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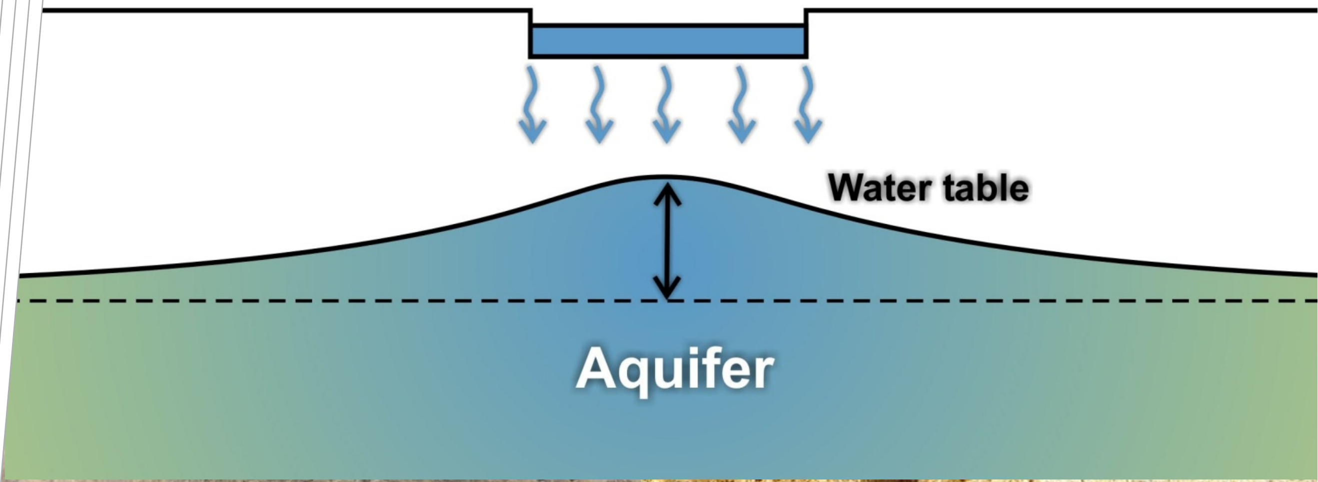

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Final Summary Report – Hydrological Controls on MAR in Perth's Coastal Aquifer (PWF Agreement Number 010 05)

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May 2012

Water Foundation, Western Australia

Water for a Healthy Country Flagship Report series ISSN: 1835-095X

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For more information about Water for a Healthy Country Flagship or the National Research Flagship Initiative visit www.csiro.au/org/HealthyCountry.html

Citation: Smith, A. J., Massuel, S., Pollock, D. W., Fitzpatrick, A., Byrne, J., Johnstone, C., Smart, N. and K. Cahill. 2012. Final Summary Report – Hydrological Controls on MAR in Perth's Coastal Aquifer (PWF Agreement Number 010 05). CSIRO: Water for a Healthy Country National Research Flagship. 19 pp.

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Cover Image:

© 2012 CSIRO
Description: Recharge basin schematic and images of Tamala Limestone.

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ACKNOWLEDGEMENTS

This work was funded by CSIRO, the Western Australian Water Foundation and in-kind contributions from the Western Australian Department of Water (DoW), Cockburn Sound Management Council (CSMC), Town of Cottesloe (ToC), Peel-Harvey Catchment Council (PHCC), Western Australian Water Corporation (WC), Perth Region NRM (PRNRM) and City of Melville (CoM).

Oversight and feedback on work in progress was provided by members of the project Reference Group: Chris O'Boy (DoW), Dr Tom Rose (CSMC), Geoff Trigg (ToC), Damien Postma (PHCC), Dr Bruce Hamilton (PRNRM).

Jeff Major, Karen Barlow, Carolyn Hills and Brigitte Hagen from DoW provided assistance with contract management and project coordination on behalf of the Western Australian Water Foundation.

Special thanks are extended to Mr Bill Bowker (Property Manager, Fremantle Prison) for arranging permission to access the prison tunnels on behalf of Fremantle Prison, and we thank the tunnel tour guides and other staff at Fremantle Prison for their valuable assistance.

Site access and drilling permissions were supported by the Western Australian Department of Environment and Conservation for the field site at White Hill Road, Bouvard; the Western Australian Land Authority (LandCorp) for the field site within the East Rockingham Industrial Park, East Rockingham; City of Fremantle for the field site at Fremantle Park, Fremantle; and Town of Cambridge for the field site at Perry Lakes, Floreat.

The main report (Smith et al. 2012) was reviewed by Peter Dillon, Dirk Mallants and Don McFarlane of CSIRO Land and Water. This summary report was reviewed by Peter Dillon and Chris O'Boy of the WA Department of Water.

CSIRO thanks Lloyd Townley, Director of NTEC Environmental Technology (NTEC), for facilitating the timely completion of the write up of this report under a subcontract from CSIRO to NTEC following the change of employment of Tony Smith from CSIRO to NTEC on 2 September 2011.

1. INTRODUCTION

1.1. This Report

This report forms Deliverable #10 (Appendix A) of PWF Grant Agreement Number 010 05 entitled *Hydrological Controls on MAR in Perth's Coastal Aquifer*. The report is intended as a brief summary of the project, its aims and methodologies, and the key findings. More detailed information and extended discussion of the project methodologies, results and conclusions is contained in the project publications listed in Table 1.

Section 1 of this report contains a brief outline of the project context and objectives. Section 2 reviews the project achievements against each of the Technical Objectives and Reportable Outcomes established in the project agreement (Appendix B and C). The third and final section contains a brief summary of the key findings from the project, which are compiled mainly from Reports 1 and 2 (Deliverables #4 and #8).

