. The behaviour of trace elements during schwertmannite precipitation and subsequent transformation into goethite and jarosite. Geochimica et Cosmochimica Acta 70:4130-4139.

Adams, F. and B.F. Hajek. 1978. Effects of solution sulphate, hydroxide, and potassium concentrations on the crystallization of alunite, basaluminite, and gibbsite from dilute aluminium solutions. Soil Science 126:169-173.

Adams, F. and Z. Rawajfih. 1977. Basaluminite and alunite: a possible cause of sulphate retention by acid soils. Soil Science Society of America Journal 41:686-692.

Andersen, M.S., Larsen, F., Postma, D. 2001. Pyrite oxidation in unsaturated aquifer sediments. Reaction stoichiometry and rate of oxidation. Environmental Science & Technology 35:4074-4079.

Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ). 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Canberra, ACT, Australia.

Ben-Dov, E., Brenner, A., Kushmaro, A. 2007. Quantification of sulfate-reducing bacteria in industrial wastewater, by real-time polymerase chain reaction (PCR) using dsrA and apsA genes. Microbial Ecology 54:439-451.

Bigham, J.M., L. Carlson and E. Murad. 1994. Schwertmannite, a new iron oxyhydroxysulfate from Pyasalmi, Finland, and other localities. Mineralogical Magazine 58:641-648.

Bigham, J.M., U. Schwertmann, S.J. Traina, R.L. Winland and M. Wolf. 1996. Schwertmannite and the chemical modelling of iron in acid sulphate waters. Geochimica et Cosmochimica Acta 60:2111-2121.

Browne, B.A. and C.T. Driscoll. 1994. Soluble aluminium silicates: Stoichiometry, stability, and implications for environmental geochemistry. Science 256:1667-1670.

Chen, M. and L.Q. Ma. 2001. Comparison of three aqua regia digestion methods for twenty Florida soils. Soil Science Society of America Journal 65:491-499.

Church, S.E., E.L. Mosier and J.M. Mootooka. 1987. Mineralogifcal basis for the interpretation of multi-element (ICP-AES), oxalic acid, and aqua regia partial digests of stream sediments for reconnaissance exploration geochemistry. Journal of Geochemical Exploration 29:207-233.

Cornell, R.M., R. Giovanoli and P.W. Schindler. 1987. Effect of silicate species on the transformation of ferrihydrite into goethite and hematite in alkaline media. Clays and Clay Minerals 35:21-28.

Davidson, L.E., S. Shaw and L.G. Benning. 2008. The kinetics and mechanisms of schwertmannite transformation to goethite and hematite under alkaline conditions. American Mineralogist 93:1326-1337.

Dean, W.E., Jr. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. Journal of Sedimentary Petrology 44:242–248.

Descourvieres, C., Prommer, H., Oldham, C. Greskowiak, J., and Hartog, N. (2010a). Identification and quantification of reductant reactivity in heterogeneous aquifer sediments: Kinetic reaction modeling framework. Environmental Science Technology 44(17), 6698-6705.

Descourvieres, C., Hartog, N., Patterson, B.M., Oldham, C., Prommer, H. (2010b). Geochemical controls on sediment reactivity and buffering processes in a heterogeneous aquifer. Applied Geochemistry 25:261-275.

Duckworth, O.W., Martin. S.T. 2004. Role of molecular oxygen in the dissolution of siderite and rhodochrosite. Geochimica et Cosmochimica Acta 68(3):607-621.

Hartog, N., Griffioen, J., Van der Weijden, C.H., 2002. Distribution and reactivity of O_2-reducing components in sediments from a layered aquifer. Environmental Science and Technology 36:2338–2344.

Harvey, R.W., Smith, R.L., George, L. 1984. Effect of organic contamination upon microbial distributions and heterotrophic uptake in a cape-cod, mass, aquifer. Applied and Environmental Microbiology 48:1197-1202.

Hem, J.D. 1970. Aluminum-abundance in natural waters and in the atmosphere. In: Handbook of Geochemistry Vol. II-2(Ed. K.H. Wedepohl), Section 13-1. Springer-Verlag, Berlin.

Hill, V.R., Polaczyk, A.L., Hahn, D., Narayanan, J., Cromeans, T.L., Roberts, J.M., Amburgey, J.E. 2005. Development of a rapid method for simultaneous recovery of diverse microbes in drinking water by ultrafiltration with sodium polyphosphate and surfactants. Applied and Environmental Microbiology 71:6878-6884.

Kawano, M. and K. Tomita. 2001. Geochemical modelling of bacterially induced mineralization of schwertmannite and jarosite in sulphuric acid spring water. American Mineralogist 86:1156-1165.

Kittrick, J.A. 1970. Precipitation of kaolinite at 25ºC and 1 ATM. Clays and Clay Minerals 18:261-267.

Ma, R., Zheng, C., Zachara, J. M. and Tonkin, M. (2012). Utility of bromide and heat tracers for aquifer characterization affected by highly transient flow conditions. *Water Resources Research*, *48*(8).

Mazjlan, J., A. Navrotsky and U. Schwertmann. 2004. Thermodynamics of iron oxides: Part III. Enthalpies of formation and stability of ferrihydrite ($\sim Fe(OH)_3$), schwertmannite ($\sim FeO(OH)_{3/4}(SO_4)_{1/8}$), and ε-Fe_2O_3. Geochimica et Cosmochimica Acta 68:1049-1059.

Morton, A.C., Hallsworth, C.R. 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. Sedimentary Geology 124:3-29.

Nordstrom, D.K. 1982. The effect of sulphate on aluminium concentrations in natural waters: some stability relations in the system Al_2O_3-SO_3-H_2O at 298 K. Geochimica et Cosmochimica Acta 46:681-692.

Parkhurst, D.L. and Appelo, C.A.J. 1999. User's guide to PHREEQC (version 2) - A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. USGS Water Research Investigation Report 99-4259. Washington, D.C., United States Geological Survey. 312 pp.

Pettijohn, F.J. 1963. Chapter S. Chemical composition of sandstones, excluding carbonates and volcanic sands. Geological Survey Professional Paper 440-S, in: Fleischer, M. (Ed.) 1963. Data of Geochemistry, Sixth Ed. United states Government Printing Office, Washington, DC.

Preston, J., Hartley, A., Hole, M., Buck, S., Bond, J., Mange, M., Still, J. 1998. Integrated whole-rock trace element geochemistry and heavy mineral chemistry studies: aids to the correlation of continental reed-bed reservoirs in the Beryl Field, UK North Sea. Petroleum Geoscience 4(1):7-16.

Probst, A., J.P. Party, C. Fevrier, E. Dambrine, A.L. Thomas, and J.M. Stussi. Evidence of springwater acidification in the Vosges Mountains (North-east of France): Influence of bedrock buffering capacity. Water, Air and Soil Pollution 114:395-411.

Schwertmann, U. and R.M. Taylor. 1977. Iron oxides. Pp.145-180 in: Dixon, J.B. and S.B. Weed (Eds.), Minerals in the Soil Environment. American Society of Agronomy, Madison, WI.

Scott, W.D., T.J. Wrigley and K.M. Webb. 1991. A computer model of struvite solution chemistry. Talanta 38:889-895.

Sutherland, R.A. 1998. Loss-on-ignition estimates of organic matter and relationships to organic carbon in fluvial bed sediments. Hydrobiologia 389:153-167.

Thorne, D., Langevin, C. D. and Sukop, M. C. (2006). Addition of simultaneous heat and solute transport and variable fluid viscosity to SEAWAT. *Computers & Geosciences*, *32*(10), 1758–1768.

Totland, M., I. Jarvis and K.E. Jarvis. 1992. An assessment of dissolution techniques for the analysis of geological samples by plasma spectrometry. Chemical Geology 95:35-62.

USDA-NRCS, 2002. Field book for describing and sampling soils. Version 2.0. September 2002. National Soil Survey Center, Natural Resources Conservation Service and U.S. Department of Agriculture. Washington, D.C. 228 pp.

U.S. EPA, 2007. Method 3051A. Microwave assisted acid digestion of sediments, sludges, soils and oils. United States Environmental Protection Agency. Washington, D.C. 30 pp. http://www.caslab.com/EPA-Methods/PDF/EPA-Method-3051A.pdf

Vandenbohede, A., Hermans, T., Nguyen, F. and Lebbe, L. (2011). Shallow heat injection and storage experiment: Heat transport simulation and sensitivity analysis. *Journal of Hydrology*, *409*(1-2), 262–272.

Wilfert, L. 2009. Experimental identification and quantification of reductive processes to anticipate water quality changes during aerobic water injection into an anaerobic aquifer. Master Thesis. Duisburg, 3 November 2009. University of Duisburg – Essen.

Younger, P.L. 2004. Environmental impacts of coal mining and associated wastes: a geochemical perspective. Pp. 169-209 in: Giere, R., Stille, P. (Eds.) 2004. Energy, Waste, and the Environment: a Geochemical Perspective. Special Publication 236. Geological Society, London.

Appendix 1

Table B1 - Mineralogical composition (wt. %) of preliminary Yarragadee aquifer core samples

	Quartz	Albite/ Anorthite	Microcline/ Orthoclase	Pyrite	Calcite	Kaolinite	Illite/ Mica
	%	%	%	%	%	%	%
BPG 1 612-615m	89.1	2.1	7.6	0.5	0.2	0.4	0.1
BPG 1 681-684m	90.8		8.8	0.2		0.2	
BPG 1 729-732m	85.6	0.8	11.8	0.3	0.2	0.8	0.5
BPG 1 900-903m	86.9	0.8	9.1	0.6	1.5	0.5	0.6
BPG 1 975-978m	86.4	0.8	11.2	0.5	0.4	0.3	0.4

Table B2 - Major elemental composition (wt. %, as oxides) and Cl content (mg/kg) of preliminary Yarragadee aquifer core samples.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	Cl	Sum
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(ppm)	(%)
BPG 1 612-615m	92.80	0.13	2.40	0.59	0.01	0.16	0.35	0.29	1.38	0.03	0.75	<0.01	98.86
BPG 1 681-684m	95.03	0.09	2.28	0.13	0.00	0.06	0.04	0.16	1.63	0.02	0.15	<0.01	99.60
BPG 1 729-732m	91.47	0.20	3.75	0.46	0.00	0.15	0.16	0.22	2.23	0.03	0.49	<0.01	99.16
BPG 1 900-903m	89.88	0.15	3.00	1.60	0.02	0.21	0.90	0.23	1.66	0.05	0.77	<0.01	98.48
BPG 1 975-978m	91.78	0.10	3.20	0.91	0.01	0.16	0.21	0.20	1.97	0.03	0.53	<0.01	99.10

Appendix C – Curtin Report

Dispersion testing for risk mitigation

(Preliminary Assessment)

Brett Harris – Curtin University

Preliminary results have been obtained from a small particle mobilization experiment completed on core plugs from recent coring into the Yarragadee Formation at the Beenyup site. In essence the experiment was designed to flow product water from the GWRT advanced water recycling plant through core plugs at in-situ temperature, confining pressure and pore pressure.

Core collected from the Yarragadee aquifer was immediately wrapped in two layers of plastic as it came out of the hole during drilling at Beenyup. The samples were only taken out of plastic wrapping when the plugs were cut. For this experiment samples were not at any stage frozen or dried, and specialized equipment and sample preparation procedures were required.

The testing cell was required to deliver confining pressures of the order 10 MPa and pore pressure of the order 5 MPa according to the depth that each sample was recovered from. Further plug samples were cut parallel to bedding (horizontal) along the axis of expected highest horizontal permeability to a length of 7cm (i.e. across the core). Several of the samples needed to be cut with a high speed slightly larger diameter core cutting bit then shaped to a 38mm diameter plug by hand.

As the core plugs were cut they were filled with degassed Yarragadee water in a vacuum chamber. The core was then sealed into the experimental cell and the test commenced. Product water was flowed through the sample in 266ml slugs. The first injection rate through the plug was 7ml/min. Once the test was completed for the first 266ml slug the equipment was then checked and the reservoir connected to the pump was refilled with the next 266ml slug of product water. Then the next test commenced (i.e. next 266 ml slug of product water). The process was repeated until the full set of 21 tests was completed for each core sample. The total volume flowed through each sample during the test was 5586ml. The total number of slugs passing through the sample was 21 (i.e. 21 x 266 ml slugs is 5586 ml).

For each slug, water samples were acquired, first in small 14 ml vials, then later bigger samples were collected in 50ml vials. For later tests 125ml bottles were used on repeat slugs for 100ml/min flow rates. The flow rates used were 7ml/min, 14ml/min, 36ml/min, 50ml/min and 100 ml/min. Approximately 182 samples were taken during each full test (i.e. for each plug).

Turbidity has been recovered for the first ten 14ml water sample (i.e. 14ml vials) collected at each step change in flow rate, and results are presented in Figure C.1. A significant number of tests remain to be completed, however the preliminary results are instructive for the risk assessment stage of progressing approvals for the Perth Groundwater Replenishment Scheme, recharging up to 14GL/yr into the Yarragadee aquifer at the Beenyup site.

At low rates of flow small particles are mobilized at an almost continuous rate. At much higher rates small particles (colloid sized particles as inferred form turbidity) tend to be mobilized as a pulse. Another important conclusion is that there is significant difference in small particle mobilization from samples that look very similar to the naked eye. For example core plug 554.7 has an order of magnitude lower turbidity for most flow rates compared to 640.6. However on closer inspection sample 554.7 is relatively clean compared to 640.6 which is very poorly sorted. More work will be required to assess the size and chemistry of particles mobilized at various stages of the flow through test for each plug sample.

