Prepared for **Department of Water**

Review of inland drainage research (2003-2015)

January 2017

Summary

GHD was engaged by the Department of Water, with support from the Department of Agriculture and Food WA (DAFWA), the Shire of Dumbleyung and the Wheatbelt Catchment Alliance, to undertake a review of agricultural deep drainage research in Western carried out over the period 2003-2015. In particular, the review was to include an assessment of 18 key reports and papers identified by the Department of Water.

The purpose of the review is to provide practitioners and policy-makers with a better understanding of the impacts, benefits and consequences of deep drainage and to support their future decisions.

The following conclusions can be drawn from the reports reviewed for this study. Although these reports and papers address the key issues of drainage performance, they do not represent the full extent of inland drainage research undertaken in Western Australia during this period.

Drainage design

Although drainage theory and design tools are available, these tools were rarely used to design the depth of deep drains in the wheatbelt. Most of the drains reviewed for this study were 2-3 m deep, with 2.5 m being the most common depth. This depth appears to have been chosen as a pragmatic depth, arrived at on the advice of drainage contractors and based on their experience and the available plant and equipment. The Beynon Road study (Cox and Tetlow, in prep.) found that 3 m deep drains were more cost-effective than 2 m deep drains, suggesting the widely used 2.5 m depth may not be the optimum depth for deep drains.

Most of the drains in studies included in this review had side slopes of 0.5(H):1(V). This slope has been largely determined by the experience of the drainage contractors who have developed excavator buckets to efficiently construct drains of this profile. Based on the batter trials at Wubin (Cox and Tetlow, 2009) the drain with 0.5(H):1(V) batter slope had a lower combined construction and maintenance cost that drains with 1(H):1(V) batter slope or a stepped batter.

The impact of climate on groundwater levels

In the decade leading up to 2000, rainfall in the northern parts of the wheatbelt was above average, resulting in rising groundwater levels and increasing salinity risk, which was a key driver in the increased construction of deep drains. From 2001-2007, rainfall was well below average and groundwater trends in many valley floors were mostly falling or stable.

The monitoring periods for all the drainage sites reviewed in this study fall within this period of declining rainfall after 2000. Declining groundwater levels (as well as observations of crop productivity, soil salinity and vegetation health) that are influenced by rainfall trends can be incorrectly attributed solely to the construction of a deep drain. The absence of good pre-drainage groundwater level data and appropriate control or comparison bores makes it difficult to clearly identify the impact of drainage on the watertable.

Single deep drains are unlikely to effectively lower and control groundwater

The results from the studies reviewed show that single deep drains were not effective at lowering and controlling the watertable at the levels required to recover land for agricultural production. Comprehensive monitoring programs at Pithara, Morawa, Wallatin Creek and Hillman River South all concluded that single deep drains were unable to lower and control groundwater at the critical depth necessary to reclaim salt-affected land and return it to reliable agricultural production.

Parallel deep drains may be effective in some instances

The results from the two studies of parallel drains at Dumbleyung and Morawa suggest that deep drains constructed in parallel may be effective in some instances.

Parallel deep drains are more effective than single deep drains because they are able to provide a hydrological boundary around the drainage area, reducing groundwater inflow from the surrounding aquifer to the area between the parallel drains.

Internationally, most agricultural drainage schemes comprise of a network of parallel lateral drains connected to a main drain and most agricultural drainage theory and design tools have been developed for these parallel drainage networks. Drain spacing, or drainage intensity, is a key design parameter for these systems.

Soil and crop response to deep drainage

The lowering of groundwater by deep drains is intended to lead to a reduction in soil salinity and the restoration of soil productivity. However, the processes and timescales for the leaching of salt from the soil profile, the importance of soil solution salinity, the impact of occasional high-watertable events on soil salinity, the recovery of soil structure and soil organic matter and the crop response to these processes have not been adequately considered in relation to the effectiveness of deep drainage.

To understand the feasibility of deep drainage as a tool for restoring salinized land to agricultural production requires a better understanding of the impacts of drainage on soil productivity, the effects of soil and soil solution salinity on crops and of methods to improve the recovery of salt-affected land after drainage. These processes are more difficult to measure than watertable response, more difficult to isolate and require longer-term research programs

Financial viability of deep drains

Parallel deep drains may be financially viable in some situations but single drains are unlikely to be financially viable because of their narrower zone of benefit (Cox and Tetlow, in prep.). Although the cost of drain construction is well understood, the economic benefit from drains is less certain and will depend on the increased crop yield achieved and the market price.

Where deep drains are unable to return salt-affect land to agricultural production, they may still have sufficient impact to slow the rate of salinisation or to allow some revegetation. These intangible benefits were not considered in the economic evaluation and may be sufficient to influence some landowners to install deep drains.

Drainage discharge water quality is variable and can be acidic

The characteristics of water discharged from deep drains are closely linked to the surrounding groundwater. In many parts of the wheatbelt the groundwater is saline, particularly under the flat valley floors, and commonly, although not always, acidic with elevated metal concentrations.

Acid groundwater is naturally occurring across the wheatbelt. It is highly variable spatially, although predicted to be more frequently found in valley floors of palaeo drainage lines. The hydrolysis of dissolved iron in the groundwater (when it is exposed to oxygen in the drain) sometimes results in lower pH in the drainage discharges than in the surrounding groundwater. Consequently, total acidity of groundwater is a much better indicator of the final pH of drainage discharge than groundwater pH alone.

Drainage discharges can have downstream impacts but those impacts can be managed

Drainage discharge can have a detrimental impact on downstream receiving environments due to the increased salinity and concentrations of metals and nutrients in the drainage discharge, particularly when the drainage discharge is acidic.

Acidic saline discharge from the Fence Road arterial drainage system had a measurable impact on aquatic ecology of the receiving waterway for a distance of at least 15 km downstream, with lower macroinvertebrate diversity, different macroinvertebrate community composition and visibly less healthy in-stream flora.

Discharges to some salt lakes, such as the Yarra Yarra lakes, may have limited and acceptable environmental impacts. However, before salt lakes are approved as disposal sites it is important to identify and protect those systems with high environmental values. Most naturally saline systems are alkaline, so acidification poses a threat to the biodiversity of wheatbelt playas and wetlands.

Farmers support deep drainage and rely on other farmers for advice

Farmers who have installed drains generally believed their drains were effective in reducing waterlogging and improving productivity and were value for money. Landholders do not rely on groundwater monitoring data in forming an opinion regarding the performance of deep drains, but are more likely to rely on qualitative cropping data, waterlogging and adjacent vegetation health.

As a result, landholders do not appear to access technical advice available from government agencies, which they claim is considered too broad, not specific to individual farms and not providing clear guidance on actions. They say they want face-to-face information about their particular situation.

Appropriate governance arrangements must be in place before drain construction

The Policy Framework for Inland Drainage (Department of Water, 2012) recognises the need for effective governance structures and processes to be in place to manage deep drains over the long term and recommends strategies to deliver appropriate governance.

Of the drainage systems reviewed in this study, the Fence Road Drainage Scheme had an appropriate ongoing governance structure in place. The drainage system is managed by the Shire of Dumbleyung and the necessary access arrangements and funding arrangements are in place. However, the Local Land Drainage Advisory Committee has been less active since 2013 and some landowners expressed concern about weed management and drain maintenance.

The Yarra Yarra Regional Drainage Program has an active catchment management group in the YYCMG and was previously managed by a regional local government in the Yarra Yarra Catchment Regional Council. However, the recent dissolution of the Yarra Yarra Catchment Regional Council has created uncertainty regarding ongoing responsibilities and arrangements that need to be resolved by stakeholders.

Governance arrangements at Wallatin Creek rely on the collaborative relationship between neighbouring farmers and a breakdown in that relationship represents a significant risk for the long-term management of the drainage system.

The Narembeen deep drainage system has no governance structure and sections of the drain are in poor condition and need of maintenance, potentially resulting in flooding and damage to land and infrastructure with no obviously accountable body.

The implementation of appropriate governance arrangements remains a significant challenge for the successful construction and management of deep drainage systems in the wheatbelt. It is critical that government ensures that appropriate long-term governance arrangements are in place before the construction of further deep drainage systems in Western Australia.

Recommendations for further work

- The Department of Water prepare a brief information note presenting the conclusions from this review. The information note would provide landholders and other stakeholders with an update of the current knowledge of deep drainage in Western Australia and key recommendations for implementation. Noting the results from the stakeholder evaluation, landholders are unlikely to access the information in this report but may be more inclined to read a more concise and accessible summary available through agency websites. The information note should draw attention to the need for feasibility assessment using tools such as the GRDC-funded DrainLogic and the benefits of rigorous engineering design.
- The Department of Water provide a more complete list of the research projects funded by government and addressing the research priorities identified in Dogramaci and Degens (2003). Table 2 and Table 3 in section 2 have listed the reports reviewed in this study that have addressed the research priorities identified in Dogramaci and Degens (2003). However, that list represents only some of the research projects funded by government under programs including, but not only, the Engineering Evaluation Initiative. It would useful to prepare a more complete list of research completed since 2003 to confirm which research priorities have been addressed and identify any remaining research questions. A list of any remaining research questions would be a useful guide for investment by government and research institutions.
- Understand soil and crop response to deep drainage. The processes and timescales for the leaching of salt from the soil profile, the importance of soil solution salinity, the impact of occasional high-watertable events on soil salinity, the recovery of soil structure and soil organic matter and the crop response to these processes have not been adequately considered in relation to the effectiveness of deep drainage. These warrant further investigation but are more difficult to measure than watertable response, more difficult to isolate amongst the complex dataset collected from field experiments and require longer-term research programs.
- No further watertable monitoring required (or funded) unless for compliance or for specific research objectives. Based on the most recent reports reviewed for this study, there is now a broad consensus on the performance of deep drains in Western Australia. Unless monitoring is needed to demonstrate compliance with a condition of approval, to investigate soil and crop response to drainage or monitoring data are required for a specific research objective, there is no further need for performance monitoring of deep drains in Western Australia.

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1. Introduction

Widespread clearing of native vegetation for agriculture over the past century has caused rising groundwater and increasing salinisation across large areas of the Western Australian wheatbelt. As the impact of salinity increased, farmers and land managers explored a range of measures to arrest the rate of salinisation and to reclaim salt-affected land, including recharge management, surface water management and groundwater management. One of the key engineering interventions favoured by farmers has been deep drainage.

Deep drains

The primary objective of deep drainage is to lower and control groundwater levels, to alleviate waterlogging and to allow rainfall recharge to leach salts from the upper soil profile, reclaiming salt-affected land and returning it to agricultural production. For productive cropping, saline groundwater needs to be controlled at depths below 1.5 m and 1.8 m, for barley and wheat respectively (Nulsen, 1981). To arrest salinization by capillary rise and allow leaching of salts from the upper soil profile, groundwater levels need to be maintained 1.4 m to 2.0 m below ground level, depending on soil type (George, 1985; Cox, 2010).

Effective deep drains work by lowering the watertable along the length of the drain (to approximately the level of the base of the drain) so that groundwater flows from an area of adjacent land into the drain and is then conveyed downstream for disposal. A good introduction to drainage mechanisms and their application to deep drainage is presented in Chandler and Coles (2003) and a more detailed presentation of drainage theory can be found in Skaggs and Van Schilfgaarde (1999).

In the Western Australian wheatbelt, deep drains are typically excavated to depths greater than 2 m and are trapezoidal in cross section. In many cases the soil excavated during construction of the drain is used to form levees on one or both sides of the drain to prevent surface water entering the deep drain.

Drainage evaluation programs

As early as 1985, the Department of Agriculture devoted a volume of the *Journal of Agriculture* to a review of drainage research (Volume 26, No 4, 1985). That volume provided advice on site investigation and drainage design (George, 1985a), a comparison of drainage methods for salinity control (George, 1985b) and the use of drainage to control waterlogging (McFarlane, Negus and Cox, 1985). Although open deep drains were seen as an option for reclaiming salt affected land, it was recognised that there was insufficient data on the effectiveness of drains in the Western Australian wheatbelt and that deep drains were not likely to be cost-effective at all sites.

Evaluation of some early deep drains in the Northern Agricultural Region raised questions regarding their effectiveness. Speed and Simons (1992) carried out a detailed monitoring program before and after construction of a deep drain at South Buntine, including groundwater levels and soil conductivity (EM38) surveys. They found that the drain construction had a negligible effect on the watertable, limited to only 10 m from the drain. Although soil salinity measurements suggested leaching of salt, it was also limited to areas in close proximity of the drain.

In the 1996 the Western Australian State Salinity Action Plan recognised the need to understand the performance and impact of deep drains and the Department of Agriculture and Food WA (DAFWA) completed an assessment of deep drains (Coles, George and Bathgate, 1999).

That study surveyed drainage at 25 sites across the wheatbelt, evaluating the impact of drains on adjacent vegetation, cost-effectiveness and offsite impacts. The review found that although most drains were installed in valley floors, drains installed at the break of slope were considered to be more effective. It found the performance of deep drains was variable. Factors affecting the efficiency of drains included inadequate site investigations, inappropriate design (or no design), lack of maintenance and the impact of surface water flows (flooding). Although most landholders reported that drains had alleviated water logging and salinity problems to various degrees, there was no detailed benefit-costs analysis to evaluate their financial viability. The study recommended monitoring and evaluation of a number of drainage projects aimed at developing and communicating principles of best practice.

Subsequently, in 2002, the Western Australian State Government, with support from the Commonwealth Government under the National Action Plan for Salinity and Water Quality, established the Engineering Evaluation Initiative (EEI) to investigate the effectiveness of engineering options to manage salinity. An early outcome of the EEI was a review of deep drains (Chandler and Coles, 2003), which summarised previous drainage research, identified technical knowledge gaps and recommended potential research projects. Combined with the outcomes from a series of workshops (Dogramaci and Degens, 2003), a program of research priorities and projects was developed and subsequently implemented over the following decade. Most of the reports included in this review were funded under this program.

In response to growing interest in larger scale arterial drainage schemes, in 2005 the State Government established the Wheatbelt Drainage Evaluation (WDE) program to use the outcomes from the EEI to develop a framework for the implementation of sustainable catchment-scale and regional-scale drainage, including drainage management and governance. The Western Australian State Government subsequently established the Wheatbelt Drainage Council, which implemented a broad public engagement and consultation exercise that resulted in the *Policy Framework for Inland Drainage* (Department of Water, 2012).

Despite the significant investment in research and evaluation of deep drainage in Western Australia, the construction of deep drains remains a contentious issue. Although previous scientific review such as Coles et al. (1999) found drain performance to be variable and often not cost effective, landholders with drains generally believe that drains are effective and a good investment (Kingwell and Cook, 2007).

This review

GHD was engaged by the Department of Water, with support the Department of Agriculture and Food WA (DAFWA), the Shire of Dumbleyung and the Wheatbelt Catchment Alliance to undertake a review of agricultural deep drainage research in Western Australia carried out over the period 2003-2015. In particular, the review was to include an assessment of 17 key reports and papers identified by the Department of Water. A further report, evaluating drains in the Yarra Yarra catchment (GHD, 2016), was subsequently included in the review.

The purpose of the review is to provide practitioners and policy-makers with a better understanding of the impacts, benefits and consequences of deep drainage and to support their future decisions.

This report provides a summary of the key outcomes and findings from each of the key reports reviewed with the aim of bringing the collective knowledge together in a single report. In assessing the outcomes from each of the projects, consideration has been given to the quality and completeness of the monitoring data available and the analysis presented. Particular attention has been given to identifying the separate impacts of drain construction, climate and adjacent land-use so that the impact of deep drains can be determined. For some projects, the quality or completeness of the available data prevents these separate impacts from being identified and the findings from those projects are therefore less useful than the findings from reports where the data supports a more rigorous assessment.

The selected reports

The 18 reports assessed in the review are listed in Table 1, together with some summary information about the drainage sites and project outcomes. Where relevant, Table 1 includes assessment of data quality and completeness for each report, based on the following attributes:

- length and completeness of monitoring record (pre- and post-drain groundwater data)
- bore spacing and transect alignment
- comparison bores
- comparison with climate data
- drain discharge data

For each report, one tick given for each attribute and the total score is shown in Table 1 (refer to the table column *Data quality & completeness*). The assessment of data quality and completeness has been used to weight the validity of any conflicting statement or conclusions between reports.

About this report

This report first presents the reviews of each of the 18 reports. The reports are grouped under the following topics, with each report separately reviewed:

- Performance of deep drains
- Drainage design and construction
- Drainage discharge quality
- Downstream impacts
- Evaluation tools and methods
- Stakeholder evaluation

The reviews of individual reports are followed by a discussion in which the key findings are consolidated for each topic.

The report concludes by presenting key conclusions and some recommendations for further work.

Scope and limitations

This report has been prepared by GHD for Department of Water as a review of 18 key reports and papers identified by the Department of Water and related to agricultural deep drainage research in Western Australia.

GHD otherwise disclaims responsibility to any person other than Department of Water arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

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Table 1 Summary of previous studies included in this review

Site/Report	Author/s	Year of publication	Drain completion	Monitoring period	Monitoring data	Adjacent impacts	Downstream impacts	Cost/benefit information	Date quality & completeness
Review of engineering and safe disposal options	S. Dogramaci & B. Degens	2003	N/A	N/A	N/A	0.5 m decrease in g'water level at 150 m	Identified knowledge gaps	No information	✓
Narembeen *Evaluation of the impacts of deep open drains on groundwater levels in the wheatbelt of Western Australia*	R. Ali, T. Hatton, R. George, J. Byrne, G. Hodgson	2004	Various: 1998-2001	2000-2003	G'water levels	Latham: 0.75 m decline in g'water levels <200 m from drain (Town, Pini, Deluis: similar to Latham); Bailey: 1.2 m decline in g'water levels <15 m from drain; John Deluis: No observed impact on adjacent g'water	No information	No information	✓✓
Wallatin Creek *The initial hydrological effect of deep drains at Wallatin Creek 2006-2008*	R. George & G. Stainer	2006	2006	2006-2008	G'water levels, drain flows, pH, EC, T	0.2 m decrease in g'water level < 28 m; barley increased adjacent to drain over two years following construction; no reduction in topsoil salinity	No information	No information	✓✓✓✓
Pithara *Drainage for salinity control at Pithara*	N. Cox	2010	2004	2004-2006	G'water levels, drain flows, pH, EC, WQ	0.5 m decrease in g'water level <50 m, poor barley crop, reduced soil salinity	No information	Drain: $6,453/km	✓✓✓✓✓
Morowa *The use of drains and basins to manage salinity at Morawa*	N. Cox	2011	2005	2004-2007	G'water levels, drain flows, pumped discharge, pH, EC, WQ	0.2-0.45 m decrease in g'water level < 50 m; reduced topsoil salinity adjacent to drain	Drain discharge neutral pH; saline plume under evaporation basin	Drain: $6,944/km	✓✓✓✓✓
Hillman River South *Hillman River South drainage project*	R. McDougall	2012	2009	2009-2010	G'water levels, drain flows, pH, EC, T, WQ	No clear effect on waterlogging or watertable levels	No measurable impact 10 km downstream,	Drain: $13,500/km	✓✓✓✓
Northern Agricultural Region *Evaluation of drains in the Northern Agricultural Region*	A Stuart-Street, R Speed, A Beattie & P Whale	In prep.	Various: 2005-2009	2006-2015	G'water levels, pH, EC and soil EC	Only at Three Springs did drain lower and control adjacent g'water (and only when open trench)	No information	No information	✓✓✓
Beacon & Morawa *Watertable responses to parallel drains in Western Australian Wheatbelt*	N. Cox & S. Tetlow	2015	2010	2010-2011	G'water levels	No data; no attempt to plant crop between the drains	No information	No information	✓✓✓✓✓
Dumbleyung *Drainage in the Dumbleyung catchment of Western Australia*	N. Cox & S. Tetlow	In prep.	2002	2001-2005	G'water levels, drain flows, pH, EC, WQ	G'water lowered and controlled between parallel drains; barley crop between drains; reduced topsoil salinity; re-vegetation of previously salt-affected land	Drainage discharge saline (5,000-95,000 mg/L) and acidic (pH 3.2-3.6)	1 m: $1,800/km 2 m: $6,100/km 3 m: $14,600/km	✓✓✓✓✓
Yarra Yarra (final report)	YYCMG	2010	2006-2009	2007-2010	G'water: level; Drain water: flow, pH, Eh, EC, WQ; Drain sediment	Southern drains (Mongers 55, Jibberding, Xantippe & Burakin) reported to caused	No observed downstream vegetation can be	Drains $8,000-9,000/km	✓

Final Report of the Yarra Yarra Regional Drainage and Research Project					geochemistry; Ecological: Vegetation surveys and photographic records, micro- and macroinvertebrate surveys	decline in g'water levels; Northern drains (Merkanooka) reported no decline in g'water levels	ascribed to drainage discharge		
Yarra Yarra *Evaluation of Xantippe, Jibberding and Mongers 16 drains*	GHD	2016	2006-2009	2007-2010	G'water levels	Qualitative and anecdotal reports of improved crop productivity and adjacent vegetation condition suggest some impacts but these may be affected by other nearby drainage features	No information	No information	✓✓✓
Wubin *Drain batter erosion trial at Wubin*	N. Cox & S. Tetlow	2009	2006	2006-2007	Cross-section surveys and visual/photographic observations	No information	No information	No information	✓
The distribution ad origins of acidic groundwaters in the South West Agricultural Area	A. Lillicrap & R. George	2010	N/A	N/A	Groundwater pH, vegetation and geology	N/A	Acid groundwater is linked to Eucalyptus woodlands and shrublands and subsoil alkalinity	N/A	N/A
Yarra Yarra *Yarra Yarra aquatic monitoring: assessing the effect of deep drainage on the ecological health of the Yarra Yarra playas and wetlands*	Wetland Research & Management	2008	2006-2009	2008	Micro- and macroinvertebrate surveys, pH, EC, T, DO, WQ	No information	Yarra Yarra catchment supports moderately rich aquatic invertebrate fauna; macro-invertebrates influenced by salinity; Micro-invertebrates influenced by pH; elevated metals at most sites	N/A	N/A
Fence Road, Dumbleyung *Fence Road drainage system*	K. Seewraj	2010	2008	2007-2009	Surface water WQ: pH, total acidity, total alkalinity, EC, T, DO, turbidity, metals, nutrients, Ecological: macro-invertebrates	No information	Acid drainage discharge measured 13 km (sometimes 30 km) downstream with impact on ecology at least 15 km downstream	No information	N/A
Yarra Yarra *Monitoring activities in the Yarra Yarra area over the period Sep 2011 - Jan 2012*	I. Fordyce	2012	2006-2009	2011-2012	Vegetation surveys and photographic records, drain water pH, EC, total acidity, WQ; sediment profiles	Land adjacent to Canna-Guther and Mongers 16 observed to have improved.	No observed downstream impacts, except waterlogging at Jibberding	No information	N/A
Dumbleyung, Narembeen, Beacon, Pithara, Morawa *Remote sensing for assessing the zone of benefit where deep drains improve productivity of land affected by shallow saline groundwater*	H. Kobryn, R. Lantzke, R. Bell & R. Admiral	2015	Various 1999-2005	1987-2009	Landsat TM derived NDVI	All sites showed improvement (as measured by NDVI) due to drains	No information	No information	✓✓
Drainage benchmarking in Northern Agricultural Region: landowner survey	A Beattie & A Stuart-Street	2008	Various	2006-2007	Landowner feedback by survey/questionnaire/interview	Landholders generally believed drains were effective at reducing waterlogging and improving productivity	No information	Most landholders felt drains provided value for money	N/A

2. Review of engineering and safe disposal options (Dogramaci and Degens, 2003)

The Review of Engineering and Safe Disposal Options (Dogramaci and Degens 2003) was written to present a summary of the current understanding (at the time of writing in March 2003) of the performance of engineering options (including deep drains) in regards to managing salinity in the wheatbelt and to identify gaps to guide investment under the Engineering Evaluation Initiative (EEI). The review relied on previously published reports and the outcomes of two meetings of stakeholders in March 2003. The review addressed a range of engineering options: groundwater pumping, siphon and relief bores, deep drainage, disposal options and surface water management. The following section only presents key outcomes relating to deep drainage.

Reported current understanding in 2003

The report (Dogramaci and Degens 2003) relied heavily on workshop discussions and the key findings and recommendations of the report do not refer to further publications, reports or projects. Noting the purpose of the report was to provide a high-level summary of the current knowledge at the time of writing and to guide investment needed to fill gaps in that knowledge, it is understandable that many of the statements about the performance of deep drainage have been superseded by subsequent studies, many initiated by the recommendations of the report.

The following key points taken from the report (Dogramaci and Degens 2003) were not supported by data or analysis and should not be taken as evidence to support the effectiveness or otherwise of deep drains. The key points are presented here to provide context of the state of knowledge regarding deep drainage in the wheatbelt in 2003 and issues identified at that time as needing to be addressed.

Drainage performance

The report states that preliminary results from Dumbleyung and Narembeen indicate that 2 m deep drains are effective in lowering the watertable up to 0.5 m at distances of 150 m from the drain and that the lateral extent of a drain's influence depends mainly on the soil characteristics. The report does not cite any reference for these conclusions and it is unclear whether they are derived from an analysis of monitoring data from the two projects or from discussions with stakeholders.

The report (Dogramaci and Degens 2003) pre-dates the comprehensive report on the Dumbleyung drainage trials (Cox and Tetlow 2015) reviewed in section 3.8 and which does not support the statements regarding the effectiveness of 2 m deep drains and links the performance of the Dumbleyung drains (Beynon site) to their parallel configuration.

Causes of variability with drain performance

Transmission losses (i.e. water lost from the drain as it flows towards the outlet) are reported to be significant, particularly for large-scale drainage networks, although the extent and impact are not well understood.

The report underlines the difficulty transferring the results of drainage between different areas because of the variability in wheatbelt soils and landforms.

Chemistry of drainage waters

The report finds that the geochemical processes occurring in deep drains are poorly understood, particularly processes related to iron and acidity. It also draws attention to the difficulties associated with the treatment of sodic soils.

Financial aspects

The report refers to an uncited economic evaluation that concluded a break-even zone-of-benefit (ZOB) of between 25 m and 90 m. This is in contrast to Cox and Tetlow (2015), who estimated the break-even ZOB to be in the range 171-288 m. Without access to the analysis on which Dogramaci and Degens (2003) base their break-even ZOB estimates, it is difficult to attach as much weight to their assessment compared with the more detailed assessment presented in Cox and Tetlow (2015).

Recommended further work

The review recommended ten priority areas for further work and nine areas of lower priority, with the aim of filling knowledge gaps in the current understanding (in 2003 at the time of publication). Those priority areas are presented in Table 2, Table 3 and Table 4, together with projects and reports subsequently completed that address those priority areas.

The 18 reports reviewed for this current project addressed some but not all of the priority areas identified in the Dogramaci and Degens (2003). However, other projects and reports have addressed other of the priority areas. Table 2, Table 3 and Table 4 should not be taken as a complete survey of work completed under EEI and other programs to address the priority areas. It is recommended that the Department of Water consider reviewing the wider body of salinity and drainage research completed since Dogramaci and Degens (2003) and preparing a more complete version of Table 2, Table 3 and Table 4. Such a survey would provide a useful reference for practitioners, policy-makers and researchers and would identify issues that remain unanswered.

Table 2 High-priority recommendations (Dogramaci & Degens 2003)

Recommendation for further work	Completed projects and publications (since 2003)
1. Develop an appropriate test site to assist with effective drain planning and design	• Beynon (Cox and Tetlow, in prep.)* • Yarra Yarra (GHD, 2016)* • Hillman River South (McDougall, 2012)* • Morawa (Cox, 2011; Cox & Tetlow, 2009)* • Pithara (Cox, 2010)* • Beacon (Cox and Tetlow, 2009)* • Wallatin Creek (George and Stainer, 2009)* • Wubin (Cox and Tetlow, 2009)*
2. Construct a series of deep drains in different soil and landscape types, with pre-drainage data and monitor.	
3. Collate all crop productivity data and examine whether it is likely to be a realistic measure of drainage performance, compared with soil salinity, soil moisture and depth to water table.	• Bell, Raphael & Mann (2009)
4. Develop a list of standard methods for monitoring deep drains.	
5. Quantify transmission losses along constructed drains, compared to evaporative loss.	
6. Improve prediction of drainage discharge water quality from pre-construction measurements of water chemistry, pH and EC.	• Lillicrap and George (2010)* • Degens and Shand (2010) • Seewraj (2010) • Shand and Degens (2008)
7. Develop field tools for determining the level of sodicity of soil and required treatment.	
8. Investigate the process of acid water generation in drains, impacts and solutions.	• Degens (2013) • Lillicrap and George (2010)* • Degens (2009a)

Table 3 Financial aspects recommendations (Dogramaci & Degens 2003)

Recommendation for further work	Completed projects and publications
1. Evaluate costs and benefits of drainage systems	• Cox and Tetlow (in prep.)* • Hardy and Ryder (2013) • URS (2006) • Abraham, Speed and Peek (2004)
2. Compile an up-to-date list of costs for constructing and maintaining deep drains.	

