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Department of **Water**

Hillman River South drainage project

Looking after all our water needs

Salinity and land use impacts series

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by

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Department of Water
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Disclaimer

Cover photograph: Main drain channel downstream of Transect 2
Photographer: R McDougall

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Summary

A single channel groundwater drainage scheme in a catchment in the 'Woolbelt', the south-west Western Australian area within the medium annual rainfall (500–800 mm) zone, provided an outlet for groundwater but was unable to lower watertables to reduce waterlogging and assist salinity reduction.

Deep open drains have been constructed in many catchments in Western Australia and are increasingly seen as useful in lowering the watertable and reducing the salinity impact on agricultural land. Their effectiveness has recently been studied in inland areas of WA to identify and evaluate the factors that contribute to their success or otherwise.

The Hillman River South drainage site, unlike Wheatbelt drainage sites, has steep slopes, incised valleys and is in an area of medium rainfall. The saline watertable is near the surface across the valley floors causing the land to become salt-affected and unable to support productive dryland pastures. The valley becomes waterlogged and frequently inundated by high rainfall and runoff during winter. In 2009 approximately 10 km of groundwater drain was dug, mainly as a single channel that wound along one or other side of the valley floor. The surface water was kept in the natural creek line or in a modified surface water channel. The main objective of this project was to assess the benefit of drainage to reduce salinity and waterlogging in an area of medium rainfall. The scheme was monitored from January 2009 to February 2010.

High rates of recharge to the watertable alongside the drain exceeded the drain's discharge rate so preventing any noticeable watertable decline. During summer and prolonged absences of recharge watertables sat above the impermeable clay layer as groundwater inflow was limited by preferred pathway flow. During periods of peak recharge the watertables rose quickly, saturated the permeable A horizon and remained near the surface.

The single drain acted as a conduit for the movement of water and salt that would previously have left the catchment as natural streamflow only during winter. The drain increased discharge and salinity from the catchment only during late spring to summer when before drainage there would have been no natural summer flow. Despite these seasonal changes in salt discharges the drain is unlikely to increase long-term salt export as this is still controlled by groundwater discharge.

The changes in downstream effects of the drain discharge are confined to spring and summer as ephemeral discharge from the catchment becomes perennial. The perennial flow exports from the catchment salts that would otherwise have accumulated in-situ. These salts would have detrimental effects if the saline drain water evaporated and concentrated in downstream perennial water bodies. With no such water bodies within at least 12 km of the drain outlet discharge is unlikely to reach downstream perennial water bodies without other contributing sources of groundwater seepage and runoff. Under these conditions salt export from the drain would be indistinguishable from other natural salt contributions.

With the high degree of variability in aquifer characteristics at this site, such as thickness and permeability, a combination of techniques may be needed to address groundwater and salinity-related issues throughout the catchment.

1 Introduction

1.1 Land salinisation and waterlogging

Western Australia is estimated to have approximately 1.1 million hectares of land affected in the South West of Western Australia (Environmental Protection Authority 2007).

Dryland salinity is caused by the removal of deep-rooted native perennial plants and replacement by shallow-rooted annual crops which use less water. The unused water from rain seeps into the groundwater. Continuous recharge to the groundwater results in rising watertables, bringing stored salts to the surface and causing salinisation of the land (Environmental Protection Authority 2007). This rising watertable also causes waterlogging of the lower landscape and groundwater seepage areas (Fig. 1).

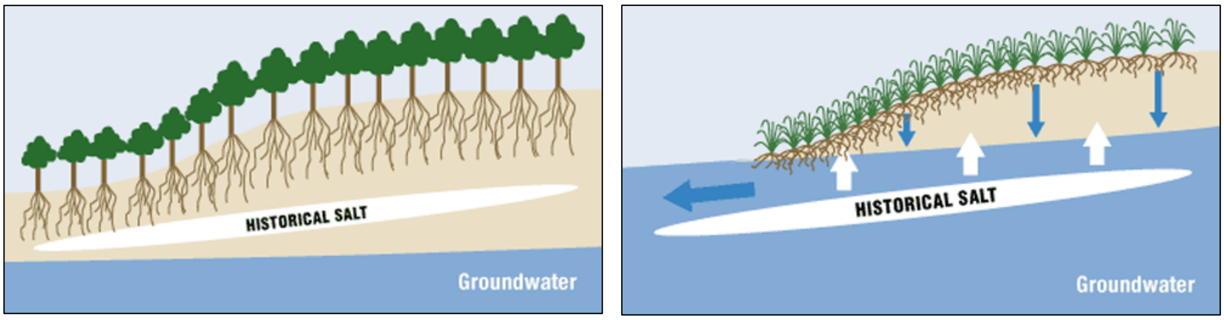


Figure 1 The process of dryland salinisation

Source: Commonwealth Government of Australia, n.d.

Waterlogging occurs when there is excess water in the plant root zone leading to anaerobic conditions (Moore 1998) and is common in duplex soil profiles across Western Australia. Duplex (or texture contrast) soils have a clear and abrupt boundary between the A and B horizons, with an increase in clay in the B horizons (Isbell 1996). This abrupt boundary results in a reduction in the hydraulic conductivity between the topsoil and subsoil, allowing the formation of a seasonal perched watertable (Hardie et al. 2011).

Waterlogging can occur in three ways: through perched watertables in duplex soils, inundation of valleys, and by discharge from permanent groundwater systems where pressure heads are at or above the ground surface (McFarlane & Williamson 2002).

Waterlogging and salinity interact because the pressure heads cause groundwater to discharge salts to the surface (McFarlane & Williamson 2002). So both waterlogging and salinity need to be addressed to reduce the landscape salinity.

1.2 Deep drainage

Deep drainage is one engineering method used to combat salinity problems in Western Australia. Deep drains intercept subsurface seepage, lower groundwater and maintain the watertable deep enough below the surface to reduce salinity and waterlogging. The drained groundwater must then be conveyed to and discharged at a safe disposal point (Cox et al. 2004). Deep drains can be constructed and managed at a farm scale where all the water is retained 'on-farm' or at a catchment level where farm-scale drains discharge into evaporation basins, existing saline lakes or natural watercourses.

1.3 Objectives

The Hillman River South project was to build on the knowledge of drainage from the Engineering Evaluation Initiative (EEI). The higher rainfall at this site compared to the EEI project sites offered the opportunity to test drainage practices and drain responses in a wetter and steeper environment. With funding from the South West Catchments Council (SWCC) the objectives of the Hillman River South project were:

- Demonstrate and evaluate the performance of groundwater drainage as a tool for reducing the incidence of waterlogging and salinisation on rural land.
- Demonstrate current practice in drain construction in higher rainfall areas.
- Assess changes in downstream water volume and quality in response to drain construction and discharges.

2 Site characteristics

2.1 Location

The Hillman River South site is located on properties owned by M Ewen (Lot 101 on Plan 19020), W Duffield (Lots 2578 and 2579 on Plan 141054) and EK Duffield (Lot 1 on plan 9770 or Lot 100 on plan 19019). The drain crosses the Quindanning-Darkan Road at coordinates 468 480 mE and 6 318 900 mN. The site is in the Blackwood River catchment in south-west Western Australia (Fig. 2). Darkan is approximately 150 km south-east of Perth within the Shire of West Arthur. The study site is approximately 11 km north-west of the Darkan townsite and access to the site from Darkan is via the Quindanning-Darkan Road (Fig. 3).

Unlike the flat drainage sites of the Zone of Ancient Drainage in the Eastern Wheatbelt, this site, located on the border of the eastern Darling Range zone and the Zone of Rejuvenated Drainage, is characterised by steeper topography, relatively shallow bedrock and medium rainfall (Fig. 2). This site is also within the Western Australian 'Woolbelt', which is defined by a rainfall zone of 500–800 mm/yr (Catchment Hydrology Group 1998).

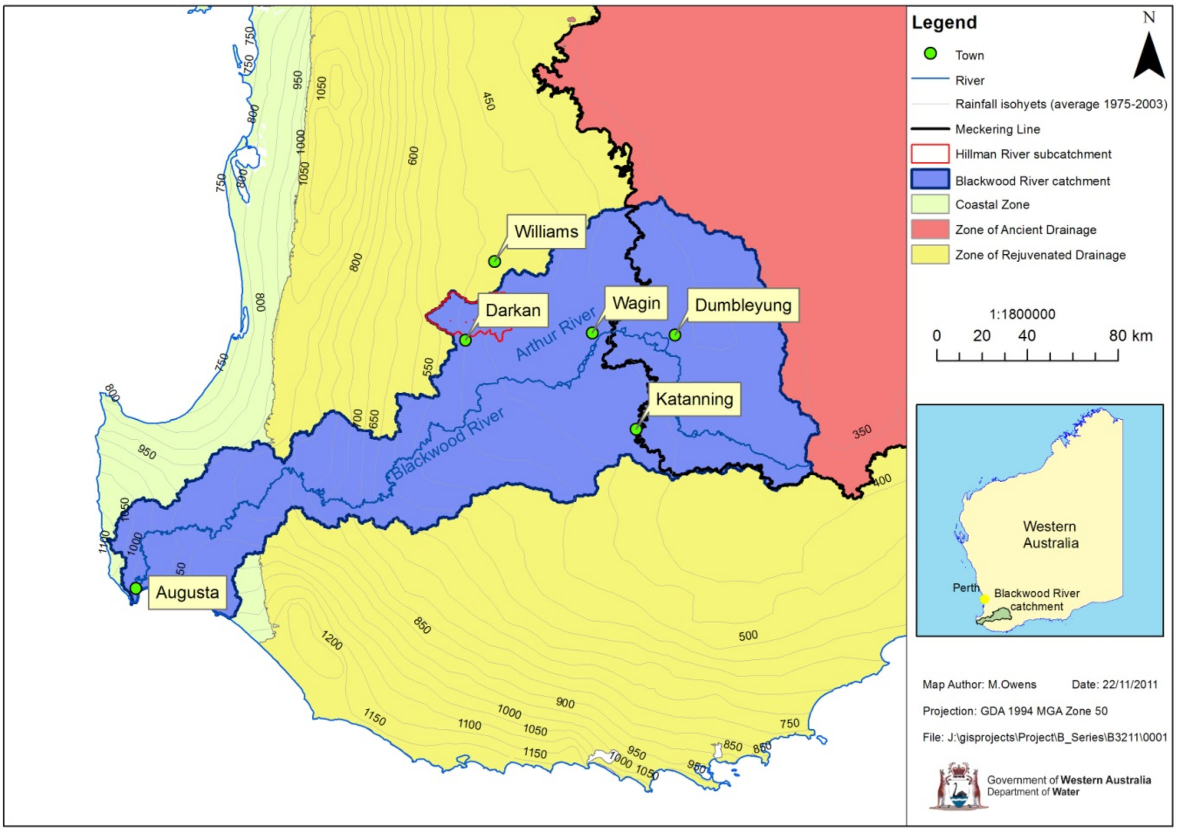


Figure 2 Location of towns in the Blackwood River catchment

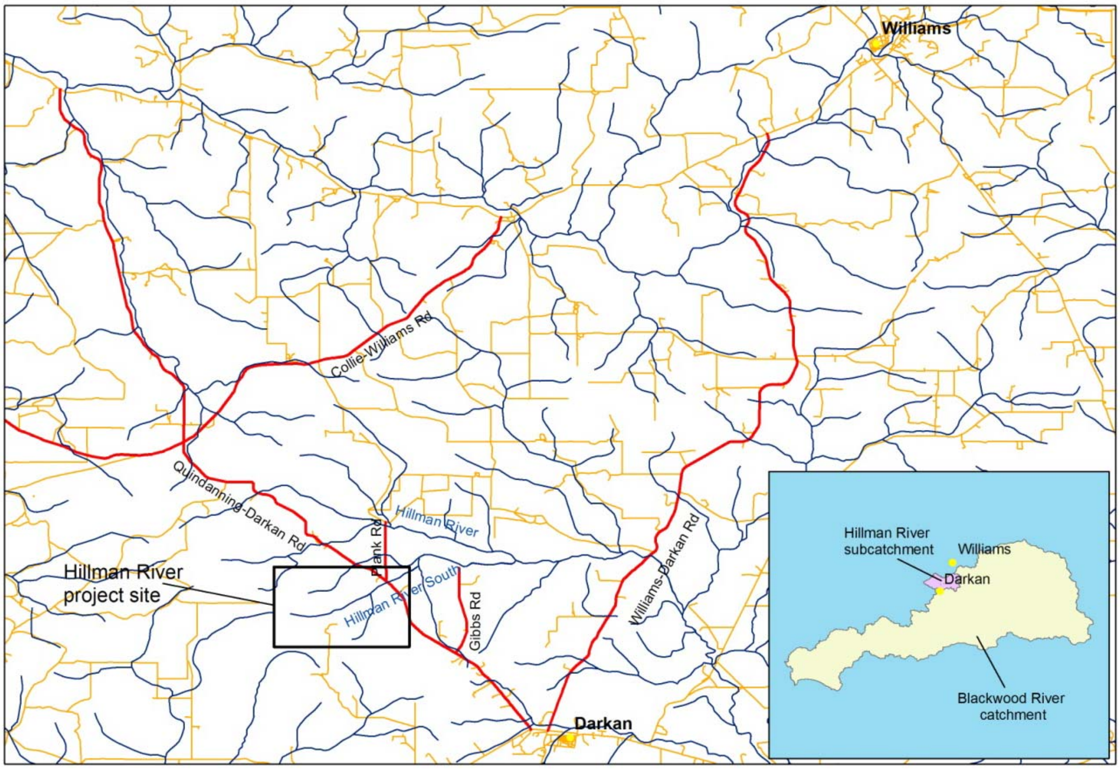


Figure 3 Location of the project site in relation to the surrounding towns

2.2 Climate

The south-west of Western Australia has a temperate climate, so summers are warm and dry while winters are cool and wet. Approximately 80% of the rain falls between May and October (Mayer et al. 2005).

The study site is located in a medium–high rainfall zone. The long-term (1889–2009) average annual rainfall at the Darkan townsite (Station 10542) was 559 mm, with most of the rain in winter (June–August). The long-term (1889–2009) evaporation was 1484 mm (Bureau of Meteorology 2010).

The average annual rainfall 1970–2009 was 504.5 mm (Fig. 4), down from the long-term average of 559 mm. Annual average evaporation in the same period was 1460 mm, slightly less than the long-term average. The evaporation data used in Figure 4 is SILO evaporation data which uses original Bureau of Meteorology data with missing values interpolated from the local rainfall and measured pan evaporation from surrounding sites (SILO 2009).

An automated pluvio rain gauge (Station 509645) operated at Station B (mid catchment) from 5 February 2009 to 16 February 2010 (Fig. 5). Over the 375 days of operation 544.5 mm of rain was recorded. There were three significant rainfall events greater than 20 mm, with the highest daily rainfall being 29.5 mm on 21 May 2009 (Fig. 5). The combined Darkan station and Hillman River South site cumulative daily rainfall for the entire project was 1529 mm. The combination provided a more reliable rainfall trend before and during drain monitoring.

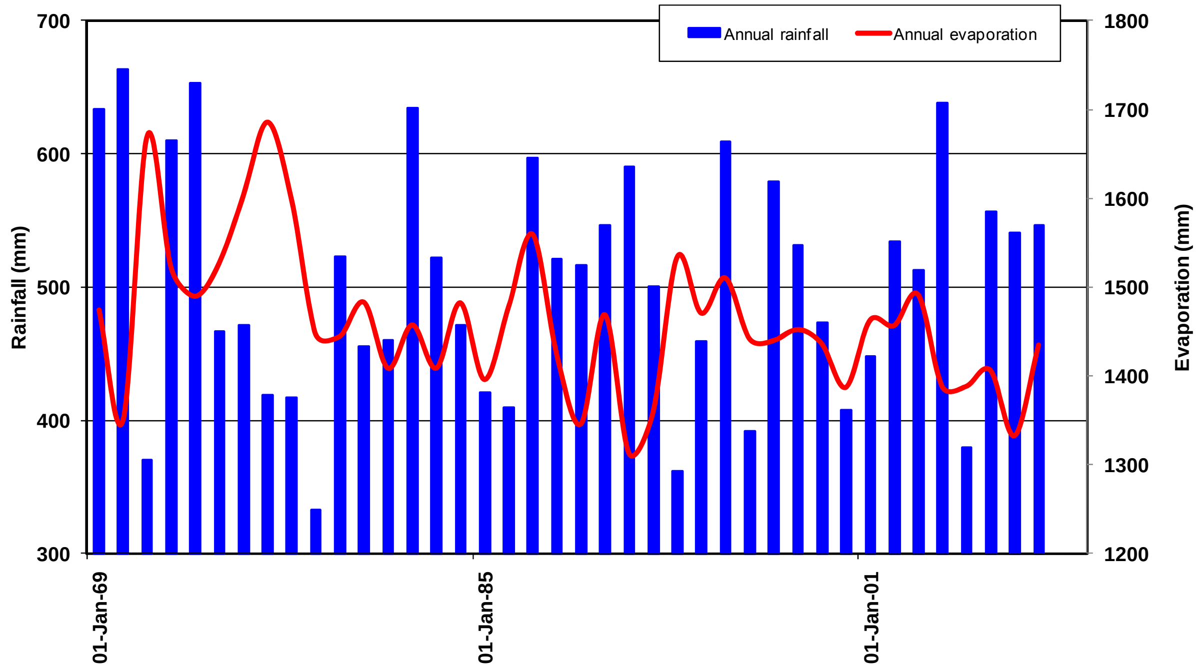


Figure 4 Annual rainfall and evaporation for Darkan townsite

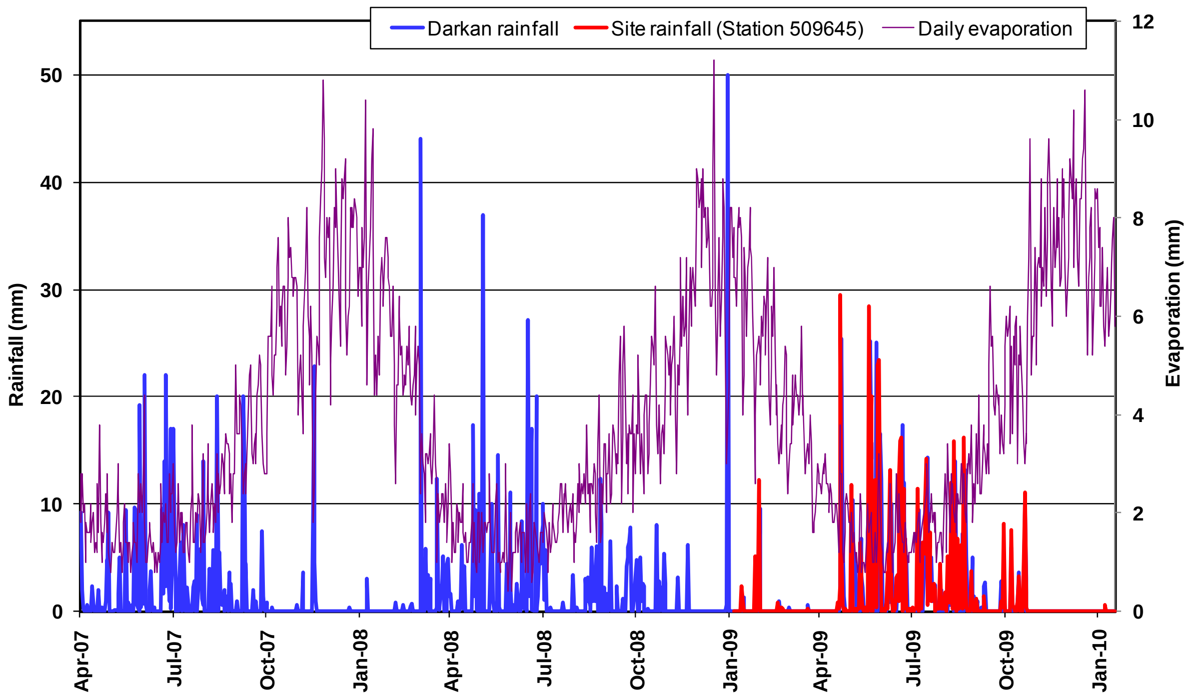


Figure 5 Combined site (Station 509645) and Darkan SILO daily rainfall and SILO evaporation (Station 10542)

Accumulated monthly residual rainfall (AMRR) has previously been used to reflect the correlations between rainfall, recharge and watertable level trends within the inland areas of the state. AMRR is the accumulation of monthly rainfall less the average monthly rainfall for the period of analysis.