Table 1. Project reporting

Type	Title	Reference / Date
Report 1 (Deliverable #4)	Artificial Recharge Potential of the Perth Region Superficial Aquifer: Lake Preston to Moore River	CSIRO [1]WfHC report (Smith and Pollock 2010)
Report 2 (Deliverable #8)	Geohydrology of the Tamala Limestone Formation in the Perth Region: Origin and role of secondary porosity	CSIRO WfHC report (Smith et al. 2011)
Final Report (Deliverable #10)	Final Report – PWFG Agreement Number 010 05 Hydrological Controls on MAR in Perth's Coastal Aquifer	CSIRO WfHC report (this report)
Journal paper	Assessment of Managed Aquifer Recharge Potential Using Ensembles of Local Models	*Ground Water* journal (Smith and Pollock 2011)
Journal paper	Tidal propagation in dual-porosity aquifers	In preparation
Public seminar for Report 1 (Deliverable #11)	Potential for MAR in Perth's Superficial Aquifer	[2]CELS Seminar Series (August 2011)
Public seminar for Report 2 (Deliverable #11)	Is the Tamala Limestone Aquifer Safe for Managed Aquifer Recharge?	CELS Seminar Series (March 2012)
Conference presentation	Carbonate Eolianites of the Perth Coastal Aquifer: Early Investigations and Hydraulic Characterisation	GW2010 Conference Canberra (October 2010)

[2] Water for a Healthy Country (WfHC) National Research Flagship
[1] Centre for Environment and Life Sciences (CELS) Floreat, Perth

1.2. Project overview

Increasing urbanization, rapid population growth and an estimated ten to fifteen percent decrease of post-1975 annual rainfall (CSIRO 2009) has placed considerable stress on traditional water resources in the Perth region. The impacts of less rainfall and increasing water demand have been evident as declining stores of surface water and groundwater for the past several decades. In 2005 groundwater levels were falling under about forty percent of Perth and watertable trends beneath approximately forty-five percent were unknown due to insufficient monitoring information (Smith et al. 2005).

Water planning is now proceeding on the basis that reduced water yields from traditional sources are permanent. New strategies for meeting future demand include development of groundwater supplies from untapped sources, seawater desalinisation, reducing per capita consumption and improved water-use efficiency and water recycling, including Managed Aquifer Recharge (MAR). The Perth region is critically reliant on groundwater for both drinking water and non-potable uses. Groundwater supplies around sixty percent of drinking water in the metropolitan area (WC 2009) and about eighty-five percent of the total water demand for all uses (Smith and Pollock 2010). Artificially enhancing groundwater storage in aquifers through MAR schemes has been identified as both a practical and necessary strategy for achieving water recycling goals.

The main sources of water for MAR in Perth include treated wastewater, stormwater and groundwater drainage, which are collected in useful quantities mostly within the coastal strip. The Government of Western Australia (DoW 2009) has stated that it encourages proposals for suitable MAR activities but cautions that MAR will not be feasible at all sites due to hydrogeological, environmental and cost limitations. A risk management approach has been adopted, with the objective to maximise community benefit and minimise community cost.

While it is acknowledged that community perception and acceptance of wastewater reuse is a critical issue in planning and implementing successful MAR, there also needs to be an accompanying evaluation of the hydrogeological suitability of aquifers for MAR. This study explores the physical characteristics of Perth’s superficial aquifer that control the hydraulic potential for MAR and the associated benefits and risks. A particular focus is the coastal strip of the superficial aquifer where the major wastewater treatment plants are located over limestone areas with uncertain groundwater flow and transport characteristics. The principle aim is to progress current hydrogeological understanding of these areas to assist with improved assessments of the potential for MAR.

2. TECHNICAL OBJECTIVES AND REPORTABLE OUTCOMES

This section provides a review of project activities and achievements against the seven Technical Objectives (Appendix B) and four Reportable Outcomes (Appendix C) established in the original project agreement. Corresponding technical objectives and reportable outcomes are grouped together where appropriate.

Technical objective #1
Infill the State groundwater database with historical watertable information recovered from the Swan Catchment Council's Superficial Aquifer monitoring project.

No additional information was uncovered in the Swan Catchment Council (SCC) Superficial Aquifer monitoring report project (GHD 2008) or in the current study to infill the WIN (Water Information) database. Gap areas in the existing superficial aquifer monitoring network identified by Smith et al. (2005) were overlayed on Local Government Authority (LGA) boundaries to identify a list of relevant LGAs to contact. Subsequent enquiries revealed that the groundwater information held for these areas consists mainly of pumping records from irrigation bores and opportunistic static water levels collected infrequently when irrigation bores are installed, serviced or repaired. These types of data are not useful for the analysis of long-term trends in aquifer storage and therefore no further action was possible.

Technical Objective #2
Map the suitability of the Superficial Aquifer for MAR with respect to the potential benefits (e.g. water supply supplementation, watertable control, prevention of seawater intrusion) and the existing hydrological controls on MAR (e.g. karst features preventing water table mounding).

Reportable Outcome #1
Regional suitability analysis: regional scale maps and descriptions of the hydrological suitability of the Superficial Aquifer for MAR.

This work was completed successfully and is documented in Report 1. The report contains maps of MAR potential in the superficial aquifer that are derived from a new method developed for the study. The new methodology and Perth case study are also published in an international journal paper entitled *Assessment of Managed Aquifer Recharge Potential Using Ensembles of Local Models* (Smith and Pollock 2011).

Technical Objective #3
Review international experience in karst hydrology and hydrological characterisation methods for karst systems.

An EndNote reference library was created based on extensive literature review. The database contains source information for around two-hundred papers and reports relating to Tamala Limestone, coastal eolianites, and characterisation and investigation of karst groundwater systems. A synthesis of the literature review pertaining to the Tamala Limestone is contained in Report 2.

Reportable Outcome #3
Field investigation program: datasets and results from field site (e.g., drilling, coring and hydraulic testing results).

The field investigation program and datasets are documented in Report 2. Datasets were collected at four localities and include drilling records, full-depth limestone cores, water level measurements and geophysical surveys. The geophysical datasets consist of downhole conductivity and gamma logs, resistivity sections, and surface and downhole *NMR profiles of water content and porosity.

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* Nuclear Magnetic Resonance

Technical Objective #4
Develop a conceptual porosity model for Tamala limestone and characterise the structure and spatial heterogeneity of cast features in the limestone at a selected field site.

Technical Objective #5
Develop a geostatistical model of Tamala limestone that is relevant to assessing groundwater flow and contaminant attenuation in the coastal aquifer.

Reportable Outcome #2
Hydrological characterisation of Tamala Limestone: description and quantification of karst structures in Tamala Limestone; and conceptual and geostatistical models of groundwater flow through karst pathways.