* Included in this review

Table 4 Lower-priority recommendations (Dogramaci & Degens 2003)

Recommendation for further work	Completed projects and publications
1. Develop standardised list of criteria for determining the success of drainage systems.	• Cox and Tetlow (in prep.)* • Ali, R., Hatton, T., Byrne, J. & Hodgson, G, Lambert, T. & George, R. (2004)
2. Investigate use of watertable levels as criteria for success of drainage. Determine the critical depth for different soil types and uses.	• Bennett and Barrett-Lennard (2013) • Bennett and Barrett-Lennard (2008)
3. Investigate innovative approaches such as the use of passive relief wells in conjunction with deep drains.	• Seymour and George (2004)
4. Investigate post-drainage treatment required to assist with crop productivity or asset protection	• Bell, R.W., Raphael, C., Mann, S., Gebrewahid, T. & van Dongen, R. (2009) • Bell and Mann (2004)
5. Investigate in-drain methods to reduce discharge volumes and treat low quality drainage water to minimise disposal problems.	• Degens (2009a, b and c) • Franzmann et al. (2007)
6. Investigate deep drains with stepped batters and compare with standard batters.	• Cox and Tetlow (2009)*
7. Investigate existing drains in sodic soils, develop best practice guidelines for drains in sodic soils and construct a drain to test the design.	• Department of Agriculture and Food (2016) • Cox and Tetlow (2009)* • George, Abadi and Raper (2009) • Ali et al. (2004)* • Yandle (2004) • Cox, Tetlow and Coles (2004) • Ali, R., Hatton, T., Byrne, J. & Hodgson, G, Lambert, T. & George, R. (2004)
8. Develop design tools for contractors and landholders that calculates drain spacing, width and slope based on soil type, permeability, depth, grade and depth to watertable.	
9. Investigate current best-practice design and revise to reduce risk of downstream impacts	

3. Performance of deep drains

3.1 Evaluation of the impacts of deep open drains on groundwater levels in the wheatbelt of Western Australia (Ali et al., 2004)

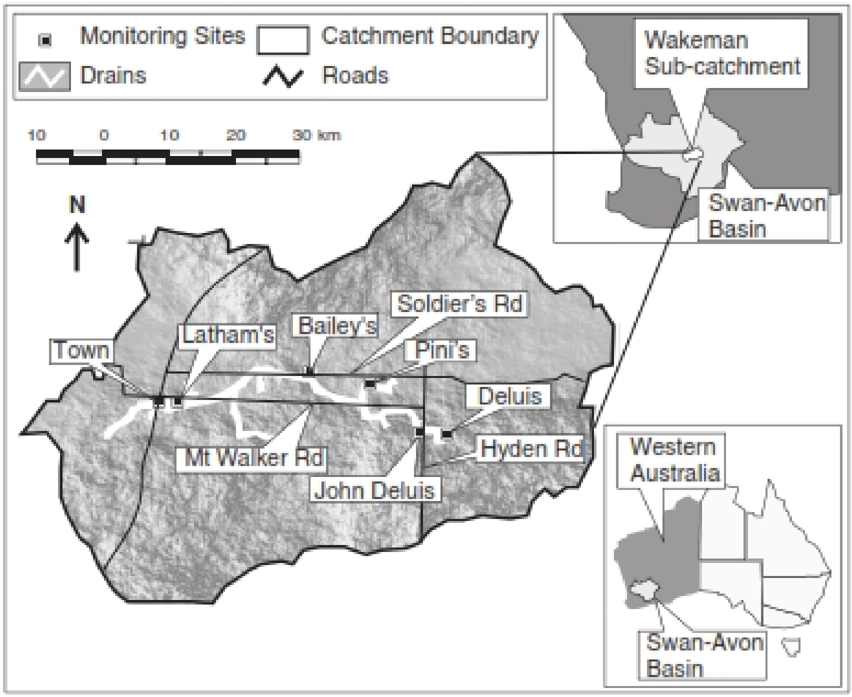

Figure 1 Narembeen drainage sites - locations

This project investigated the effects of deep drains on adjacent groundwater in the Narembeen area. The study focussed on privately constructed deep drains at six sites: five sites with existing deep drains and one site planned for drainage and subsequently considered suitable for use as a comparison site. All sites are east of Narembeen within the Wakeman sub-catchment of the Avon Basin.

The area is characterised by broad valley floors and ephemeral drainage. Soils in the area generally comprise 1-3 m of sands, sandy clays and clays over a layer of discontinuous ferricrete and silcrete, beneath which is more sandy clay and clay. Lenses of porous material are associated with the ferricrete and silcrete layers and provide preferred pathways for groundwater flow. Groundwater levels in the undrained areas of the Wakeman catchment generally fluctuate within 1 m of the ground level.

The area around Narembeen was largely cleared by the 1930s and has been mainly used for winter cropping of barley and wheat. Salinity developed in the valley floor in the 1960s and sandplain seeps are common on the sandy hillslopes.

Commencing in the late 1990s, the Narembeen drainage system was constructed to alleviate rising saline groundwater in the valley floor. The drainage system comprises a network of over 70 km of deep drains extending approximately 40 km east of Narembeen and discharging to the natural waterway approximately 10 km west of the town site.

3.1.1 Deluis site

The Deluis site is about 40 km east of Narembeen in the upper catchment and was constructed in July 1999.

The drain is 2.5 m deep, with a 1.3 m wide base and 0.4(H):1(V) batter slopes. The drain was not connected to the downstream waterway until late 2001. Before it was connected, the drain discharge was pumped to the downstream creek.

The drain is excavated though duplex soils comprising loamy sands and sandy clay and a layer of ferricrete at about 2 m depth with associated lenses of porous material. It is enclosed by levees along both sides preventing surface water inflows to the drain.

Groundwater monitoring bores installed at the site in April 2000 included two transects extending from either side of the drain: one of two nested pairs of bores (shallow and deep) and the other of three nested pairs. The site was also equipped with a weather station.

Drain performance

Since the hydraulic response of the Deluis site was similar to the response observed at the Latham site, the paper only presents an analysis of data from the Latham site, discussed in section 3.1.5 below.

3.1.2 Town site

The Town site is on the main drain as it passes through the town of Narembeen. Located near the bottom of the drainage scheme, this section of drain was constructed in February 1999.

The drain is 3.0 m deep, with a 2.3 m wide base and 0.4(V):1(H) batter slopes. The drain is excavated though sandy clay above a layer of ferricrete at about 2.5 m depth. The drain has a levee along one side only and is not protected from surface water inflows.

Groundwater monitoring bores installed at the site in April 2000 included a nested pair of piezometers (shallow and deep) on one side of the drain and a transect of three nested pairs extending from the other side of the drain.

Drain performance

Since the hydraulic response of the Town site was similar to the response observed at the Latham site, the paper only presents an analysis of data from the Latham site, which is discussed in section 3.1.5 below.

3.1.3 Pini site

The Pini site is about 30 km east of Narembeen and was constructed in October 1999.

The drain is 3.0 m deep, with a 1.3 m wide base and 0.35(H):1(V) batter slopes. The drain is excavated though sandy clay and a layer of ferricrete at about 2 m depth with associated lenses of porous material. The drain is enclosed by levees along both sides preventing surface water inflows to the drain.

Groundwater monitoring bores installed at the site in April 2000 included a transect of two nested pairs (shallow and deep) extending from one side of the drain. The site was also equipped with a weather station and rainfall gauge.

Drain performance

Since the hydraulic response of the Pini site was similar to the response observed at the Latham site, the paper only presents an analysis of data from the Latham site, which is discussed in section 3.1.5 below.

3.1.4 John Deluis site

The John Deluis site is about 2 km downstream of the Deluis site, 40 km east of Narembeen in the upper catchment.

When selected for this study, the site was planned for future drainage so that the site has a significant pre-drainage data set. Groundwater monitoring bores were installed at the site in April 2001 included two transects extending from either side of the planned drain: one of three nested pairs of bores (shallow and deep) and the other of four nested pairs.

The drain was constructed in September 2001 and is less than 1.5 m deep, with a 1-1.5 m wide base and 0.5(H):1(V) batter slopes. The drain is enclosed by levees along both sides preventing surface water inflows to the drain. The drain discharges to the creek line about 3 km downstream of the site. The drain is excavated though duplex soils similar to the upstream Deluis site except that the drain does not cut through the layer of ferricrete, which is below the base of the drain.

Drain performance

Before the construction of the drain, groundwater levels at the John Deluis site fluctuated within 1 m of the natural surface. After excavation of the drain in September 2001 there was no observed change in groundwater levels beyond 7 m either side of the drain.

The absence of any observed impact of the drain on adjacent groundwater levels (beyond 7 m) was attributed to the shallow depth of the drain (< 1.5 m deep), which prevented it from intersecting the ferricrete layer and associated lenses of permeable material. Obstructions in the drain were also observed to restrict drainage flows and increase water levels, which would also be expected to reduce the effectiveness of the drain.

Since the drains were ineffective, the John Deluis site was consequently treated as a control site for comparison with other drained sites.

3.1.5 Latham site

The Latham site is located approximately 3 km upstream from the Town site and was constructed in 1998.

The drain is a similar construction to the downstream Town site, being 3.0 m deep, with a 2.3 m wide base and 0.4(H):1(V) batter slopes. The drain has a levee along one side only and is not protected from surface water inflows.

Groundwater monitoring bores installed at the site in April 2000 included a transect of three nested pairs (shallow and deep) extending from one side of the drain. The site was also equipped with a weather station and rainfall gauge.

The drain at the Latham site is not the main arterial drain but a spur drain, running south of and parallel to the main drain. Although the Latham drain is approximately 1 km from the main drain and was not designed as a parallel drain to increase the drainage density in the valley floor, the main drain may provide a hydrological barrier to the north, isolating the area between the drains from the wider regional aquifer system. The bore transect extends nearly 600 m north from the Latham drain into this area towards the main drain.

Drain performance

No pre-drain groundwater level data were available for the Latham site.

The paper considers the watertable response to an extreme rainfall event in January 2000 that resulted in high groundwater levels across the catchment. By June 2001, groundwater levels up to 200 m either side of the Latham drain had fallen 0.75 m and were close to the invert level of the drain. The paper states that the overall decline in groundwater levels at the Latham site was very significant, relative to the John Deluis site (control). However, monitoring data from the John Deluis site (which only commenced in April 2001 so does not include 2000) show a similar decline (0.75 m) in the watertable in 2001 and 2002 (Figure 4 in Ali et al., 2004). This decline at the John Deluis site may well be the result of drainage constructed in September 2001, but the paper claims that the drain at the John Deluis site was not effective and the site can be treated as a control site. Similar fluctuations were also observed in the south-east Hyden regional bores, which are also presented in Ali et al (2004) as comparison bores in a nearby undrained catchment.

The paper notes the substantial rise in groundwater levels at the Latham site at the end of winter rainfall in 2001. It claims that the drain was able to maintain water levels at or below 2 m from the surface but presents data showing the watertable rising to within 1 m of the surface in September 2003 (Figure 5 in Ali et al., 2004). Groundwater levels at the Latham site rose over 1 m at the end of winter 2003 (Figure 8(a) in Ali et al., 2004).

The substantial rises in groundwater levels in response to rainfall events and the similarity of the response to the John Deluis site suggests that the reported ability of the Latham drain to control groundwater levels is over-stated in the paper.

3.1.6 Bailey site

The Bailey site is a branch drain about 20 km east of Narembeen and was constructed in July 2000.

The drain is 2.5 m deep and rectangular in cross-section with a 1.3 m wide base. The drain is excavated in similar conditions to the Pini site, except with relatively more transmissive soils. The drain is enclosed by levees along both sides preventing surface water inflows to the drain.

Two shallow groundwater monitoring bores were installed 15 m either side of the drain one week before construction in July 2000. Two transects, each of three nested pairs of bores (shallow and deep), were subsequently installed in April 2001, extending from either side of the drain.

Similar to the Latham site, the drain at the Bailey site is not the main arterial drain but a spur drain, running north of and parallel to the main drain. Although the Bailey drain is approximately 1 km from the main drain and was not designed as a parallel drain to increase the drainage density in the valley floor, the main drain may provide a hydrological barrier to the south, isolating the area between the drains from the wider regional aquifer system. The bore transect extends over 500 m south from the Bailey drain into this area towards the main drain.

Drain performance

At the Bailey site, pre-drain groundwater levels in July 2000 were 0.5 m from the surface at about 15 m either side of the drainage line. Three weeks after excavation of the drain, groundwater levels in these bores had fallen approximately 1.2 m and remained at or below 2 m below the surface over the monitoring period.

The statements that the groundwater levels have generally remained at or below 2 m from the soil surface, as opposed to 0.5-1.0 m prior to drain construction appear to be based on one week of data from two shallow bores within 15 m of the drain.

The watertable did fluctuate in response to winter rainfall. Immediately adjacent to the drain (15 m from the drain) the watertable rose 0.25 m in 2001 and 0.5 m in 2003 with greater fluctuations at 200 m from the drain (Figure 8(a) in Ali et al., 2004).

The paper claims that the areal effectiveness of the Bailey drain was more than 300 m. The transect and time-series data (Figure 7 and Figure 8(a) in Ali et al., 2004) show that the groundwater levels 200 m from the drain sloped away from the drain and to the south (i.e. the groundwater levels in bore 5 was higher than in bore 6). This confirms that the drain had no impact at distances of 200 m from the drain and hints at the potential influence of the main drain, which is parallel to the Bailey drain and approximately 1 km to the south.

Comments on data quality and analysis

This article (Ali et al., 2004) is the earliest report of those reviewed and primarily investigated the impacts on the watertable of existing drains, constructed before the installation of the monitoring network and mostly constructed without the objective of serving as a trial.

This article (Ali et al., 2004) only presents groundwater level data. Separate papers have been published by the same authors on the water quality and quantity of the drainage discharge from these drains (Ali, Hatton, Lambert, Byrne & Hodgson & George, 2004) and their impacts on soil root zone salinity (Ali, Hatton, George, Lambert, Byrne & Hodgson, 2004).

The analysis presented in the paper relied on data from monitoring bores installed after the construction of deep drains at four of the sites and bores providing very limited pre-drain data for the other two sites. The paper refers to the John Deluis site as a control site, although a 1.5 m deep drain was constructed at the site during the monitoring period (the site was originally intended to be one of the drainage monitoring sites). In the absence of pre-drain data and without an independent control site, it is difficult to clearly demonstrate the impact of deep drains on the adjacent groundwater levels.

The selection of the Latham and Bailey spur drains and the location of the bore transects for these drains did not consider the potential influence of the adjacent parallel main drain. The paper concludes that the findings are similar to those from the Beynon Road trial but does not acknowledge the parallel alignment of the Beynon drains. Both the Latham and Bailey drains are spur drains, constructed parallel to the main drain although at a separation of approximately 1 km. The potential influence of the main drain is not considered in the paper but it may have provided a hydrological barrier, separating the area between the main drain and the spur drains from the surrounding regional aquifer and enhancing the performance of the drain.

The conclusions drawn in the paper are not clearly attributable to the data presented in the published figures. Journal publications are sometimes limited in length by the publisher and the authors may have additional analysis and plots that support the conclusions but that could not be included in the paper. However, on the basis of the data presented in the paper, the impact of the deep drains at Narembeen appears to be over-stated.

Stuart-Street et al. (in prep.) showed that to accurately describe the drawdown curve from a deep drain, monitoring bores need to be closely spaced, especially near the drain. Most of the transects in this study of the drains at Narembeen (Ali et al, 2004) are too widely spaced to resolve the drawdown adjacent to the drain and are likely to have estimated the drawdown impact of the drains (Stuart-Street et al., in prep.).

Key findings

- The authors propose 5 measures of success for deep drainage: impact on groundwater levels, root zone salinity, physical and chemical properties of soil, crop yield and drainage disposal. This paper only considers the impact of drainage on groundwater.
- The paper claims that deep drains can effectively lower and control watertables at depths of 2 m below ground surface for significant distances (200 m) either side of the drain, provided that the drain was at least 2 m deep, although the deep drains monitored for this study were significantly deeper at 2.5-3.0 m deep. However, an assessment of the data presented in the paper suggests the impact of the drains at Narembeen is over-stated. At Latham drain the groundwater level rose to within 1 m of the surface. The groundwater gradient at the Bailey drain shows that the drain had no impact at a distance of 200 m from the drain. The watertable fluctuations at the drained sites did not appear significantly different at drained and undrained sites.
- Both the Latham and Bailey drains are spur drains, constructed parallel to the main drain although at a separation of approximately 1 km. The main drain may have provided a hydrological barrier, separating the area between the main drain and the spur drains from the surrounding regional aquifer and enhancing the performance of the drain.
- The baseflow in the drainage system was groundwater discharge. In the Narembeen drains this groundwater discharge was 5-10 ML/day. The high transmissivity of the soils in the Wakemen sub-catchment was associated with porous ferricrete and sand seams intercepted by the drain.

3.2 The initial hydrological effect of deep drains at Wallatin Creek 2006-2008 (George and Stainer, 2009)

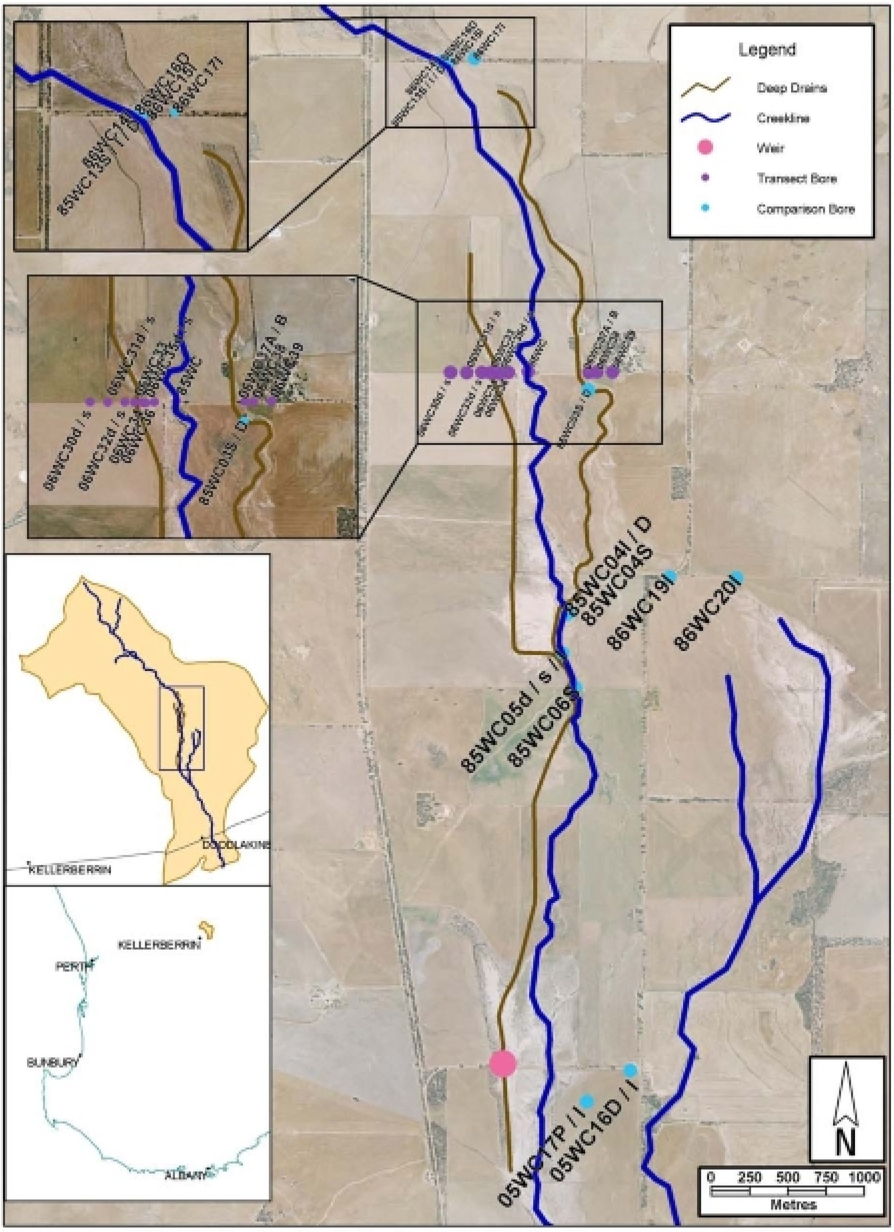

Figure 2 Wallatin Creek drainage project – location and site layout

The Wallatin Creek drainage project assessed the performance of deep drainage at a site 12 km north of Doodlakine in the Central (Wheatbelt) Agricultural Region. The Wallatin Creek drains towards the Woolundra Lakes and is a tributary of the Yilgarn River. The climate is characterised by long dry summers. The average rainfall (1900-2006) is 330 mm/year and pan evaporation exceeds 2472 m/year.

The site is located in the broad valley floor and was designed to dewater several large salt scalds. The adjacent farmland is used for dryland cropping and some sheep grazing.

The typical soil profile in the valley floor varies from sandy to saline clay.

Before the construction of the drains, groundwater levels at the site were typically within 2 m of the natural surface and the land was moderately to severely affected by salinity.

Design and construction

The project monitored nearly 9.7 km of 2.5 m deep drain constructed in June-July 2006 as part of the Wallatin-O'Brien Catchment Demonstration Initiative (CDI). The drains were located in the valley floor. The upper length of drain consists of two parts, a 3 km length along the western side of Wallatin Creek and a 4 km length along the eastern side of the creek. These drains are parallel and separated by approximately 560 m before converging to form a single drain that runs a further 3 km along the western side of the creek before discharging to the natural waterway.

The drain is enclosed by levees that prevented surface flows (other than rainfall and runoff from the drain and levees) entering the drain. The report does not provide detailed information regarding the design profile of the drain but refers to Cox (2005).

Monitoring

The groundwater monitoring program included 15 bores installed along a transect that crossed the western arm of the upper drain, Wallatin Creek and the eastern arm of the upper drain. The bores included both shallow (3 m deep) and deeper (to 6 m) bores.

In addition to the transect bores, a set of new and existing bores located in the valley floor was also monitored. Some of those bores were well away from the drain and served as comparison bores. A set of five bores constructed in 1985 and 1986 and located south of the transect bores provided a useful longer-term record (1985-1989 and then 2006-2008).

Groundwater level monitoring commenced in April 2006, two months before construction of the new drain, and continued until September 2008. Water levels were measured manually at approximately monthly intervals, except for eight of the transect bores which equipped with water level sensors and monitored at 30 minute intervals over the period June 2006-June 2007 (although some of these data were not used because of concerns regarding data quality).

A gauging station was installed at the outlet of the drain in 2007 and recorded drainage flow, conductivity and temperature over the period July 2007-February 2009.

Climate (rainfall and evaporation) data were obtained from nearby Bureau of Meteorology stations at Kellerberrni and Doodlakine. These data were supplemented with further rainfall data from local farms.

Drain performance

Over the first week after the construction of the drain, watertable levels fell by up to 0.2 m at a distance of 28 m of the drain. Beyond this initial fall, the study could identify no further drainage impact on watertable levels. Other observed changes were attributed to climate.

The older bores installed in 1985-86 provided an opportunity to compare relatively long pre- and post-drainage records. Long-term records from bores 3 m (85WC03) and 30 m (85WC05) from the drain were analysed statistically (using HARTT) by comparing the groundwater levels and rainfall (AARR) over the period 1986-2009. The analysis showed that rainfall was the dominant driver of groundwater levels and that the drain reduced groundwater levels by approximately 0.5 m at a distance of 3 m from the drain but had no measureable impact at a distance of 30 m from the drain.

A simple water balance over the drainage area found that the long-term drainage discharge approximately balanced local recharge. This suggests aquifer discharge does not play a significant role in the water balance of the Wallatin Creek drain. On this point it is important to note the layout of the drains (Figure 2); the upper drain comprises of two parallel sections, running each side of the natural waterway and approximately 560 m apart. It is possible that each drain provided a hydrological boundary for the other drain, isolating it from any wider aquifer discharge from that direction.

Drainage discharge was saline (average conductivity of 4790 mS/m) and acidic (pH ~3.5) and varied seasonally due to the respective impacts of rainfall dilution and evapo-concentration. No groundwater quality data were presented in the report.

The report cites results from crop trials at Wallatin Creek. Pre-drain crops showed a gradient in barley yield associated with a soil salinity gradient, with yield increasing as salinity decreased with distance from the drainage line. Barley yields increased over the two years after the construction of the drain in response to decreasing watertable levels, although there was no significant change in topsoil salinity over this period.

Comments on data quality and analysis

This report (George and Stainer 2009) is based on a high quality dataset and sound experimental design.

The results include monitoring data spanning the drain construction – extending over more than two years and mostly commencing four months before construction. Of particular value was the inclusion of a number of longer-term bores, installed in 1985-86, which allowed a more detailed statistical comparison of pre- and post-drainage groundwater levels and rainfall. Importantly the data also include groundwater levels from several comparison bores unaffected by the drain, allowing an assessment of the impact of climate.

The data also include drainage discharge and salinity measurements, which were used to develop a water balance presented in the report.

The data and analysis presented are consistent with the conclusions and recommendations of the report.

Key findings

- The construction of the 2.5 m deep drain at Wallatin Creek resulted in an initial minor (0.2 m) decline in watertable levels immediately adjacent to the drain. However, no further drainage impact could be identified over the monitoring period (2006-2008).
- A water balance developed for the site showed that the measured drainage discharge could be balanced by recharge over an area 100 m either side of the drain. The layout of the drains and the presence of the natural waterway (the drains are approximately parallel and 560 m apart and either side of the waterway) may provide hydrological boundaries isolating the drains from the wider aquifer.
- The ongoing decline in watertable and improvements to productivity can be mostly attributed to climate (specifically declining rainfall) and not simply to the construction of the drain.

3.3 Drainage for salinity control at Pithara (Cox, 2010)

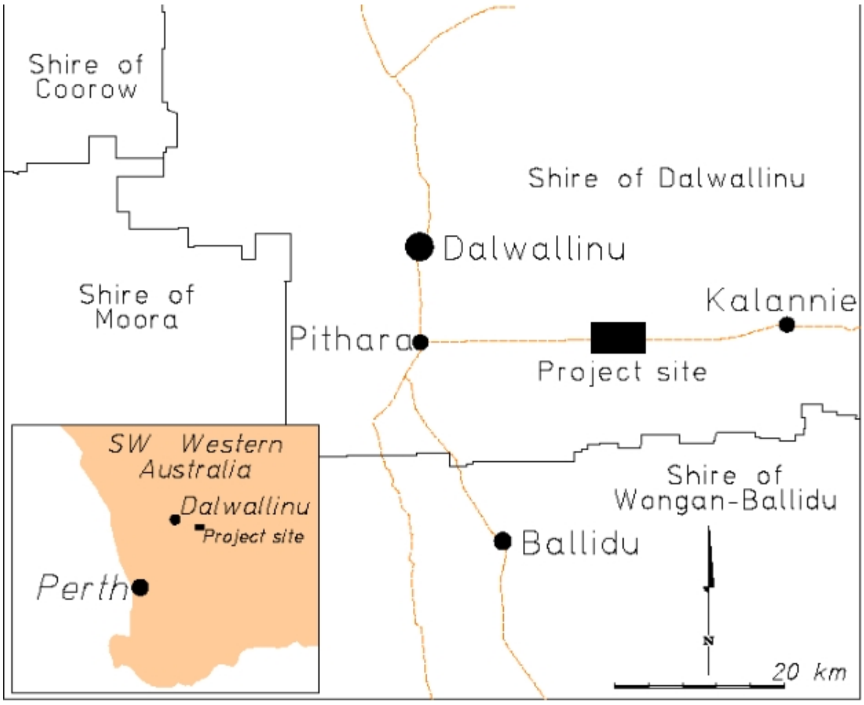

Figure 3 Pithara drainage project - location

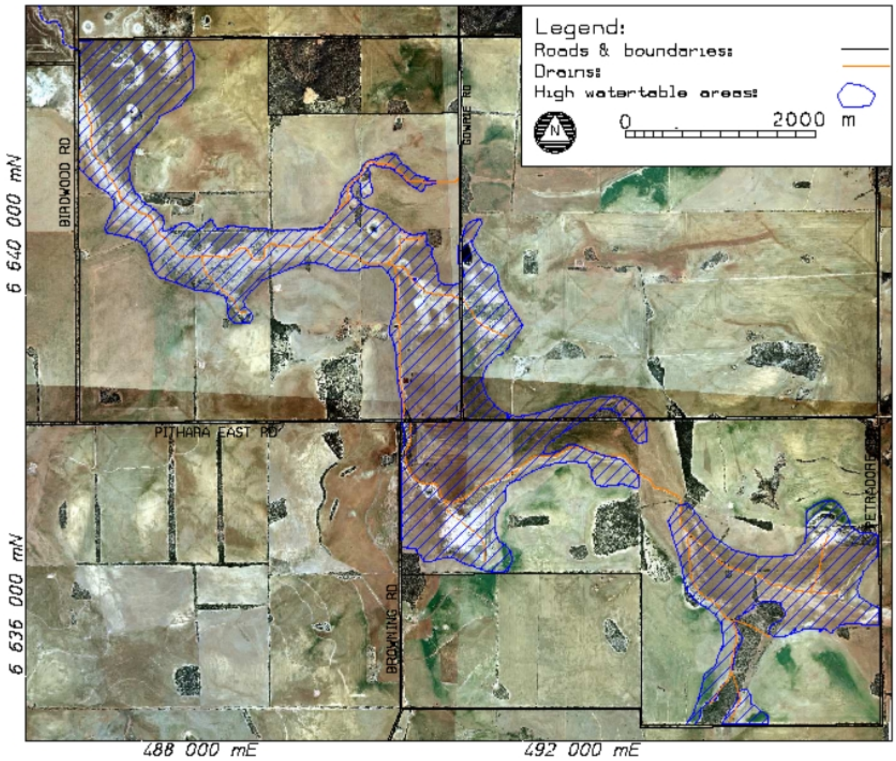

Figure 4 Pithara drainage project – site layout

The Pithara drainage project assessed the performance of deep drainage at a site 25 km east of Dalwallinu, in the upper North Mortlock catchment in the Northern Agricultural Region. The project was funded under the EEI.

The site is typical of the north-eastern wheatbelt with low relief and poorly defined natural drainage in a broad valley floors. The drain is located in the valley floor, which is almost entirely salt-affected and colonised by halophytes. The adjacent farmland is used for dryland cropping and sheep grazing.

The typical soil profile in the valley floor is comprised of loamy and silty sand overlying a mottled medium to heavy clay subsoil. Drain construction encountered intermittent layers of silcrete along a 1 km length, but otherwise the excavation of the drain was relatively easy.

The project monitored nearly 19 km of deep drain. Approximately 5 km of drain had been constructed before the project commenced and the remaining 14 km of 2.5 m deep drain was constructed in June-July 2004.

Design and construction

The purpose of the Pithara deep drain was to lower groundwater levels in the valley floor to protect against further salinisation and potentially recover adjacent agricultural land for productive use.