During the normal wet winter–dry summer rainfall pattern AMRR rises around May–July and declines around September–October (Fig. 6). This corresponds with the usual onset of winter rainfall from May and its decline towards the end of winter from September each year.

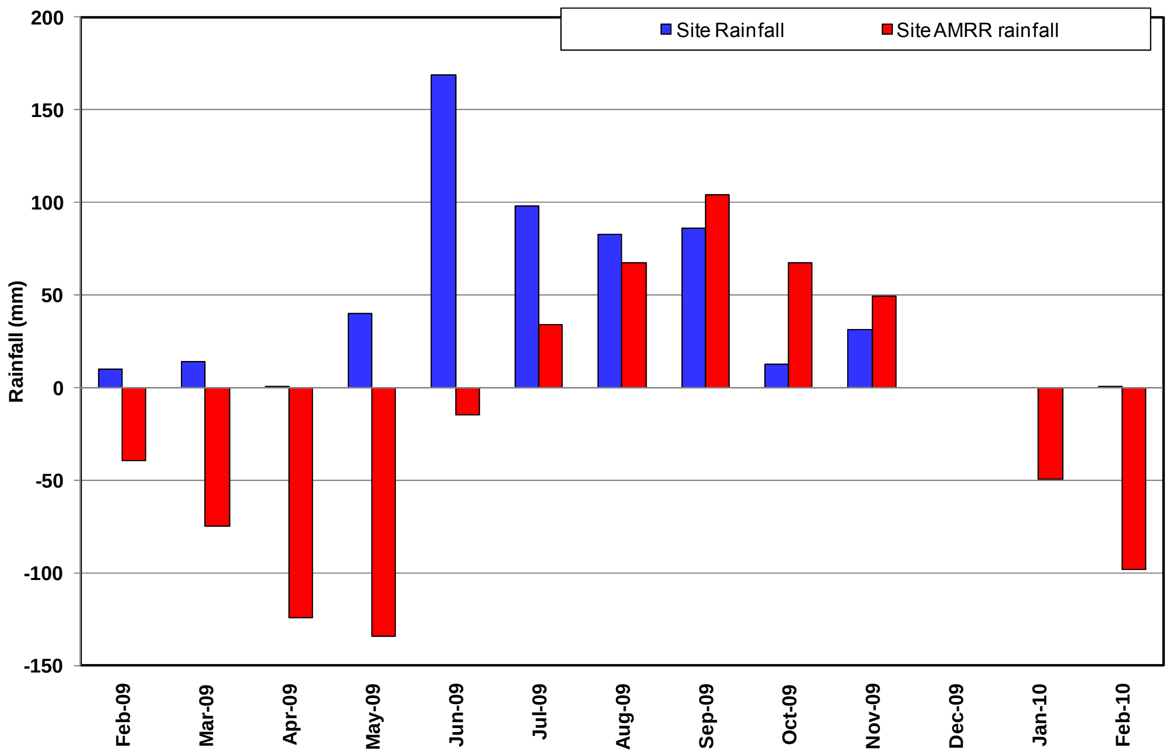


Figure 6 Rainfall versus AMRR for the drainage monitoring period

2.3 Land use

The Western Australian 'Woolbelt' has been largely cleared of native vegetation for agricultural land uses. In the West Arthur shire only 29.8% of the native vegetation remains (Shepherd et al. 2001). The farming systems in the Darkan area are mixed cropping and livestock grazing of pastures and crop residues. In the Blackwood Zone 8: Hillman Zone (as defined by the Department of Agriculture; South West Appraisal Team 2005) nearly half the agricultural production is pasture and grazing. The main crops are barley and oats with other cereals and pulses grown where conditions are suitable (South West Appraisal Team 2005).

The landholders in this study grow annual winter crops (oats, canola) and run livestock (predominantly sheep).

2.4 Topography and drainage

The Hillman River South catchment is north of the Arthur and Blackwood rivers. The Hillman River flows eastward in shallow valleys that are 20–100 m deep (Tille et al*.* 2001). The streams are mostly ephemeral but may keep flowing year round after above-average winter or out-of-normal growing season summer rainfall. Stream salinities are brackish to highly saline (2000–20 000 mg/L), mostly depending on their position in the landscape, groundwater contributions and the effects of evapoconcentration (Mayer et al. 2005).

The Hillman River catchment landscape is characterized by gently undulating rises and low hills with narrow alluvial plains of the Hillman, Blackwood and Arthur rivers (Percy 2000). The upper catchment has steep incised valley flanks with slopes at 5–15% that give way to the downstream flat, narrow valley floors 200–1000 m wide. The valley floor is at 295 m AHD.

The contours of the catchment are shown in Appendix A.

2.5 Geology and hydrogeology

The Hillman River South catchment area is in the lower south-west corner of the Yilgarn Craton. The basement rock comprises mainly granitoid rocks, gneiss and adamellite (Rutherford 2000) and is extensively fractured and intruded by dolerite.

The Tertiary deep weathering of the basement produced an extensive lateritic profile that is preserved today as remnants along the most elevated parts of the landscape. Subsequent erosion has partially or completely stripped the lateritic profile from the now incised valley flanks. Undifferentiated Tertiary and Quaternary deposits now occupy most of the valleys.

Regolith varies in depth and composition, usually comprising one or more of:

- residual or relict material including ferruginous, siliceous and calcareous duricrust
- slope deposits including colluvium and sheet wash
- valley floor deposits including lateritised and podsolised valley fill
- exposed rock, saprolite or saprock.

The low interstitial permeability of the basement rock renders it impermeable within the context of this project. Groundwater within the basement is confined to the development of localised aquifers within fracture zones.

Aquifers within the weathered regolith of the valley flanks and hilltops are generally unconfined and localised in scale. Aquifer permeabilities are generally considered low. The aquifers downslope become semi-confined and confined beneath a clay-rich aquitard developed within the valley floor. A very shallow seasonal perched watertable aquifer can develop within the podsols that often overlie the aquitard within the valley floor.

Similarities can be drawn between the aquifer material of the Hillman River South and adjacent Maxon Farm sites. The drilling at the Maxon Farm site can provide a more detailed understanding of the aquifer characteristics likely to underlie the Hillman River site. As described by Dogramaci (2004), the aquifer materials at the Maxon Farm site can be divided into three distinct zones above the basement/bedrock. The depth to basement varies from 6–31 m, with an average depth of 25 m. Drilling at the Hillman River site did not go to bedrock but it could be assumed, due to the similarities between the sites, that depth to bedrock at Hillman River would also be variable, with average depth around 25 m.

The lowest zone, 4–10 m thick, has relatively high hydraulic conductivities. Above this the middle zone consists of weathered clay and quartz sand, is semi-permeable and can impede the upward movement of groundwater from the lowest zone to the top zone – the surficial sediments. The surficial sediments consist of medium to coarse quartz sands and clays (Dogramaci 2004). This same layering of the regolith was seen in the Hillman River drill logs with varying depths of surficial sediments over the in-situ weathered clays.

2.6 Soils

The Hillman River South site lies within the Darkan soil landscape system in the Eastern Darling Range Zone (South West Appraisal Team 2005). The dominant soils within this land system from an agricultural perspective are sandy gravels; in particular, duplex sandy gravels with yellow clay or clay loam subsoils (Schoknecht 2002). Other common soil types are yellow brown loamy gravels, deep sandy gravels, shallow gravels and grey deep sandy duplex soils with yellow, slightly acidic to neutral sodic subsoils (Percy 2000).

Soils near the drain are duplex, with the overlying gravels and sands varying in texture, thickness and permeability. Duplex sandy gravels vary in thickness from a few centimetres to more than 60 cm. These topsoils are very permeable, with the water moving via matrix or pore flow. This layer often develops a seasonal perched aquifer when the water sits above the impermeable clay subsoil. Some of the deeper duplex soils are podsols with bleached, dark stained or yellow sandy profiles sometimes exceeding the full 2 m depth of the drain. When saturated these topsoil sands and podsols can become unstable and, during heavy rainfall and/or large groundwater inflow events, collapse into the drainage channel. Podsols adjacent to transect 1 bores caused frequent such collapses of some drain channels (Fig. 7).

The medium to heavy subsoil clays have low permeability, with most water movement restricted to preferred pathways, like those formed from old tree roots. The depth to this less permeable subsoil layer varies across the site from near surface to the full drain depth, as discussed above (Fig. 8a). The variability can be seen in Figure 8b where the clay subsoil is 1 m deep on the drain batter in the foreground and near the surface some 10 m into the background.

Pockets of blue, green and black ‘plasticine’ clays found at 1.5–3 m below the valley floor emphasised the impermeable nature of some of the subsoils. These ‘glayed’ soils are formed under anaerobic conditions where the supply of oxygen was restricted by saturation and low permeability.

The variability in soil profile thickness and type is illustrated in Appendix B.

Figure 7 Drain slumping

a

b

Figure 8 Soil profiles of the drain showing varying depths of sand over clay soil at (a) Transect 1 and (b) Transect 4

3 Drainage project

3.1 Drain design and construction

Construction of the Hillman River South drain took 64 days from 25 November 2008 to 28 January 2009. The constructed section of drain is approximately 8715 m long while the entire system, including the creek, is 9669 m. Ten culvert crossings were installed: one on the Quindanning-Darkan Road and the others for farm access and surface runoff management.

An excavator with a trapezoidal-shaped bucket was used to dig the drain channel with 1:1 batter slopes and 0.9 m floor width (Fig. 9). Excavation of the mostly sandy and clay soils was easy. Some shallow basement was encountered along both of the southern tributaries, requiring realignment or shallowing of some sections of the drain. On average, the drain was 2 m deep, 5 m wide with 1.2 m high spoil banks on both sides forming continuous levee banks. The levee banks completely excluded surface runoff from entering any sections of the drain other than the water entering the lower section of the drain from the creek at Station B (Fig. 10).

Figure 9 Excavator at the Hillman River South drain

Approximately 2660 m of drainage channels, including spur drains that intersected the main drainage channel, were constructed upstream of the western gauging station (Station A). Downstream from this point no drainage channel was constructed for 950 m, as the incised and well defined creek line provided groundwater drainage. A 460 m section of drain was constructed midway along the creek to intercept a saline seep on the southern side (Fig. 10). Discharge from this drain section was diverted back into the creek line.

The mid gauging station (Station B) was at the transition between the creek line and head of the main drain. Depending on the flow rate streamflow could either bypass and/or be diverted into the head of the main drain through Station B. During summer or times of low flow streamflow was diverted into the main drain and flowed down the main drainage channel. During high flows a proportion of the water was diverted into Station B while excess water bypassed the station and contributed to streamflow parallel to the main drain. Where possible the streamflow was diverted into the main drain to reduce the streamflow and inundation along the southern side of the valley floor. Station C is at the eastern end of the main drain and measured total discharge from 5010 m of drain and streamflow that entered through Station B. Streamflow through Station B flows along 2410 m of drain to Station C. The remaining 2590 m of drains between Stations B and C are tributary drains that discharge into the main drain (Fig. 10).

The drains dug immediately downstream and to the north of Station B were where the drainage contractor experimented with two short sections placed to intercept a saline seep. Approximately 1500 m of drain extends from about midway along and to the south of the main drain, parallel to a minor natural watercourse and intercepting saline seeps along its length. A further 770 m of drain connects with the main drain immediately upstream of Station C, bringing seepage water from the northern side of the waterlogged valley floor and footslopes. A 70 m section of culvert was constructed within this drain to allow streamflow from the upstream catchment to flow over the drain from west to east.

Downstream from Station C the drain passes under the Quindanning-Darkan Road at a depth of about 2.5 m. The drain depth progressively shallows to about 1 m over the 600 m between the road and Hillman River South to enable it to discharge directly at the river bed level.

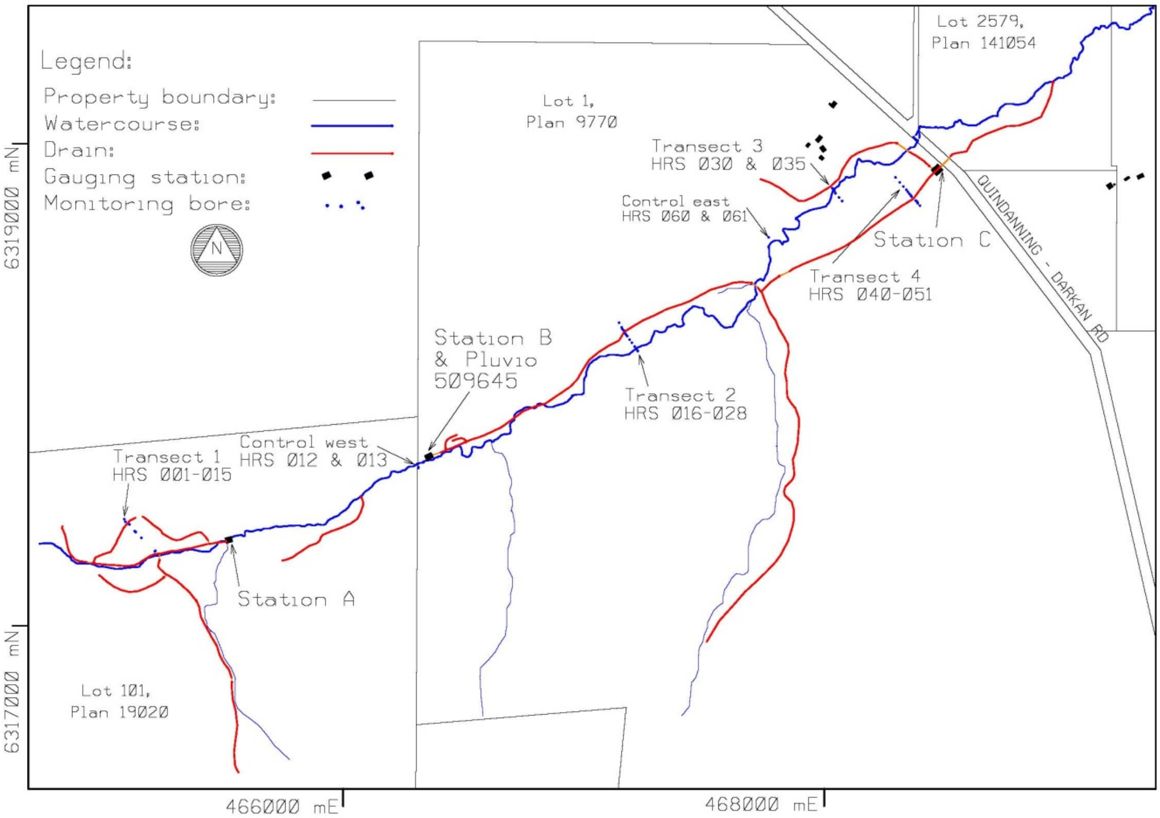


Figure 10 Hillman River South drainage scheme site plan

3.2 Monitoring methods and data availability

The objectives of the monitoring program were:

- Establish base line and comparison streamflow conditions downstream from and within an adjoining catchment unaffected by the drain.
- Measure watertable responses and drain discharges to correlate responses with discharges and assess drain effectiveness.
- Measure post drain and comparison streamflow conditions downstream from and within an adjoining catchment unaffected by the drain.

Rainfall

A (pluvio) rain gauge (Station 509645) recorded data from 07 February 2009 to 16 February 2010, adjacent to Station B at coordinates (MGA 50) 466 368 mE and 6 317 711 mN. This station operated from 5 February 2009 to 16 February 2010, as discussed in Section 2.2.

Groundwater levels

Sixty-five bores (HRS01–61) were drilled across the site (Fig. 10). Due to seasonal site inaccessibility only bore transect 3 was drilled before its adjacent drain construction. The water levels were measured monthly from 12 January to 15 December 2009. Automated sensors recorded water levels at two-hourly intervals in nine of the perched watertable bores from 18 February to 15 December 2009. The perched watertable was expected to be most responsive to drainage.

The bores are numbered and bores with the same number are labelled according to their depth: the suffix ‘a’ indicates an intermediate bore, ‘b’ a shallow bore and SS perched water.

Some levels rose or remained at or above ground level or the bore casing height (i.e. flowing bore) during the monitoring period. On a few occasions these water level heights were measured as their true heights above top of casing; they are the true piezometric water levels and are indicated in the charts as separate points. The values measured between these times were not considered accurate, as they provided a true representation of the water level in the bore but were restricted by the casing height.

In-situ groundwater salinities were measured monthly from 21 January until 15 December 2009 and pH was measured monthly until May 2009.

Fifty-eight of the bores make up the four transects placed to measure watertable responses to different sections of the drain. Each transect was perpendicular to the drain and included shallow bores, and shallow and intermediate nested bores. The transects extended 80–200 m from the main drainage line (Fig. 10).

The remaining seven bores (HRS 12A, 12D, 13, 13SS, 61, 60, 61SS in transects control east and west) were used as comparison bores placed to be unaffected by the drainage (Fig. 10). These bores are grouped in two sites towards the western and eastern ends of the drainage site. The comparison bores were intended to indicate the groundwater level and salinity trends across the site in the absence of drainage. Comparison bores are not regarded as control bores because they may not represent all the variable conditions affecting water levels across the site.

Groundwater salinities increased downstream from west to east: averaging 9500 mg/L towards the upstream end of the catchment, 11 000–13 000 mg/L toward the central section and 15 000 mg/L at the downstream end.

The bore placements in the landscape are shown in Appendix C and detailed bore construction details are in Appendix D.

Drain discharge

Station A (Fig. 10) is at the end of the first section of the drain (Drainage Site A; Station 609070) and measured continuous discharge from these drains. Station B (Drainage Site B; Station 609071) is at the mid section of drain and measured both drain flow and streamflow. During summer or periods of low flow drain and creek water flowed into the second sump and down the main drainage channel. During high flows water was still diverted into the sump, and the excess continued down the adjacent creek. The third gauging station, Station C, was located downstream at the Quindanning-Darkan Road crossing (Drainage Site C; Station 609072) measuring the accumulation of drain flow and streamflow from the drain (Fig. 11). This station also measured salinity and temperature continuously. Stations A and B operated from 16 January 2009 to 15 February 2010 and Station C from 15 December 2008 to 15 February 2010. In-situ samples of pH, EC and flow were measured monthly at each station.

Weirs were installed as inserts into the inlet ends of the 600 mm diameter HDPE culverts at gauging stations A, B and C, upstream, mid-site and downstream, respectively. The 60° V-notch weirs restricted flow through the culverts to about 25 L/s before becoming flooded. Water level transducers measured the water levels in stilling ponds immediately upstream of each weir and converted their levels to discharge volumes from flow rating tables. Both the weirs and rating tables provided discharge results even when the weirs were completely submerged and acting as ‘flooded orifices’.