Conceptualisation of pore system evolution in Tamala Limestone is documented in Report 2. Investigation and description of karst structures at each of the field sites include visual observations, sample collection, sample analysis and geophysical surveys. A dual porosity conceptual model is proposed for the Tamala Limestone based on the eogenetic karst model of Vacher and Mylroie (2002). A dual porosity mathematical model is also proposed to explain observations of tidal water level fluctuation in Tamala Limestone that cannot be explained by conventional single-medium approaches. The model is applied with a range of plausible parameter values to estimate the likely volume fractions of primary porosity and secondary porosity media.

Technical Objective #6
Develop a site investigation protocol for assessing the feasibility, likely benefits and risks, and the existing hydrological controls on MAR in the coastal margin of Perth's Superficial Aquifer (Moore River to Mandurah) where Tamala Limestone is present.

Technical Objective #7
Carry out case study assessments of MAR in conjunction with local government authorities (stormwater) and the Water Corporation (wastewater).

Reportable Outcome #4
Hydrological assessment protocol and case studies: standard approach for assessing the feasibility and hydrological controls on MAR in Perth's coastal aquifer; case studies where the methodology has been developed and applied.

Ojective #6 and reportable outcome #4 were considered to be redundant in light of new state and national MAR guidelines released during the course of the project (e.g., NRMMC, EPHC and NHMRC 2009; Dillon et al. 2009 and DoW 2009). In consultation with the project Reference Group the objective was modified as follows:

Compare and validate the conceptual and geohydrologic models of Tamala Limestone developed in this study against case study information from sites where MAR into Tamala Limestone is or has been practiced (e.g. wastewater treatment plants).

Reviews of groundwater monitoring information at four wastewater infiltration sites and nine contaminated sites were reviewed and are documented in Report 2. Groundwater level and water quality data from the wastewater infiltration sites is found to be insufficient to deduce local groundwater flow patterns; however, the plume geometries at the contaminated sites are generally consistent with diffuse matrix flow with evidence of increased dispersion due to dual porosity.

3. KEY FINDINGS

3.1. Suitability of the superficial aquifer for MAR

Although the specific objectives of MAR vary according to location, opportunity and circumstance, one or both of the following hydrological objectives must be achievable to attain the desired economic, social or environmental benefits:

1. Ability to manipulate aquifer storage
2. Ability to manipulate watertable elevation.

For example, to enhance groundwater supply by MAR requires an aquifer in which local storage can be controlled in the desired way and by practical means. Similarly, to manage saltwater intrusion or impacts of watertable decline on wetland ecosystems requires an aquifer in which groundwater level can be controlled within the required elevation range, over the required extent of aquifer, and at the location where this need exists.

The degree of hydrological manipulation that can be achieved through MAR and the associated benefits and risks relies fundamentally on the physical properties of the aquifer, existing hydrological conditions such as depth to watertable below ground surface, and the rate at which water can be injected or infiltrated. Spatial datasets describing how these factors vary across the Perth region have been compiled during the past few years for several large-scale groundwater modelling projects. In this study they are used to assess MAR potential quantitatively across the Perth region.

The technique developed for this study is suitable for assessing the potential for MAR over large water resource regions by evaluating analytic models of watertable response to recharge wells and infiltration basins at many locations across the assessment area. Detailed description of the methodology is contained in Report 1 (Smith and Pollock 2010) and the related journal paper (Smith and Pollock 2011). The main result obtained for the study area between Lake Preston and Moore River (Figure 1) is reproduced in Figure 2.

Key findings:

- Potential for MAR within the Perth region superficial aquifer varies considerably dependent on the hydraulic capacity for well injection and surface infiltration, the locations of suitable water sources, land and water availability, the objective to be achieved through MAR, and the risk of preferential groundwater flow and transport in limestone areas.
- The potential for successful MAR is greatest where a proposed scheme is hydraulically feasible, a secure water source is available, there is a clear community benefit, and the risks to groundwater users and the environment are minimal. More of these criteria are met along the coastal strip of the Perth region where the aquifer characteristics are suitable for well injection and surface infiltration, where fresh groundwater storage is declining, and secure water sources are available from main drains and wastewater treatment plants.
- The Tamala Limestone, extensive parts of Gnangara Mound and some parts of Jandakot Mound are found to be suitable for small, medium and large scale MAR schemes. The presence of sandy surface soils and moderate to very large aquifer transmissivity allow large infiltration and injection rates and promote lateral spreading of recharge mounds rather than excessive vertical rise toward ground surface beneath MAR operations.
- Extensive inland areas located south of the Swan-Canning Estuary are generally unsuitable for medium and large scale MAR. Groundwater is relatively shallow in these areas and the soil and aquifer have greater clay and silt contents that restrict infiltration, injection and lateral groundwater drainage. These characteristics prevent useful recharge rates from being achieved and promote excessive vertical growth of recharge mounds toward ground surface.
- Although large-scale MAR is a feasible proposition in coastal areas, it is essential that risk assessments must address the potential for preferential flow within secondary porosity in

the limestone, and the implications for the movement and fate of recharge water in the aquifer.

- Control over local watertable elevation and aquifer storage by MAR in limestone areas is hydraulically limited by very large transmissivity and constant watertable elevation at the ocean boundary. There is potential for mitigating saltwater intrusion through small but sustained watertable rise over broad areas. MAR facilities located close to the coast are more likely to contribute contaminants in the wastewater to the ocean or estuary, whereas a facility located further inland will allow the recharge water to be retained for longer in the aquifer but could create more opportunity for impacts on ‘downstream’ groundwater users.
- Further inland within sandy parts of Gnangara Mound the risk of preferential flow in the aquifer is diminished but the opportunity for MAR is limited by the lack of potential water sources. The land surface in these areas is elevated relative to the coastal strip and inland conveyance of water from the coastal wastewater treatment plants to MAR facilities on the mound would be required, along with new infrastructure and ongoing pumping costs.