To support the design of the drain, 27 investigation and groundwater monitoring bores were installed along the drainage line to investigate soil profile and aquifer properties (hydraulic conductivity, water levels and water quality). The drain design applied the Hoodghoudt steady-state equation (Ritzema 1994) to estimate discharge volume and drawdown. The basis for the nominal 2.5 m depth is not clear but appears to be recommended by drainage contractors as the optimum depth and is the widely accepted minimum effective depth for deep drains in the Western Australian wheatbelt.

The drain was constructed as close as possible to the lowest alignment along the valley floor. It comprises two main reaches. The first and lower section includes approximately 3 km of new 2.5 m deep drain extending upstream from 5 km of existing shallower (1.2-2.0 m deep) drain and south to the Pithara East Road culvert. This section of drain was constructed with discontinuous levees that allow surface water to flow into the drain at some points. The second and upper section of drain extends south of the Pithara East Road culvert and comprises 9.2 km of new 2.5 m deep drain with continuous levees to exclude surface water inflow. Seven tributary drains flow into the main drain along its length.

The Pithara drain discharges into the natural creek line. The project report does not include any reference to potential downstream impacts due to discharge water quality or altered hydrologic regime, which was the subject of a separate report (Strehlow et al., 2006).

The new drain, funded under the EEI, was constructed over 45 days in June-July 2004 using a 51 t excavator. The drain was constructed with a trapezoidal cross-section with 0.5(H):1(V) batter slopes. The drain included 11 culvert access crossings and two culvert road crossings (Pithara East Road and Guthrie Road).

Monitoring

Monitoring of the Pithara drainage project commenced in May 2004, two months before construction of the new drain, and continued (although not for all parameters) until January 2007.

The groundwater monitoring program included 37 bores. Drainage induced drawdown was measured using four transects with bores at 20, 50, 100, 175, 275 and 400 m from the centreline of the drain. Nine existing bores were included in the monitoring program as comparison bores (i.e. bores considered to be unaffected by the new drain).

Groundwater levels were measured manually fortnightly to monthly over the monitoring period. Water quality samples were collected from the selected bores in September 2004, May and September 2005 and March 2006 and analysed for salinity, pH and major ions, metals and nutrients.

Drainage flows were measured at two gauging stations. The upstream station was located at the downstream end of the leveed upper section of drain, which had only limited surface inflow from direct run-off from the drain and its batters and levees. The downstream gauging station was located at the lowest point in the drainage system and measured flow from the whole drainage system, including open drains that were not protected from surface water inflows.

The drainage gauging stations continuously measured flow and salinity. Water quality samples were collected from the drainage discharge in September 2004, May and September 2005 and March 2006 and analysed for salinity, pH and major ions, metals and nutrients.

Drain performance

Construction of the Pithara drain produced some small reductions in groundwater levels adjacent to the drain. The greatest effect was confined to within 50 m of the drain, although some groundwater response to the construction of the drain was measured as far as 175 m from the drain. At a distance of 20 m from the drain, the measured water level reductions were of the order of 0.5 m. At a distance of 50 m and beyond, the effect of drain on groundwater levels is less obvious.

A water balance calculated for the site found that the drain removed groundwater approximately equivalent to the local recharge over an area 100 m either side of the drain. However, this discharge to the drain was replaced by discharge from the surrounding regional aquifer.

Less than 5% of the discharge from the upstream leveed drain originated from rainfall and runoff. In the case of the downstream drain, which was partly open to surface water inflows, 25% of the discharge was from rainfall and runoff (although half of this was from a summer rainfall event in January-February 2006).

Both the transect bores and comparison bores showed very similar water level fluctuations over the monitoring period and reflected trends in the AMRR. The drainage discharge also reflected AMRR.

The measured pH of drainage discharge was seasonably variable in the range 2.9-8.2, compared with groundwater pH ranged from 2.6 to 8.8. The groundwater pH was relatively constant over time, although variable across the site. Drain discharge in periods of surface water inflow tended towards neutral-alkaline and discharge dominated by groundwater flow was acidic. During periods dominated by groundwater inflow and low pH, the drainage discharge showed elevated concentrations of iron, aluminium, lead and nickel.

Groundwater salinities varied over the project area from 1,750 mg/L to more than 74,000 mg/L. Groundwater salinity generally increased towards the lower parts of the valley floor and the salinity of the deeper aquifer was generally greater than the salinity of the shallow groundwater. In general, water table salinities within 100 m of the drain decreased slightly over the monitoring period.

A limited salt balance for the drainage site suggested a net export of salt from the site by the drainage system. Adjacent to the drain, soil salinity in the upper 15 cm of soil reduced over the monitoring period.

A barley crop sown in 2006 produced poor emergence rates, confirming that the reductions in groundwater level and soil salinity produced by the drain were insufficient to return the land to productive agricultural use.

Reported average construction costs (2004$) for the leveed deep drain was $6,453/km. Culverts for 11 access crossings cost an additional $1,819 each (including delivery). The report does not comment on any maintenance of the drain, although reports that soil erosion caused by dispersion and slaking in the more saline environments quickly silted up some channels.

Comments on data quality and analysis

This report (Cox 2010) is based on a relatively high quality dataset and sound experimental design. The results include monitoring data spanning the drain construction – extending over more than two years and commencing two months before construction. Importantly the data include groundwater levels from several comparison bores unaffected by the drain, allowing an assessment of the impact of climate. The data also include drainage discharge and salinity measurements, which are used to develop the water and salt balances presented in the report. The data and analysis presented are consistent with the conclusions and recommendations of the report.

The report includes the results from modelling using the Hoodghoudt steady-state drainage equation (Ritzema 1994) to investigate theoretical drawdown from the drain. The application of the model relies on some coarse assumptions (e.g. homogeneous aquifer, fixed groundwater level at boundaries and steady state conditions) but demonstrates the difficulty faced by single drains in an unbounded aquifer (unbounded horizontally). The report proposes the use of parallel drains to bound the drainage area and improve the effectiveness of the drains in reducing and controlling groundwater levels. Based on the modelling results, the report suggests a drain spacing of 160 m would be needed to maintain groundwater levels at 1.5 m below the surface in an average rainfall year.

Key findings

- Single deep drains at Pithara did not control groundwater levels beyond a narrow area immediately adjacent to the drain because the aquifer discharge exceeded the capacity of the drain.
- Drainage efficiency was limited by the low permeability of the clay subsoils.
- Over the monitoring period there was insufficient effect on adjacent groundwater levels or salinity to return the adjacent land to productive agricultural use
- Watertable could be controlled by increasing the drainage density though the use of parallel drains. However, parallel drains at Pithara would need to be spaced at 160 m, which may restrict agricultural production (and not be financially viable)
- The report did not consider downstream impacts

3.4 The use of drains and basins to manage salinity at Morawa (Cox, 2011)

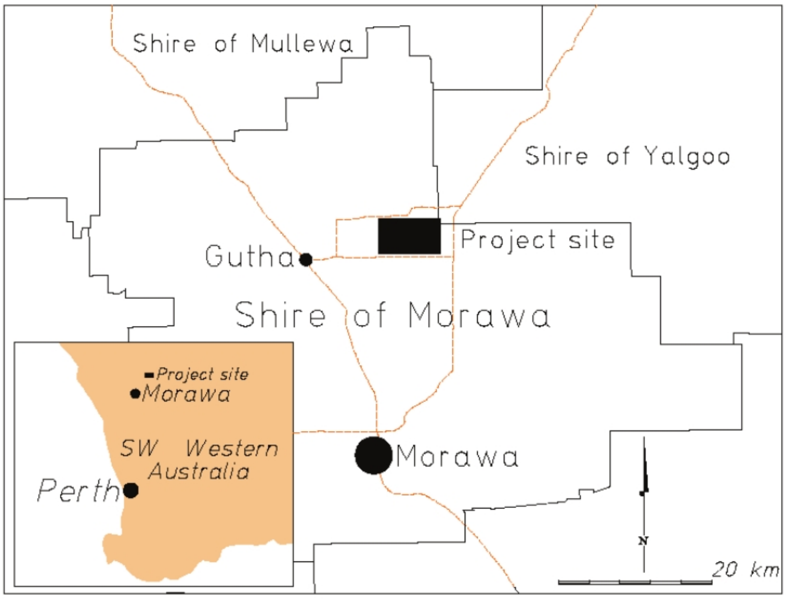

Figure 5 Morawa drainage project - location

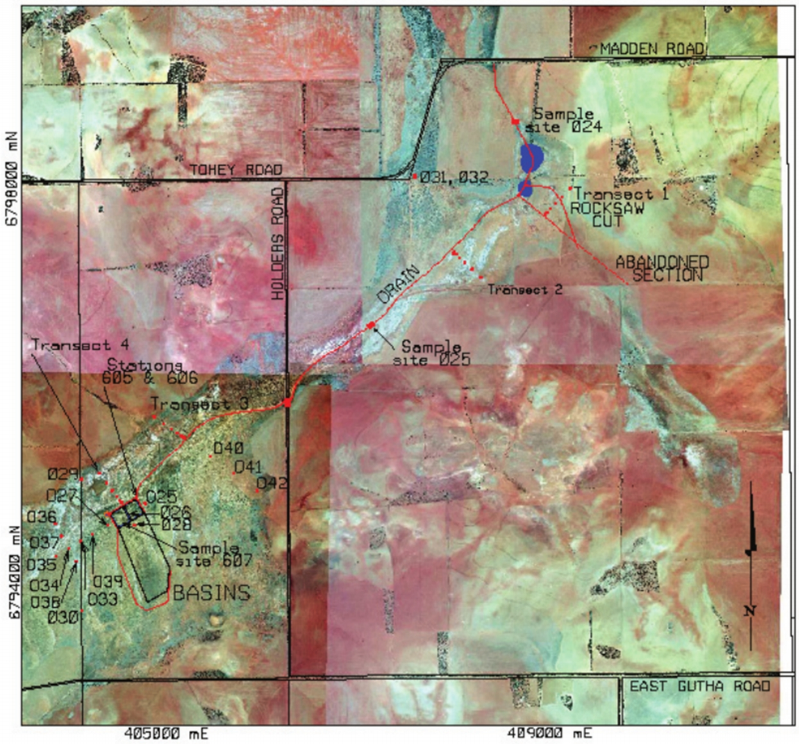

Figure 6 Morawa drainage project – site layout

The objective of the Morawa drainage project was to assess the effectiveness of deep drainage for lowering the groundwater table and the usefulness of a local-scale evaporation basin for disposal of drainage discharge. The project site was 28 km north of Morawa, in the Yarra Yarra catchment in the Northern Agricultural Region. The project was funded under the EEI.

The site is characterised by low relief and a broad valley floor. The site includes two natural playas and the natural drainage line discharges westwards to the salt lake chain of the Yarra Yarra system.

The valley floor had become increasingly salt-affected after clearing and was colonised by salt bush and blue bush. At the time of the commencement of the Morawa drainage project in 2004, the salt-affected area was being used for limited and opportunistic grazing and had not been cropped since 1996.

The typical soil profile in the valley floor is deep clayey/loam topsoil overlying cemented calcareous subsoils, often with silcrete layers.

Groundwater levels in the valley floor were within 1 m of the surface.

The project monitored nearly 8 km of deep drain and an evaporation basin, initially 5 ha but subsequently extended to 26 ha.

Drain design and construction

The primary purpose of the Morawa deep drain was to lower groundwater levels in the valley floor to recover adjacent land for productive agricultural use.

A geotechnical investigation comprising eight backhoe pits along the drain alignment was completed to inform the design. The pits provided information on soil profile, aquifer properties (hydraulic conductivities) and water table depth. The drain design applied the Hoodghoudt steady-state equation (Ritzema 1994) to estimate discharge volume and drawdown, which were calculated to be 217 ML/year and extending 365 m each side of the drain. The basis for the nominal 2.5 m depth is not clear although this depth would intersect the cemented subsoils, which were expected to provide an open fabric with higher capacity for drainage.

The drain was constructed as close as possible to the lowest alignment along the valley floor. It comprised approximately 8 km of 2.5 m deep drain with a trapezoidal cross-section with 1.1 m wide base and 0.5 (H):1(V) batter slopes. Spoil from drain excavation was used to construct continuous 1.1 m high levees, separated from the drain by a 2 m berm. The levees prevented surface flows (other than rainfall and runoff from the drain and levees) entering the drain. The drain included one culvert road crossing.

The drain was constructed over 57 days from December 2004 to February 2005 using a 52 t excavator.

Evaporation basin design and construction

A further purpose of the Morawa project was to evaluate the usefulness of evaporation basins for disposal of drainage discharge, to mitigate community concerns regarding potential downstream impacts from discharges into existing natural waterways.

Although the Hoodghoudt equation had estimated an annual discharge of 217 ML/year, experience from other wheatbelt drains was used to initially size the basin with a volume of 48 ML. The original basin had a surface area of 5.12 ha, divided into two approximately equal cells. The basin was constructed by a bulldozer pushing soil from inside each cell to form 1.5 m high walls, with 1(V):5(H) batters and 4 m wide crest. The basin was surrounded by a 2.5 m deep cut-off drain designed to control leakage, which was diverted into the main drain and pumped back into the evaporation basin.

In 2005 the original evaporation basin had filled and was extended by constructing a new 26.6 ha cell with 1 m high walls, providing a further 250 ML of storage.

Drainage water from the deep drain was pumped from a sump at the downstream end of the deep drain into the evaporation basin. Initially a pump with a maximum capacity of 20 L/s was install but this was replaced in February 2005 by a pump with a capacity of 60 L/s.

Monitoring

A comprehensive monitoring program over the period 2004 to 2007 included the following:

- Site rainfall and evaporation (November 2004 – January 2007)
- Groundwater levels and quality (salinity, pH, major ions, metals and nutrients) from 39 bores (May 2004 – March 2007), including four transects (20, 50, 100, 175, 275 and 400 m from the centre of the drain) and comparison bores
- Drainage discharge, measured by a meter at the pump (December 2004 – January 2007) and at a gauging station (V-notch) approximately midway up the drain (January 2006 – January 2007)
- Drainage discharge water quality (salinity, pH, major ions, metals and nutrients)
- Evaporation basin water level (December 2004 – January 2007) and water quality (February 2005 – December 2006)

Drain performance

Construction of the Morawa drain resulted in an immediate groundwater response up to 175 m from the drain and groundwater levels were subsequently maintained below ground surface in the adjacent valley floor. A year after construction of the drain the groundwater levels within 275 m of the drain were typically 0.2-0.45 m lower than before drain construction. However, the groundwater response was insufficient to reduce groundwater levels to more than 1.5-1.8 m below ground surface, the depth required for cropping.

The water levels in the transect bores and the comparison bores broadly reflect the AMRR trends, which include a groundwater level rise of over 0.6 m in response to a wet period in June 2005, followed by a steady 0.6 m decline in groundwater levels over the following 18 months.

The report concluded that, although the drain affected groundwater levels, it was difficult to separate drainage effects from climatic impacts on the watertable and that the effect of the drain beyond tens of metres from the drain was minor and inconclusive.

A water balance was developed based on estimates of local recharge, aquifer discharge and measured rainfall and evaporation over the drainage area and measured drainage discharges. The water balance found that groundwater inflow to the drain initially exceeded groundwater supply to the site for a short period following construction of the drain, resulting in the observed small reductions in groundwater levels. However, after six months (May 2005), groundwater discharge to the drain rarely exceeded groundwater supply to the site.

Although the drain exported 10,400 t/y of salt to the evaporation basin, the constant supply of saline groundwater from the regional aquifer means that groundwater salinities reflect the salinities of the regional aquifer and are unlikely to be affected by the drain.

The water balance suggested that the observed small reduction in groundwater level was sufficient to reduce capillary discharge over the area. This in turn could lead to reductions in topsoil salinity. Soil salinities measured as part of a separate study (Bell et al. 2009, cited in Cox 2011) show reduction in salinity of the upper 15 cm of the soil profile between January 2005 and October 2006.

The relatively dry season and the reduction in topsoil salinity enabled a crop to be planted on previously saline land in 2006. It is unknown whether cropping has continued adjacent to the drain.

Groundwater under the Morawa drainage project was neutral (pH ranged from 5.5 to 8.6) with very low concentrations of dissolved metals. Nutrient concentrations were low to moderate, with higher concentrations of nitrogen linked to cropping practices. The water quality of the drainage discharge reflected the composition of the groundwater. The neutral pH largely reduced the potential to mobilise metals, which is often a concern in wheatbelt drainage schemes.

Evaporation basin performance

The initial design for the evaporation basin required a storage volume of 48,000 kL with a surface area of 5.12 ha. The initial design was based on estimated values from other wheatbelt drains but was substantially less than annual discharge to the drain of 217,905 kL predicted by the Hoodghoudt equation. The initial basin filled within approximately six months and was subsequently extended by a further 26.6 ha.

Leakage from the evaporation basin was greater than anticipated. Water balance calculations suggest 79% of the water pumped into the evaporation was lost to leakage through the uncompacted base (the remaining 21% was lost to direct evaporation). The resulting groundwater plume extended over approximately 60 ha down-gradient of the basin. Over this area, locally elevated groundwater levels increased capillary rise and evaporation, increasing soil salinity across this area and resulting in visible salt crust at the surface. The report found that the consequences of leakage from the Morawa basin did not appear significant, presumably due to the salt-effected condition of the area before the construction of the drain and basin.

Costs

Reported key costs (2005$) for the construction and operations (excluding monitoring) of the Morawa drainage system:

- Site investigation and approvals: $5 000 (est)
- Drain excavation: $55, 500 ($6,944/km)
- Culvert supply and installation: $6, 000
- Evaporation basin earthworks: $48, 000
- Cut-off drain and sump: $7, 200
- Diesel lift pump and motor: $15, 000
- Diesel for lift pump (2 years): $12, 000 (est)
- Sundries and maintenance (est.): $6 000

Comments on data quality and analysis

This report (Cox 2011) is based on a relatively high quality dataset and sound experimental design. The results include monitoring data spanning the drain construction – extending over nearly three years and commencing six months before construction. Importantly the data include groundwater levels from several comparison bores unaffected by the drain or the evaporation basin, allowing an assessment of the impact of climate. The data also include drainage discharge and salinity measurements, which were used to develop the water and salt balances presented in the report. The data and analysis presented are consistent with the conclusions and recommendations of the report.

As with the Pithara drainage report (Cox 2010), this report includes the results from modelling using the Hoodghoudt steady-state drainage equation (Ritzema 1994) to investigate theoretical drawdown from the drain. The results were used to investigate the potential for parallel drains to control groundwater levels at the site and suggest a drain spacing between 270 m and 660 m, depending on the required reliability.

The report includes estimates of errors and accuracy in key variables. Monitoring data and calculations presented in the report are available on CD from the Department of Water. Neither the data not the calculations were reviewed in this project.

Key findings

- Single deep drains at Morawa did not reduce groundwater levels sufficiently to recover adjacent land for profitable cropping.
- The inability of the single deep drain to lower and control groundwater levels was due to the aquifer discharge exceeding the capacity of the single drain.
- Unlike other sites where drainage efficiency was limited by the low permeability of the clay subsoils, at Morawa the relatively high transmissivity of the subsoils simply enhanced the aquifer discharge.
- The paper proposes that groundwater levels could be lowered and controlled by the use of parallel drains. The transmissive aquifer at Morawa could enhance the effectiveness of parallel drains, which would need to be spaced at 270-660 m, depending on acceptable risk and required depth to water table.
- The report did not consider downstream impacts.

3.5 Hillman River South drainage project (McDougall, 2012)

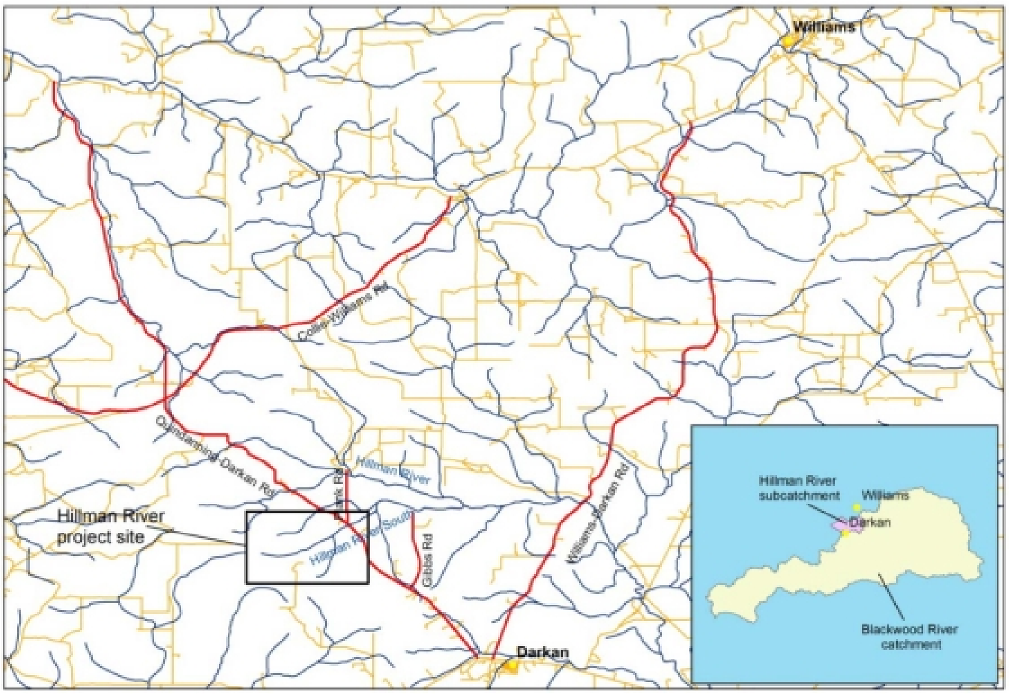

Figure 7 Hillman River South drainage project – location

The Hillman River South drainage project evaluated the performance of deep drains in an area of higher rainfall and moderate relief, compared with the low rainfall low relief areas of the wheatbelt where most deep drainage trials have been located.

The project site is along the upper reach of the Hillman River South, a tributary of the Blackwood River, and located approximately 11 km north-west of Darkan in the Southwest Agricultural Region.

The site is in a flat relatively narrow valley floor set within an undulating landscape. The Hillman River South is ephemeral, although it may run all year in years of above average rainfall.

The valley floor is characterised by duplex soils, with sands and gravels overlying medium to heavy clay subsoil. The aquifer in the valley floor can become confined below this clay layer and a very shallow seasonal perched aquifer can form immediately above the clay subsoil.

Groundwater under the site is saline, with an average salinity of 9,000 mg/L, although downstream bores located in the valley floor showed an increasing salinity trend with salinities of approximately 15,000 mg/L. Groundwater pH followed a similar pattern, with pH increasing from about 4.4-4.5 at the upstream end of the valley to 6.2-6.7 at the downstream end.

The adjacent land is used for winter cropping of oats and canola and for grazing sheep.

Design and construction

The Hillman River South project included the construction of approximately 8.7 km of deep drain with the objective of reducing the incidence of waterlogging and salinization along the valley floor.

The drain was 2 m deep (on average) with a base width of 0.9 m and 1:1 batter slopes. The drain was enclosed by 1.2 m high levees over most of its length to prevent surface flows entering the drain, other than flows from the creek that discharged to the lower section of constructed drain.

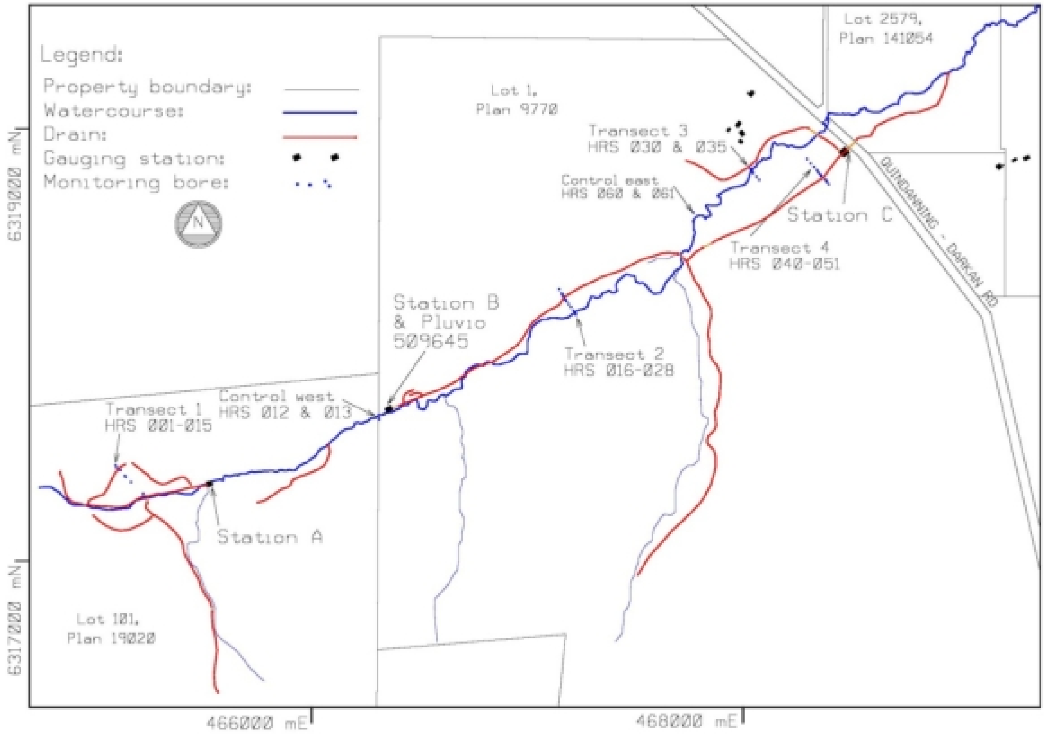

Figure 8 Hillman River South drainage project – site layout

The drain can be considered as two distinct sections:

- The upstream (western) section, consists of 2.7 km of branching channels connected to a short length of main drain that discharges a natural creek.
- The middle section comprises approximately 1 km of natural creek, together with a short section of connecting branch drain
- The main downstream section receives the discharge from the natural creek, and is comprised of 2.4 km of main drain joined by two branch drains of 1.5 km and 0.8 km (Figure 8).

The main downstream section of drain runs along the northern side of the creek for about half its length, before crossing under the creek to the southern side via a culvert. The project required ten culverts including this creek crossing, a road crossing at the Quindanning-Darkan Road and other farm access crossings.

The drainage system discharges to the Hillman River South approximately 0.6 km downstream from the downstream gauging station at the Quindanning-Darkan Road.

The drain was constructed by an excavator equipped with a trapezoidal-shaped bucket. Construction took 64 days over November 2008 to January 2009.

Monitoring

Groundwater monitoring

The groundwater monitoring program included 65 bores. Fifty-eight bores were arranged in four transects extending 80-200 m from the drain: one at the upstream section, one at a downstream branch drain and two at the downstream main drain. Only one of these transects (transect 3 at the downstream branch drain) was drilled and monitored before the drainage system was excavated. The remaining seven bores were located away from the drain and used as comparison bores.

Water levels in the bores were measured monthly over January-December 2009. Automated water level sensors were installed in nine of the shallow bores and recorded water level every two hours over February-December 2009. In-situ groundwater salinity was measured monthly over January-December 2009 and pH was measured monthly over January-May 2009.

Water levels in some bores rose above the top of the bore casing so the bores flowed freely, confirming the presence of the confined aquifer below the clay layer.

Drainage discharge

Three gauging stations (vee-notch) were constructed along the drainage system (see Figure 8):

- Station A at the downstream end of the western section of drain, measuring discharge from that section of drain into the creek
- Station B at the upstream end of the main drain, measuring flow from the creek into the downstream drain
- Station C at the downstream end of the drain, measuring drainage discharge from the system.

The gauging stations continuously recorded water levels, which were converted to flows using rating curves developed for each site. Station C also continuously measured in-situ conductivity and temperature. Stations A and B operated from January 2009 until February 2010 and Station C operated from December 2008 until February 2010.

In-situ measurements of pH and EC were made monthly at each gauging station. Water quality samples were collected from each gauging station in April 2009 and analysed for major ions, metals and nutrients.

Catchment and downstream streamflows

Streamflow and surface water quality in waterways of the Hillman River South project were monitored to investigate potential downstream impacts. Surface water flows, salinities and pH were measured from April 2007 to December 2009, which included more than a year of data before construction of the drains. Water samples were also collected in October 2008 and April 2009 and analysed for the same major ions and elements as the drain discharge samples

Drain performance

The drain had no clear effect on water logging or watertable levels in the valley floor. The construction of the drain provided a new groundwater outlet for the catchment, enhancing discharge that previously flowed into the natural creek. This allowed groundwater discharge to continue over the summer months, a time when the creek would typically cease to flow.

A water balance for the site suggested that the drainage discharge approximately balanced the annual recharge over a catchment extending approximately 500 m either side of the drain. During winter, the local recharge exceeded the drainage capacity and the report could not identify any drawdown response from the drain. The watertable remained at ground level and the heads in some deeper bores were above ground level.

The average salinity of the drainage water generally reflected the groundwater, increasing downstream from 7,164 mg/L at Gauging Station A to 8,627 mg/L at Gauging Station C. This trend was overlayed by a strong seasonal signal resulting from dilution by winter rainfall and surface run-off.

The results from the downstream streamflow and surface water monitoring showed that the construction of the drainage system increased surface water flows and salinity in Hillman River South within a kilometre of the discharge point but no changes could be detected at the next monitoring point, approximately 10 km downstream. There was no similar detectable change in downstream surface water pH. Consequently, the report found that the effects of the drainage discharge were unlikely to be detrimental.

Drainage construction and maintenance costs

Reported average construction costs (2009$) for the leveed deep drain was $13,500/km. Culverts for access crossings cost an additional $33,325. Together, excavation of the drain and installation of the culverts and crossings cost $155,673 at an average cost of $17,200/km.

The report notes rapid groundwater inflow in sandy sections of the drain caused the batters to collapse, requiring regular de-silting. It found that although the 1:1 batter slope was too steep, a flatter batter slope would be impractical and costly. The report suggests buried pipe drains could be more cost effective in unstable and saturated soils such as those at Hillman River South.