Figure 11 Downstream gauging station C (Station 609072)

Drainage discharge from the scheme was measured by three gauging stations. The catchment upstream of Station A (609070) is 293 ha and rises from 305 to 340 m AHD. The catchment between Stations A and B is 386 ha and its elevation is 290–300 m (AHD). It also has an incised creek that directs stream and surface water flows down the catchment. The catchment upstream between Stations B and C is 1127 ha, is in the valley floor and with elevations 280–290 m AHD is flatter than the upstream catchment. Poor drainage results in waterlogging and inundation.

Water chemistry samples were taken from Stations A, B and C on 8 April 2009 and laboratory tested for major ions, elements (Al, As, Cd, Cr, Co, Cu, Fe, Mg, Mn, Mo, Hg, Ni, Zn, U, Th, Se, Pb), N and P.

Streamflows

Surface water flows, salinities and pH were measured in selected waterways within and downstream of the drainage site from April 2007 to December 2009. Measurement began one and a half years before drain construction to establish the pre-drain conditions against which drain discharges could be assessed. The EC, pH and estimated flow were measured monthly at HRS04, HRS06, HRS07 and HRS14 from 24 April 2007 to 15 December 2009. Due to seasonal conditions sites were inaccessible on some occasions (Fig. 12).

Two rounds of water chemistry sampling were conducted at selected sites: HRS03–06 and HRS14 on 24 October 2008 and sites HRS03–04 and HRS14 on 8 April 2009. All samples were laboratory tested for the same major ions and elements as the drain discharge samples.

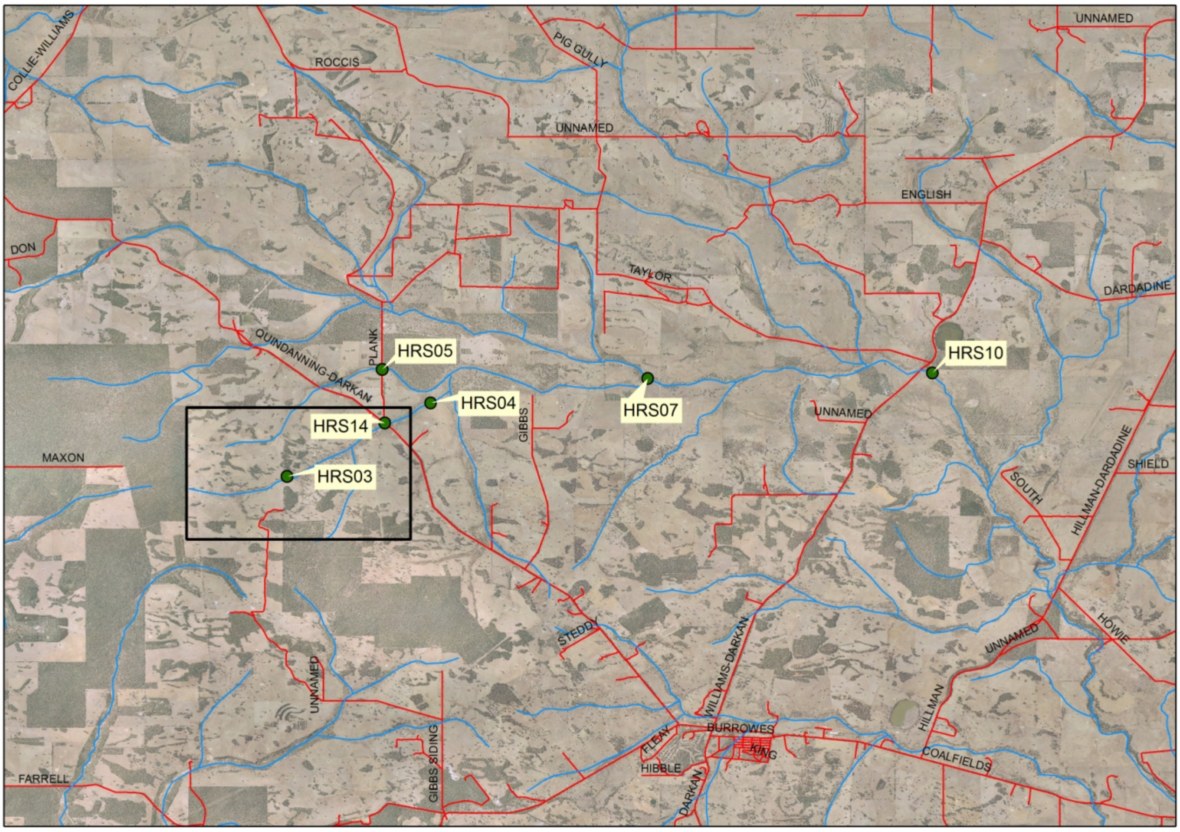


Figure 12 Surface water sampling sites

4 Results

4.1 Groundwater results

4.1.1 Groundwater responses

The groundwater levels in the bores reflect the relationship between bore depth and the groundwater head while their watertable level trends correlate with AMRR. The water levels observed in the valley flats are controlled by the heads developed beneath the adjacent hill sides. Due to the relative proximity between recharge and discharge areas within this valley and the clay confining layer, groundwater heads beneath the valley floor can exceed several metres above ground.

Pressure heads

The comparison bores had varying groundwater heads appeared to partially correlate with the bore depths (i.e. the deeper bores generally had higher water levels than nearby shallow bores). In HRS12 (8.2 m deep) the pressure heads were about 0.5–0.8 m above ground level (Fig. 13), in HRS13SS (2.4 m deep) below ground level while in HRS12A (5.5 m deep) and HRS13 (3.5 m deep) the heads fluctuated between the two levels (Fig. 13).

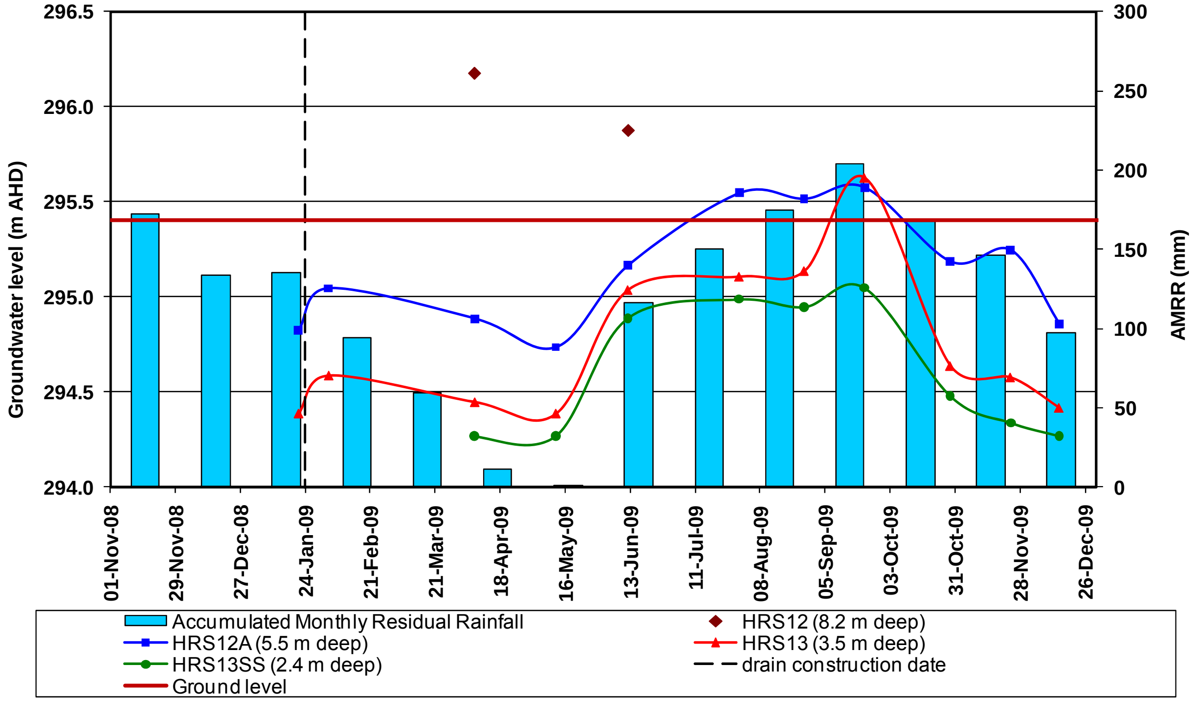


Figure 13 Comparison bores hydrograph with normalised AMRR

The bore construction information (Appendix D) shows that it is unlikely that any of the bores across the site have gone through the aquitard and into any permeable underlying strata (Section 2.5). There appears to be a relationship between bore depth and water levels with deeper bores generally having higher water levels, with some recorded above ground level.

All the comparison bores are at about the same elevation (295.4 m ± 0.04 m AHD) so showing the overriding relationship between bore depth and water levels.

Rising deeper groundwater heads remained the primary cause of rising winter water levels in the shallower bores HRS13 and 13SS. This was shown by the fairly uniform trend and consistent differences in water levels that persisted between nearly all the bores throughout the monitoring period. If in-situ recharge was the primary cause of groundwater rise the expectation was that the water levels in the shallower bores would rise to levels near or above those of the deeper bores. Such responses would produce results similar to the water level rise measured in HRS13 during September–October 2009.

Soil profile and bore construction

Groundwater levels and changes are in response to pressure heads and correlated to AMRR. The water levels are strongly influenced by the bore and position of screen in relation to the upper sandy and deeper clayey soil profiles. Those bores measuring the unconfined watertable in the upper sandy layer are most responsive to rainfall and drainage. For example, in the comparison bores, the water levels of the shallower bores (HRS13 and 13SS) rose more than 0.5 m in May–June 2009 in response to 29.5 mm of rainfall on 21 May 2009 and 28.4 mm on 18 June 2009 and the onset of the winter season. HRS13 experienced the greatest groundwater response – just over 1 m (Fig. 13).

Transect 3 bores had the same responses to their location in the soil profile as the comparison bores. The bores showed a response to the underlying groundwater heads and a relationship with AMRR (Fig. 14). The significant water level rises of 0.6–0.8 m in bores HRS30 and HRS31b are a combination of pressure heads, rainfall and their location in the sand layer (Fig. 15). This sand layer allows rapid infiltration of rainfall so groundwater levels respond quickly to winter rainfall, and also drain quickly afterwards. The seemingly unresponsive nature of the remaining bores in Transect 3 is due to their screens being positioned well into the confined clay layer (Section 2.6). The water level responses of the two bores located in the sand profile may be isolated responses and not necessarily linked to the drain. This is due to the variability in the soil profiles as described in Section 2.6 and Appendix B, with the sand layer varying from 1 m deep to the surface (Fig. 15).

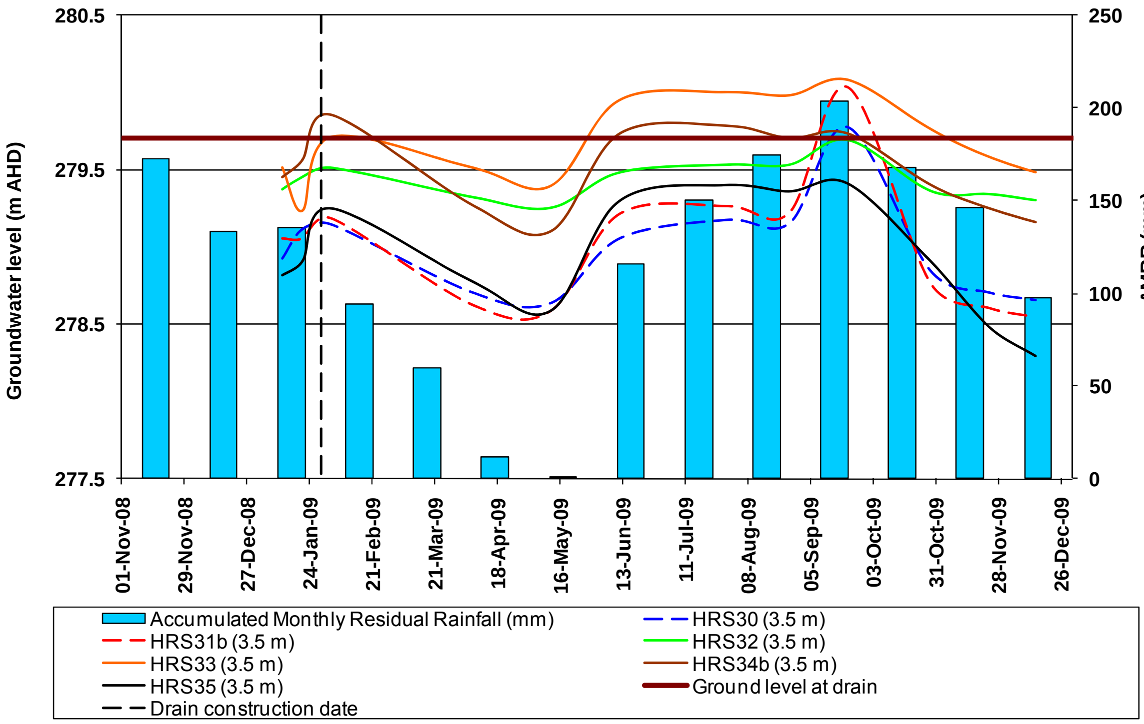


Figure 14 Groundwater level responses in Transect 3 bores

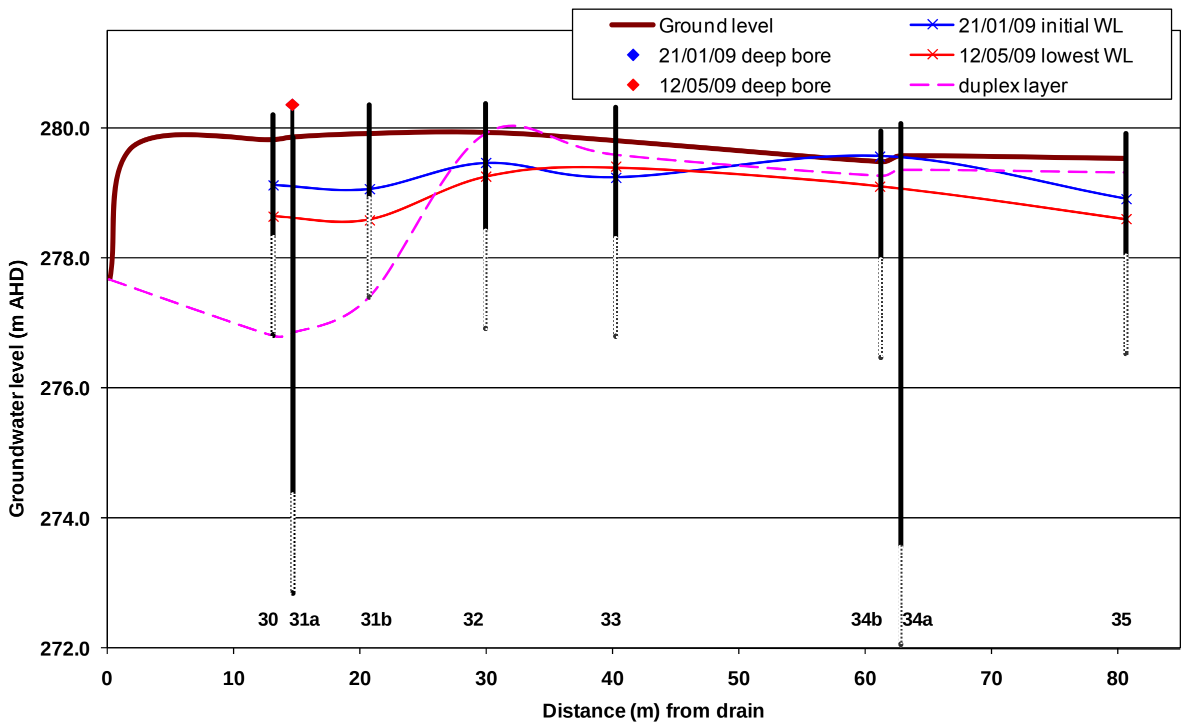


Figure 15 Groundwater profiles in Transect 3 bores

Watertable responses to the drain construction

Water level responses to drain construction would be seen if the magnitude or rate of water level changes in bores decreased with distance from the drain. In a time-series chart this would be depicted by the hydrograph of a bore close to the drain falling more steeply (or faster) than the hydrograph of a more distant bore. For example, the water level in the bore closest to the drain (i.e. HRS30) would have a steeper downward slope than the level in the furthest bore (i.e. HRS35). This expected response was not seen in the water level trends in the low-lying Transect 3 bores; HRS30 and HRS35 have similar responses (i.e. the same slope; Fig. 15). So the drain is not noticeably reducing water levels at this transect.

Transect 2 bores may show a water level response to drainage. A drawdown closest to the drain indicates that the drain may be draining the soil profile at this site. For example, there is a drop in water levels of 0.6 to 0.9 m from bore HRS22 to HRS21 (Fig. 16). There is also a drawdown of over 1 m between bores HRS20 and HRS19 on the opposite side of the drain channel.

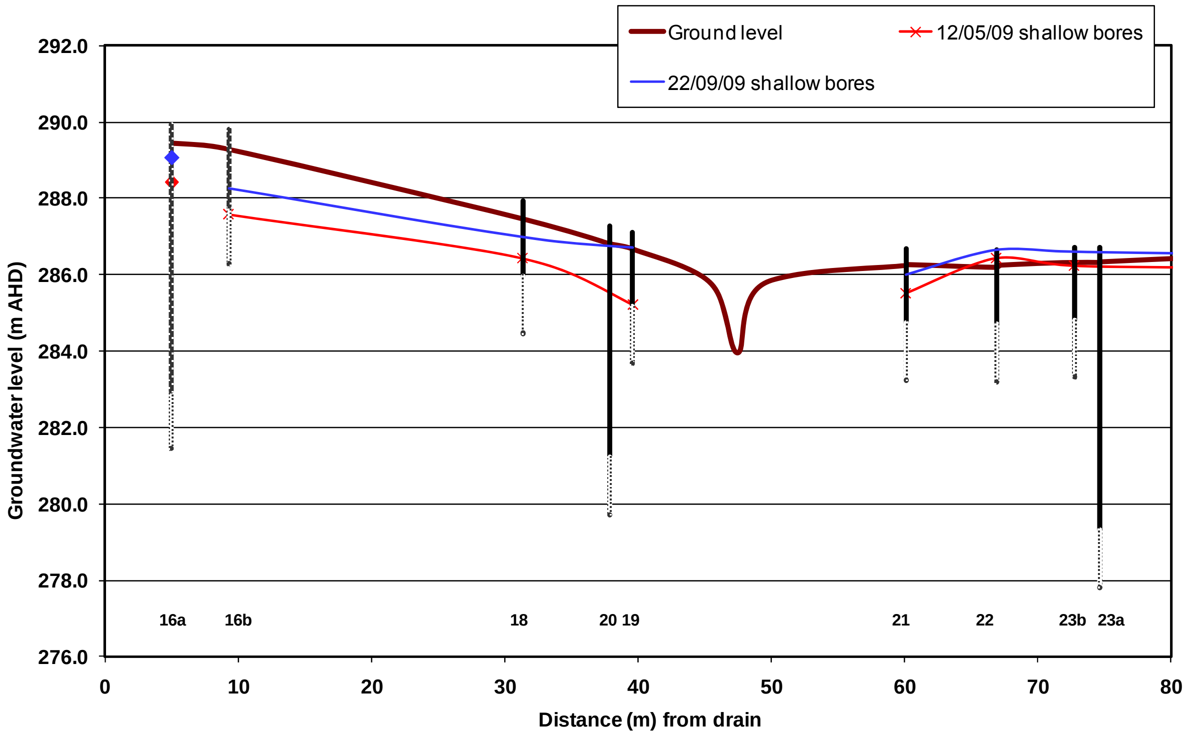


Figure 16 Watertable response in Transect 2 shallow bores

A response or drawdown was not seen at this site unless the bore water levels were above that of the impermeable clay layer, as seen in the perched water bores in Transect 2. During May, before the onset of winter, the water levels were at their lowest and did not show a response to drainage. With the onset of the winter rains, bore water levels began to rise, and were highest during September (Fig. 17). A 0.2 m drawdown was observed between the bores closest to the drain (Fig. 17) where the perched water above the impermeable clay layer drained away. As described in Section 2.6 this is where a drainage response would more likely be seen.

