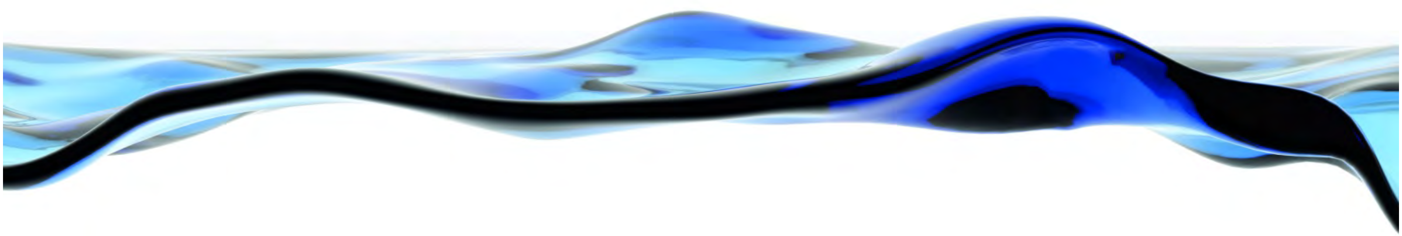
Evaluation of approaches to modelling surface water-groundwater interactions around drains in the South East of South Australia. Phase 1.



Goyder Institute for Water Research
Technical Report Series No. 12/1

www.goyderinstitute.org

Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Water, CSIRO, Flinders University, the University of Adelaide and the University of South Australia. The Institute will enhance the South Australian Government's capacity to develop and deliver science-based policy solutions in water management. It brings together the best scientists and researchers across Australia to provide expert and independent scientific advice to inform good government water policy and identify future threats and opportunities to water security.

The following Associate organisations contributed to this report:

Enquires should be addressed to: Goyder Institute for Water Research
Level 1, Torrens Building
220 Victoria Square, Adelaide, SA, 5000
tel: 08-8303 8952
e-mail: enquiries@goyderinstitute.org

Citation

Harrington, N, Noordijn, S and Cook, P, 2012, Evaluation of approaches to modelling surface water-groundwater interactions around drains in the South East of South Australia. Phase 1., Goyder Institute for Water Research Technical Report Series No. 12/1

Acknowledgements

Funding for this research was provided by the National Centre for Groundwater Research and Training, an Australian Government initiative, supported by the Australian Research Council and the National Water Commission, and by the Goyder Institute for Water Research.

The spatial data used to construct the maps in this report was obtained directly from the Department for Water and Geoscience Australia and via the Department for Water's Obswell website (https://obswell.pir.sa.gov.au/new/obsWell). The Lidar DEM data used to construct the depth to water table map was obtained through the Department for Water under licence from SERIC.

The work detailed in this report would not have been possible without the help of the following people:

Nicholas White, Lawrence Burke, Lauren Stephens and Cameron Wood (NCGRT), and Glenn Harrington (CSIRO) for their help in installing instrumentation and collecting field data. Mark De Jong from the South East Water Conservation and Drainage Board provided advice and assistance in the field. The maps for the report were constructed by South East Spatial Services and Saad Mustafa (DFW) provided comments on the draft of the report.

Contents

List of Tables

List of Figures

Executive Summary

This report provides details of a preliminary study into the spatial and temporal variability of surface water-groundwater interactions around the drains in the South East, and the utility of electrical conductivity (EC) and radon measurements to quantitatively and qualitatively assess these processes at a regional scale. Also included are the details of instrumentation installed at two sites, on the Reflows Western Floodway and the Fairview Drain, to investigate surface water-groundwater interactions at a smaller scale. The project was funded through the Goyder Institute for Water Research as part of a priority Phase 1 round of the South East Program and both components will provide a foundation for further work on surface water-groundwater interactions around the drains in the South East.

Regional surveys of drain flows, EC and radon activity values were carried out on two occasions at 150 sites across 14 drains, in both the Lower and Upper South East. Radon activities of drain water suggested predominantly gaining conditions across the drains sampled, with 90% of values indicating at least some input from groundwater (>0.1 Bq/L) and 53% indicating at least a moderate input (>0.5 Bq/L). The range of radon activity values observed (0.02 Bq/L to 4.21 Bq/L) indicates that this environmental tracer could be a powerful tool in at least qualitatively assessing the spatial variability of groundwater inflow to the drains at a regional scale in the South East. Additionally, slight temporal differences in the radon data between the two sampling rounds were observed, indicating that this tracer could be useful in characterizing the temporal variability in these processes at a regional scale.

Evaluation of the EC data suggested that, for many but not all drains, surface water EC values were sufficiently different from regional groundwater ECs, and fluctuations along the drain flow paths were large enough, to allow a qualitative assessment of groundwater inputs. In most cases, where this was possible, the interpretation loosely agreed with that of the radon data. However, due to the likelihood of large local variations in groundwater EC in the South East, confident use of this parameter, which is cheap and simple to measure, can only be achieved after properly characterizing groundwater ECs adjacent the drains.

Comparisons of preliminary radon and hydraulic mass balances showed that additional work is required to be able to quantitatively estimate groundwater inputs to the drains. The first step in this would be an assessment of the spatial variability of radon activities in groundwater in the unconfined aquifer and for many of the drains, this may adequately constrain quantitative estimates of groundwater inflow using a radon mass balance approach. However, for some of the drains, particularly those with "sludgy" bottoms, hyporheic exchange may be an important process affecting surface water radon activities, and additional experiments using applied tracers may be required to resolve this.

1 Introduction

1.1 Project Background

In the South East of South Australia, large quantities of water are managed via an extensive network of groundwater and surface water drains to control flooding and salinisation of agricultural land, whilst maintaining the health of the remaining natural wetlands. At the same time, a lucrative and economically important agricultural industry relies heavily on the groundwater resource. Currently, decisions regarding the management of the surface water and groundwater systems rely on outcomes from separate surface water and groundwater models. However, there is a recognised need and increasing pressure to manage these resources as one integrated resource. This requires a robust methodology for modelling the interaction between the surface water and groundwater systems. Fully coupled surface water – groundwater models are labour and data intensive and hence one has not yet been attempted for the South East. However, there is a need to assess the degree to which fully coupled models are required to inform water resources management in the South East, including the necessary scale. Conversely, the applicability and accuracy of simpler methodologies, where coupled models are not feasible based on data limitations, must also be assessed. A preliminary requirement of any of these approaches is the development of tools to measure surface water – groundwater interactions around the drains and collect data for the calibration of these models.

A program of work is currently being developed by CSIRO and Flinders and Adelaide Universities to be funded through the Goyder Institute for Water Research, addressing key research priorities in the South East, as identified by the Department for Water. One proposed component of this program, will aim to better understand surface water-groundwater interactions around the drains in the South East and evaluate approaches to modelling the water resources in the region in an integrated way.

This report provides details of preliminary work carried out as Phase 1 of the "**Evaluation of approaches to modelling surface water-groundwater interactions around drains in the South East of South Australia"** project. This work was listed as a high priority for preliminary funding through the Goyder Institute to allow for (a) a preliminary assessment of the spatial and temporal variability of groundwater discharge to drains across the South East, (b) an evaluation of the utility of tracer techniques in understanding and quantifying this process in the region, and (c) installation of monitoring infrastructure in the newly constructed REFLOWS floodway prior to the release of floodwaters. It was considered that outcomes from Phase 1 would be invaluable in developing an appropriate scope and methodology for the main body of the project, anticipated to be carried out in 2012-2013.

1.2 Phase 1 Objective, Outputs and Outcomes

The objectives of Phase 1 of the "**Evaluation of approaches to modelling surface water-groundwater interactions around drains in the South East of South Australia"** project were to:

(1) Improve the understanding of the relationship between groundwater and drains in the South East, and how this varies in time and space.
(2) Evaluate methodologies for qualitatively and quantitatively assessing the interactions between groundwater and the drains in the South East.

The proposed outputs of Phase 1 were:

1) Regional maps showing areas where drains are gaining and losing, and the magnitudes of these exchanges, and water quality variation across the drainage network.
2) Infrastructure at two sites that will permit detailed assessments of how interactions between groundwater and drains change in time, and vary with land use.

The long-term outcome of this research project, in conjunction with further work, will be improved management of the drainage network for water table management and ecological outcomes, and a clearer understanding of the technical work and modeling approaches required to inform the conjunctive management of surface water and groundwater resources in the South East.

1.3 Methods for Quantifying Stream – Groundwater Interactions

A review by Kalbus et al. (2006) outlines the various methods available for quantifying regional discharge of groundwater to streams over a range of temporal and spatial scales. Many methods provide only point measurements of the exchange flux (e.g., seepage meters), which, although important for understanding processes, are difficult to upscale due to spatial variability of streambed properties (Calver, 2001; Kennedy et al., 2008). Water management often requires spatially and temporally averaged exchange fluxes. Although there are currently no well-tested and routinely applied methods for providing this information, recent studies have advanced the techniques of modeling transient water balances of streams and wetlands using combined stream gauging and environmental and applied tracer techniques (e.g. Cook et al., 2003; 2006; 2008).

Differential flow gauging has been widely used to determine surface water and groundwater exchanges (Arnott et al., 2009; Cey et al., 1999; Harte and Kiah, 2009; Langhoff et al., 2006; Opsahl et al., 2007; Schmadel et al., 2010). If flow gauging takes place when surface runoff is negligible, then net groundwater inflow can be assumed to be the difference between river flows measured at two points along the river, after other gains (e.g. tributaries) and losses (e.g. pumping, evaporation) are accounted for. Errors in this technique arise from errors in the measurement of river flows and estimation of other components of the water balance. Estimates of surface water and groundwater exchange will only be accurate in reaches where inflow or outflow is significantly greater than this uncertainty (Cey et al., 1999; Harte and Kiah, 2009).

Additional information about inflow of groundwater to streams can be obtained by observing downstream changes in stream chemistry. Using a mass balance technique and assuming knowledge of a groundwater end member, inflow of groundwater can be estimated from the change in concentration between two points (Holtzman et al., 2005; Meredith et al., 2009). Ion concentrations, including chloride, calcium, magnesium and sulphate, have been used for this purpose (e.g., Genereux at al., 1993; Cook et al., 2003). Several authors have also used the dissolved gas radon (^{222}Rn) to estimate groundwater inflow to streams (Ellins et al., 1990; Genereux and Hemond, 1990; Genereux et al., 1993; Mullinger et al., 2007; Wu et al., 2004).

Radon is produced in groundwater as part of the radioactive decay of the uranium-series isotopes. Radon can be added to the river by groundwater inflow and by hyporheic exchange due to decay of radium in river bed sediments (Cook et al., 2006). Radon is lost from the system due to radioactive decay (half life of 3.8 days) and loss of the gas tracer to the atmosphere. These properties mean that radon is a particularly useful tracer in that elevated levels indicate that groundwater inflow has occurred a short distance upstream of the measurement point. Furthermore, because radon is continually lost from the river, the contrast between river and groundwater concentrations remains high, making the tracer highly sensitive to groundwater inflow.

The mass balance of radon in a stream or river can be developed as follows. If surface runoff and tributary inflow is negligible, then changes in stream flow are quantified as:

$$\frac{dQ_S}{dx} = I - O - wE \tag{1}$$

where Q_S is streamflow (L^3T^{-1}), dx is the distance over which the change in flow is observed (L), I represents inflow to the stream from groundwater (L^2T^{-1}), O represents outflow from the stream (consisting of both groundwater outflow and pumping from the stream, L^2T^{-1}), E is evaporation rate (LT^{-1}) and w is the stream width (L). (I, O, w and E, are all a function of x.) Thus, if the spatial distributions of wE and Q_S are measured, we can estimate the spatial distribution of net inflow ($I - O$).

For a conservative tracer (such as chloride), the solute mass balance is given by:

$$\frac{dQ_S c_s}{dx} = Ic_i - Oc_s \quad [2]$$

where c_s and c_i are the concentrations of the stream and groundwater inflow respectively (ML^{-3}). Changes in stream flow chemistry are therefore related to groundwater inflow rate by:

$$Q_s \frac{dc_s}{dx} = I(c_i - c_s) + wEc_s \quad [3]$$

Groundwater inflow rates can therefore be calculated if the other parameters are known.

As discussed above, non-conservative tracers can also be used for estimating groundwater inflow. Radon, in particular, has been widely used (Cook et al., 2006; Ellins et al., 1990; Genereux and Hemond, 1990; Genereux et al., 1993; Mullinger et al., 2007; Wu et al., 2004). However, radon is also affected by radioactive decay, gas exchange and hyporheic exchange so additional terms are required in the mass balance. Changes in stream radon concentrations are described by Cook et al. (2006) as:

$$Q_s \frac{dc_s}{dx} = I(c_i - c_s) + wEc_s - kwc_s - dw\lambda c_s + \frac{\gamma hw\theta}{1+\lambda t_h} - \frac{\lambda hw\theta}{1+\lambda t_h} \quad [4]$$

where:

$$t_h = \frac{wh\theta}{q_h} \quad [5]$$

and k is the gas transfer velocity (LT^{-1}), t_h is the mean hyporheic residence time (T), h is the thickness of the hyporheic zone (L) , θ is the porosity of the hyporheic zone, λ is the radioactive decay constant (T^{-1}), γ is the production rate within the hyporheic zone ($ML^{-3}T^{-1}$) and q_h is the hyporheic flux ($L^3T^{-1}L^{-1}$). (The radioactive decay constant for radon is λ = 0.18 day^{-1}.) The first term in Equation 4 represents the change in concentration due to groundwater inflow; the second, third and fourth term represent evaporation, gas exchange and radioactive decay, respectively. The fifth and sixth terms represent the change in concentration due to hyporheic exchange processes. The approach used by Cook et al. (2006) models hyporheic exchange using a single reservoir beneath the stream, and a first order exchange coefficient. Tributary inflow can be included as discrete sources of water and solute mass to the river, at the point of confluence.

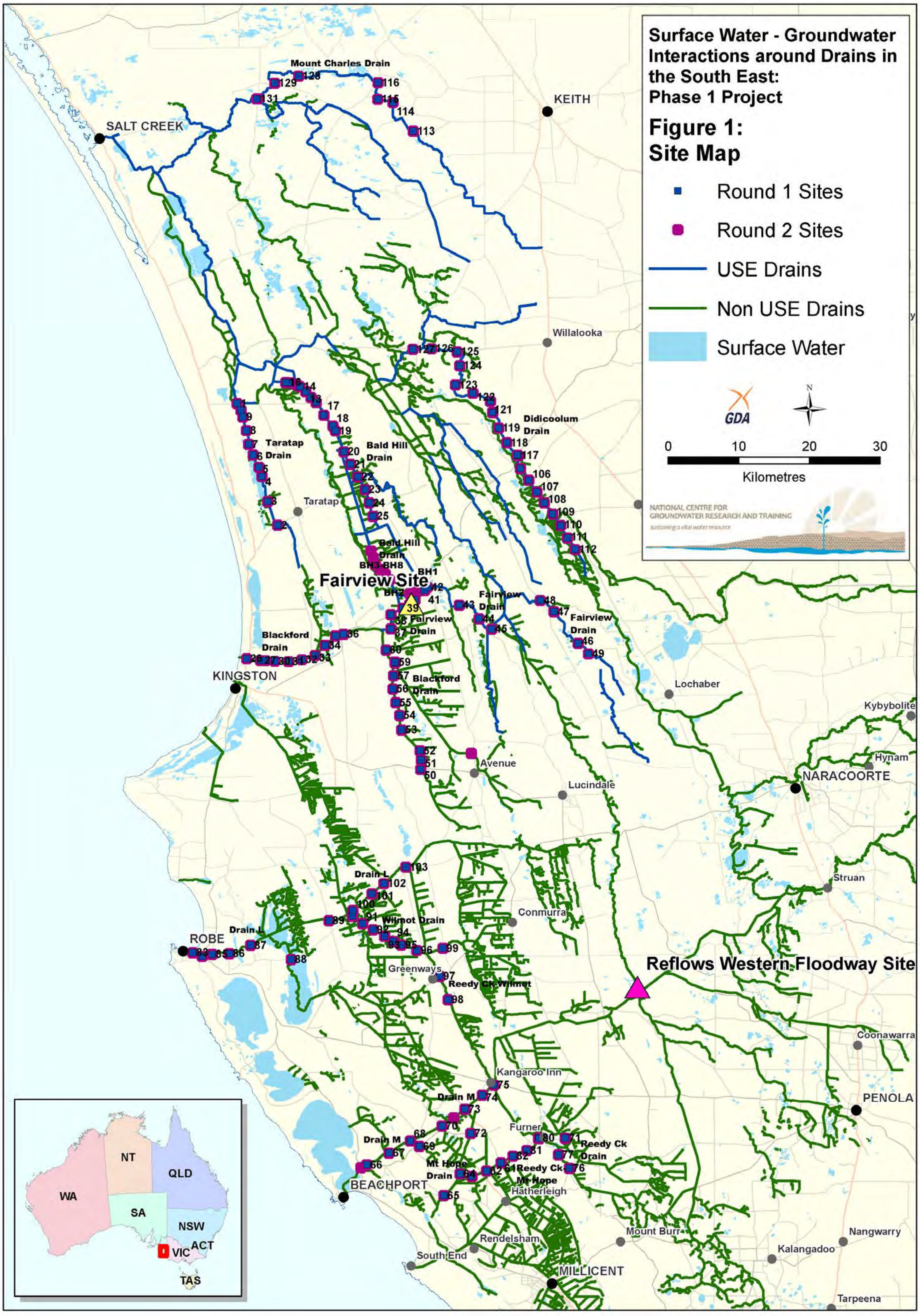
Although a loss (stream leakage to groundwater) term is incorporated in these equations, studies using tracer methods have generally focused on groundwater inflows. However, knowledge of both inflows and outflows is important when understanding solute transport and biogeochemical processes (Bencala et al., 2011). The use of both flow gauging and tracers allows net inflow to be partitioned into gross inflow and outflow rates.

1.4 Site Description

The study area for this project is located in the South East of South Australia (Fig. 1). The climate is characterized by relatively hot, dry summers and cool, wet winters. Average annual rainfall ranges from 463 mm at Keith, on the northern boundary of the study area, to 748 mm at Millicent, near the southern boundary. Pan evaporation ranges from approximately 1400 mm/yr at Mount Gambier, just south of the study area, to approximately 1700 mm/yr at Keith.

The site is located in the Otway Basin, a Tertiary sedimentary basin containing carbonate-rich marine deposits. The two main aquifers in the Basin are a confined sand aquifer, referred to as the Dilwyn Formation (also known as the Tertiary Confined Sand Aquifer (TCSA)), and a shallower unconfined aquifer consisting of the Tertiary Gambier Limestone Formation and other Quaternary sediments, the Bridgewater and Padthaway Formations. The Gambier Limestone, also known as the Tertiary Limestone Aquifer (TLA) has karstic features resulting in preferential pathways for groundwater flow and numerous sinkholes of various sizes, many of which host groundwater dependent ecosystems (GDEs). The overlying Bridgewater Formation consists of unconsolidated calcareous sand and sandstone with limestone interbeds, and forms north-west south-east trending dunal ranges. The Padthaway Formation occurs within the inter-dunal corridors and ranges from rubbly limestone to marl and silt (Preiss and Drexel, 1995). The water table depth in the unconfined aquifer varies from less than 1 m to more than 20 m, depending largely on surface topography (Fig. 2).

A number of man-made drains have been constructed in the South East over the past 150 yrs to drain water and salt from the landscape and the region now contains an extensive drainage network, consisting of shallow surface water drains, natural ephemeral watercourses and deeper groundwater drains excavated into the unconfined aquifer (Fig. 1). The objective of the drainage network was originally to collect and divert water to the coast via the most direct route possible, increasing agricultural productivity (particularly by reducing winter flooding), but disturbing the natural pattern of flow, which was predominantly to the north, along the inter-dunal corridors, towards the Coorong. Acknowledgement of the importance of ecological assets in the South East, and an increasing understanding of their water requirements, has led to a reassessment of the priorities for the drainage system. One of the results of this has been establishment of the REFLOWS scheme, whereby floodways were constructed to divert water from the Lower South East Drains, which would normally be carried across the natural flow path to the coast, into the Upper South East drains, restoring crucial flows to the wetlands and watercourses of the Upper South East.


Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 1: Site Map
Round 1 Sites
Round 2 Sites
USE Drains
Non USE Drains
Surface Water
GDA
0 10 20 30
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Fairview Site
Reflows Western Floodway Site
SALT CREEK
KEITH
KINGSTON
ROBE
BEACHPORT
MILLICENT
NARACOORTE
PENOLA
Mount Charles Drain
Taratap Drain
Bald Hill Drain
Didicoolum Drain
Fairview Drain
Blackford Drain
Drain L
Wilmot Drain
Drain M
Mt Hope Drain
Reedy Ck Drain
WA
NT
QLD
SA
NSW
ACT
VIC
TAS

1.5 Previous Investigations of Surface Water – Groundwater Interactions in the South East

There have been a number of studies on the impacts of drains on groundwater levels in the South East of SA (e.g. Armstrong and Stadter, 1992; Mackenzie and Stadter, 1992; Kennett-Smith et al., 1996, SKM, 2002, Telfer et al., 2002 and REM, 2005; Cox et al., 2006; McCallum et al., 2007). The majority of these have been numerical modeling studies, using MODFLOW (MacDonald and Harbaugh, 1988) to predict groundwater fluctuations around the drains. A number of drilling and monitoring investigations have also been carried out, including one on groundwater levels across three transects in the Upper South East (McEwan and Kennett-Smith, 1995) and one on pH and EC of soils and groundwater on the Didicoolum flat by Durkay (2004). Mustafa et al. (2006) examined the relationship between drain flows and groundwater levels adjacent the Baker's Range Watercourse using a hydrograph separation technique. The field site for this study was located approximately 25 km west of Penola, just south of the Reflows Western Floodway site described below in Section 2.2.1. Studies of groundwater inputs to, residence times and chemical evolution of, the Blue Lake, located in Mount Gambier, form a special subset of research into surface water – groundwater interactions in the South East (e.g. Leaney et al., 1995; Lamontagne, 2002; Herczeg et al., 2003).

Recently, a few studies aiming to identify and quantify surface water – groundwater interactions in the South East through the use of field and laboratory techniques have utilized radon as a tracer of groundwater discharge and focused on natural groundwater dependent creeks and wetlands (Fass and Cook, 2005; Cook et al., 2008; Wood, 2011; Harding, unpublished data). Fass and Cook (2005) carried out a reconnaissance survey of the groundwater dependency of 37 wetlands in the South East. They used steady state mass balances of radon and chloride to calculate volumes of surface water and groundwater inflow. The 70 surface water samples collected, from 38 sites, had radon activities ranging from 0 Bq/L to 5.47 Bq/L. Of the measured activities, 63 % were below 0.1 Bq/L (indicating negligible groundwater input), 26 % were between 0.1 and 0.5 Bq/L (low groundwater input), 1 % were between 0.5 and 1 Bq/L (moderate groundwater input) and 10 % were above 1 Bq/L (high groundwater input). 25 groundwater samples were also analysed for radon activity and these ranged between 0.08 and 13.8 Bq/L, with a mean of 3.87 Bq/L.

Cook et al. (2008) constructed steady state and transient mass balance models of a shallow wetland in the Honan Native Forest Reserve, approximately 16 km west-northwest of Mount Gambier in the Lower South East. Radon activities of surface water within the wetland were measured at up to 60 locations on three occasions, revealing patterns of spatial and temporal variability. Surface water radon activities ranged from 0.08 Bq/L to 0.72 Bq/L. Radon activities in groundwater from piezometers screened from 0-1 m below ground to 4-13.6 m below ground ranged from 8.4 Bq/L to 38.3 Bq/L. All components of the radon budget were estimated, with radon emanation rates from the sediments below the wetland being measured in laboratory experiments using sealed chambers, and the gas exchange velocity estimated through an injected tracer experiment using SF_6. The result was an ability to construct both steady state and transient models of groundwater fluxes to the wetland, with groundwater inflow rates estimated to vary between 12 and 18 m^3/day.

Wood (2011) collected and analysed samples for major ion and isotope chemistry from six groundwater dependent ecosystem (GDE) sites in the Lower South East, ranging from shallow, ephemeral spring-fed creeks (Cress Creek and Jerusalem Creek) to deeper perennial systems (Ewens Ponds and Piccaninnie Ponds). The objective was to improve the understanding of the hydrogeological flow regime to significant GDEs in the Lower South East and then develop an ongoing monitoring strategy for these sites. Surface water and groundwater samples were collected on three occasions, between August 2007 and October 2008. Measured surface water radon activities ranged between 0.03 Bq/L and 7.42 Bq/L.

Radon activities of the spring source to Cress Creek, considered to be representative of groundwater from the Gambier Limestone, ranged between 5.88 Bq/L to 6.06 Bq/L. Radon activities of 17.8 to 22.3 Bq/L observed in one part of Cress Creek were considered to be high for the Gambier Limestone and more representative of the soils overlying the limestone, as were values of 8 to 38 Bq/L measured by Cook et al. (2008) in shallow perched groundwater below the wetland in the Honan Native Forest Reserve.

Besides the above studies, there are a few additional datasets available for radon activities measured in surface water and groundwater in the South East. Herczeg et al. (1994) provide a summary of a dataset for groundwater from the Gambier Limestone, with a minimum activity of 0.5 Bq/L, a maximum of 15 Bq/L and a mean of 3.2 Bq/L. The number of samples in this study and their locations are not specified. Surface water and groundwater radon activities measured by DFW, on wetlands and groundwater to the west of the Bald Hill Drain in October 2009 ranged between 0.06 and 0.50 and 1.2 and 6.0 Bq/L respectively (C. Harding, unpublished data).

2 Methodology

2.1 Preliminary Regional Assessment of Water Exchange Between Drains and Groundwater

Sampling of surface water in drains in the South East was carried out on two occasions, between 30th November and 1st December 2010 (round 1) and between 10th and 13th October 2011 (round 2). During these sampling rounds, measurements of surface water electrical conductivity (EC) and temperature were recorded using digital EC meters at numerous locations along selected drains, (Figure 1; Table 1). EC probes were held out into the main part of the channel using a 1.5 m long rod and held approximately 10 -20 cm below the water surface. Water samples for radon (^{222}Rn) analysis were collected from the drains using a small submersible pump held approximately 10-20 cm beneath the water surface in the main part of the channel, and prepared on-site for analysis using the methodology of Leaney and Herczeg (2006). A series of manual flow gaugings were carried out within the drains using an electromagnetic flowmeter. Detailed measurements of drain width and depth were made at flow gauging sites, and visual estimates were made at many of the other radon sampling sites. Site spacings along the drains were generally 1 – 2 km, considered to be reasonable based upon preliminary calculations (Cook et al., 2006).