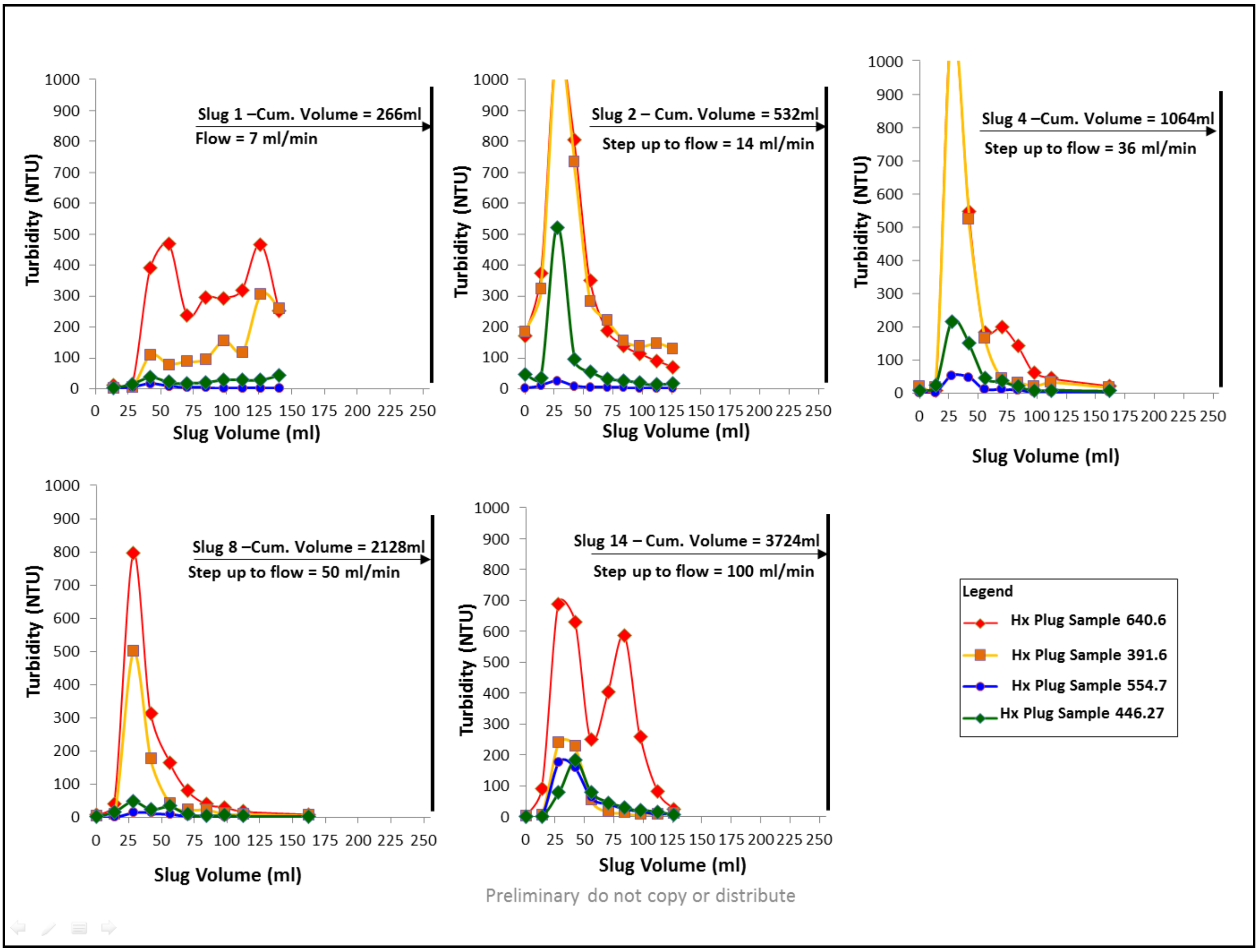


Figure C.1: Turbidity results from dispersion tests

Seismic for risk mitigation

1. Background

Large scale stresses in the earth result in faulting and shearing in the subsurface. This process is ongoing throughout geological time. Large faults have identified in the Yarragadee and Leederville formation by displacement of these formations at different drill hole locations. Significant displacement in these formations or changes in formation properties around faulting or fault zones has the potential to materially impact on local hydraulics and injectivity. At present the evidence for much of the large scale faulting in the Perth Region and the Gnangara mound is inconclusive (mostly geological interpretation on sparse drill holes). The only method that has the potential to directly image the subsurface and to identify faulting is seismic reflection.

2. Project objectives

The Water Corporation have recognized a low but present risk of drilling into a fault zones at Beenyup. While the likelihood of drilling into a faulted zone at the Beenyup site is low the consequence of displacement of aquifers or change in aquifer properties in is potentially significant. It was recognized that the risk of drilling into a faulted zone could be significantly reduced by completing seismic reflection along a North South and East West transect at a site scale. These data would be combined with the small pre-existing 3D seismic to identify the risk of large scale faulting existing at the Beenyup site.

3. Survey details

The survey consisted of a one 1.8km North South transect (displayed in green) and one 750m East West transect (displayed in blue) of high resolution 2D seismic at identified in Figure C.2 below. The survey was executed in 3D mode. That is geophones where spaced at 5 m intervals along the two lines and "shot" points were completed at 10 m intervals with all geophones active (i.e. both lines). The source consisted of a free falling weight of 800 kg dropped from about 1.5 m above the ground. Up to 8 full records were completed at each 10m spaced "shot" (i.e. source) point location. The lines were selected because they were the longest continuous, straight east-west and north-south lines close to the Beenyup site. Note that the North South transect is immediately adjacent to the Mitchell freeway (within 20m). Signal to noise along the North South transect was poor which is why up to 8 repeat blows of the weight drop were complete at each source location. The strongest source of noise was air waves and surface waves originating from trucks and cars as the passed the line. The lines were located such that, should any significant East West or North South fault exist it would be have a high probability of being identified on one of the two lines at site scale.

Figure C.2 - Location and position of both 2D transects over the Beenyup site. The blue line is the East – West Transect and the green line is the North South Transect. The transparent red box is the approximate extent of the 3D seismic survey.

4. Results

Given the challenges of operating in an urban setting and the high noise from the freeway the results should be considered highly acceptable. Figure C.3 provides a processed seismic image (apparent relative reflectivity) of the subsurface below the East West line (see Figure C.2). The result is clear. In the high fold part of the transect Top of Wanneroo, Bottom of Wanneroo, Top of Yarragadee and several reflectors within the Yarragadee are approximately continuous. Clearly fold (i.e. related to the number of source and receiver combinations) drops off and naturally resolution diminishes towards the end of each line. Fold and resolution are at maximum at the middle of the line. Figure C.4 is a 3D representation of the seismic reflection data along both north south and east west transects. Again the 3D image shows the bottom of Wanneroo, bop of Yarragadee and several reflectors within the Yarragadee to be approximately continuous. In short there is no clear evidence in the seismic data for large scale site scale faulting.

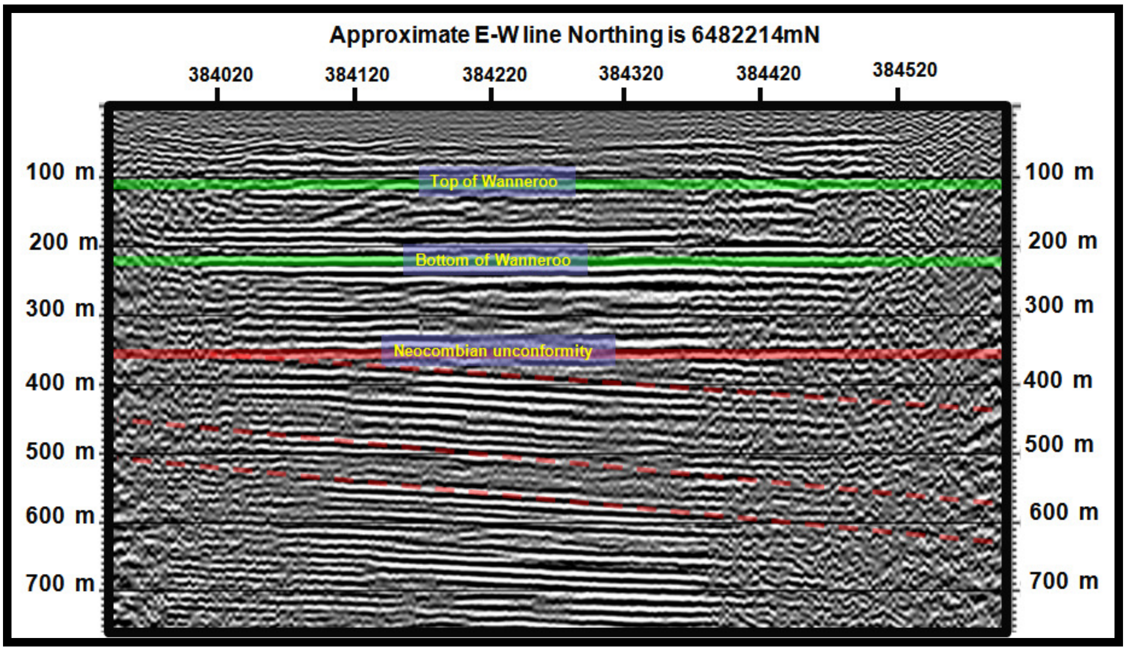


Figure C.3 - East West Line showing clear continuity of the interfaces at the top and bottom of the major unconformities and for several layers in the Yarragadee. The left and right axis is depth below seismic datum (close to surface level) and the top axis is easting along the East West Line

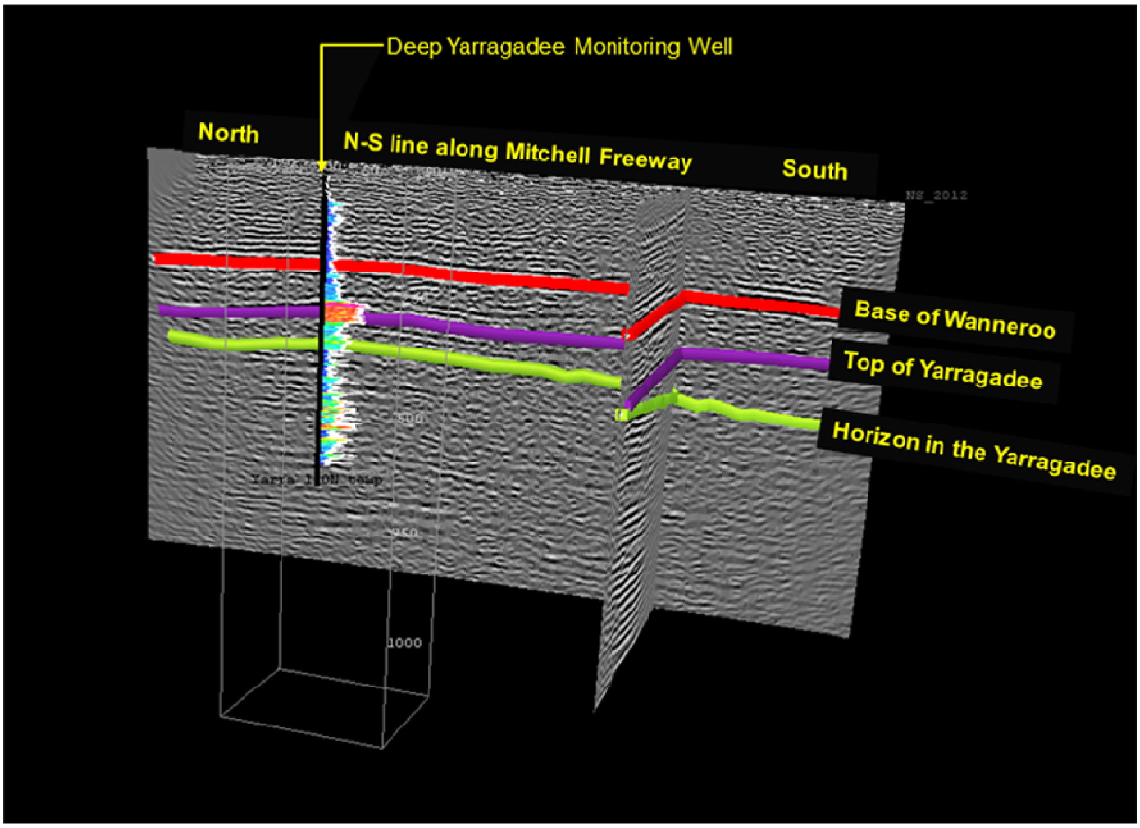


Figure C.4 - East West and North South Seismic transects show approximately continuous reflectors at the base of Wanneroo, Top of Yarragadee and for a horizon near the top of the Yarragadee. The location of the deep Yarragadee monitoring wells is also shown. The seismic reflection data gives no indications of large scale faulting at the site scale.

Appendix D - Evaluation of vertical groundwater movement

As part of determining the Environmental Values for the Leederville aquifer, the Groundwater TRG investigated the likelihood of vertical flow. This was based on information gained from the Groundwater Replenishment Trial, particularly upward flow of recycled water into the Superficial aquifer. As a result of these investigations, the Groundwater TRG developed a process as outlined in Figure D.1 to guide decision making by Agency representatives.

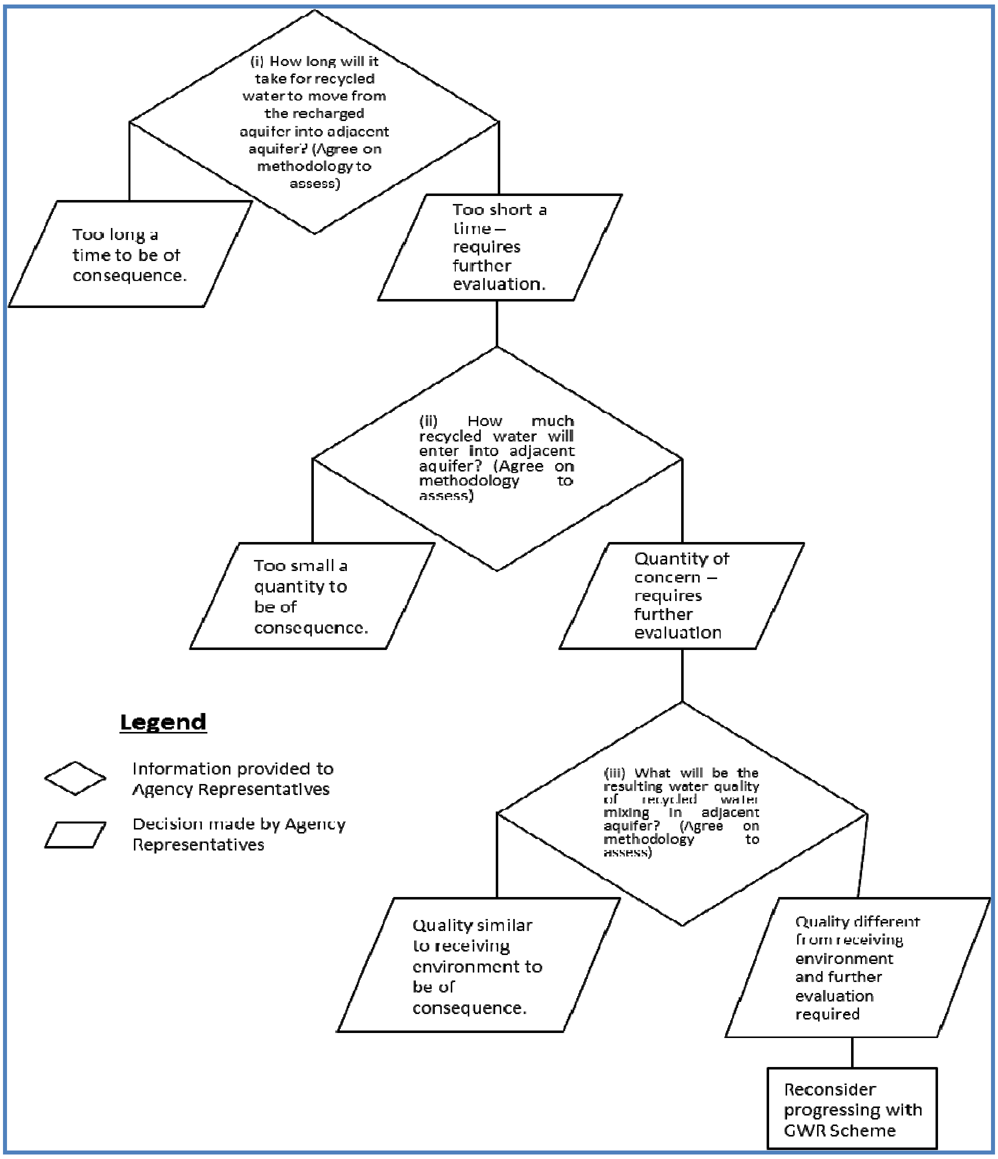


Figure D.1 - Guidance in evaluating aquifer characteristics to determine Environmental Values

Hydro-stratigraphic logs from the Beenyup site indicate that up to 75m of sediments lie between the recharge interval in the Leederville aquifer and the Superficial aquifer (Table D.1). As the rate of recharge increases there is an increased potential for water from the recharge interval to enter the overlying sediments due to an increase in recharge pressures. Any upward flowing recharge water would need to move through these layers before reaching the Superficial aquifer.