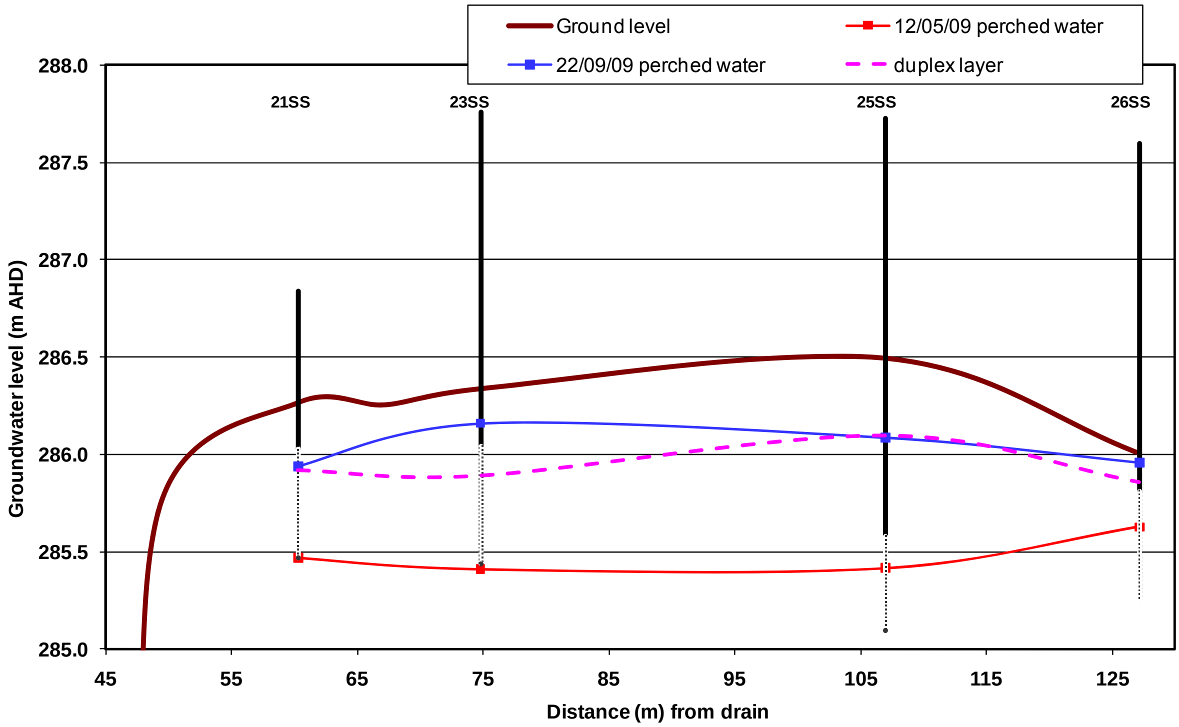


Figure 17 Water level responses for perched water bores in Transect 2

4.1.2 Groundwater salinity

Groundwater salinities generally increased:

- with increasing distance downstream
- nearer the valley floor and/or main drainage channel.

The in-situ monthly measured groundwater salinities across the site varied from 1627 to 32 460 mg/L.

Through the year salinity varied minimally and similarly in proportion to other bores in the same transect. Salinities are influenced by localised recharge, evapoconcentration and deeper groundwater discharge.

Transect 3 bores, except HRS31b, had very little change in salinities throughout the monitoring period (Fig. 18) and there was no change in the bores in proportion to each other.

The minimal changes in salinities over the monitoring period were likely due to bore construction and position of the screens in the low permeability clay subsoil. The only bore with large fluctuations was HRS31b, 3600 to 29 000 mg/L. (Fig. 18). These fluctuations were noticeable because the bore and its screen are within the sandy A horizon. The recharge dilution and the upward leakage evapoconcentration drove the salinity fluctuations in this bore. The exception to this was HRS30, which is located in the sand layer, and showed movement in the groundwater levels. This reflects the variability in the site, with changes in salinities being very localised.

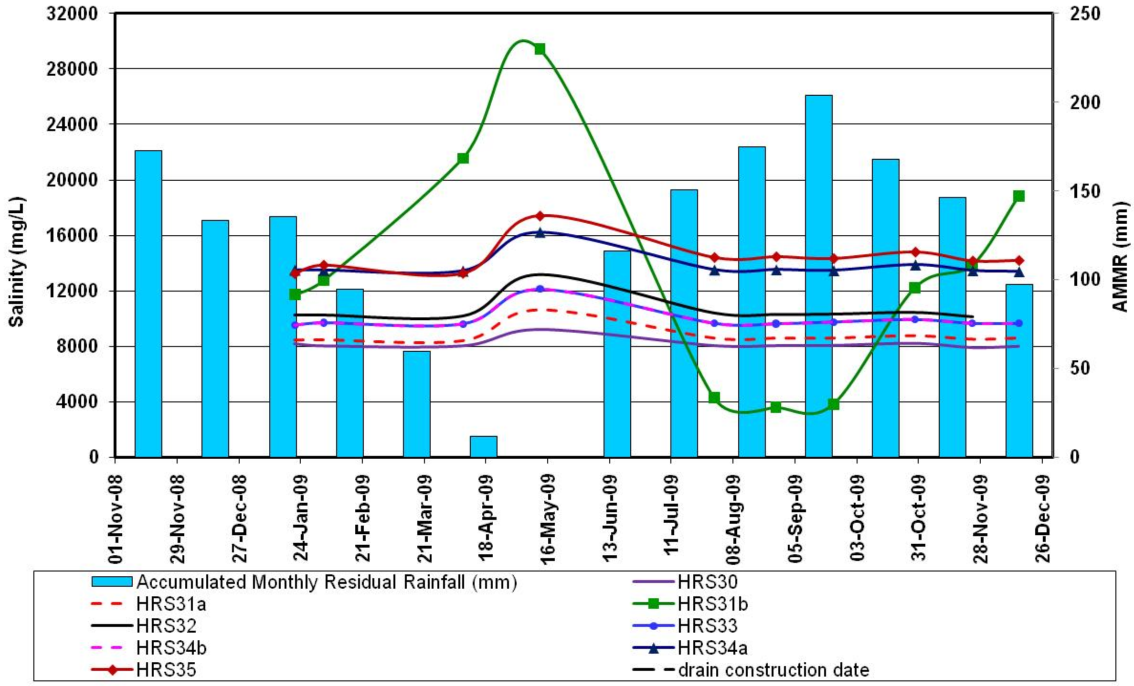


Figure 18 Salinity trends for Transect 3

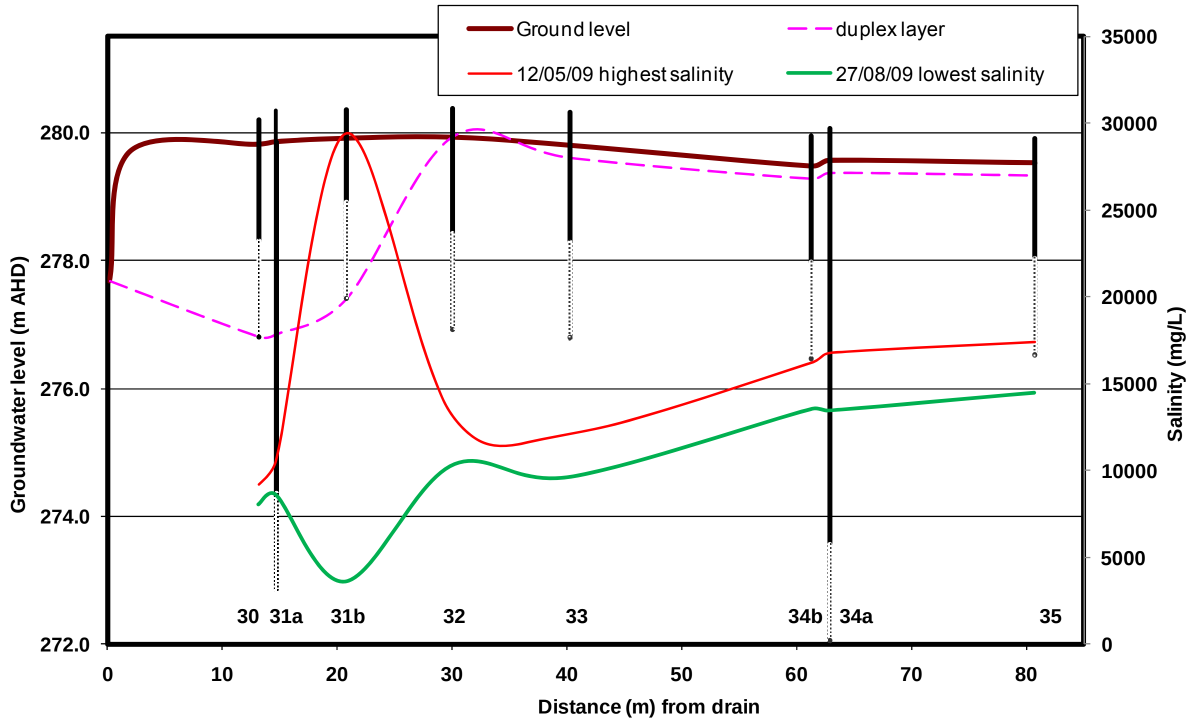


Figure 19 Transect 3 salinities with respect to the soil profile

Groundwater salinities increase nearer the valley floor and/or main drainage channel across the site. In Transect 3, HRS35, closest to the main drain and on the valley floor, had salinities 13 000–17 000 mg/L while HRS30 (furthest from the main drain and nearest to the valley floor) had salinities 8000–9000 mg/L (Fig. 19).

The salinities at this site generally increased with distance downstream. Transect 1 bores located towards the headwaters of the catchment had an average salinity of 9000 mg/L while Transect 4 bores in the valley flat toward the discharge end had an average salinity of 15 000 mg/L.

The trend for rising salinity downstream is due to the location of the transects in the landscape, with those nearer the valley flat having higher salinities (Fig. 20). The average transect salinities are similar to those in the comparison sites, with the average salinity for comparison west 9500 mg/L and 13 000 mg/L for comparison east. These similarities show the groundwater salinities were not affected by the drain.

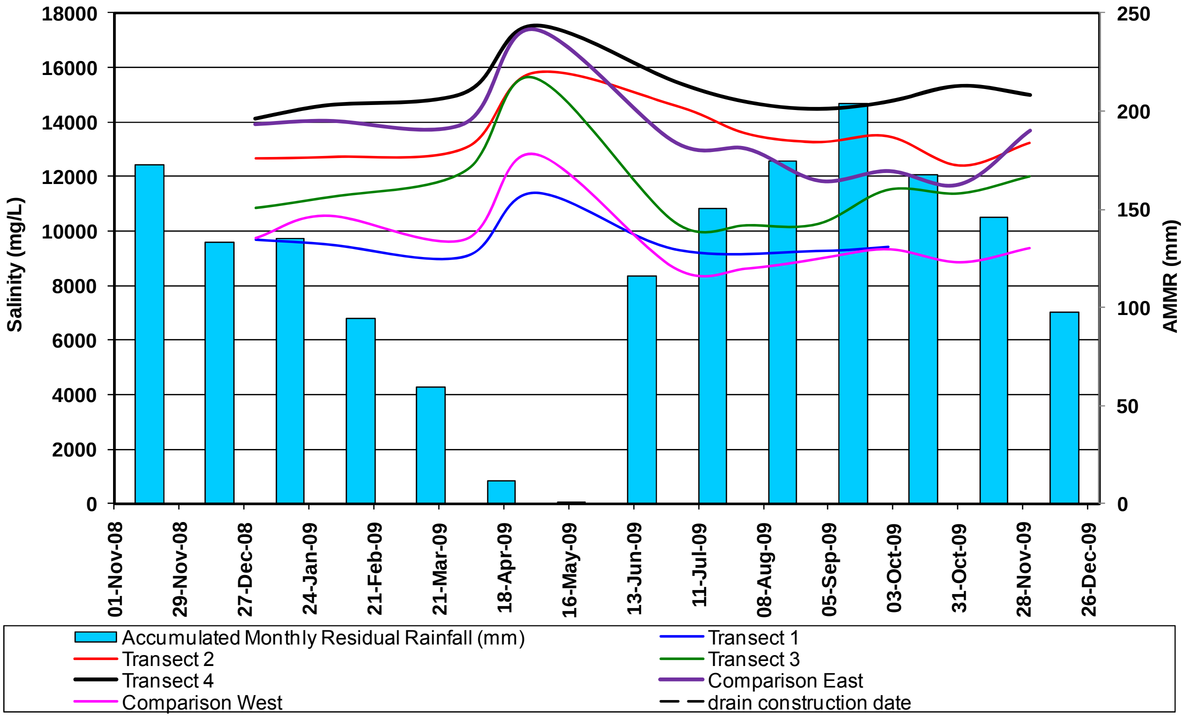


Figure 20 Average salinities across transects

4.1.3 Groundwater pH

The average groundwater pH, measured in the bores, increased with distance downstream. The average pH in Transect 1 bores was 4.4, 4.5 in Transect 2, 6.2 in Transect 3 and 6.7 in Transect 4. The lower pH values in the two upstream transects resulted from the iron in the soil profile. Iron concentrations decreased downstream at the three gauging stations: 4.1 mg/L at Station A, 2.3 mg/L at Station B and 0.6 mg/L at Station C. Acidic groundwater was generated by microbial reduction of iron around the root zone, leaked into the deeper groundwater causing it to become acidic (Shand & Degens 2008).

4.1.4 Discharges

Three gauging stations measured the discharge along the main drainage channel. The drain upstream of Station A discharged a total of approximately 269 000 kL/d with an average of 255 kL/d/km during the 396-day drain monitoring period 16 January 2009–15 February 2010.

Station B discharged 267 000 kL/d with an average of 476 kL/d/km, and the downstream Station C discharged 512 000 kL/d, with an average of 133 kL/d/km (Fig. 21).

The drain discharges comprised seasonally varying volumes of groundwater inflows with short periods of increased discharge in response to rainfall and streamflow (through Station B). Drain flow increased with distance downstream, with Station C producing the highest discharges (Fig. 21). In the summer of drain construction all station discharges were low, with groundwater, mainly from two seeps in the middle of the upper reaches of the catchment, the only source of the flow.

The onset of winter rainfall increased drain flow as a result of streamflow through Station B, runoff from the drain berms and batters, and increased inflow from the saturated upper sandy soil profile (i.e. perched water). These increases in inflow were reflected through increased discharges from all stations May to September 2009 (Fig. 21).

As rainfall declined with the onset of summer, the discharges declined and returned to being dominated by deeper groundwater inflows.

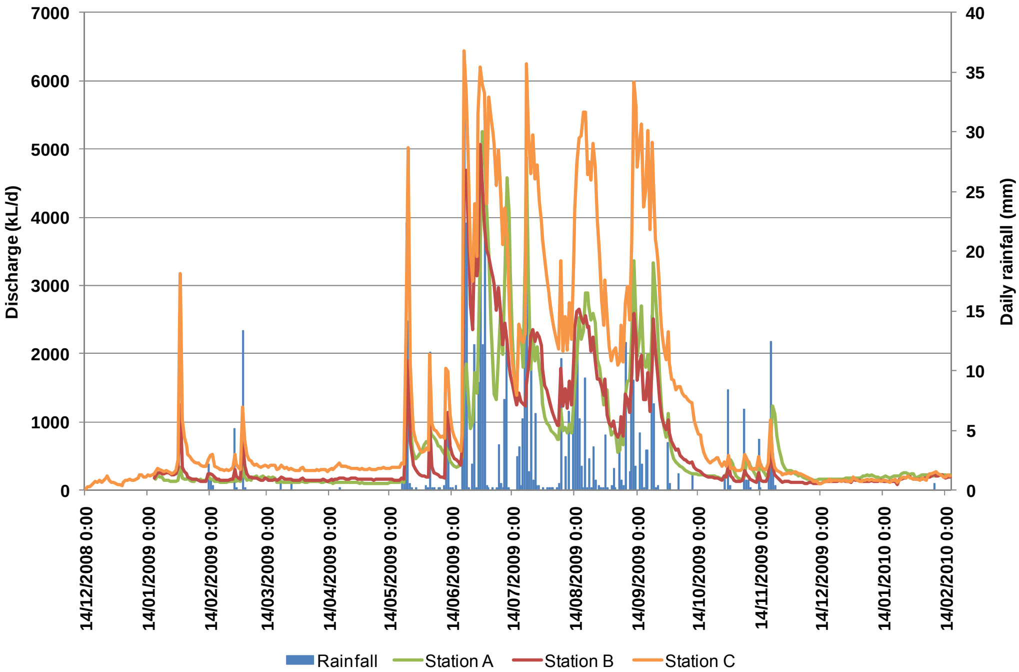


Figure 21 Raw daily discharge from Stations A, B and C

During July, the discharges from Station A were significantly higher than from Station B, because of additional inflow from rainfall/runoff and through the perched watertable and preferred pathways. Rapid groundwater inflow during winter and the presence of podsols can cause the collapse of drain batters, as occurred in the upstream drain in July 2009.

The raw or measured discharge at Station C included both drain flows generated between Stations B and C and streamflow that entered the drain via Station B (Section 3.2). To properly represent drain flows only, the streamflow component had to be subtracted from total drain discharge to calculate the downstream drain discharge (i.e. the difference between discharge from Station B and C). The total drain discharge from the downstream drain section, now known as Station C only, was 244 434 kL/d (average of 123 kL/d/km). This total downstream discharge is less than half of the total discharged from the entire system. This shows the majority of the flows in the drain originated from the upper catchment, with Stations A and B showing higher discharges than drain flow at Station C only (Fig. 22).

During summer, discharges through Station B were mostly true representations of the flows from the upper catchment, and this is reflected in the similarities between the discharges of Stations A and B (Fig. 22).

With the onset of winter rainfall Station B has lower discharges than A, particularly during July 2010, because during high flows much of the streamflow bypasses Station B and continues down the creek adjacent to the downstream drain section. So the discharges from Station B do not fully represent flows coming from the upper catchment.