Improving drain efficiency

The paper (McDougall, 2012) examines alternative drainage options to improve efficiency.

Shallow drainage (0.5-0.75 m deep) is offered as a cheaper alternative but replacing the deep drain with a shallow drain would not have lowered groundwater.

The need to increase drainage density is highlighted. Preliminary calculations are presented indicating that parallel drains spaced at 239 m in the permeable sands would manage the average recharge. However, the relatively steep landscape and unstable side slopes present difficulties for parallel deep drains.

Buried pipe drainage is suggested as an alternative to open drains. Although more expensive to construct, buried slotted pipe would overcome the problem of unstable drain batters in the sandy soils and would retain access to and use of the land overlying the drain, especially at the higher drainage densities proposed.

Groundwater pumping or siphoning is also investigated. The relatively steep landscape and sandy soils of the Hillman River catchment appear to make the site suitable for siphons.

Comments on data quality and analysis

This report (McDougall, 2012) is based on a relatively high quality dataset and sound experimental design. The monitoring data were limited to only one year and only one transect was installed before construction of the drain. However, the installation of such a large number of bores (65 bores) across the site (including seven comparison bores), the use of automated water level sensors and three gauging stations (measuring salinity as well as flow) provided a relatively high quality dataset for the analysis.

Analysis made use of the groundwater and drainage salinities to identify separate groundwater and surface water inflows to the system. The discussion considered the effect of climate by comparing measured groundwater fluctuations with AMMR, although the length of record was limited to just over one year.

Overall, the data and analysis presented are consistent with the conclusions and recommendations of the report.

Key findings

- Deep drains at Hillman River South had no measurable effect on waterlogging or watertable levels because the recharge adjacent to the drain exceeded the capacity of drain. In winter the watertable remained at ground level and the heads in some bores were above ground level. At the end of winter, it was difficult to distinguish between drawdown from natural drainage and any impact from the drain.
- The downstream impact of the drainage discharge was unlikely to be detrimental and were not detected 10 km downstream.
- Typically used batter slopes (e.g. 0.5(H):1(V) or 1:1) may be too steep in sandy soils with high groundwater discharge but flatter batter slopes are impractical and costly.
- Increased drainage density is needed to lower the watertable at Hillman River. Parallel drains at a spacing of 239 m should manage the average recharge but the steep landscape and unstable side slopes present challenges
- Buried pipe drains could be more cost effective in unstable and saturated soils such as those at Hillman River South and would retain access and use of the land at higher drainage densities.
- The relatively steep landscape and sandy soils of the Hillman River catchment appear to make the site suitable for siphons.

3.6 Evaluation of drains in the Northern Agricultural Region (Stuart-Street et al., in prep.)

This project evaluated the performance of deep drains across five sites in the Northern Agricultural Region: Mongers 55, Three Springs, Perenjori, Canna-Gutha and Wubin. The Northern Agricultural Region extends from Gingin in the south to Kalbarri in the north and eastward to Kalannie. All five sites are within the Yarra Yarra Catchment and four of the drains are within the Yarra Yarra Catchment Regional Drainage Program (the Three Springs site is not part of the Yarra Yarra regional drainage system).

Mongers 55

The Mongers 55 drain begins in cleared agricultural land before flowing through a series wetlands and then into Mongers Lake.

Soils in the agricultural land (transect 1) were described as saline wet soil (red loamy earth), overlying light to medium clay with a neutral to alkaline trend. Towards the lower end of the drain (transect 3) the soils range from medium clay at the drain to sandy at 400 m from the drain, overlying acidic subsoils.

Three transects of bores were installed across the drain. Transect 1 is located mid-way along the section in agricultural land, transect 2 approximately 2 km upstream at the head of the drain, and transect 3 approximately 3 km downstream of transect 1, at the end of the drain where it leaves the agricultural land. Bores in each transect were nominally spaced 2 m, 5 m, 10 m, 25 m, 50 m, 100 m and 200 m from the drain, with additional bores extending to 400-500 m.

Water level data from Transect 2, at the head of the Mongers 55 drain, show the watertable is below the invert of the drain and so is not affected by the drain.

The watertable at transect 1, approximately 2 km downstream, continued to fluctuate within 1 m of the surface after the construction of the drain, reflecting changes in AMRR, suggesting the drain was not able to lower or control groundwater levels, even within close proximity of the drain.

Further downstream at transect 3, the watertable immediately adjacent to the drain fell approximately 0.5 immediately after the construction of the drain. There is some evidence that the initial watertable drawdown may have extended as far as 100 m from the drain. However, after construction of the drain the watertable at transect 3 continued to fluctuate within 1 m of the surface, reflecting changes in AMRR, suggesting the drain was not able to lower or control groundwater levels, even within close proximity of the drain.

Three Springs

The Three Springs drain intercepts a salt-affected playa to one side of a broad flat valley floor. Aerial photographs show the land surrounding the playa to be cropped.

The Three Spring drain was intended to trial 100 mm diameter slotted plastic pipe. The route for the pipe was initially excavated to a depth of 2 m in January 2007. The trench remained open for five months before the slotted pipe was installed. The pipe was installed with a gravel bed and surround and the trench backfilled with previously excavated material. In early 2010 the trench was re-excavated and left as an open trench, presumably due to the poor performance of the slotted pipe drain observed in the monitoring data.

When the monitoring bores were drilled before the installation of the drain, the soils were found to be light to medium clay with a pH of 9.0. When the drain was installed, excavation intercepted a profile of highly permeable dolomite rubble.

A single transect of bores was installed across the drain in the centre of the playa. Bores were nominally spaced 2 m, 5 m, 10 m, 20 m, 30 m, 60 m and 100 m from the drain with a further two bores approximately 10 m and 20 m on the opposite side of the drain.

The bore transect showed a clear response to the initial excavation of the trench for the drain, with groundwater levels dropping 0.5 m adjacent to the drain and 0.3 m at 100 m from the drain. When the trench was backfilled, the watertable rose to near pre-drain levels. When the drain was subsequently re-excavated, the watertable fell again by more than 0.5 m adjacent to the drain and 0.3 m at 100 m from the drain. The open drain appears to have controlled the watertable at the lower levels until the end of the monitoring period in 2015.

Perenjori

No information is provided regarding the design or construction of the Perenjori drain, which was existing at the time the monitoring bore transect was installed in 2006. The soils encountered during drilling the bores were light to moderate alkaline clay (pH 8.5).

A single transect of bores was installed about mid-way along the drain. Bores were nominally spaced 5 m, 10 m, 20 m, 30 m, 50 m and 100 m from the drain with a further bore approximately 20 m on the opposite side of the drain.

Water level data show no impact of the drain on the watertable. The authors report that the adjacent land was becoming increasingly salt-affected.

Canna-Gutha

The Canna-Gutha drain is located in the base of a broad salt-affected valley floor at the northern end of the Yarra Yarra lake system near Morawa.

Soils at the Canna-Gutha site are loamy topsoil overlying light to medium clay with a calcrete layer at a depth of 0.5-1.0 m in some locations.

The drain comprises approximately 11 km of deep drain constructed by the YYCMG in July 2007. Although not stated in this report, the YYCMG drains were generally constructed as 2.1-2.5 m deep channels with 0.5(H):1(V) batter slopes. The drain discharges to a creek which in turn flows into the Yarra Yarra lakes.

Two transects of bores were installed across the Canna-Gutha drain. Transect 1 is located mid-way along the drain and transect 2 approximately 3 km downstream, near the discharge. Bores in each transect were nominally spaced 2 m, 5 m, 10 m, 25 m, 50 m and 100 m from the drain.

After excavation of the drain, bore data show a drawdown in the watertable of up to 0.6 m immediately adjacent to the drain that can be observed only as far as 10 m from the drain. The time-series bore data show that the watertable adjacent to the drain continues to fluctuate after construction of the drain. Although there appears to be a slight reduction in post-drain groundwater levels, these coincide with a period of steadily falling AMRR.

Wubin

The Wubin drain is in the Buntine-Marchagee Natural Diversity Recovery Catchment. The site is an area of flat salt-affected sandplain and the drain discharges to a natural salt lake. The soils at the site are sand over a light clay subsoil.

A single transect of bores was installed about mid-way along the drain. Bores were nominally spaced 5 m, 10 m, 20 m, 30 m, 50 m and 100 m from the drain with a further bore approximately 20 m on the opposite side of the drain.

Water level data show no impact of the drain on the watertable. Reported observations indicate the adjacent land was becoming increasingly salt-affected.

Discussion

Spacing of monitoring bores

This report (Stuart-Street et al., in Prep) highlights the importance of spacing of monitoring bores to resolve the drawdown from deep drains. Using bore transects from the Cann-Gutha site, it is shown that using only a sub-set of widely-widely spaced bores will significantly over-estimate the extent of drawdown, extending the apparent zone of benefit from 15 m (estimated from 13 closely spaced bores) to 200 m (estimated using only three widely spaced bores).

Influence of climate on groundwater levels

The authors (Stuart-Street et al., in Prep) suggest that groundwater hydrographs can over-state the impact of deep drains if the effect of evaporation is not considered. Using groundwater hydrographs from Morawa, the ongoing watertable recession at depths greater than 2 m bgl suggest the evaporative influence extends to at least 3 m depth. When coupled with the close correlation between declining AMRR and watertable recession supports the conclusion that climate is the dominant influence on groundwater levels at the Morawa site.

Soil salinity

By lowering groundwater levels, deep drains are intended to allow leaching of salts from the upper soil reducing soil salinity. This report (Stuart-Street et al., in Prep) includes extensive soil data, including soil salinity measurements from soil samples and EM38 surveys. The EM38 results showed that any reduction in conductivity was limited to 10-20 m from the drain. The failure of the drains to reduce soil salinity is attributed to the failure to adequately lower groundwater levels.

Soil structure across all sites present further challenges for leaching of salts from the upper soil profile. Soils across almost half the sites were identified as hardsetting surface soils, which are likely to reduce infiltration and increase surface sun-off, reducing leaching of salts from the soil.

Drainage construction

The report (Stuart-Street et al., in Prep) presents observations of drain construction and condition, comparing field measurements and observations with current best practice guidelines (the guidelines referred to are equivalent to DAFWA, 2016). Most drains were found to share the following faults and problems:

- Batters were generally subject to rilling and slumping
- Windblown debris was commonly observed, particularly roly-poly (*Salsola kali*)
- Only one of the drains had constructed surface water drains outside the levees
- Measured depths were generally 1.5-2.0 m
- Levees appeared to be uncompacted and many banks were eroded and unstable
- Berm widths were providing some protection from sedimentation but were generally too narrow for machine access for maintenance

Comments on data quality and analysis

This report (Stuart-Street et al., in Prep) makes use of existing monitoring bore transects installed by the YYCMG at the Mongers 55, Canna-Gutha and Three Springs sites as well as transects installed by DAFWA at the Perenjori and Wubin sites. The monitoring records extend over a number of years and in some instances includes more than a year of pre-drain data. In most cases the bore furthest from the drain was assumed not to be influenced by the drain and was used as a comparison bore. The groundwater data are compared with climate data over the same period (AMRR).

The report also includes useful soil data, including soil characteristics, structure and salinity and EM38 transects. These data are useful in characterising the sites but do not support an assessment of the performance of the deep drains, due to the failure of the drains to lower the watertable sufficiently to generate significant change in adjacent soil salinities.

Key findings

- The Three Springs drain suggested that open excavated deep drains are more effective than buried 100 mm diameter slotted pipe drains.
- Only the drain at Three Springs (as an open excavated drain) demonstrated that it could lower and control adjacent groundwater levels. Deep drains at Mongers 55, Perenjori, Canna-Gutha and Wubin all had no significant impact on adjacent groundwater levels.
- At all sites climate was the key factor controlling groundwater levels. Groundwater levels generally reflected changes in AMRR.
- The placement and spacing of monitoring bores is critical for the accurate determination of watertable drawdown and estimations of the zone of benefit caused by deep drains. If bores are too widely spaced, the zone of benefit will be over-estimated. The report suggests that the bore spacing used by Ali et al. (2004) to evaluate drains at Narembeen may have over-estimated the drawdown attributed to the drains.
- Evaporative influence on groundwater extends to 3 m below the ground surface at some sites. When coupled with the close correlation between declining AMRR and watertable recession, this supports the conclusion that climate is the dominant influence on groundwater levels across much of the wheatbelt.

3.7 Watertable responses to parallel drains in the Western Australian Wheatbelt (Cox and Tetlow, 2015)

The aim of the parallel drains project was to assess the performance of parallel deep drains to control groundwater levels in areas where single deep drains had been shown to be ineffective. The project built on the outcomes from the Dumbleyung drainage scheme (Cox & Tetlow 2015), which had demonstrated that parallel drains could lower and control groundwater levels so that previously waterlogged and saline land could be returned to agricultural production.

The project assessed the performance of parallel drains at two sites in the northern agricultural region: one near Beacon approximately 300 km northeast of Perth and the other 28 km north of Morawa, in the Northern Agricultural Region. Both sites were the subject of previous EEI drainage projects and the Morawa site is the same as the single deep drain project included in this review (Cox, 2011).

3.7.1 Beacon parallel drains

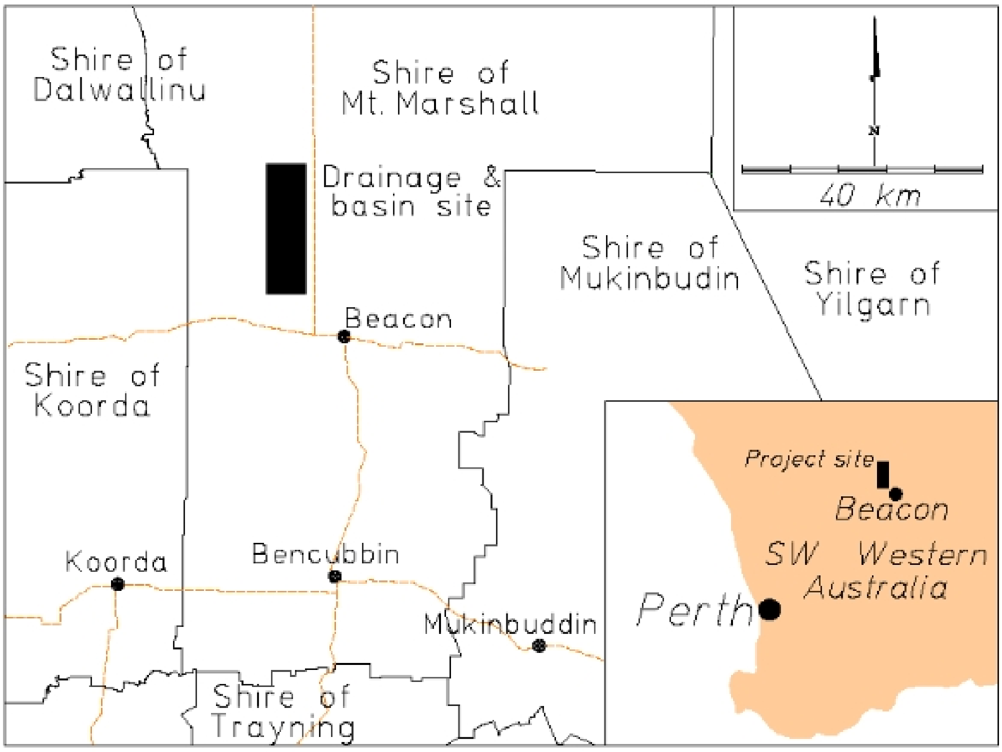

Figure 9 Beacon parallel drains - location

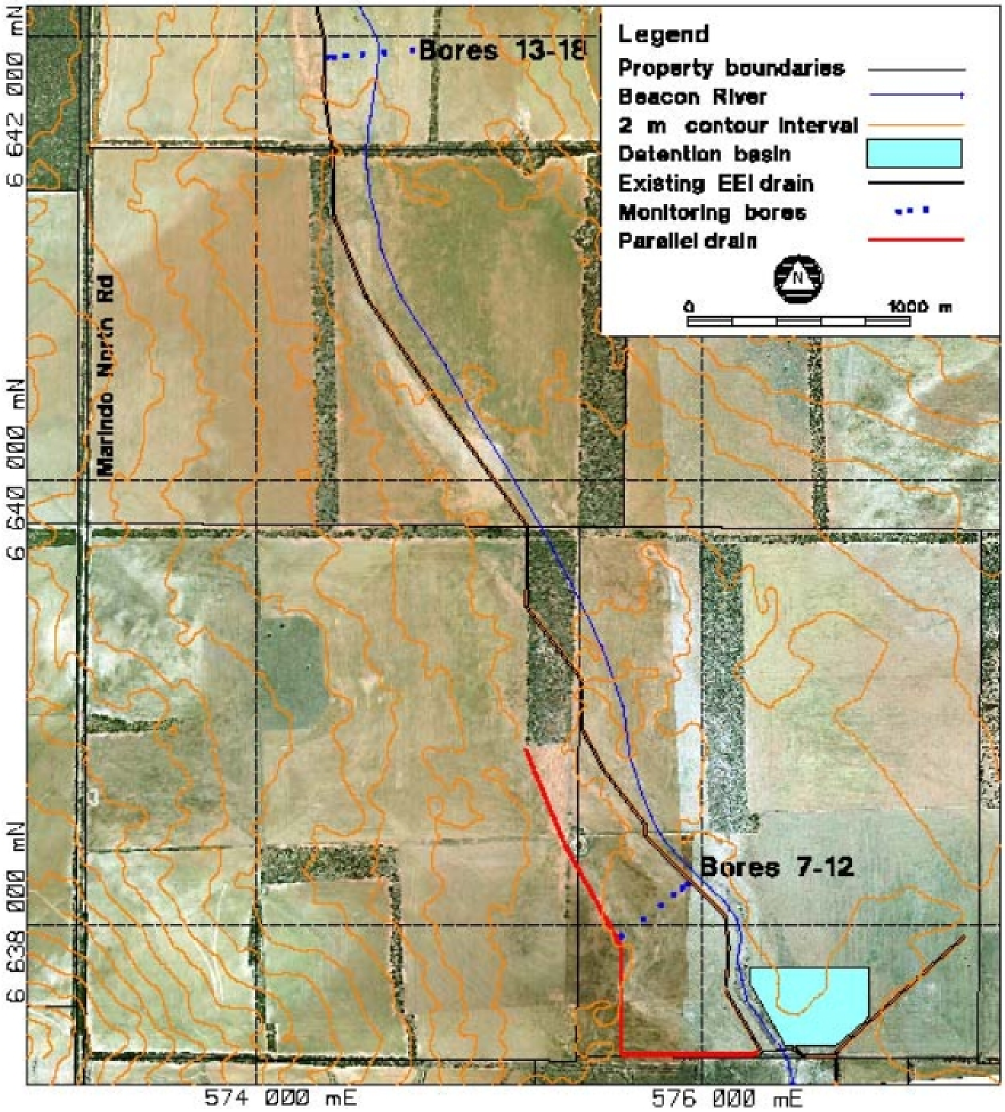

Figure 10 Beacon parallel drains – site layout

The site is adjacent to the Beacon River, which runs (ephemerally) along a broad flat valley floor and into Job's Lake.

The project site was used for dryland cropping until 2005 when it developed waterlogging and signs of salinization. Apart from crop productivity trial in 2006-2008, the site was no longer used for cropping and was subsequently colonised by halophytes.

The shallow soil profile in the Beacon River valley floor is comprised of sandy and coarse clayey sands, with relatively high (compared with other eastern wheatbelt sites) hydraulic conductivities of around 0.6 m/d. Groundwater was previously found to be within 2 m of the natural surface.

As part of an earlier project, an existing single deep drain had been previously constructed parallel to the Beacon River and discharged (pumped) into evaporation basins. The parallel drains project assessed an additional 1.5 km of drain constructed parallel with and approximately 400 m from the lowest section of the existing drain. The original single drain was constructed in 2005 and the parallel drain was excavated in June 2010.

Design and construction

The objective of the study was to assess the performance of parallel drains in reducing and controlling groundwater levels to a minimum of 1.5 m below surface, being the critical depth for barley in saline conditions. The performance of the parallel drains was compared with the performance of a length of single drain approximately 4 km upstream of the parallel drains.

The original single drain, which also subsequently formed one of the parallel drains, was 2.5 m deep with a 1.2 m wide base and 0.5(H):1(V) batters. Levee banks along the entire length of the drain prevented the entry of surface water. The new parallel drain was constructed to the same specification and discharged to the original single drain.

The discharge from both the single and parallel drains was disposed of by pumping to an evaporation basin.

The required spacing of the parallel drain was originally calculated to be 350 m, using the Hoodghoudt steady-state drainage equation. However, at the request of the landowner, the drain was constructed with a spacing of 400 m, resulting an area of 63 ha between the drains.

Monitoring

The monitoring program for the Beacon parallel drains comprised of 14 groundwater bores installed at the time of the original single drain (2004-05) and arranged in two transects, each of seven bores. One of the transects was located in the area between the parallel drains and the second adjacent to the single drain, approximately 4 km upstream from the parallel drains.

Monitoring of the parallel drains commenced in March 2010, before the parallel drain was constructed in June 2010, and continued in the parallel drain transect until August 2011. Groundwater levels in all bores were measured monthly. In addition, water levels were recorded automatically at 6 hourly intervals in the parallel drain transect bores and in one of the bores from the comparison transect.

Salinity and other water quality parameters were not monitored as part of the parallel drains study, although salinity data from the previous single drainage study were available.

Drain performance

Before the construction of the single drain in 2005, groundwater levels at the Beacon site fluctuated 0.5 m to 1.5 m below ground level. The impact of the single drain beyond the closest bore (approximately 20 m) was difficult to distinguish from ongoing climate induced fluctuations. Groundwater levels continued to rise to within 0.5 m of the natural surface after rainfall events and lower groundwater levels were attributed to periods of below average rainfall. Although the single drain appeared to lower groundwater levels, it did not control water levels below the critical depth of 1.5 m below natural surface.

After construction of the parallel drain, groundwater levels between the drains fell and remained below levels measured before the parallel drain was constructed. Over the period June 2010-August 2011 groundwater levels between the parallel drains rose by less than half the rise recorded at the comparison transect adjacent to the single drain. The watertable between the parallel drains remained relatively stable compared to the water table adjacent to the single drain.

However, after a relatively wet period in June 2011 the groundwater level between the parallel drains rose approximately 0.6 m to above the critical depth (1.5 m below ground level). The report suggests that this may have been partly affected by intermittent pumping from the drain.

Calculations based on the measured drainage rate (22 mm/year) between the Beacon parallel drains found that the design drainage rate (31 mm/year) would have required a drain spacing of 283 m, compared with the originally calculated 350 m spacing and the constructed 400 m spacing.

No attempt was made to plant a crop adjacent to the parallel drains at Beacon.

3.7.2 Morawa parallel drains

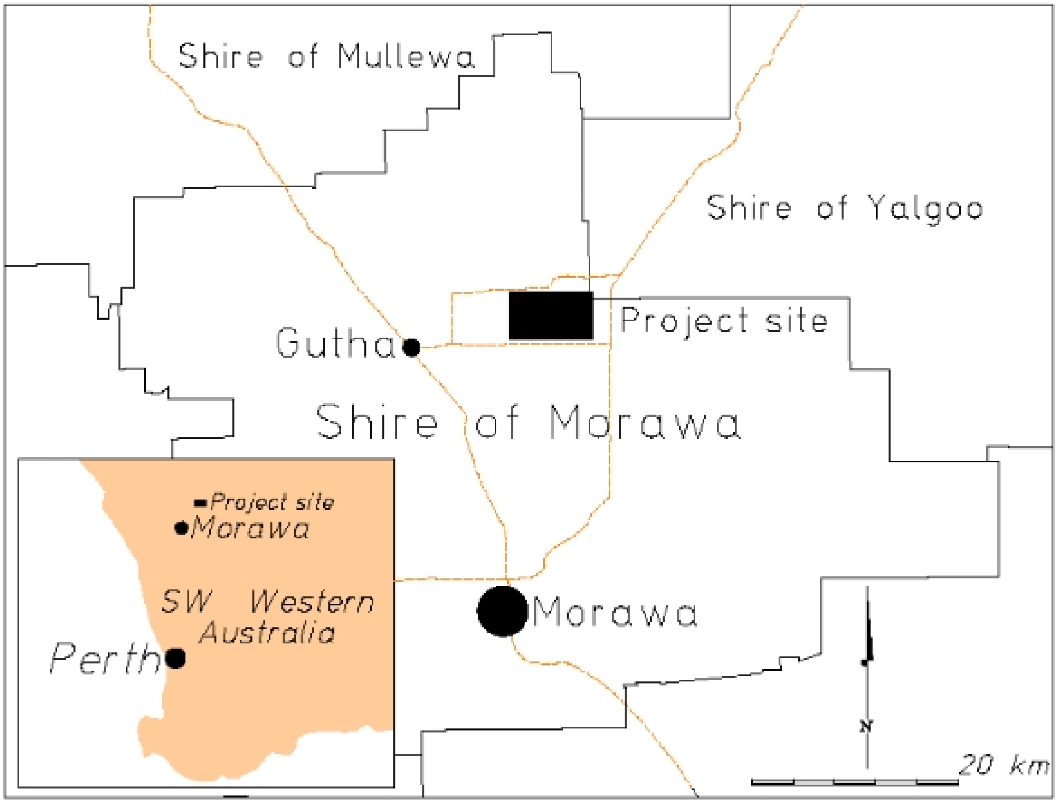

Figure 11 Morawa parallel drains - location

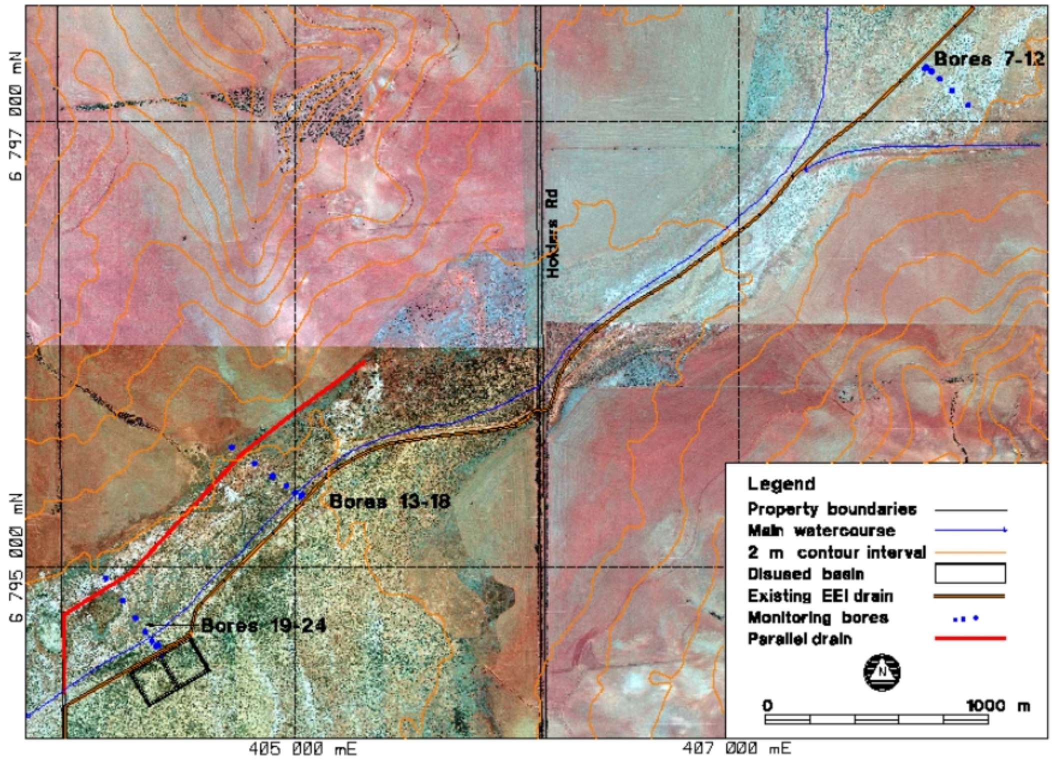

Figure 12 Morawa parallel drains – site layout

The site of the Morawa parallel drain is the lower part of the earlier EEI funded Morawa drainage project, which included 8 km of single drain and an evaporation basin (Cox, 2011 - see section 3.4 above). The site is 28 km north of Morawa, in Yarra Yarra catchment in the Northern

Agricultural Region. It is characterised by low relief and a broad valley floor containing a natural drainage line which discharges westwards to the salt lake chain of the Yarra Yarra system.

The valley floor has become increasingly salt-affected after clearing and is colonised by salt bush and blue bush. The area around the parallel drain was cropped until the late 1960s although cropping continued upstream until 1996.

The typical soil profile in the valley floor is deep clayey/loam topsoil overlying cemented calcareous subsoils, often with silcrete layers. Groundwater levels in the valley floor before the construction of drains were within 1 m of the surface.

Under the previous EEI funded project, 8 km of single deep drain was constructed in 2004-2005, running along the natural drainage line and discharging (pumped) into constructed evaporation basins. In May 2010 the downstream end of the single deep drain was extended to allow it to discharge to the waterway further downstream. The parallel drains project assessed an additional 1.7 km of drain constructed parallel with and approximately 400 m from the lowest section of the previous single drain. The parallel drain was excavated in May 2010.

Design and construction

The objective of the study was to assess the performance of parallel drains in reducing and controlling groundwater levels to a minimum of 1.5 m below surface, being the critical depth for barley in saline conditions. The performance of the parallel drains was compared with the performance of a length of single drain approximately 4 km upstream of the parallel drains.

The original single drain, which also subsequently formed one of the parallel drains, was 2.5 m deep with a 1.2 m wide base and 0.5(H):1(V) batters. Levee banks along the entire length of the drain prevented the entry of surface water. The new parallel drain was constructed to the same specification and discharged to the original single drain.

At the time of the construction of the parallel drain at Morawa the original single drain had been connected downstream drainage system so that drainage water was no longer pumped to the evaporation basins.

The required spacing of the parallel drain was originally calculated to be 360 m, using the Hoodghoudt steady-state drainage equation, resulting an area of approximately 64 ha between the drains.