The selection of sampling locations for round 1 was based upon factors such as locations of suspected groundwater discharge, accessibility and, avoidance of shallow stagnant pools where degassing of radon would dominate. Results from round 1 were used in conjunction with a depth to groundwater map (Fig. 2) to guide an expanded sampling plan for round 2, with the objectives of the second round of sampling being to:

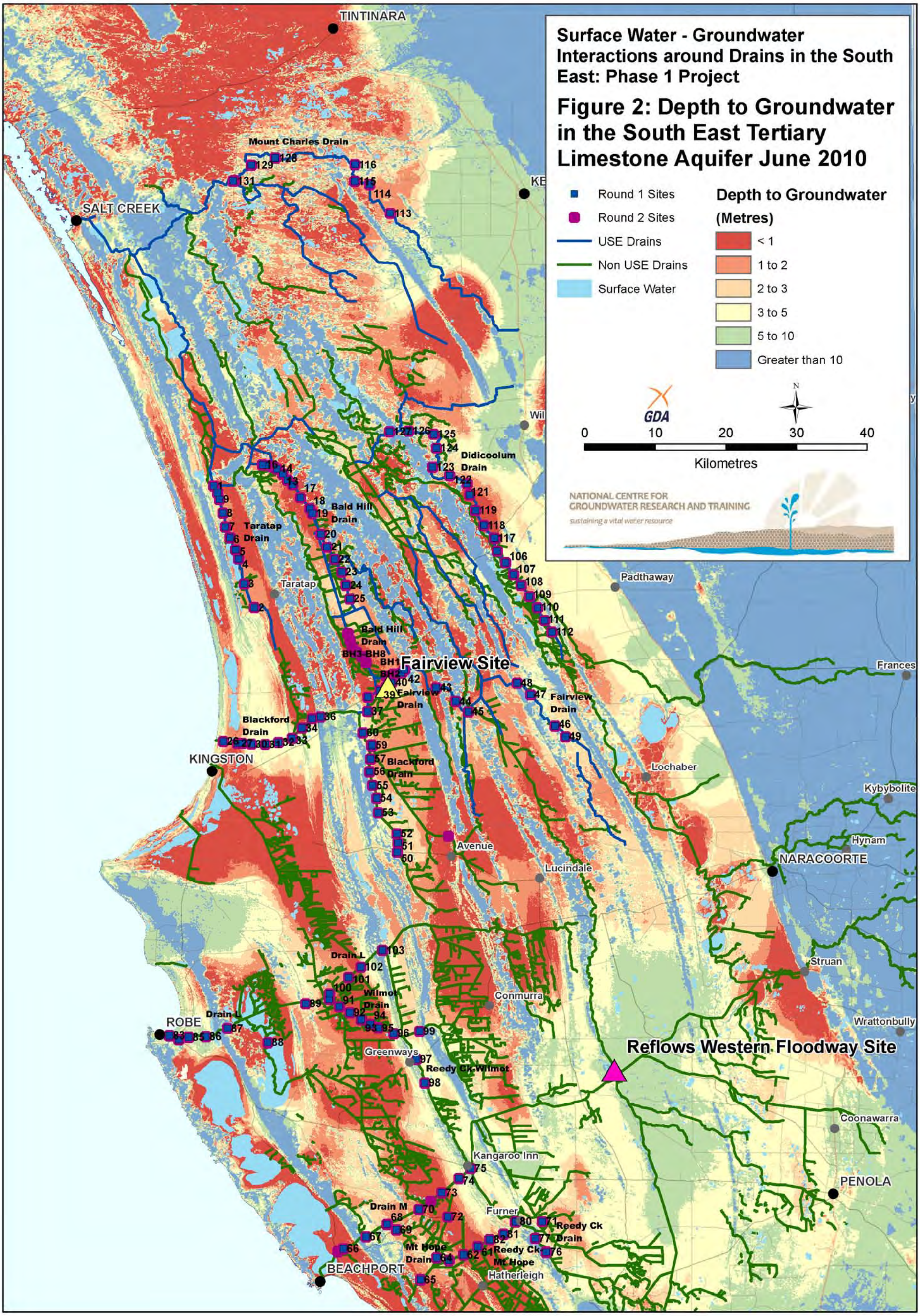
1. Repeat sampling of round 1 sites, to identify any temporal differences in groundwater discharge to the drains.
2. Collect additional radon samples, particularly along reaches of the drains overlying shallow groundwater tables, to investigate the relationship between depth to groundwater and groundwater discharge to drains, and obtain a greater range of radon activity values.
3. Carry out additional drain flow gaugings in conjunction with radon sampling, with a focus on reaches of the drains where significant groundwater inputs were identified from round 1 data, or would be expected based on the depth to groundwater map. The objective of this was to test the viability of the radon mass balance approach of Cook et al. (2006) in quantifying groundwater inflows to the drains in the South East.

Radon analyses were carried out at the CSIRO Land and Water Adelaide laboratory by liquid scintillation counting.

Table 1. Number of field measurements and radon samples collected along each drain.

	Round 1			**Round 2**		
Drain	EC and Temp	Radon Samples	Flow	EC and Temp	Radon Samples	Flow
Bald Hill	16	4		26	12	5
Blackford	21	3	1	22	5	
Didicoolum	20	5	1	12	7	5
Drain L	11	3	1	11	5	
Drain M	7	1		9	4	
Fairview	13	5		12	8	2
Mt Charles	6	4	1	6	3	3
Mt Hope	2	0		1		
Reedy Creek	4	0		1		
Reedy Ck-Mt Hope	7	1		7	1	
Reedy Ck-Wilmot	2	1		2	1	
Symon Main Drain	1	0		1		
Taratap	10	2	2	1	8	8
Wilmot	8	1		8	4	
Total	**128**	**30**	**6**	**128**	**58**	**23**

Photos of some of the drains, showing their various characteristics, are included in Appendix A.



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 2: Depth to Groundwater in the South East Tertiary Limestone Aquifer June 2010
Round 1 Sites
Round 2 Sites
USE Drains
Non USE Drains
Surface Water
Depth to Groundwater (Metres)
< 1
1 to 2
2 to 3
3 to 5
5 to 10
Greater than 10
GDA
0 10 20 30 40
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
sustaining a vital water resource
TINTINARA
SALT CREEK
KINGSTON
ROBE
BEACHPORT
NARACOORTE
PENOLA
Padthaway
Lochaber
Lucindale
Avenue
Taratap
Conmurra
Greenways
Kangaroo Inn
Furner
Hatherleigh
Frances
Kybybolite
Hynam
Struan
Wrattonbully
Coonawarra
Mount Charles Drain
Didicoolum Drain
Bald Hill Drain
Taratap Drain
Blackford Drain
Fairview Drain
Fairview Site
Reflows Western Floodway Site
Drain L
Wilmot Drain
Reedy Ck-Wilmot
Drain M
Mt Hope Drain
Reedy Ck Drain
Reedy Ck-Mt Hope

2.2 Installation of Infrastructure for Detailed Measurement of Surface Water – Groundwater Interactions

Two sections of the South East drainage system were selected for installation of infrastructure for detailed monitoring of surface water – groundwater interactions around the drains.

The first site, on the newly constructed Reflows Western Floodway (Fig. 1), was selected because it provided an excellent opportunity to investigate groundwater recharge from losing streams in a controlled field setting. When sufficient water is present in Bool Lagoon water can be allowed to flow down Drain M, which will then discharge into the Reflows Western Floodway when subsequent flow regulators are emplaced.

The second site, on the Fairview Drain (Fig. 1), was selected because it provided a similar flow control capacity as the Western Reflows Floodway, but in a gaining stream. This capacity to control flow can then be used to investigate bank storage processes and groundwater discharge quantities.

2.2.1 Reflows Western Floodway Site

Table 2 and Figure 3 show details of the instrumentation installed at the Reflows Western Floodway site.

Table 2. Instrumentation installed at Reflows Western Floodway Site.

Instrumentation	Date installed	Sites	Depth (m bgl)	Temporal Resolution
Soil Moisture Sensors	16/05/2011	trans 1 and 2	(0.3, 0.6, 1.2, 1.8)	10 mins
Thermistors	18/05/2011	5 sites; between trans 2 and 3	(0.4, 0.7, 1.1, 1.5)	5 mins
Drive Points	7/4/2011	Trans 1, 2, 3 within the channel	~1.5 and 3	1 min
	16/05/2011	Trans 1, 2, 3 without the channel	~1.5-3	
Differential Gauging (temporally adjusted)	19/05/2011 20/05/2011 3/6/2011	2 sites; 300m and 1800m from weir pool		Variable; mins-days
Surface water levels	18/05/2011	21 locations	0	1 min
Piezometers with pressure transducers	31/6-2/7/2011	Trans 1,2,3;adjacent to floodway	10	10 mins

A topographic site survey was carried out prior to release of surface water flows down the floodway. Installation of all monitoring equipment, with the exception of the piezometers, was carried out prior to the release of the initial flows down the floodway (Fig. 3; Fig. 4).

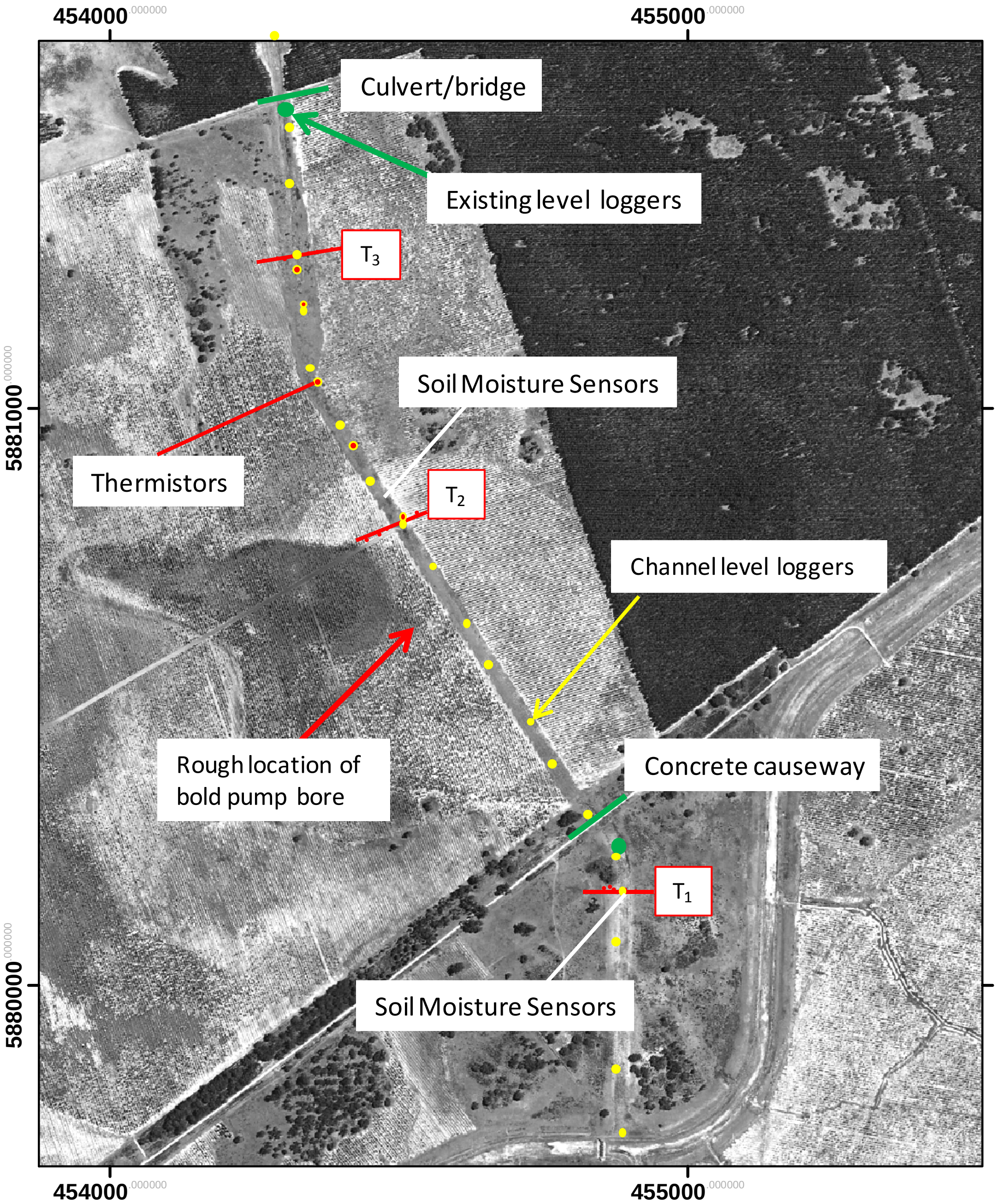


Figure 3. Site schematic, showing the location of monitoring infrastructure installed at the Reflows Western Floodway site.

a) b) c) d)

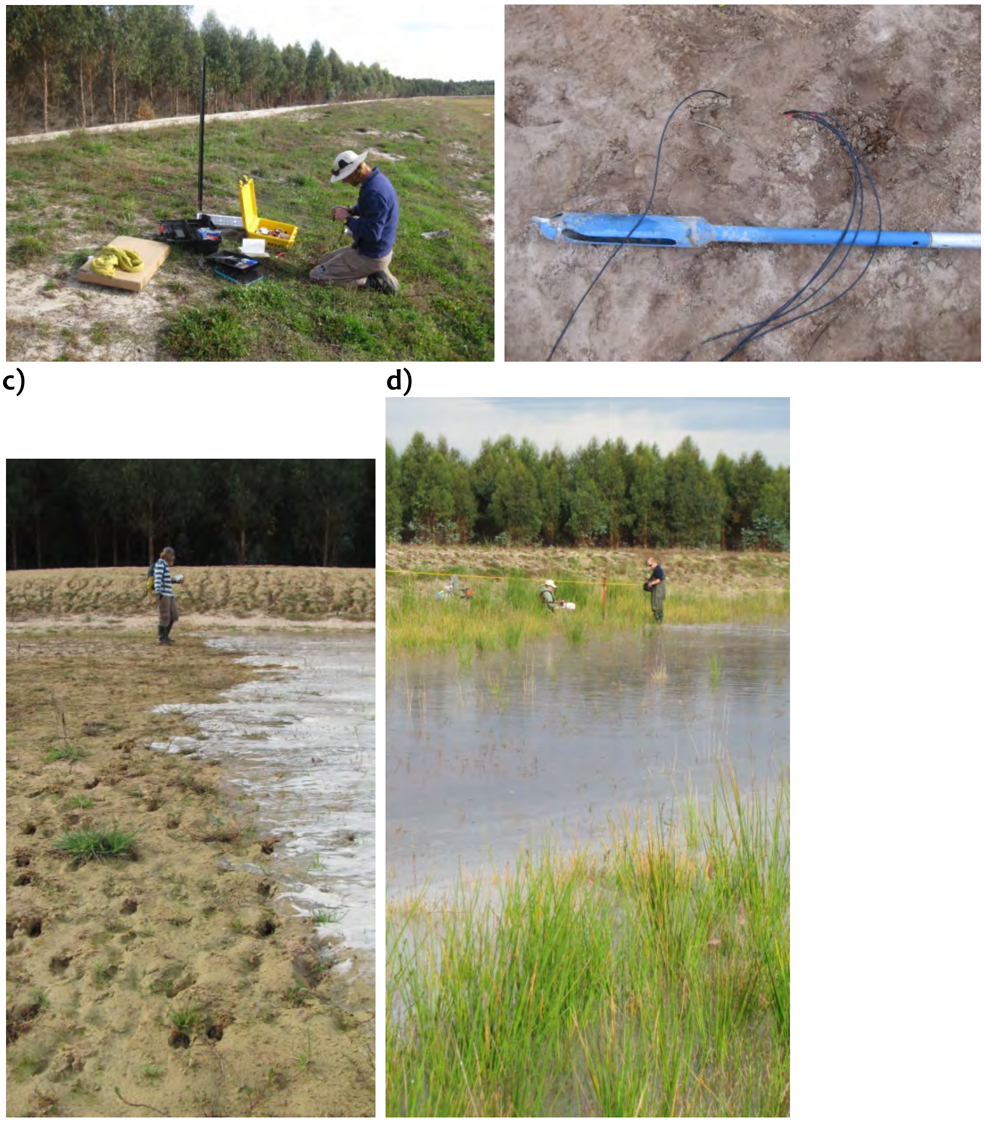


Figure 4. Photos of fieldwork at the Reflows Western Floodway site. a) Installation of Campbell logger; b) Soil Moisture sensors in the ground; c) flood wave tracking; d) flow gauging.

2.2.2 Observation of Initial Flows along the Reflows Western Floodway

The Callendale regulator was closed on 17/06/2011, and the Bool Lagoon regulator opened on 18/06/2011 to allow surface water to flow down the Western Floodway. The flood wave arrived at the Callendale regulator at 10am 19/06/2011, after which the weir pool built up and flows into the Reflows Western Floodway occurred at approximately 12pm 19/06/2011.

Table 3 shows the data that was collected during the onset of flooding down the Reflows Western Floodway.

Table 3. Summary of data collected at the Reflows Western Floodway site between 18/06/2011 and 3/07/2011.

Data type	Frequency	Scale	Temporal Resolution
Soil Moisture Data	2	point	10 mins
Temperature Data	5	point	5 mins
Temporally adjusted Differential Gauging	1 (1.5km)	Reach	variable
Surface water levels	21 (100m)	Reach	1 min

2.2.3 Fairview Site

Drilling and installation of piezometers was carried out at the Fairview site between 19/09/2011 and 21/09/2011. Drilling was conducted with a rotary air rig due to the presence of calcrete, all piezometers were installed with gravel pack around the screens and backfilled with bentonite to ground surface. Table 4 and Figure 5 show the details of the piezometers installed. Figure 6 shows photos from the Fairview site.

Table 4. Summary of piezometer construction details for the Fairview site.

Type	Depth (m bgl)	Screened Interval (m bgl)	Quantity	Piezometer I.D.
Observation bore	3.5	1.5-3.5	30	W1A-W11E
Nested bores	1.2	1.0-1.2	4	W3.HT[1-4].A
	1.7	1.5-1.7	4	W3.HT[1-4].B
	2.2	2.0-2.2	2	W3.HT[1&3].C
Pump bore	15	Sep-15	1	W3PMP

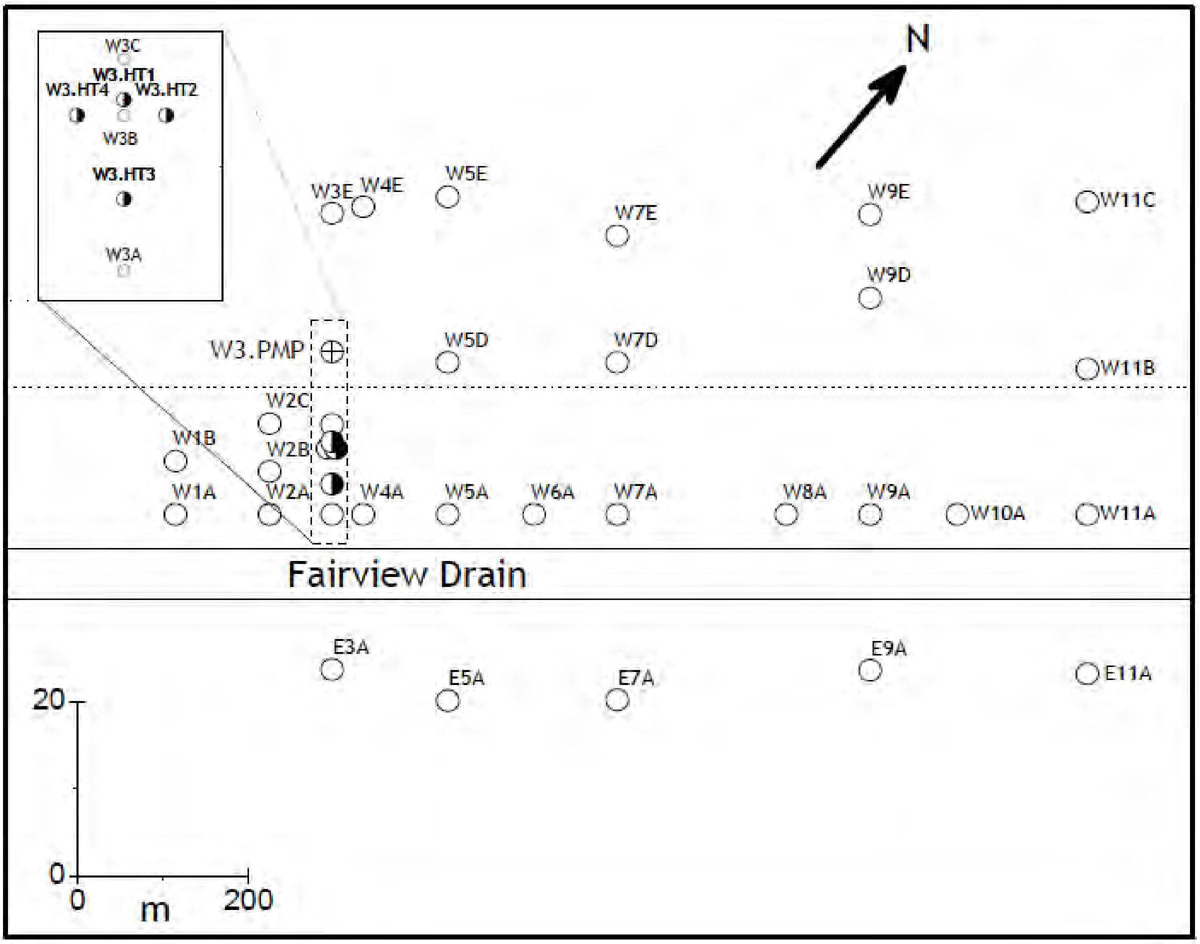


Figure 5. Schematic diagram of the piezometers installed at the Fairview site.
○ observation bores, ◑ nested bores and ⊕ pumping bore.

a)

b)

Figure 6. Photos of the Fairview site. a) transect 3 looking east, b) drill rig adjacent to drain.

2.2.4 Fairview Stage Change Experiment

A Stage Change Experiment was carried out at the Fairview site between 26/9/2011 and 26/10/2011, with the following objectives:

1. Investigate the impact of piezometer location relative to the stream on groundwater discharge calculations.
2. Understand how knowledge of the aquifer heterogeneity will increase the accuracy of the discharge calculation when relying on point groundwater measurements.

The regulator located downstream of the site was blocked on 26/09/2011. The water level behind the regulator built up to approximately 1.4 m on the day of the experiment (13/10/2011). Flow at the Keilira gauging station (upstream of the site) remained at approximately 0.6 m^3s^{-1} during this period. Installation of all monitoring equipment at the Fairview site occurred on the 11/10/2011 to capture the groundwater response of the stage change experiment. Initial groundwater levels were also measured on installation of the equipment. The Fairview regulator was unblocked at 10.19am on 13/10/2011, prior to which the upstream regulator (approx 2 km east of downstream regulator) was closed and flow was directed along the Bald Hill drain (a tributary of the Fairview). The data collected following the stage change, between 13/10/2011 and 26/10/2011 is summarized in Table 5. The upstream regulator remained blocked to allow the reach of the Fairview Drain to empty.

Table 5. Data collected during the Fairview Stage Change Experiment, between 13/10/2011 and 26/10/2011.

Data type	Frequency	Scale	Temporal Resolution
Groundwater Level	21	point	1 mins
Groundwater level and EC	11	point	15 mins
Surface water level and EC	2	point	15 mins

3 Results

3.1 Preliminary Regional Sampling Program

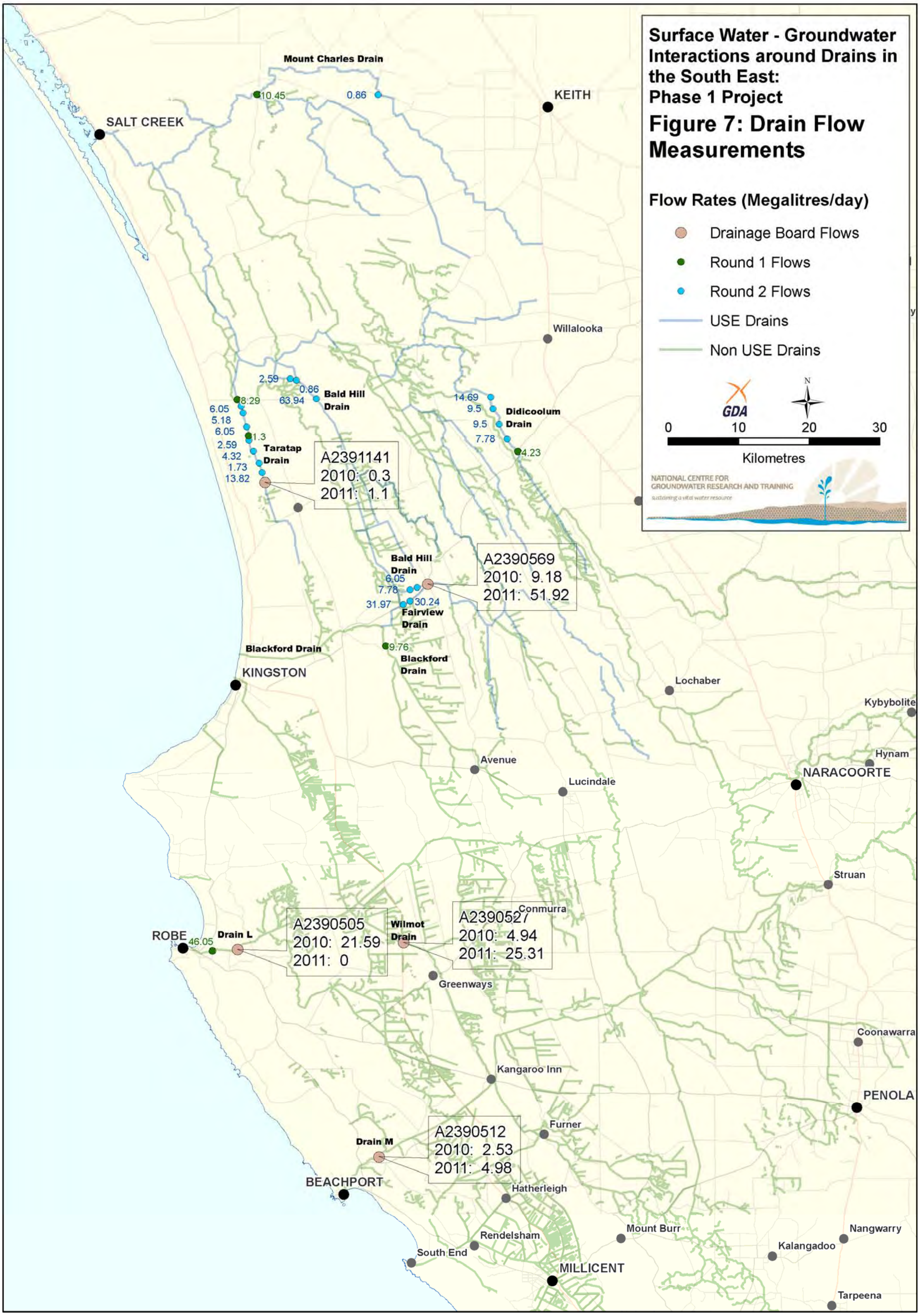
3.1.1 Surface Water Flows

Surface water flows in the drains were measured manually, using an electromagnetic flow meter, during both sampling rounds (Round 1: Nov/Dec 2010 and Round 2: Oct 2011). The flow data collected during both rounds are included in Appendix B. Only six flow measurements were carried out during round 1, and these ranged between 1.3 ML/d (0.015 m^3/s) at a site on the Taratap drain to 46.1 ML/d (0.533 m^3/s) at a site on Drain L (Table 6; Fig. 7). An Acoustic Doppler Current Profiler (ADCP) was tested on Drain L, however high winds and dense weed prevented the float from being moved smoothly across the drain and this methodology was abandoned for the rest of the sampling round, with all other measurements being carried out using the manual electromagnetic flow meter.

The number of flow measurements was increased to 23 in round 2, to provide flow values for use in radon mass balance calculations, and also to allow estimates of groundwater inflow along sections of the drains to be made via the differential flow gauging technique. The flows measured during round 2 ranged between 0.9 ML/d (0.01 m^3/s) at two Mt Charles and one Bald Hill drain site and 63.9 ML/d (0.74 m^3/s) at Bald Hill site 11 (Table 6; Fig. 7). Note that there were no flow measurements carried out on Bald Hill drain during round 1. Deep water (>1.1 m) and fast flows prevented additional manual flow measurements being carried out safely on Bald Hill Drain (between sites BH2 and 11) during round 2. It was noted that the ADCP may be useful here in the future due to the deep water and negligible weed in the drain at these locations.

Table 6. Summary of flows measured for each drain during round 1 and round 2.

Drain	Round 1 Flows (ML/d)	Round 2 Flows (ML/d)
Bald Hill		0.9-63.9(5)
Blackford	9.8(1)	
Didicoolum	4.2(1)	6.9-14.7(5)
Drain L	46.1(1)	
Drain M		
Fairview		30.2-32.0(2)
Mt Charles	10.5(1)	0.9-26.8(3)
Mt Hope		
Reedy Creek		
Reedy Ck-Mt Hope		
Reedy Ck-Wilmot		
Symon Main Drain		
Taratap	1.3-8.3(2)	1.7-6.9(7)
Wilmot		


Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 7: Drain Flow Measurements
Flow Rates (Megalitres/day)
Drainage Board Flows
Round 1 Flows
Round 2 Flows
USE Drains
Non USE Drains
GDA
N
0
10
20
30
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Mount Charles Drain
10.45
0.86
KEITH
SALT CREEK
Willalooka
2.59
0.86
63.94
Bald Hill Drain
8.29
6.05
5.18
6.05
1.3
2.59
4.32
1.73
13.82
Taratap Drain
A2391141
2010: 0.3
2011: 1.1
14.69
9.5
9.5
7.78
Didicoolum Drain
4.23
Bald Hill Drain
6.05
7.78
31.97
30.24
Fairview Drain
A2390569
2010: 9.18
2011: 51.92
Blackford Drain
9.76
Blackford Drain
KINGSTON
Lochaber
Kybybolite
Hynam
NARACOORTE
Avenue
Lucindale
Struan
Conmurra
ROBE
46.05
Drain L
A2390505
2010: 21.59
2011: 0
Wilmot Drain
A2390527
2010: 4.94
2011: 25.31
Greenways
Coonawarra
Kangaroo Inn
PENOLA
Furner
Drain M
A2390512
2010: 2.53
2011: 4.98
BEACHPORT
Hatherleigh
Mount Burr
Nangwarry
Kalangadoo
Rendelsham
South End
MILLICENT
Tarpeena

Flows measured in the Taratap drain during round 2 should be viewed with caution as velocities were extremely low and the water was deep, meaning that fairly small errors in the flow velocity measurements would result in large errors in flow volumes estimated. A value of 1.1 ML/d recorded at the Drainage Board gauging station near site 4 suggests that the flow rates derived from the manual gauging may be artificially high. In particular, a value of 13.8 ML/d, measured at site 4 was considered to be erroneous and has been disregarded.