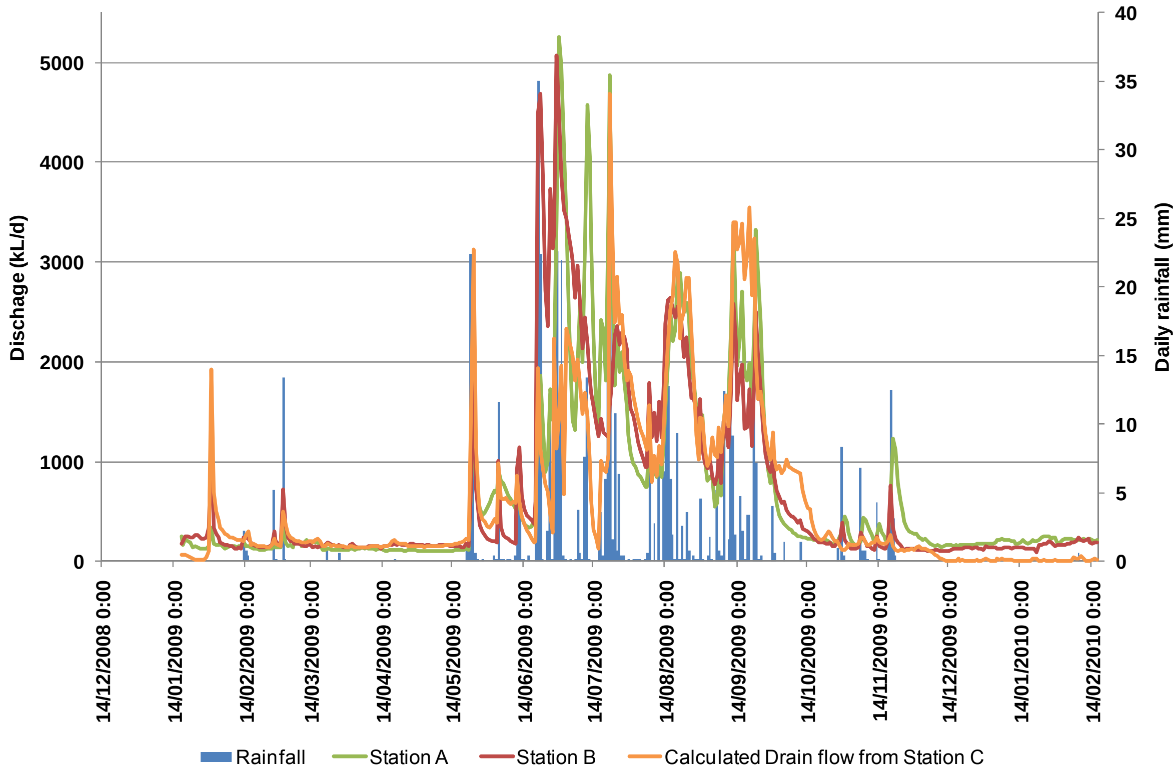


Figure 22 Calculated upper and lower drain discharges

With the onset of summer and a decrease in rainfall, the flows in the downstream section of drain decreased, with drain-induced flows reaching zero in Station C only (December 2009 to February 2010; Fig. 22). This zero denotes that this section generated no flows during summer. Before drainage the creeks and streams in this lower catchment dried up during summer, but after drainage small continuous flows at Station C originating from the upper catchment flow through Station B.

The discharges that corresponded to the same timeframe (4 April–29 Dec 2009) as the continuous salinity measurements were 246 800 kL/d (94 kL/d/km) for the upstream Station A, 243 330 for Station B and 227 567 kL/d (87 kL/d/km) for Station C only.

Discharge salinity and salt loads

In-situ salinities and salt loads were measured at each gauging station while continuous salinity was also recorded at Station C (Table 1). A trend of increasing salinity and salt load downstream was observed. The higher averages for Station C reflect the accumulation of salts and streamflow down the entire drain system. The salinities were highest during May and June with the flushing of salts after the first rains. The lowest salinities were around September after winter rainfall had diluted saline discharges (Fig. 23). Both continuous discharge and in-situ salinities followed the same trend: decreased salinities during winter. Once rainfall and dilution decreased, the deeper groundwater salinities dominated and discharge salinities rose. The trend seen in the continuous discharge salinities is typical of rivers in the south west.

Table 1 Average in-situ salinity and salt loads for Stations A, B and C in 2009

	Salinity (mg/L)	Salt load (t)	Continuous salinity (mg/L)
Station A	7164	2.51	n/a
Station B	7831	2.6	n/a
Station C	8627	6.53	5759

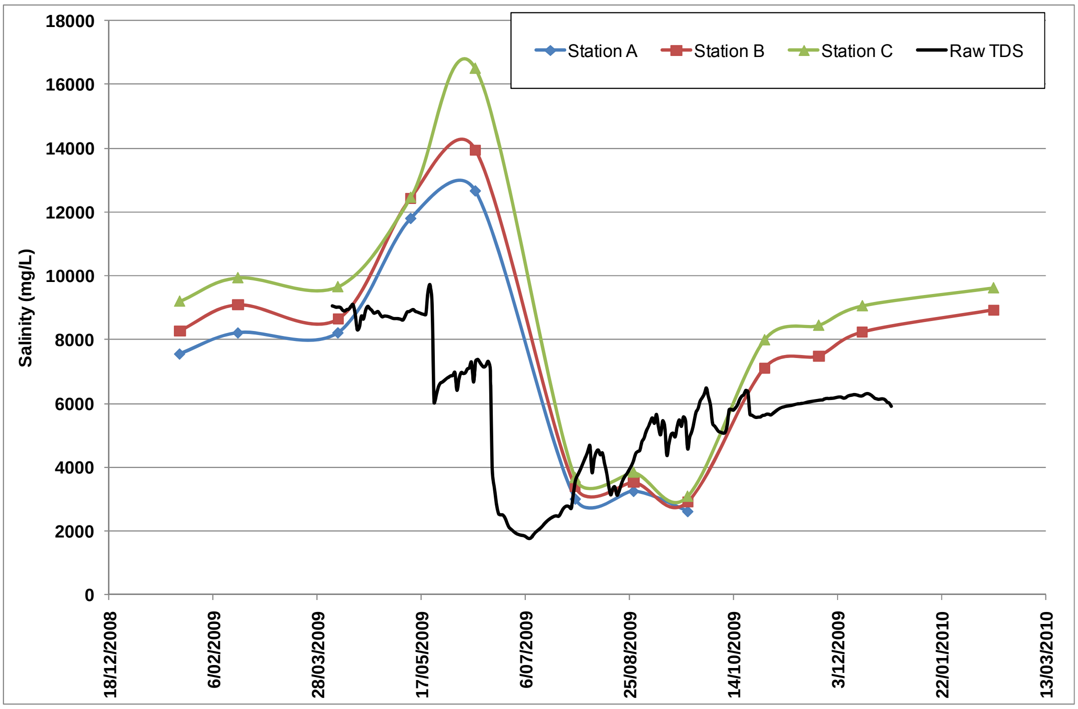


Figure 23 Gauging station salinities

4.2 Surface water results

The results were normalised (calculated on a per hectare basis) to their catchment area (Fig. 24). Due to the availability of data and their positions in relation to the drain, HRS04, HRS05, HRS07 and HRS10 were chosen for comparison of flow, salinity, salt load and pH.

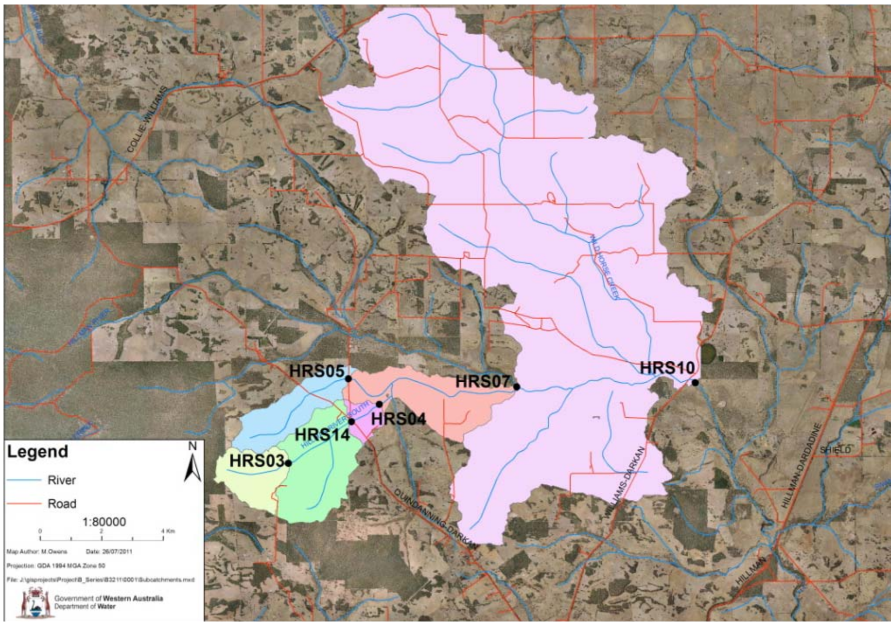


Figure 24 Subcatchment areas for surface water sampling sites

HRS04, the catchment outlet that collects the flows drained from HRS03 and HRS14 had lower discharge and salt load than before drain construction (Fig. 24). These comparative decreases were also seen in the comparison catchment HRS05 (Table 2). The diminished discharge could be due to natural variations in rainfall distribution or cropping rotations. The salinity ranges for the monitoring period before and after drainage were similar for HRS04 and the comparison catchment.

The pH was around neutral (pH ≈ 7) and did not vary much before and after drainage at HRS04 or HRS05 and further downstream at HRS07 and HRS10.

Table 2 Surface water results before and after drain construction

	HRS04	Comparison HRS05
Average flow (kL/ha/d)	6.20 / 3.16	2.83 / 2.03
Salinity range (mg/L)	(4500–27 500) / (3200–20 100)	(1500–13 800) / (1600–13 250)
Average salt load (t/ha/d)	0.035 / 0.021	0.009 / 0.005
Average pH	6.52 / 6.92	6.76 / 6.55

NB: Black numbers are before drainage (24 April 2007–24 October 2008) and red numbers are after drainage (3 March–15 December 2009).

5 Water balance

5.1 In-channel water balance

An in-channel water balance was the most appropriate method to identify the sources and causes of contributions and losses to and from the drain channel. The losses and additions of the drain flow before it became discharge from the drain outlet were estimated using the following water balance equation:

$$Q = G_I + (P + RO) - E \qquad \textit{Equation 1}$$

Where: Q: discharge from the drain outlet

E: Evaporation from the drain channel

G_I: Groundwater inflow to the channel

(P + RO): rainfall and runoff-generated drain flow

Equation 1 was used to calculate the accessions and losses of drain flow to and from the channel for the entire drainage system, upstream of Station A, and between Stations B and C. The daily discharge was used to calculate Q, the (P+RO) was calculated using the site rainfall multiplied by runoff coefficients. These runoff coefficients were 1 (or 100% runoff) from the channel floor and 0.2 for channel batters. The evaporation (E) was calculated from the continuously wetted surfaces of the channel which included the channel floor and lower 0.5 m of each batter above the channel floor. An evaporative coefficient of 0.9 for the channel floor and 0.2 for the batters was multiplied by pan evaporation to produce a potential daily evaporative loss. The potential evaporative loss was then adjusted for salinity (Turk 1970) using the daily flow-weighted salinities to represent the salinity of the drain flow.

The in-channel water balances below were calculated daily, with the results an aggregation of the daily values. Station C includes the total discharge from the drain section between Stations B and C and the inflows from the upper catchment into the drain from Station B (235 419 kL). It should be noted that because a proportion of discharge from Station A bypassed Station B (Section 3.1) the discharge from Station A (263 201 kL) is greater than the inflow into Station B (235 419 kL).

Through substituting values into Equation 1 the in-channel water balances (in kL) from 6 February 2009 to 6 February 2010 were:

Station C:	498 620 = 239 017 + 8171 – 8047 + 235 419
Station A:	263 201 = 262 744 + 4348 – 3890
Station C only:	239 141 = 239 017 + 8171 – 8047

The equations show that the total groundwater inflow was 501 700 kL (239 017 + 262 744) and that most of the discharge from the drains was from groundwater inflow. By expressing the values as per kilometre of drain highlights that the groundwater inflow into the drain upstream from Station A was nearly twice the inflow to the drain between Stations B and C (from Station C only). The water balance per kilometre was as follows:

Station A: 98 799 = 98 628 + 1632 – 1460

Station C only: 47 761 = 47 737 + 1632 – 1607

The monthly water balance for the section of drain between Stations B and C showed an increase in groundwater inflow in response to rainfall. This is evident by the increase in the rainfall/runoff component of the water balance (Fig. 25). The water balance also shows a slight difference between the inflows and drain discharges in winter and summer, with summer values dominated by evaporative losses. The trends in the downstream section of drain are the same for the drain upstream of Station A.

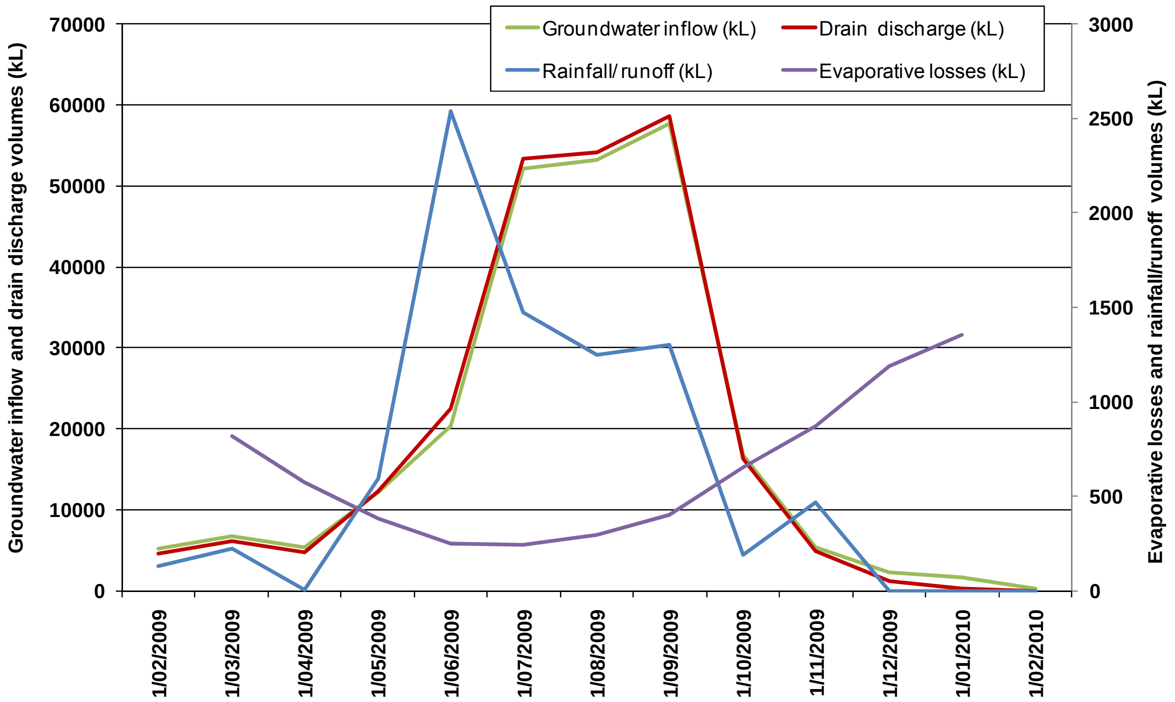


Figure 25 In-channel water balance for downstream drain between Stations B and C

6 Discussion

6.1 Groundwater inflows

There was an expectation that after drain construction the watertable level alongside the drain would fall as groundwater moved into the channel (Ritzema 1994). A declining inflow rate is associated with this falling watertable as the head difference between the watertable and drain floor decreases.

Following drain construction, groundwater inflow rates remained uniform at around 250 kL/d until the onset of winter rainfall and increased by one order of magnitude between summer and winter, with the onset of winter rain-fed recharge (Section 5.1). This occurred in response to the seasonal development and drainage of perched groundwater from the more permeable sandy A horizon.

During times of no or little rainfall groundwater inflows to the drain only originate from preferred pathway flow through impermeable clay subsoil. These flows are restricted by the number and size of preferred pathways expressing in the drain channel. The groundwater inflow rates are uniform, being primarily driven by the groundwater pressure heads developed within the underlying aquifer (Section 4.1.1).

The onset of winter recharge and runoff can completely saturate the sandy A horizon. The saturated condition and permeability of this layer result in high groundwater inflow rates into the drain (Section 2.6). At the end of winter when recharge stops the A horizon drains and its contribution to drain inflow reduces accordingly.

Groundwater inflow to the drain was nearly equivalent to the estimated annual average recharge for its entire topographical catchment. The estimated groundwater recharge to the Woolbelt is about 50 mm (Baxter & O'Neill 1995) or approximately 10% of rainfall. Over the 1103 ha catchment area of the drain, 50 mm of recharge equated to around 551 100 kL. The total groundwater inflow to the drains was 501 700 kL (Section 5.1). If this recharge area was evenly distributed along the 9670 m drain, the distance from which groundwater migrated towards the drain theoretically could be calculated:

$$W = (G_I/R)/L \qquad \textit{Equation 2}$$

Where: W = width (m)

G_I = Groundwater inflow (kL)

R = rainfall/runoff (kL/m^2)

L = drain length (m)

Substituting into Equation 2 gives a value of 520 m each side of the drain based on 50 mm/yr of recharge. As the drain is in the lowest part of the catchment, the recharge adjacent to it could have increased because of increased runoff to the valley floor and infiltration to the sandy profile. Leakage from the natural watercourse may also have contributed significant recharge.

The distance from which groundwater migrates into the drain is affected by recharge rates and so available groundwater alongside it. The greater the volume of available groundwater close to the drain the shorter the flow distance between the groundwater source and the drain. If recharge rates are 0.75 m/yr in response to regular flooding and valley floor inundation the drainage distance would reduce to about 35 m each side of the drain, about equal to the width of much of the valley floor.

The drain provides a groundwater outlet for the catchment in addition to the natural watercourse and valley floor. Before drainage, runoff from the catchment was by surface water flows within natural watercourses and groundwater discharge by evaporation from the valley floor. Drain construction enhanced the movement of groundwater within the sandy A horizon and provided an outlet for some of the preferred pathway discharge. Groundwater inflows vary in response to recharge that varies spatially and seasonally, drainage efficiency, and aquifer conditions along the drain length.

6.2 Watertable response

There was an expectation that after drain construction the watertable alongside the drain would fall as groundwater moved into the channel. Such a falling watertable creates what is usually referred to as a drawdown curve in response to the head differences between the drain floor and watertable (Ritzema 1994).

The drain had inconclusive or non-existent effects on the watertable. During summer and periods of no recharge groundwater levels remained at or below the impermeable clay layer, with little or no change in response to the drain as the inflow rates were low due to low soil permeability and little preferred pathway flow (Section 6.1).

In winter the continuous and consistent rain-fed recharge rate to the sandy A horizon was as high as the infiltration rate of the soil surface. Watertables rose quickly, saturated the sandy A horizon (Section 6.1) and remained close to ground level. An inundated valley floor, the natural watercourse alongside and natural hydraulic gradients extending to the drain all enhanced additional recharge.

The continuous recharge to the watertable alongside the drain exceeded its drainage rate and the water level did not fall. The drainage rate and the potential for watertable drawdown were reduced along drain sections where the sandy A horizon is thin. The surface gradients and natural drainage system allowed good natural drainage of the sandy A horizon. At the end of winter it was hard to distinguish drain drawdown responses from natural drainage.

Under typical drainage conditions fluctuating watertable height is related to drain inflow rate. Watertable rises result in corresponding proportional increases in groundwater inflows and vice versa (Ritzema 1994). There was a strong relationship between monthly groundwater levels and inflow rates at Hillman River South (Fig. 26), with correlations of water level rise to inflow of 0.8 for Transect 3 and 0.6 for Transect 4.