3.2. Suitability of Tamala Limestone for MAR

The coastal strip of Western Australia, stretching from Cape Range on the central coast to Albany on the south coast contains the world’s largest tract of carbonate eolianites (Figure 3). Known commonly as coastal limestone, and more formally as Tamala Limestone, the formation is familiar as cream to grey coloured chalky rock exposed at the surface in coastal areas (Figure 4). Within the Perth region Tamala Limestone extends below the watertable and contains fresh groundwater that is utilised for major water supplies. The coastal limestone aquifers are distinct from their sandy counterparts located further inland beneath the coastal plain due to the presence of a dual-pore system that has formed through dissolution of the carbonate cement that binds the formation. Tamala Limestone is a form of karst and contains voids (open spaces within the limestone) that vary in size from less than a millimetre up to cavern size.

Despite awareness of secondary porosity in Tamala Limestone and potential for preferential flow there is a general lack of consensus among groundwater practitioners about whether MAR into extremely transmissive limestone is useful, due to potential lack of recoverability of water and potential for contamination. Thus, the characteristics of the limestone that make it an economic target for recharge are the same characteristics that cause concern about ensuring suitable quality of recovered water.

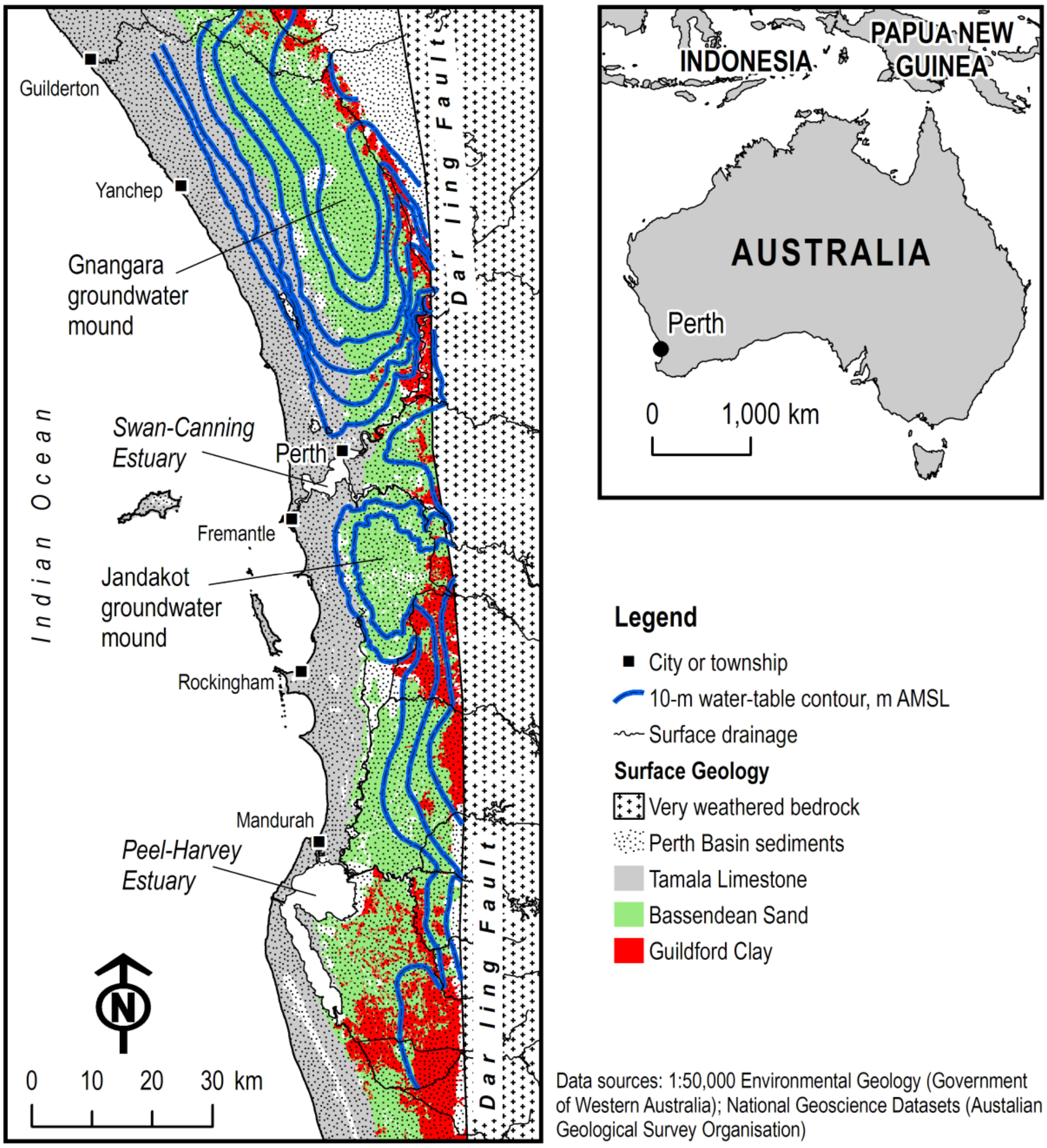
Two distinct views exist regarding groundwater movement within the limestone. In the first, the eolianite is conceptualised as containing large connected void structures that readily conduct groundwater, such as conduits and caverns. It is argued that prediction of groundwater flow and transport through these void networks is too uncertain to enable reliable assessment of MAR suitability in limestone areas without knowing the structure and local detail of the network. The second contrary viewpoint is based on the apparent lack of evidence of water quality problems in karst areas after more than 180 years of groundwater utilisation, and similar lack of evidence of groundwater contamination at existing sites where infiltration of treated wastewater already occurs.

Key findings:

- Pleistocene to Holocene carbonate eolianites of the Tamala Limestone in the Perth region extend up to ten kilometres inland of the modern coast and up to forty kilometres or more offshore in their submarine extent. During the past 500,000 years eustatic sea level has fluctuated by more than one-hundred metres on five occasions, which has caused cyclic inundation of Tamala Limestone by the sea. Contemporary sea level is at an interglacial high stand and the present-day watertable is estimated to be within 2–6 m of the palaeo-watertable maximum.
- Although surface exposures of Tamala Limestone are extensively investigated by geologists, the present-day sub-aerial zone has not been subjected to prolonged saturated conditions and does not provide suitable evidence for developing conceptual

models for the aquifer pore-system and geohydrology below the modern watertable where the formation has undergone different diagenesis.