Monitoring

The monitoring program for the Morawa parallel drains comprised of 21 groundwater bores installed at the time of the original single drain (2004-05) and arranged in three transects, each of seven bores. Two of the transects were located in the area between the parallel drains and the third adjacent to the single drain, approximately 4 km upstream from the parallel drains.

Monitoring of the parallel drains commenced in April 2010, before the parallel drain was constructed in May 2010, and continued in the two parallel drain transects until August 2011. Groundwater levels in all bores were measured monthly. In addition, water levels were recorded automatically at 6 hourly intervals in the two parallel drain transects.

Salinity and other water quality parameters were not monitored as part of the parallel drains study, although salinity data from the previous single drainage study were available.

Drain performance

Before the construction of the original single drain, groundwater levels at the Morawa site were about 0.8 m below ground level. After construction of the single drain in January 2005, the groundwater level reduction adjacent to the drain was typically in the range 0.2-0.45 m.

However, over the six years before the parallel drains project, the single drain did not control the watertable at lower than pre-drain levels.

At the lower end of the single drain, at the site of the parallel drain, leakage from the drain to the groundwater contributed to the failure of the single drain to lower and control groundwater levels. The extension of the single drain to allow it to discharge to a downstream waterway produced an immediate effect on groundwater levels adjacent to the drain

After construction of the parallel drain in May 2010, groundwater levels between the parallel drains fell 0.6 - 1.0 m. The groundwater levels between the drains were maintained at the lower levels with minor fluctuations of 0.2 m until the end of the monitoring period in June 2011, a period of increasing AMRR.

Before drainage, the Morawa parallel drain site had not been expected to support a barley crop because of the high watertable and high soil salinities (Bell et al. 2009). The year after the construction of the parallel drain at Morawa, a barley crop was planted in the area. Noting that it was unlikely that soil salinity had significantly reduced, the report concludes that lowering groundwater levels at Morawa produced an immediate cropping benefit.

Comments on data quality and analysis

This report (Cox and Tetlow 2015) is based on a relatively high quality dataset and sound experimental design and builds on previously collected data and experience from the Morawa (Cox, 2011) and Beacon (Cox et al., in press). The results include nearly seven years of data from this and previous studies at the sites (2004-2011), although there are gaps in the data between the intensive monitoring of the initial (2004-2009) and subsequent (2010-11) projects. The parallel drain monitoring data spans the drain construction, commencing two months before construction and extending over nearly two years.

Monitoring bores from the original single drain studies and 400 m from the drain were considered unaffected by the drain, allowing an assessment of the impact of climate. However, the analysis focussed on a comparison between data from the single and parallel drains and did not use the comparison bores to explicitly consider the impact of climate on watertable response, although climate impacts were broadly discussed throughout the report.

The data and analysis presented are consistent with the conclusions and recommendations of the report.

Key findings

- Parallel drains at Morawa and Beacon were found to be more effective than single drains at lowering and controlling groundwater levels between the drains. This is because parallel drains can reduce aquifer discharge (from the surrounding regional aquifer) to the drainage area.
- The drain spacing at Beacon (400 m) was too wide to maintain groundwater levels below the critical depth (<1.5 m below ground level) although they resulted in a lower and more stable watertable.
- The more closely spaced drains at Morawa (360 m) lowered and controlled groundwater levels at below the critical depth.
- The lowering of groundwater levels at Morawa allowed cropping on previously salt-affected land between the parallel drains.

3.8 Drainage in the Dumbleyung catchment of Western Australia (Cox and Tetlow, *in prep.*)

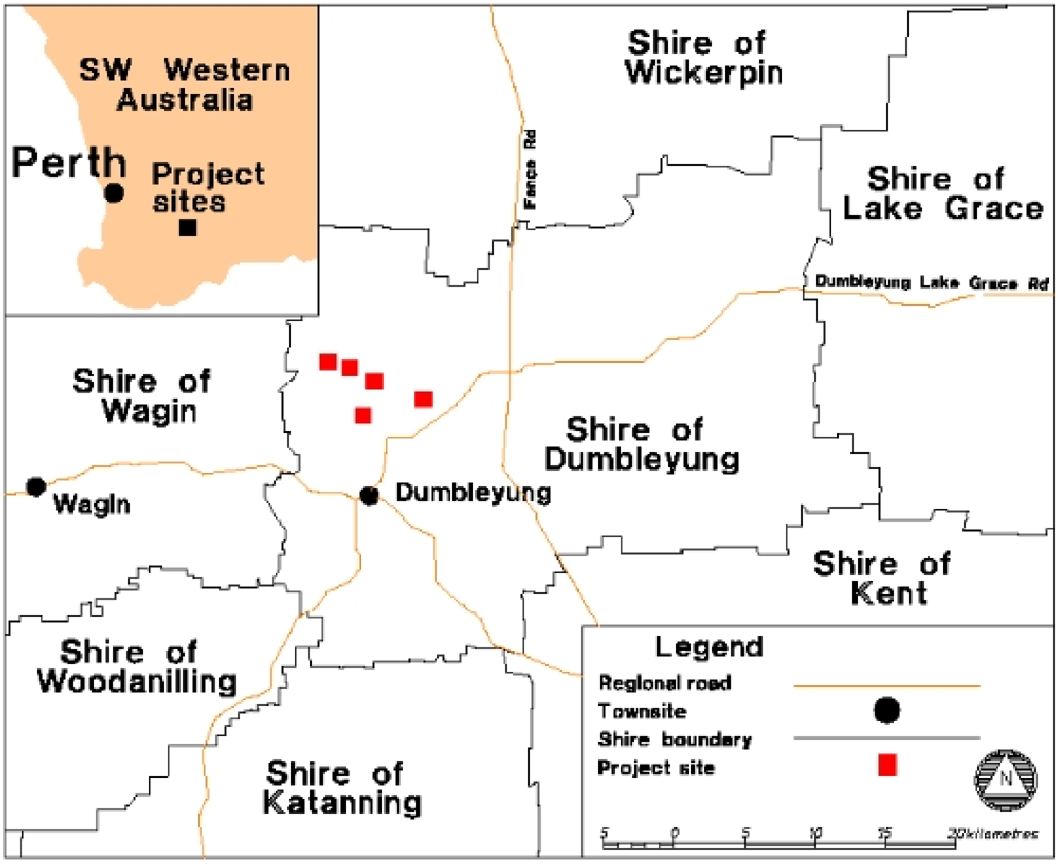

Figure 13 Dumbleyung drainage projects - locations

This report presents the results from five sites in the Shire of Dumbleyung, approximately 250 km south-east of Perth in the Southern Agricultural Region. Two sites, Temby and White Well assessed the performance of existing single deep drains. The Beynon site consisted of both parallel and single deep drains, designed and constructed for this project. The Doradine and Mt Pleasant sites were undrained comparison sites.

The project sites are all located in the Doradine sub-catchment of Dongolocking Creek, which flows into Lake Dumbleyung. The Dumbleyung sites are in low relief valleys floors with more clearly defined drainage lines, compared with the broad flat valleys of the northern and eastern agricultural regions. The land in the project area is used primarily for dryland cereal cropping, with some sheep grazing.

The sites have similar alkaline, shallow sandy duplex soils and shallow depth to groundwater. All of the sites were salt-affected and groundwater salinities typically ranged from 12,000 to 45,000 mg/L.

This report brings together the results of two separate studies and is presented in two parts: Part A presents the results of original Dumbleyung Water Management Sterring Committee (DWMSC) project comprising all five sites and Part B presents the results of monitoring of the Department of Water Engineering Evaluation Initiative (EEI) Beynon project.

3.8.1 Comparison sites – Doradine and Mt Pleasant

The Doradine site was one of two comparison sites for the Dumbleyung project. The site is located in a valley floor that includes the Doradine Creek and a secondary drainage line. The soils consisted of mostly clayey sand with some sandy clay.

The Mt Pleasant site was second of the two comparison sites for the project. The site is located in a valley floor drainage line that flows ephemerally to the Doradine Creek. The valley floor is severely salt-affected and groundwater is within 0.5 m of the surface. The soils at the site consist of 5 m of sand, silty loam and clay overlying weathered granite.

Monitoring

In May 2001 eight bores were drilled at the two comparison sites. Four bores were drilled at the Doradine Creek in a 60 m transect parallel to and approximately 120 m from Doradine Creek. Four bores were drilled at the Mt Pleasant site in a 45 m transect, extending from near the centre of the valley floor. Each transect comprised 3 shallow bores (3 m) and a deeper bore (6-10 m), nested close to one of the shallow bores.

Monitoring of the Doradine and Mt Pleasant comparison bores extended over the period May 2001 until January 2004. Monitoring comprised in situ measurements of groundwater level, conductivity and pH collected initially at three monthly intervals from May 2001 until August 2002, then weekly during the construction of the Beynon Rdrain (November 2002-January 2003) and then monthly until December 2005 (in situ salinity and pH were measured at irregular intervals between January 2004 and December 2005).

Monitoring results

Fluctuations in groundwater level at both the comparison sites generally reflected changes in AMRR. Groundwater levels at Doradine fluctuated 0.5-0.7 m over the monitoring period, with generally declining levels from November 2002 to June 2003 and then rising levels over the remaining period in response to rainfall recharge and increasing AMRR.

Groundwater levels in the Doradine bores were considered to be more useful as a comparison because groundwater at the Mt Pleasant site sometimes rose to the surface, limiting measurements of any further rise in groundwater level.

The deeper bores generally recorded higher groundwater levels than the shallower bores, except after periods of rain, suggesting a general upward head except during periods of rainfall recharge.

Groundwater at both the Doradine and Mt Pleasant comparison sites was saline (15,000-35,000 mg/L) and slightly acidic to neutral (pH 5.5-7.4).

3.8.2 White Well

The White Well site is located along a natural drainage line that drains to Doradine Creek.

Soils at the site consist of up to 7 m of loamy and clayey sands overlying sandy clay. Salinity was evident on the eastern side of the valley below the break of slope.

Design and construction

In 1997, 4.8 km of deep drain was constructed along one side of the valley floor, discharging into Doradine Creek, 2.3 km downstream from the monitoring site. The drain is approximately 2 m deep, with 0.5(H):1(V) batters and a 1.2 m wide channel floor. The drain is completely enclosed by levees to prevent surface water flows entering the drain. A shallow (0.3 m) surface water drain outside the levee bank conveys surface flows intercepted from the adjacent footslopes. Some surface water can enter the drain through a small number (5) of 100 mm diameter pipes installed through the base of the levee to alleviate ponding in some areas outside the levees.

By 2001, at the time of the DWMSC project, up to 0.5 m of sediment had accumulated in the base of the drain, although the drain batters appeared relatively stable.

Monitoring

In May 2001 six bores were drilled in a transect that extended approximately 50 m either side of the drain. Monitoring of these bores comprised in situ measurements of groundwater level, conductivity and pH collected at three monthly intervals from May 2001 until July 2003. No pre-drain monitoring data are presented in the report.

Drain performance

At White Well the average groundwater level was approximately 1.0-1.4 m below ground level at 20-60 m from the drain. Water levels in all bores fluctuated about 0.5 m, generally following rainfall patterns. Bores closer to the drain had lower groundwater levels and the data suggest drawdown extends at least 50 m either side of the drain. Although the report claims the effect of the drain was inconclusive, it notes the Mt Pleasant comparison site had similar landscape characteristics but the groundwater levels were much closer to the surface.

3.8.3 Temby

The Temby site is located along a natural depression that runs parallel to Doradine Creek.

Soils at the site consist of up to 7 m of loamy and clayey sands overlying sandy clay. Salinity was evident on the eastern side of the valley below the break of slope.

The valley floor either side of the Temby site is cropped for wheat and canola, although areas of shallow groundwater (approximately 1 m below ground level) and salinity affected about 2 ha of crop near the drain.

Design and construction

In 1997, approximately 1.5 km of deep drain was excavated alongside the drainage depression, discharging into a surface drain, which in turn flows into Doradine Creek. The drain is approximately 2 m deep, with 0.5(H):1(V) batters and a 1.2 m wide channel floor.

By 2001, at the time of the DWMSC project, the drain batters were eroded and up to 0.5 m of sediment had accumulated in the base of the drain.

The drain is mostly enclosed by levees to prevent surface water flows entering the drain. A breach in the levee allows surface water from a 76 ha catchment to enter the drain near its upstream end. Some surface water can also enter the drain through a small number of 100 mm diameter pipes installed through the base of the levee to alleviate ponding in some areas outside the levees.

Monitoring

In May 2001 10 bores were drilled in a transect that extended approximately 70 m either side of the drain. The bores included six shallow bores and four intermediate bores, drilled to 6-11 m. Monitoring of these bores comprised in situ measurements of groundwater level, conductivity and pH collected at three monthly intervals from May 2001 until July 2003.

A gauging station (v-notch weir) was installed 50 m upstream from the bore transect. The gauging station recorded water level, conductivity and temperature at 30-minute intervals from August 2001 until December 2002. Drainage discharges were calculated using the recorded water levels and a calibrated rating curve for the weir. Drain discharge pH was measured in situ at monthly intervals from May 2001 to July 2002. No pre-drain monitoring data are presented in the report.

Drain performance

At Temby the water levels in all bores fluctuated by about 0.4-0.5 m, generally following rainfall patterns, although with a time lag. Bores closer to the drain generally had lower groundwater levels than bores further from the drain, although some short-term groundwater mounding appeared to reversed hydraulic gradient for short periods following heavy rainfall.

The effect of the drain is observed in bores at least 70 m either side of the drain although in the absence of any pre-drain data it is difficult to quantify the effect.

The annual average drainage discharge measured at the gauging station was 5900 kL/year. Groundwater inflow contributed approximately 35% of the total discharge. In summer the baseflow reduced to between 0-5 kL/day and stopped for periods (five days in 2001 and a month in 2002).

Salinity of the drainage discharge varied from 10,000 mg/L to 70,000 mg/L, largely due to the effects of dilution by rainfall and evapo-concentration.

Drain flow was alkaline to highly alkaline (pH 8.5-9.3). This pH was higher than the surrounding groundwater and possibly the result of interactions with calcium carbonate sediments in the drain.

3.8.4 Beynon

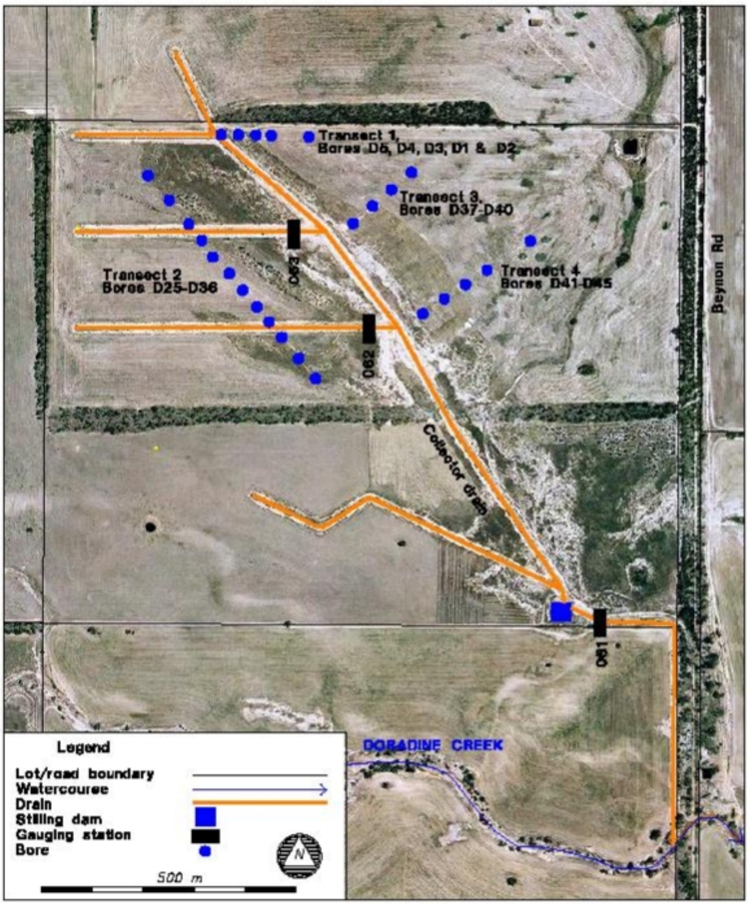

Figure 14 Beynon Road drainage project – site layout

The Beynon site is located in a valley floor north of and discharging into the Doradine Creek. The lower parts of the valley floor are salt-affected, including a 50 ha salt scald.

Soils at the site comprise of sandy loam and silty clay over medium to heavy clay.

Groundwater levels are within 0.5 m of the natural surface under the salt scald and generally .

The area surrounding the drainage site had been historically cropped, although the western side of the valley floor had not been cropped during the six years before the Beynon drainage project, due to salinity.

Design and construction

The Beynon site was the only site in the Dumbleyung project that included the design and construction of new drains. Nearly 4 km of drainage was constructed in November-December 2002, comprising four parallel drains (two 3 m deep drains and two 2 m deep drains) and a collector drain that discharged into Doradine Creek.

The collector drain is located in the salt-affected valley floor and the parallel lateral drains extend westward through more recently salt-affected land. The collector drain is 2 m deep along the lower length, increasing to 2.5 m deep at transect 4 (junction with the central 2 m deep parallel drain) and 3 m deep at transect 3 (junction with the central 3 m deep parallel drain). The collector drain was considered to represent the performance of single deep drains, with 2.5 m deep and 3 m deep sections.

The Hoodghoudt steady state equation was used to calculate design drainage spacing required to achieve a maximum groundwater level of 0.6 m below ground level based on average winter rainfall. The theoretical spacing was calculated to be 172 m for 2 m deep drains and 206 m for 3 m deep drains. The two northern 3 m deep parallel drains were constructed 190 m apart. The adjacent 2 m deep parallel drain was constructed 172 m and to the south and the final 2 m deep parallel deep drain about 320 m further south (Figure 14).

All the drains were excavated with 0.5(H):1(V) batters and a 0.9 m wide channel floor. The drains were enclosed by levees to prevent surface water flows entering the drain. The levees were each separated from the drain channel by a 4 m wide berm. Some surface water can enter the drain through a small number of 100 mm diameter pipes installed through the base of the levee to alleviate ponding at drain intersections.

Monitoring

In May-June 2001 27 monitoring bores were installed in four transects. Three transects (transects 1, 3 and 4) extended perpendicular to the collector drain and one transect (transect 2) running parallel with the collector drain and intersecting the central parallel drains (the southernmost 3 m deep drain and the adjacent 2 m deep drain). The bore transects included shallow bores (typically to 4-6 m) and deeper bores (to 14 m).

Groundwater monitoring comprised in situ measurements of groundwater level, conductivity and pH collected initially at three monthly intervals from May 2001 until August 2002 (before drain construction), then weekly during the construction of the drain (November 2002-January 2003) and then monthly until December 2005 (in situ salinity and pH were measured at irregular intervals between January 2004 and December 2005).

Three gauging stations (flumes) were installed in different sections of the drainage system: in each of the central parallel drains (the southernmost 3 m deep drain and the adjacent 2 m deep drain) and in the collector drain downstream of the parallel drains.

The gauging stations recorded water level, conductivity and temperature at 5-minute intervals over the period December 2002-March 2005, except the downstream collector drain station, which remained in operation until March 2007. In January 2004 the gauging stations were modified by fixing stainless steel inserts to improve accuracy. Drainage discharges were calculated using the recorded water levels and an uncalibrated theoretical rating curve for the weir.

Conductivity, temperature and pH were measured at each of the gauging stations at 5-minute intervals over the period December 2002-March 2005. Drainage discharge pH was measured at each of the gauging stations at 5-minute intervals over the period December 2002-December 2003 and then at irregular intervals between January 2004 and December 2005.

Results and analysis

Before the Beynon drains were constructed, groundwater levels at the site were approximately horizontal across the valley floor 0.8-2.0 m below the ground level, fluctuating up to 0.5 m in response to seasonal recharge and barometric pressure.

During construction of the drains, groundwater levels were observed to immediately fall adjacent to the newly excavated drain. Initial rates of decline in groundwater level of 0.3 m/day were recorded within 20 m of the drain. After one week the rate of decline reduced but continued at a slower rate for about ten weeks. In the two months immediately after the construction of the drain, all the Beynon monitoring bores (except one bore at 300 m from the drain) recorded a greater decline than the Doradine comparison bores, which fell by an average of 0.8 m over the period.

The post-drainage watertable remained at its new lower level throughout the monitoring period, although the groundwater levels continued to show fluctuations reflecting changes in AMRR. This period coincided with an increasing AMRR (from 0 mm in January 2003 to 120 mm in December 2005), which resulted in a 0.1-0.4 m rise in groundwater levels in the comparison bores.

The number and location of monitoring bores across the Beynon site allowed the estimation of groundwater contours. The pre-drainage contours converge along the natural drainage line in the valley floor. The post-drainage contours are reorientated to align with the new drainage system with steep hydraulic gradients towards the drains.

Drain performance

Single drains versus parallel drains

The Beynon drainage project demonstrated that parallel drains could lower and control groundwater levels more effectively than single drains. At the Dumbleyung sites, an acceptable reduction in groundwater levels was only achieved within 50 m of the single drains, whereas the parallel drains demonstrated that groundwater levels could be effectively controlled over the 220 m distance between the drains. Subsequent analysis suggested that parallel drains at Beynon could have been effective at a spacing of 360 m.

The conceptual model and supporting analysis (water balance and modelling) suggests the local drawdown caused by single drains in transmissive aquifers generates additional horizontal groundwater flow from the adjacent aquifer. This aquifer discharge can explain the relatively high discharge volumes observed in some single drains, which were previously unexplained by local recharge and drawdown. Consequently, single drains can only effectively control adjacent groundwater levels if the drainage capacity is greater than the discharge from the adjacent aquifer.

The parallel drains were able to maintain groundwater levels below critical depth because there is no aquifer discharge – adjacent drains provide boundary to the drainage catchment.

The report suggests previous deep drainage designs in the wheatbelt have misinterpreted drainage theory and the accompanying tools, which were generally developed for parallel drains and assume a no-flow boundary at some distance. When the theory is applied to Beynon parallel drains it was found to be consistent with the monitoring results, but when it was applied to single drains it underestimates the drainage discharges and overestimates the groundwater drawdown.

An approach for adapting (parallel) drainage theory is presented that includes an additional groundwater source at a boundary. The method was able to reproduce the key features observed in the performance of the single drains at Dumbleyung.

The report introduces the term: zone of benefit (ZOB), defined as the area under which groundwater levels are controlled to a particular depth below the ground surface. For barley, this is the area under which groundwater is maintained below 1.5 m of the ground surface with 90% reliability.

It is recommended that the ZOB be used to measure the effectiveness of deep drains in preference to the drawdown distance, since ZOB enables a direct comparison of performance of a drain against the required final outcome, based on critical depth needed for salinity recovery. A comparison of the performance of single and parallel drains found that the ZOB between parallel drains will always be more than twice the ZOB from a single drain.

2 m deep drains versus 3 m deep drains

In general, groundwater levels adjacent to the 3 m drain fell more than groundwater levels adjacent to the 2.5 m deep drain.

The report concludes that it is unlikely that 2 m deep drains can be used to adequately control groundwater levels.

Adjacent impacts

Modelling undertaken in this study showed that drain construction at Beynon lowered groundwater levels sufficiently to reduce capillary discharge, which is the source of salinity in the upper soil pofile. Modelling showed that slowing capillary discharge may allow leaching of deposited salt by rainfall recharge.

Data quoted from another study (Bell et al. 2007) show the 2004-07 annual average topsoil salinity reduced by up to 60% at 20-50 m from the drain with smaller reductions at distances of 80-100 m from the drain.

The control in groundwater levels and improvement in topsoil salinity allowed barley crops to be harvested at the site in 2006 (0.24-0.3 t/ha) and 2007 (2.1 t/ha).

The study also reports qualitative improvements in the land adjacent to the Beynon drains such as the colonisation of previously bare salt-affected land by halophytes and annual pasture plants following drainage.

Drainage discharge

Salinity of the drainage discharge varied from 5,000 mg/L to 95,000 mg/L, largely due to the effects of dilution by rainfall or evapo-concentration.

Drain flows were acidic to strongly acidic (pH 3.2-3.6). This pH was lower than the surrounding groundwater and possibly the result of hydrolysis of dissolved iron in the groundwater when it is exposed to oxygen in the drain.

Benefit-cost analysis

Key costs (2005$) of from the construction of the Beynon drainage included:

- Excavation of 23,435 m^3 of drainage channel - $30,296
- Culvert and pipe installations - $13,704

After making assumptions regarding the relative costs for different depths and spreading the sundry costs, the average construction cost of drainage of 1 m, 2 m and 3 m deep drains was estimated (Table 5).

Table 5 Construction costs of the Beynon drains

Drain depth (m)	Cross-sectional area (m^2)	Excavation cost ($/$m^3$)	Excavation cost ($/m)	Total cost ($/m)
1	1.4	1.30	1.80	5.30
2	3.8	1.60	6.10	9.60
3	7.3	2.00	14.60	18.10

A 30-year benefit cost analysis (BCA) of the Beynon drains concluded that only the 3 m deep parallel drains produced a consistently high enough benefit/cost ratio to be considered financially viable. The 3 m deep parallel drains at Dumbleyung had benefit/cost ratio of 1.8, compared with 2 m deep parallel drains with a benefit/cost ratio of 1.2 (financially marginal) and 3 m single drain with a benefit/cost ratio of 0.74 (not financially viable).

Using the same costs and benefits it is possible to estimate the minimum zone of benefit required to break even (Table 6). These results apply to both single and parallel deep drains.

Table 6 Break-even zone-of-benefit (ZOB) widths for 2 m and 3 m deep drains at Dumbleyung

Drain depth	ZOB for barley	ZOB for wheat
2 m	172 m	171 m
3 m	290 m	288 m

Comments on data quality and analysis

This report (Cox and Tetlow, in prep.) includes data and analysis from three drainage sites and two comparison sites.

Although the monitoring data from the White Well and Temby drainage sites are relatively high quality, they were collected approximately four years after the drains were constructed and no pre-drainage data are presented in the report. The absence of any pre-drainage data limits the analysis and makes the effect of the drains more difficult to identify.

The Beynon drainage site includes over three years of monitoring data including over one year of quarterly pre-drain data, three months of intensive data during and immediately following construction and nearly three years of post-drainage monitoring data. The length of the monitoring period, experimental design, inclusion of 27 monitoring bores, three gauging stations and access to monitoring data from two comparison sites makes the results from the Beynon drainage project particularly valuable.

The report also considers the impact of atmospheric pressure on groundwater levels. Daily watertable fluctuations of up to 0.1 m/day were observed in the Dumbleyung bores during periods without rainfall and were attributed to fluctuations in atmospheric pressure. Where groundwater level differences of the order of 0.1 m may be significant in assessing the performance of a drain, groundwater levels should be corrected to account for atmospheric pressure.

Key findings

Temby and White Well results are not particularly helpful because of absence of any pre-drain data, although they both suggest the single deep drain had some effect on adjacent groundwater over distances of 50-70 m.

The key findings presented below are from the Beynon site.

- Drawdown responses to deep drains occur within weeks of construction. Subsequent changes in groundwater levels are due to local rainfall recharge, aquifer discharge and barometric pressure.
- Parallel drains can lower and control groundwater levels more effectively than single drains. At the Dumbleyung sites, an acceptable reduction in groundwater levels was only achieved within 50 m of the single drains, whereas the parallel drains demonstrated that groundwater levels could be effectively controlled over the 220 m distance between the drains. Subsequent analysis suggested that parallel drains at Benyon could have been effective at a spacing of 360 m.
- Previous expectations of the performance of deep drainage in the wheatbelt have misinterpreted drainage theory and the accompanying tools, which were generally developed for parallel drains and assume a no-flow boundary at some distance. When the theory is applied to Beynon parallel drains it was found to be consistent with the monitoring results, but when it was applied to single drains it underestimates the drainage discharges and overestimates the groundwater drawdown.
- In general, groundwater levels adjacent to the 3 m drain fell more than groundwater levels adjacent to the 2.5 m deep drain. It is unlikely that 2 m deep drains can be used to adequately control groundwater levels at the critical depth required for cropping.
- It is recommended that the zone of benefit (ZOB) be used to measure the effectiveness of deep drains in preference to the drawdown distance. The ZOB is defined as the area under which groundwater levels are controlled to a particular depth below the ground surface. For barley, this is the area under which groundwater is maintained below 1.5 m of the ground surface with 90% reliability. A comparison of the performance of single and parallel drains found that the ZOB between parallel drains will always be more than twice the ZOB from a single drain
- Salinity of the drainage discharge varied from 5,000 mg/L to 95,000 mg/L, largely due to the effects of dilution by rainfall and evapo-concentration. Drain flows were acidic to strongly acidic (pH 3.2-3.6). This pH was lower than the surrounding groundwater and possibly the result of hydrolysis of dissolved iron in the groundwater when it is exposed to oxygen in the drain. Drains do not change groundwater salinity or pH.
- The immediacy of crop productivity between the Beynon parallel drains suggests that maintaining groundwater levels below the critical depth may be sufficient to allow cropping and to arrest and slowly reverse deteriorating topsoil salinity.
- A 30-year benefit cost analysis (BCA) of the Beynon drains concluded that only the 3 m deep parallel drains produced a consistently high enough benefit/costratio to be considered financially viable. The 3 m deep parallel drains at Dumbleyung had benefit/costratio of 1.8, compared with 2 m deep parallel drains with a benefit/costratio of 1.2 (financially marginal) and 3 m single drain with a benefit/costratio of 0.74 (not financially viable).

3.9 Final Report of the Yarra Yarra Regional Drainage and Research Project (YYCMG, 2010)

Figure 15 Yarra Yarra Regional Drainage Program - location

The Yarra Yarra Catchment Management Group (YYCMG) was formed in 2007 to support sustainable natural resource management in the Yarra Yarra catchment, in the Northern Agricultural Region. The agricultural area of the catchment extends west of the clearing line to Carnamah and Three Springs, from Kalannie in the south to Morawa in the north (Figure 15).