The relationship exists because the drain inflows and watertables are responding to the same changing recharge conditions that saturate the sandy A horizon. As discussed above these changes occur rapidly between summer and winter but remain stable between these periods of change resulting in the strong relationship between water levels and inflows.

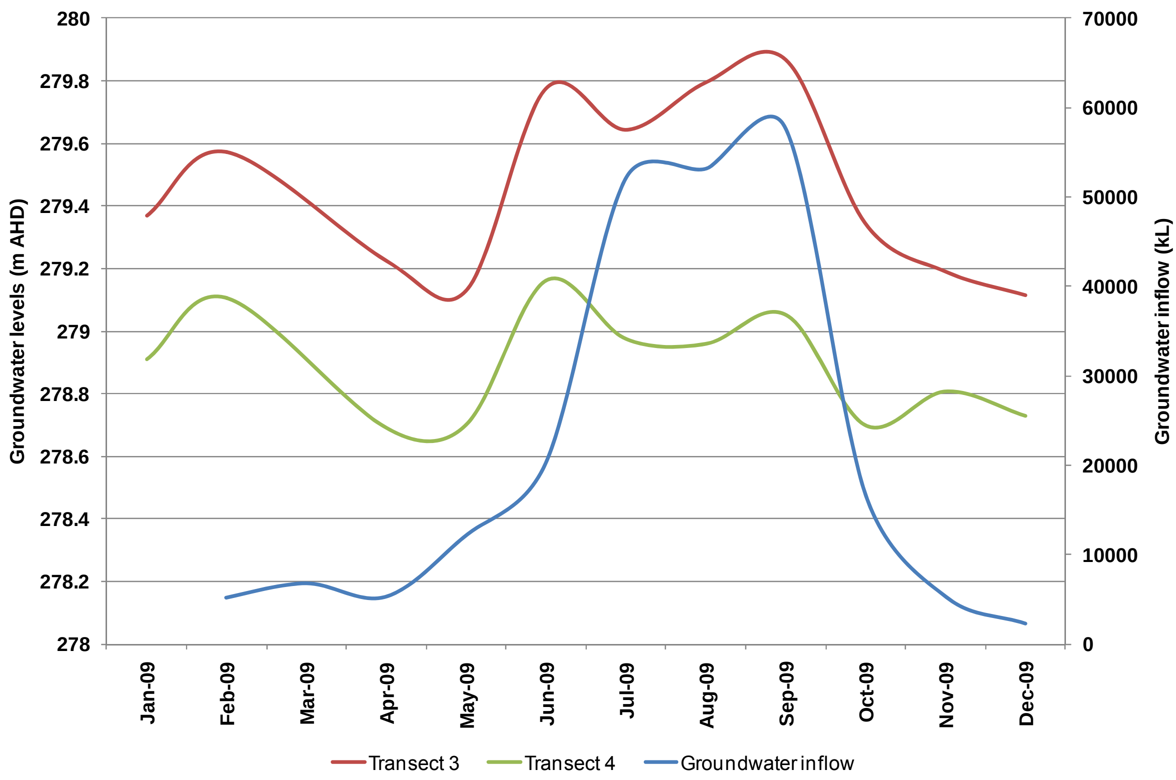


Figure 26 Average transect watertable levels and downstream drain groundwater inflow

6.3 Salinity and salt loads

To be able to assess its downstream contributions to the receiving environment, the salinities and salt loads from the drains only were calculated.

To estimate the daily salt loads and salinities for the downstream drain section (Station C only) the differences between monthly in-situ salinities of stations B and C were used. The salinities for Station B were first calculated by taking the mean value of the differences in corresponding in-situ salinity measurements between Stations C and B. This value was redistributed against the daily continuous salinities measured at Station C.

The salt loads for Station B were calculated using the discharge and newly estimated continuous salinity from Station B.

The salt loads for the downstream drain section (Station C only) were calculated from the differences in salt loads from Station C and B. The downstream drain salinities were determined from the salt loads and discharges of the section.

The continuous salt loads and salinities for Station A were calculated using a regression analysis between the in-situ salinities and the corresponding discharges for those days.

The upstream and downstream drains discharged a total of 2198 t of salt from 4 April to 29 December 2009, with average salinities of 7000 and 6500 mg/L respectively. The upstream drain section discharged twice the salt load of the downstream drain section (i.e. 413 t/km versus 218 t/km). This is consistent with the upstream drain groundwater inflows being twice that of the downstream inflows (Section 5.1).

Salinities vary with the quality and rate of groundwater discharge and its subsequent dilution or evapoconcentration. While drain flows were dominated by preferred pathway discharge during summer (Section 6.1) salinities were about 10 000 mg/L (Fig. 27), reflecting the salinities of the surrounding groundwaters (Fig. 20). With the onset of rainfall, drain discharge volumes increased and salinities decreased.

Salinities were lowest in July with a rapid rise in groundwater levels and inflows (Fig. 26) due to saturation of the sandy A horizon and dilution of salts. The increasing salinities from July were due to deeper more saline groundwater levels rising and progressively contributing more salts to the system via preferred pathway discharge (Fig. 27). The fluctuating salinities in December reflected the changes between evapoconcentration of low flows and no flow within the drain.

Had both drain flow and monitoring continued, the expectation is that salinities would return to their pre-winter levels of around 10 000 mg/L, dependent on seasonal variability.

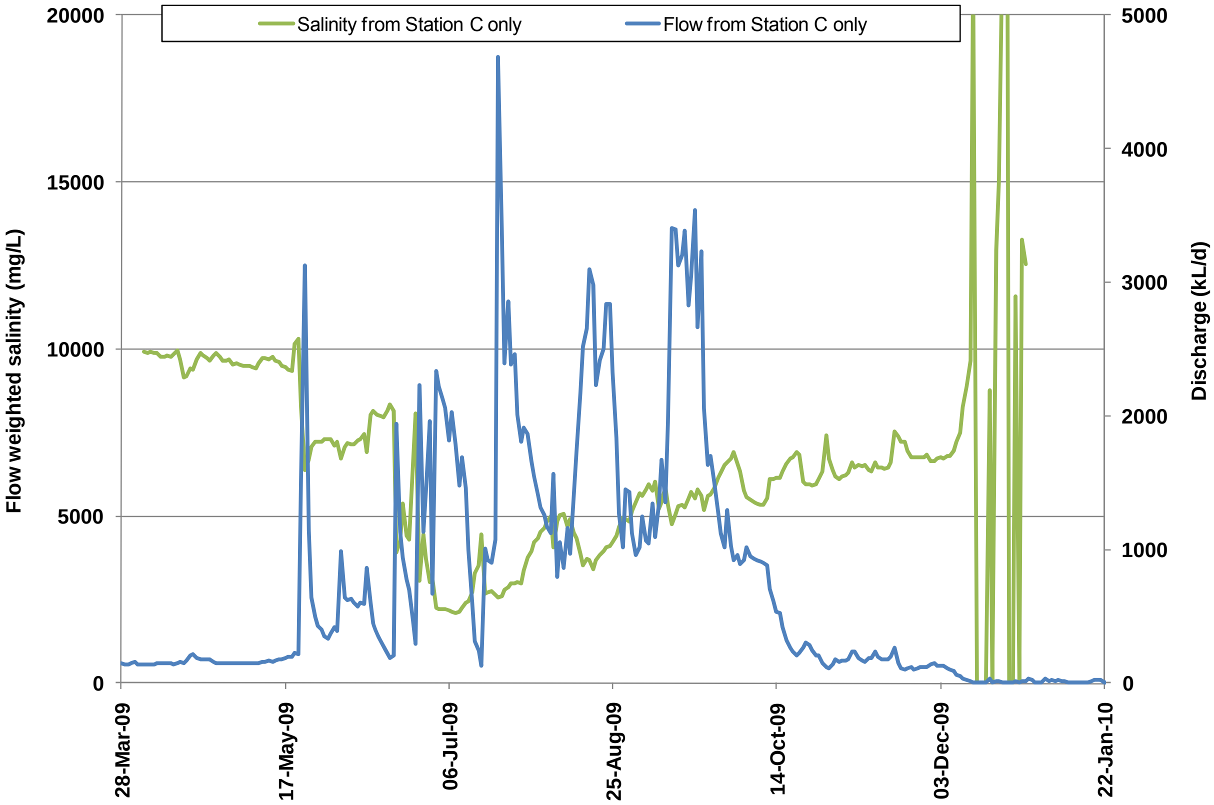


Figure 27 Station C only flow-weighted salinities

The salt load is a measure of the salt export rate from the catchment. In the case of Hillman River this rate is controlled by the interactions between the groundwater hydrology and the underlying historical salt stores (Fig. 1). Salts are transported from the deeper groundwater to the surface by preferred pathway groundwater discharge and subsequently exported from the catchment by streamflow.

During summer the deeper groundwater discharged upwards into the perched aquifer and evaporated leaving its salts in the A horizon. With the first significant rainfall on 22 May 2009, groundwater levels rose, saturating the A horizon and leaching the accumulated salts into the drain (Fig. 28).

During periods of minimal rainfall (e.g. April to mid May 2009), calculated salt loads (about 2 t/d) to discharge were proportionally higher than during winter (Fig. 28), and remained proportionally higher than discharge during the initial flushing of salts from the catchment following the first winter rainfalls in May 2009.

From the beginning of June the relative proportions of salt load to discharge fell as salts were leached from the A horizon and low-salinity recharge diluted the salts from the deeper groundwater (Fig. 28). This period corresponded with the lowest salinities and higher discharges (Fig. 27). The gradually rising groundwater discharge rate resulted in rising salinities and, from early September 2009, a return to the pre-winter proportional relationship between salt loads and discharge.

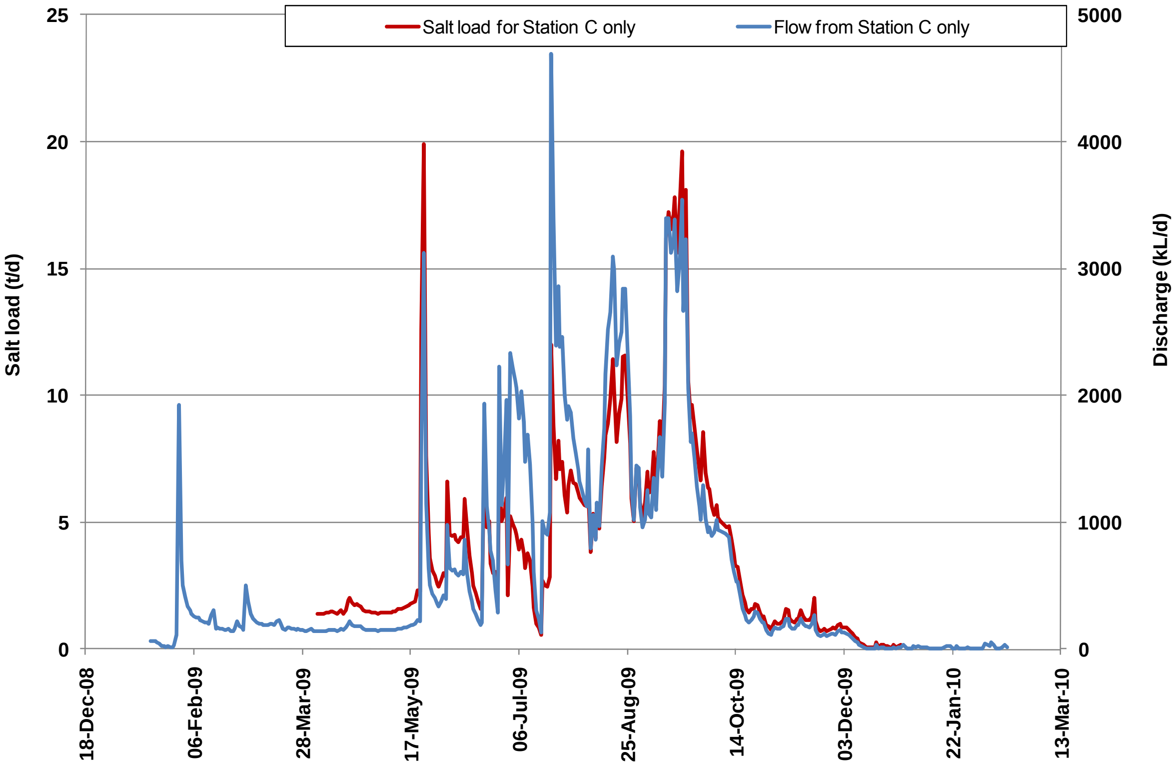


Figure 28 Station C only salt load

Irrespective of the relationship between salt load and discharge the salt loads trended upwards from May to late September 2009. From September 2009 salt loads and drain discharges fell sharply. Except for the initial leaching of salts from the A horizon, most of the salt load into the drain is from deeper groundwater discharge.

Like salt loads, groundwater levels rose from May and peaked in September 2009 (Fig. 29) and the proportion of groundwater in total drain discharge increased (shown by increasing salinities and salt loads from May 2009). The relationship between groundwater levels and salt loads exists irrespective of the drain because the drain had no effect on this groundwater (Section 6.2).

Groundwater discharge is the primary mechanism controlling the salt export rate from the catchment. In most years, as natural runoff is sufficient to remove all accumulated salts from the upper aquifer (A horizon) and topsoil, the medium to long-term salt export rate will be in equilibrium with the salt discharged from groundwater.

The drain now serves as a conduit for some salt export and could result in decreasing the salinity in some immediately adjacent land but the overall impacts on salinity and salt loads were small because the drain cannot increase the discharge rate and reduce groundwater heads.

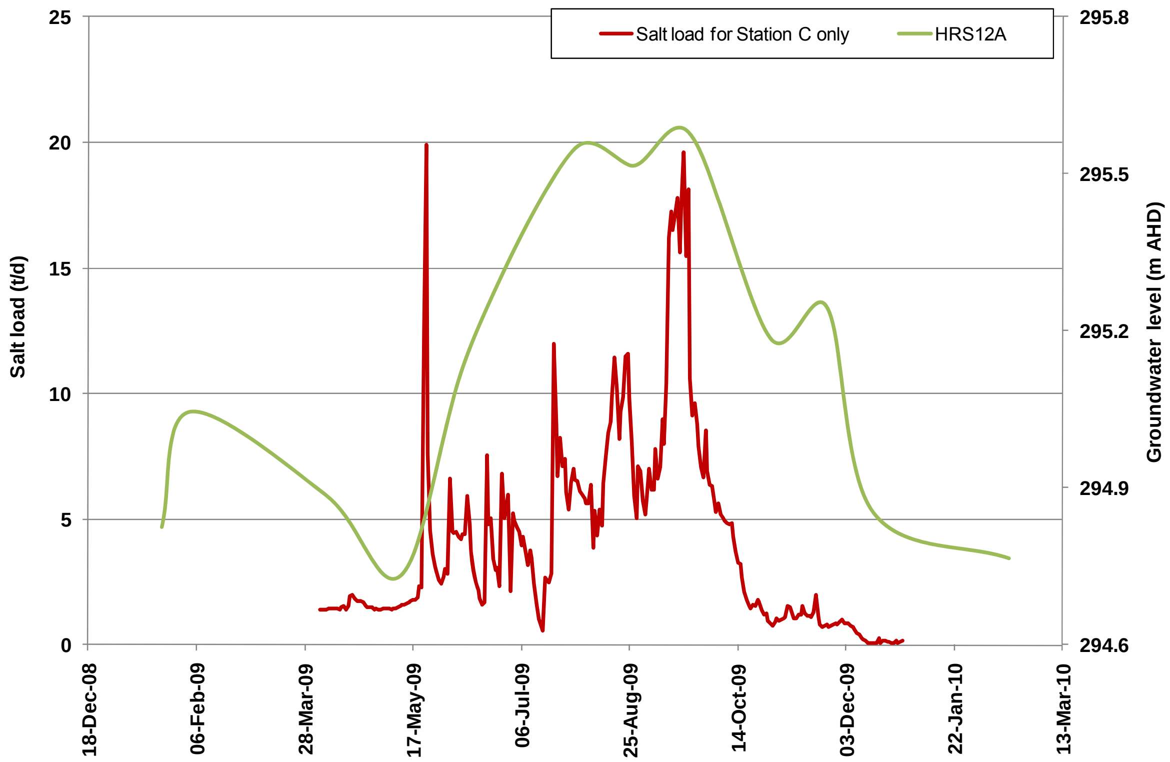


Figure 29 Comparison bore groundwater levels versus salt loads

6.4 Downstream impacts

The downstream impacts of the drain are most noticeable during the late spring to summer (October to March) when natural streamflows are low or absent. During this time the continuous saline groundwater discharge from the drain can increase in proportion to and dominate natural streamflows. As a consequence streamflows become hypersaline as evapoconcentration removes water, leaves salts in the channels and salt accumulates within downstream receiving environments.

Under pre-drain conditions salt discharge from the Hillman River South catchment was controlled by deeper groundwater discharge (Section 6.3). During periods of high winter runoff and seepage the catchment salt export was similar to the salt transported to the shallow aquifer and land surface by rising groundwater. When runoff and seepage subsided these salts accumulated in the A horizon and topsoil to be mobilised with the next significant rainfall (Section 6.3).

Natural perennial streamflows with salinities as high as 15 000 mg/L were observed originating from the large seepage areas in the upper part of the catchment (Appendix C) but during most summers flows stopped at or below Station B due to infiltration and evaporation. During wetter summers these flows combined with runoff were enough to produce discharge from the catchment outlet.

Drain construction has ensured perennial streamflow from the catchment as it is a conduit between the groundwater discharge sources and the outlet. During winter, the drain makes little difference to the natural catchment salt and water discharge characteristics and has no noticeable effect on streamflow but, during spring and summer, the drain continuously produces saline discharges.

From January to March 2009 streamflow was dominated by drain flow which altered the natural hydroperiod at HRS04, 500 m downstream of the drain outlet. The streamflow was about 400 kL/d with 10 000 mg/L salinity in response to drain flows with a similar rate and salinity about 9000 mg/L. No streamflow was detected 10 km downstream at HRS07.

During January to March 2009 salt from the drain accumulated in the stream bed until the natural runoff flushed them from the natural drainage system. This highlights that the seasonal variability of drain flows and other streamflow contributions determine the salinity of the streamflow and how far downstream it is observed. During the dry 2009 summer salts concentrated and remained within a short distance downstream from the drain outlet. Had natural streamflows been higher during this period the salinity at HRS04 may have been lower but the salt would have been transported further downstream.

The effects of the salts exported from the drain would be considered detrimental if they accumulated within a downstream perennial water body, thereby temporarily raising its salinity. As no such water body occurs within 12 km of the drain outlet drain flows are unlikely to penetrate this far downstream without other sources of groundwater seepage and runoff. Under these conditions the drain's salt contribution would then be indistinguishable from the natural contributions from other sources within the landscape.

6.5 Drain construction costs

The total cost of constructing approximately 8715 m of 2.5 m deep drainage and associated works was $155 673. This sum was calculated as if it had been built by the landowner and does not include the costs associated with monitoring the site.

Construction of the drain channel and levee banks cost $122 348, with an average cost of $13 500/km. The culvert supply and installation totalled $33 325. This combined with the drain costs would have an average cost of $17 200/km.

6.6 Improving drain efficiency

The drain and aquifer characteristics at the Hillman River South site demonstrated that although the drain could remove substantial volumes of water from the catchment it was unable to lower watertables. Efficient drainage at this site would require changes in drain type and density and in some cases alternative engineering options.