- The Eogenetic Karst model developed for carbonate eolianite aquifers of Bahamas and Bermuda is considered to provide the best conceptual model for pore-system development and geohydrology of the Tamala Limestone Formation in the Perth region. According to the equivalent porous medium model of Vacher and Mylroie (2002) the Tamala Limestone can be classified as an eogenetic karst of early- to mid-development.
- Evidence considered in this study connecting the Tamala Limestone to the eogenetic karst model includes the hydrogeological similarities between Tamala Limestone, Lucayan Limestone (Bahamas) and carbonate eolianites of Bermuda; plus evidence of a predominantly diffusive flow matrix based on sub-surface visual observations, full-depth coring, geophysical surveys, and analysis of aquifer tidal propagation.
- Assessing recoverability risk associated with MAR in Tamala Limestone depends fundamentally on the adopted hydrogeological conceptual model. The eogenetic karst model implies a dispersive flow paradigm, except in areas where cavern development and large-scale conduit flow is prevalent. Tamala Limestone has large to very large transmissivity owing to a well-developed dual-pore system and there is potential for recharge water to move rapidly away from infiltration and injection sites under forced hydraulic gradients induced by those operations.
- There is sufficient evidence to suggest that conventional single-medium models are inadequate for the purpose of assessing MAR into Tamala Limestone. The dual-medium approach provides a plausible explanation of observed tidal propagation at coastal sites and this approach has proven to be a better alternative for explaining observed mass transport in groundwater at field sites where the aquifer contains small-scale preferential flow pathways.
- The dual-medium approach is not implemented in most groundwater simulation software and therefore specialised groundwater modelling capability and services might be required to develop and implement these approaches. Detailed field investigations may also be necessary to enable determination of realistic model parameters and for calibration and validation of model predictions.



Data sources: 1:50,000 Environmental Geology (Government of Western Australia); National Geoscience Datasets (Austalian Geological Survey Organisation)

Figure 1. Project study region (from: Smith and Pollock 2011)

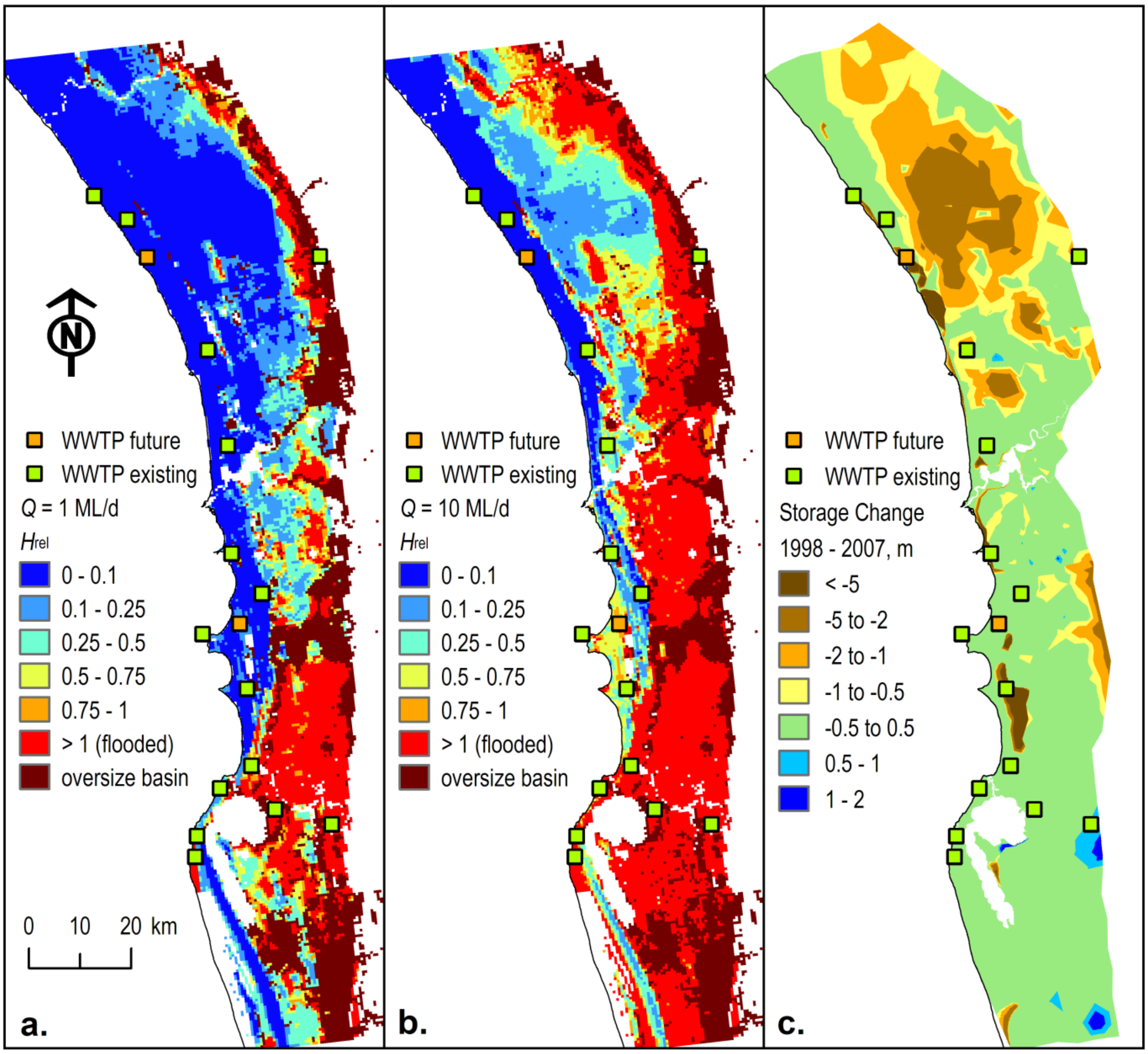


Figure 2. Relative water-table rise beneath the center of a square recharge basin at 30 days continuous operation calculated in 21,335 contiguous cells using Glover's (1961) solution. (a) Small (1 ML/d) hydraulic load. (b) Large (10 ML/d) hydraulic load. (c) Calculated 10-year change of aquifer storage expressed as change of fresh water thickness in the superficial aquifer between 1998 and 2007 (from: Smith and Pollock 2011).