Table D.1 - Hydro-stratigraphic summary for the Beenyup Site

Summary Depth (m) From	To	Description	Geological Unit	Hydrogeology
0	20	Sand, medium to coarse grained quartz and limestone grains	Tamala Limestone	Superficial aquifer
20	50	Limestone	Tamala Limestone	Superficial aquifer
Unconformity				
50	65	Sandstone, silty, medium to coarse grained quartz and glauconite with silt and shale beds.	Osborne Formation	Mirrabooka aquifer Kardinya Shale aquitard
Unconformity				
65	95	Sandstone, fine to coarse grained, moderately sorted, sub-rounded quartz with thin dark grey siltstone beds	Leederville Formation (undifferentiated)	Leederville aquifer
95	125	Siltstone and shale	Leederville Formation	aquitard
125	175	Sandstone, fine to coarse grained quartz with thin siltstone and mudstone beds	Leederville Formation: Wanneroo Member	Leederville aquifer
175	190	Siltstone, mudstone and poorly sorted sandstone.	Leederville Formation: Wanneroo Member	Intra-formational siltstone
190	225	Sandstone, fine to coarse grained quartz with thin siltstone and mudstone beds	Leederville Formation Wanneroo Member	Leederville aquifer
225	260	Siltstone and mudstone	Leederville Formation: Mariginiup Member	aquitard
260	320	Siltstone and mudstone	South Perth Shale	aquitard
Unconformity				
320	390	Sandstone and siltstone	Gage Formation	Yarragadee aquifer
390	>750	Sandstone and siltstone	Yarragadee Formation	Yarragadee aquifer

Note: yellow shading highlights the recharge interval for the Leederville aquifer.
After (Water Corporation, 2012)

An analytic model was developed by the Groundwater TRG to predict travel times of upward flow, and is applicable for a range of potential recharge rates (Figure D.2). The model utilises the observed strata from a site, and can be quickly reconfigured for a new site as information from drilling and testing becomes available.

The model provides a conservative prediction of travel time as it does not take into account lateral flow due to spreading and regional through flow in the overlying sediments or head reduction due to abstraction.

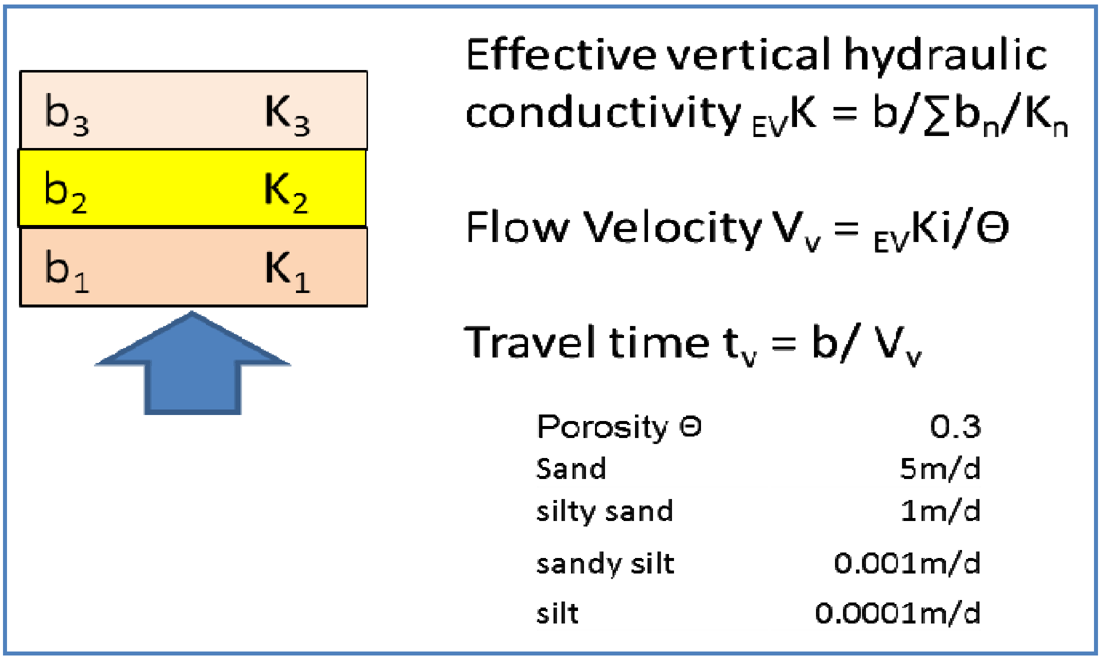


Figure D.2 - Calculation of effective vertical hydraulic conductivity and travel time

Note: Layer thickness (b_n), hydraulic conductivity of individual layer (K_n) vertical hydraulic gradient (i) over total thickness (b). Estimated values of porosity (Θ) and K_n (m/d) for Beenyup sediments.

A comparison of effective vertical hydraulic conductivity was made between descriptions based on core samples of bore BNYP1/07, drill cuttings from BNYP1/08, about 50m away, and layer thickness and vertical hydraulic conductivity applied in PRAMS3.4, and is shown in Table D.2. The good agreement between values indicates that carefully collected and described drill cuttings in conjunction with geophysical logs can provide a suitable estimate for this level of assessment.

Table D.2: Comparison of effective vertical hydraulic conductivity

1/07 Core and geophysical log	1/08 Cuttings and geophysical log	PRAMS3.4 Layers 4,5,6
4.33×10^{-4} m/d	4.78×10^{-4} m/d	6.13×10^{-4} m/d

Assessment of the likelihood of flow to adjacent aquifers at a regional scale has been made using the Perth Regional Aquifer Modelling System (PRAMS3.4) and particle tracking (PMPATH). Evaluations based on a solute transport derivative PRAMSOL3.4, and PRAMS3.4 with PMPATH indicate that PMPATH provides a suitable estimate for water movement at a regional scale (CyMod Systems, 2013 *in press*), and have been applied using head conditions from a 30 – year simulation of recharge.

Leederville aquifer

Flow velocity and potential travel time between the recharge zone in the Leederville aquifer and base of the superficial aquifer were assessed using lithological descriptions from the cored hole BNYP1/07.

The head at the base of the superficial aquifer (3mAHD) was based on the hydrograph from bore BNYP05-08_20N_43, (Figure D.3).

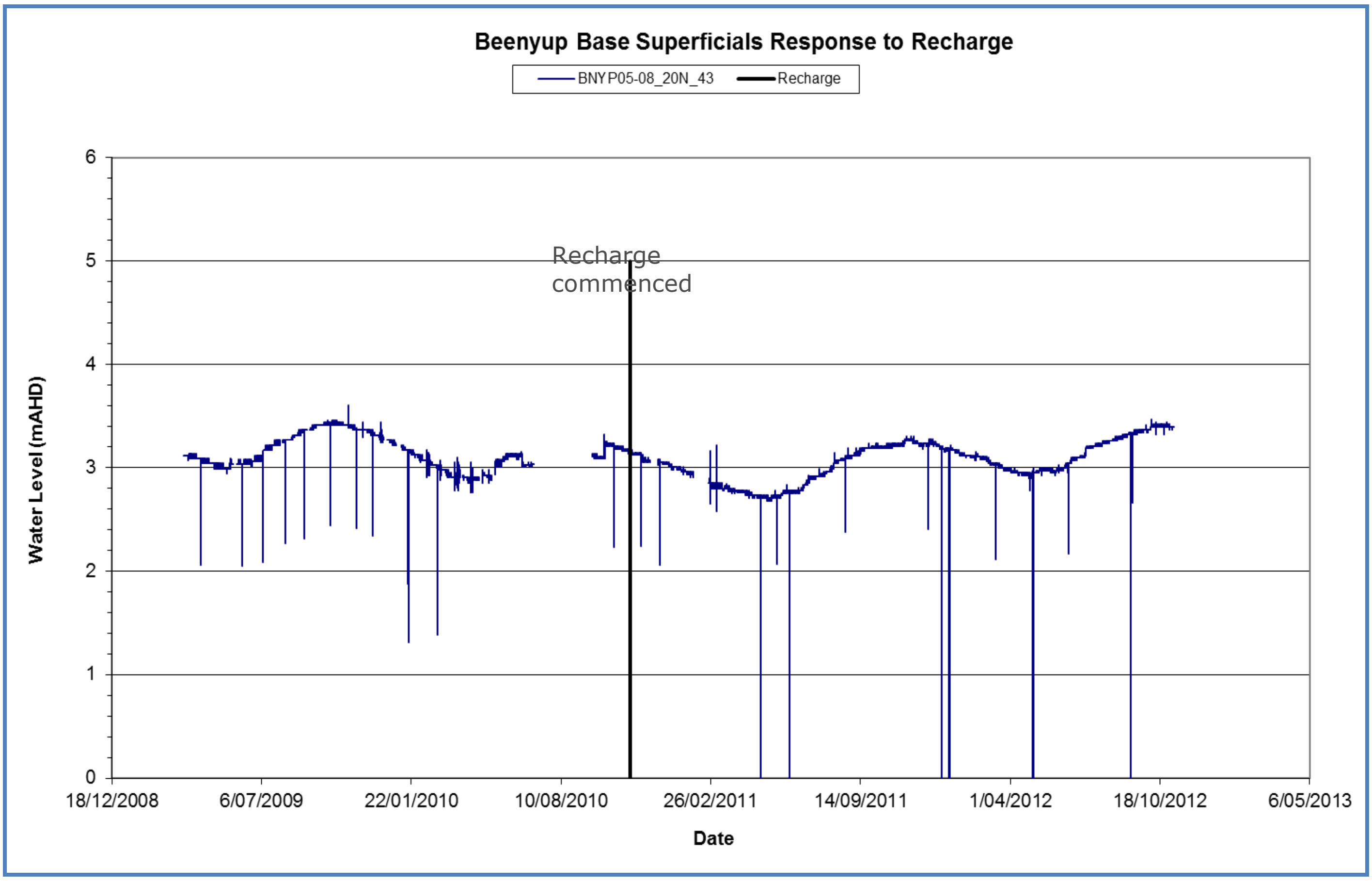


Figure D.3 - Head at the base of the superficial aquifer at Beenyup

The average head within the recharge interval prior to recharge was determined from the long term record of Artesian Monitoring bore AM27A, about 980m north east, which monitors the same interval as the recharge bore (Water Corporation, 2009a). A correlation was made with monitoring bore BNYP11/08 20N 129, which monitors the top of the recharge interval 20m north of the recharge bore, and the pre recharge (2000 – 2010) heads at AM27A (Figure D.4). The average pre recharge head for AM27A was -5.45mAHD and an adjustment of ~0.5m to account for the head difference between the two sites results in an average head prior to recharge of -5mAHD at Beenyup.

The head build up after 10 years for a range recharge rates was determined from scaling and extrapolation of the late time (post boundary effect), extended pumping test results (Rockwater 2011a, Water Corporation 2012a), and are shown in Table D.3, and travel times are shown on Figure D.5. The maximum head in the recharge bore, based on Phase 2 MAR Guidelines (NRMMC-EPHC-NHRMC, 2009), of 180m above ground level is also included in Table D.3 for comparison.

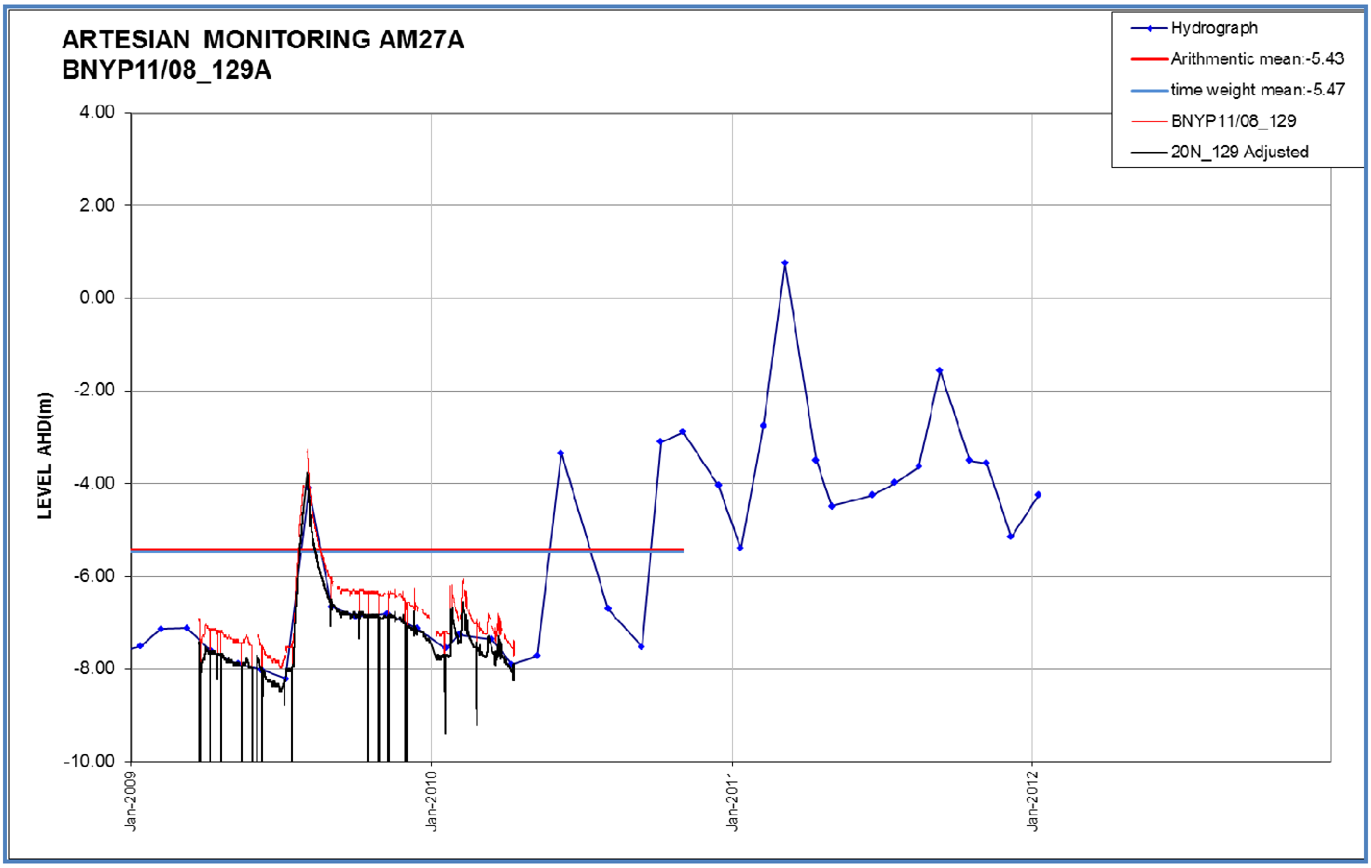


Figure D.4 - Potentiometric head correlation for AM27A and BNYP11/08

Table D.3 - Recharge rate and head response

Recharge		Head above ground level (m)	Head difference (m)	Travel time (Years)
GL/yr	ML/d	Max = 180m		
1.5	4.1	-22.7	-2.7	0
3.5	9.6	-15.6	4.4	1500
7	19.2	-3.3	16.7	600
10	27.4	7.2	27.2	440
14	38.4	21.3	41.3	250
20	54.8	42.5	62.5	100