The area is characterised by relatively small catchments, broad valleys with little or no defined channel, draining toward a series of playas and saltlakes that make up the Yarra Yarra lake system.

An early focus for the YYCMG was the rising saline groundwater in valley floors leading to widespread salinization. Following a broad stakeholder consultation program, YYCMG developed a conceptual arterial drainage plan for the catchment, designed to allow landholders to connect privately constructed deep drains to the arterial drains, which would convey and dispose of the drainage water.

The YYCMG secured funding from the Commonwealth and State Governments for the construction of the first stage of the Yarra Yarra Regional Drainage Program in 2006.

Design and construction

The Yarra Yarra Regional Drainage Program comprises approximately 99 km of arterial deep drains constructed over the period December 2006–July 2009. The arterial drains were constructed in eight sub-catchments, each discharging to a salt lake, wetland or playa within the Yarra Yarra lake chain:

- Burakin
- Xantippe
- Jibberding
- Mongers 16
- Bowgada
- Merkanooka and
- Canna-Gutha.

For each sub-catchment, topographic surveys and geotechnical surveys (trial pits) were carried out along the proposed drain alignment. The drains were constructed just upslope of the lowest alignment along the valley floor to maintain floodway capacity in the valley for significant events. The design of the Yarra Yarra drains incorporated a central deep drain, with the spoil used to form continuous 1.5 m high levee banks on both sides of the channel to prevent surface water inflow and silt accumulation in the drain. The levee banks are set back 1.5 metre either side of the channel with shallow surface water channels formed on the outer edge of the levee banks to convey surface water out of the catchment. The drains were generally 2.5 m depth, with 1.25 m width bottom and 0.5(H):1(V) batter slopes. There is no discussion of the basis of design for the drains other than that previously constructed drains (Mongers 55) had been excavated to 2.1 m deep but 2.5 m depth was found to be more effective.

Following construction, the arterial drains were surveyed to confirm the final elevation and position of the drain.

Monitoring

The Yarra Yarra Regional Drainage Program has been the subject of a range of monitoring activities by the YYCMG to evaluate the performance of deep drains and to identify potential downstream impacts. Monitoring activities have included: groundwater levels, drainage discharges, surface water and groundwater quality, adjacent vegetation health and aquatic fauna.

The report (YYCMG, 2010) presents a mix of qualitative and quantitative data as well as information describing the Yarra Yarra Regional Drainage program. The report describes the methods and equipment used for monitoring. Quantitative data presented includes summary flow data from flumes in the Merkanooka and Canna Gutha drains and construction costs for each drain.

A more comprehensive dataset is available on CD and is referred to in the report as Appendices 1 through 10. The appendices do not include any further analysis or interpretation of the data and were not reviewed for this report. Those data in the appendices are the basis of further analysis and interpretation of the performance of the Xantippe, Jibberding and Mongers 16 drains presented in GHD (2016). Other data related to vegetation health are reported in Fordyce (2012) and Fordyce (2015) and aquatic invertebrate survey data are presented in Wetland Research & Management (2008).

Drain performance

The report (YYCMG, 2010) does not present any analysis or interpretation of groundwater level data to assess the impact of the drains on the watertable. The report does include comments and observations on drain performance. For example, it is noted that the drain at Merkanooka, in the north of the catchment, moved large volumes of water, but did not lower the watertable. In contrast the southern drains (Mongers55, Jibberding, Xantippe and Burakin) were reported to have resulted in clear falls in groundwater levels following drain construction. The report states that the differences in performance of the northern and southern drains cannot easily explained but suggests the differences may be linked to the absence of a silcrete/ferricrete layer at the northern sites.

The report (YYCMG, 2010) identifies the Burakin drain as an example of the positive effect of deep drainage. A groundwater hydrograph from bore BU 66 is presented (Figure 58 in YYCMG, 2010) is presented and shows the watertable declining approximately 1 m from July 2008 to April 2009. However, the hydrograph suggests that the decline is at least partly the recession from a rainfall event in July 2008 and the groundwater levels increase by a similar amount (0.9 m) in July 2009 (presumably in response to winter rainfall). Noting that the bores (BU 66) is 400 m from the drain, it is unlikely that the fluctuations in groundwater level can be attributed to the drain. The hydrograph does not clearly support the claim that the Burakin drain has lowered or controlled groundwater levels adjacent to the drain. There are no rainfall data presented with the hydrograph to enable the relative impacts of climate and drain construction to be identified.

Construction Costs

The report presents the recorded costs and observations regarding the construction of the drains and associated infrastructure. The photographs, maps and cost tables provide a useful summary of techniques used and challenges overcome. For example, horizontal line boring was employed to reduce costs and disruption for the construction of the Jibberding drain crossing of the Great Northern Highway.

The reported excavation costs for the Yarra Yarra drains are presented in Table 7. The costs presented include 150 km of surface water drains ($2,000/km), road, rail and access crossings as well as the excavation costs for the 2.5 m deep drain were $8,000-$9,000/km. These rates appear to be based on costs incurred during construction in 2007-2008 and do not include escalation to allow for inflation to the time of the report (2010).

Table 7 Yarra Yarra drain construction costs

Catchment	Length of drain (km)	Cost ($)	Rate ($/m)
Bowgada	10.4	$127,700.00	$ 12,278.85
Merkanooka	12.8	$136,448.00	$ 10,660.00
Canna Gutha	10.7	$153,930.00	$ 14,385.98
Jibberding	11.5	$243,542.00	$ 21,177.57
Xantippe	6.75	$119,300.00	$ 17,674.07
Mongers 16	14	$249,510.00	$ 17,822.14
Burakin	17.75	$359,922.00	$ 20,277.30
Merkanooka ext.	13.1	$232,136.00	$ 17,720.31
Total	**97**	**$1,622,488.00**	**$ 16,726.68**

Rehabilitation of adjacent land and downstream impacts

YYCMG (2010) reports on the revegetation of the drainage corridor. All sections of the arterial drain were fenced on completion of construction and 150 ha of the drainage corridor was revegetated, mostly with Broombrush (*Melaleuca hamata* and *Malaleuca atrovirides*). The report presents photographs showing early growth of some Broombrush seedlings and notes the opportunity for future harvesting for brushwood fences.

The report (YYCMG, 2010) describes the disposal of drainage discharge to playas and saltlakes. Anecdotally, drainage discharges are reported as being matched by evaporation in the lakes. The results of aquatic ecology surveys (Wetland Research and Management, 2008) are summarised to support the conclusion that downstream impacts from the drains are not significant. Similarly, vegetation surveys at the wetland discharge sites observed no vegetation changes that could be linked to drainage discharge.

Comments on data quality and analysis

The descriptive text provided in the report (YYCMG, 2010) is helpful in understanding the process and activities completed by YYCMG in planning and constructing the drainage system. However, many of the comments regarding the effect of the drain on the adjacent watertable are not supported by any detailed presentation or analysis of the monitoring data. There is no consideration of the potential impacts of climate on the observed changes in groundwater levels. There are no rainfall data presented and no groundwater level data from control or comparison bores.

Although the Yarra Yarra Regional Drainage Program included a substantial number of monitoring bores, installed in transects at all of the drain, the bore levels were not surveyed and groundwater levels are presented as depth below ground level. The Department of Water has subsequently surveyed eight transects from five sites and data from those bores were the basis of analysis presented in GHD (2016).

Key findings

- Although changes in adjacent groundwater levels and vegetation were observed and reported, it is difficult to identify the relative effects of climate and drain construction in the data presented.
- Drainage discharges to playas and salt lakes were not as significant as predicted. Wetland Research and Management (2008) presents a more detailed assessment of the impacts on aquatic ecology.

3.10 Evaluation of Xantippe, Jibberding and Mongers 16 drains (GHD, 2016)

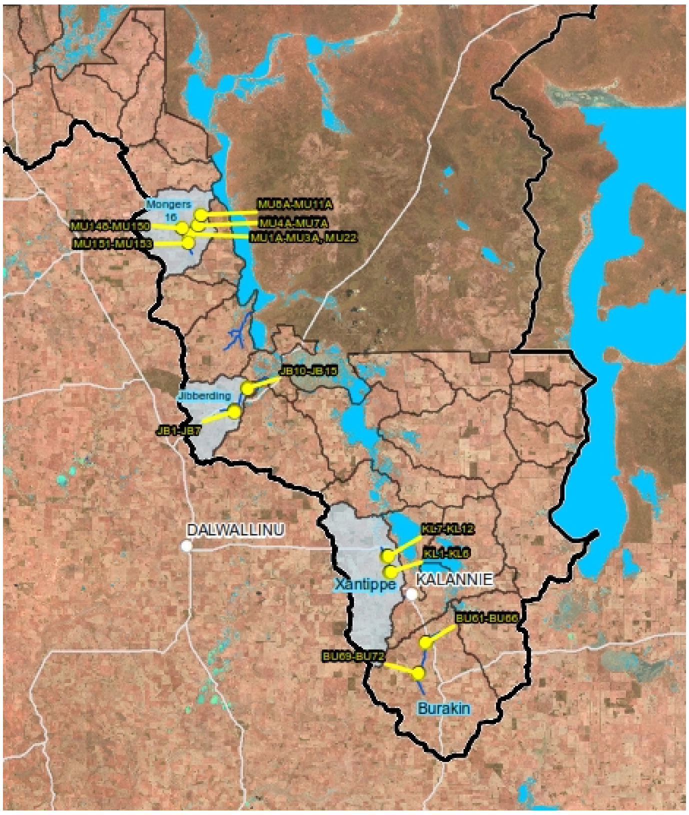

Figure 16 Xantippe, Jibberding and Mongers 16 drains - locations

This report presents an evaluation of the performance of three deep drains in the Xantippe, Jibberding and Mongers 16 sub-catchments of the Yarra Yarra Regional Drainage System (Figure 16).

The Yarra Yarra catchment is one of four sub-regions of the Northern Agricultural Region of southwestern Western Australia. The greater Yarra Yarra catchment covers an area of approximately 41,800 km^2, extending from Carnamah in the west, to Mt Magnet in the northeast and Kalannie in the south.

Natural drainage within the Yarra Yarra catchment is internal, with irregular surface flow directed to a chain of several thousand ephemeral salt lakes and samphire covered claypans approximately 300 km long and 2,500 km^2 in area near the catchment's western edge. The lake system drains from the south, toward the north, then to the southwest, culminating in the Yarra Yarra Lakes.

The agricultural portion of the catchment, west of the clearing line, is an area of approximately 10,600 km^2 and is characterised by relatively small catchments, broad valleys with little or no defined channel, draining toward low-lying areas along the major lake system. Prior to clearing for agriculture, these valleys supported tree-based woodland systems and probably produced infrequent surface water flow to the lake systems.

The Yarra Yarra Regional Drainage Program

The Yarra Yarra Regional Drainage Program is a regional network of arterial deep drains constructed for the purpose of providing landholders with access to a discharge point for deep drainage they may construct on their own land.

The arterial drainage network comprises approximately 99 km of arterial deep drains constructed by the YYCMG over the period December 2006–July 2009 with funding from the Commonwealth and State Governments. The arterial drains were constructed in eight sub-catchments, each discharging to a salt lake, wetland or playa within the Yarra Yarra lake chain. This report presents an evaluation of the performance of three of those drains in the Xantippe, Jibberding and Mongers 16 sub-catchments.

Design and construction

Pre-construction site investigations included preliminary surveys for drain alignment, and geotechnical investigation comprising observation pits excavated at approximately 2 km intervals along the drain alignment. The observation pits were used by YYCMG to assess the soil profile, measure rate of inflow (to estimate drawdown), identify the presence of hardpans and assess the ease of excavation (YYCMG 2007). No observation pit data was available for inclusion in the evaluation of the watertable response to deep drains. Following construction, the arterial drains were surveyed to confirm the final elevation and position of the drain.

The basic design of the drain incorporates a central deep drain, with the spoil used to form continuous 1.5 m high levee banks on both sides of the channel to prevent surface water inflow and silt accumulation in the drain (Plate 1). Drains were constructed just upslope of the lowest alignment along the valley floor to maintain floodway capacity in the valley for significant events. The levee banks are set back 1.5 metre either side of the channel with shallow surface water channels formed on the outer edge of the levee banks to convey surface water out of the catchment. The arterial drains were generally 2.5 m depth, with 1.25 m width bottom and 1(V):0.5(H) batter slopes, forming a channel with cross-section of approximately 5.6 m^2.

Monitoring

The Yarra Yarra Regional Drainage Program has been the subject of a range of monitoring activities by the YYCMG to evaluate the performance of deep drains and to identify potential downstream impacts.

The YYCMG monitoring program included groundwater levels, drainage discharges, surface water and groundwater quality, vegetation health (Fordyce, 2012; Fordyce, 2015) and aquatic ecosystem monitoring (Wetland Research & Management, 2008). DAFWA has also monitored groundwater levels in the Mongers 55 and Canna-Gutha catchments (Stuart Street *et al.,* in publication) and the Department of Water used part of the Mongers 55 drain for batter trials (Cox and Tetlow, 2009).

Groundwater monitoring bore transects (Figure 16) comprised 4-10 groundwater bores spaced at distance from the arterial drain and were installed prior to drain construction.

Groundwater levels in the monitoring bores were manually dipped, typically monthly before drain construction and with more frequent (weekly or fortnightly) measurements during and immediately after drain construction.

Groundwater levels were initially reported by the YYCMG as depth below ground level. Following survey of the groundwater transects by Department of Water (Cox, pers. comm.) the groundwater levels were converted by GHD to metres above local height datum (m LHD).

3.10.1 Xantippe

The Xantippe arterial drain was constructed as part of the Yarra Yarra Regional Drainage Program between March and June 2008. The total length of arterial drain was 6.7 km, which included modification to an existing privately funded drainage line established in 1988 to address salinity issues within the upper part of the Xantippe sub-catchment (YYCMG 2007).

The drain was initially approximately 2.5 m deep near the Dalwallinu-Kalannie Road, however over time this has reduced to approximately 2 m deep (S. Hathaway pers. comm.).

Soil landscape mapping (DAFWA) shows variable soils of the valley floor in the Xantippe sub-catchment. Within the vicinity of the arterial drain and bore transects the soil landscape is primarily mapped as *Calcareous loamy earth and red sandy earth* (Map unit: 258BCL). Downstream sections of the valley floor are also mapped as *Red sandy earth and alkaline grey shallow sandy duplex* (Map unit: 258BrWI) and *Red sandy earth, salt lake soil and grey deep sandy duplex* (Map unit: 258Wa_2).

Monitoring

The report (GHD 2016), presents data from two groundwater monitoring transects.

The Campbell Road transect (KL1-KL6) is located toward the upper end the Xantippe deep drain alignment, and comprises six bores installed along a transect perpendicular to the drain. Water levels in all bores were manually measured between 29 September 2007 and 15 October 2013. The arterial drain was excavated past the transect on or about the 20 April 2008.

The Angel transect (KL8-KL12) is located two thirds of the way down the Xantippe deep drain alignment, and comprises five bores installed along a transect perpendicular to the drain. Water levels in all bores were manually measured between 29 September 2007 and 15 October 2013. The arterial drain was excavated past the transect on or about the 31 March 2008.

Drain performance

Initial watertable responses to drain construction were observed in bores closest to the drain in both the Campbell Road transect (KL1-KL3, 17-98m from drain) and the Angel transect (KL8-KL10, 57-207 m from drain). However, drain construction at both locations occurred following rainfall events which influenced the selected pre-drain watertable level, and the observed initial response occurred during groundwater recession periods. The watertable at both transects subsequently returned to above the pre-drain levels in response to significant rainfall events after drain construction.

The watertable across all bores generally followed trends in AMRR. The report could not identify any long term watertable response that could be attributed to the construction of the Xantippe drain.

GHD (2016) refers to anecdotal reports of observed cropping improvements in the paddocks to the west of the arterial drain. This area lies between the Xantippe drain and another existing deep drain that runs north along the Dalwallinu-Kalannie Road, at a separation of approximately 120 m. It is likely that these drains act as parallel drains to control groundwater levels between the drains (Cox and Tetlow, 2014; Cox and Tetlow, in prep.). Groundwater levels between the two drains was not recorded by the monitoring bore transect, which is located to the east of the Xantippe arterial drain.

3.10.2 Jibberding

Construction of the Jibberding arterial drain occurred between December 2007 and April 2008 to a total length of 11.5 km.

Soil landscape mapping (DAFWA) describes the soils of the valley floor as *Red-brown hardpan shallow loam, red deep sandy duplex and red shallow sandy duplex* (Map unit: 271Gn_4).

Water quality in groundwater monitoring bores prior to excavation of the arterial drainage was reported as having salinity ranging from 5 to 98 mS/cm and pH ranging from 3.3 to 7.4 (YYCMG 2007).

Monitoring

The report (GHD 2016), presents data from two groundwater monitoring transects.

The Woolf Road transect (JB1-JB7) is located toward the upper end the Jibberding deep drain and comprises seven bores installed along a transect perpendicular to the drain. Water levels in all bores were manually measured between 1 November 2007 and 16 August 2013. The arterial drain passes through a wide vegetated valley floor, and was excavated past the transect on or about the 29 February 2008.

At the Woolf Road transect (JB1-JB7) the landholder has constructed private spur drains, with one drain constructed parallel to and to the east of the transect prior and a second parallel to and to the west of the monitoring bore transect. The resulting drain configuration results in deep drainage constructed on three sides of the of the monitoring bore transect location.

Additional land treatments in proximity to the Woolf Road transect include privately funded revegetation of the valley floor with saltbush vegetation and tree belts. The report notes that the proximity of the spur drains and vegetation treatments to the monitoring bore transect may influence the watertable response at this site.

The Wasley Road transect (JB10-JB15) is located toward the lower end the Jibberding drain and comprises six bores installed along a transect perpendicular to the drain. Water levels in all bores were manually measured between 10 October 2007 and 16 August 2013. The arterial drain was excavated past the transect on or about the 3 January 2008. A playa is located in proximity to the southern end of the Wasley Road transect.

Drain performance

Following construction of the Jibberding arterial drain an immediate watertable response was observed in bores closest to the drain at the Woolf Road transect. The response in bores at distance from the drain (214 m and beyond) was delayed and subdued by comparison.

The bore transect shows an increased watertable slope towards the arterial drain along the transect and there appears to have been a reduction in the watertable response to rainfall events in bores within approximately 100 m of the drain (JB1-JB3, 36-106m from drain).

Following arterial and spur drain construction at the Woolf Road site, the watertable levels in the bore closest to the arterial drain were maintained deeper than 1.6 m below ground level (and below observed pre-drain levels), even following significant rain periods. A similar response was observed in bores JB2 (72 m) and JB3 (106 m) with watertable levels maintained below pre-drain levels. Beyond this distance the watertable in the bores is observed within the range of pre-drain levels.

Based on the observed watertable response at the Woolf Road site the increased drainage density around the monitoring bore transect appears to have resulted in watertable control within the area between the three drains. This is supported by crop productivity improvements reported by the landholder at the Woolf Road transect.

In contrast, the construction of the Jibberding arterial drain as a single deep drain had no significant impact on the adjacent watertable at the Wasley Road transect.

3.10.3 Mongers 16

Construction of the Mongers 16 arterial drain occurred between March and July 2008 to a total length of 14 km. Several privately funded farmer drains have also been constructed within the sub-catchment.

Soil landscape mapping (DAFWA) describes the soils of the valley floor as *Red-brown hardpan shallow loam, red deep sandy duplex and red shallow sandy duplex* (Map unit: 271Gn_4).

Water quality in groundwater monitoring bores prior to excavation of the arterial drainage was reported as having salinity ranging from 16.5 to 45 mS/cm and pH ranging from 6.3 to 6.9 (YYCMG 2007).

Monitoring

The report (GHD 2016), presents data from one groundwater monitoring transects - Simpson Road transect, MU8-MU11. The YYCMG established five groundwater monitoring bore transects in the Mongers 16 sub-catchment, but the other transects were considered unsuitable or had significant gaps in the monitoring record and were not included in the analysis.

The Simpson Road transect (MU8A-MU11A) is at the downstream end of the Mongers 16 deep drain and comprises four bores installed along a transect perpendicular to the drain. Water levels in all bores were manually observed between 20 July 2007 and 16 August 2013. The arterial drain was excavated past the transect on or about the 1 May 2008.

Drain performance

Following construction of the Mongers 16 drain, groundwater levels in bores closest to the drain fell. However, this corresponded with a period of watertable recession following a rainfall event.

Following this initial decline the watertable recovered to within the range of observed pre-drain levels until the next rainfall event on the 6 August 2008. Groundwater levels in all bores were observed to rise following the onset of winter rainfall in July 2008.

The observed watertable response broadly reflects AMRR trends, although significant gaps in the data record mean that later periods of above average rainfall do not appear in watertable response.

The construction of the Mongers 16 arterial drain did not lower and control the watertable within the vicinity of the Simpson Road transect to the critical depth required for reliable crop growth.

Comments on data quality and analysis

This report (GHD, 2016) uses groundwater bore data collected over a long period (September 2007 – August 2013, which included typically six months' pre-drain data and five years' post-drain data. The measurement frequency was relatively high immediately in the months following construction of the drains but was less frequent during 2010 and 2011. This meant that the impact of rainfall events on the watertable (and the ability of the drain to control the watertable) during that time could not be assessed over that period.

The report claims a measurement error of ±0.5 m. However, atmospheric pressure fluctuations can produce daily watertable fluctuations of up to 0.1 m (Cox and Tetlow, in prep.). Since no barometric pressure data were available, the groundwater level error may be under-estimated.

The report does not present any control or comparison bore data, which prevents the impact of climate on regional groundwater levels from being identified and separated from any impact from deep drainage.

Key findings

- The measured watertable response at the Xantippe, Jibberding and Mongers 16 drains show that single deep drains are unable to lower and control groundwater levels to a sufficient depth and at a sufficient distance from the drain to reliably return adjacent agricultural land to cropping.
- Long-term declines in watertable of up to 0.5 m were observed across bores at all three drains. However, these long-term groundwater declines are more likely due to climate than the deep drains. Within all sub-catchments the groundwater levels measured at all bore transects generally followed trends in AMRR.
- Watertable responses at some bore transects were influenced by the location of the arterial drain in relation to other constructed drains and drainage features. Bore transects in areas with increased drainage density (e.g. spur drains) showed some drainage impact on groundwater levels.
- Clearly identifying the separate impacts of drain construction, climate and other hydrological features is difficult. Closer spacing of monitoring bores adjacent to drains, the use of appropriate control or comparison bores and the availability of long record, local rainfall data would assist the assessment of drain impacts.

4. Drainage design and construction

4.1 Drain batter erosion trial at Wubin (Cox and Tetlow, 2009)

Erosion of the side batters, berms and levees of deep drains results in sediment washing into the drains. Accumulation of sediment in the base of a drain reduces its effective depth, reducing its efficiency at lowering and controlling adjacent groundwater levels. Current practice is to remove accumulated sediment using an excavator when the depth of sediment reaches 0.5 m, which can be typically every 3-10 years. The cost of de-silting were reported to be of the order of $1000/km (2009$).

The currently favoured design for deep drains features batter slopes of 0.5(H):1(V), which has evolved through practice as a compromise between slope stability, excavated volume and the capabilities of commonly available equipment.

The objective of the Wubin trials was to:

- compare the rates of erosion and sedimentation of three batter designs
- assess batter erosion beneath 4 m and 1 m wide berms
- evaluate the cost of construction and maintenance of the three drain designs.

The site for the Wubin batter trials was approximately 24 km northeast of Wubin, in the Northern Agricultural Region. The site is an area of flat salt-affected land, no longer used for cropping and colonised by halophytes.

The soils at the trial site are saline, sodic and erosive. The subsoil is variable across the site but is generally clay, mottled with sandy-clay loam and cemented nodules.

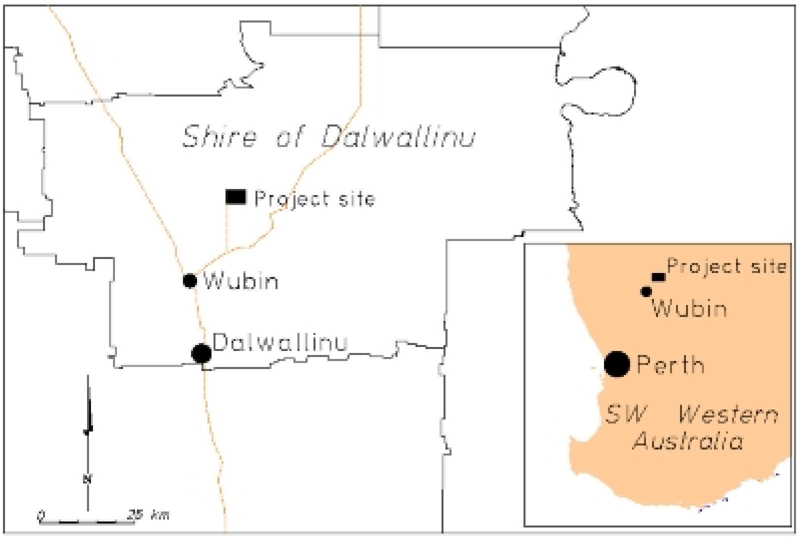

Figure 17 Wubin batter trials – location

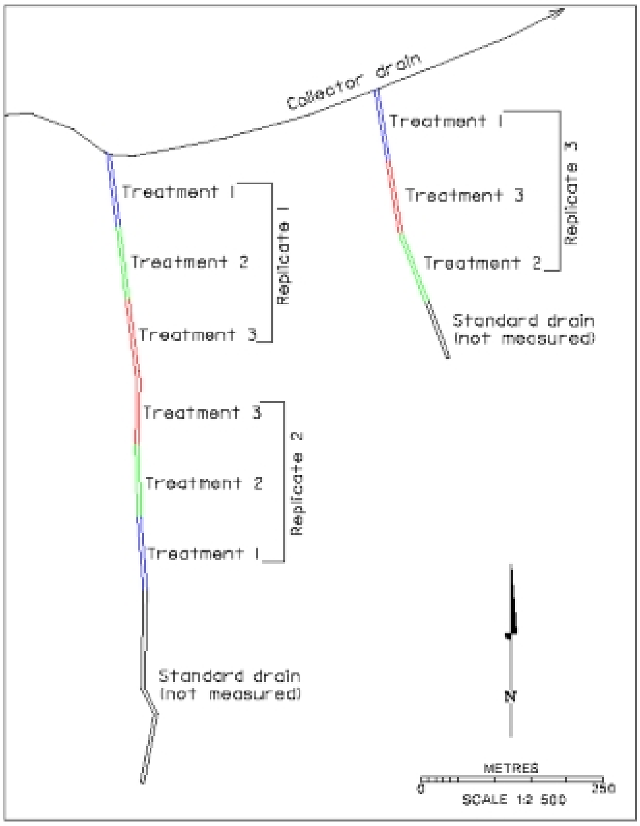

Figure 18 Wubin batter trials – site layout

Design and construction

The trial applied the following three batter designs to a 2 m deep drain with 1.2 m wide base and continuous levees to exclude surface water inflows:

1. Trapezoidal channel with batter slope 0.5(H):1(V)
2. Stepped side batters, comprising two benches approximately 0.65 m horizontal and 0.65 m vertical, forming 1(H):1(V) average batter slope
3. Trapezoidal channel with batter slope 1(H):1(V)

Each length of drain also included a 1 m wide berm on one side and a 4 m wide berm on the other side. The purpose of the different berm widths was to investigate the effect of berm width on erosion from run-off from the drain levees.

The trial drain comprised three separate sets (replicates) of 100 m lengths of each of the three batter designs, incorporated into two parallel drains constructed 400 m apart (Figure 18). The purpose of the three replicates was to expose each of the batter designs to a range of soil types and groundwater and drain flow conditions.

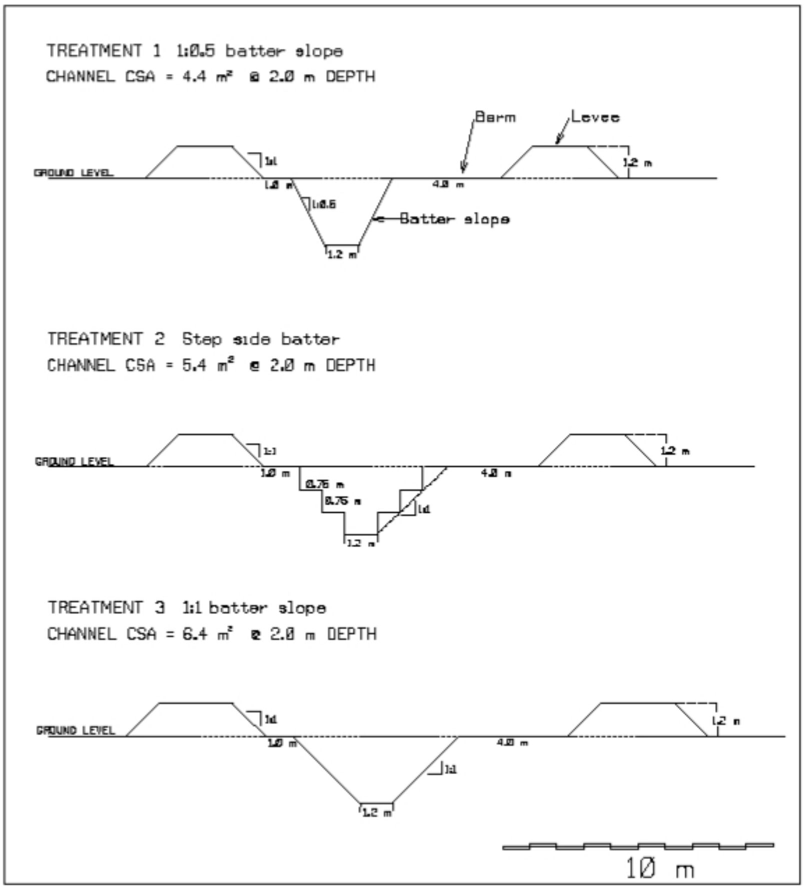

Figure 19 Wubin batter trials – cross sections

Monitoring

Each of the nine trial sections was surveyed at two cross-sections (18 cross sections) on three dates over a year: 24 October 2006 (initial survey within one month of construction), 2 May 2007 (before winter rain) and 8 October (after winter rain and one year after construction).