It is difficult to compare drain flows over the two periods due to the different number and locations of measurements taken. However, observational comparisons between the two sampling rounds suggested that drain flows were greater during round 2 than round 1, as expected as round 2 was carried out slightly earlier in the year (early October compared with late November / December for round 1). The rainfall in the 30 days prior to the two sampling events were also quite different, with 21 mm recorded at Kingston prior to round 1 and 63.6 mm prior to round 2 (BoM, 2011), leading to the different flows in the drains.

3.1.2 EC

The surface water EC data collected during rounds 1 and 2 are shown spatially at the drain scale on Figure 8(a-f). As expected, due to a significant north-south gradient in rainfall and ET, the EC of the water in the drains generally increases towards the northern part of the study area. The trends in EC of the drain water along the flow direction are quite variable (Fig. 9). Many of the drains exhibit slight increases in EC along their flow directions (e.g. Mt Charles Drain, Fairview Drain, Drain L and the Blackford Drain (prior to confluence with the Jackie White and Fairview drains)). However, in some cases, there are significant decreases in EC along the flow direction (e.g. the Didicoolum and Taratap drains). Spatial variations in drain water ECs may be due to both groundwater and tributary inflow. This will be discussed in more detail in Section 4.1.

Despite the differences in rainfall during the preceding month and the associated observed differences in drain flows, the ECs of the drain water were fairly constant between the two sampling rounds (Fig. 8; Fig. 9). The exceptions to this were the Blackford drain (downstream of the Fairview / Jackie White confluence) and the Fairview Drain. Flow along the Fairview drain had been restricted at the regulator between sites 40 and 39 (on Figure 9, x =45800 and 47900 m) for the purpose of the Fairview Stage Change Experiment. This change in conditions would have led to differences in the amount of groundwater inflow to the drain at that time.

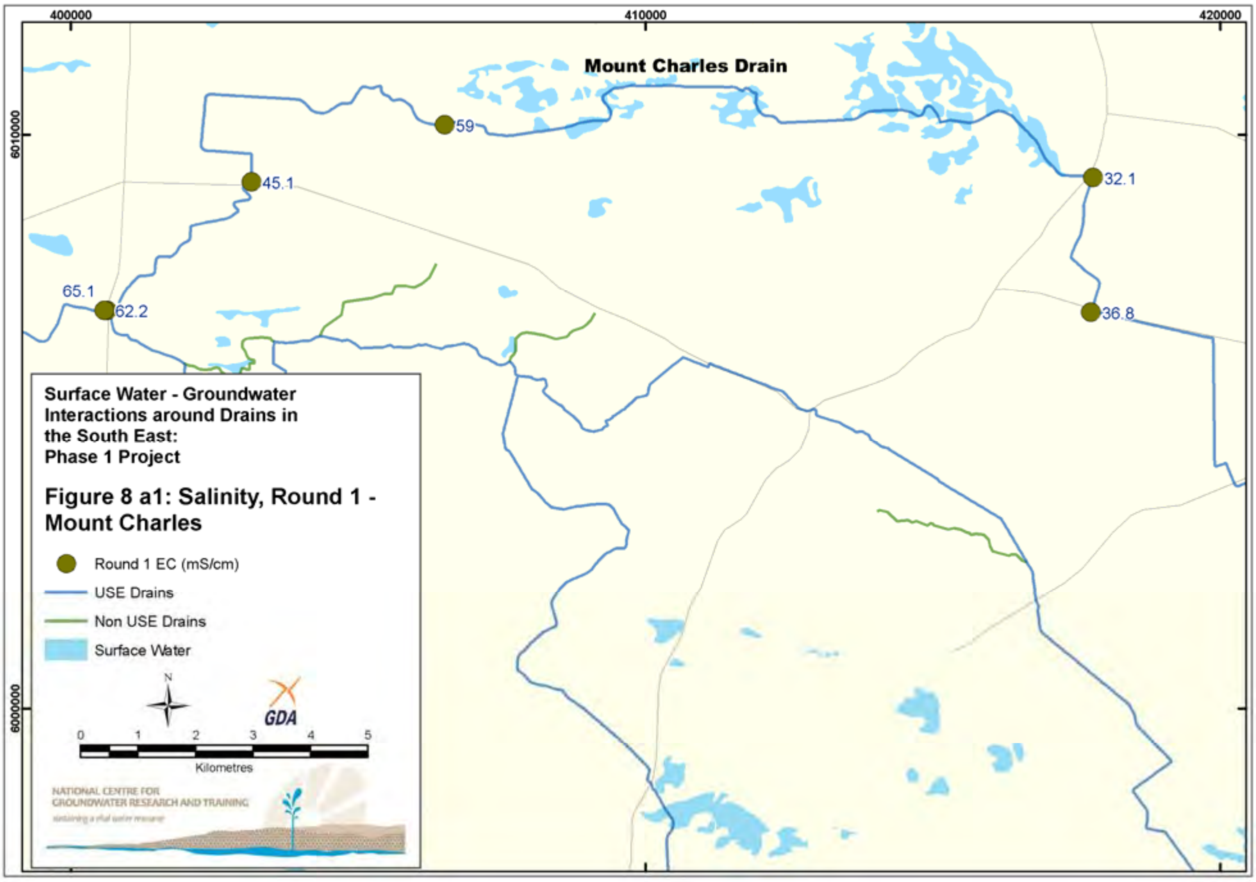


Figure 8 a1: Salinity, Round 1 - Mount Charles

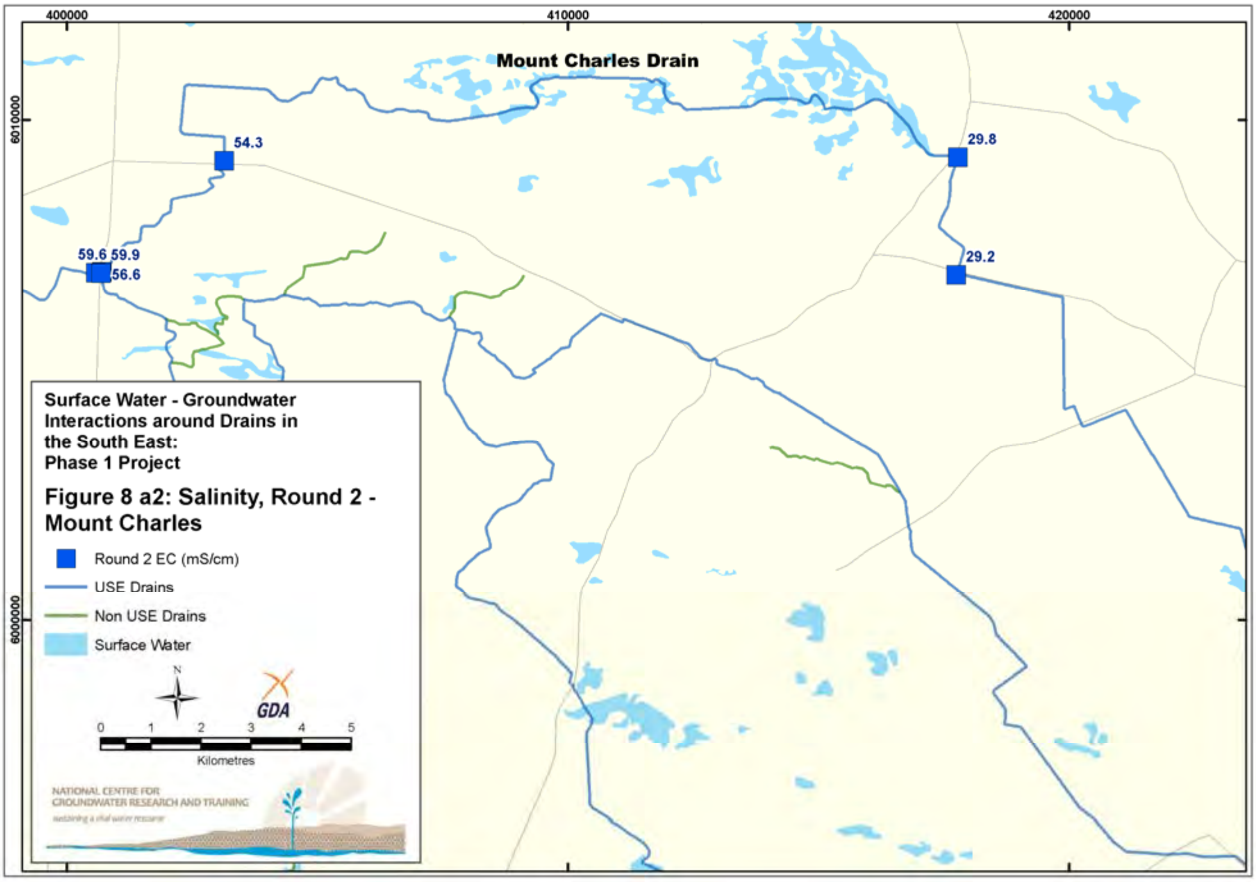
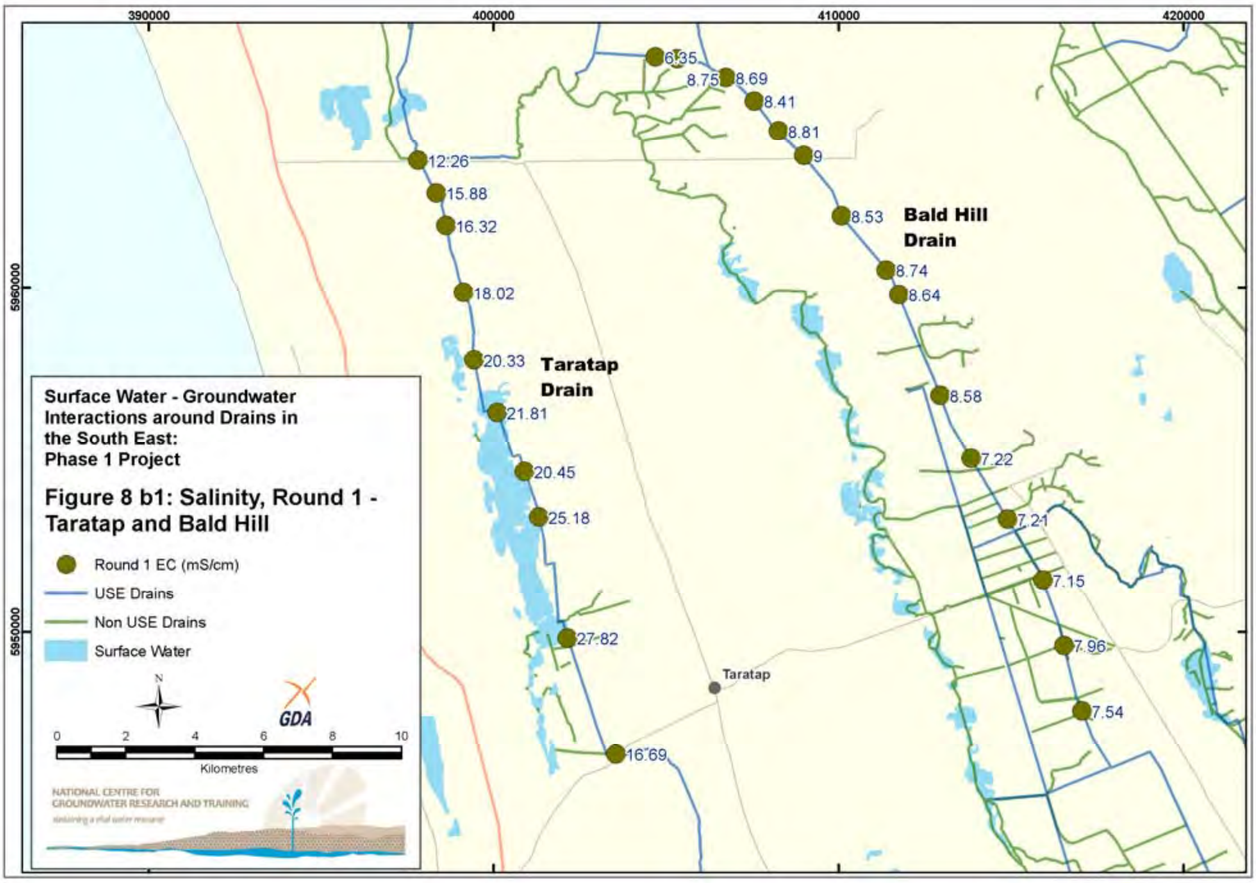
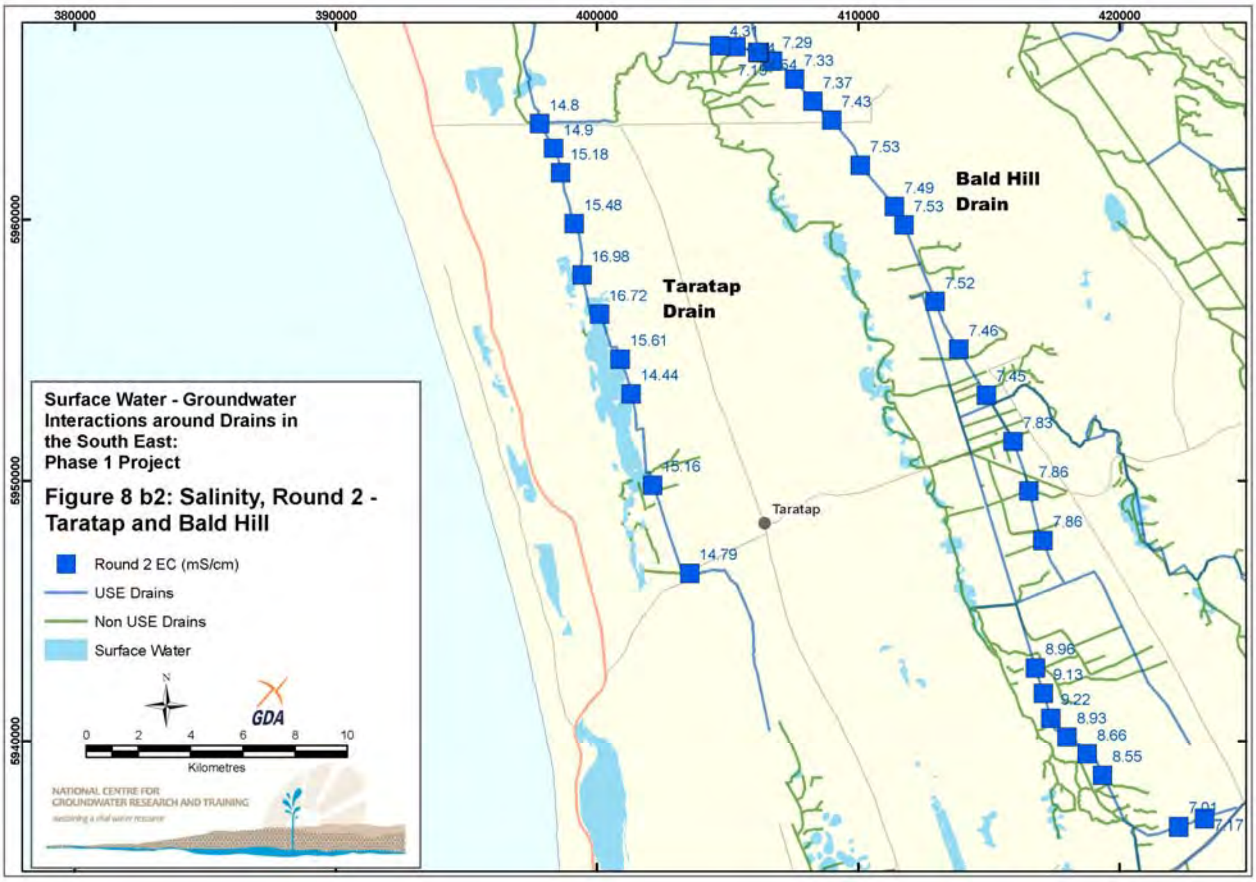
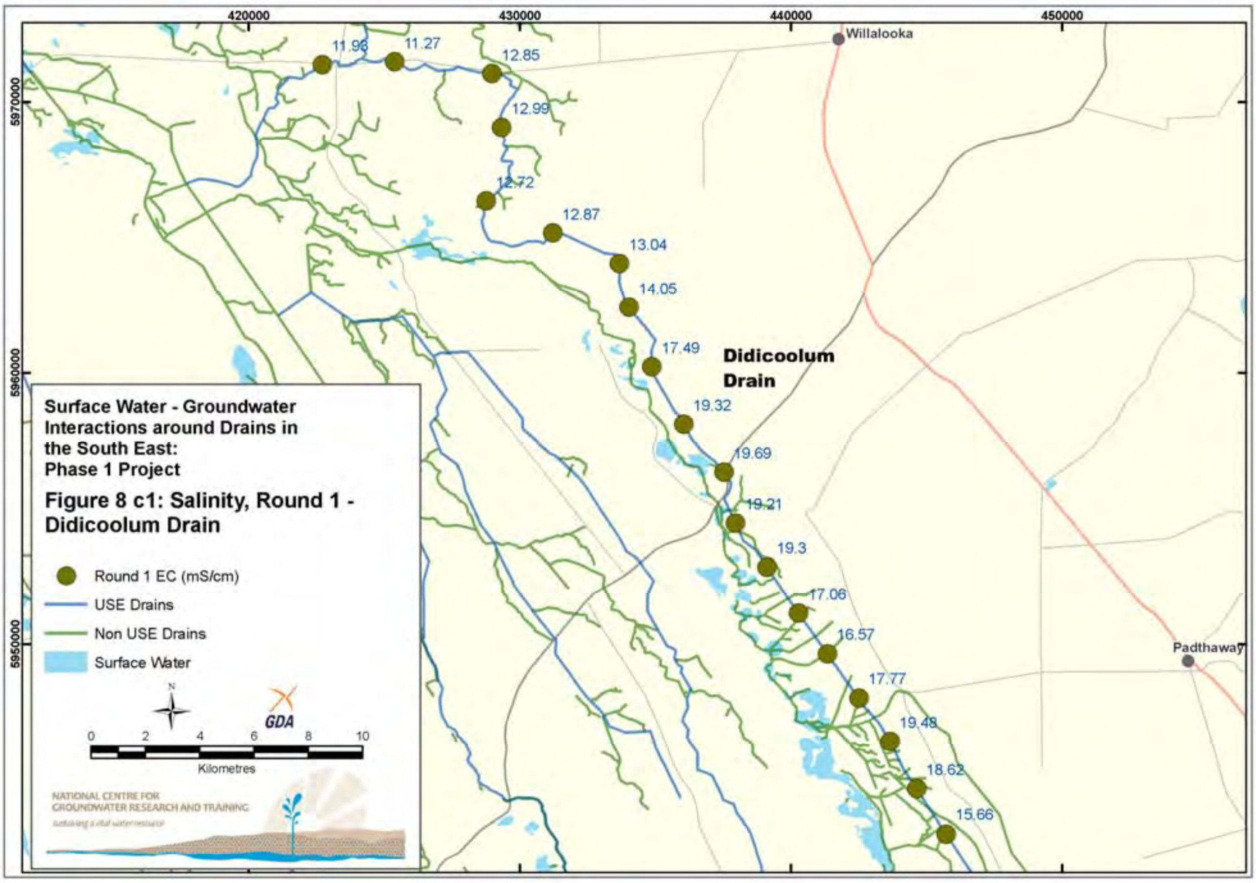


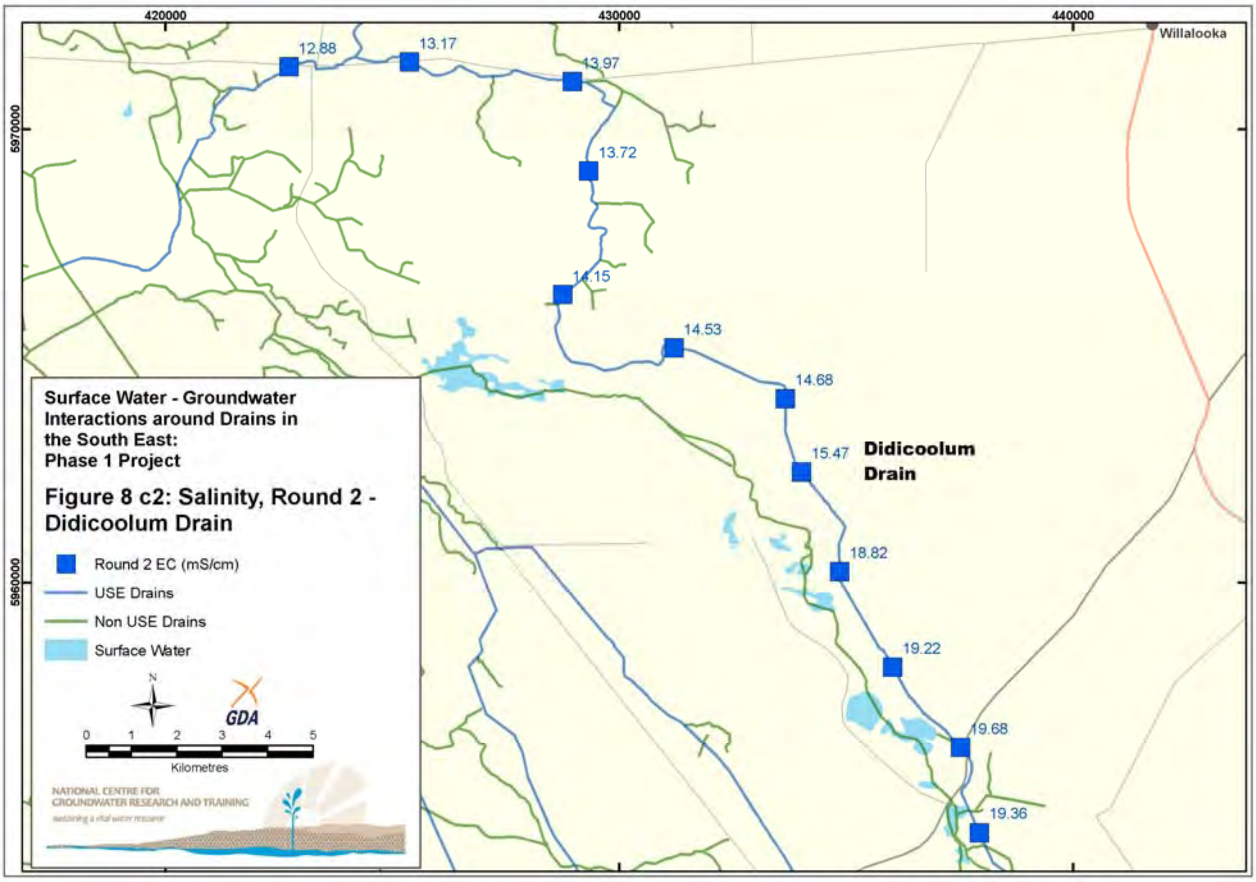
Figure 8 a2: Salinity, Round 2 - Mount Charles


390000
400000
410000
420000
5960000
5950000
12.26
15.88
16.32
18.02
20.33
21.81
20.45
25.18
27.82
16.69
6.35
8.75
8.69
8.41
8.81
9
8.53
8.74
8.64
8.58
7.22
7.21
7.15
7.96
7.54
Bald Hill Drain
Taratap Drain
Taratap
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8 b1: Salinity, Round 1 - Taratap and Bald Hill
Round 1 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
N
GDA
0 2 4 6 8 10
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

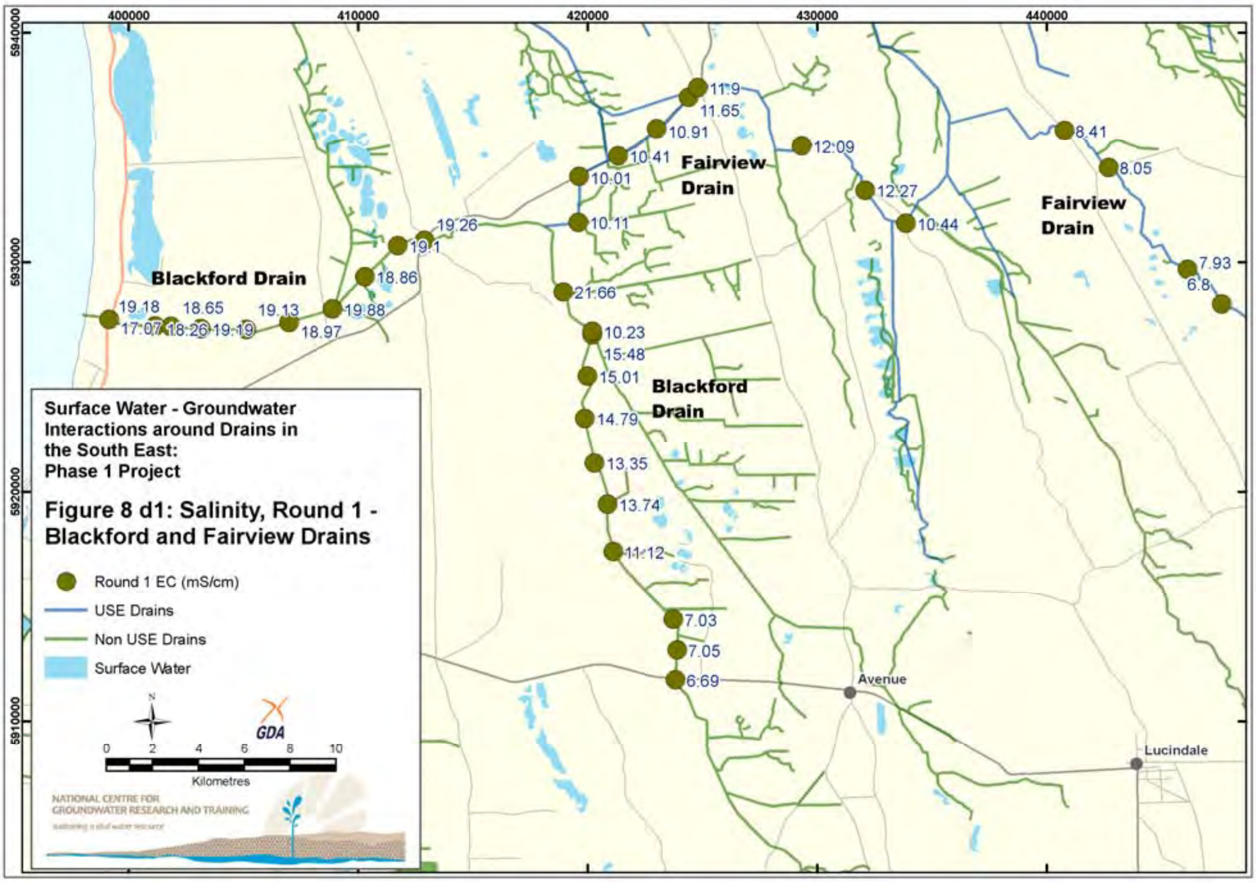

380000
390000
400000
410000
420000
5960000
5950000
5940000
14.8
14.9
15.18
15.48
16.98
16.72
15.61
14.44
15.16
14.79
4.31
7.29
7.18
7.33
7.37
7.43
7.53
7.49
7.53
7.52
7.46
7.45
7.83
7.86
7.86
8.96
9.13
9.22
8.93
8.66
8.55
7.01
7.17
Bald Hill Drain
Taratap Drain
Taratap
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8 b2: Salinity, Round 2 - Taratap and Bald Hill
Round 2 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
N
GDA
0 2 4 6 8 10
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING



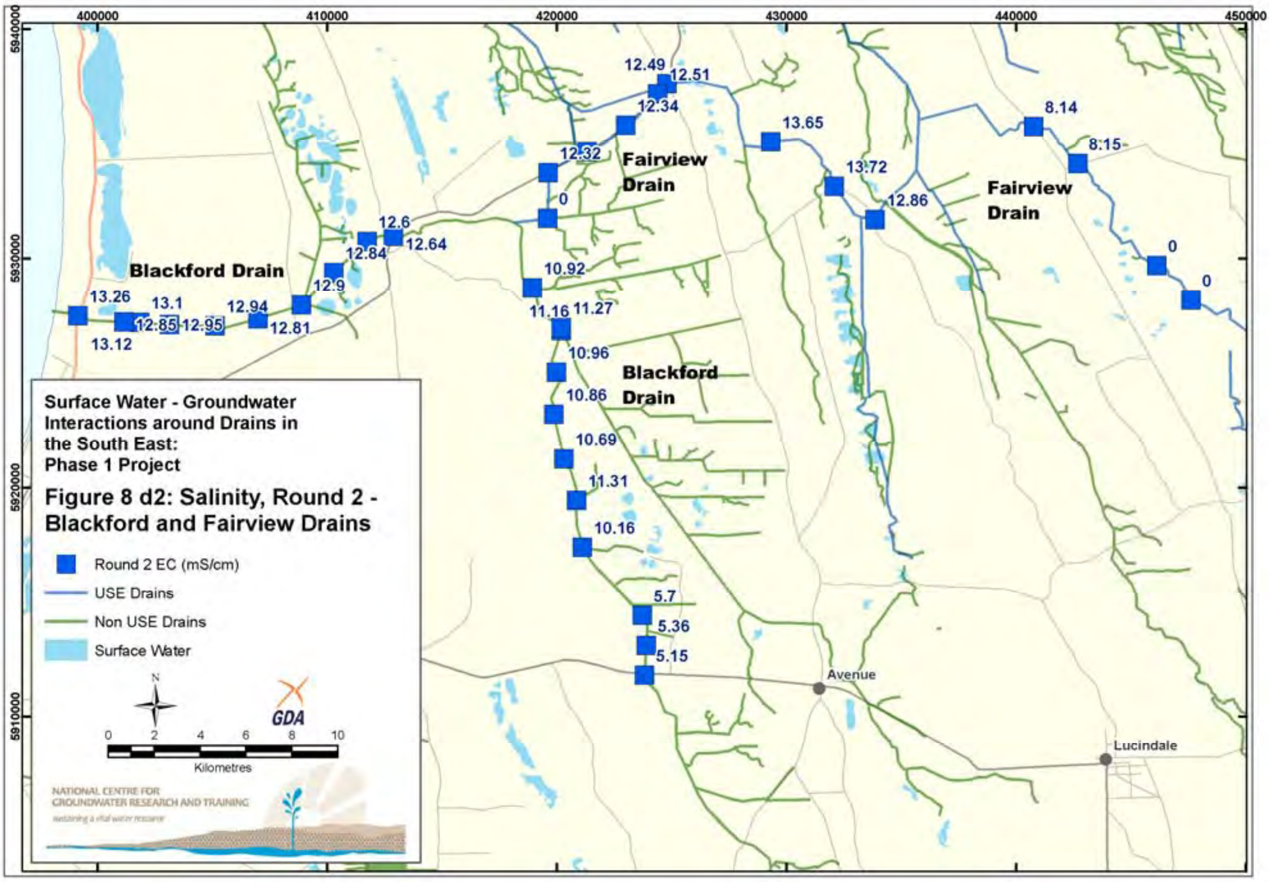
420000
430000
440000
450000
5970000
5960000
5950000
Willalooka
Padthaway
11.98
11.27
12.85
12.99
12.72
12.87
13.04
14.05
17.49
19.32
19.69
19.21
19.3
17.06
16.57
17.77
19.48
18.62
15.66
Didicoolum Drain
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8 c1: Salinity, Round 1 - Didicoolum Drain
Round 1 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
GDA
0 2 4 6 8 10
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING



420000
430000
440000
5970000
5960000
Willalooka
12.88
13.17
13.97
13.72
14.15
14.53
14.68
15.47
18.82
19.22
19.68
19.36
Didicoolum Drain
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8 c2: Salinity, Round 2 - Didicoolum Drain
Round 2 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
GDA
0 1 2 3 4 5
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8 d1: Salinity, Round 1 - Blackford and Fairview Drains
Round 1 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
Kilometres
GDA
Blackford Drain
Fairview Drain
Avenue
Lucindale



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8 d2: Salinity, Round 2 - Blackford and Fairview Drains
Round 2 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
Kilometres
GDA
Blackford Drain
Fairview Drain
Avenue
Lucindale

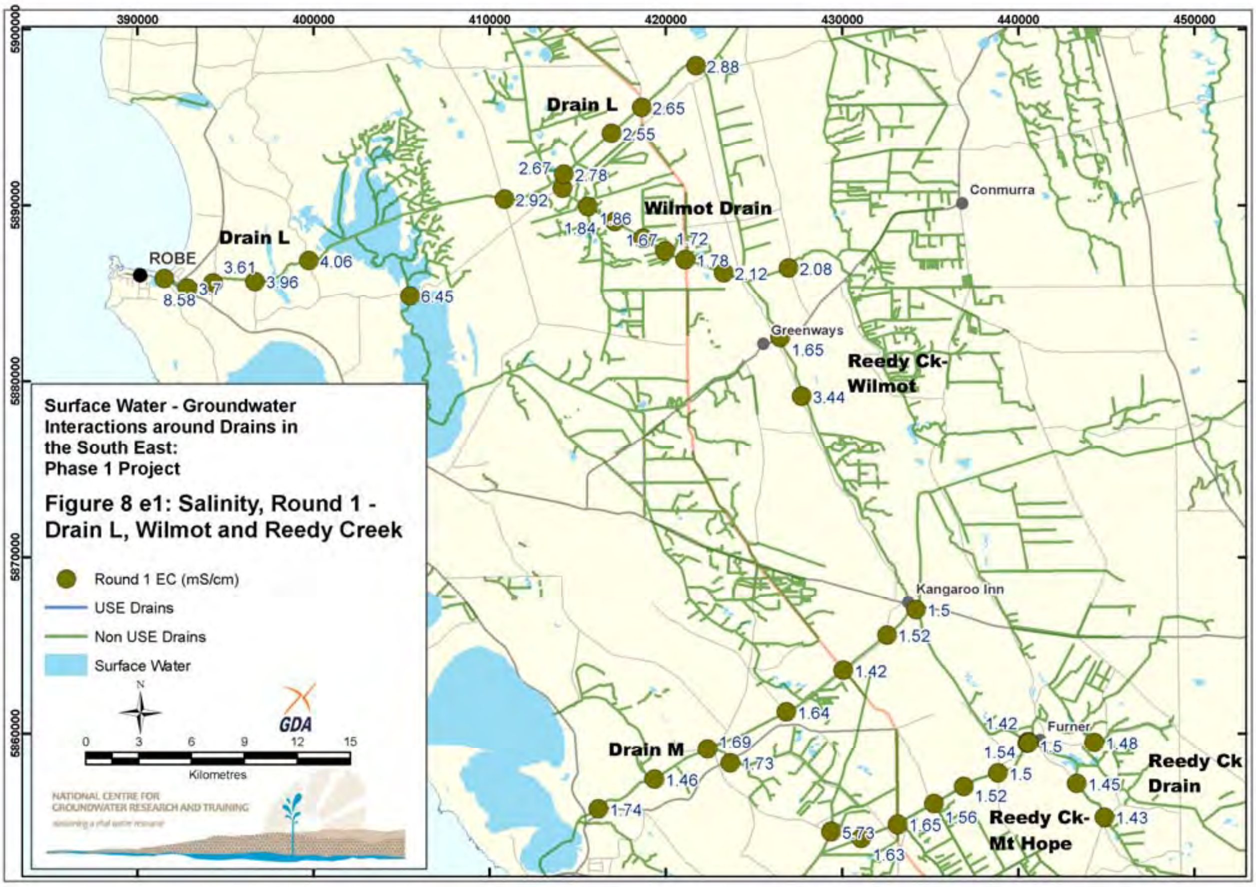
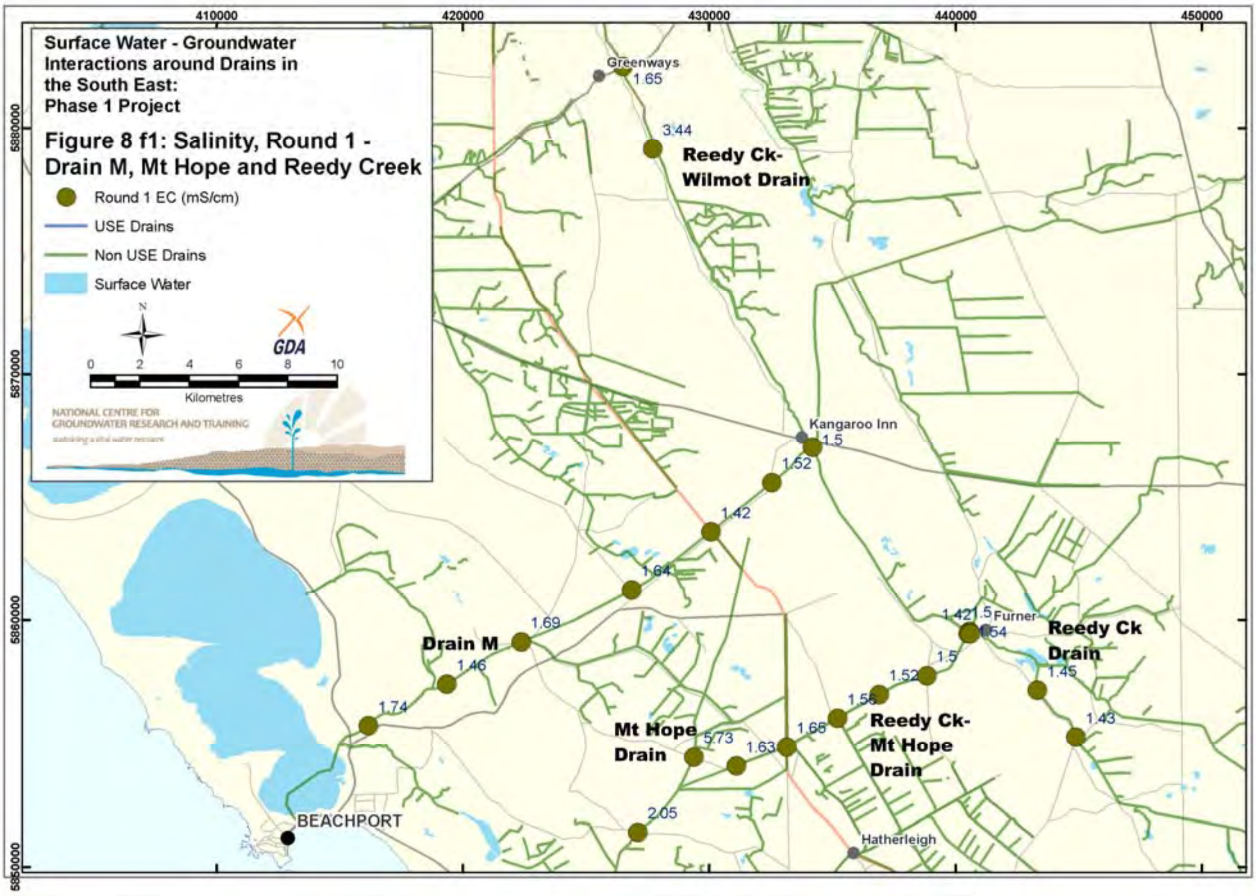
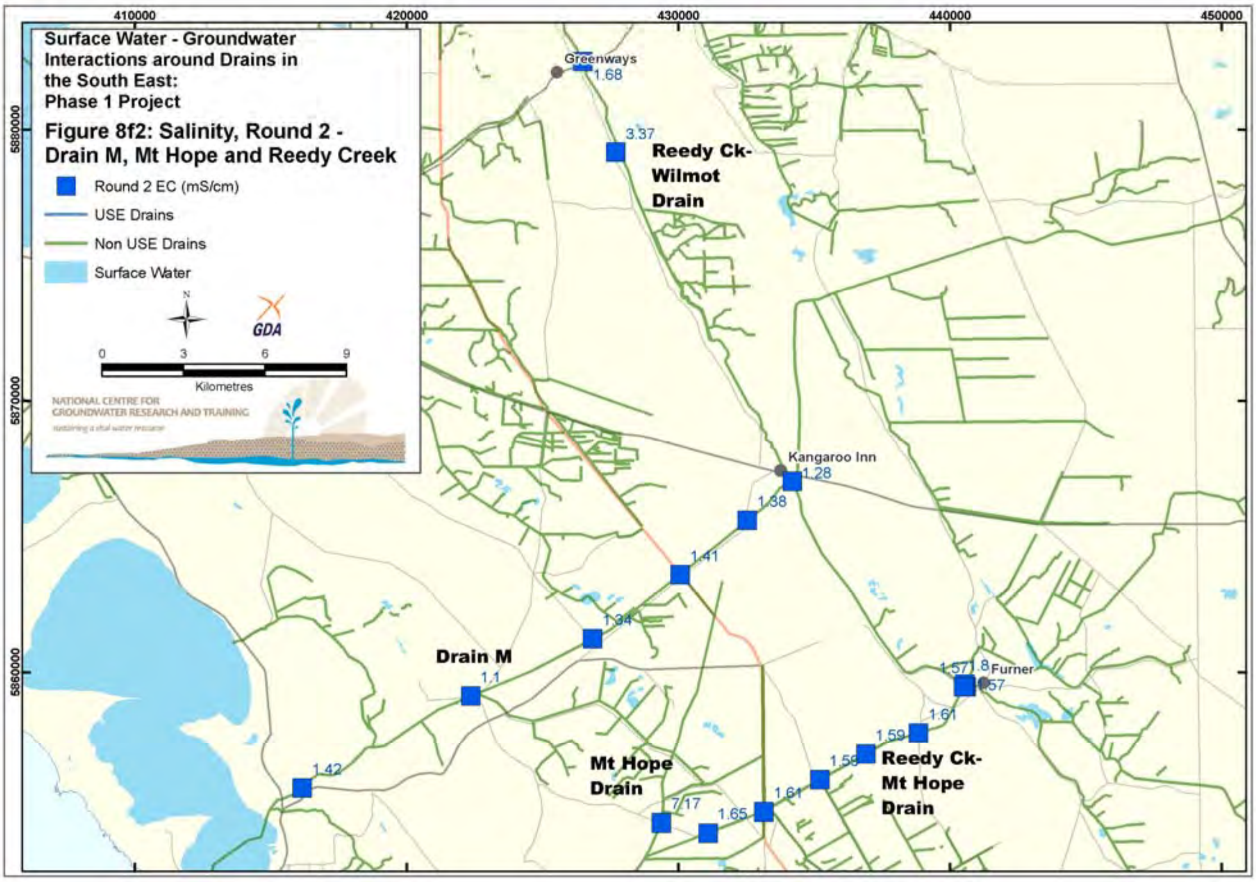


Figure 8 e1: Salinity, Round 1 - Drain L, Wilmot and Reedy Creek

Figure 8e2: Salinity, Round 2 - Drain L, Wilmot and Reedy Creek


Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8 f1: Salinity, Round 1 - Drain M, Mt Hope and Reedy Creek
Round 1 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Greenways
Reedy Ck-Wilmot Drain
Kangaroo Inn
Drain M
Mt Hope Drain
Reedy Ck-Mt Hope Drain
Reedy Ck Drain
Furner
BEACHPORT
Hatherleigh


Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 8f2: Salinity, Round 2 - Drain M, Mt Hope and Reedy Creek
Round 2 EC (mS/cm)
USE Drains
Non USE Drains
Surface Water
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Greenways
Reedy Ck-Wilmot Drain
Kangaroo Inn
Drain M
Mt Hope Drain
Reedy Ck-Mt Hope Drain
Furner

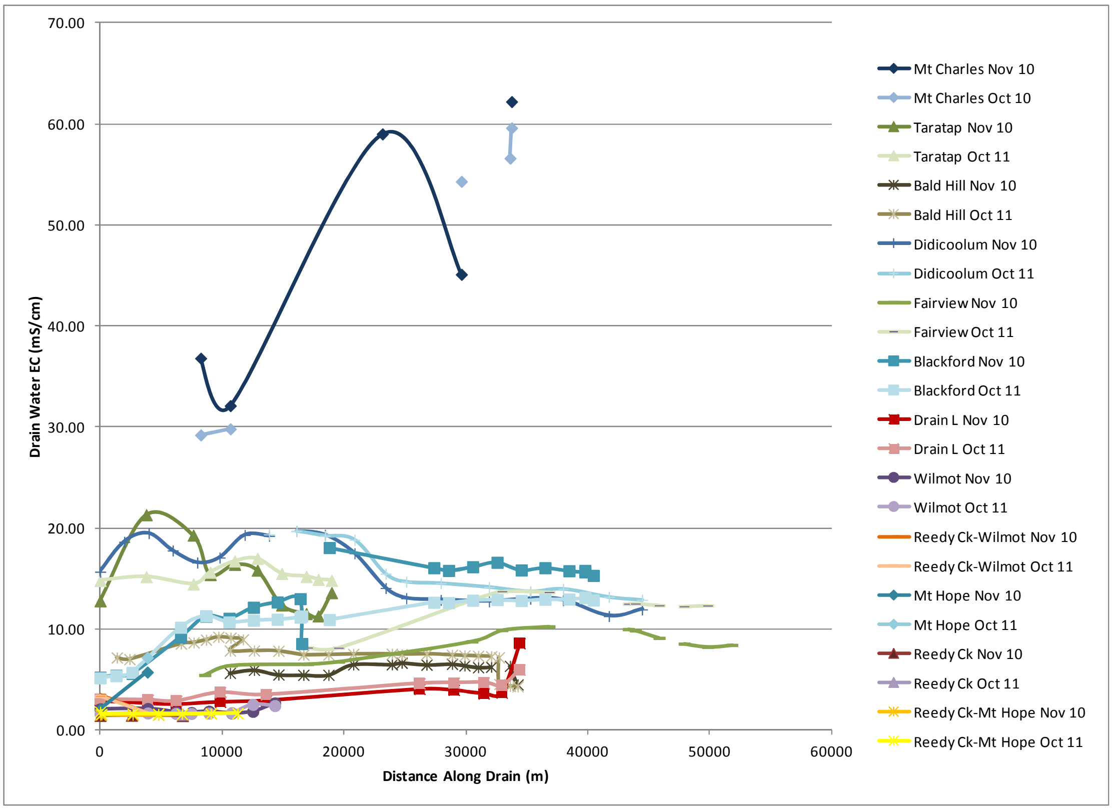


Figure 9a. Drain water EC versus distance along the drain for all drains sampled.

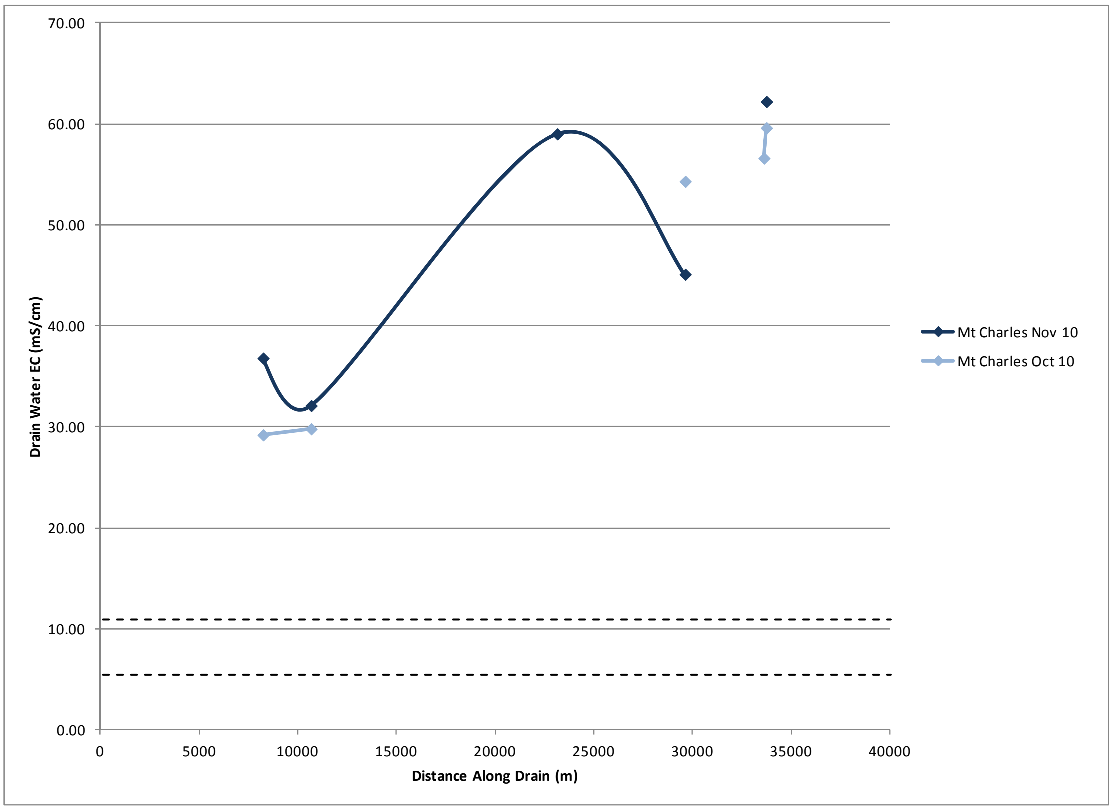


Figure 9b. Drain water EC versus distance along the drain for drains located in the "high regional groundwater EC zone". Ambient regional groundwater EC (5-11 mS/cm) is shown as a band between dashed lines on the graph.

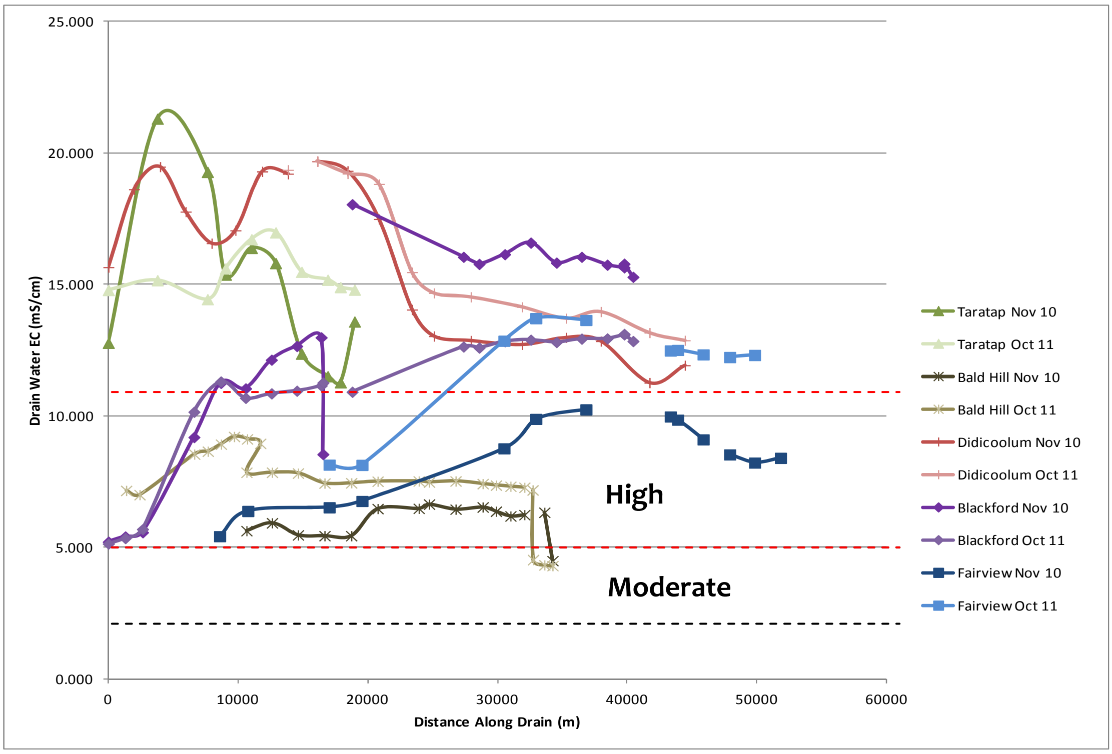


Figure 9c. Drain water EC versus distance along the drain for drains located in the "moderate-high regional groundwater EC zone". The main ambient regional groundwater EC (2.5-5 mS/cm) is shown as a band between black dashed lines on the graph. The high regional groundwater zone (5-11 mS/cm) is also shown (red dashed lines) as parts of the Bald Hill and Didicoolum Drains extend into this region.

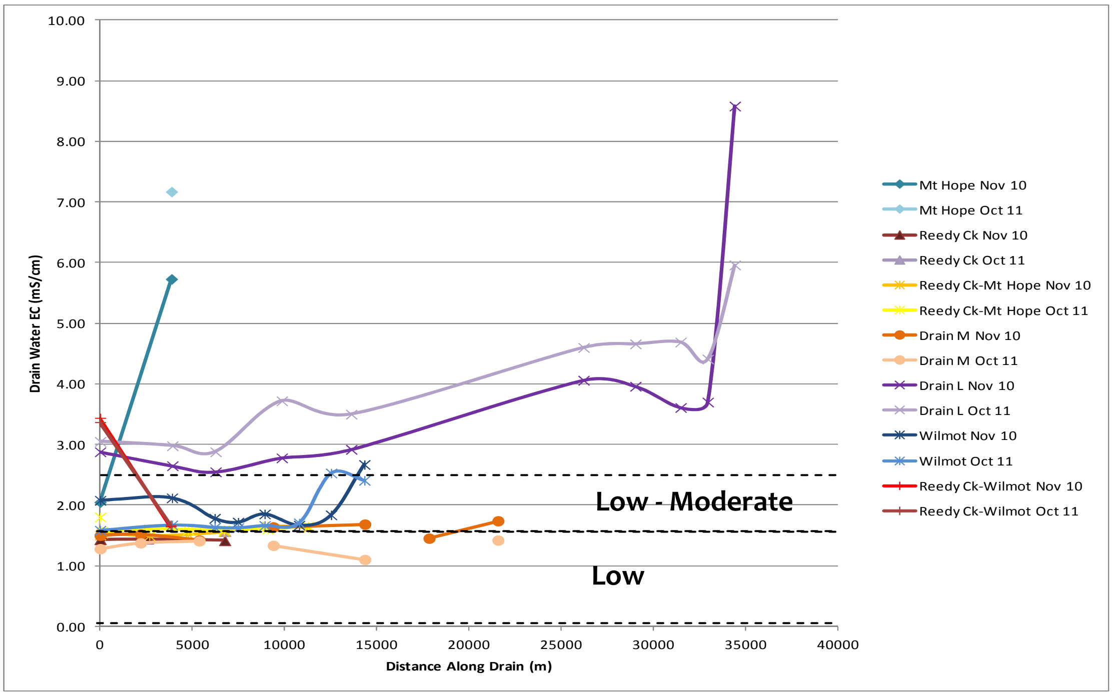


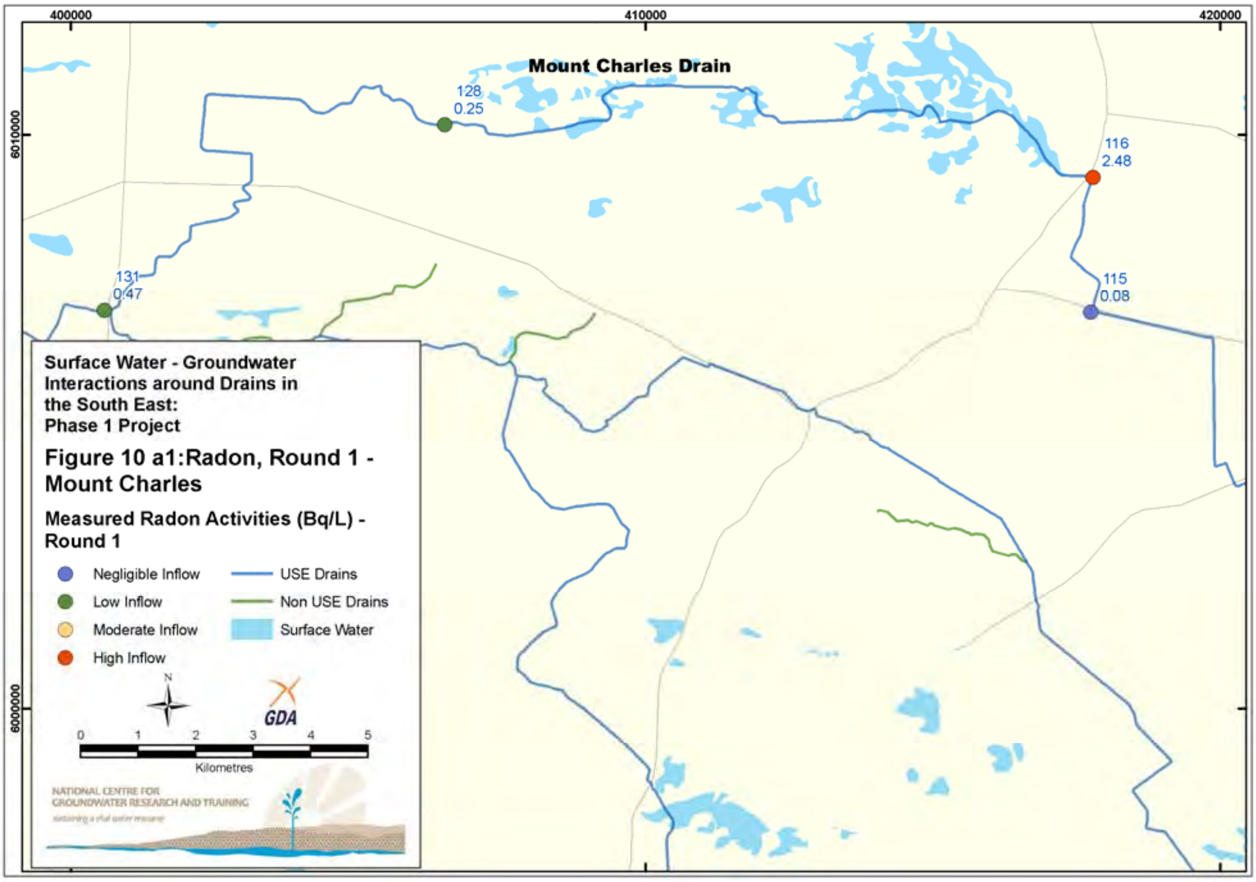
Figure 9d. Drain water EC versus distance along the drain for drains located in the "low-moderate and low regional groundwater EC zone". The two ambient regional groundwater EC zones are shown as dashed bands, low-moderate EC (1.5-2.5 mS/cm) and low EC (< 1.5 mS/cm).