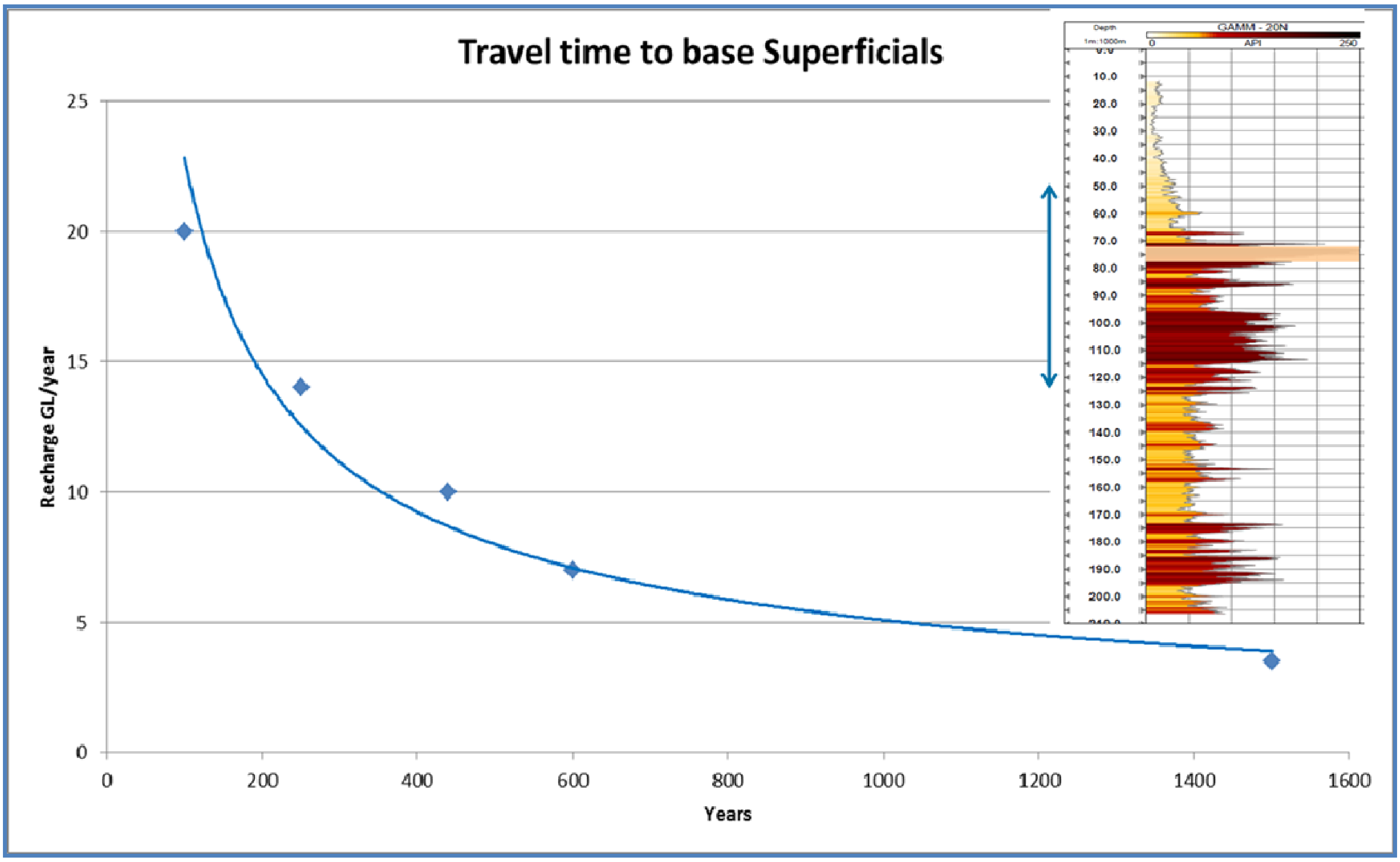


Figure D.5 - Travel Time for upward flow into the Superficial aquifer

Note: insert at top right of Figure D-5 is a representation of the strata at Beenyup from the geophysical log of the Leederville recharge bore. The interval between the recharge zone and base of superficial aquifer is shown by the blue arrow. The dark lines represent the low permeability siltstone strata that impede upward movement of recharged water.

An assessment of travel time further from the recharge bore was made based on a calibrated distance - head relationship derived from the extended pumping test (Rockwater, 2011a) and calculated travel times (Figure D.6). At a recharge rate of 14GL/yr, the potential travel time increases from 250 years near the recharge bore to 550 years at 500m distance.

A 3D visualisation of the steady state (1000 years) solute transport based on PRAMS3.4 PMPATH for recharge at 14GL/yr to the Leederville aquifer is shown in Figure D.7. This indicates that recharged water does not move out of the Leederville aquifer in the long-term. This result is consistent with the long travel times predicted for upward flow at a site scale, and highlights the conservative nature of the analytic approach which does not include lateral flow where water would travel much faster in a lateral direction than vertical direction.

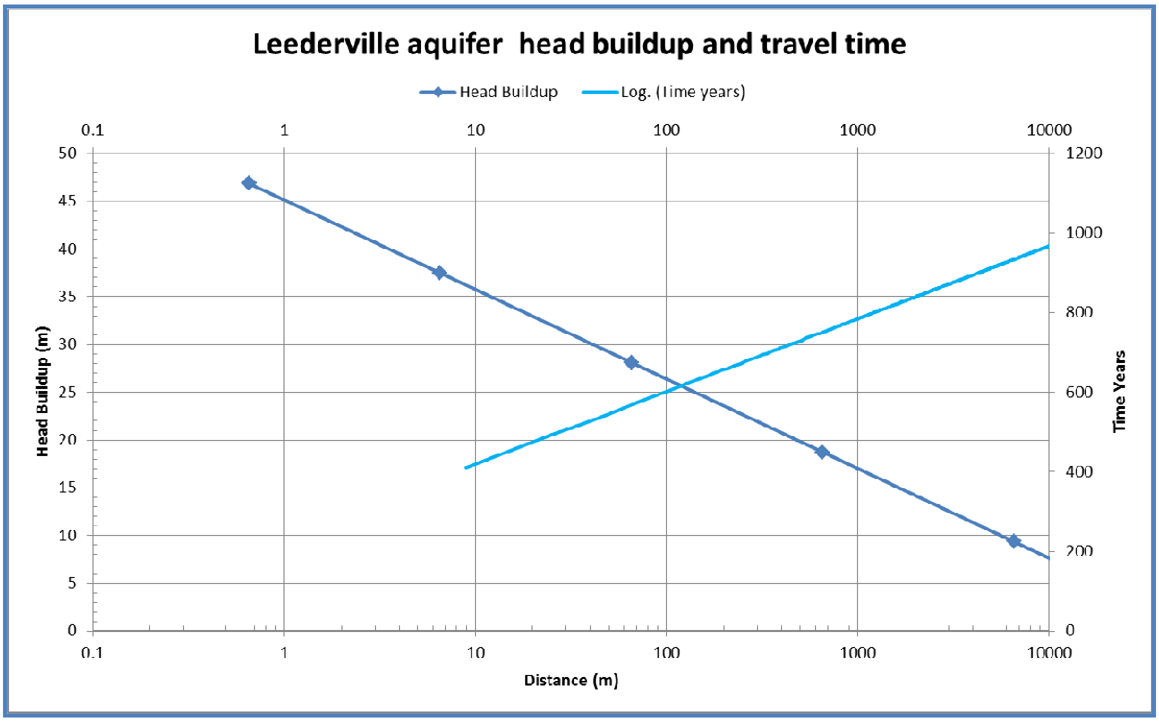


Figure D.6 - Potential travel time based on head build-up after 3 years recharge at 14GL/yr

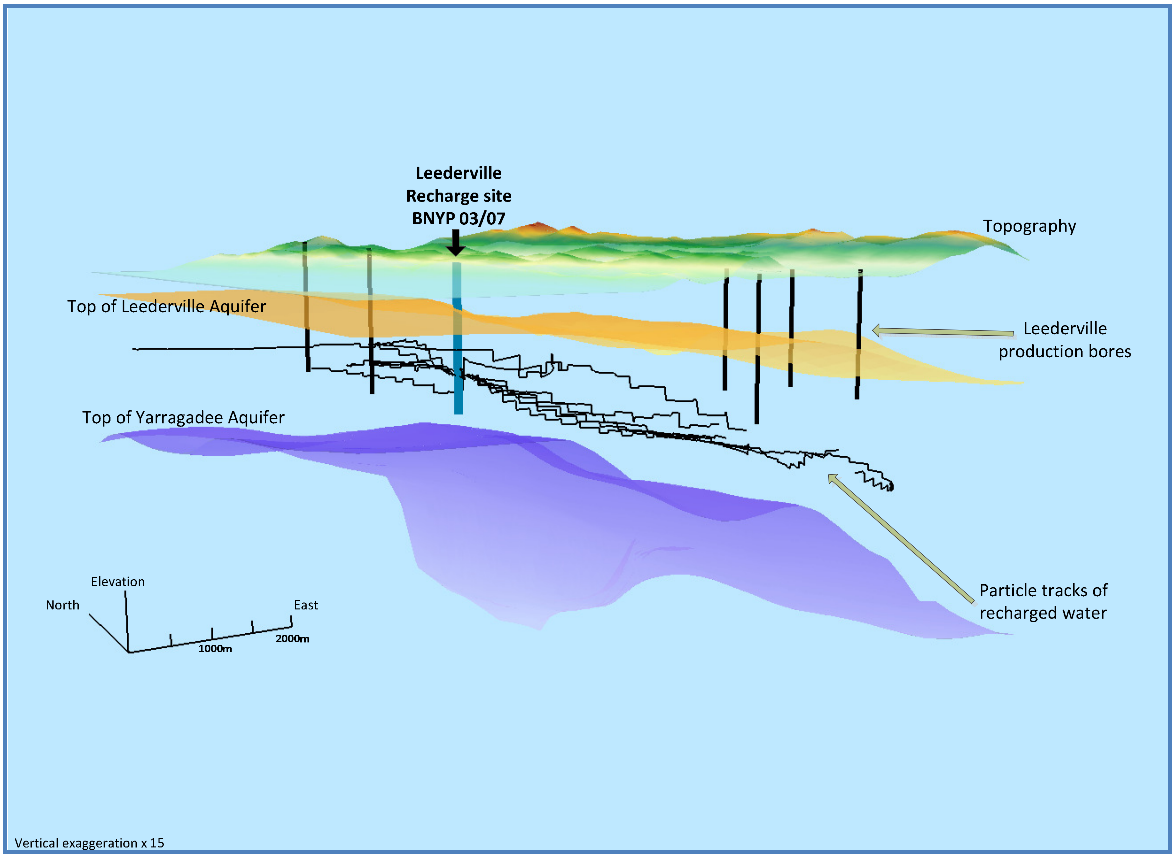


Figure D.7 - Flow path for recharge at 14GL/yr to the Leederville aquifer over 1000 years

Yarragadee aquifer

Because of the thick and extensive nature of the low permeability sediments that overlie the Yarragadee aquifer, it is considered that upward flow of recharge water across this layer is unlikely.

If conditions allowed for recharged water from the Yarragadee to flow upwards, it would have to first flow into the Leederville aquifer, through the overlying sediments before reaching the base of the Superficial aquifer. Travel time from the top of the Yarragadee aquifer to the base of the Leederville aquifer at a recharge rate of 14GL/yr would be more than 1000 years (Table D.4). Under current conditions, there is a downward head within the Leederville aquifer (Water Corporation, 2009a) and therefore no potential for upward flow, and water recharged to the Yarragadee aquifer would not reach the Superficial aquifer.

Table D.4: Heads and travel time from Yarragadee aquifer to base of Leederville aquifer at 14GL/yr recharge

Head in Yarragadee (AM27)	-20mAHD
Head in Leederville (Beenyup)	-5mAHD
Avg Specific capacity /m screen	2kl/d/m/m
Yarragadee screen length	200m
Specific capacity	400kl/d/m
Recharge rate	38400kl/d
Head rise	96m
Head difference	81m
Aquitard thickness	115m
Hydraulic conductivity	0.0001m/d
Effective porosity	0.3
Velocity	0.000235m/d
	0.085396m/yr
Travel time	**1342 years**

The steady state flow path based on PRAMS3.4 PMPATH for recharge at 14GL/yr to the Yarragadee aquifer is shown in Figure D.8, and indicates that recharged water does not leave the Yarragadee aquifer.