Improvement options to the current approach include:

- shallow drainage
- changed batter slopes and buried drainage

Alternative engineering approaches include:

- parallel drains which increase drainage density and,
- groundwater pumping and siphoning.

Alternative drain options

Shallow drainage

There was no demonstrated advantage in terms of watertable control from excavating the drain deeper than the sandy A horizon. The 2 m deep drain only demonstrated the capacity to enhance the drainage of significant volumes of groundwater from the permeable A horizon (Section 6.2). A drain, shallow or deep, would not enhance the preferred pathway discharge of groundwater through the impermeable clay layer, merely provide an outlet for the groundwater.

Alternative shallow drainage within the lower part of the catchment would range from 0.5 to 0.75 m deep, similar in depth to the natural watercourse. At this depth the drain floor would maintain contact with the clay subsoil layer along the majority of its length and convey surface runoff with minimal risk of erosion. Where the clay subsoil layer is deeper, or deeper drainage may be of benefit, additional drains could be constructed alongside and feed into the shallow drain. This approach has been taken adjacent to the section of creek between Stations A and B (Appendix C).

Advantages of the shallow drainage approach include lower construction and maintenance costs, retained farm accessibility and lower risk of accident or injury to people and livestock.

Changed batter slopes

Rapid groundwater inflow through the sandy A horizon caused sections of the drain batters to collapse and deposit silt in the downstream channel. This occurred most frequently in the drain upstream of Station A where the sandy A horizon extended to well below the drain depth. Regular de-silting was required during the life of the project to maintain drain depth and performance and operation of the gauging station. Desilting of the drains and sumps would also be a long-term maintenance requirement.

The current drain batter slope of 1:1 (Section 3.1) is too steep to stabilise in the saturated sandy soil conditions. A more appropriate drain batter slope of 1:3 (Smedema & Rycroft

1983) would be required but this slope would be impractical, resulting in a 12 m wide drain given its current 2 m depth.

Buried pipe drainage

Buried pipe drainage could be used as an alternative to open channels to achieve groundwater drainage in unstable and saturated soil conditions. If correctly installed, buried slotted pipe drainage overcomes issues associated with channel collapse and drain silting. Although the installation costs are higher than for deep drainage (Bakker et al. 2010) these additional costs could be quickly recouped through reduced maintenance expenses of the upper drain section.

Additional benefits such as safety, accessibility and the ability to retain the use of the land overlying the drain would come from using this drainage option. Subsurface slotted pipe drainage has been used successfully to lower the watertable in an area of unstable sandy soils in the nearby Date Creek catchment (Bakker et al. 2010).

Drain density

Increased drainage density and/or the incorporation of other water management techniques are needed to provide adequate drainage conditions to lower the watertable during periods of peak recharge at Hillman River. Although 501 700 kL (Section 6.1) of groundwater was drained this was often less than the volumed supplied to the drain site from rainfall and runoff recharge and groundwater rise. As long as the rate of groundwater to the drainage site is greater than the drain can remove watertables will not fall.

For drains to lower and control watertables the drainage efficiency needs to be the same or greater than its groundwater supply. The standard approach to achieve this is to subdivide the groundwater catchment between parallel drains with drain spacing calculated from the recharge rate, aquifer characteristics and potential watertable height.

The Hoodghoudt steady-state drainage equation was used to estimate some theoretical spacings for Hillman River (Ritzema 1994). For modelling purposes two recharge and aquifer scenarios were evaluated. A target minimum 0.6 m depth to watertable was chosen to address waterlogging at the site. The two chosen recharge scenarios were based on an average recharge of 50 mm/yr (Section 6.1) and peak recharge of 202.6 mm/yr. The peak recharge rate was estimated based on 10% of June 2009 rainfall of 168.8 mm multiplied for the 12 months of the year.

The recharge and watertable control parameters were modelled using sandy and clay aquifer characteristics representative of different sections of the drain. In both cases the impermeable layer was modelled as being level with the 2 m deep drain floor. Sandy soils were assigned a hydraulic conductivity of 1 m/d and clay soils 0.001 m/d (Brassington 1988).

Soil permeability (hydraulic conductivity) is the most significant factor affecting drain spacing and the ability to control the watertable between the drains. The spacing between drains constructed in sand to manage average recharge is nearly 30 times that of those constructed in clay (Table 3). Under peak recharge drain spacing reduces to about half of average recharge conditions.

Table 3 Drain spacing scenarios (m each side of the drain)

	Drain spacing (m each side)	
Aquifer material	At average recharge (50 mm/yr)	At peak recharge (202.6 mm/yr)
Sand	239	118
Clay	8	3

The modelling scenarios represent the changing aquifer parameters along and recharge conditions to which the Hillman River drain was exposed. Shallow clays were present along much of the lower section of the drain with the modelled close drain spacing confirming the poor watertable drawdown observed (Section 6.2). This also supports the suggestion that shallow drainage would have a similar benefit to deep drainage along this drain alignment.

Although multiple drains show the potential to lower watertables in the upper part of the catchment, the steep landscape and unstable soils would make drain installation difficult. Using pipe drainage may avoid these issues while still achieving watertable control.

Alternative engineering options

Groundwater pumping or siphoning is thought to be a viable alternative to drainage for watertable control at Hillman River. Pumping or siphoning from bores or wells would enable the extraction of groundwater directly from the more permeable aquifer immediately overlying the basement rock (Section 2.5) and decrease the underlying pressure heads responsible for the upward mobilisation of salts from the regolith.

As siphons are passive gravity-driven vacuum pumps, the outlet end of the pipe needs to be lower than the water level at the inlet end (George 2004). This makes siphons more applicable in areas with steep gradients and associated hillside seeps; the upper Hillman River catchment has landscape and aquifer characteristics that appear to be suitable for this method of groundwater extraction.

Where siphons are not an option due to lack of gradient, groundwater can be physically lifted from the bores and wells using various pumping options. Although the extraction of groundwater using either of these techniques may be viable and produce beneficial results, the management of saline discharge is an important consideration.

7 Conclusions

High rates of recharge to the watertable alongside the Hillman River drain exceeded its drainage rate so preventing any noticeable watertable decline. During summer or prolonged absences of recharge the perched watertables remained just above the impermeable clay layer as the groundwater inflow was being controlled by preferred pathway flow. During periods of peak recharge the watertables rose quickly and saturated the permeable A horizon and remained near the surface.

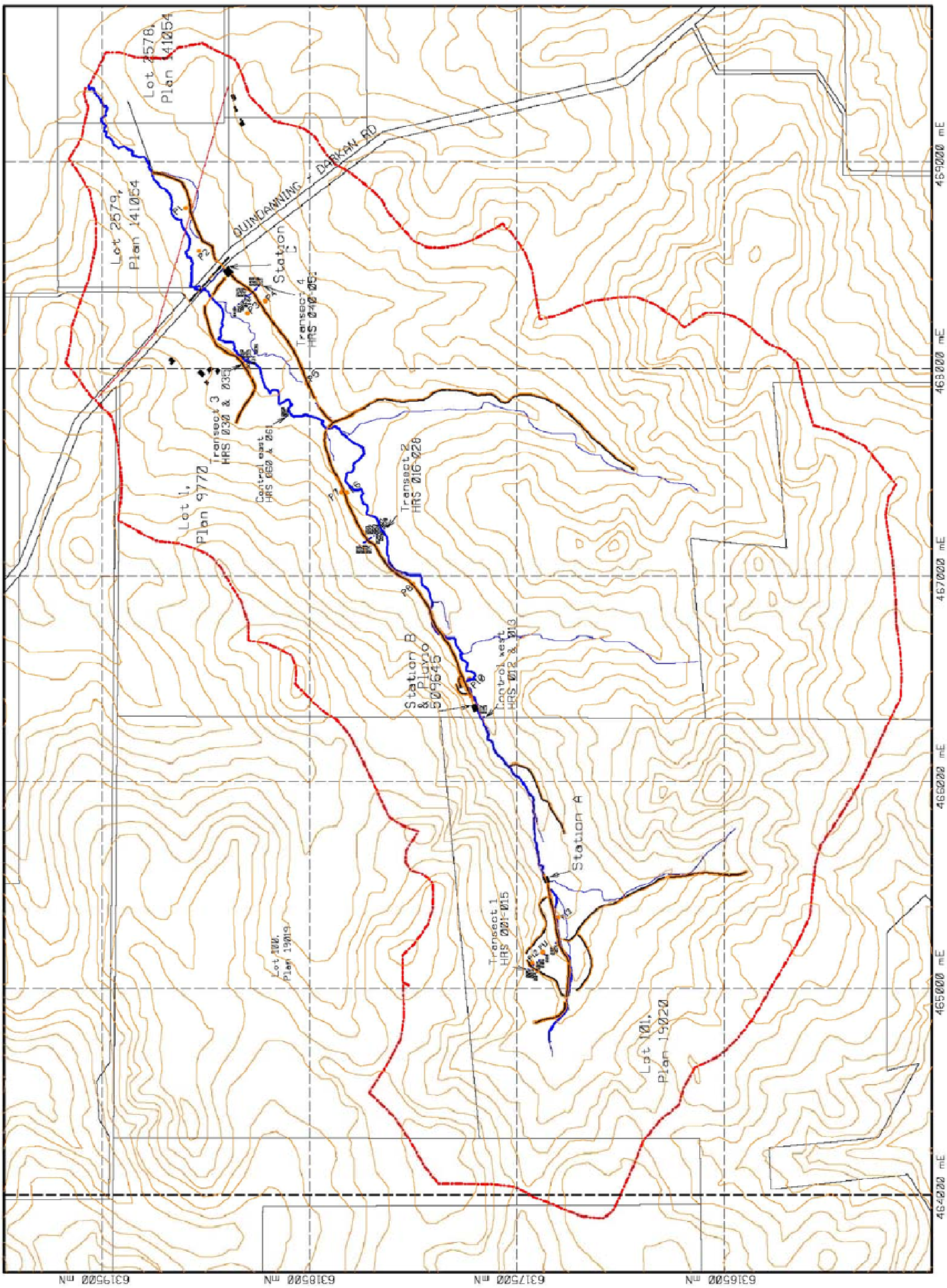
Although 501 700 kL of groundwater were discharged from the drain with an associated 2198 t of salt, before drainage most of this water and salt would have left the catchment as streamflow. Only during late spring to summer did the drain have a noticeable effect on the salinity of the catchment discharge; without the drain there was no streamflow. The drain is unlikely to have increased the amount of salt exported from the catchment as this is controlled by deeper groundwater discharge.

The changes in downstream effects of the drain discharge are confined to spring–summer months associated with ephemeral discharge from the catchment becoming perennial. The perennial streamflow means that salt is being exported from the catchment when it would have otherwise accumulated in-situ. The salt’s effects would be considered detrimental if it accumulated by evapoconcentration within downstream perennial water bodies. As there are no such water bodies within at least 12 km of the drain outlet it is unlikely that discharge would reach downstream perennial water bodies without other contributing sources of groundwater seepage and runoff. Under these conditions salt export from the drain would become indistinguishable from other natural salt contributions.

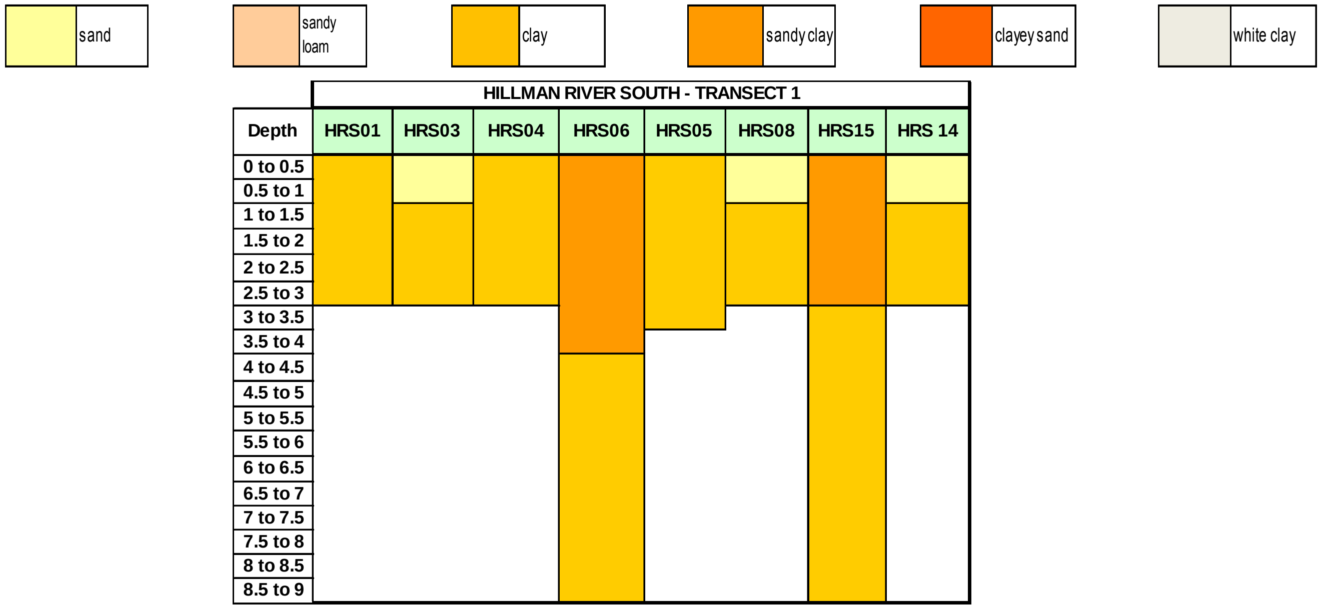
With the high degree of variability in aquifer characteristics at this site, such as thickness and permeability, a combination of techniques may be needed to address groundwater and salinity-related issues throughout the catchment.

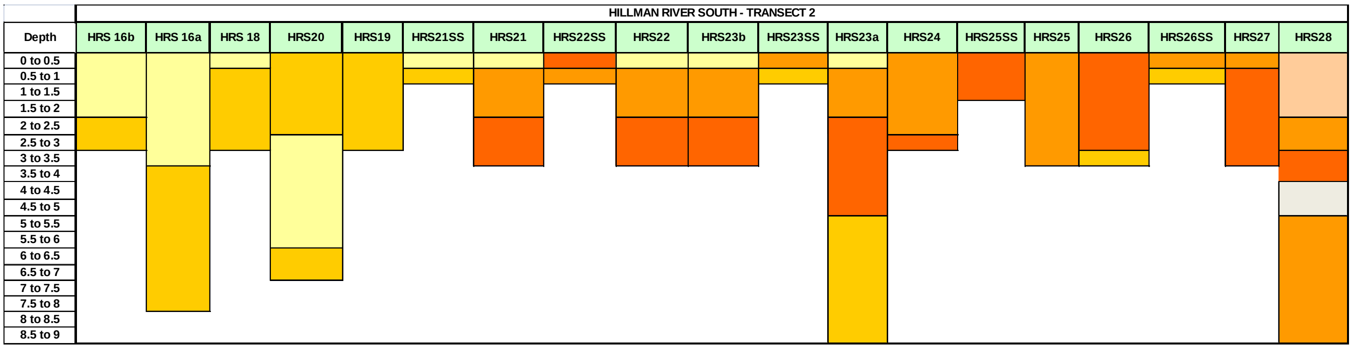
Appendix A — Monitoring plan map

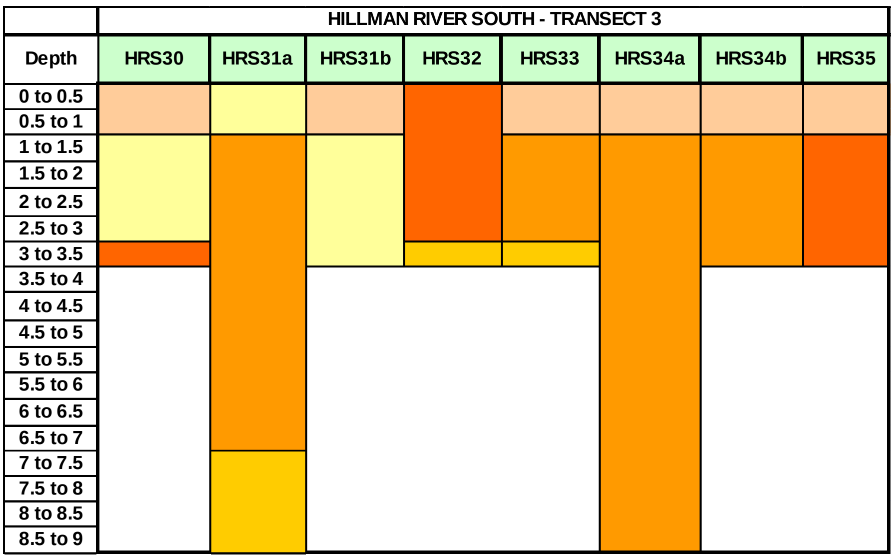
Hillman River South catchment contours, see Section 2.4