The data from each survey were used to calculate changes in the cross-sectional area of the drain, which was interpreted as an indicator of net erosion (increasing cross-sectional area) or sedimentation (decreasing cross-sectional are).

At the first and last survey, the drain cross-sections were photographed to record sedimentation on the channel floor, the condition of the batters and berms.

The short length of the monitoring period and the relatively low rainfall limited the relative accuracy of the erosion measurements. Many of the result differences between trial sections were within the reasonable error bands for the survey data. The photographic record and field observations supported the interpretation of the surveyed measurements.

The batter trials did not monitor the performance of the drains at lowering or controlling groundwater at the site.

Drain performance

Over the one-year monitoring period all batters experienced erosion and sediment accumulated on the floor of all the surveyed drains. Batter treatment 3 (1H:1V) was found to be the most stable. Batter treatment 2 (0.5H:1V) appeared to lose the greatest volume of soil from its batters and accumulate the greatest volume of sediment in the base of the drain.

Based the cross-sectional area calculations, batter treatment 2 (stepped) appeared stable, but observations revealed that the vertical step faces were highly eroded and the horizontal benches retained the eroded sediment, preventing it from reaching the base of the drain over the monitoring period. The report concluded that over time the continued erosion of the vertical steps would lead to an increased accumulation of sediment in the base of the drain. The report concluded that batter treatment 2 (stepped) was likely to be less stable in the long term than batter treatment 1 (0.5H:1V).

Impact on lifecycle costs

The report used the measured rate of accumulation in each drain to predict the period in which desilting would be required and to estimate the cost of de-silting over a nominal 20 year drain life (refer to Table 8). Although the cost of de-silting drains with treatment 2 (stepped batter) and treatment 3 (1H:1V) were expected to be considerably cheaper than for treatment 1 (0.5H:1V), the substantially lower construction cost of treatment 1 (mostly due to reduced excavation volumes) means that the overall lifecycle cost of treatment 1 is the lowest.

Table 8 Excavation and de-silting costs over 20 years (2009$)

	Treatment 1 0.5H:1V batter	Treatment 2 Stepped batter	Treatment 3 1:1 batter
Predicted period for de-silting	4.3 years	6.7 years	8.1 years
Initial construction cost	\$6.50/m	\$10.80/m	\$12.50/m
De-silting cost over 20 years	\$4.65/m	\$2.98/m	\$2.47/m
Total cost over 20 years	\$11.15/m	\$13.75/m	\$14.97

The cost analysis presented in the report is very simplistic and does not consider the present value of future cash outflows for de-silting, nor does it include the value of the land taken for drainage purposes, both of which further support the reduced overall cost of treatment 1 (0.5H:1V) compared with the other treatments.

Effect of berm width

The report found that the batters beneath the wide (4 m) berm eroded less than the batters beneath the narrow (1 m) berm. This was attributed to the ability of the wider berms to attenuate peak runoff from the levee batters.

The survey data suggested that the narrow berms suffered net erosion whereas the wide berms experienced net accumulation of sediment eroded from the levee batters. Sediment eroded from the levee batters must be transported across the berm before accumulating in the channel. Observations suggested the narrow berm allowed sediment eroded from the levee banks to be washed directly into the drain channel.

Key findings

- The drain with 0.5(H):1(V) batter slope had a lower combined construction and maintenance cost that drains with 1(H):1(V) batter slope or a stepped batter.
- The drain with flatter batter slopes (1H:1V) was the most stable with the lowest rates of erosion and lowest maintenance cost but had the highest cost of construction.
- The erosion of batters below wide (4 m) berms was on average less than the on batters below narrow (1 m) berms

5. Drainage discharge quality

5.1 The distribution and origins of acid groundwaters in the South West Agricultural Area (Lillicrap & George, 2010)

This study investigated the extent of acid groundwaters across the agricultural regions of southwestern Australia, an area southwest of a line from Esperance on the south coast to Kalbarri on the west coast.

Data and analysis

This study used groundwater data from a total of 2088 bores from the following sources: Department of Agriculture and Food (DAFWA) – AgBores database, Department of Water – WIN database, CSIRO Exploration and Mining – Mount Holland exploration and Department of Environment and Conservation (now Department of Parks and Wildlife) – Buntine-Marchagee Recovery Catchment.

Spatial datasets for vegetation, geology and regolith were sourced from the Department of Agriculture and Food – Land and Resource Assessment Group (DAFWA – LRAG) and the Geological Survey of Western Australia (GSWA).

Statistical modelling to investigate relationships between acidity, vegetation, geology, regolith and depth.

Results and discussion

The distribution of groundwater pH was found to be bi-modal, with distinct acid (median pH 3.5) and non-acid (median pH 6.6) populations.

Acid bores were found across the study area, although most commonly in the zone of ancient drainage. Acid and non-acid bores occurred within hundreds of metres of each other, suggesting very localised occurrences.

Statistical modelling was used to determine the significance of the spatial variables of vegetation, geology, depth and regolith in explaining the distribution of acid and non-acid bores.

Vegetation type was found to be the most significant spatial variable, explaining about one third of the variability. Acid groundwater was most commonly associated with Eucalyptus woodlands and shrublands, particularly salmon gum and sand mallee. In contrast, Banksia and Acacias had the lowest incidence of acid groundwater.

Acid groundwater most frequently occurred between 5-10 m depth and less frequently at greater depths.

There was a strong correlation between subsoil alkalinity and acid groundwater, although the relationship was weaker in the zone of rejuvenated drainage than in the zone of ancient drainage. (Alkaline subsoils are more commonly found in the zone of ancient drainage than the zone of rejuvenated drainage.)

The relationship between alkaline subsoils and acid bores was used to develop a predictive map across the zone of ancient drainage, identifying areas of low, medium and high probability of acid groundwater.

The report proposes a conceptual model for the generation of acidic groundwater, which links acid generation with vegetation type and alkaline subsoils. The model combines the processes of podzolisation and biogenic calcrete formation to generate iron rich, acid groundwater below calcareous subsoils. Eucalyptus communities are commonly associated with organic (carboxylic) acids, iron mobilisation and podzolisation, providing the link between Eucalyptus communities and acidic groundwater.

Key findings

- Acid groundwaters are a naturally occurring phenomena.
- Groundwater in southwestern Australia can be broadly allocated to one of two groups: acid (median pH of 3.5) and non-acid (median pH of 6.6).
- Acid groundwater is more common in the drier, inland drainage lines of the Zone of Ancient Drainage. In particular, the occurrence of acid groundwater was strongly correlated with Eucalyptus woodlands and shrublands and subsoil alkalinity.
- Subsoil alkalinity was used to predict the occurrence of acid groundwater across the Zone of Ancient Drainage in southwestern Australia. That probability mapping suggested that acid groundwater are mainly confined to valley floors of palaeo drainage lines but are more widespread than previously thought.
- A new conceptual model is proposed for the origins of acid groundwater, linking the generation of acid groundwater to biogeochemical processes in the unsaturated zone.

6. Downstream impacts

6.1 Yarra Yarra aquatic monitoring: assessing the effect of deep drainage on the ecological health of the Yarra Yarra playas and wetlands (Wetland Research & Management, 2008)

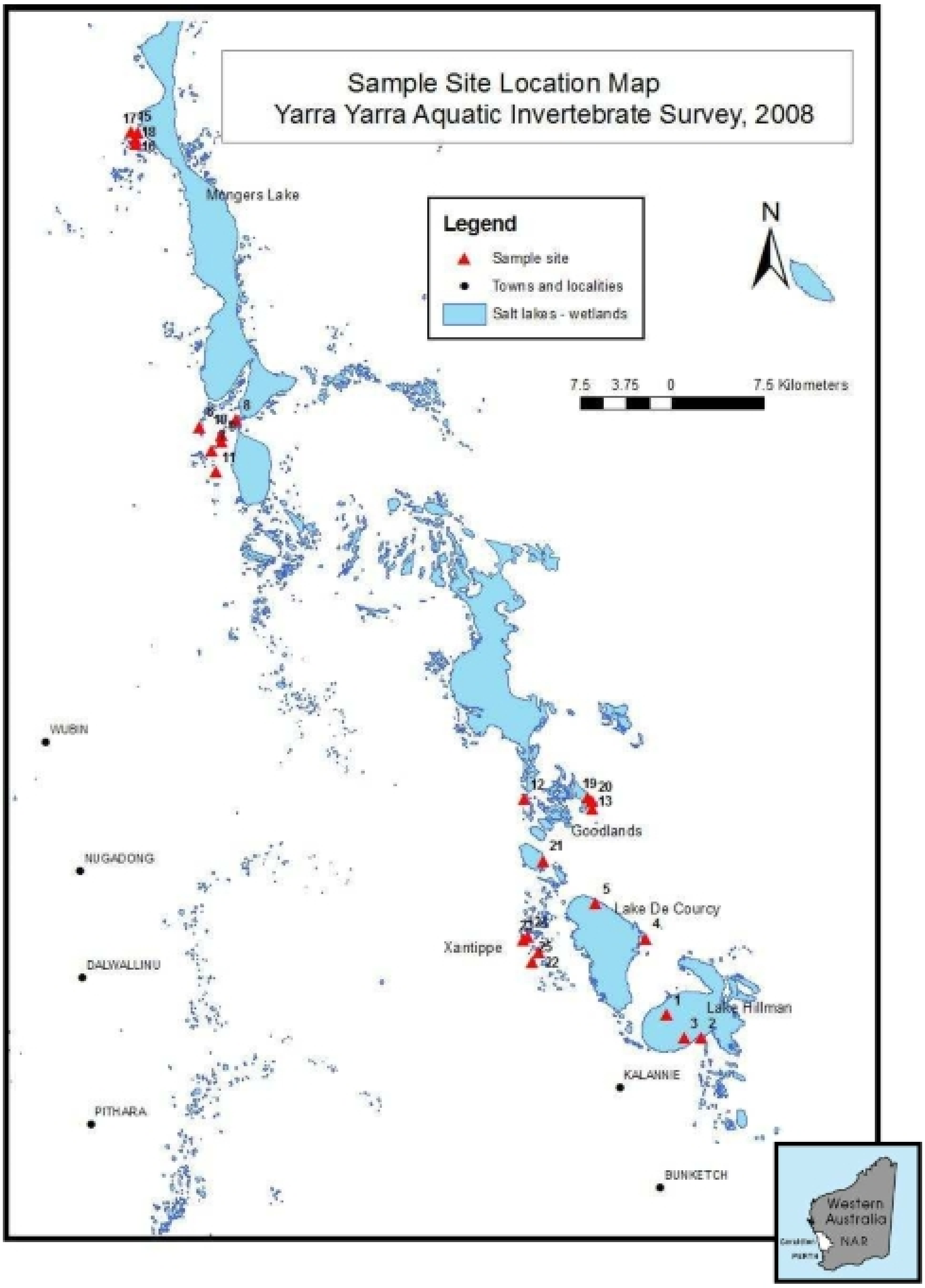

Figure 20 Yarra Yarra aquatic monitoring sites

The Yarra Yarra Regional Drainage Program comprises approximately 97 km of arterial deep drains constructed in the Yarra Yarra catchment for the purpose of lowering groundwater levels and controlling soil salinity.

A total of eight drains were constructed over the period December 2006–July 2009. The drains are located across the western part of the Yarra Yarra catchment, which extends from Burakin in the south to beyond Morawa in the north, the Northern Agricultural Region. The drains discharge to natural playas and salt lakes of the Yarra Yarra lake system and since their construction there has been concern about the possible impacts of drainage discharge on the downstream environments.

This report (Wetland Research & Management, 2008) presents the results of a study to assess the effects of deep drainage on the ecology of the receiving playas and wetlands.

Monitoring

The monitoring program included a number of playas and wetlands across six sub-catchments with a range of physico-chemical characteristics (Lake Hillman, Lake DeCourcy, Mongers 55, Mongers 16, Goodlands and Xantippe). Although not highlighted in the report, the study sites were all located in the southern half of the Yarra Yarra Regional Drainage Program, which has been found to be generally acidic in comparison to sites in the northern parts of the catchment. Only Mongers 16 is one of the separately identified neutral-alkaline sub-catchments found in the northern half of the Yarra Yarra catchment (the others being Bowgada, Meranooka and Canna-Gutha).

The sampling sites were selected to represent control (without drains), exposed (with drains), and future exposed sites within each sub-catchment.

All sites had sufficient standing water (although mostly shallow < 1 m) to allow a comparison of water quality and micro- and macroinvertebrate communities between the reference and exposed sites. Sampling was completed in May 2008.

At each monitoring site, in-situ measurements were made of pH, conductivity, dissolved oxygen, redox potential and temperature. Maximum water depth was measured using a graduated pole and turbidity estimated using a Secchi disk. Water samples were collected and analysed for key ions, metals and nutrients. Micro-and macroinvertebrate samples were collected at each site and preserved for later identification.

Results

Water quality

Twenty-one of the sites were hypersaline, two saline and one brackish.

Nine of the sites were acidic (pH 3.04-4.16). Four of these were exposed to drainage discharges but the remaining five were control sites, suggesting wider acidification of the system. Although not highlighted in the report, the study sites were all located in the southern half of the Yarra Yarra Regional Drainage Program, which has been found to be generally acidic in comparison to sites in the northern parts of the catchment. Only Mongers 16 is one of the separately identified neutral-alkaline sub-catchments found in the northern half of the Yarra Yarra catchment (the others being Bowgada, Meranooka and Canna-Gutha).

Irrespective of acidity, most of the sampling sites had elevated concentrations of dissolved metals, often exceeding the ANZECC/ARMCANZ guidelines for the protection of aquatic ecosystems. Concentrations of some metals (Co, Fe, Pb and Mn) were higher at acidic sites and iron concentrations were higher at acidic exposed sites than at acidic control sites. The report notes that although the measured dissolved metal concentrations were high, the bioavailability of the metals in the Yarra Yarra system is not known.

Nutrient concentrations at most sites were high and well above ANZECC/ARMCANZ guidelines for the protection of aquatic ecosystems. Total nitrogen concentrations were in the range 0.61-36 mg/L and total phosphorus in the range 0.005-0.75 mg/L, although the maximum values were from a reference site in the Mongers 16 sub-catchment experiencing an algal bloom and low water levels and are most probably due to evapo-concentration, so should not be taken as representative of drainage discharge water quality. The report notes that spot measurements of water quality (salts, pH, metals and nutrients) may not be indicative of conditions throughout the year. Winter rains can dilute and transport constituents and evaporation over summer conditions can lead to increasing concentrations.

There was no significant difference in nutrient concentrations between the exposed and control sites. The high nutrient concentrations were attributed to agricultural practices in the catchment.

Micro-invertebrates

All the micro-invertebrate fauna collected were considered permanent residents of the wetland in which they were collected (i.e. their life-cycle was completed within the wetland). None of the 23 species collected were considered to be rare, although their endemicity remains unknown due to lack of adequate survey data across Western Australia.

Species richness was highly variable between sites and many species were found only at one site. Maximum species richness occurred at neutral-alkaline sites.

Abundances were generally low with zero species at all acidic (pH < 5.5) sites and the most species at an alkaline (pH 8.97) site.

Acidity exerted a strong influence on species richness and abundance, even at relatively low salinity. At neutral-alkaline sites, increasing salinity did reduce species richness.

Macro-invertebrates

In contrast to the micro-invertebrate fauna, most of the macro-invertebrate fauna collected were considered temporary residents of the wetland in which they were collected because of their generally highly mobile adult phases (especially insects). Only the snails, mites and brine shrimp were considered to be permanent residents of the wetland in which they were collected.

None of the 39 species collected were considered to be rare, although four were endemic to Western Australia (three brine shrimp and a beetle).

Species richness was highly variable between sites and many species were found only at one site. Salinity appeared to be more significant than acidity in determining species richness, although low pH may have a marginal effect on species richness, perhaps associated with the associated elevated concentrations of dissolved metals.

Abundances were generally low.

Discussion

The sites surveyed for this this study include only six of the sub-catchments of the 11 sub-catchments of the Yarra Yarra Regional Drainage Program and are restricted to the southern half of the Yarra Yarra catchment, which is an area associated with acidic groundwater.

Degens and Shand (2010) found that acidic groundwater occurs in the valley floors of the Yarra Yarra south of Perenjori, which coincides with the most northern of the sites in this study. They found that some of the lakes of the southern part of the Yarra Yarra system to be naturally acidic, probably due to groundwater discharge. Similarly, Lillicrap and George (2010) identify the southern part of the Yarra Yarra catchment as the northern extent of the acid groundwater zone.

Key findings

- The Yarra Yarra catchment continues to support a moderately rich aquatic invertebrate fauna. Aquatic invertebrate fauna is an important component of wheatbelt biodiversity and are a major dietary component for water birds.
- Macro-invertebrate community structure is primarily influenced by salinity, with species richness declining with increasing salinity.
- Micro-invertebrate communities are primarily affected by acidity and secondarily by salinity (many wheatbelt species are naturally salt-adapted). Most naturally saline systems are alkaline, so that acidic saline wetlands represent extreme environments. Acidification poses a substantial threat to the biodiversity of wheatbelt playas and wetlands.
- Salinity and pH appear to provide good predictors of biodiversity and offer cost effective proxies to more expensive invertebrate fauna monitoring.
- Most of the study sites had elevated concentrations of dissolved metals and the dissolved metals in acidic drainage water may have an impact on invertebrate fauna.
- Monitoring programs should adopt sampling and analysis methods that allow the speciation of metals to provide better estimates of bioavailable metal concentrations where metal concentrations are expected to exceed the guideline trigger values.

6.2 Fence Road drainage system (Seewraj, 2010)

The Fence Road arterial drainage system comprises 58 km of deep drains in an area about 20 km northeast of Dumbleyung, in the Southwest Agricultural Region. The system was constructed between November 2007 and April 2008.

The report does not describe the project site, which is in the catchment of Dongolocking Creek, which flows into Lake Dumbleyung. The area is characterised are in low relief valleys floors with more clearly defined drainage lines, compared with the broad flat valleys of the northern and eastern agricultural regions.

In September 2008 low pH discharge water travelled 30 km downstream of the drainage system discharge point. The Fence Road Interim Monitoring Data Assessment report was intended to assess how the drainage discharge was effecting the downstream environmental and to recommend improvements for the prediction and management of downstream impacts.

Design and construction

The Fence Road arterial drainage system comprises 36.5 k of 2 m deep leveed drains, 17.5 km of 2 m deep open drains (i.e. combined surface water and groundwater drains) and 4 km of siphon pipes.

The drainage system discharges into Dongolocking Creek.

Monitoring

The water quality monitoring data presented in this report are drawn from three programs: the Dumbleyung Water Management Strategy (DWMS) Fence Road monitoring program, the University of Western Australia aquatic ecological survey and a Department of Water Dumbleyung catchment water quality monitoring program.

The DWMS Fence Road monitoring program was established in 2007 to assess potential impacts of the Fence Road arterial drainage system. This program included one transect of monitoring bores and 18 surface water monitoring sites extending from upstream of the drainage system to well downstream of the discharge point. Monitoring was generally monthly in-situ measurements of temperature, pH, total; acidity, conductivity and dissolved oxygen. Four of the sites were stream gaging stations equipped to continuously monitor flow.

An ecological survey of surface water upstream, within and downstream of the Fence Road arterial drainage system, undertaken by the University of Western Australia. The survey comprised 28 sites, 12 of which were shared with the DWMS Fence Road monitoring program. The sites were surveyed on three occasions (August 2008, October 2008 and March 2009) recording in-situ measurements of temperature, pH, conductivity, dissolved oxygen and turbidity and collecting samples for analysis of macroinvertebrate biodiversity.

A broader surface water quality survey of the broader Dumbleyung catchment was subsequently undertaken by the Department of Water. The survey included 38 sites, 12 of which were shared with the DWMS Fence Road monitoring program. The sites were surveyed in September 2009, recording in-situ measurements of temperature, pH, conductivity, dissolved oxygen and collecting samples for analysis of total acidity, total alkalinity, dissolved metals and nutrients.

Results

Drainage discharge flow rates

The groundwater discharge (baseflow) measured at the discharge from the Fence Road arterial drainage system was approximately 4 L/s during summer and 11 L/s during winter, which compares well with the design discharges of 4.2 L/s expected in summer and 13.2 L/s expected in winters.

Measured peak discharges (not during baseflow conditions), however, were significantly less than predicted at design. Using data from a gauging station in the adjacent Doradine Creek catchment, peak surface water flows of between 6.9 L/S (summer) and 92.6 L/s (winter) were expected, compared with measured flows of 2.7 L/s (summer) and 12.1 L/s (winter). The report suggests a high degree of variability in surface run-off in wheatbelt catchments requires site specific streamflow measurements for the purpose of predicting post-drainage surface water flows.

Groundwater salinity and pH

Groundwater salinity in each of the monitoring bores remained fairly constant over the monitoring period. Salinity in the bore closest to the drain (6 m from the drain) was approximately 45,000 mg/L and in the two further bores (36 m and 67 m from the drain) approximately 55,000 mg/L.

Groundwater acidity was more variable, with pH in the range 4.5-6.

Drain discharge and stream salinity and pH

The salinity at the discharge from the Fence Road arterial drainage system varied from 9,000 mg/L to 79,000 mg/L, with the measured high salinity coinciding with periods of low flow. The average stream salinity over the summer (December 2008-January 2009) was 64,000 mg/L compared with 37,000 mg/L over the following winter (June-October 2009).

The measured salinity of the discharge from the drainage system was similar to predicted salinities during baseflow conditions (i.e. groundwater discharges).

The acidity at the discharge from the Fence Road arterial drainage system showed the similar seasonal (flow-related) pattern as salinity, with average summer pH of 2.7 and an average winter pH of 3.7.

In contrast to salinity, the measured pH of the drainage discharge was significantly lower than expected, and significantly lower than the pH measured in the groundwater monitoring bores. The original predictions of discharge pH were based on measurements of groundwater pH. However, high concentrations of iron in the groundwater can lead to a reduction in pH when the groundwater is exposed to oxygen in the drainage system. The report suggests that groundwater pH is a poor indicator of the acidity and potential pH of the discharge from the drainage system.

The measured total acidity of the drainage discharge was similar to the groundwater. Total acidity of adjacent groundwater is a much better indicator of acidity and pH of drainage discharge.

The pH of the streamflows remained low (below pH 5) and often declined until the junction with Doradine Creek, 13 km downstream from the Fence Road drainage system. Surface water flows in the broader Dumbleyung catchment were generally alkaline and streamflows entering Dongolocking Creek from Doradine Creek generally resulted in significant increase in the pH of the combined streamflow. On some occasions, however, streamflow remained acidic with pH below 5 below Doradine Creek at least as far as 30 km downstream from the discharge from the drainage system.

Further downstream, streamflow pH continued to increase and was generally above pH 8 before it entered Lake Dumbleyung.

The report describes the risk that low pH of the drainage discharge can mobilise trace elements including aluminium, manganese, lead, nickel and zinc, which can be precipitated downstream as the pH increases.

Ecological monitoring

The ecological survey found a significant difference in the species composition and diversity upstream and downstream of the drainage system. Generally, the macroinvertebrate species richness was poorer in the drainage system and the receiving environment for a distance of up to 15 km downstream, than in the upstream and more distant downstream environments.

The survey also reported visible effects from the drainage discharge on aquatic flora, notably the poor health of *Ruppia* immediately downstream, of the drainage discharge site, compared with other areas of healthy *Ruppia* at more distant sites.

The extent to which the impacts were individually due to salinity, acidity or metals was not reported.

Key findings

- Acidic saline discharge from the Fence Road arterial drainage system was generally detectable 13 km downstream to the junction with Doradine Creek and occasionally up to 30 km downstream. Further downstream, streamflow pH increased and was generally above pH 8 before it entered Lake Dumbleyung.
- Average groundwater salinity is a good predictor of the salinity of drainage discharge. Drainage salinity varies salinity, decreasing in winter due to dilution by rainfall and surface run-off. Salinity in the drainage system increases in the direction of flow due to evapo-concentration.
- Groundwater pH is a poor indicator of the acidity and potential pH of the discharge from the drainage system and total acidity is a much better indicator of the final pH of drainage discharge. There is little seasonal variation in the pH of the drainage water, indicating that the acidity of the discharged groundwater dominates the pH of the drainage discharge.
- The drainage discharge had a measurable impact on aquatic ecology of the receiving waterway for a distance of at least 15 km downstream, with lower macroinvertebrate diversity, different macroinvertebrate community composition and visibly less healthy in-stream flora.
- In predicting potential downstream impacts, assume the neutralising capacity of the environment is limited to dilution and mixing with surface water with minimal alkalinity (<10 mg $CaCO_3$/L).

6.3 Monitoring activities in the Yarra Yarra area over the period Sep 2011 – Jan 2012 (Fordyce, 2012)

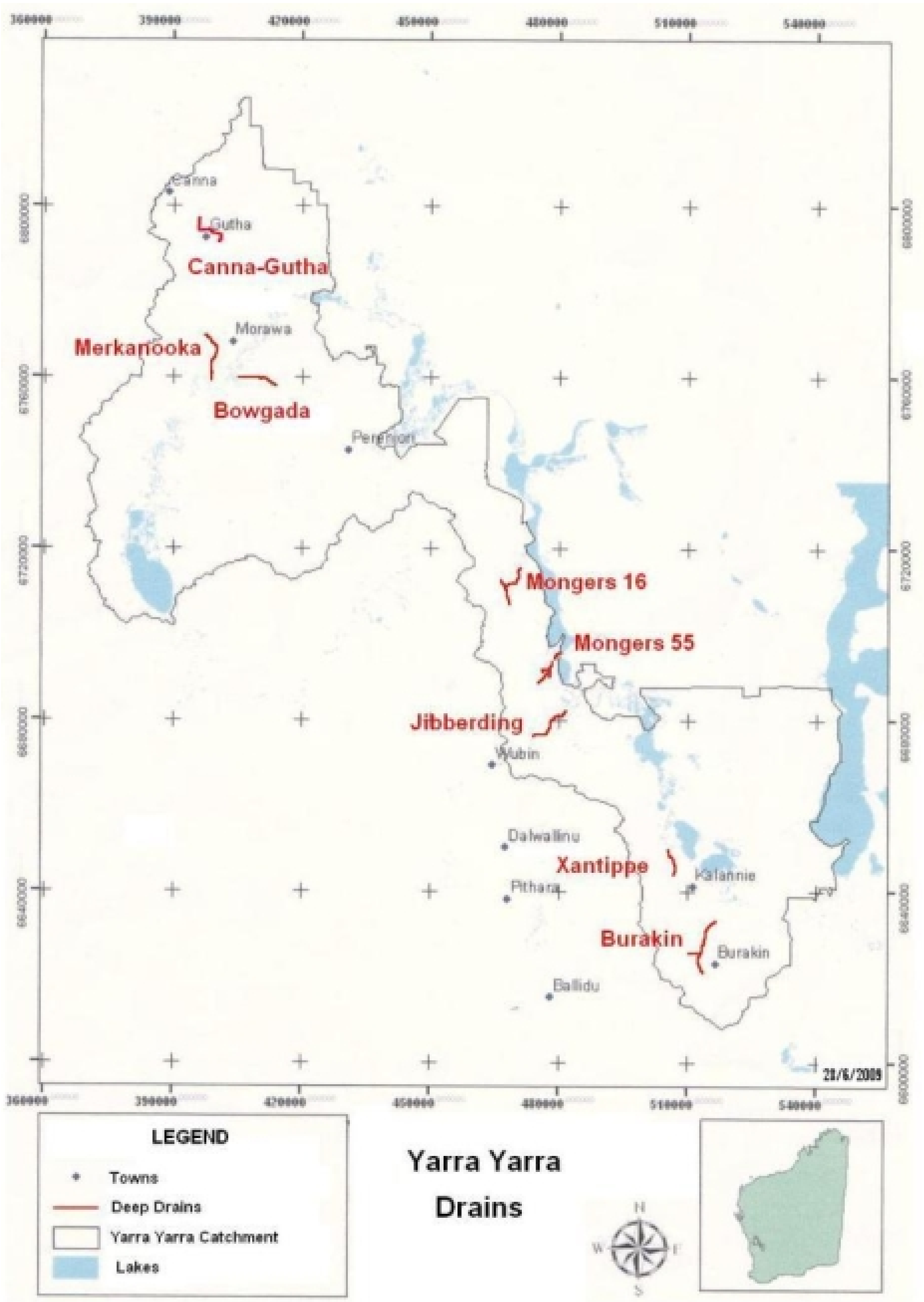

Figure 21 Yarra Yarra drainage projects - locations

The Yarra Yarra Regional Drainage Program comprises approximately 97 km of arterial deep drains constructed in the Yarra Yarra catchment for the purpose of lowering groundwater levels and controlling soil salinity. A total of eight drains were constructed over the period December 2006–July 2009. The planning, construction and maintenance of the drainage program was initiated and managed by the Yarra Yarra Catchment Management Group (YYCMG), with funding from the Commonwealth and State Governments.

The project sites are located across the western part of the Yarra Yarra catchment, which extends from Burakin in the south to beyond Morawa in the north, in the Northern Agricultural Region. The drains discharge to natural playas and salt lakes of the Yarra Yarra lake system and since their construction there has been concern about the possible impacts of drainage discharge on the downstream environments.

Monitoring

The YYCMG has been engaged in a wide range of monitoring activities in the catchment to evaluate the performance of deep drains and to identify potential downstream impacts. Monitoring commencing in 2003, three years before drainage construction, and continuing until 2013. The monitoring program included groundwater levels, drainage discharges, surface water and groundwater quality, vegetation health and aquatic ecosystem monitoring.

The report (Fordyce, 2012) presents a summary of results from environmental monitoring of five of the Yarra Yarra drains (Jibbering, Mongers 55, Mongers 16, Merkanooka and Canna-Gutha) over the period September 2011-January 2012.