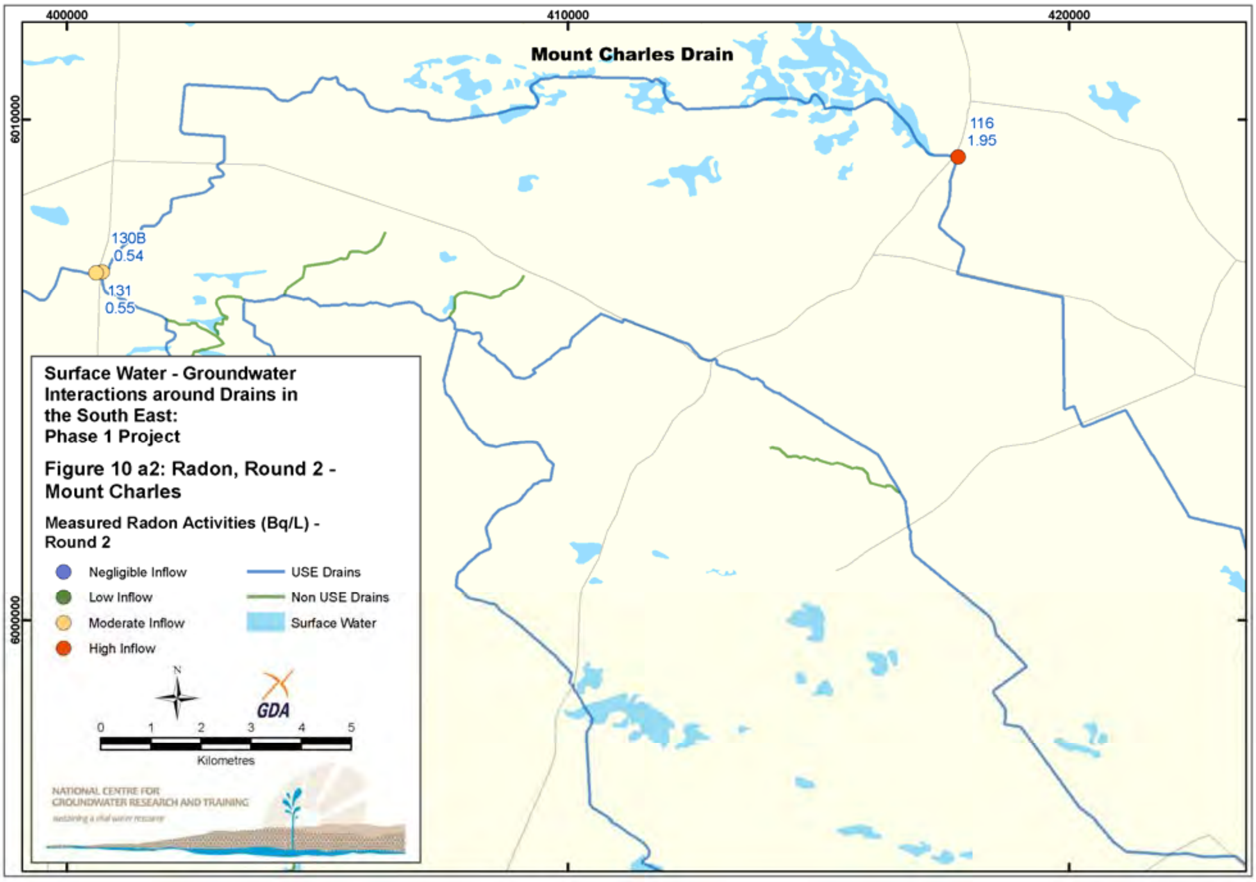
3.1.3 Radon

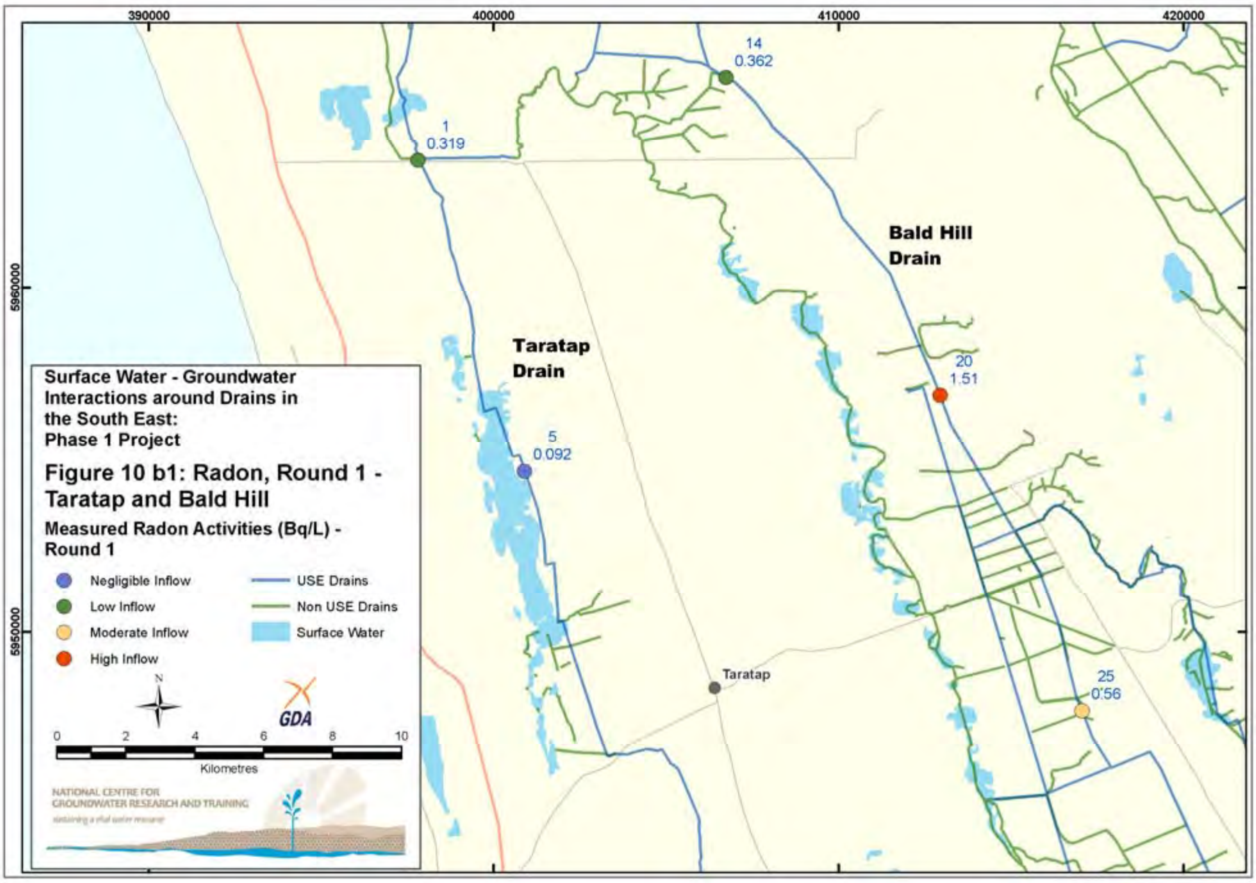
The radon activities measured on the drain water samples collected during both rounds 1 and 2 are shown on Figure 10(a-f). The sampling points are labeled with the site number (upper number) and radon activity (lower number). All data is provided in tabular form in Appendix B. Measured radon activities ranged between 0.02 Bq/L and 4.21 Bq/L. Table 7 is a qualitative guide to interpreting the surface water radon activities with regard to groundwater input. Radon activities above 0.1 Bq/L are considered to be significant with respect to groundwater input. Hence, it is of note that almost all of the samples (90% in round 2) showed some influence of groundwater inputs. The radon sampling program for round 2 was expanded from round 1 to attempt to gain a broader range of radon activities, particularly in the high range. Of the 58 samples collected during round 2, 31 (53%) had radon activities greater than 0.5 Bq/L, indicating at least moderate groundwater input and 13 (22%) had activities greater than 1 Bq/L, indicating a high influence of groundwater. The drains where this was most significant were those located in the northern part of the study area, with radon activities greater than 1 Bq/L being observed in the Mt Charles, Didicoolum and Bald Hill Drains (Fig. 10). The highest values of 3.66 and 4.21 Bq/L (these were the only values measured above 3 Bq/L) were from the upstream end of the Bald Hill Drain, just after the divergence of flow from the Fairview Drain. One value, just over 1 Bq/L, was also observed in each of the Reedy Creek-Wilmot (site 97) and Drain M (site 73) systems.

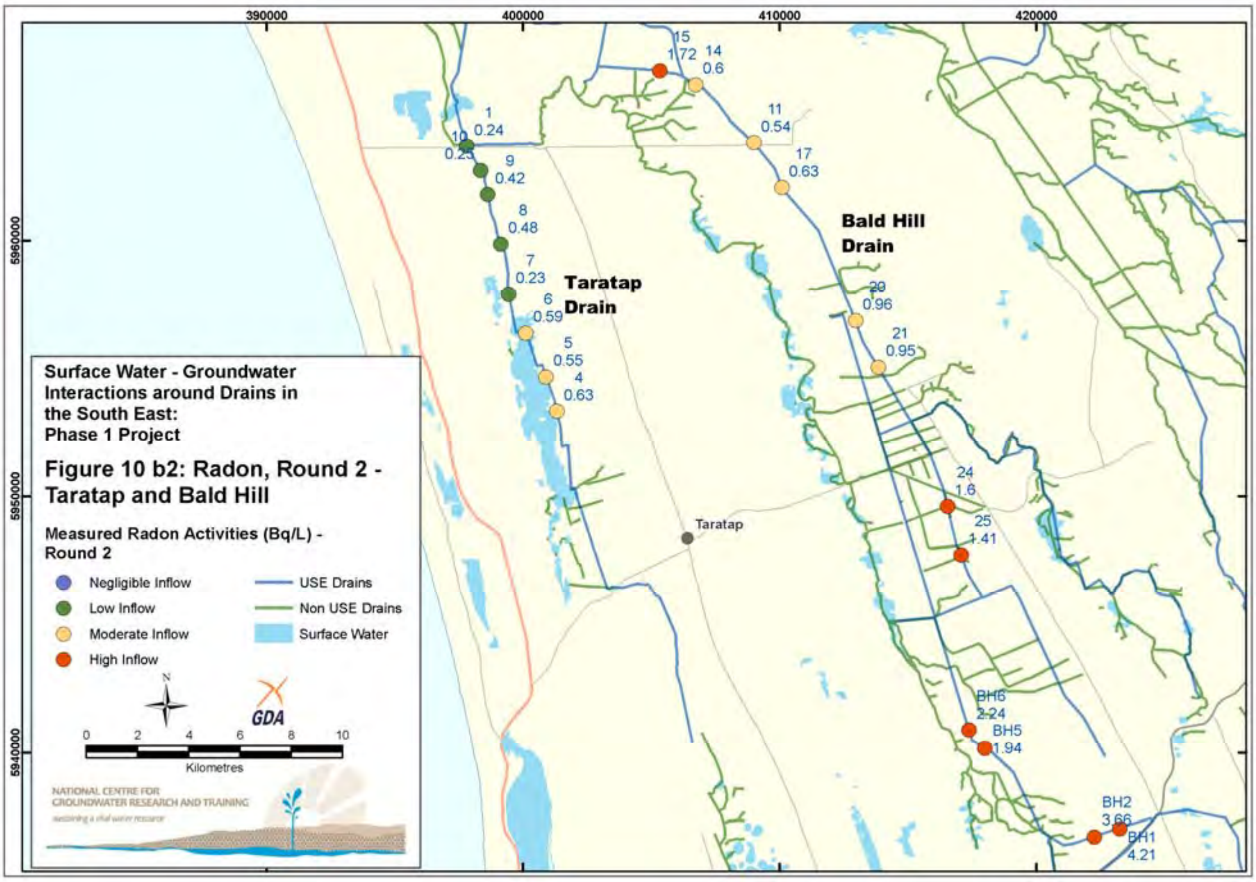
Table 7. Indicative guide to interpreting surface water Rn-222 activities with regard to groundwater input.

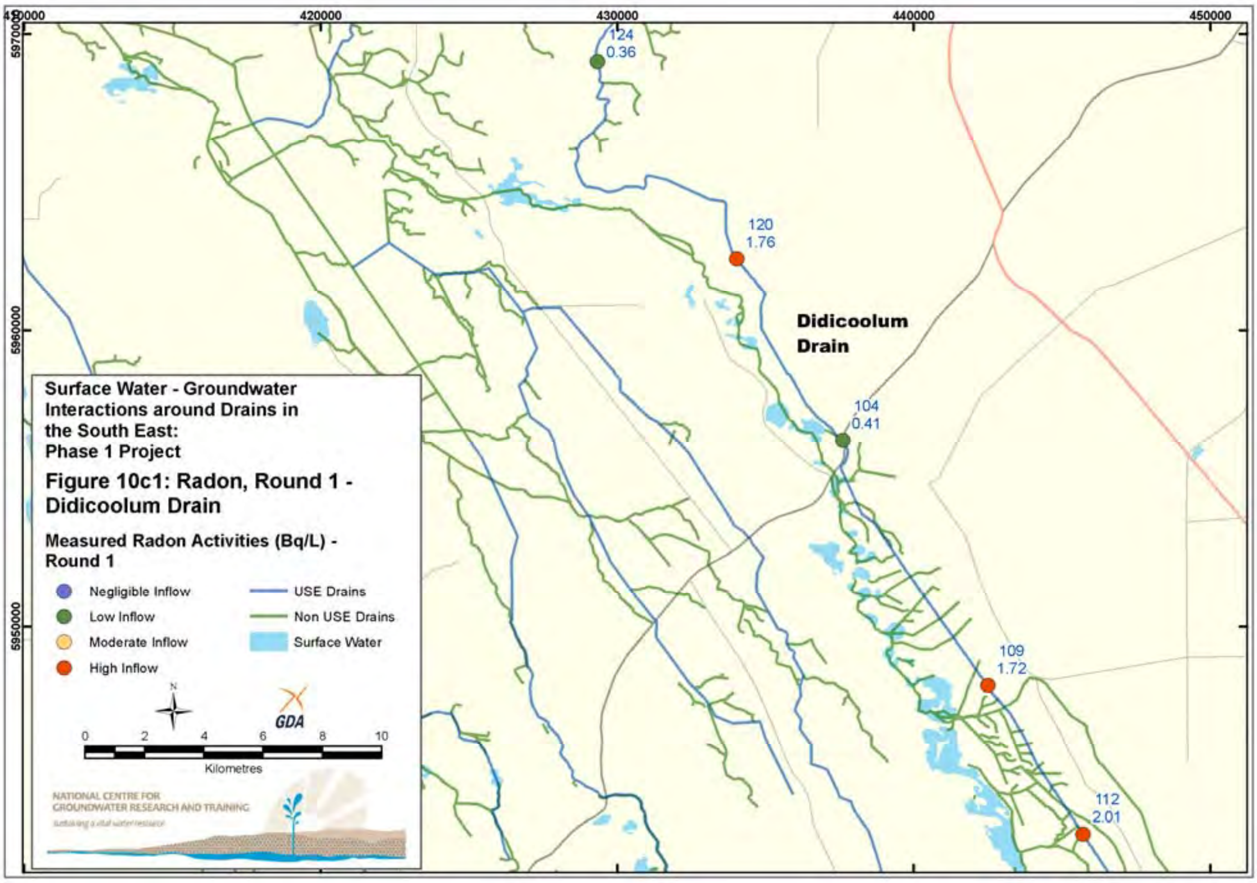
Rn-222 (Bq/L)	**Indicative groundwater input**
< 0.1	Negligible
0.1 – 0.5	Low
0.5 - 1	Moderate
> 1	High

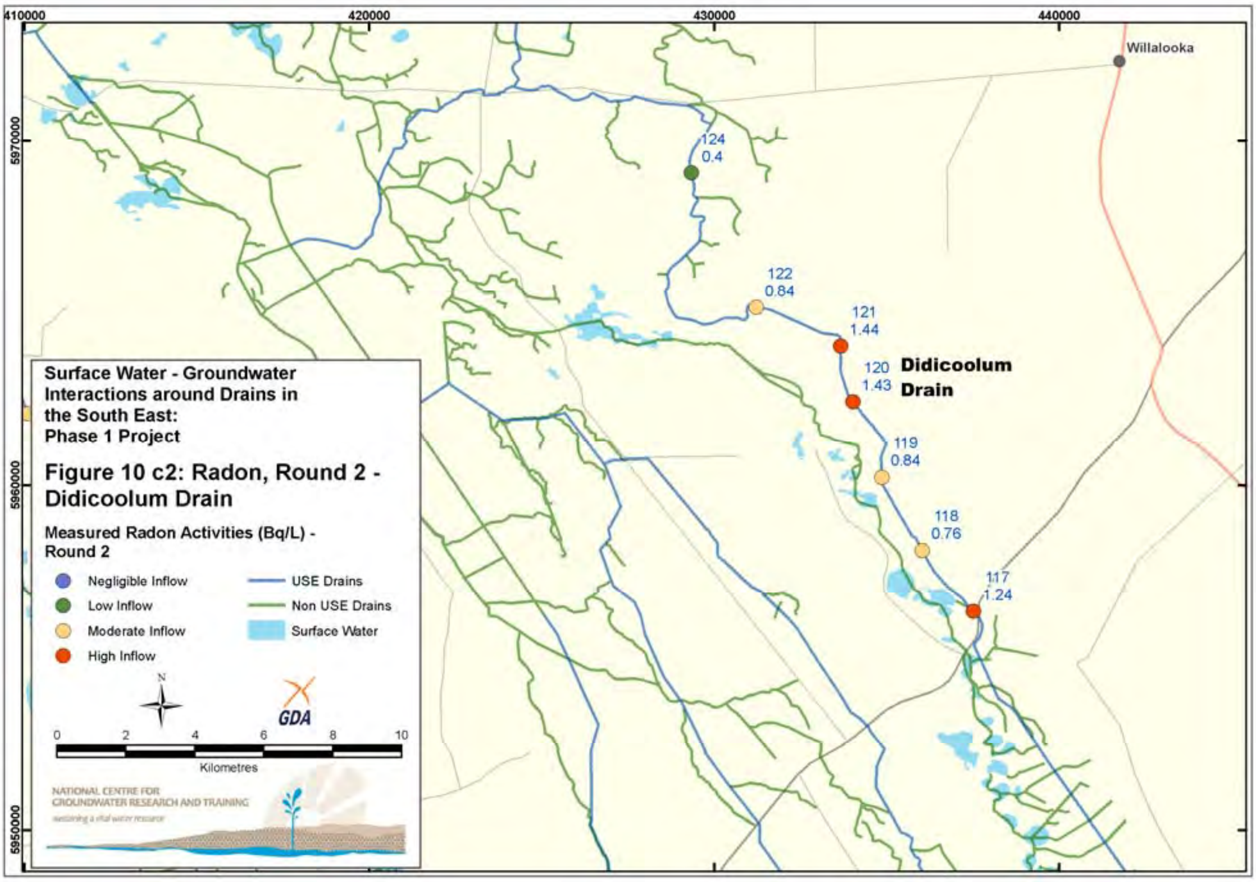

400000
410000
420000
6010000
6000000
Mount Charles Drain
128
0.25
116
2.48
131
0.47
115
0.08
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 a1:Radon, Round 1 - Mount Charles
Measured Radon Activities (Bq/L) - Round 1
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
N
GDA
0 1 2 3 4 5
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

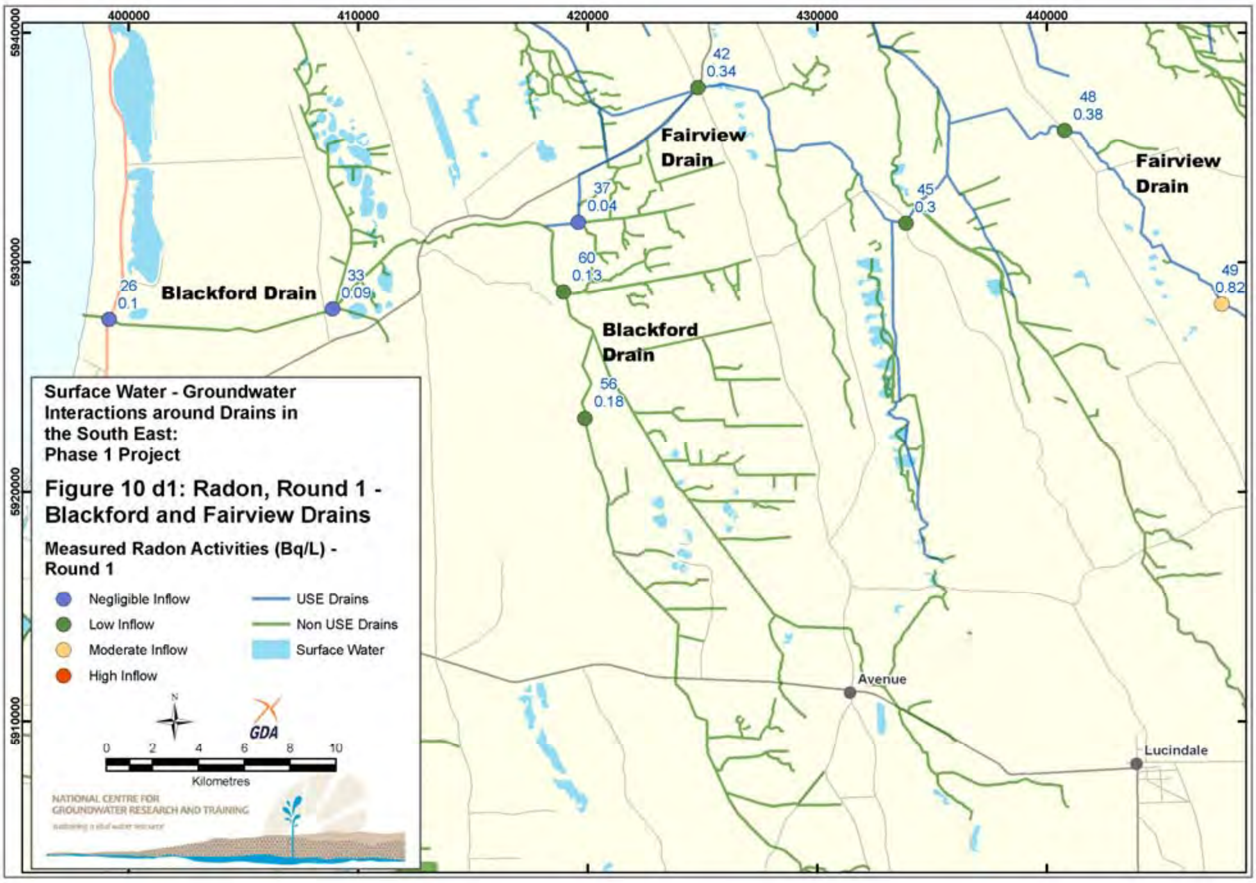

400000
410000
420000
6010000
6000000
Mount Charles Drain
116
1.95
130B
0.54
131
0.55
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 a2: Radon, Round 2 - Mount Charles
Measured Radon Activities (Bq/L) - Round 2
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
N
GDA
0 1 2 3 4 5
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

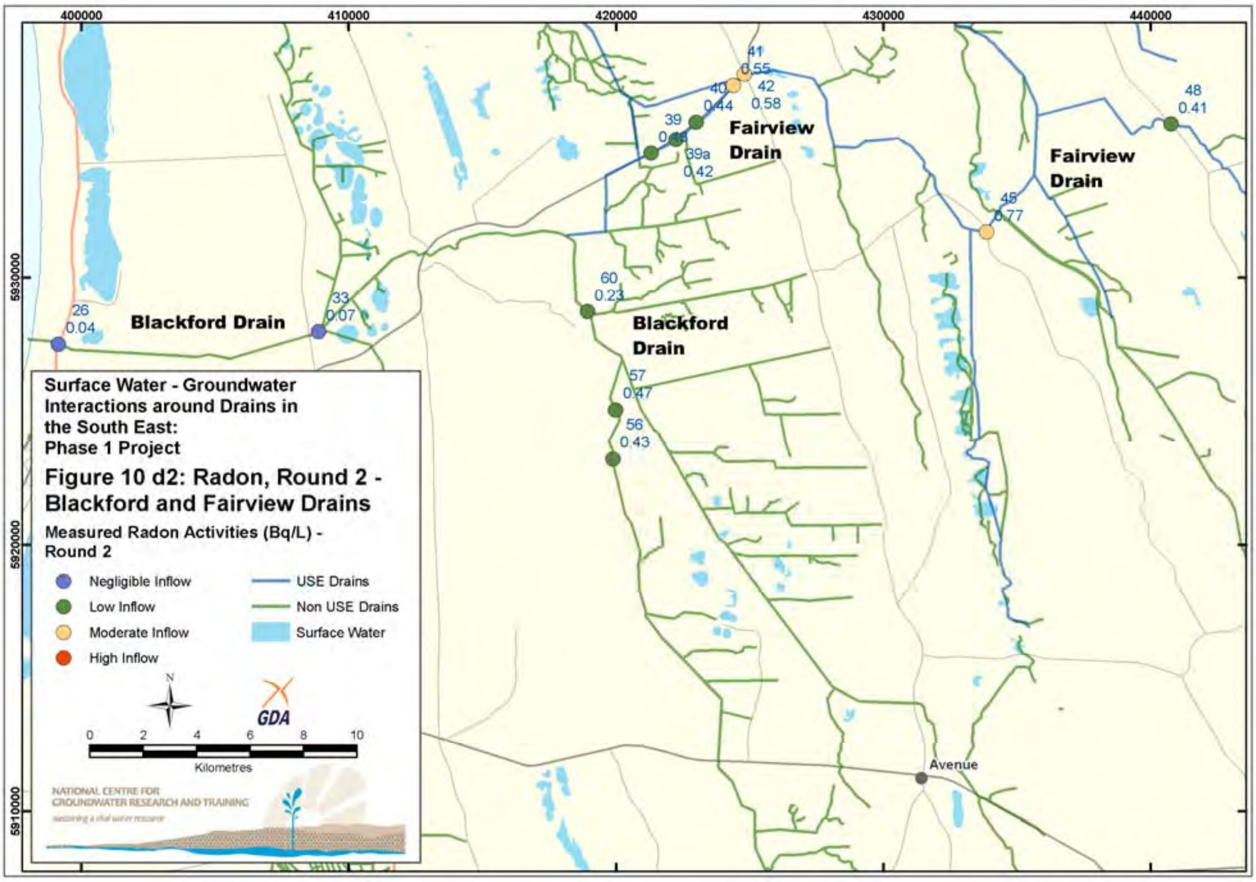

390000
400000
410000
420000
5960000
5950000
14
0.362
1
0.319
Bald Hill
Drain
Taratap
Drain
20
1.51
5
0.092
Taratap
25
0.56
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 b1: Radon, Round 1 - Taratap and Bald Hill
Measured Radon Activities (Bq/L) - Round 1
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
N
GDA
0
2
4
6
8
10
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