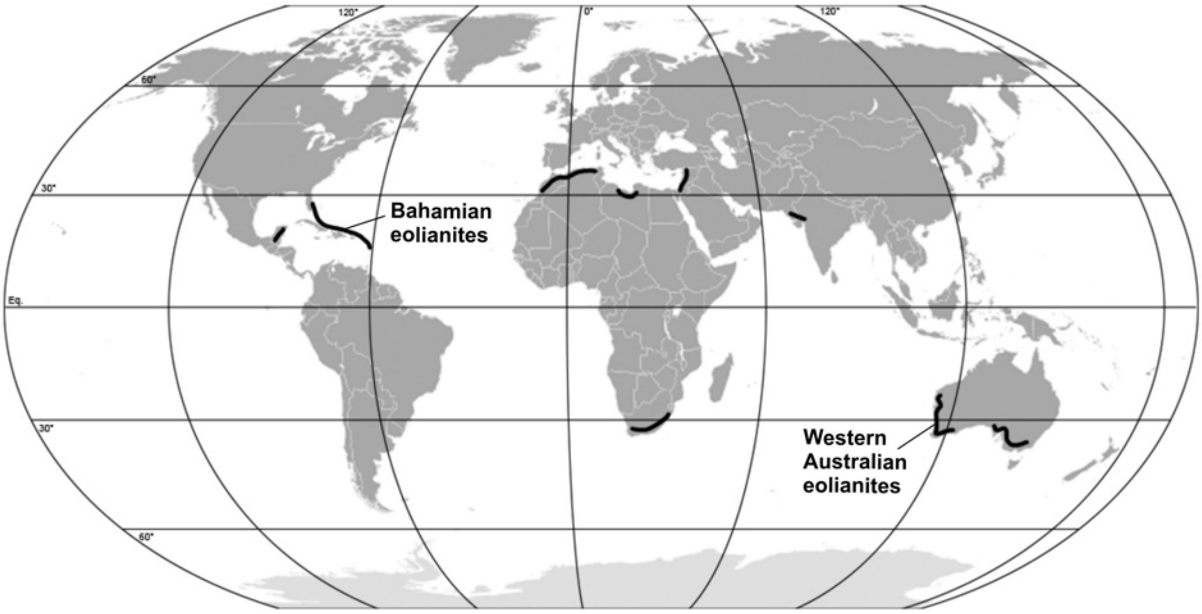


Figure 3. Major tracks of carbonate eolianite in the world (after Brooke 2001)