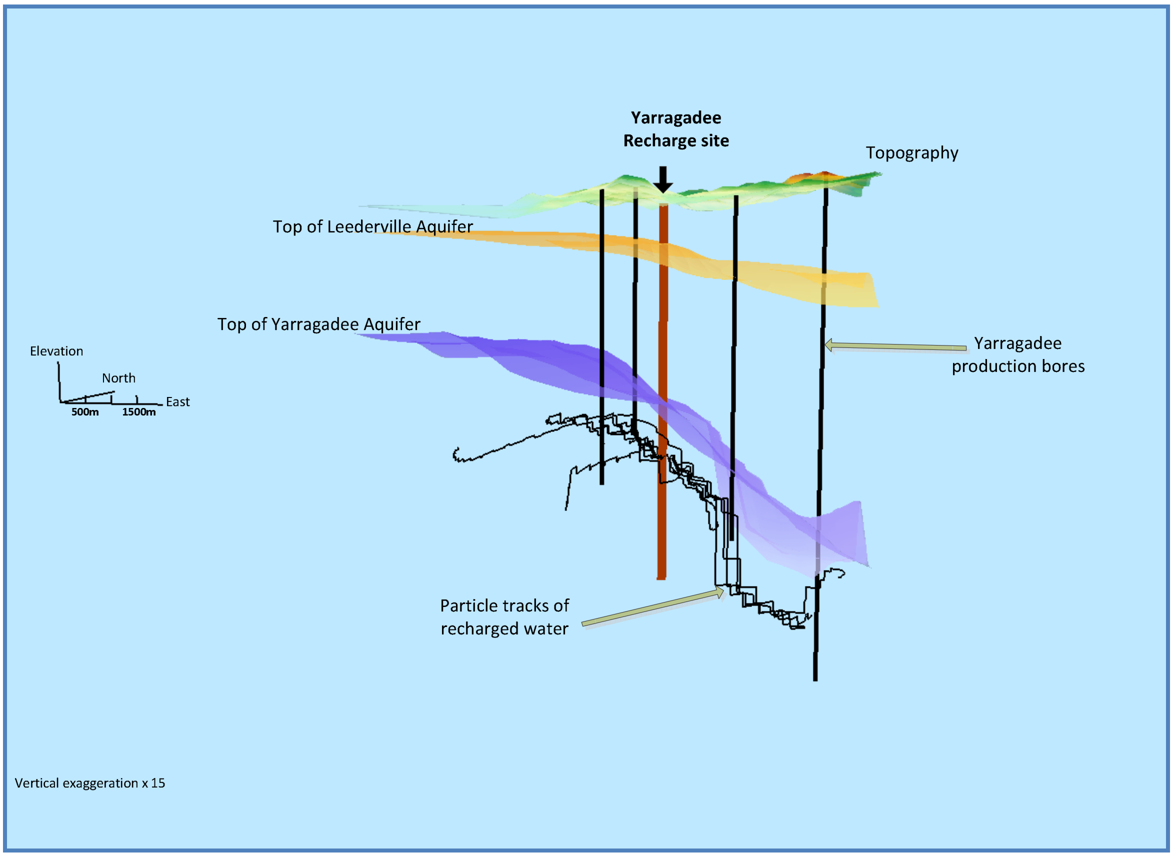


Figure D.8 - Flow path for recharge at 14GL/yr to the Yarragadee aquifer over 1000 years

Appendix E – Clogging Assessment Trends

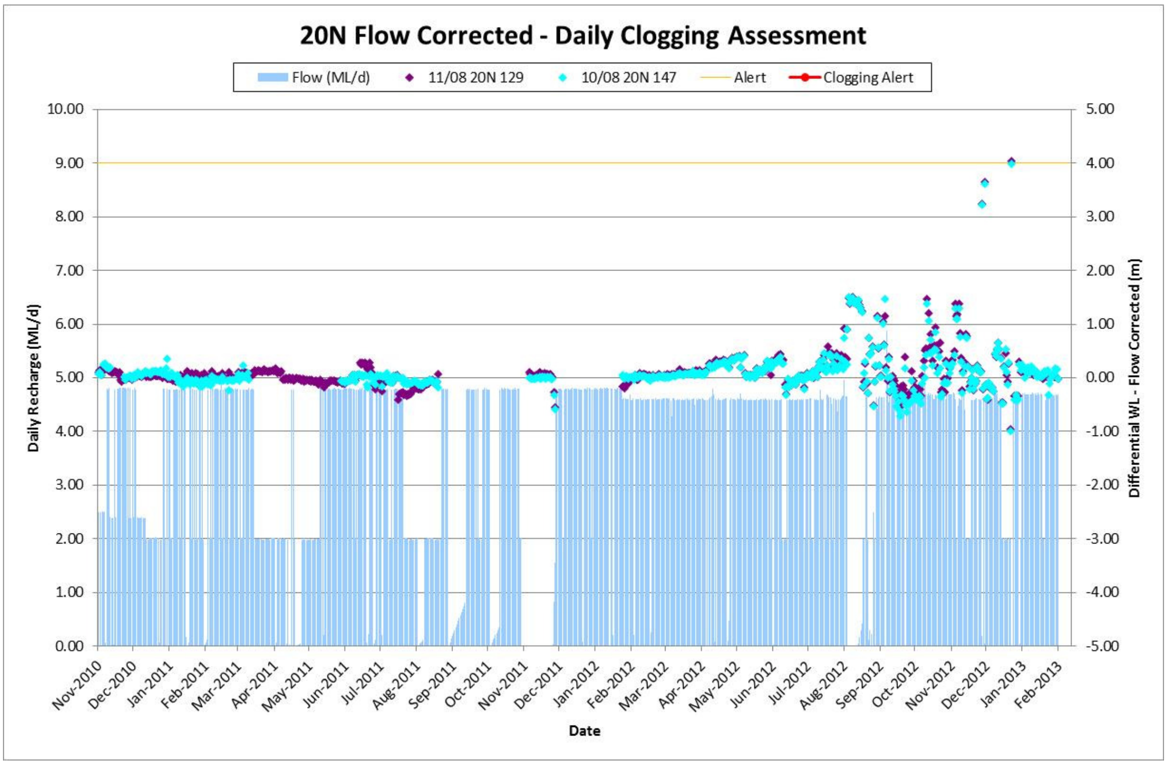


Figure E.1 – 20N clogging assessment trends (BNYP11/08 20N 129, BNYP10/08 20N 147)

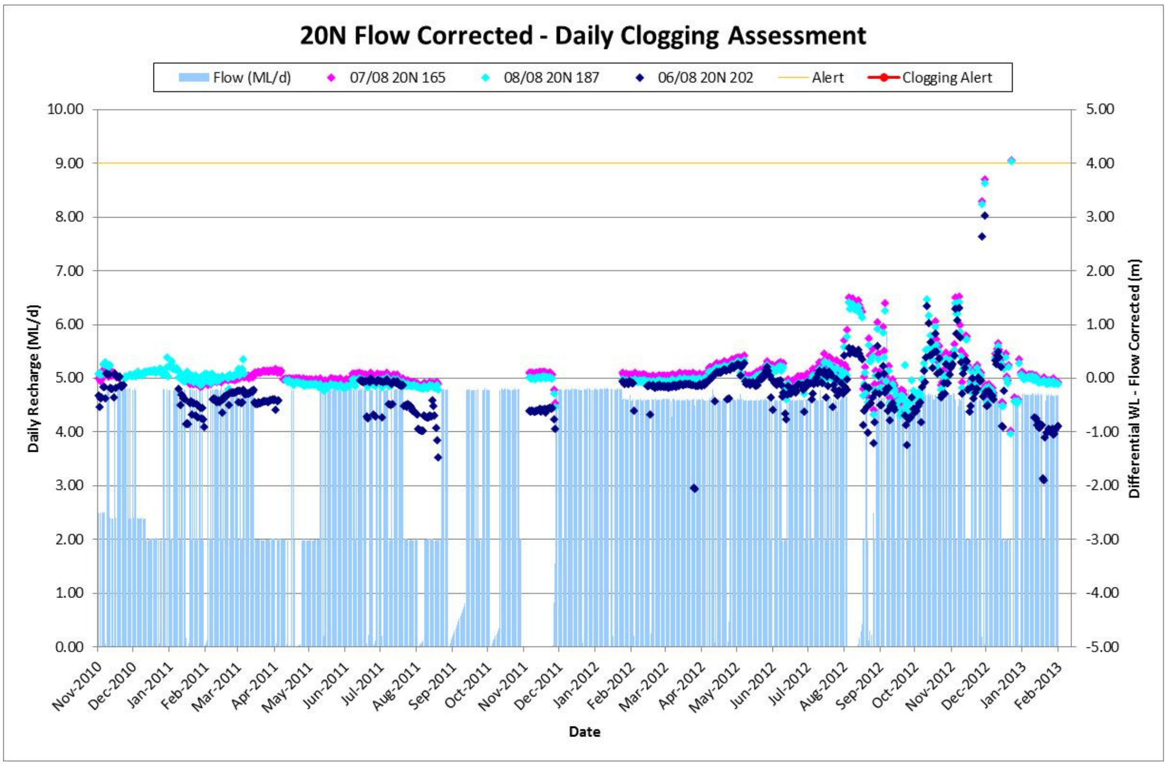


Figure E.2 - 20N clogging assessment trends (BNYP07/08 20N 165, BNYP08/08 20N 187, BNYP06/08 20N 202)

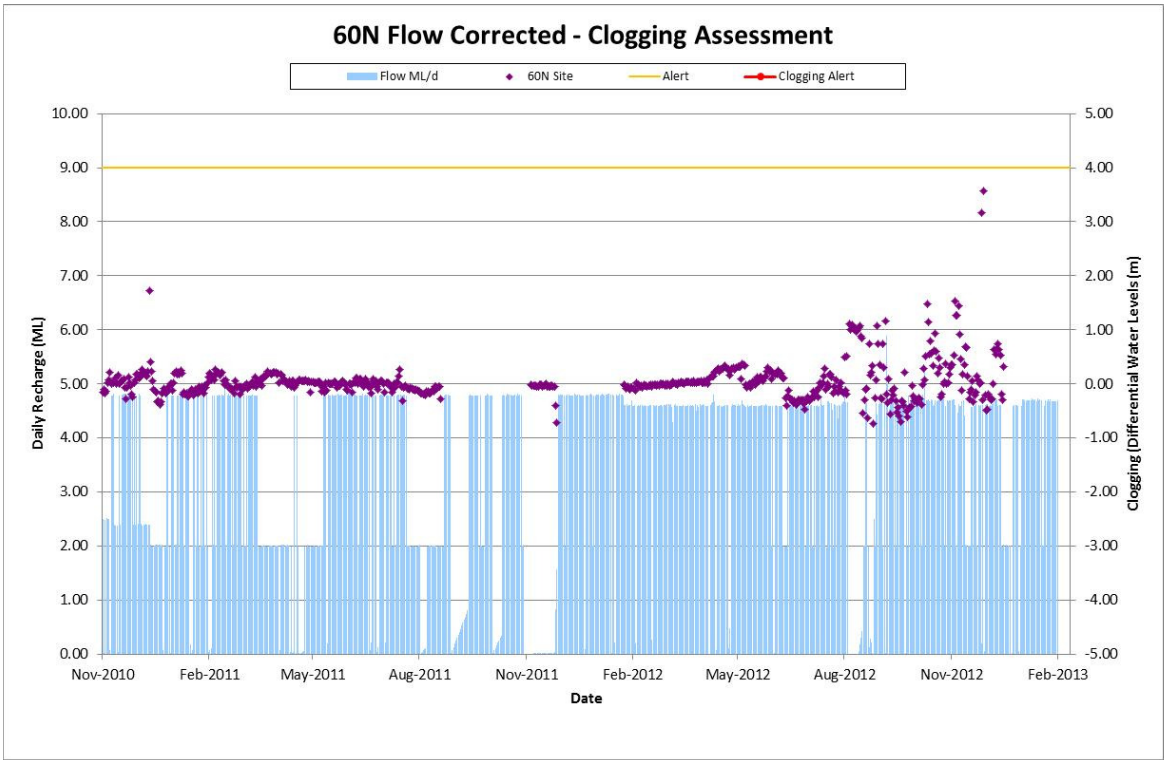


Figure E.3 – 60N clogging assessment trend (site average)

Appendix F – Recycled Water Quality Data

Group	Parameter	Unit	GWRT DoH Guideline	LOR	Average	StDev	Max	Min	N
Metals	Arsenic	mg/L	0.007	0.001	<0.001	0	<0.001	-	6
	Barium	mg/L	0.7	0.002	<0.002	0	<0.002	-	29
	Boron	mg/L	4	0.02	0.09	0.02	0.12	0.06	29
	Cobalt	mg/L	0.001	0.0001	<0.0001	0	<0.0001	-	6
	Iron (Unfiltered)	mg/L	0.3	<0.01	<0.01	0	0.01	<0.01	29
	Manganese (Unfiltered)	mg/L	0.5	0.0005	<0.001	0	<0.001	-	29
	Strontium	mg/L	4	0.002	<0.002	0	0.002	<0.002	29
Major Ions	Alkalinity as CaCO3	mg/L	n/a	1	11.1	6.1	38	5	29
	Bicarbonate	mg/L	n/a	1	13.2	7.2	46	6	29
	Calcium	mg/L	n/a	0.1	<0.1	0	0.1	<0.1	29
	Chloride	mg/L	250	1	6.6	1.9	9	3	29
	Fluoride	mg/L	1.5	0.05	0.09	0.05	0.18	<0.05	29
	Magnesium	mg/L	800	0.1	<0.1	0	0.3	<0.1	29
	Potassium	mg/L	n/a	0.1	1	0.3	1.6	0.6	29
	Sodium	mg/L	180	0.1	9.7	2.2	14.2	6	29
	Sulphate	mg/L	500	0.1	0.2	0.1	0.5	<0.1	29
Nutrients	Ammonia as N	mg/L	0.5	0.01	0.26	0.08	0.44	0.11	29
	Nitrate as N	mg/L	11	0.01	1.99	0.84	3.6	0.87	29
	Total Nitrogen	mg/L	n/a	0.02	2.34	0.83	3.9	1	29
	Total Phosphorus	mg/L	n/a	0.01	0.02	0.01	0.06	<0.01	29
Physical	Conductivity	mS/m	n/a	0.2	5.8	1.5	8.2	3.4	29
	pH		6-8.5	0.1	6.9	0.2	7.2	6.5	29
	TDS	mg/L	500	10	29	10.2	50	13	29
	TSS	mg/L	n/a	1	1.2	0.7	4	1	29
	Turbidity	NTU	5	0.5	<0.5	0	,0.5	-	29