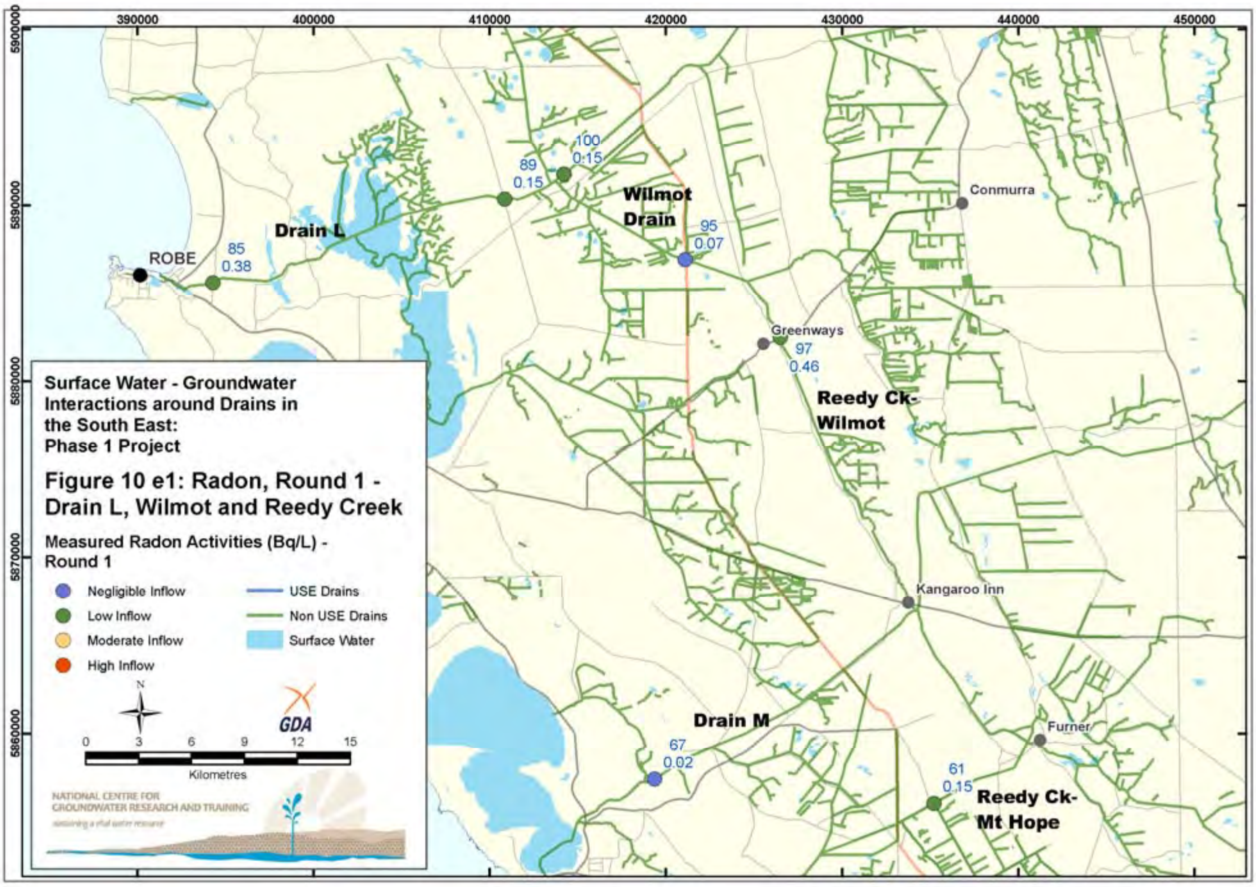

390000
400000
410000
420000
5960000
5950000
5940000
15
1.72
14
0.6
11
0.54
17
0.63
1
0.24
10
0.23
9
0.42
8
0.48
7
0.23
6
0.59
5
0.55
4
0.63
Taratap
Drain
Bald Hill
Drain
20
0.96
21
0.95
24
1.6
25
1.41
Taratap
BH6
2.24
BH5
1.94
BH2
3.66
BH1
4.21
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 b2: Radon, Round 2 - Taratap and Bald Hill
Measured Radon Activities (Bq/L) - Round 2
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
N
GDA
0
2
4
6
8
10
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING


410000
420000
430000
440000
450000
5970000
5960000
5950000
124
0.36
120
1.76
Didicoolum Drain
104
0.41
109
1.72
112
2.01
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10c1: Radon, Round 1 - Didicoolum Drain
Measured Radon Activities (Bq/L) - Round 1
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
GDA
0
2
4
6
8
10
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

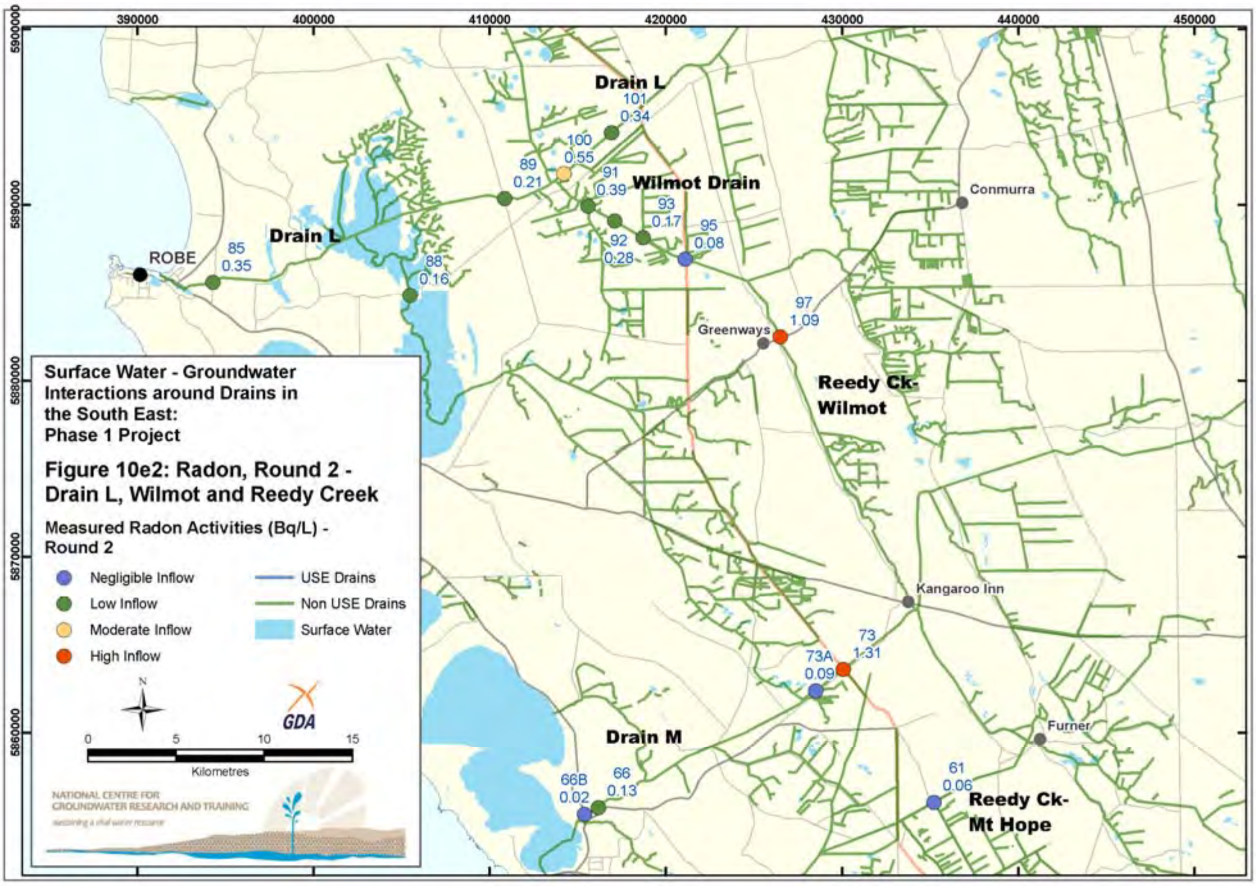

410000
420000
430000
440000
5970000
5960000
5950000
Willalooka
124
0.4
122
0.84
121
1.44
120
1.43
Didicoolum Drain
119
0.84
118
0.76
117
1.24
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 c2: Radon, Round 2 - Didicoolum Drain
Measured Radon Activities (Bq/L) - Round 2
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
GDA
0
2
4
6
8
10
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING


Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 d1: Radon, Round 1 - Blackford and Fairview Drains
Measured Radon Activities (Bq/L) - Round 1
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
Kilometres
Blackford Drain
Fairview Drain
Avenue
Lucindale
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

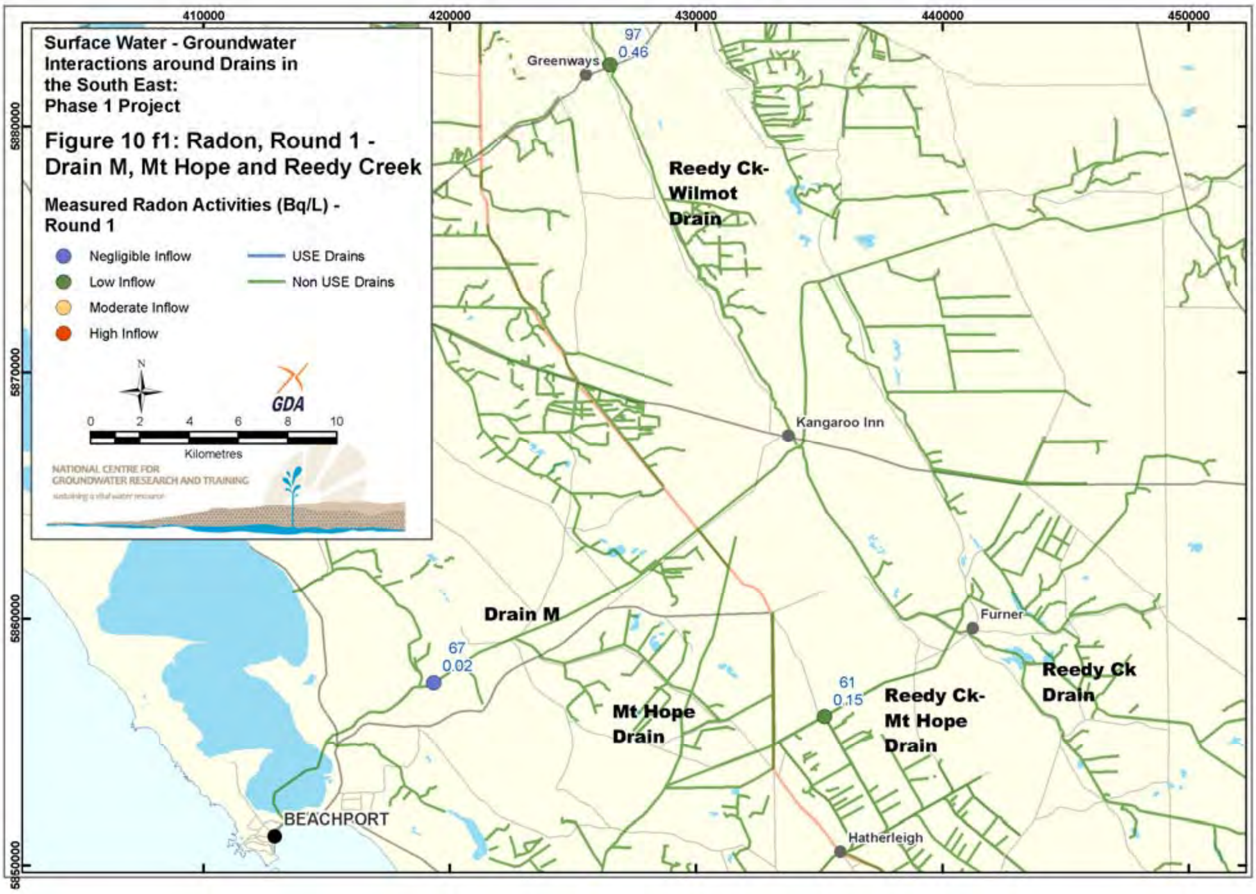

Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 d2: Radon, Round 2 - Blackford and Fairview Drains
Measured Radon Activities (Bq/L) - Round 2
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
Kilometres
Blackford Drain
Fairview Drain
Avenue
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING



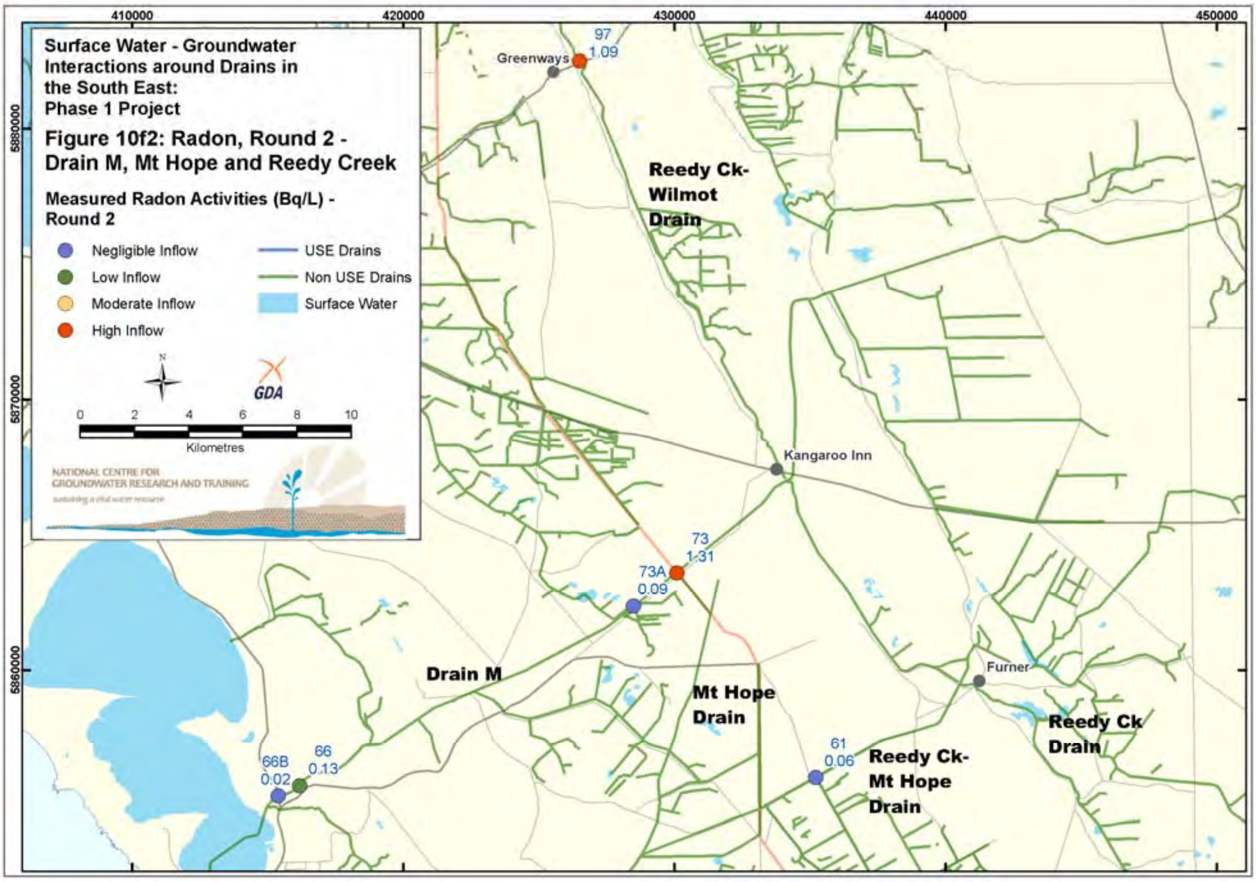
Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 e1: Radon, Round 1 - Drain L, Wilmot and Reedy Creek
Measured Radon Activities (Bq/L) - Round 1
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
GDA
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
ROBE
Drain L
Wilmot Drain
Conmurra
Greenways
Reedy Ck-Wilmot
Kangaroo Inn
Drain M
Furner
Reedy Ck-Mt Hope
85 0.38
89 0.15
100 0.15
95 0.07
97 0.46
67 0.02
61 0.15



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10e2: Radon, Round 2 - Drain L, Wilmot and Reedy Creek
Measured Radon Activities (Bq/L) - Round 2
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
GDA
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
ROBE
Drain L
Wilmot Drain
Conmurra
Greenways
Reedy Ck-Wilmot
Kangaroo Inn
Drain M
Furner
Reedy Ck-Mt Hope
85 0.35
88 0.16
89 0.21
100 0.55
101 0.34
91 0.39
93 0.17
92 0.28
95 0.08
97 1.09
73 1.31
73A 0.09
66B 0.02
66 0.13
61 0.06



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10 f1: Radon, Round 1 - Drain M, Mt Hope and Reedy Creek
Measured Radon Activities (Bq/L) - Round 1
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
GDA
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Greenways
97
0.46
Reedy Ck-Wilmot Drain
Kangaroo Inn
Drain M
67
0.02
Mt Hope Drain
61
0.15
Reedy Ck-Mt Hope Drain
Furner
Reedy Ck Drain
BEACHPORT
Hatherleigh



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 10f2: Radon, Round 2 - Drain M, Mt Hope and Reedy Creek
Measured Radon Activities (Bq/L) - Round 2
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
USE Drains
Non USE Drains
Surface Water
GDA
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Greenways
97
1.09
Reedy Ck-Wilmot Drain
Kangaroo Inn
73
1.31
73A
0.09
Drain M
Mt Hope Drain
66B
0.02
66
0.13
61
0.06
Reedy Ck-Mt Hope Drain
Furner
Reedy Ck Drain

3.2 Installation of Infrastructure for Detailed Measurement of Surface Water – Groundwater Interactions

This project aimed to install infrastructure that will be subsequently used for research projects to study surface water – groundwater interactions at local scales. This section provides some results from preliminary experiments and monitoring using the new instrumentation.

3.2.1 Preliminary Data from Initial Flooding of Reflows Western Floodway

The current focus for this site is to use the flood wave progression data to characterize the stream bed hydraulic conductivity (K). The variability in flood wave velocity (Fig. 11(a)) is a function of channel friction and surface water infiltration thereby enabling calculation of streambed K. Figure 11 (b) shows the flow data collected during this experiment.

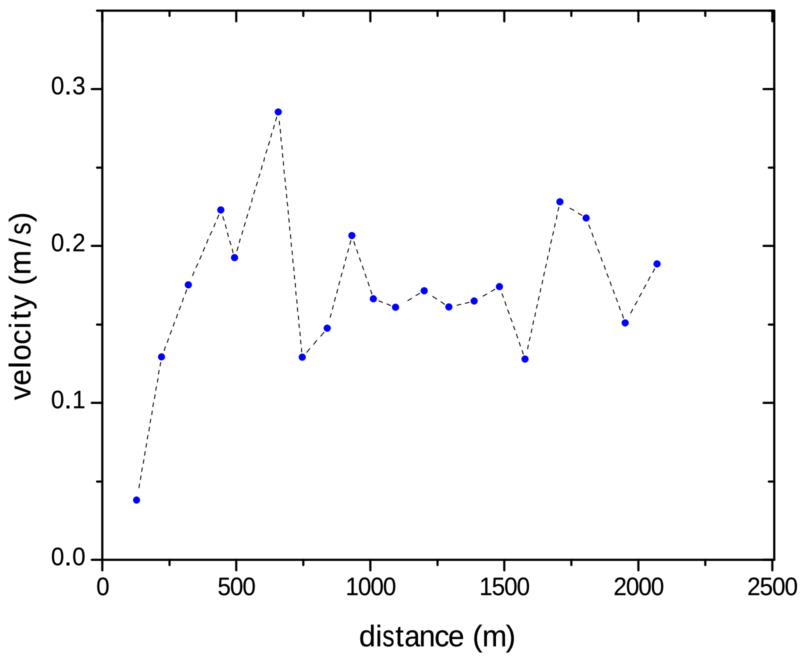


Figure 11(a). Flood wave velocity as it flows down the channel

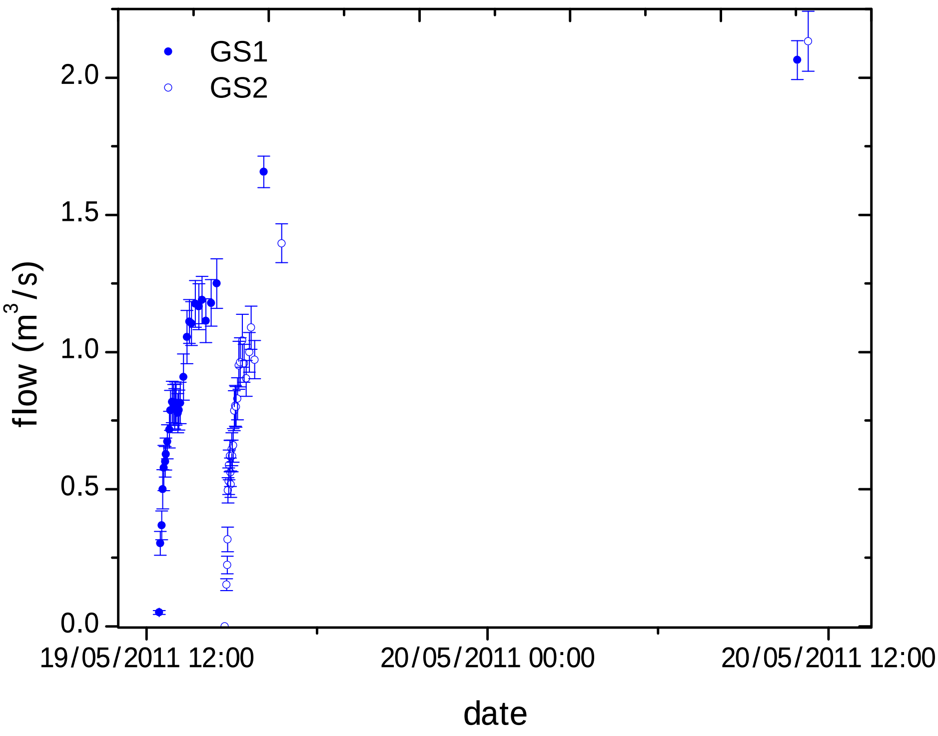


Figure 11(b) Flow at the upstream (GS1) and downstream (GS2) gauging point.

3.2.2 Fairview Stage Change Experiment

A 0.9m decline in stream stage was achieved in this trial stage change experiment; it resulted in a ~0.6m drop in groundwater level adjacent (up to 30m) to the drain. Figure 12 shows both the groundwater and salinity responses to the stage change. The variability in the groundwater salinity response is indicative of the bank storage processes whereby the rise in stream stage infiltrates into the bank and the subsequent gradient reversal in response to the decline in stream stage moves this water back into the stream.

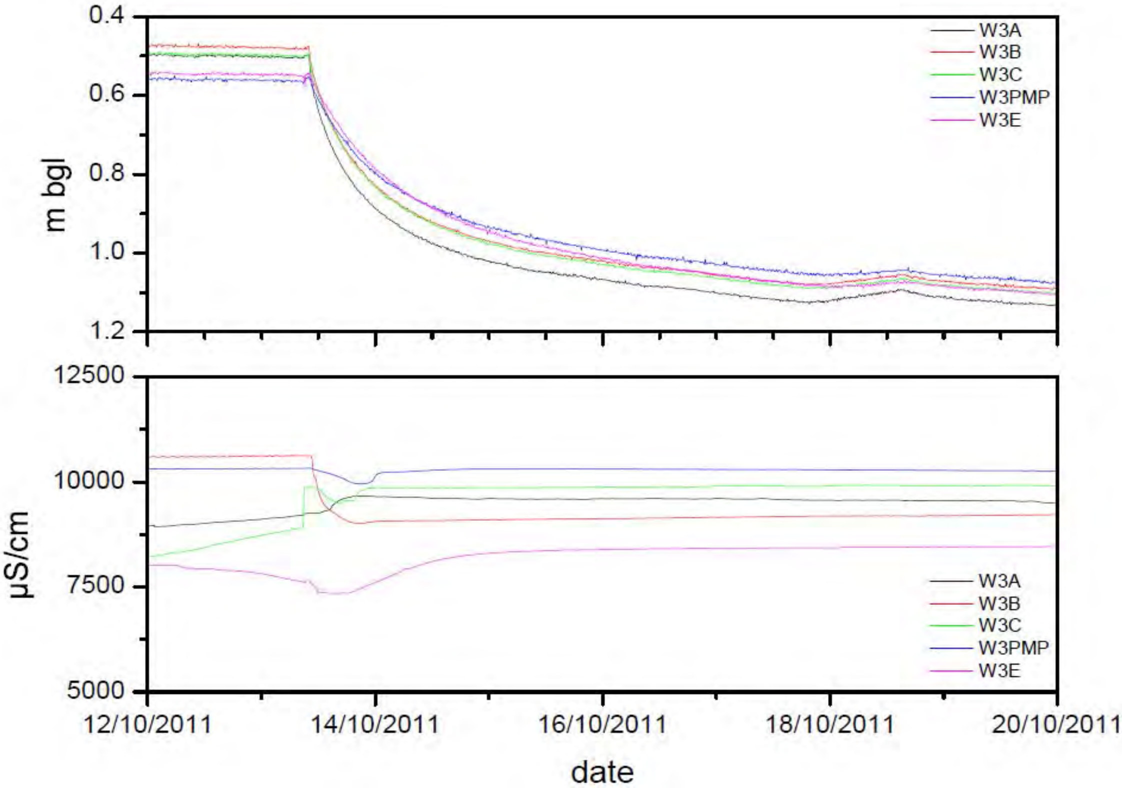


Figure 12(a) Transect 3 observation bore groundwater response.

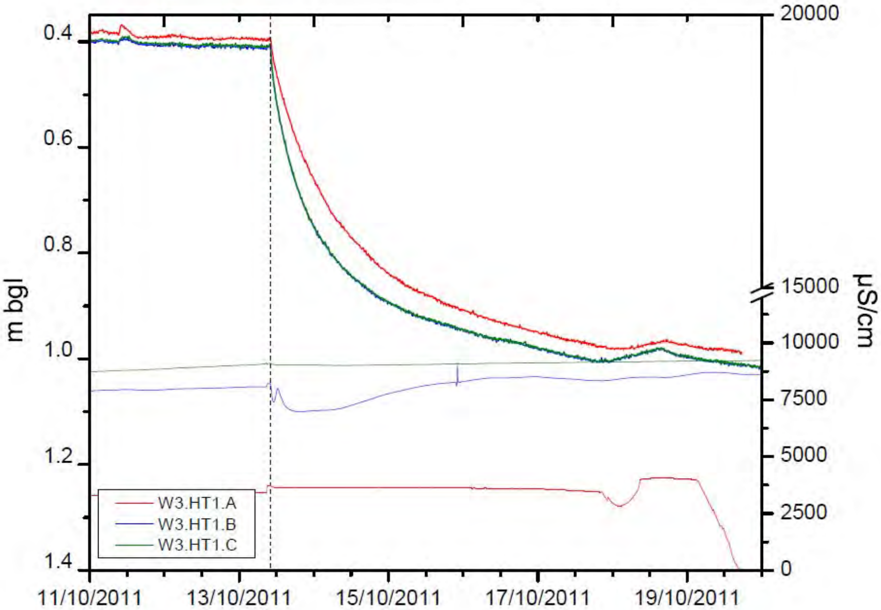


Figure 12(b). Nest Bore W3.HT1 groundwater response.