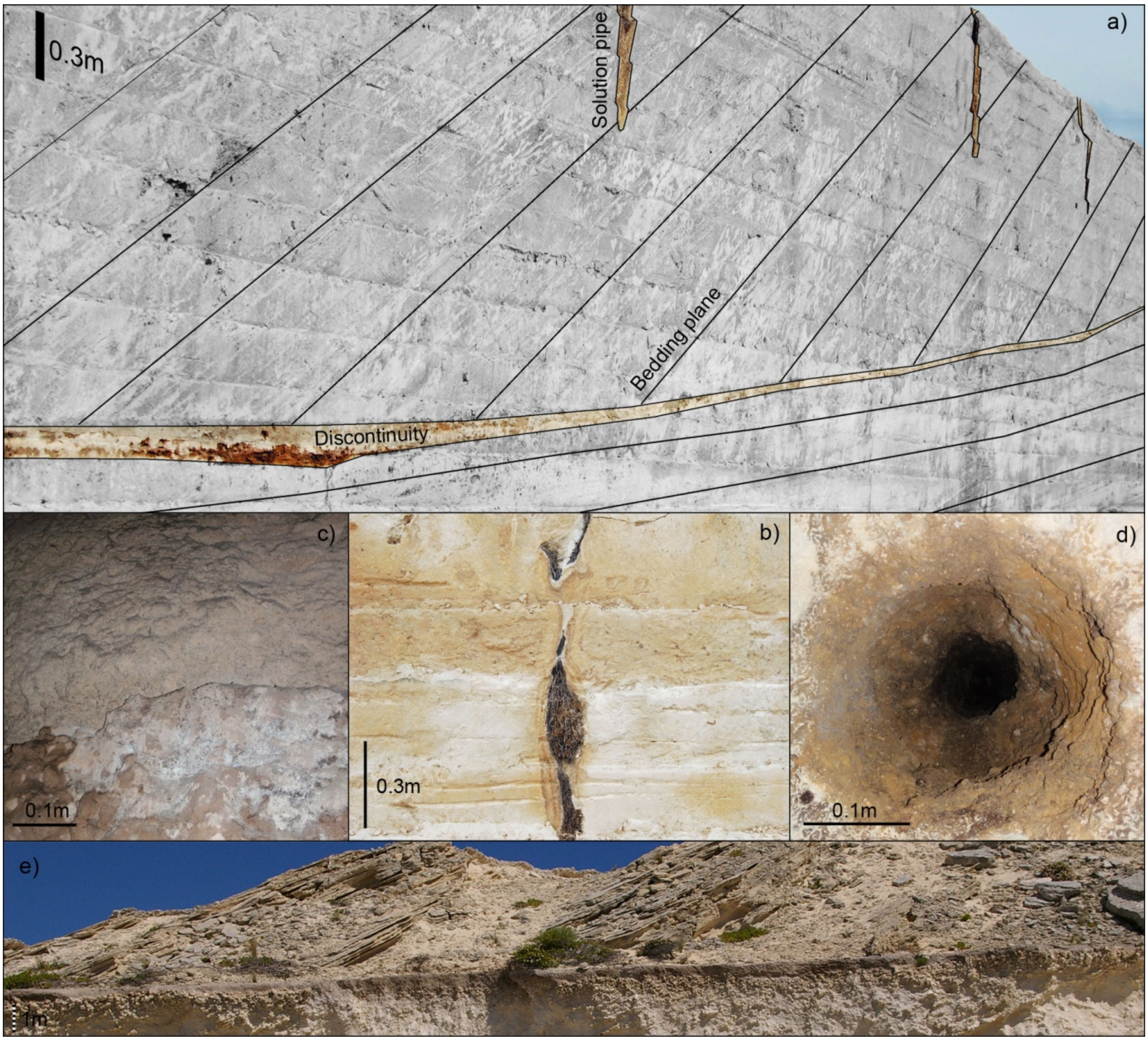
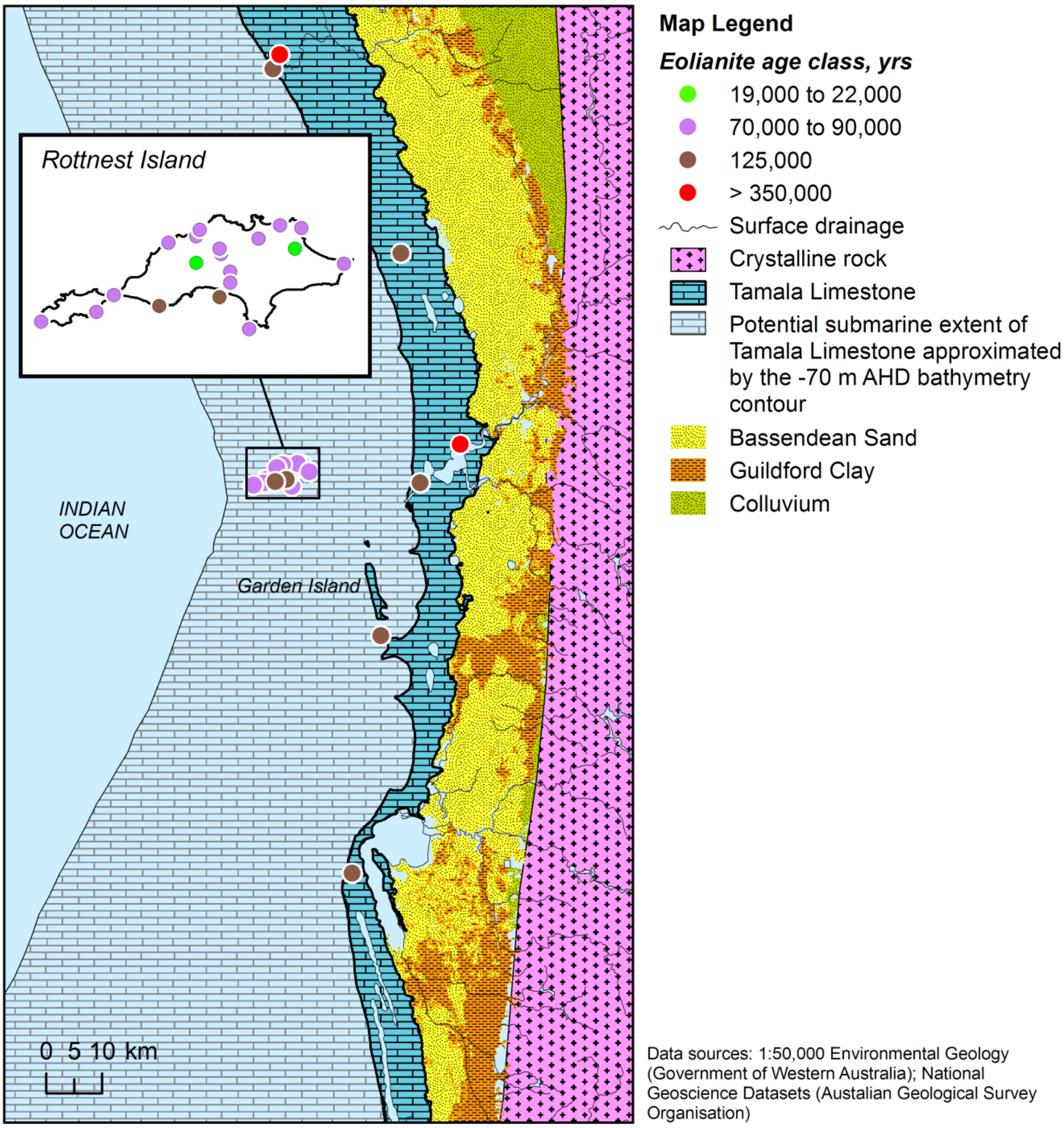


Figure 4. Images of Tamala Limestone: a-b) Meteor Quarry, c-d) Fremantle Prison tunnels, e) Hamelin Bay (from: Smith et al. 2012)



Data sources: 1:50,000 Environmental Geology (Government of Western Australia); National Geoscience Datasets (Austalian Geological Survey Organisation)

Figure 5. Onshore and extrapolated offshore submarine distribution of Tamala Limestone in the Perth region, and surface age dates (from: Smith et al. 2012)

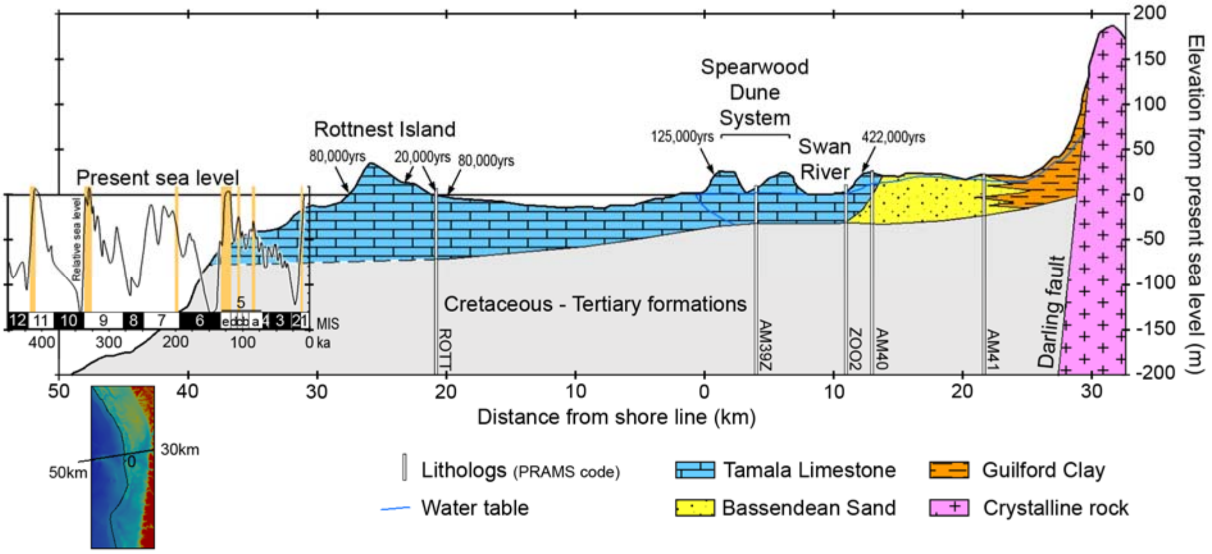


Figure 6. Cross section of Tamala Limestone and relative sea level change derived from Australian studies; sporadic dating of surface deposits indicates that carbonate eolianite age decreases seaward and offshore (from: Smith et al. 2012).