Appendix G – Water Corporation Risk Assessment Matrix

Table F.1 - Measures of consequence or impact

Rank	Financial	People & Public	Environmental	Service Interruption / Customer Impact	Reputation	Compliance	Descriptor
1	Less than $1M	Injuries or illness not requiring medical attention, or Minor first aid Injury	No lasting effect on the environment or social amenity, and/or Recovery– less than 1 week, and/or Cosmetic remediation	Brief loss of local services, and No measurable operational impact.	Low public awareness, no media coverage, possible localised impact on trust and credibility, and/or Inconsequential complaints from the community, and/or No government/ministerial involvement.	Licence or regulatory limit exceedance, informal approach with no formal action or no Regulator involvement.	Insignificant
2	$1M - $10M	Injury requiring medical treatment(no alternative duties), or Localised illnesses requiring medical attention	Short term or low-level long-term impact on the environment or social amenity, and/or Recovery – 1 week to several months, and/or Easy remediation	Localised operations or service interruption, and Temporary, short term service cessation (<6 hours)	Limited local media coverage, localised impact on trust and credibility with Minor Stakeholders, and/or Random substantiated complaints from the community, and/or Local member of parliament enquiry.	Non-compliance or breach of regulation – Formal direction by a Regulator or administrative / Statutory body with administrative or minor operational impacts	Minor
3	$10M - $100M	Middle to long term injury (able to return to work), or Long term condition, or Localised illnesses requiring hospitalisation	Long term impact on the environment or social amenity, and/or Recovery – several months to several years, and/or Challenging remediation	Wide-spread customer impacts – entire regional centre or country scheme, multiple metropolitan suburbs, and Temporary loss of operations and services (<24 hours)	Local and state-wide media coverage, impacts on trust and credibility with Minor and Major Stakeholder, and/or Coordinated communication of community concerns and complaints, and/or Parliamentary question / Ministerial directive.	Non-compliance or breach of regulation – Formal direction by a Regulator or administrative / Statutory body with threat of prosecution or localised public undertakings Loss of accreditations (e.g. Environmental, OH&S)	Moderate
4	$100M - $500M	Permanent disabling injuries, or Widespread illness requiring hospitalisation, or Single death	Extensive, long term impact on the environment or social amenity, and/or Recovery – several years to several decades, and/or Uncertain reversibility of remediation	Widespread degradation of operations or services, and Sustained service cessation (>24 hours)	State-wide and National media coverage, impacts on trust and credibility with Significant and Major Stakeholders, and/or Sustained community outrage, and/or Government Department Investigation.	Non-compliance or breach of regulation – Formal direction a Regulator or administrative / Statutory body with significant operational constraints/restriction and/or public undertaking Criminal / quasi-criminal charges for Water Corporation and/or personnel Loss of multiple/significant abstraction licence	Major
5	Greater than $500M	Multiple deaths	Significant extensive impact on the environment or social amenity, and/or Impacts are irreversible and/or permanent.	Significant widespread degradation of operations or services, and Long, sustained, loss of operations or services	Extensive National and/or some International media coverage, and/or Impacts on trust and credibility with all Corporate stakeholder categories, and/or Sustained community outrage.	Non-compliance resulting in cancellation or loss of operating licence. Loss of significant or major licence	Catastrophic

Table F.2 - Qualitative measures of likelihood

Rank	Descriptor	Frequency	Description
A	Almost Certain	Will occur more than once a year Multiple times in a year	The event is expected or known to occur often
B	Likely	Once per year Once in a year or so	Known to re-occur approximately annually
C	Possible	Will occur once every 5 years Once in 5 years or multiple times over 10 years	The event should occur at some time Is sporadic, but not uncommon
D	Unlikely	Will occur once in 10 years Could occur once in 10 years or multiple times over 20 years	The event could occur at some time, usually requires combination of circumstances to occur
E	Rare	Will occur once every 30 years Once in 30 years or less frequent	The event may occur in exceptional circumstances Not likely to occur, but it's not impossible

Table F.3 - Control effectiveness rating

Rank	Descriptor	Description
O	Optimal	The control is designed and operating effectively and consistently Improvements to the control are not feasible or are unnecessary
A	Adequate	Control is designed to be effective The control is operating effectively Errors in control application can result in isolated cases of inconsistencies Improvements should be made if feasible
I	Improvement Required	The control is not designed and/or operating effectively Improvements are required

Table F.4 - Water Corporation risk matrix

CONSEQUENCES	LEVEL OF RISK				
5 Catastrophic	H	H	E	E	E
4 Major	M	H	H	E	E
3 Moderate	L	M	H	H	H
2 Minor	L	L	M	H	H
1 Insignificant	L	L	L	M	M
	E Rare	**D** Unlikely	**C** Possible	**B** Likely	**A** Almost Certain
	LIKELIHOOD				

Groundwater Replenishment Scheme – Stage 2A

Aquifer Risk Assessment Workshop

14GL/yr – Leederville and Yarragadee Aquifers

14th March 2013

Attendee	Organisation	Signature
Adrian Parker	Department of Water	
Brad Degens	Department of Water	
Brad Patterson	CSIRO	
Brett Harris	Curtin University	
Cahit Yesertener	Department of Water	
Henning Prommer	CSIRO	
Karen Johnston	Rockwater Pty Ltd	
Michael Martin	Water Corporation	
Peter Dillon	CSIRO	
Scott Garbin	Water Corporation	
Simon Higginson	Water Corporation	
Stacey Hamilton	Water Corporation	
Tran Huynh	Water Corporation	
Vanessa Moscovis	Water Corporation	

Appendix I – GWRS – Stage 2A – Leederville Aquifer Risk Assessment Tables

		Leederville Aquifer - GWR Inherent Risk Identification and Assessment				Inherent Risk (Without Controls)					Leederville Aquifer - Inherent Risk Mitigation and Assessment		Post Mitigation Risk		
Ref	**Hazard/Compound or Barrier Failure/Hazardous Event**	**End Point**	**Description (Failure or process upset)**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**Risk Level**	**Ref**	**Risk**	**Mitigations (Tasks and Actions)**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**Risk Level**
Risks from Drilling and Bore Construction															
L1	**Screens corrosion**	Bore Infrastructure	Low ionic strength recycled water causes low pH when mixed with native groundwater, potentially causing damage to recharge bore infrastructure	Minor - [Service Interruption] Bore infrastructure failure caused by corrosion	Likely - expected minimal buffering capacity of recycled water, corrosion will occur if inadequate materials are used for construction	2	B	**High**	L1	Low ionic strength recycled water causes low pH when mixed with native groundwater, potentially causing damage to recharge bore infrastructure	Appropriate construction materials used in bore construction (FRP casing, SS screens) pH adjustment (NaOH dosing) assists in ongoing mitigation of risk *Monitoring*: Inspect with Camera log when recharge bore infrastructure removed	Optimal	2	D	**Low**
L2	**Risk of deteriorating recharge bore integrity**	Operator and Visitor safety	Infrastructure damage caused by recharge pressure. Damage to pipes and bores releases water under pressure at surface injuring a by-stander	Minor - [people and public] Upward leakage caused by inadequately sealed bore casing Injured by-stander	Rare	2	E	**Low**	L2	Infrastructure damage caused by recharge pressure. Damage to pipes and bores releases water under pressure at surface injuring a by-stander	Adequate drilling techniques were used during construction Design criteria and WI in place to ensure appropriate materials/fittings used in future maintenance *Monitoring:* Pressure monitoring in recharge bore	Optimal	2	E	**Low**

Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
		Leederville Aquifer - GWR Inherent Risk Identification and Assessment				Inherent Risk (Without Controls)					Leederville Aquifer - Inherent Risk Mitigation and Assessment		Post Mitigation Risk		
Bore Clogging and Reduced Aquifer Permeability															
L3	**Clogging of recharge bore** caused by solids in recycled water	Bore Infrastructure	Clogging of bore-aquifer interface due to solids introduction post-RO	Minor - [Service Interruption] Physical clogging of recharge bore , resulting in reduced efficiency - potentially to the extent that recharge cannot occur.	Unlikely - with current level of treatment (i.e. no introduction of solids after RO)	2	D	Low	L3	Clogging of bore-aquifer interface due to solids introduction post-RO	Limited opportunity for solids introduction in treatment process post RO Strainer on NaOH dosing line WI regarding flushing/cleaning of pipe/fittings after maintenance *Monitoring:* Manual daily turbidity sampling of recycled water at headworks	Optimal	2	D	Low
L4	**Clogging of aquifer pore spaces** caused by mobilisation of fines/colloids	Aquifer	Mobilisation of particulates (such as Al release from kaolinite clay) due to recharging water with low ionic strength	Minor - [Service Interruption] Clogging/reduced permeability of aquifer	Unlikely - Successive depletion of colloids as source exhausted as recycled water flushes through. Expect peak of colloids around time of initial breakthrough, with subsequent decline. Confirmed by GWRT.	2	D	Low	L4	Mobilisation of particulates (such as Al release from kaolinite clay) due to recharging water with low ionic strength	Step flow recharge rates *Monitoring:* Water quality at 60mN Amend recycled water at AWRP Further investigation would be required to determine correct dosing requirements and design	Adequate	2	D	Low
L5	**Air entrainment in recycled water** caused by recycled water cascading into the recharge bore	Aquifer	Clogging of recharge bore due to entrained air (cascading water)	Minor - [Service Interruption] Reduced recharge bore efficiency	Possible - Not possible with current design, however it IS possible if there are changes to the design without consideration of this risk.	2	C	Moderate	L5	Clogging of recharge bore due to entrained air (cascading water)	Current design of the Leederville recharge bore headworks (positive recharge head and equipment installed below resting water level is provided by the current DHV) mitigates the risk. Any changes to this design requires review to ensure risk is sufficiently mitigated.	Optimal	2	D	Low
L6	**Microbiological clogging** caused by microbiological communities increasing their growth rate creating biofilm/biomat	Aquifer	Recycled water (nutrients or organic carbon) provides a food source for native microbiological communities, causing excessive growth, resulting in clogging.	Minor - [Service Interruption] Clogging of aquifer due to microbial population growth	Possible - No significant microbiological clogging observed during Trial, however microbiological monitoring has confirmed populations increase after recharge commenced Surface area for potential clogging increases as recycled water moves through aquifer, reducing likelihood of aquifer clogging	2	C	Moderate	L6	Recycled water (nutrients or organic carbon) provides a food source for native microbiological communities, causing excessive growth, resulting in clogging.	Maintain low concentrations of nutrients in recycled water to limit biomass growth. Disinfect DHV and equipment after maintenance prior to returning to service. Undertake bore remediation - camera log to view screens/sample/backwash/ airlift. *Monitoring:* pressure to determine clogging and trigger corrective action. Design recharge bore to allow backwash/airlift.	Adequate	2	D	Low

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Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Bore Clogging and Reduced Aquifer Permeability															
L7	**Geochemical clogging** caused by reaction between recycled water and groundwater and/or aquifer matrix	Aquifer	Reactions between recycled (recharged) water, groundwater or aquifer matrix, may result in precipitating of minerals. Have not seen this risk in the Leederville aquifer during the Trial	Minor - [Service Interruption] Reduced permeability of the aquifer.	Unlikely - Precipitation of chemicals in concentrations high enough to cause clogging is unlikely.	2	D	**Low**	L7	Reactions between recycled (recharged) water, groundwater or aquifer matrix, may result in precipitating of minerals. Have not seen this risk in the Leederville aquifer during the Trial	*Monitor*: pressure Corrective action may include constructing a new recharge bore on site	Optimal	2	D	**Low**
L8	**Clogging of bore/aquifer interface** caused by scaling	Bore Infrastructure	Clogging of bore-aquifer interface due to geochemical reactions with recycled water	Minor - [Service Interruption] Bio-geo chemical reaction causes 'scale' clogging May affect rate of recharge and require downtime during maintenance.	Unlikely - Not seen during two years recharge during GWRT.	2	D	**Low**	L8	Clogging of bore-aquifer interface due to geochemical reactions with recycled water	*If detected:* Determine cause and try to limit trigger in AWRP *and* Conduct regular bore maintenance *Monitor:* pressure, bore performance	Optimal	2	D	**Low**

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Ref	**Hazard/Compound or Barrier Failure/Hazardous Event**	**End Point**	**Description (Failure or process upset)**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**Risk Level**	**Ref**	**Risk**	**Mitigations (Tasks and Actions)**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**Risk Level**
Risks to Human and Environmental Health															
Mobilisation of Chemicals															
L9	**pH change**	Human Health	Geochemical reactions resulting from the addition of recycled water causes a change in pH outside health guidelines DoH GL - 6-8.5	Minor [Compliance] Non-compliance to health guidelines	Rare - Limited decrease further away from recharge bore due to slower reacting minerals increasing buffering capacity	2	E	**Low**	L9	Geochemical reactions resulting from the addition of recycled water causes a change in pH outside health guidelines DoH GL - 6-8.5	Corrective action is to buffer at AWRP if required Aquifer buffering predicted to keep pH at 6.2 Continue to monitor pH at the 20mN research monitoring bore until 2014. Research monitoring at 240mN site to confirm 60mN site representative of RMZ boundary	Optimal	2	E	**Low**
L10	**Metal mobilisation** Arsenic Barium Boron Cobalt Manganese	Human Health	Geochemical reactions resulting from the addition of recycled water causes mobilisation of metals Arsenic - DoH GL = 0.007mg/L - (ADWG 2011 - 0.01mg/L - may cause GWR guideline to increase to align) Barium - DoH GL= 0.7mg/L - (ADWG 2011 - 2mg/L - may cause GWR guideline to increase to align) Boron DoH GL - 4mg/L Cobalt - DoH GL - 0.001mg/L Manganese - DoH GL - 0.5mg/L	Minor [Compliance] Non-compliance to health guidelines	Unlikely - Groundwater max: As - 0.004mg/L, Ba 0.14mg/L (prior to recharge), B - 0.12mg/L, Co - 0.0006mg/L, Mn - 0.14mg/L Mobilisation studies max: As - <LOD, Ba - 0.13mg/L, B - 0.23 Natural buffering capacity of aquifer likely sufficient to reduce risk of mobilisation Modelling indicates Co to be release to a maximum of 0.0006mg/L, <GL	2	D	**Low**	L10	Geochemical reactions resulting from the addition of recycled water causes mobilisation of metals Arsenic - DoH GL = 0.007mg/L - (ADWG 2011 - 0.01mg/L - may cause GWR guideline to increase to align) Barium - DoH GL= 0.7mg/L - (ADWG 2011 - 2mg/L - may cause GWR guideline to increase to align) Boron DoH GL - 4mg/L Cobalt - DoH GL - 0.001mg/L Manganese - DoH GL - 0.5mg/L	*Monitor:* pH/ORP/HCO3 (possible trigger values) at 60mN for compliance at Recharge Management Zone (RMZ) Initiate corrective action if monitoring indicates a metal is approaching set level (lower than GLV) and moving to further monitoring bores Corrective action may include AWRP buffering GWTP designed for manganese removal Continue to monitor pH at the 20mN research monitoring bore until 2014. Research monitoring at 240mN site to confirm 60mN site representative of RMZ boundary	Adequate	2	E	**Low**