4 Discussion

4.1 EC as an Indicator of Surface Water – Groundwater Interactions around the Drains in the South East

One of the objectives of this study was to evaluate methodologies for qualitatively and quantitatively assessing the interactions between groundwater and the drains in the South East. EC is cheap, quick, and easy to measure and hence is one of the first methodologies that should be assessed. EC can be a useful indicator of groundwater inputs to streams if the EC of the groundwater end-member is well defined and sufficiently different from that of the surface water being investigated.

Figure 13 shows a regional map of EC of groundwater in the unconfined aquifer as zones interpolated from observation well EC data. These zones are based on data from wells that are generally of the order of 10 km apart across most of the study area. In a landscape where processes such as irrigation water recycling, water table fluctuations, dryland salinization (accumulation of salt in the root zone and subsequent flushing of this salt into groundwater) and evapotranspiration from surface water and shallow groundwater are likely to cause large localized variations in groundwater salinity, it is clear that the EC of any groundwater inflows to the drains (also a localized process) will be difficult to constrain without large amounts of groundwater EC data. This limits the applicability of EC to quantifying surface water-groundwater interactions in the South East. However, any significant fluctuations in EC of the drain waters may be qualitatively interpreted in the context of the ambient regional groundwater EC, provided that the limitations described above are also considered.

Figure 13 shows where the drains included in this study lie in relation to the regional groundwater EC zones. Many lie in distinct zones, whilst some straddle groundwater EC zones. The drains are separated into groups based on the zones in which they predominantly lie in Figure 9 (b-d) and the regional groundwater EC zones are shown as horizontal bands on the graphs. Fluctuations in drain water ECs have been qualitatively interpreted using these graphs in relation to interactions with the groundwater system. The conclusions from this are summarized in Table 8, and on Figure 14, and discussed below.

Figure 13 and Figure 9 (b-d) show that, in some cases, e.g. Mt Charles Drain, Taratap Drain, Didicoolum Drain, and Blackford Drain, drain water ECs are sufficiently different from regional groundwater ECs and there are large reaches with no tributary inflows, so that some qualitative conclusions can be drawn from EC data about groundwater inputs to the drains (Table 8). In the case of the Fairview drain and the upper reaches of the Blackford Drain, drain ECs are sufficiently different from groundwater values, but there are numerous tributaries flowing into the drains making interpretation of EC data complex. In the case of the Wilmot Drain, Reedy Creek, Reedy Creek – Mt Hope and Drain M, drain water ECs are similar to regional groundwater ECs, making interpretation of EC data in terms of groundwater inflow non-viable. As described above, there is considerable uncertainty in the interpretations summarized in Table 8 due to the possibility of local variations in groundwater EC around the drains that are not reflected on the regional map. The only way of resolving this and hence improving confidence in conclusions drawn from EC data is to better characterize groundwater EC at a local scale around the drains of interest.

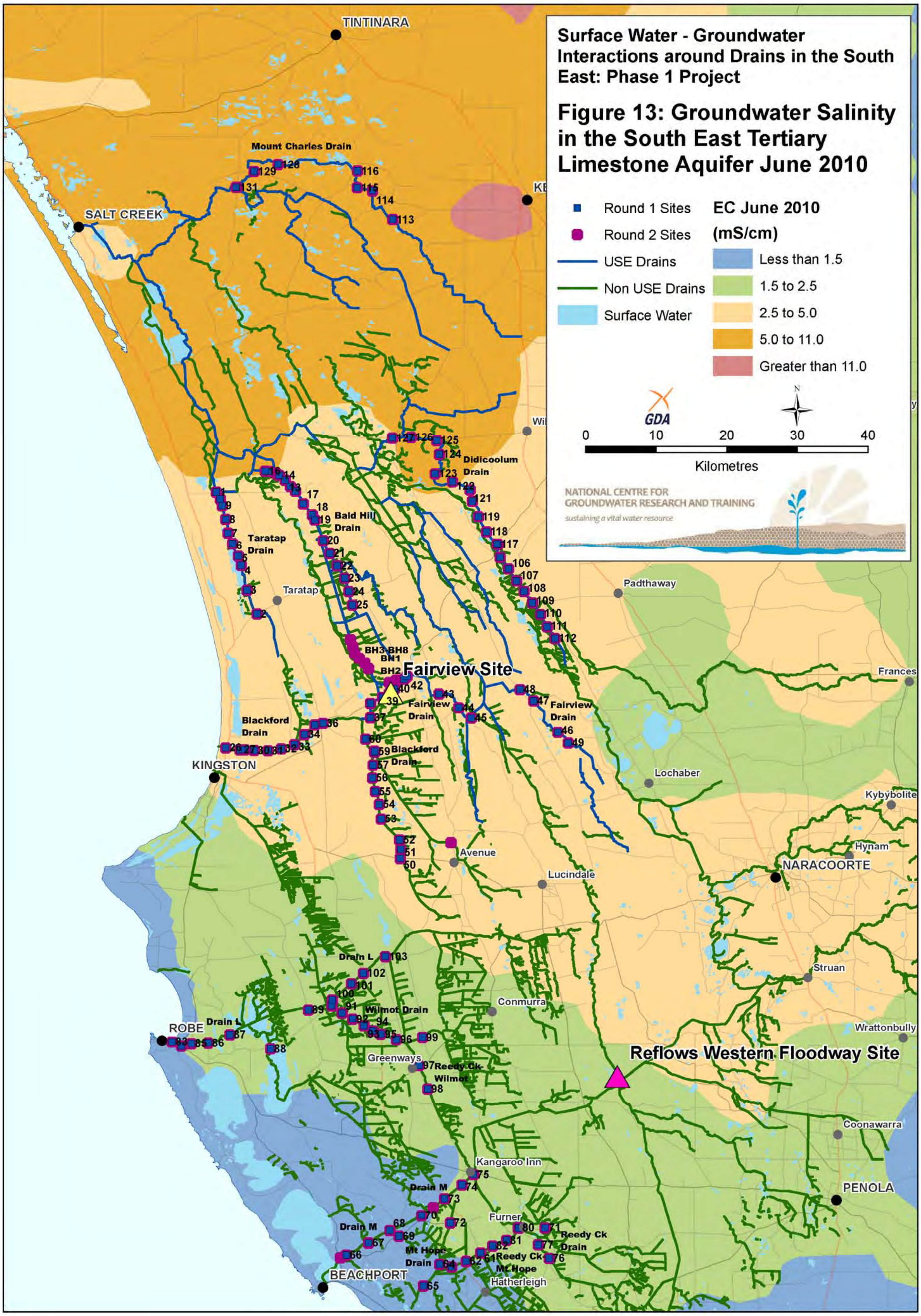
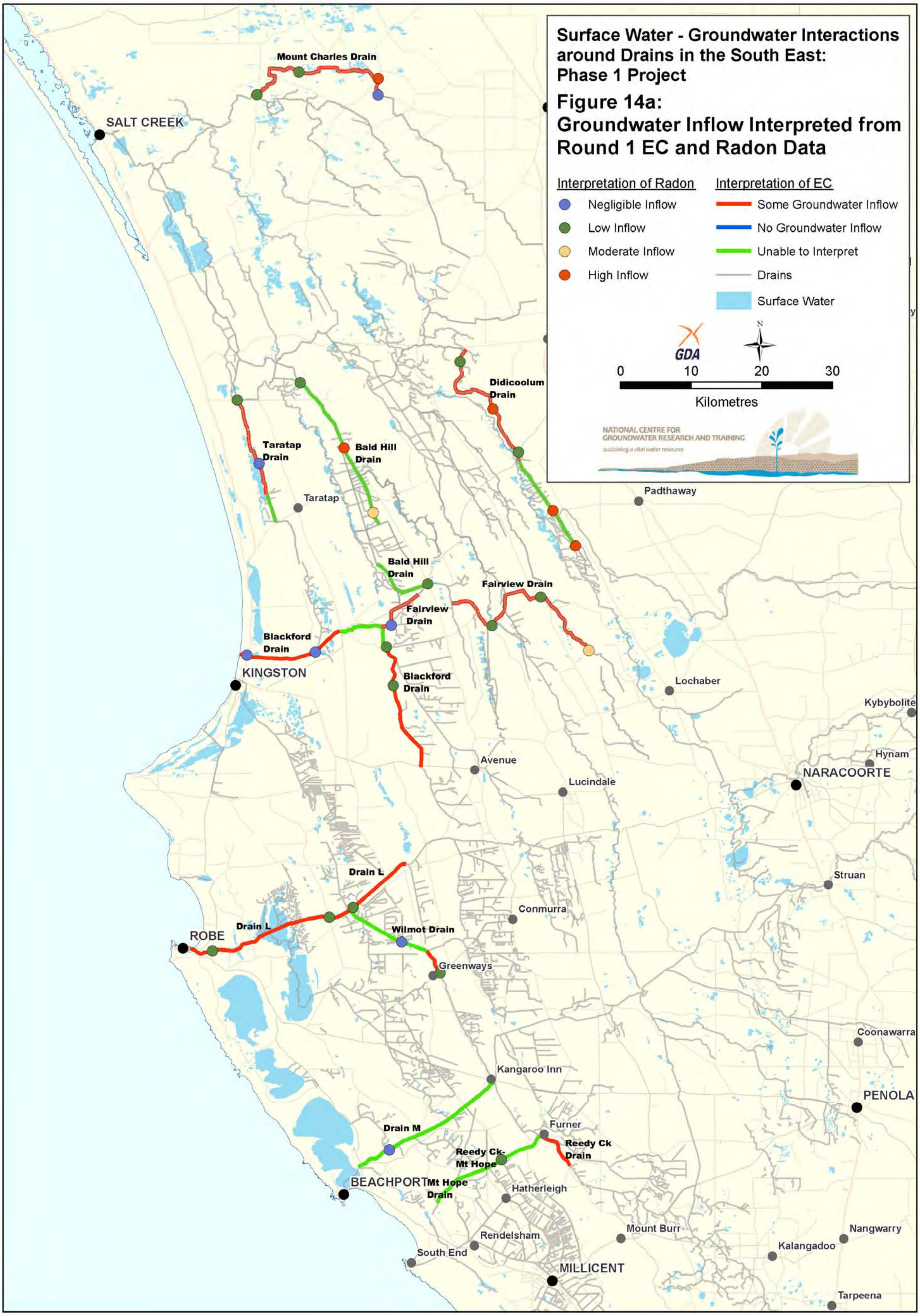

Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 13: Groundwater Salinity in the South East Tertiary Limestone Aquifer June 2010
Round 1 Sites
Round 2 Sites
USE Drains
Non USE Drains
Surface Water
EC June 2010 (mS/cm)
Less than 1.5
1.5 to 2.5
2.5 to 5.0
5.0 to 11.0
Greater than 11.0
GDA
N
0 10 20 30 40
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
sustaining a vital water resource
TINTINARA
SALT CREEK
Mount Charles Drain
Didicoolum Drain
Bald Hill Drain
Taratap Drain
Taratap
Padthaway
Fairview Site
Fairview Drain
Blackford Drain
KINGSTON
Lochaber
Kybybolite
Avenue
Lucindale
Hynam
NARACOORTE
Frances
Drain L
Wilmot Drain
Conmurra
Struan
ROBE
Greenways
Reedy Ck-Wilmot
Wrattonbully
Reflows Western Floodway Site
Coonawarra
Kangaroo Inn
Drain M
PENOLA
Furner
Reedy Ck Drain
Mt Hope Drain
Reedy Ck-Mt Hope
BEACHPORT
Hatherleigh

Table 8. Summary of qualitative conclusions that can be drawn from comparisons of EC fluctuations in the drains with regional groundwater salinity.

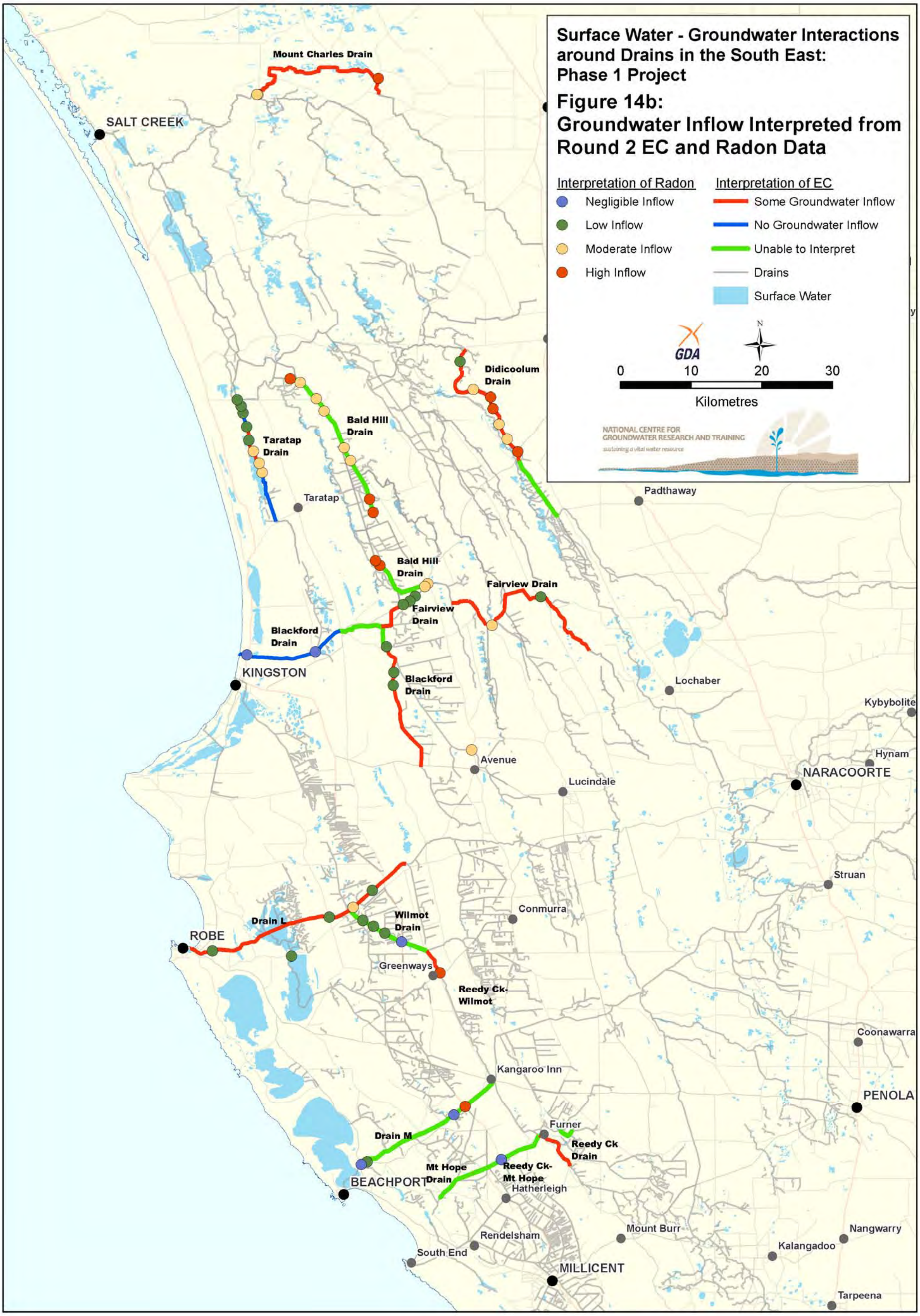
Regional Groundwater EC Zone	**Drain**	**Trend in Drain Water EC along flow path**	**Interpretation**
High (5-11 mS/cm)	Mt Charles	Generally increasing from approx. 30 mS/cm to 60 mS/cm, with some local decreases.	Generally gaining. Possibly gaining more saline local groundwater between 116 and 128 (wetland complex). Inflow of fresher regional groundwater between 128 and 129. Saline tributary inflow at site 131.
	Taratap	Drain water EC starts much higher than regional GW. Nov 10 data shows an increase from site 2 to 3 and then steady decrease back towards regional groundwater values. Oct 11 data is constant, above regional groundwater values. Slight fluctuation between sites 4 and 8.	Nov 10: Inflow of regional groundwater (fresher) from sites 3 onward. Oct 11: Negligible groundwater input, except between sites 4 and 8, where there may be some groundwater input.
	Bald Hill	Drain EC is relatively constant, above regional groundwater EC. Some increases in EC, some decreases towards regional GW EC, particularly near end of study reach.	Difficult to interpret as there are numerous shallow drains flowing into Bald Hill. Also, local groundwater salinities may be particularly influenced by a calcrete layer (S. Mustafa, pers. comm.)
Med-High (2.5-5 mS/cm)	Didicoolum	Drain water starts much higher than ambient groundwater EC. Minor increases and decreases in EC up to site 105, followed by steady decline towards regional groundwater value. Decline is consistent for both sampling rounds.	Drain is gaining after site 105. Data before this is difficult to interpret due to numerous tributary inflows.
	Fairview	Nov 10: Steady increase from approximately regional groundwater values (5 mS/cm) up to 10 mS/cm at site 44, after which values are fairly constant to site 42 (just upstream	Possibly gaining more saline local groundwater prior to site 44, however there are some tributary inflows along this reach that may also contribute more saline water. Possibly gaining some fresher regional

		of junction with Bald hill Drain), then a steady decrease back towards regional groundwater values. Oct 11: Similar trend to Nov 10, but with higher absolute values. EC decrease downstream of Bald Hill junction is reduced.	groundwater after site 42, but there are also some shallow drains flowing into this reach that may contribute fresher water.
	Blackford	Starts at approximately regional groundwater value (5 mS/cm) and then increases, sharply at first, and then more gradually up to site 58, after which there is a junction with Fairview Drain. From site 36 onwards, EC decreases slightly in Nov 10, but is fairly constant in Oct 11.	Possibly gaining more saline local groundwater prior to site 58, then minor inflow of fresher groundwater after site 36 in Nov 10, but not in Oct 11.
Low-Med (1.5-2.5 mS/cm)	Drain L	Gentle increase in EC away from regional groundwater values until last site (88, near the coast), where there is a sharp increase in EC.	Possible inputs of localized saline groundwater (associated with shallow water tables and wetlands, combined with inflow from saline tributaries draining shallow water tables).
	Wilmot	Relatively constant within regional groundwater values, sharp increase at the end (sites 92-90), but still within regional groundwater values.	Difficult to interpret due to similarity between drain water EC and regional groundwater EC. Interaction may range from 0% groundwater input to 100% groundwater input. Sharp increase between sites 92 and 90 may be due to tributary inflow.
	Reedy Creek-Wilmot	Sharp decrease in EC between sites 98 and 97, from above groundwater EC to within groundwater EC range.	Possible inflow of fresher groundwater, although water tables are potentially deep here.
Low (< 1.5 mS/cm)	Mt Hope	EC starts within ambient regional groundwater range. Sharp increase in EC from approx. 2 mS/cm to 6 mS/cm between sites 65 and 64.	Saline tributary inflow.
	Reedy Creek	EC fairly constant within groundwater EC	Difficult to interpret due to similarity between drain

		range.	water and groundwater.
	Reedy Creek – Mt Hope	EC fairly constant within groundwater EC range.	Difficult to interpret due to similarity between drain water and groundwater.
	Drain M	EC fairly constant within groundwater EC range.	Difficult to interpret due to similarity between drain water and groundwater.



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 14a:
Groundwater Inflow Interpreted from Round 1 EC and Radon Data
Interpretation of Radon
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
Interpretation of EC
Some Groundwater Inflow
No Groundwater Inflow
Unable to Interpret
Drains
Surface Water
GDA
N
0
10
20
30
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Mount Charles Drain
SALT CREEK
Didicoolum Drain
Taratap Drain
Bald Hill Drain
Taratap
Padthaway
Bald Hill Drain
Fairview Drain
Fairview Drain
Blackford Drain
KINGSTON
Blackford Drain
Lochaber
Kybybolite
Hynam
NARACOORTE
Avenue
Lucindale
Drain L
Struan
Conmurra
Drain L
ROBE
Wilmot Drain
Greenways
Coonawarra
Kangaroo Inn
PENOLA
Furner
Drain M
Reedy Ck Drain
Reedy Ck-Mt Hope
BEACHPORT
Mt Hope Drain
Hatherleigh
Mount Burr
Nangwarry
Rendelsham
Kalangadoo
South End
MILLICENT
Tarpeena


Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 14b:
Groundwater Inflow Interpreted from Round 2 EC and Radon Data
Interpretation of Radon
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
Interpretation of EC
Some Groundwater Inflow
No Groundwater Inflow
Unable to Interpret
Drains
Surface Water
GDA
N
0
10
20
30
Kilometres
NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING
Mount Charles Drain
SALT CREEK
Didicoolum Drain
Bald Hill Drain
Taratap Drain
Taratap
Padthaway
Bald Hill Drain
Fairview Drain
Fairview Drain
Blackford Drain
KINGSTON
Blackford Drain
Lochaber
Kybybolite
Hynam
NARACOORTE
Avenue
Lucindale
Struan
Conmurra
Drain L
Wilmot Drain
ROBE
Greenways
Reedy Ck-Wilmot
Coonawarra
Kangaroo Inn
PENOLA
Furner
Reedy Ck Drain
Drain M
Reedy Ck-Mt Hope
Mt Hope Drain
BEACHPORT
Hatherleigh
Rendelsham
Mount Burr
Nangwarry
Kalangadoo
South End
MILLICENT
Tarpeena

4.2 Regional Spatial and Temporal Patterns of Surface Water - Groundwater Interactions

Figure 14 shows inferred surface water – groundwater interaction conditions based on EC data, from Table 8 (colour coded drain reaches), and radon data interpreted in relation to groundwater inputs (colour coded circles) for (a) round 1 (November 2010) and (b) round 2 (October 2011). The limitations of the interpretation based on the EC data are discussed in Section 3.1.2.

In general, the qualitative interpretation of both the EC and radon suggest a dominance of gaining conditions in the drains sampled (Fig. 14). Temporal variations in surface water-groundwater interactions between the two sampling rounds are difficult to resolve using the EC data. However, comparison between the two radon data sets suggests a slight increase in gaining conditions in round 2 compared with round 1, perhaps associated with higher rainfall conditions prior to round 2 (see Section 3.1.1).

Comparison between the EC and radon data for both rounds show general agreement in their inferences regarding the occurrence of groundwater inflow to the drains. For EC, the reaches colour coded in red are inferred to be gaining, and those in blue not gaining (i.e. losing). The degree of groundwater input is not indicated due to the large uncertainty that would be incorporated in any quantitative assessment of the EC data. The radon data provides a semi-quantitative assessment of the gaining conditions and the dots colour coded green, yellow or red are inferred as different degrees of gaining conditions, whilst those in blue are not gaining (i.e. losing).

Where comparisons can be made between the two data sets, there is general agreement in their inferences regarding the occurrence of groundwater inflow to the drains. Exceptions for round 1 are site 5 on the Taratap Drain and site 33 on Blackford drain, the latter possibly due to tributary inflow influencing ECs. The exceptions for round 2 are non-agreement for some parts of Taratap Drain, where EC data suggests not gaining and radon data suggests gaining conditions. A possible explanation for the non-agreement between the two data sets on the Taratap Drain may be the occurrence of different local groundwater EC conditions from the ambient regional groundwater EC shown on Figure 13. In general, however, interpretation of the EC data in the context of the ambient regional groundwater zones has yielded a qualitative analysis that is similar to that of the radon data. This is encouraging, although further investigation of the spatial variability of groundwater EC around the drains is required if EC is to be used confidently as a tracer of surface water-groundwater interactions in the South East.

4.3 Quantitative Estimates of Groundwater Inputs using a Radon Mass Balance and Differential Flow Gauging

Detailed sampling for surface water radon activity along selected drain reaches was combined with flow gauging during round 2 to enable quantification of groundwater inflows at the reach scale using the model of Cook et al. (2006), i.e. Equation (4). The reaches selected were those where round 1 radon data or the depth to water table map had identified potentially gaining conditions. In this preliminary assessment, to simplify the calculations, (a) evaporation has been neglected as it is likely to represent a small component of the water balance of the drains, and (b) hyporheic exchange has been neglected due to a lack of knowledge of any of the parameters required to represent this process in the South East drains. Following this, eliminating the second, fifth and sixth terms on the right hand side of equation 4, it becomes:

$$Q_s \frac{dc_s}{dx} = I(c_i - c_s) - kwc_s - dw\lambda c_s \qquad [5]$$

Cook et al. (2006) showed that neglecting hyporheic exchange can cause a significant overestimation of groundwater inflow to streams. Hence, neglecting hyporheic exchange could be a large source of error in the calculations of groundwater inflow here, particularly in the drains observed to have a "sludgy" bottom. The source of values for each of the parameters in equation 5 is shown in Table 9. Table 10 shows a comparative summary of the results from the two methods.

Table 9. Source of parameters for calculations using equation 5.

Parameter	**Description**	**Adopted Value**	**Comment**
Q_s	Streamflow (L^3T^{-1})	Measured flow at upstream site (m^3/d)	
dc_s/dx	Change in radon activity over reach of interest.	Difference between measured upstream and downstream radon activity (Bq/L), divided by reach length.	
c_i	Radon activity of groundwater inflow.	6 Bq/L	Broad assumption based on the range of radon activities observed in the Gambier Limestone aquifer.
c_s	Radon activity of the drain water.	Radon activity measured at upstream site (Bq/L).	
k	Gas transfer velocity (LT^{-1})	1.6 m/d	Used by Cook et al. (2006) for the Cockburn River, which has similar dimensions and flow rate to the South East Drains.
w	Stream width	Measured value (m)	
d	Average stream depth	Measured value(m)	
λ	Radioactive decay constant for radon	0.181 day-1	Cook et al. (2003)

Table 10. A comparison of groundwater inflow rates calculated from the radon mass balance and differential flow gauging (Δ Q) methods for specific drain reaches. Numbers in brackets represent fluxes per metre of drain to allow point comparisons of groundwater inflow rates.

Drain	Reach	(1) Q_i from radon mass balance (m^3/d)	(2) Q_i from Δ Q (m^3/d)	Error (%) ((1)-(2))/smallest value x 100	Comments
Mt Charles	Site 115-116	549 (0.2)		NA	Site spacing is >> representative scale length of Cook et al. (2006).
	Site 116-130B	104,993 (4.6)	3,888 (0.2)	2,200	Large stretch of drain. Site spacing is >> representative scale length.
Bald Hill	Site BH1-BH2	10,426 (10.1)	2,160 (2.1)	381	C_i of 12 Bq/L gives a match between the two inflow estimates. Site spacing is within representative scale length.
	Site 17-11	871 (0.4)		NA	Site spacing is within representative scale length.
	Site 15C-15	620 (0.7)	1,555 (1.8)	-157	C_i of 2.8 Bq/L gives a match between the two inflow estimates. Site spacing is slightly greater than representative scale length.
Didicoolum	Site 117-118	4,679 (2.0)	778 (0.3)	567	Site spacing is > representative scale length.
	Site 118-119	3,523 (1.5)	1,987 (0.8)	88	C_i of 9.5 Bq/L gives a match between the two inflow estimates. Site spacing is > representative scale length.
	Site 119-120	3,905 (1.5)		NA	Site spacing is > representative scale length.
	Site 120-121	2,415 (1.4)	5,443 (3.2)	-129	C_i of 3.5 Bq/L gives a match between the two inflow estimates.
	Site 121-122	3,463 (1.2)		NA	Site spacing is within representative scale length.