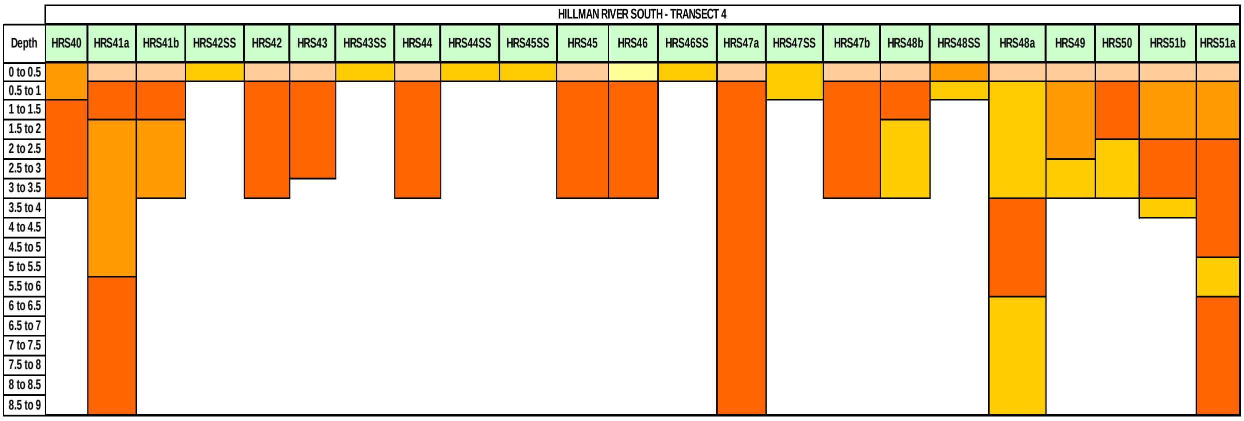


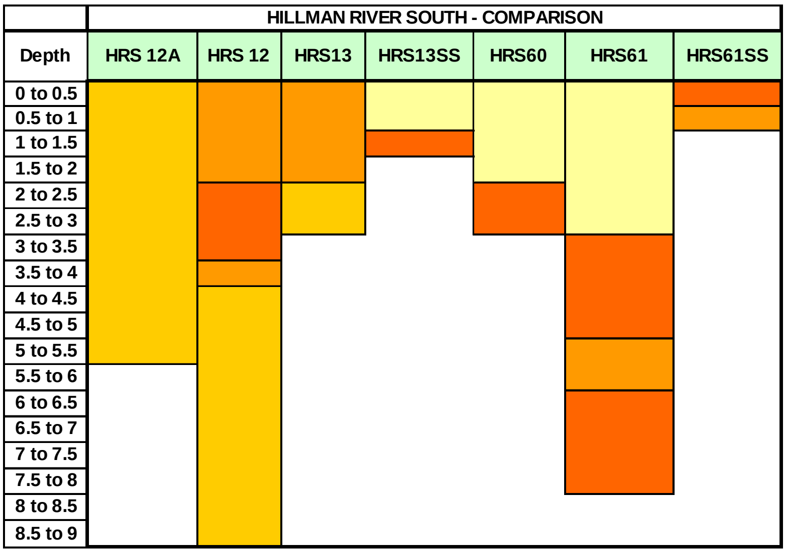
Appendix B — Soil profiles



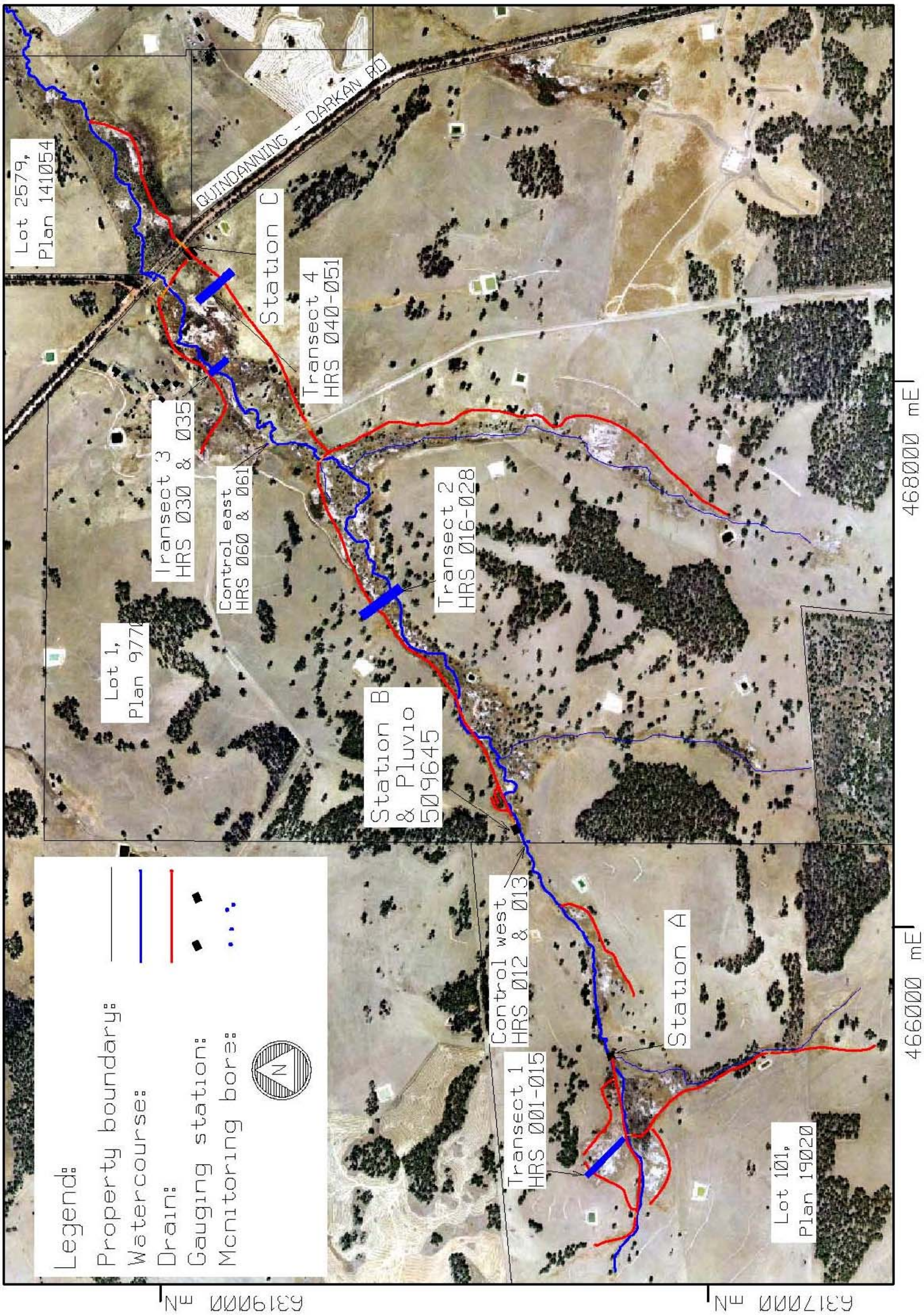





HILLMAN RIVER SOUTH - TRANSECT 4
Depth
HRS40
HRS41a
HRS41b
HRS42SS
HRS42
HRS43
HRS43SS
HRS44
HRS44SS
HRS45SS
HRS45
HRS46
HRS46SS
HRS47a
HRS47SS
HRS47b
HRS48b
HRS48SS
HRS48a
HRS49
HRS50
HRS51b
HRS51a
0 to 0.5
0.5 to 1
1 to 1.5
1.5 to 2
2 to 2.5
2.5 to 3
3 to 3.5
3.5 to 4
4 to 4.5
4.5 to 5
5 to 5.5
5.5 to 6
6 to 6.5
6.5 to 7
7 to 7.5
7.5 to 8
8 to 8.5
8.5 to 9


HILLMAN RIVER SOUTH - COMPARISON
Depth
HRS 12A
HRS 12
HRS13
HRS13SS
HRS60
HRS61
HRS61SS
0 to 0.5
0.5 to 1
1 to 1.5
1.5 to 2
2 to 2.5
2.5 to 3
3 to 3.5
3.5 to 4
4 to 4.5
4.5 to 5
5 to 5.5
5.5 to 6
6 to 6.5
6.5 to 7
7 to 7.5
7.5 to 8
8 to 8.5
8.5 to 9

Appendix C — Hillman River South site plan with photo



Appendix D — Bore construction summary

LOCAL BORE NUMBER	Depth	Site	EASTING (GDA)	NORTHING (GDA)	Transect distances (m)	Elevation (mAHD)	Total Depth (m)	For steel cased bores Outer casing height AGL(m)	For steel cased bores Inner casing height AGL(m)	For SS bores only PVC pipe length (m) (AGL)	For SS bores only Screen length (m)
HRS01	S	Transect 1	465090.62	6317440.51	193.74	316.329	3.43	0.62	0.62		1.50
HRS03	S	Transect 1	465098.56	6317428.78	179.78	315.054	3.43	0.45	0.53		1.50
Drain shoulder					175.00	314.767					
Upper drain CL					173.00	312.806					
Drain shoulder					171.00	314.556					
HRS04	S	Transect 1	465112.60	6317417.79	162.12	314.341	3.43	0.64	0.67		1.50
HRS06	I	Transect 1	465136.85	6317391.86	126.62	313.474	6.1	0.57	0.64		1.50
HRS05	S	Transect 1	465139.81	6317390.87	123.87	313.401	3.65	0.50	0.58		1.50
HRS08	S	Transect 1	465164.16	6317363.38	87.16	312.549	3.45	0.45	0.45		1.50
HRS15	I	Transect 1	465221.55	6317309.51	9.82	310.186	8.83	0.62	0.66		1.50
HRS14	S	Transect 1	465218.68	6317307.53	9.22	310.234	3.4	0.51	0.58		1.50
Drain shoulder					5.00	309.945					
Lower drain CL					0.00	307.943					
HRS16a	I	Transect 2	467147.71	6318256.18	0.00	289.443	8.70	0.52	0.51		1.50
HRS16b	S	Transect 2	467147.39	6318250.82	4.27	289.285	3.55	0.54	0.57		1.50
HRS18	S	Transect 2	467160.66	6318233.17	26.35	287.467	3.55	0.50	0.47		1.50
HRS20	I	Transect 2	467162.79	6318226.38	32.87	286.818	7.55	0.50	0.47		1.50
HRS19	S	Transect 2	467164.21	6318225.40	34.58	286.681	3.47	0.45	0.55		1.50
Drain shoulder					40.50	285.780					
Drain CL					42.50	283.961					
drain shoulder					44.50	285.775					
HRS21	S	Transect 2	467175.97	6318208.89	55.11	286.245	3.43	0.47	0.51		1.50
HRS21SS	SS	Transect 2	467174.52	6318208.03	55.29	286.268	1.37	0.57	0.00	0.24	0.56
HRS22	S	Transect 2	467179.36	6318203.01	61.90	286.196	3.43	0.50	0.54		1.50
HRS22SS	SS	Transect 2	467178.45	6318202.10	62.29	286.257	0.00	0.00	0.00	0.33	0.39
HRS23b	S	Transect 2	467182.89	6318198.32	67.72	286.326	3.45	0.43	0.48		1.50
HRS23a	I	Transect 2	467183.96	6318196.66	69.69	286.324	9.30	0.42	0.44		1.50
HRS23SS	SS	Transect 2	467183.04	6318196.01	69.80	286.340	2.35	1.42	0.00	0.30	0.60
HRS24	S	Transect 2	467192.42	6318184.68	84.33	286.534	3.45	0.45	0.50		1.50
HRS25SS	SS	Transect 2	467202.92	6318170.39	102.00	286.496	2.31	1.23	0.00	0.92	0.48
HRS25	S	Transect 2	467202.10	6318169.89	102.04	286.464	3.45	0.45	0.50		1.50
HRS26	S	Transect 2	467213.48	6318153.28	122.14	286.006	3.42	0.42	0.45		1.50
HRS26SS	SS	Transect 2	467212.59	6318152.68	122.16	286.007	2.34	1.59	0	0.2	0.55
HRS27	S	Transect 2	467222.13	6318146.01	133.01	286.119	3.35	0.37	0.42		1.50
HRS28	S	Transect 2	467226.82	6318135.45	144.37	287.589	8.30	0.45	0.46		1.50
Drain CL					0.00	277.678					
Drain shoulder					2.00	279.702					
HRS30	S	Transect 3	468032.80	6318811.74	13.17	279.811	3.45	0.43	0.44		1.50
HRS31a	I	Transect 3	468034.34	6318810.75	14.69	279.853	7.50	0.63	0.53		1.50
HRS31b	S	Transect 3	468038.61	6318806.13	20.78	279.906	2.76	0.51	0.52		1.50
HRS32	S	Transect 3	468044.23	6318798.76	30.01	279.923	3.45	0.45	0.50		1.50
HRS33	S	Transect 3	468049.39	6318789.84	40.31	279.795	3.60	0.58	0.60		1.50
HRS34b	S	Transect 3	468063.27	6318773.92	61.25	279.472	3.43	0.5	0.55		1.50
HRS34a	I	Transect 3	468062.77	6318771.64	62.85	279.562	8.07	0.58	0.58		1.50
HRS35	S	Transect 3	468075.00	6318758.42	80.68	279.523	3.40	0.48	0.47		1.50
HRS40	S	Transect 4	468298.50	6318855.61	0.00	278.213	3.42	0.43	0.42		1.50
HRS41a	I	Transect 4	468315.52	6318835.33	26.47	278.252	8.44	0.43	0.41		1.50
HRS41b	S	Transect 4	468316.85	6318834.05	28.31	278.290	3.49	0.45	0.43		1.50
HRS42SS	SS	Transect 4	468330.09	6318817.28	49.67	278.443	2.47	1.71	0.00	0.19	0.56
HRS42	S	Transect 4	468330.89	6318817.93	49.67	278.384	3.47	0.47	0.43		1.50
HRS43	S	Transect 4	468344.10	6318803.66	69.06	278.530	3.50	0.56	0.60		1.50
HRS43SS	SS	Transect 4	468343.15	6318802.79	69.15	278.530	1.32	0.67	0.00	0.035	0.57
HRS44	S	Transect 4	468351.55	6318795.30	80.22	278.609	3.50	0.50	0.46		1.50
HRS44SS	SS	Transect 4	468350.10	6318794.08	80.29	278.650	1.19	0.53	0.00	0.06	0.55
HRS45SS	SS	Transect 4	468356.61	6318786.14	90.56	278.695	0.88	0.37	0.00	0.20	0.30
HRS45	S	Transect 4	468358.09	6318787.24	90.58	278.703	3.40	0.51	0.50		1.50
HRS46	S	Transect 4	468362.60	6318781.56	97.81	278.787	3.40	0.45	0.46		1.50
HRS46SS	SS	Transect 4	468361.08	6318780.13	98.05	278.758	2.43	1.86	0.00	0.16	0.42
HRS47a	I	Transect 4	468367.26	6318776.42	104.62	278.964	8.66	1.01	0.90		1.50
HRS47SS	SS	Transect 4	468366.72	6318775.50	105.13	278.873	2.45	1.65	0.00	0.17	0.53
HRS47b	S	Transect 4	468366.02	6318774.69	105.39	278.902	3.47	0.50	0.52		1.50
Drain shoulder					114.55	279.220					
Drain CL					116.55	277.283					
Drain shoulder					118.55	279.062					
HRS48b	S	Transect 4	468381.85	6318760.62	126.93	279.426	3.45	0.45	0.42		1.50
HRS48SS	SS	Transect 4	468381.63	6318759.08	127.62	279.544	1.99	0.83	0.00	0.60	0.53
HRS48a	I	Transect 4	468383.12	6318759.30	128.71	279.489	8.40	0.53	0.47		1.50
HRS49	S	Transect 4	468387.39	6318754.19	135.18	279.671	3.42	0.51	0.47		1.50
HRS50	S	Transect 4	468392.07	6318747.83	142.90	279.879	3.39	0.54	0.55		1.50
HRS51b	S	Transect 4	468399.03	6318739.48	153.70	280.236	3.39	0.53	0.53		1.50
HRS51a	I	Transect 4	468400.07	6318738.16	155.38	280.316	8.40	0.56	0.46		1.50
HRS12	I	Control west	466311.29	6317656.90		295.382	8.20	0.48	0.55		1.50
HRS13	S	Control west	466314.48	6317656.69		295.406	3.45	0.42	0.42		1.50
HRS13SS	SS	Control west	466314.70	6317655.18		295.388	2.41	1.14	0.00	0.73	0.62
HRS12A	S	Control west	466314.53	6317652.86		295.441	5.50	0.38	0.34		1.50
HRS60	S	Control east	467769.32	6318608.55		281.689	3.75	0.64	0.71		1.50
HRS61SS	SS	Control east	467770.33	6318607.29		281.671	2.42	1.43	0.00	0.48	0.50
HRS61	I	Control east	467771.43	6318606.01		281.676	4.87	0.77	0.77		1.50

Glossary

A Horizon	The upper most layer of the duplex soil profile
AMRR	Accumulated monthly residual rainfall is the progressive accumulation of rainfall for each month less the average monthly rainfall for the period of analysis
Aquifer	A water-bearing soil layer that can store and transmit extractable volumes of water
Aquifer discharge	(A_D) The movement of groundwater into the drainage catchment (kL)
Baseflow	Discharge from the drain that is derived from groundwater inflow
Batter	The inside edges of the drain channel that extend from the natural ground level down to the floor of the channel
Batter slope	The slope of the batter expressed as a ration X:1, vertical to horizontal distance
Bounded drain	A drain in parallel scheme where each drain forms a groundwater boundary to another. When appropriately spaced, the zone of influence (ZOI), watertable zone of influence (WT-ZOI) and zones of benefit (WT-ZOB) are all equal and aquifer discharge is at or near zero
Channel	The excavated part of the drain structure that conveys or intercepts water
Confined aquifer	A confined aquifer is a completely saturated aquifer with upper and lower impervious boundaries. In confined aquifers the pressure of the water (i.e. hydraulic head) is usually higher than that of the atmosphere and the water in bores stands above the top of the aquifer (Salama et al 2003).
Discharge	The total volume of all water that flows from the outlet of a drain or drain section (kL)
Drawdown	A reduction in watertable height caused by the drainage of groundwater by a groundwater drain (see watertable zone of influence)
Groundwater	Water within an aquifer below the watertable
Groundwater drain	An excavated channel that penetrates the aquifer for the purpose of draining groundwater
Groundwater drainage	The groundwater component of discharge from the drain outlet

Groundwater head	Also known as pressure head. The hydrostatic pressure of water in the soil at a certain point, expressed as the height of a water column that can be supported by the pressure. The pressure head is negative in the unsaturated zone and the capillary fringe (Ritzema 1994).
Groundwater inflow	The movement of groundwater into the channel of a groundwater drain from the surrounding aquifer
Kilolitre	1000 L or 1m^3 (approx.) of water (kL)
Kilometre	1000 metres distance
m AHD	Height in metres above the Australian Height datum taken as 0.026 m above Mean Sea Level at Fremantle
mg/L	measure of salinity, expression of the mass of salts dissolved in one litre water
Normalised AMRR rainfall	Adjustment of AMRR by addition of the lowest value to all values so to make all values greater than zero
Open drain	A dual purpose groundwater/surface water drain that is not completely enclosed within levee banks
Perched watertable	A local watertable at least temporarily higher than and isolated from a deeper regional watertable, formed in a layer of saturated soil or rock underlain by a layer of unsaturated soil or rock
Rain-fed/fall recharge	Recharge from the percolation of rainfall and runoff to the groundwater system (mm)
Recharge	The addition of water to the groundwater system (mm)
Runoff	The volume or depth of water moved over the land surface (kL or mm)
Saline seep	Discharge of saline groundwater onto the land surface
Salinity (specific)	The concentration of total dissolved salts in water or soil (mg/L TDS)
Salinity (gen)/salinisation	The reduction in the productivity or biodiversity of land or water due to an excess of salts within the environment
Salt load	Salt transported in flowing or dissolved in standing water (t)
Sediment	Material (soil) that is or has been moved from its site of origin by erosion
Semi confined aquifer	A completely saturated aquifer bounded above by a semi-permeable layer and below by either an impermeable or a semi-permeable layer (Salama et al 2003).

Soil	The natural unconsolidated mineral and organic material at the surface of the land
Spur drain	A drain that is linked to and transports groundwater to the main drain channel
Streamflow	The discharge of water through a natural channel such as a river, stream or creek (m^3/s)
Surface water	Water found above the land surface level
Tonne	1000 kg mass (t)
Transect (bore)	An alignment of bores used to measure a locus/line of points of the watertable
Unbounded drain	A single groundwater drain that is subject to groundwater inflow from the aquifer. The zone of influence (ZOI) of an unbounded drain is greater than the watertable zone of benefit (WT-ZOB) which in turn is greater than its zone of benefit (ZOB)
Unconfined aquifer	A permeable bed partly filled with groundwater the surface boundary of which is the watertable. The groundwater is in direct contact with the atmosphere through the open pore spaces of the overlying soil or rock, the upper boundary is the watertable
Water balance	An equation of all the inputs and outputs of water for a volume of soil or hydrological area over a given period of time
Waterlogging	The accumulation of excess water in the soil root zone
Watertable	Surface of unconfined groundwater at which the pressure is equal to atmospheric pressure
Woolbelt	Western Australian area defined by annual rainfall 500–800 mm/yr (Catchment Hydrology Group 1998)
Zone of Ancient Drainage	Is west of Meckering Line and has an undulating landscape, wide divides, gentle side slopes and broad valley floors (2–10 km wide). The salt lake chains are remnant of ancient drainage systems that flow in wet years. The valley floors have low gradients (Moore 1998).
Zone of Rejuvenated Drainage	Has gentle rises and low hills with narrow divides. It has narrow valley floors with creeks and rivers that flow every winter. To the east is the Meckering Line and the west is the Darling Range (Moore 1998).

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