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Ref	**Hazard/Compound or Barrier Failure/Hazardous Event**	**End Point**	**Description (Failure or process upset)**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**Risk Level**	**Ref**	**Risk**	**Mitigations (Tasks and Actions)**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**Risk Level**
Risks to Human and Environmental Health															
L11	**Mobilisation of chemicals** Fluoride	Human Health	Mobilisation of fluoride (release from crandallite) due to recharging water with low ionic strength DoH guideline = 1.5mg/L	Minor [Compliance] Non-compliance to health guidelines	Possible - Transient increases following breakthrough of the recycled water	2	C	**Moderate**	L11	Mobilisation of fluoride (release from crandallite) due to recharging water with low ionic strength DoH guideline = 1.5mg/L	Transient increases in fluoride on breakthrough, at different times in different layers. Aquifer concentration (weighted average) will be less than a discrete layer concentration. Discrete layer concentrations will successively decrease after an initial peak with time after breakthrough. Step flow recharge rates Further investigation - refine reactive model for fluoride - predictive run Natural levels of fluoride in some production bores can exceed guideline concentrations Fluoridation of DW occurs in WA (pop >3000, range of 0.7-1.0mg/L with target of 0.9mg/L) Discuss with DoH if required *Monitor:* At 60mN for compliance at Recharge Management Zone (RMZ) Continue to monitor pH at the 20mN research monitoring bore until 2014. Research monitoring at 240mN site to confirm 60mN site representative of RMZ boundary	Adequate	2	D	**Low**
L12	**Mobilisation of Metals** Total Iron	Human Health	Geochemical reactions resulting from the addition of recycled water causes mobilisation of total iron DoH GL= 0.3mg/L	Minor [Compliance] Non-compliance to health guidelines	Rare - Baseline concentrations greater than maximum mobilised concentration	1	E	**Low**	L12	Geochemical reactions resulting from the addition of recycled water causes mobilisation of total iron DoH GL= 0.3mg/L	Naturally occurring in native GW at higher than guideline concentrations GWTP designed for iron removal	Optimal	1	E	**Low**

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Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Risks to Human and Environmental Health															
L13	**Mobilisation of chemicals** Total Phosphorus	Environmental Health	Mobilisation of phosphorus (release from crandallite) due to recharging water with low ionic strength (as indicated by Total P) Environmental target - 2.1mg/L Environmental limit - 2.3mg/L	Minor [Compliance] Non-compliance to environment guidelines	Possible - Transient increases following breakthrough of the recycled water	2	C	Moderate	L13	Mobilisation of phosphorus (release from crandallite) due to recharging water with low ionic strength (as indicated by Total P) Environmental target - 2.1mg/L Environmental limit - 2.3mg/L	Transient increases of phosphorus on breakthrough, at different times in different layers. Aquifer concentration (weighted average) will be less than a discrete layer concentration. discrete layer concentrations will successively decrease after an initial peak with time after breakthrough. Step flow recharge rates Further investigation - Refine of reactive model for TP - predictive run *Monitor:* At 60mN for compliance at Recharge Management Zone (RMZ) Continue to monitor pH at the 20mN research monitoring bore until 2014. Research monitoring at 240mN site to confirm 60mN site representative of RMZ boundary	Adequate	2	D	**Low**

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Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Risks to Human and Environmental Health															
L14	**Metal mobilisation** Strontium	Human Health	Geochemical reactions resulting from the addition of recycled water causes mobilisation of strontium increasing radioactivity DoH GL= 4mg/L	Minor [Compliance] Non-compliance to health guidelines	Unlikely Groundwater max= 0.27 mg/L Sr-90 would be a small contribution to radiation should it occur	2	D	**Low**	L14	Geochemical reactions resulting from the addition of recycled water causes mobilisation of strontium increasing radioactivity DoH GL= 4mg/L	*Monitor:* pH/ORP/HCO3 (possible trigger values) At 60mN for compliance at Recharge Management Zone (RMZ) Initiate corrective action if monitoring indicates strontium is approaching set level (lower than GLV) and moving to further monitoring bores Corrective action may include AWRP buffering Continue to monitor pH at the 20mN research monitoring bore until 2014. Research monitoring at 240mN site to confirm 60mN site representative of RMZ boundary	Adequate	2	E	**Low**
Recycled Water Quality															
L15	**Recycled water quality** Organics/chemicals in recycled water recharged	Human Health	Low levels of NDMA (max detected 1.5ng/L) GL = 10ng/L to be changed to 100ng/L Low levels of metals (Boron average 0.09mg/L, GL = 4mg/L	Minor [Compliance] Non-compliance to health guidelines	Unlikely - GWRT demonstrated that recycled water is well below guideline limits	2	D	**Low**	L15	Low levels of NDMA (max detected 1.5ng/L) GL = 10ng/L to be changed to 100ng/L Low levels of metals (Boron average 0.09mg/L, GL = 4mg/L	Current AWRP is adequate to reduce levels to below guideline Column studies indicate degradation of NDMA (20-200 days) (Patterson, B.M., et al., 2012)	Adequate	2	E	**Low**

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Ref	**Hazard/Compound or Barrier Failure/Hazardous Event**	**End Point**	**Description (Failure or process upset)**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**Risk Level**	**Ref**	**Risk**	**Mitigations (Tasks and Actions)**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**Risk Level**
Risks of Poor Aquifer Response															
L16	**Hydrogeological barriers**	Aquifer	Hydrogeological barriers (e.g. Kings Park Formation)	Minor - [Service Interruption] Reduced recharge capacity Increased head build-up	Rare - Considers Likelihood of service interruption	2	E	**Low**	L16	Hydrogeological barriers (e.g. Kings Park Formation)	Monitor pressure in recharge and 60mN monitoring bore	Adequate	2	E	**Low**
L17	**Integrity of the confining layer**	Aquifer	Confining layer damage due to over pressurising in the Leederville aquifer	Minor - [Service Interruption] Upward leakage of recycled water	Rare - Pressure applied is too low and thickness of confining layer is too great for this to occur Hydraulic calculation for maximum pressure confining layer can tolerate, as per MAR guidelines (1.5 x depth to base of aquitard) = 180m above ground level	2	E	**Low**	L17	Confining layer damage due to over pressurising in the Leederville aquifer	Recharge at 14GL/yr would result in head increase to 21m above ground level, well below the MAR guidelines of 180m above ground level	Optimal	2	E	**Low**
L18	**Risk of leakage to the overlying aquifer**	Aquifer	Vertical movement of recycled water through the confining layer into the Superficial aquifer	Minor - [Compliance] Upward leakage of recycled water recharged the identification of the current EVs did assumed that there was no upward flow to the superficial aquifer.	Rare - Vertical flow model >250yrs to travel through confining layer @ 14GL/yr PRAMS3.4 PMPATH indicates no upward movement of recycled water	2	E	**Low**	L18	Vertical movement of recycled water through the confining layer into the Superficial aquifer	Not required	Optimal	2	E	**Low**
L19	**Aquifer dissolution** due to pH (high or low)	Human Health	Recycled water causes a change in pH when mixed with native groundwater, causing dissolution of the aquifer	Increased permeability caused by dissolution of the aquifer - thus faster travel time to abstraction bore. Expected time to abstraction bore is >30yrs, so even if reduced will still be years to abstraction WQ will meet health guidelines at boundary of RMZ	Rare - Aquifer characterisation indicates low carbonates therefore unlikely to occur pH is unlikely to increase to levels that may cause silica dissolution	1	E	**Low**	L19	Recycled water causes a change in pH when mixed with native groundwater, causing dissolution of the aquifer	*Monitor:* pressure flow water quality indicators for dissolution	Optimal	1	E	**Low**
L20	**Aquifer dissolution** due to pH (high or low)	Aquifer	Recycled water causes a change in pH when mixed with native groundwater, causing dissolution of the aquifer	Increased permeability caused by dissolution of the aquifer, consequence in highly sandy aquifer insignificant	Rare - Aquifer characterisation indicates low carbonates therefore unlikely to occur pH is unlikely to increase to levels that may cause silica dissolution	1	E	**Low**	L20	Recycled water causes a change in pH when mixed with native groundwater, causing dissolution of the aquifer	*Monitor:* pressure flow water quality indicators for dissolution Check filter pack on recharge bore and replace if required	Optimal	1	E	**Low**

		Yarragadee Aquifer - GWR Inherent Risk Identification and Assessment				Inherent Risk (Without Controls)				Yarragadee Aquifer - Inherent Risk Mitigation and Assessment			Post Mitigation Risk		
Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Risks from Drilling and Bore Construction															
Y1	**Bore failure** caused by geological conditions	Bore Infrastructure	Cavernous limestone causing loss of drilling fluids.	Increased construction times and costs.	Almost Certain	1	A	**Moderate**	Y1	Cavernous limestone causing loss of drilling fluids.	Current practices mitigate this risk, i.e.: (1) Using proven drilling techniques. (2) Drilling pre-collar holes using dual rotary technique.	Optimal	1	E	**Low**
Y2	**Bore failure** caused by geological conditions	Bore Infrastructure	Swelling of clays resulting in loss of drilling equipment.	Increased construction times and costs.	Possible	2	C	**Moderate**	Y2	Swelling of clays resulting in loss of drilling equipment.	Current practices mitigate this risk, i.e.: (1) Utilise appropriate drilling contractor and drilling mud.	Optimal	2	D	**Low**
Y3	**Bore failure** caused by geological conditions	Bore Infrastructure	Encountering hark rock resulting in slow penetration of water through the aquifer	Increased construction times and costs.	Possible	1	C	**Low**	Y3	Encountering hark rock resulting in slow penetration of water through the aquifer	Current practices mitigate this risk, i.e.: (1) Utilise appropriate drilling contractor and equipment, (2) Regularly change drill bit.	Adequate	1	C	**Low**
Y4	**Bore failure** caused by bore construction technique	Bore Infrastructure	Loss or collapse of casing string.	Increased construction times and costs. Required to redesign and drill new a bore.	Possible	2	C	**Moderate**	Y4	Loss or collapse of casing string.	Current practices mitigate this risk, i.e.: (1) Utilise appropriate drilling contractor and equipment and process control.	Adequate	2	D	**Low**
Y5	**Bore failure** caused by bore construction technique	Bore Infrastructure	Failure of packer during cement grouting of casing resulting in cement setting in screens.	Increased construction times and costs. Change in bore design.	Possible	2	C	**Moderate**	Y5	Failure of packer during cement grouting of casing resulting in cement setting in screens.	Current practices mitigate this risk, i.e.: (1) Utilise adequate bore design and drilling techniques. (2) Telescopic bore construction.	Optimal	2	E	**Low**

		Yarragadee Aquifer - GWR Inherent Risk Identification and Assessment				Inherent Risk (Without Controls)					Yarragadee Aquifer - Inherent Risk Mitigation and Assessment		Post Mitigation Risk		
Ref	**Hazard/Compound or Barrier Failure/Hazardous Event**	**End Point**	**Description (Failure or process upset)**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**Risk Level**	**Ref**	**Risk**	**Mitigations (Tasks and Actions)**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**Risk Level**
Risks from Drilling and Bore Construction															
Y6	**Bore failure** caused by bore construction technique	Bore Infrastructure	Bore screens are not set in selected geological unit.	Water quality results do not reflect geological units as expected.	Unlikely	1	D	**Low**	Y6	Bore screens are not set in selected geological unit.	Current practices mitigate this risk, i.e.: (1) Utilise adequate drilling techniques (2) Use longer screens (3) Geophysical logging In addition, thicker sandstone beds are present in Yarragadee aquifer which will make it easier to set screens in required geological unit.	Adequate	1	D	**Low**
Y7	**Recharge of non-target layers** caused by poor sealing of bore annulus	Aquifer - layer recharged	Poor sealing allows unintended transfer of the recharged water into other layers of the aquifer	Bore no longer reliable, potentially resulting in: * inefficient recharge. * upward leakage into overlying aquifer. * flow into Superficial aquifer.	Unlikely	2	D	**Low**	Y7	Poor sealing allows unintended transfer of the recharged water into other layers of the aquifer	Current practices mitigate this risk, i.e.: (1) Utilise adequate bore design and drilling techniques (2) Geophysical logging	Adequate	2	D	**Low**
Y8	**Ingress of non-target groundwater into bore samples** caused by poor sealing of bore annulus	Aquifer - layer sampled	Poor sealing allows ingress of groundwater from overlying and underlying strata resulting in incorrect sampling.	Bore no longer reliable and could result in sampling layers other than that intended, therefore water quality results do not reflect geological units as expected.	Unlikely	1	D	**Low**	Y8	Poor sealing allows ingress of groundwater from overlying and underlying strata resulting in incorrect sampling.	Current practices mitigate this risk, i.e.: (1) Utilise adequate bore design and drilling techniques (2) Geophysical logging	Adequate	1	D	**Low**
Y9	**Screens corrosion - due to low pH**	Bore Infrastructure	Low ionic strength recycled water causes low pH when mixed with native groundwater, potentially causing damage to recharge bore infrastructure	Minor - [Service Interruption] Bore infrastructure failure caused by corrosion	Likely - expected minimal buffering capacity of recycled water, corrosion will occur if inadequate materials are used for construction	2	B	**High**	Y9	Low ionic strength recycled water causes low pH when mixed with native groundwater, potentially causing damage to recharge bore infrastructure	Use appropriate construction materials in bore construction (FRP casing, SS screens) pH adjustment (NaOH dosing) will assist in ongoing mitigation of risk *Monitoring*: Inspect with Camera log when recharge bore infrastructure removed	Optimal	2	D	**Low**

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Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Risks from Drilling and Bore Construction															
Y10	**Risk of deteriorating recharge bore integrity**	Operator and Visitor safety	Infrastructure damage caused by recharge pressure. Damage to pipes and bores releases water under pressure at surface injuring a by-stander	Minor - [people and public] Upward leakage caused by inadequately sealed bore casing Injured by-stander	Rare -	2	E	**Low**	Y10	Infrastructure damage caused by recharge pressure. Damage to pipes and bores releases water under pressure at surface injuring a by-stander	Use appropriate drilling techniques Design criteria and WI in place to ensure appropriate materials/fittings used Design limit for headworks is 150m head above ground level *Monitoring*: Pressure monitoring and control of recharge	Optimal	2	E	**Low**