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APPENDIX A – PROJECT DELIVERABLES

Notes:

1. This table is reproduced from Schedule C *Deliverables and Payment Schedule* of PWF Grant Agreement Number 010 05.

No.	**Deliverable Name**	**Description**
1	Update of WIN Database	Update the Department of Water's Water INformation (WIN) database with the historical groundwater elevation data (time and watertable elevation values) provided through the Swan Catchment Council's Superficial Aquifer monitoring project.
2	Aquifer levels and storage trends 1995–2006	Complete extended maps of trends in water table elevation and storage in Perth's superficial aquifer from Moore River to Mandurah and update to include information resulting from Deliverable 1.
3	MAR regional suitability maps	Develop regional scale maps from Moore River to Mandurah of the opportunities and suitability of the Superficial Aquifer for MAR, with respect to the potential benefits and risks of MAR, and hydrological controls on those benefits and risks.
4	Report 1	Provide technical report, in 4 bound hard copies and electronic PDF form, to the Principal's Representative that accurately portrays the findings of Deliverables 1, 2 & 3, and Reportable Outcome 1; and in relation to the report the requirements set out in Clause 10, paragraphs 2 and 3 of the Standard Terms and Conditions have been satisfied.
5	Literature review and data review	Complete a review of International karst hydrology and characterisation methods for karst systems. Compile and review hydrogeological and geophysical information for Tamala Limestone to ascertain the existing information base and to guide the selection of appropriate field methods and the collection of appropriate new data during the field investigation program.
6	Field datasets	Identify a suitable field site and compile and assess data resulting from drilling, coring, hydraulic testing and geophysical surveys at the field site.
7	Conceptual and geostatistical models	Develop a conceptual porosity model and geostatisitical parameterisation of Tamala Limestone that is relevant to risk based modelling and prediction of subsurface transport through karst structures in the coastal aquifer.
8	Report 2	Provide technical report, in 4 bound hard copies and electronic PDF form, to the Principal's Representative that accurately portrays the findings of Deliverables 5,6 & 7, and Reportable Outcomes 2 & 3; and in relation to the report the requirements set out in Clause 10, paragraphs 2 and 3 of the Standard Terms and Conditions have been satisfied.
9	Hydrological assessment framework and case studies	Develop a standard protocol for assessing the hydrological controls on MAR at proposed MAR locations, particularly where Tamala Limestone is present, using case studies as examples of the benefits achieved through MAR and the hydrological controls on MAR at those sites.
10	Final Report	Provide a comprehensive plain English final report, in 12 bound hard copies and electronic PDF form, to the PWF Board that outlines the Project, its aim and methodologies, and clearly and accurately portrays the findings of the Project against each item on listed in Schedule E – Technical Objectives of the Project and Schedule F – Reportable Outcomes; and in relation to the report the requirements set out in Clause 10, paragraphs 2 and 3 of the Standard Terms and Conditions have been satisfied.

11	Communication package	Report the study findings contained in Reports 1 & 2 at two separate public seminars conducted through the CELS (Centre for Environmental and Life Sciences) public seminar series at the CSIRO Floreat laboratory and co-ordinated and supported through CSIRO's Communication group. Present the study findings from the final report to: 1. Water Corporation; 2. Department of Water; and 3. Western Australian Local Government Association.

APPENDIX B – TECHNICAL OBJECTIVES

Notes:

2. This table is reproduced from Schedule E *Technical Objectives of the Project* of PWF Grant Agreement Number 010 05.

No.	Description
1	Infill the State groundwater database with historical watertable information recovered from the Swan Catchment Council's Superficial Aquifer monitoring project.
2	Map the suitability of the Superficial Aquifer for MAR with respect to the potential benefits (e.g. water supply supplementation, watertable control, prevention of seawater intrusion) and the existing hydrological controls on MAR (e.g. karst features preventing water table mounding).
3	Review international experience in karst hydrology and hydrological characterisation methods for karst systems.
4	Develop a conceptual porosity model for Tamala limestone and characterise the structure and spatial heterogeneity of cast features in the limestone at a selected field site.
5	Develop a geostatistical model of Tamala limestone that is relevant to assessing groundwater flow and contaminant attenuation in the coastal aquifer.
6	Develop a site investigation protocol for assessing the feasibility, likely benefits and risks, and the existing hydrological controls on MAR in the coastal margin of Perth's Superficial Aquifer (Moore River to Mandurah) where Tamala Limestone is present.
7	Carry out case study assessments of MAR in conjunction with local government authorities (stormwater) and the Water Corporation (wastewater).

APPENDIX C – TECHNICAL REPORTS

Notes:

3. This table is reproduced from Schedule F *Reportable Outcomes of the Project* of PWF Grant Agreement Number 010 05.

No.	Outcome	Reported in	Description
1	Regional suitability analysis	Technical report	Regional scale maps and descriptions of the hydrological suitability of the Superficial Aquifer for MAR.
2	Hydrological characterisation of Tamala Limestone	Technical report	Description and quantification of karst structures in Tamala Limestone; and conceptual and geostatistical models of groundwater flow through karst pathways.
3	Field investigation program	Technical report	Datasets and results from field site (e.g., drilling, coring and hydraulic testing results).

4	Hydrological assessment protocol and case studies	Technical report	Standard approach for assessing the feasibility and hydrological controls on MAR in Perth’s coastal aquifer; case studies where the methodology has been developed and applied

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