Table 10 shows that estimated groundwater inflow rates range between 0.2 m^3/m/d and 10.1 m^3/m/d. In all cases, there are large differences between the values estimated using the radon mass balance and the differential flow gauging methods, indicating errors in one or both of the calculations. Potential sources of error are:

- Lack of knowledge of the radon activity of the groundwater inflow. A universal value of 6 Bq/L has been used for these calculations as it approximates an average of the groundwater data available, which range between 0.08 Bq/L and 15 Bq/L (see Section 1.5). The C_i values noted in the right hand column of Table 10 as being able to provide a match between the two methods of groundwater inflow estimation are all within this range.
- Large distances between surface water radon activity samples. Sample spacings that are greater than the representative scale length (distance for radon activities to reduce to negligible values) mean that variations in groundwater input along the reach are not captured properly by the sampling program and groundwater input is over- or under-estimated. Efforts were made to keep sample spacings within these scale lengths, but the regional scale of this preliminary regional sampling program meant that this was not always practical. Prioritization of specific drains or regions of the drainage system in future sampling rounds would allow mass balance calculations to be more of a focus.
- Not accounting for hyporheic exchange. This would lead to an over-estimation of groundwater input, i.e. could contribute to positive errors in column 5 of Table 10.
- The radon mass balance does not account for losing conditions (i.e. it accounts for gross groundwater inputs only), whilst the differential flow method does account for losing conditions (i.e. net input is estimated). If losing conditions exist in a study reach, this would result in an overestimation of groundwater input by the radon method, i.e. a positive error in column 5 of Table 10.

4.4 Detailed Measurement of Surface Water – Groundwater Interactions

The initial stage change experiment at the Fairview site was conducted to obtain information regarding the possible hydraulic gradients that could be induced. It also provided an insight into the groundwater response at the site, which is necessary to help with the planning of further investigations.

The flow down the Reflows Western Floodway has provided significant data, and coupled with installation of further temperature sensors will give a good insight into the efficiency of such channels in the transportation of surface water and subsequent groundwater recharge.

5 Conclusions and Recommendations

The following conclusions and recommendations can be made from Phase 1 of the **"Evaluation of approaches to modelling surface water-groundwater interactions around drains in the South East of South Australia"** project:

- Surface water radon activities indicate predominantly gaining conditions across the drains sampled.
- A significant range of surface water radon activity values can be observed in the drains (0.02 Bq/L to 4.21 Bq/L), making radon a useful semi-quantitative indicator of the spatial variability of groundwater inflows at a regional scale.
- Additionally, slight temporal differences in the radon data between the two sampling rounds suggest that this tracer can also distinguish temporal variability in these processes at a regional scale.
- EC data may be able to be used to make a qualitative assessment of groundwater inputs to some of the drains, which loosely agree with interpretation of the radon data. However, for some drains, surface water EC is not sufficiently different from groundwater EC to be able to do this.
- Additionally, the likelihood of large local variations in groundwater EC in the South East limits the confident use of EC in assessments of surface water – groundwater interactions. Detailed characterization of groundwater ECs adjacent the drains would be required to overcome this.
- At least some additional work is required to be able to quantitatively estimate groundwater inputs to the drains using a radon mass balance approach. An assessment of the spatial variability of radon activities in groundwater in the unconfined aquifer in the South East may greatly improve our ability to do this and this should be investigated given the promising radon data from this study.
- However, for some of the drains, particularly those with "sludgy" bottoms, additional experiments, perhaps using applied tracers, may ultimately be required to quantify hyporheic exchange and properly quantify groundwater inputs.

6 Planned Future Work

The work described here is considered to be a preliminary study, with the two components aimed at providing a foundation for further work in the following ways:

1) Preliminary regional assessment of water exchange between drains and groundwater. This regional survey has identified radon as a potentially useful tracer

in quantifying surface water – groundwater interactions around the drains, and improving our qualitative understanding of these processes. The NCGRT proposes to build on this by:

(a) Better characterizing unconfined groundwater radon activities in the South East,
(b) Conducting some focused sampling programs on smaller sections of the drains that have proved to be interesting, e.g. the Bald Hill Drain
(c) Expanding the temporal data set through additional regional sampling rounds,
(d) Further evaluating the data in conjunction with the development of local and regional scale numerical models.

2) Installation of infrastructure for detailed measurement of surface water – groundwater interactions. This infrastructure will be used in the future to carry out a range of research projects that will be of direct benefit to the understanding of the drains in the South East. In particular, a current PhD project, due to be completed in 2014, is addressing the following research questions:

Losing Stream (Reflows Western Floodway Site):

1. How do we estimate fluxes in a losing stream? What is the potential uncertainty and error in the calculations of this?
2. What are the main controls on flux heterogeneity other than hydraulic head in the channel, e.g. hydraulic conductivity, SW-GW connectivity, or groundwater depth (connected v disconnected streams), flood wave hydrodynamics?
3. How important is the initial loss as a flood wave progresses compared with the overall losses? What is the importance of the unsaturated zone?
4. How does the loss affect the timing, surface water level, and momentum of the flood wave?

Currently, the data collected during the flooding of the Reflows Western Floodway is being used in two numerical codes, HEC-Ras (USACE, 2010) and MODFLOW (MacDonald and Harbaugh, 1988), to estimate stream bed hydraulic conductivity by coupling surface water flow and infiltration equations. The flow data (Fig. 11(b)) collected during this experiment is being used to constrain the models. The results of this characterization will be simulated using MODFLOW and compared to the drive point piezometer responses from within the channel. Soil moisture and temperature data collected will also be utilized in the design of a Distributed Temperature Sensing (DTS) system installation which is planned for 2012.

Gaining Stream (Fairview Site):

1. How do we estimate fluxes in a gaining stream? What is the potential uncertainty and error in the calculations of this?
2. How will knowledge of the aquifer heterogeneity increase the accuracy of the discharge calculation when relying on point groundwater measurements?
3. Can groundwater discharge rates be accurately obtained using point groundwater measurements? How does the distance between the bore and the stream effect the result?

In the short term, the next step at the Fairview Site is proposed to be a similar stage change experiment to the one described in this report, including measurements of groundwater velocity at a number of sites along the stream during the stage change and re-equilibration of surface- and ground-water levels. This may involve the use of point dilution and velocity probes.

A number of tracer tests will be conducted along this section of the drain to characterise the spatial variability in groundwater discharge. This, combined with the groundwater data will enable assessment of the errors in groundwater discharge estimates made using Darcy's Law.

Appendix A Photos of some of the drains sampled during regional sampling round 2.


Taratap Drain, site 6, looking south, Oct 2011


Taratap Drain, site 10, Oct 2011


Bald Hill Drain, around site BH3, Oct 2011


Bald Hill Drain, site BH6, Oct 2011


Bald Hill Drain, site 15, Oct 2011


Bald Hill Drain, looking north towards site 16, Oct 2011


Bald Hill Drain, Nov 2010


Didicoolum Drain, looking north towards site 124, Oct 2011


Didicoolum Drain, Nov 2010


Mount Charles Drain, Nov 2010


Mount Charles Drain, Nov 2010


Mount Charles Drain, Oct 2011


Fairview Drain, Nov 2010


Fairview Drain, Nov 2010


Blackford Drain, Nov 2010

Blackford Drain, Nov 2010

Blackford Drain, Oct 2011

Blackford Drain, site 28, Oct 2011

Reedy Creek – Mt Hope Drain, Site 62, Oct 2011


Reedy Creek – Mt Hope Drain, Site 82, Oct 2011


Drain M, site 68, Oct 2011


Drain L, Nov 2010


Drain L, Nov 2010

Appendix B . All regional survey data.

					EC		Flow (m3/s)	Rn (Bq/L)	
Site #	Date	Drain	Eastings	Northings	Nov-10	Oct-11	Oct-11	Nov-10	Oct-11
113	1/12/2010	Mt Charles	422780	6002352					
114	1/12/2010	Mt Charles	419880	6006432					
115	1/12/2010	Mt Charles	417749	6006911	36.80	29.2	0.013	0.08	
116	1/12/2010	Mt Charles	417785	6009263	32.10	29.8		2.48	1.95
128	1/12/2010	Mt Charles	406504	6010183	59.00			0.25	
129	1/12/2010	Mt Charles	403136	6009187	45.10	54.3			
130	1/12/2010	Mt Charles	400619	6006942	65.10				
130B			400695	6006965		56.6	0.013		0.537
131	1/12/2010	Mt Charles	400576	6006947	62.20	59.6	0.312	0.47	0.548
131A			400674	6006946		59.9			
2	29/11/2010	Taratap	403544	5946475	12.780	14.79			
3	29/11/2010	Taratap	402123	5949844	21.300	15.16			
4	29/11/2010	Taratap	401300	5953355	19.280	14.44	0.161		0.627
5	29/11/2010	Taratap	400884	5954682	15.370	15.61	0.022	0.092	0.547
6	29/11/2010	Taratap	400092	5956398	16.390	16.72	0.047		0.593
7	29/11/2010	Taratap	399420	5957917	15.810	16.98	0.03		0.227
8	29/11/2010	Taratap	399121	5959880	12.370	15.48	0.066		0.476
9	29/11/2010	Taratap	398605	5961824	11.510	15.18	0.059		0.424
10	29/11/2010	Taratap	398329	5962767	11.280	14.9	0.072		0.250
1	29/11/2010	Taratap	397796	5963715	13.590	14.8	0.083	0.319	0.238
BH1		Bald Hill	423248	5937068		7.17	0.066		4.21
BH2		Bald Hill	422268	5936746		7.01	0.091		3.66
BH3		Bald Hill	419351	5938704		8.55			

BH4		Bald Hill	418765	5939536		8.66			
BH5		Bald Hill	417996	5940187		8.93			1.94
BH6		Bald Hill	417371	5940899		9.22			2.24
BH7		Bald Hill	417081	5941860		9.13			
BH8		Bald Hill	416788	5942828		8.96			
25	29/11/2010	Bald Hill	417064	5947730	5.640	7.86		0.557	1.41
24	29/11/2010	Bald Hill	416534	5949628	5.940	7.86			1.60
23	29/11/2010	Bald Hill	415927	5951525	5.480	7.83			
22	29/11/2010	Bald Hill	414900	5953293	5.450	7.45			
21	29/11/2010	Bald Hill	413843	5955058	5.450	7.46			0.946
20	29/11/2010	Bald Hill	412947	5956884	6.480	7.52		1.51	0.956
19	29/11/2010	Bald Hill	411752	5959818	6.490	7.53			
18	29/11/2010	Bald Hill	411385	5960529	6.650	7.49			
17	29/11/2010	Bald Hill	410077	5962098	6.460	7.53			0.626
11	29/11/2010	Bald Hill	408986	5963851	6.540	7.43	0.744		0.536
12	29/11/2010	Bald Hill	408259	5964569	6.380	7.37			
13	29/11/2010	Bald Hill	407549	5965434	6.200	7.33			
14	29/11/2010	Bald Hill	406724	5966117	6.250	7.29		0.362	0.595
15A		Bald Hill	406211	5966457		7.28			
15B		Bald Hill	406183	5966439		7.19			
15C		Bald Hill	406152	5966457		4.54	0.007		
15	29/11/2010	Bald Hill	405312	5966664	6.340	4.34	0.025		1.72
16	29/11/2010	Bald Hill	404684	5966707	4.500	4.31			
112	1/12/2010	Didicoolum	445711	5943021	15.66			2.01	
111	1/12/2010	Didicoolum	444625	5944674	18.62				
110	1/12/2010	Didicoolum	443643	5946424	19.48				
109	1/12/2010	Didicoolum	442498	5948029	17.77			1.72	

108	1/12/2010	Didicoolum	441328	5949658	16.57				
107	1/12/2010	Didicoolum	440272	5951157	17.06				
106	1/12/2010	Didicoolum	439111	5952858	19.30				
105	1/12/2010	Didicoolum	437946	5954479	19.21	19.36			
104	1/12/2010	Didicoolum	437605	5956311				0.41	
117	1/12/2010	Didicoolum	437523	5956354	19.69	19.68	0.081		1.24
118	1/12/2010	Didicoolum	436034	5958129	19.32	19.22	0.09		0.759
119	1/12/2010	Didicoolum	434862	5960247	17.49	18.82	0.113		0.841
120	1/12/2010	Didicoolum	434024	5962440	14.05	15.47	0.111	1.76	1.428
121	1/12/2010	Didicoolum	433667	5964062	13.04	14.68	0.174		1.437
122	1/12/2010	Didicoolum	431210	5965187	12.87	14.53			0.838
123	1/12/2010	Didicoolum	428757	5966363	12.72	14.15			
124	1/12/2010	Didicoolum	429328	5969088	12.99	13.72		0.36	0.399
125	1/12/2010	Didicoolum	428968	5971062	12.85	13.97			
126	1/12/2010	Didicoolum	425377	5971502	11.27	13.17			
127	1/12/2010	Didicoolum	422717	5971396	11.93	12.88			
49	30/11/2010	Fairview	447607	5928199	5.430			0.82	
46	30/11/2010	Fairview	446125	5929716	6.390				
47	30/11/2010	Fairview	442680	5934160	6.530	8.15			
48	30/11/2010	Fairview	440755	5935770	6.770	8.14		0.38	0.408
45	30/11/2010	Fairview	433855	5931723	8.770	12.86		0.3	0.769
44	30/11/2010	Fairview	432071	5933167	9.890	13.72			
43	30/11/2010	Fairview	429303	5935102	10.250	13.65			
43A			431005	5914088		7.1			0.950
42	30/11/2010	Fairview	424784	5937640	9.980	12.49		0.34	0.577
41	30/11/2010	Fairview	424378	5937217	9.860	12.51			0.552
40	30/11/2010	Fairview	422988	5935843	9.110	12.34			0.436

39a		Fairview-new 2011	422243	5935186		12.26	0.354		0.419
39	30/11/2010	Fairview	421306	5934671	8.540	12.24	0.368		0.479
38	30/11/2010	Fairview	419614	5933762	8.230	12.32			
37	30/11/2010	Fairview	419587	5931773	8.410			0.04	
50	30/11/2010	Blackford	423812	5911831	5.220	5.15			
51	30/11/2010	Blackford	423888	5913128	5.420	5.36			
52	30/11/2010	Blackford	423725	5914453	5.580	5.7			
53	30/11/2010	Blackford	421096	5917421	9.200	10.16			
54	30/11/2010	Blackford	420855	5919474	11.260	11.31			
55	30/11/2010	Blackford	420294	5921280	11.050	10.69			
56	30/11/2010	Blackford	419871	5923227	12.140	10.86		0.18	0.426
57	30/11/2010	Blackford	419982	5925062	12.660	10.96			0.471
58	30/11/2010	Blackford	420193	5926870	12.990	11.16			
59	30/11/2010	Blackford	420184	5927010	8.550	11.27			
59A			420142	5927070		11.33			
60	30/11/2010	Blackford	418921	5928740	18.050	10.92		0.13	0.233
36	30/11/2010	Blackford	412888	5930983	16.050	12.64			
35	30/11/2010	Blackford	411725	5930757	15.780	12.6			
34	30/11/2010	Blackford	410282	5929409	16.150	12.84			
33	30/11/2010	Blackford	408872	5927985	16.590	12.9		0.09	0.068
32	30/11/2010	Blackford	406984	5927387	15.830	12.81			
31	30/11/2010	Blackford	405108	5927086	16.050	12.94			
30	30/11/2010	Blackford	403135	5927132	15.750	12.95			
29	30/11/2010	Blackford	401833	5927232	15.650	13.1			
28	30/11/2010	Blackford	401833	5927232	15.790	13.12			
27	30/11/2010	Blackford	401147	5927241	15.290	12.85			
26	30/11/2010	Blackford	399141	5927521	14.750	13.26		0.1	0.039

103	30/11/2010	Drain L	421692	5897958	2.88	3.05			
102	30/11/2010	Drain L	418614	5895597	2.65	2.98			
101	30/11/2010	Drain L	416906	5894139	2.55	2.88			0.340
100	30/11/2010	Drain L	414195	5891786	2.78	3.72		0.15	0.546
89	30/11/2010	Drain L	410826	5890383	2.92	3.5		0.15	0.210
87	30/11/2010	Drain L	399724	5886883	4.06	4.6			
86	30/11/2010	Drain L	396670	5885713	3.96	4.66			
85	30/11/2010	Drain L	394265	5885629	3.61	4.69		0.38	0.347
84	30/11/2010	Drain L	392840	5885323	3.70	4.41			
83	30/11/2010	Drain L	391508	5885866	8.58	5.96			
88	30/11/2010	Drain L	405471	5884889	6.45	4.7			0.156
99	30/11/2010	Wilmot	426954	5886476	2.08	1.585			
96	30/11/2010	Wilmot	423276	5886189	2.12	1.673			
95	30/11/2010	Wilmot	421088	5886939	1.78	1.634		0.07	0.078
94	30/11/2010	Wilmot	419931	5887433	1.72	1.629			
93	30/11/2010	Wilmot	418686	5888158	1.86	1.665			0.174
92	30/11/2010	Wilmot	417072	5889097	1.67	1.707			0.281
91	30/11/2010	Wilmot	415561	5889948	1.84	2.53			0.393
90	30/11/2010	Wilmot	414130	5891000	2.67	2.41			
98	30/11/2010	Reedy Creek - Wilmot	427700	5879185	3.44	3.37			
97	30/11/2010	Reedy Creek - Wilmot	426486	5882529	1.65	1.676		0.46	1.09
75	29/11/2010	Drain M	434186	5867058	1.50	1.282			
74	29/11/2010	Drain M	432536	5865618	1.52	1.378			
73	29/11/2010	Drain M	430072	5863615	1.42	1.41			1.31
73A			428484	5862399		1.337			0.088
70	29/11/2010	Drain M	426836	5861256	1.64	1.337			
68	29/11/2010	Drain M	422353	5859139	1.69	1.104			

68B						1.976			
67	29/11/2010	Drain M	419340	5857419	1.46			0.019	
66	29/11/2010	Drain M	416157	5855737	1.74	1.424			0.131
66B			415364	5855362		1.724			0.022
69	29/11/2010	Symon Main Dr	423645	5858355	1.73	1.085			
72	29/11/2010	Mt Hope	430906	5860201					
64	29/11/2010	Mt Hope	429372	5854461	5.73	7.17			
65	29/11/2010	Mt Hope	427093	5851406	2.05				
71	29/11/2010	Reedy Creek DivA	444318	5859520	1.48				
76	29/11/2010	Reedy Creek DivB	444886	5855268	1.43				
77	29/11/2010	Reedy Creek DivB	443321	5857171	1.45				
80	29/11/2010	Reedy Creek DivB	440587	5859477	1.42	1.568			
78	29/11/2010	Reedy Creek - Mt Hope	440552	5859568	1.51	1.805			
79	29/11/2010	Reedy Creek - Mt Hope	440500	5859475	1.54	1.57			
81	29/11/2010	Reedy Creek - Mt Hope	438837	5857768	1.50	1.612			
82	29/11/2010	Reedy Creek - Mt Hope	436893	5857001	1.52	1.59			
61	29/11/2010	Reedy Creek - Mt Hope	435202	5856036	1.56	1.591		0.148	0.061
62	29/11/2010	Reedy Creek - Mt Hope	433145	5854872	1.65	1.605			
63	29/11/2010	Reedy Creek - Mt Hope	431090	5854095	1.63	1.654			

References

Armstrong, D., and Stadter, F. 1992. Computer modelling to examine the performance of groundwater drains. South Australian Department of Mines and Energy, Report Book 92/57.

Arnott, S., Hilton, J., Webb, B.W. 2009. The impact of geological control on flow accretion in lowland permeable catchments. Hydrology Research, 40(6): 533-543.

Bencala, K.E., Gooseff, M.N., Kimball, B.A. 2011. Rethinking hyporheic flow and transient storage to advance understanding of stream-catchment connections. Water Resour. Res., 47.

BoM – see Bureau of Meteorology, 2011.

Bureau of Meteorology. 2011. Daily rainfall data for Station # 026012 (Kingston SE, SA), viewed 28th November, 2011, http://www.bom.gov.au/climate/data/.

Calver, A. 2001. Riverbed permeabilities: Information from pooled data. Ground Water, 39(4): 546-553.

Cey, E.E., Rudolph, D.L., Parkin, G.W., Aravena, R. 1999. Quantifying groundwater discharge to a small perennial stream in southern Ontario, Canada. Journal of Hydrology (Amsterdam), 210(1/4): 21-37.

Cook, P.G., Favreau, G., Dighton, J.C., Tickell, S. 2003. Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. Journal of Hydrology, 277(1-2): 74-88.

Cook, P.G., Lamontagne, S., Berhane, D., Clark, J.F. 2006. Quantifying groundwater discharge to Cockburn River, southeastern Australia, using dissolved gas tracers Rn-222 and SF6. Water Resour. Res., 42(10).

Cook, P.G., Wood, C., White, T., Simmons, C.T., Fass, T. and Brunner, P. 2008. Groundwater inflow to a shallow, poorly-mixed wetland estimated from a mass balance of radon., J. Hydrol., 354:213-226.

Cox, J., Durkay, M., Smitt, C., Davies, P., Walker, G. and Ferdowsian, R. 2006. Predicting the likely impacts of the Bald Hill Drain in the Upper South-East, South Australia., Report to the Department of Water, Land and Biodiversity Conservation. CSIRO Land and Water Client Report, March 2006. Commercial-in-Confidence.

Durkay, M. 2004. Soils and Groundwater Marcollat Region, Upper South east South Australia. Unpublished report, Liquid Gold Hydrology Service, August 2004.

Ellins, K.K., Romanmas, A., Lee, R. 1990. Using Rn-222 to Examine Groundwater Surface Discharge Interaction in the Rio-Grande-De-Manati, Puerto-Rico. Journal of Hydrology, 115(1-4): 319-341.

Fass, T. and Cook, P.G. 2005. Reconnaissance survey of groundwater dependence of wetlands, South East, South Australia, using a mass balance of radon and chloride., CSIRO draft report.

Genereux, D.P., Hemond, H.F. 1990. Naturally-occurring RN-222 as a tracer for streamflow generation - steady state methodology and a field example. Water Resour. Res., 26(12): 3065-3075.

Genereux, D.P., Hemond, H.F., Mulholland, P.J. 1993. Use of Rn-222 and Calcium as Tracers in a 3-End-Member Mixing Model for Streamflow Generation on the West Fork of Walker Branch Watershed. Journal of Hydrology, 142(1-4): 167-211.

Harding, C. unpublished data, Government of South Australia, through the Department for Water.

Harte, P.T., Kiah, R.G. 2009. Measured river leakages using conventional streamflow techniques: the case of Souhegan River, New Hampshire, USA. Hydrogeol. J., 17(2): 409-424.

Herczeg, A.L., Dighton, J.C., Easterbrook, M.L and Salomons, E. 1994. Measurement of radon-222 and radium-226 in ground water by liquid scintillation counting., Radon and Radon Progeny Measurements in Australia Symposium, Canberra, 18 February 1994, pp. 79-82.

Herczeg, A.L., Leaney, F.W., Dighton, J.C., Lamontagne, S., Schiff, S.L., Telfer, A.L. and English, M.C. 2003. A modern isotope record of changes in water and carbon budgets in a groundwater-fed lake: Blue Lake, South Australia., Limnon. Oceanogr., 48(6): 2093-2105.

Holtzman, R. et al. 2005. Quantifying ground water inputs along the Lower Jordan River. Journal of Environmental Quality, 34(3): 897-906.

Kalbus, E., Reinstorf, F., Schirmer, M. 2006. Measuring methods for groundwater - surface water interactions: a review. Hydrology and Earth System Sciences, 10(6): 873-887.

Kennedy, C.D., Genereux, D.P., Mitasova, H., Corbett, D.R., Leahy, S. 2008. Effect of sampling density and design on estimation of streambed attributes. Journal of Hydrology, 355(1-4): 164-180.

Kennett-Smith, A., Narayan, K., and Walker, G. 1996. *Calibration of a Groundwater Model for the Upper South East of South Australia*. CSIRO Division of Water Resources Divisional Report 96/02.

Lamontagne, S. 2002. Groundwater delivery rate of nitrate and predicted change in nitrate concentration in Blue Lake, South Australia, Mar. Freshw. Res., 53: 1129-1142.

Langhoff, J.H., Rasmussen, K.R., Christensen, S. 2006. Quantification and regionalization of groundwater-surface water interaction along an alluvial stream. Journal of Hydrology, 320(3-4): 342-358.

Leaney, F.W. J., Allison, G.B., Dighton, J.C. and Trumbore, S. 1995. The age and hydrological history of Blue Lake, South Australia, Palaeogeogr. Palaeoclimatol. Palaeoecol., 118:111-130.

Leaney, F.W. and Herczeg, A.L. 2006. A rapid field extraction method for determination of radon-222 in natural waters by liquid scintillation counting., Limnology and Oceanography: Methods 4:254-9.

Macdonald, M.G. and Harbaugh, A.W. 1988. MODFLOW, A Modular three dimensional finite-difference groundwater flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chapter A1, 586 pp.

MacKenzie, G.A. and Stadter, F. 1992. Environmental Impact Statement Background Paper: Groundwater occurrence and the impacts of various land management practices in the Upper south east of South Australia Groundwater Branch SA Dept of Mines and Energy.

McCallum, J., Crosbie, R., Cox, J., Davies, P. 2007. Groundwater, Soil and Vegetation Modelling of the Proposed Bald Hill Flat Drain. CSIRO Land and Water Client Report.

McEwan, K.L. and Kennett-Smith, A.K. 1995. Results from Hydrological Studies in the upper southeast, South Australia 2. Groundwater and Meteorological data. CSIRO Division of Water Resources Technical Memorandum 95.6 March 1995.Meredith et al., 2009

Mullinger, N.J., Pates, J.M., Binley, A.M., Crook, N.P. 2009. Controls on the spatial and temporal variability of Rn-222 in riparian groundwater in a lowland Chalk catchment. Journal of Hydrology, 376(1-2): 58-69.

Mustafa, S, Lawson, J, Leaney, F & Osei-Bonsu, K. 2006. *Land-use impact on water quality and quantity in the Lower South East, South Australia,* DWLBC Report 2006/25, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, Adelaide.

Opsahl, S.P., Chapal, S.E., Hicks, D.W., Wheeler, C.K. 2007. Evaluation of ground-water and surface-water exchanges using streamflow difference analyses. Journal of the American Water Resources Association, 43: 1132-1141.

Preiss, W.V. and Drexel, J.F. 1995. The Geology of South Australia – Vol. 2: The Phanerozoic. 347 p., Dept. of Mines and Energy / Geological Survey of South Australia.

REM. 2005. Impact Assessment of the Proposed Didicoolum Drain, Upper South East, SA, November 2005 Resource and Environmental Management.

Schmadel, N.M., Neilson, B.T., Stevens, D.K. 2010. Approaches to estimate uncertainty in longitudinal channel water balances. Journal of Hydrology, 394(3-4): 357-369.

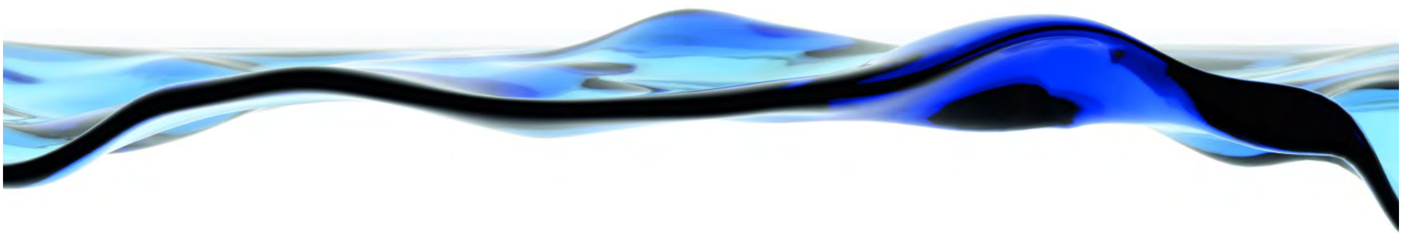
SKM. 2002. Upper south-east drainage program – Hydraulic Modelling and Cost Assessment, October 2002, Sinclair Knight Mertz.

Telfer, A., White, G., and Santich, M. 2002. Upper South-east Drains – Effectiveness Trial Stage 1 assessment of impacts, Primary Industries and Resources South Australia. April 2002.

USACE. 2010. Hydrologic Engineering Center, River Analysis System HEC-RAS, Hydraulic Reference Manual version 4.1, 2010. www.hec.usace.amry.mil

Wood, C. 2011. Measurement and evaluation of key groundwater discharge sites in the Lower South East of South Australia, DFW Technical Report 2011/14, Government of South Australia, through Department for Water, Adelaide.

Wu, Y., Wen, X., Zhang, Y. 2004. Analysis of the exchange of groundwater and river water by using Radon-222 in the middle Heihe Basin of northwestern China. Environmental Geology, 45(5): 647-653.



The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Water, CSIRO, Flinders University, the University of Adelaide and the University of South Australia.