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Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Bore Clogging and Reduced Aquifer Permeability															
Y11	**Clogging of Recharge bore - Aquifer interface** caused by solids in recycled (recharged) water	Bore Infrastructure	Clogging of bore-aquifer interface due to solids introduction post-RO	Minor - [Service Interruption] Physical clogging of recharge bore , resulting in reduced efficiency - potentially to the extent that recharge cannot occur.	Unlikely with current level of treatment (i.e. no introduction of solids after RO)	2	D	**Low**	Y11	Clogging of bore-aquifer interface due to solids introduction post-RO	Current AWRP design and operational procedures mitigate this risk, including: Current AWRP design mitigates this potential hazard as there are limited opportunities for solids to be introduced or made in treatment process. Design and operational mitigations include: * Strainers installed on the NaOH dosing line * Weekly turbidity sampling of recycled water * Work instructions describing cleaning and flushing of pipes and fittings after maintenance * Ability to flush headworks If alkalinity buffering is considered necessary in the future, to mitigate other risks, then the risk of physical clogging will need to be reviewed.	Optimal	1	D	**Low**

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Ref	**Hazard/Compound or Barrier Failure/Hazardous Event**	**End Point**	**Description (Failure or process upset)**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**Risk Level**	**Ref**	**Risk**	**Mitigations (Tasks and Actions)**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**Risk Level**
Bore Clogging and Reduced Aquifer Permeability															
Y12	**Clogging of aquifer pore spaces** caused by mobilisation of fines	Aquifer	Components of the aquifer material such as kaolinite have potential to breakdown releasing fine particles which may clog aquifer pore spaces.	Minor - [service interruption] Reduced permeability of the aquifer.	Possible - fines present, almost certain that fines will be mobilised, but it is only possible that they will clog the aquifer Preliminary dispersion tests - at low flow small particles are mobilised at an almost continuous rate - at higher rates mobilised as a pulse	2	C	**Moderate**	Y12	Components of the aquifer material such as kaolinite have potential to breakdown releasing fine particles which may clog aquifer pore spaces.	Ongoing investigation based on Yarragadee aquifer material is required to adequately assess risk, and may include trialling recharge in Yarragadee aquifer. If the risk is realised, possible mitigations may include: Design of recharge bore (appropriate screens lengths/diameters) Step flow recharge rates Operational bore development Amend recycled (recharged) water at AWRP. Further investigation would be required to determine correct dosing requirements and design. If alkalinity buffering is required to mitigate this risk, then the physical clogging risk will need to be reviewed.	Optimal	2	D	**Low**
Y13	**Air-entrainment in recycled water** caused by recycled (recharged) water cascading into recharge bore	Aquifer	Clogging of recharge bore due to entrained air (cascading water)	Minor - [Service Interruption] Reduced recharge bore efficiency	Possible - Current design of GWRT recharge bore infrastructure (positive recharge head and installed below resting water level) mitigates this potential hazard.	2	C	**Moderate**	Y13	Clogging of recharge bore due to entrained air (cascading water)	Current design of GWRT Leederville recharge bore headworks (positive recharge head installed below resting water level) to be considered in large scale AWRP and recharge bore	Optimal	2	D	**Low**
Y14	**Release of dissolved gases**	Aquifer	Higher temperature conditions within the Yarragadee aquifer may potentially result in the release of dissolved gases from the recharge water, subsequently causing clogging in the aquifer as pore spaces become blocked by air bubbles.	Reduced permeability of the aquifer, reduced recharge efficiency	Rare - Due to higher pressure in Yarragadee aquifer. Higher temperatures may allow release of gases, however high pressure should compensate for this.	2	E	**Low**	Y14	Higher temperature conditions within the Yarragadee aquifer may potentially result in the release of dissolved gases from the recharge water, subsequently causing clogging in the aquifer as pore spaces become blocked by air bubbles.	Confirmed via PHREEQC modelling. No further assessment required.	n/a	2	E	**Low**

		Yarragadee Aquifer - GWR Inherent Risk Identification and Assessment				Inherent Risk (Without Controls)					Yarragadee Aquifer - Inherent Risk Mitigation and Assessment		Post Mitigation Risk		
Ref	**Hazard/Compound or Barrier Failure/Hazardous Event**	**End Point**	**Description (Failure or process upset)**	**Consequence**	**Likelihood**	**Consequence**	**Likelihood**	**Risk Level**	**Ref**	**Risk**	**Mitigations (Tasks and Actions)**	**Control Effectiveness Rating**	**Consequence**	**Likelihood**	**Risk Level**
Bore Clogging and Reduced Aquifer Permeability															
Y15	**Microbiological clogging** caused by indigenous microbiological communities to increasing their growth rate creating biofilm/biomat.	Aquifer	Recycled water (NO3 or organic carbon) provides a food source for native microbiological communities, causing excessive growth, resulting in clogging.	Minor - [Service Interruption] Clogging of aquifer due to microbial population growth	Unlikely - Different but diverse population of bacteria. No significant microbiological clogging observed to date during the GWRT Lower levels of iron in Yarragadee than Leederville Surface area for potential clogging increases as recycled water moves through aquifer, reducing likelihood of aquifer clogging	2	D	**Low**	Y15	Recycled water (NO3 or organic carbon) provides a food source for native microbiological communities, causing excessive growth, resulting in clogging.	Maintain low concentrations of nutrients in recycled water to limit biomass growth. Disinfect DHV and equipment after maintenance prior to returning to service. Undertake bore remediation - backwash/ airlift. *Monitoring:* pressure to determine clogging and trigger corrective action. Design recharge bore to allow backwash/airlift.		2	D	**Low**
Y16	**Geochemical Clogging** caused by reactions between recycled water and groundwater or aquifer matrix	Aquifer	Reactions between recycled (recharged) water, groundwater or aquifer matrix, may result in precipitating of minerals. Have not seen this risk in the Leederville aquifer after 2 years of recharge.	Minor - [Service Interruption] Reduced permeability of the aquifer.	Unlikely - GWRT demonstrated that precipitation of chemicals in Leederville concentrations in high enough to cause clogging is unlikely. Differing water quality and mineralogy in Yarragadee to Leederville, with Yarragadee generally better quality (e.g. lower concentrations of iron) and less reactive	2	D	**Low**	Y16	Reactions between recycled (recharged) water, groundwater or aquifer matrix, may result in precipitating of minerals. Have not seen this risk in the Leederville aquifer after 2 years of recharge.	*Monitor*: pressure Corrective action may include constructing a new recharge bore on site	Optimal	2	D	**Low**

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Bore Clogging and Reduced Aquifer Permeability															
Y17	**Clogging of Bore-Aquifer interface** caused by scaling	Bore Infrastructure	Clogging of bore-aquifer interface due to geochemical reactions with recycled water	Minor - [Service Interruption] Bio-geo chemical reaction causes 'scale' clogging May affect rate of recharge and require downtime during maintenance.	Unlikely - Not seen during two years recharge during GWRT.	2	D	**Low**	Y17	Clogging of bore-aquifer interface due to geochemical reactions with recycled water	Current design should be considered in design for Yarragadee recharge bore: * Allow for backwashing/airlifting. * Online monitoring of pressure and bore performance * If detected, determine cause and where possible limit source in AWRP * Conduct regular bore maintenance. Potential mitigations - reducing exit velocities (longer/larger diameter screens)	Optimal	1	E	**Low**

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Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Risks to Human and Environmental Health															
Mobilisation of Chemicals															
Y18	**pH change**	Human Health	Geochemical reactions resulting from the addition of recycled water causes a change in pH outside health guidelines DoH GL - 6-8.5	Minor [Compliance] Non-compliance to health guidelines	Possible unsure of the buffering capacity of the Yarragadee. Also depends on the rates and the reactivity.	2	C	Moderate	Y18	Geochemical reactions resulting from the addition of recycled water causes a change in pH outside health guidelines DoH GL - 6-8.5	Corrective action is to buffer at AWRP if required aquifer buffering predicted to keep pH at 6.2 Further investigation and interpretation using current data. Could also trial removing degassing at 1.5GL AWRP If this does not provide conclusive answers, recommendation that buffering should be considered	Optimal (with pH and alkalinity buffering)	2	D	**Low**
Y19	**Metal mobilisation**	Human Health	The aquifer material contains naturally occurring metals and minerals bound up in the geological units. Addition of recycled water may cause reactions which may result in mobilisation of these metals and mineral dissolution. (Co, Cd, Cu, Ni, Zn)	Non-compliance to health and environment guidelines	Possible - Yarragadee aquifer could potentially release Cd, Co, Cu, Ni, Zn. Acid digestion tests showed release of Co, Cu, Ni, Mn. Co present in screened intervals, which in the Leederville aquifer was more prone to mobilisation with decreasing pH. Mineralogy similar to the Leederville aquifer Predominantly silica with substantial kaolinite and feldspar minerals Trace pyrite, siderite and almandine garnet detected	2	C	Moderate	Y19	The aquifer material contains naturally occurring metals and minerals bound up in the geological units. Addition of recycled water may cause reactions which may result in mobilisation of these metals and mineral dissolution. (Co, Cd, Cu, Ni, Zn)	Further investigation - interpretation from mineralogy experiments Design - AWRP buffering Trial recharge to Yarragadee from 1.5GL AWRP *Monitor:* at 60mS Sample recharge bore, which will represent worse case scenario (i.e. most oxygen and nitrogen depleted conditions)	Optimal (with pH and alkalinity buffering)	2	D	**Low**

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Risks to Human and Environmental Health															
Recycled Water Quality															
Y20	**Recycled water quality** Organics/chemicals in recycled water recharged	Human Health	Low levels of NDMA (max detected 1.5ng/L) GL = 10ng/L to be changed to 100ng/L Low levels of metals (Boron average 0.09mg/L, GL = 4mg/L	Minor [Compliance] Non-compliance to health guidelines	Unlikely - GWRT demonstrated that recycled water is well below guideline limits	2	D	**Low**	Y20	Low levels of NDMA (max detected 1.5ng/L) GL = 10ng/L to be changed to 100ng/L Low levels of metals (Boron average 0.09mg/L, GL = 4mg/L	Current design should be considered in design for a large GWR Advanced Water Recycling Plant. However if the Yarragadee aquifer is required to degrade organics, the aquifer biodegradation processes require further investigation as column studies indicate degradation of NDMA (20-200 days) (Patterson, B.M., et al., 2012)	Optimal	2	E	**Low**

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Risks of Poor Aquifer Response															
Y21	**Possible hydrogeological barrier preventing or reducing efficiency of recharge**	Bore Infrastructure	Possible hydrogeological barrier (fault, aquifer cementing, dipping beds)	Minor - [service interruption] * Reduced recharge capacity * Increased head build-up * Drilling into cemented material resulting in no recharge * Bore needs to be abandoned and new bore drilled	Unlikely - Almost certain within Yarragadee - low at Beenyup site	2	D	**Low**	Y21	Possible hydrogeological barrier (fault, aquifer cementing, dipping beds)	Confirm assessment with pumping test Regional seismic surveys planned with researchers	Optimal	2	D	**Low**
Y22	**Integrity of the confining layer**	Aquifer	Local confining layer (South Perth Shale) damage due to over pressuring Yarragadee aquifer	Minor - [Service Interruption] Upward leakage of recycled water	Rare - Pressure applied is too low and thickness of confining layer (115m thick at ~320mbgl) is too great for this to occur Using MAR guidelines (1.5x depth of overburden to base of aquitard) maximum recharge head is 480m above the surface	2	E	**Low**	Y22	Local confining layer (South Perth Shale) damage due to over pressuring Yarragadee aquifer	Thickness of confining layer Recharge at 14GL/yr would result in head increase to 56m above ground level, well below the MAR guidelines of 480m above ground level	Optimal	2	E	**Low**
Y23	**Risk of leakage to the overlying aquifer**	Aquifer	Vertical movement of recycled water through the South Perth Shale into the Leederville, through the confining layer into the Superficial aquifer	Upward leakage of recycled water recharged	Rare Vertical flow model >1000yrs to travel through SPS layer @ 14GL/yr. PRAMS3.4 PMPATH indicates no upward movement of recycled water into the Leederville	2	E	**Low**	Y23	Vertical movement of recycled water through the South Perth Shale into the Leederville, through the confining layer into the Superficial aquifer	n/a - Remove from future assessments	n/a	2	E	**Low**

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Ref	Hazard/Compound or Barrier Failure/Hazardous Event	End Point	Description (Failure or process upset)	Consequence	Likelihood	Consequence	Likelihood	Risk Level	Ref	Risk	Mitigations (Tasks and Actions)	Control Effectiveness Rating	Consequence	Likelihood	Risk Level
Risks of Poor Aquifer Response															
Y24	**Risks of aquifer dissolution**	Aquifer	Change in pH causing dissolution of the aquifer	Increased permeability caused by dissolution of the aquifer, consequence in highly sandy aquifer insignificant	Rare - Aquifer characterisation indicates low carbonates therefore unlikely to occur pH is unlikely to increase to levels that may cause silica dissolution	1	E	**Low**	Y24	Change in pH causing dissolution of the aquifer	Monitor pressure and water quality	Optimal	1	E	**Low**

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Risks of impact to local geothermal bores															
Y25	**Impact to Craigie Geothermal Bore** caused by decrease in groundwater temperature	People	Note: this has been assessed as a social and reputational risk. Decrease in temperature extending through aquifer, impacting abstraction temperature at Craigie Leisure Centre geothermal bore. Local scale heat transport modelling at 14GL/yr. Results indicate a 2℃ decrease after 40yrs and a 6℃ decrease after 70yrs	Reputation and Financial	Unlikely - * 1km between recharge bore and geothermal bore * Geothermal bore abstraction zone (700 - 800m), Geothermal recharge zone (360 - 450m) * GWR recharge zone (389.5-442.7, 460.5-487.1, 605.0-676.0, 690.6-743.8)	2	D	**Low**	Y25	Note: this has been assessed as a social and reputational risk. Decrease in temperature extending through aquifer, impacting abstraction temperature at Craigie Leisure Centre geothermal bore. Local scale heat transport modelling at 14GL/yr. Results indicate a 2℃ decrease after 40yrs and a 6℃ decrease after 70yrs	Utilise longer recharge bore screens to distribute recycled water (~25C) over larger surface area Discussions with Craigie Leisure Centre	Optimal	1	E	**Low**
Y26	**Impact to Craigie Geothermal Bore** Increase in pressure impacting Craigie Leisure Centre geothermal bore recharge zone	People	Note: this has been assessed as a social and reputational risk. Increase in pressure in Yarragadee aquifer due to WC recharge impacting Craigie geothermal bore recharge	Reputation and Financial	Likely - ~20m head change at Craigie geothermal bore when recharge rates = 20ML/d Likely to recharge at similar depths to Craigie geothermal bore recharge zone (360 - 450m)	2	B	**High**	Y26	Note: this has been assessed as a social and reputational risk. Increase in pressure in Yarragadee aquifer due to WC recharge impacting Craigie geothermal bore recharge	Some investigation required to confirm, may lead to discussion with Craigie Leisure Centre. Undertake modelling to understand pressure increases likely at Craigie geothermal bore based on 20ML/d recharge	Optimal	2	E	**Low**