Vegetation and land condition

For each drain, at least two permanent belt-transects were established near the discharge point and a further two transects were established as a nearby unexposed wetland to serve as control sites. Unlike previous quantitative vegetation surveys, the 2011-12 vegetation surveys described in this report were descriptive only. The belt transects were photographed and described.

Photographs and observations of land condition were recorded from 32 previously established permanent photo-points, for comparison with previous records.

Water quality and sediments

Water quality monitoring included in-situ measurements of pH. Seven drain water samples were collected and analysed for conductivity, total acidity, major elements, ions and metals.

Soil and sediment profiles were examined in six drains

Results

Jibberding

The Jibberding drain discharges into an ephemeral creek that meanders for a least 9 km between a series of small salt lakes before flowing into the southern end of Mongers Lake. The vegetation in the adjacent wetlands is dominated by samphires and other halophytes, typically arranged in concentric zones around a central lowpoint.

The groundwater discharge from the Jibberding drain is acidic (pH 3.4) and saline with high concentrations of dissolved iron (35 mg/L). The downstream impact of the drainage discharge is clearly visible. All samphires within a one-hectare area of at the drainage outlet appear dead or completely desiccated. Upstream of the drainage outlet the ground is waterlogged, the streambed discoloured (rusty yellow-brown) and the samphire discoloured.

The report suggests the impact on samphire is primarily due to waterlogging. The water quality data in the Jibberding drain and the reported rusty yellow-brown discolouration of the streambed and samphire suggests iron precipitation.

The report notes that the vegetation impact had not deteriorated since the previous survey in 2009.

Mongers 55

The Mongers 55 drain begins in agricultural land before flowing through a series wetlands and then into Mongers Lake. Vegetation transects were established in one of the wetlands, 15 Hectare Lake and in the nearby Placenta Lake, which is unaffected by the drain.

The vegetation in the wetlands in the area adjacent to the drain is dominated by samphires and other halophytes, typically arranged in concentric zones around a central lowpoint.

The vegetation survey of the 15 Hectare Lake transects could not detect any change that could be attributed to the drainage discharge.

Mongers 16 discharge

The Mongers 16 drain discharges through an area of samphire flat and scattered salt lakes depressions.

Since the drain was constructed in 2008, no changes to the vegetation downstream of the discharge have been observed beyond a few metres of the end of the drain.

Mongers 16 bushblock

In April 2008, prior to construction of the Mongers 16 drain, a vegetation survey was conducted in an area of remnant bush at the corner of Taylor Road and Rabbit Proof Fence Road, about midway along the drainage system. That survey found evidence of salinization in the form of dead and defoliated canopy trees, dead understorey, colonisation by semi-succulent chenopods and visible salt crystals on the soil surface.

In 2011, a number of changes to the vegetation were observed, including regeneration of the understorey with non-chenopod shrubs and the distribution of York gum seedlings.

Merkanooka

The Merkanooka drain discharges to a natural ephemeral creek line which in turn flows into the Yarra Yarra lake system. The creek line meanders across a broad flat samphire flat.

Since 2008, before the construction of the Merkanooka drain, vegetation surveys of transects established downstream of the drainage discharge and at upstream control sites have not identified any visible impact from the drain.

Canna-Gutha

The Canna-Gutha drain discharges to a creek which in turn flows into the Yarra Yarra lake system near Morawa. The creek is poorly defined and located in a broad flat valley floor, dominated by samphires and chenopods and with visible salt on the surface.

Since monitoring began, shortly after construction of the Canna-Gutha drain, no vegetation changes have been observed downstream of the drainage discharge.

Over the same period, since construction of the drain, areas of adjacent farmland have been returned to wheat production.

Water quality and sediments

The water quality in discharges from the Yarra Yarra drains was found to be variable. Drains in the southern part of the catchment (Xantippe, Jibberding and Mongers 55) were generally strongly acidic (pH 2.5-3.7), with elevated concentrations of iron and aluminium. Drains to the north (Mongers 16, Bowgada, Merkanooka and Canna-Gutha) were neutral to slightly alkaline (pH 7.6-8.3), with low concentrations of dissolved metals. This supports the findings from other studies that reported acidic groundwater occurs in the valley floors of the Yarra Yarra south of Perenjori (Degens and Shand, 2010).

Sediment profiles identified layers of monosulfidic black ooze (MBO) immediately downstream of discharge points for most drains. However, sediment profiles at many of the control sites, unaffected by deep drains, also presented layers of MBO.

Although associated with elevated concentrations of metals, none of the metal concentrations exceeded ARMCANZ/ANZECC guideline trigger values for freshwater systems.

Discussion

The vegetation surveys provide an important record of changes to downstream and adjacent environments.

The report suggests that the improvements in vegetation health at Mongers 16 drain (Bushblock) and Canna-Gutha drain (Stephens lease) are linked to the construction of the deep drains. However, in the absence of equivalent survey data from appropriate control sites it is difficult to attribute the observed changes to the construction of the drains.

The study did include vegetation surveys at two control transects at Lake Placenta, intended as control sites for the assessment of downstream impacts. Fordyce (2012) reports changes in the vegetation at these control sites at Lake Placenta (transects T4 and T5), suggesting that climate impacts are important.

Key findings

- Based on the results of vegetation surveys, the discharge from seven of the eight Yarra Yarra drains appears to have had no detrimental impact on the downstream environment. Only the Jibberding drain appears to have had a detrimental impact to an area of approximately one hectare around the discharge and which is attributed to waterlogging.
- The condition of land adjacent to Canna-Gutha and Mongers 16 drains was observed to have improved. Adjacent to Canna-Gutha drain, approximately 100 ha of samphire flat has been returned to wheat production. Salt-affected remnant bushland adjacent to Mongers 16 drain is showing signs of recovery since the construction of the drain. However, in the absence of suitable control sites it is not possible to separate the impacts of climate and the construction of the deep drains.
- Drains in the southern part of the catchment (Xantippe, Jibberding and Mongers 55) were generally strongly acidic (pH 2.5-3.7), with elevated concentrations of iron and aluminium. Drains to the north (Mongers 16, Bowgada, Merkanooka and Canna-Gutha) were neutral to slightly alkaline (pH 7.6-8.3), with low concentrations of dissolved metals.
- Layers of monosulfidic black ooze (MBO) were present in sediment profiles immediately downstream of discharge points for most drains. However, sediment profiles at many of the control sites, unaffected by deep drains, also presented layers of MBO.

7. Evaluation tools and methods

7.1 Remote sensing for assessing the zone of benefit where deep drains improve productivity of land affected by shallow saline groundwater (Kobryn et al., 2015)

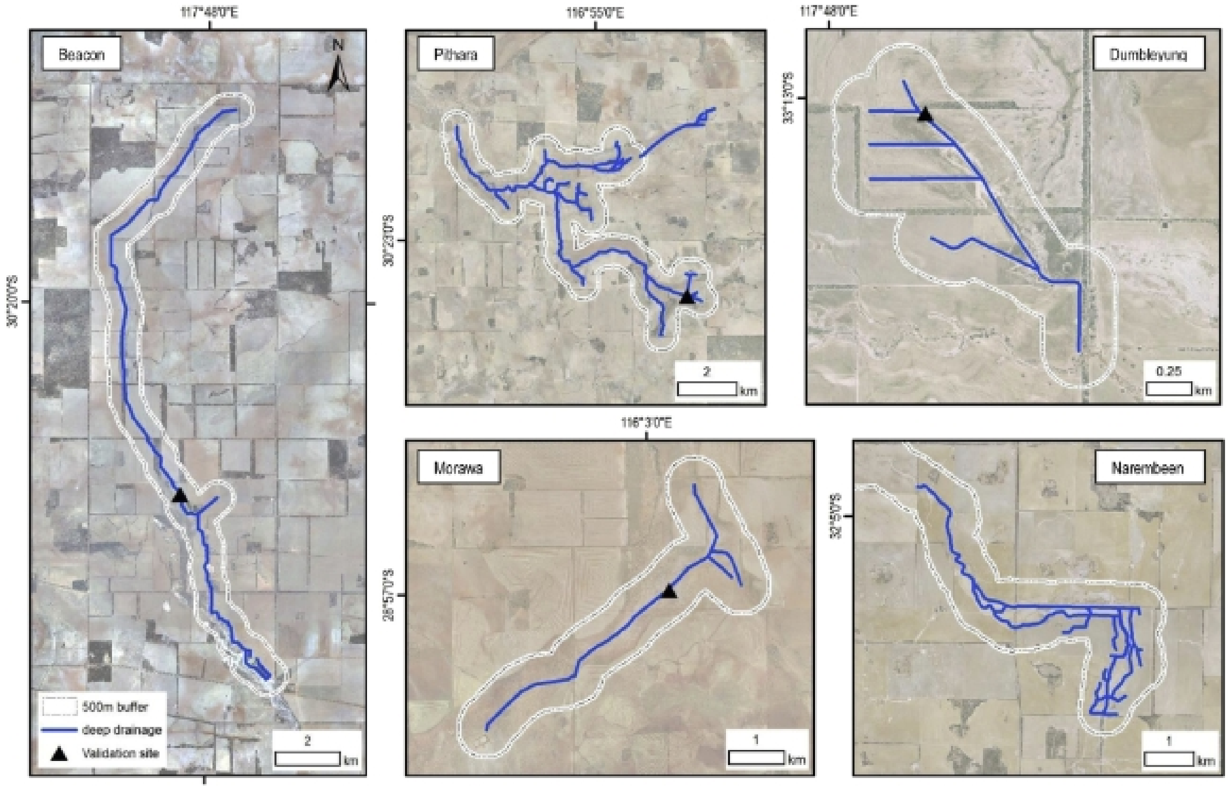

Figure 22 Remote sensing projects – site layouts

This study assessed the use of satellite remote sensing to detect changes in vegetation condition due to deep drainage and the usefulness of vegetation condition as a surrogate for biological activity.

Normalised Difference Vegetation Index (NDVI) is a quantitative assessment of vegetation condition derived from satellite data, such as Landsat Thematic Mapper (Landsat TM) data.

A previous study (Van Dongen, 2005) had found a strong relationship between NDVI and soil conductivity. The study analysed changes in vegetation condition (NDVI) over time in areas adjacent to deep drains to investigate the effect of the drains.

Five sites were selected for analysis: Dumbleyung, Narembeen, Beacon, Pithara and Morawa. (These sites are all described in other reports included in this review and are not described again in this section.)

Data analysis

The study used historical, free satellite remote sensing data in the form of Landsat TM derived NDVI data from the Land Monitor and AgImage projects. To assess the impact of the drains at each site, spring (August-September) NDVI data from pre- and post-drain years with similar spring rainfall were compared. Only cropped land was included in the analysis.

A statistical model was developed that considered the following variables for each site: NDVI, ground elevation and slope, presence (or absence) of a drain and distance from the drain.

Results

At the Dumbleyung site, pairwise comparison of spring NDVI data from 2003 (immediately after drain construction) and 2007 (post-drain) showed considerable increase in NDVI. However, the paper incorrectly associates the September 2003 NDVI data with pre-drainage conditions, yet the drain was constructed in 2002 and is clearly visible in the 2003 image.

The Narembeen data showed high spatial variability but over half the area within 500 m of the drain showed a noticeable improvement in greenness between 1997 (pre-drain) and 2007 (post-drain). Higher average NDVI values were associated with higher rainfall seasons and mostly with post-drainage years.

The paper also briefly describes the results of analysis of data from the Beacon, Pithara and Morawa sites. The authors note significant inter-annual variability in spring data before and after drain construction, which were attributed to factors including rainfall and cropping regimes.

The report claims that results from linear mixed effects modelling show that NDVI increased with installation of the drain at every site. It notes that Bell et al. (2010) had found that crop yields took 3-5 years to recover after the installation of deep drainage and suggests a future assessment of NDVI (when the drains have been in place for at least five years) may show more distinctive increases.

The mixed effects model developed for this study does not account for annual rainfall, which clearly has an effect on NDVI. The paper notes that NDVI values were generally higher in high rainfall years. For all sites, there are pre-drainage years in which the NDVI values presented are higher than post-drainage NDVI values. These data are not adequately explained in the paper and makes it difficult to identify (in the data presented in the paper) an unambiguous link between the installation of drains and an increase in NDVI values. Based on this difficulty in isolating the impact of climate, the report’s conclusion that all sites benefitted from the implementation of the drains is difficult to support.

Key findings

- Comparison of satellite-derived greenness index (NDVI) data for pre- and post-drain spring months with similar rainfall appears to be a useful indicator of the effectiveness of deep drains, but is limited by the difficulty of isolating the impact of climate.
- The difficulty in isolating the impact of climate on the NDVI casts some doubt on the claims in the report that all sites benefitted from the implementation of drainage.

8. Stakeholder evaluation

8.1 Drainage benchmarking in the Northern Agricultural Region: landholder survey (Beattie & Stuart-Street, 2008)

This study reported the views of landholders in the North Agricultural Region regarding the performance of deep drains.

The Northern Agricultural Region extends from Gin Gin in the south to Kalbarri in the north and eastwards to Kalannie. The region includes significant areas affected by salinity and many farmers in the region have either constructed or are considering constructing deep drains to lower the watertable and manage soil salinity.

The study completed interviews with 20 landholders who had already installed drains or were planning to do so. Although the survey sample may not have been representative of all drains in the region, it spanned a range of landscape and soil types from across the region.

The interview questions were grouped into six themes:

- Site conditions and alternative treatments
- Decision-making and planning processes
- Drainage design and construction details
- Changes since the drain was installed
- Impact of drain on farming operations
- Landholder satisfaction

Survey results

Site conditions and alternative treatments

Key reasons for excavation deep drains were to arrest the spread of salinity and return the land to agricultural production. Some landholders cited waterlogging and salinity caused by above average rainfall in 1999 as the reason for considering drainage.

Most of the landholders interviewed had previously tried alternative approaches to managing salinity, usually planting trees or perennial such as salt bush. However, comments from landholders suggest that tree-planting was no longer popular and was not considered a viable option for controlling groundwater levels or salinity.

Some landholders had previously installed surface water drains to manage salinity, with mixed success. One farmer had subsequently removed surface drains in preference to no-till farming practices.

Decision-making and planning processes

Most landholders took less than 2 years to decide whether to install deep drains. The actions of neighbouring landholders were often a factor in decision-making. Many (just over half) of the landholders experienced delays in installation after having made the decision to install a drain. The causes of the delays ranged from approvals documentation, negotiations with neighbours and local government, funding and weather.

The most common source of advice used by landholders before deciding to install deep drainage was drainage contractors, followed by neighbouring landholders. Landholders did not appear to access technical advice available from government agencies, which was considered too broad, not specific to individual farms and not providing clear guidance on actions.

Most landholders conducted some level of pre-construction site assessment, although the level of assessment varied with more detailed assessments being completed only when funded by a third party other than the landholder.

Drainage design and construction details

Most (but not all) of the drains were located in the valley floor, often to one side to retain separate surface water drainage. Most of the drains were excavated trapezoidal drains, enclosed with levees to prevent surface flows from entering the drain.

Two of the landholders had installed buried drains. One site was drained using slotted PVC pipe laid in a herringbone pattern over a 130 ha area with 40 m drain spacing. The landholder had wanted to avoid the loss of land required for open drains and was prepared to meet the increased cost of the buried drains. The second site was drained using buried vertical plastic sheeting, designed to intercept lateral groundwater flow and re-direct it to a natural surface water channel.

Drainage construction was generally limited to three drainage contractors, who had constructed the drains on the properties surveyed. One landholder was planning on constructing a drain himself.

The cost of construction varied between $2,000/km and $8,000/km and culverts generally up to $3,000 each. One culvert is quoted as costing $34,000 (possibly a road crossing).

A key challenge and cost is the design, approval and cost of road crossings. Landholders reported inconsistent policies, specifications and funding arrangements between Shires.

Most of the landholders’ drains crossed property boundaries so that drains discharged to downstream properties, either as part of a broader arterial drainage scheme or simply by negotiation with neighbouring landholders.

Changes since the drain was installed

Most (16 of 20) landholders reported improvements in waterlogging, soil condition and productivity of land adjacent to their drains. Of the four landholders who did not report any improvement, three felt it was too early to tell. Expected timeframes for drains to have an impact were typically a “few” years. Five landholders expected an impact within one year, two others thought 4-5 years and another as long as 10 years.

None of the landholders reported any downstream impacts on vegetation although one noted increased water at the discharge site. Drainage flows in most drains were reported to have reduced since their installation.

Half the landholders reported varying degrees of maintenance; most commonly de-silting after heavy rain due to erosion of the batters. Typical maintenance (de-silting) costs were reported in the range $1,000-$2,000/km. The landholder with the buried pipe drain reported no maintenance costs but operating cost (pumping) of approximately $1,500/year.

Impacts of the drain on farm operations

Most landholders reported that the installation of drainage had affected farm operations, mostly by restricting the movement of machinery and stock. Many reported stock in their drains, with some landholders subsequently fencing their drains.

Landholder satisfaction

Most landholders were satisfied with their drains and reported that drains were effective at reducing waterlogging and improving productivity. Most landholders felt their drains provided value for money, although the report suggests these views are not based on any detailed analysis. The report concludes that landholders are motivated by a need for action to combat the effects of salinity.

Four of the landholders received external funding for the construction of their drains, which influenced their decision to install drains. Two landholders would not have installed drainage without external financial assistance.

Discussion

The authors report that landholders generally had only limited knowledge of groundwater levels on their land, yet this is a critical factor for determining the location and design of deep drainage.

Several landholders referred to the high rainfall in 1999 as the reason for installing drains but there appeared to be no acknowledgement by landholders of the potential impact of the dry seasons and falling groundwater levels since 2000.

Key findings

- Landholders want face-to-face information about their particular situation. Written information currently available is considered too broad to be applicable at site level. The current key source of information is neighbouring landholders and drainage contractors.
- Most landholders conducted some level of pre-construction site assessment, although the level of assessment varied with more detailed assessments being completed only when funded by a third party other than the landholder
- Landholders generally believed their drains were effective in waterlogging and improving productivity.
- Most landholders felt their drains provided value for money, although these views are not generally based on any detailed analysis.
- Landholders generally have only limited knowledge of groundwater levels and the links between groundwater levels, climate and deep drainage.

9. Discussion

9.1 Drainage design and construction

The primary objective of deep drainage in the Western Australian wheatbelt is to lower and control groundwater levels to alleviate waterlogging and to allow rainfall recharge to leach salts from the upper soil profile, reclaiming salt-affected land and returning it to agricultural production. For productive cropping, the depth to saline groundwater needs to be controlled at depths below 1.5 m and 1.8 m below ground level, for barley and wheat respectively (Nulsen, 1981).

Deep drains generally work by lowering the watertable along the length of the drain (to approximately the level of the base of the drain), promoting lateral groundwater flow from the adjacent area towards the drain. The hydraulic gradient needed to drive this lateral groundwater flow and the resulting drawdown of the watertable and the rate of groundwater discharge to the drain are determined by the soil characteristics. For example, low permeability soils, such as clays, require a steep hydraulic gradient to drive groundwater flow and deep drains will typically result in narrow drawdown zones and low groundwater discharges. Highly permeable soils, such as sands, do not require steep hydraulic gradients to drive groundwater flow and deep drains can result wider drawdown zones and higher groundwater discharges. A good introduction to drainage mechanisms and their application to deep drainage is presented in Chandler and Coles (2003).

The key design parameters for deep drains are the depth, alignment and spacing (for parallel drains) of the drains. These should be determined for each site based on soil and aquifer characteristics, rainfall and target groundwater level. Other design considerations include the cross-sectional area (to safely convey the design flow), grade (to manage scour and sedimentation), side slopes (for stability and determined by soil characteristics), levees (to prevent surface water entering the drain), crossings and surface water management.

Useful guidelines for the design of deep drainage have been published (e.g. Chandler and Coles, 2003; Department of Agriculture and Food, 2016; Ali, Hatton, Byrne, Hodgson, Lambert and George, 2004). However, none of the papers reviewed explicitly presented a basis of design or supporting calculations for the deep drains constructed, other than the drain spacing for the parallel drains at Beynon Road (Cox and Tetlow, in prep.), Beacon and Morawa (Cox and Tetlow, 2015).

In some instances, drainage theory was applied to predict drainage discharge and drawdown (Cox, 2010; Cox, 2011; Cox and Tetlow, 2015; Cox and Tetlow, in prep.) but this was not used to influence the design depth of the drain. In most cases it seems that the design depth and cross section were determined based on accepted practice, taking the advice of the drainage contractor.

A summary of key design parameters for the deep drainage sites reviewed in this report is presented in Table 9.

Table 9 Drain design and construction parameters of drains reviewed

Site	Depth	Side slopes	Levees	Report
Narembeen - Deluis	2 m	0.4(H):1(V)	Yes - closed	Ali et al. (2004)
Narembeen - Town	3 m	0.4(H):1(V)	One side only	Ali et al. (2004)
Narembeen - Pini	3 m	0.35(H):1(V)	Yes - closed	Ali et al. (2004)
Narembeen – John Deluis	1.5 m	0.5(H):1(V)	Yes - closed	Ali et al. (2004)
Narembeen - Latham	2.3 m	0.4(H):1(V)	One side only	Ali et al. (2004)
Narembeen - Bailey	2.5 m	Rectangular (i.e. vertical sides)	Yes - closed	Ali et al. (2004)
Wallatin Creek	2.5 m		Yes - closed	George & Stainer (2009)
Pithara	2.5 m	0.5(H):1(V)	Yes Old – discontinuous New - closed	Cox (2010)
Morawa	2.5 m	0.5(H):1(V)	Yes – closed, 1.1. m high	Cox (2011), Cox & Tetlow (2015)
Beacon	2.5 m	0.5(H):1(V)	Yes - closed	Cox & Tetlow (2015)
Hillman River South	2 m	1(H):1(V)	Yes – closed, 1.2 m high	McDougall (2012)

Drainage depth

The choice of drain depth seeks to optimise cost against effectiveness. Deep drains are more effective but take more land and are more expensive to excavate and maintain.

Most of the drains reviewed for this study were 2-3 m deep, with 2.5 m being the most common depth. The deep drains at Narembeen were claimed to be effective at depths greater than 2 m below ground (Ali et al., 2004), although a critical factor was the interception of porous ferricrete and silcrete layers at a depth of approximately 2 m. The John Deluis drain was 1.5 m deep and was considered too shallow to be effective.

At the Beynon parallel drains near Dumbleyung (Cox and Tetlow, in prep.), groundwater levels adjacent to the 3 m drain fell more than groundwater levels adjacent to the 2.5 m deep drain and 2 m deep drains were considered too shallow to adequately control groundwater levels.

Generally, the more recent drains were 2.5 m deep. This depth appears to have been chosen as a pragmatic depth, arrived at by the experience of the drainage contractors using the available plant and equipment. The drains in the Yarra Yarra Catchment Drainage Program were mostly 2.5 m deep after early trials found 2.5 m deep drains to be more effective than 2.1 m deep drains (YYCMG, 2010).

The Beynon Road study (Cox and Tetlow, in prep.) found that 3 m deep drains were more cost-effective than 2 m deep drains. Although that assessment did not include 2.5 m drains, it suggests the widely used 2.5 m depth may not be the optimum depth for deep drains.

As already noted, although drainage theory and design tools are available, there is no evidence that these tools are used to design the depth of deep drains. Noting the substantial investment that deep drains represent, it is surprising that greater value is not placed on optimising performance through design.

Side slopes

The choice of side slope needs to consider the conflicting factors of initial construction cost (steep batters deliver smaller cross sections with reduced land area and cheaper construction costs) and ongoing maintenance costs (shallow batter slopes are more stable with less erosion, requiring less maintenance).

Most of the drains in studies included in this review had side slopes of 0.5(H):1(V). This slope has been largely determined by the experience of the drainage contractors who have developed excavator buckets to efficiently construct drains of this profile.

Based on the batter trials at Wubin (Cox and Tetlow, 2009) the drain with 0.5(H):1(V) batter slope had a lower combined construction and maintenance cost that drains with 1(H):1(V) batter slope or a stepped batter.

However, soil type is an important factor and steep batters are less stable in sandy soils. At the Hillman River South drain (McDougall, 2012) the sandy soils required a 1:1 batter. The groundwater inflows still caused these batters to collapse, requiring regular de-silting. However, a flatter batter slope would have been impractical and costly. Buried pipe drains could be more cost effective in unstable and saturated soils such as those at Hillman River South. However, buried pipes present other challenges and have not been universally successful, as demonstrated at the site in Three Springs (Stuart-Street et al., in prep.).

Levees and surface water management

It is now widely accepted that best practice in deep drainage design and construction requires the exclusion of surface water flows from the deep drain. This is usually achieved by using material from the excavation of the drain to construct levees. Levees need to be designed and constructed to exclude surface flows at crossings. Levees need to allow access for plant and machinery for de-silting, either allowing excavators to travel along the crest of the levee or on a sufficiently wide berm between the deep drain and the levee.

The deep drains in this review included drains with and without levees. Where levees had been constructed, effective maintenance is important to maintain the integrity of the levees so they continue to exclude surface water from the drain. During a visit to the Fence Road Drainage System in May 2016, landholders expressed concern that poorly constructed and maintained levees had allowed surface water to enter the deep drain, further damaging the drain. Similarly, a visit to the Narembeen drainage system in May 2016 identified breaches in levees that had allowed surface water to enter the drain, causing further damage and flooding.

The long-term stability of levees is determined by soil characteristics, batter slopes and construction. Stuart-Street et al. (in prep.) found that only one of the five drains in that study had followed published guidelines for design and construction of the levee banks.

9.2 Performance of deep drains

The monitoring periods for all sites coincide with declining AMRR

With the notable exception of the areas between the parallel drains at Beynon Road and Morawa, groundwater levels across most of the sites are closely correlated to rainfall and climate, typically represented by Accumulated Monthly Residual Rainfall (AMRR). This applies to groundwater levels measured in monitoring bores adjacent to drains and, where available, to comparison bores (bores located to be unaffected by drain construction).

When a groundwater monitoring period coincides with a period of declining rainfall, declining groundwater levels (as well as observations of crop productivity, soil salinity and vegetation health) can be incorrectly attributed to the construction of a deep drain.

Figure 23 plots the approximate monitoring periods for each of the deep drainage sites against the AMRR (1985-2015) for Bowgada (Yarra Yarra), Narembeen and Bunkin (near Dumbleyung) Bureau of Meteorology stations, representing the northern, eastern and southern parts of the wheatbelt. The residual rainfall data clearly show the period of increasing AMRR in the late 1990s, which resulted in rising groundwater levels across the wheatbelt around the year 2000, followed by a decade of steadily declining AMRR.

Groundwater trend analysis (Raper et al., 2014) confirms that in the northern parts of the southwest agricultural region rainfall was above the long-term average in the years prior to 2000 and rising groundwater trends were widespread. Rising groundwater trend was a major factor for increasing salinity risk. Perhaps unsurprisingly, this period coincided with the growth in interest in deep drainage. The Narembeen drainage system (Ali et al., 2004) was commenced during this period of rising groundwater and many landowners referred to the high rainfall in 1999 as the reason for installing drains (Beattie and Stuart-Street, 2008).

From 2001-2007, rainfall was well below average and groundwater trends were mostly falling or stable. Since 2007 rainfall has been closer to the long-term average and rising groundwater trends are returning to some areas.

The monitoring periods for all of the projects reviewed in this study fall within the period of declining rainfall and falling groundwater levels, making it difficult to isolate the impact of climate from observed groundwater data (Figure 23).

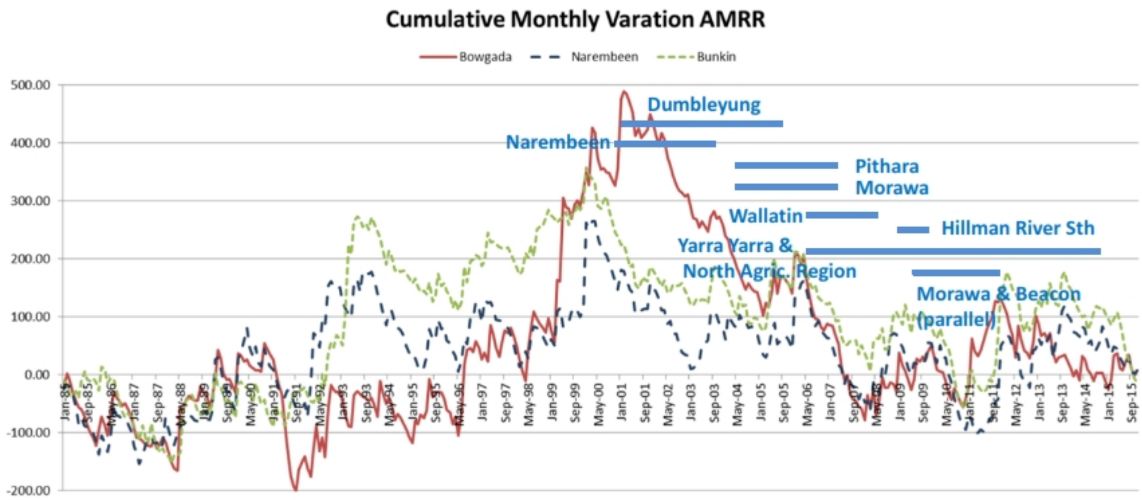

Figure 23 Drain monitoring periods compared with long-term AMRR

Single deep drains are unlikely to effectively lower and control groundwater

The results from the studies reviewed show that single deep drains were not effective at lowering and controlling the watertable at the levels required to recover land for agricultural production. Where a watertable response to drainage was observed, it was generally close to the drain.

Single deep drains at Pithara did not control groundwater levels beyond a narrow area immediately adjacent to the drain because the aquifer discharge exceeded the capacity of the drain. Although the landowner at the Pithara site reported that he had been successfully cropping areas adjacent to the drains since the failed 2006 crop reported in Cox (2010), he was uncertain whether this was due entirely to the drains or to climate. Both the monitoring bores close to the Pithara drain and comparison bores at a distance from the drain showed very similar water level fluctuations over the monitoring period and reflected trends in the AMRR, suggesting that the declining watertable may have been the result of a period of reduced rainfall and not the construction of the drain (Figure 24).

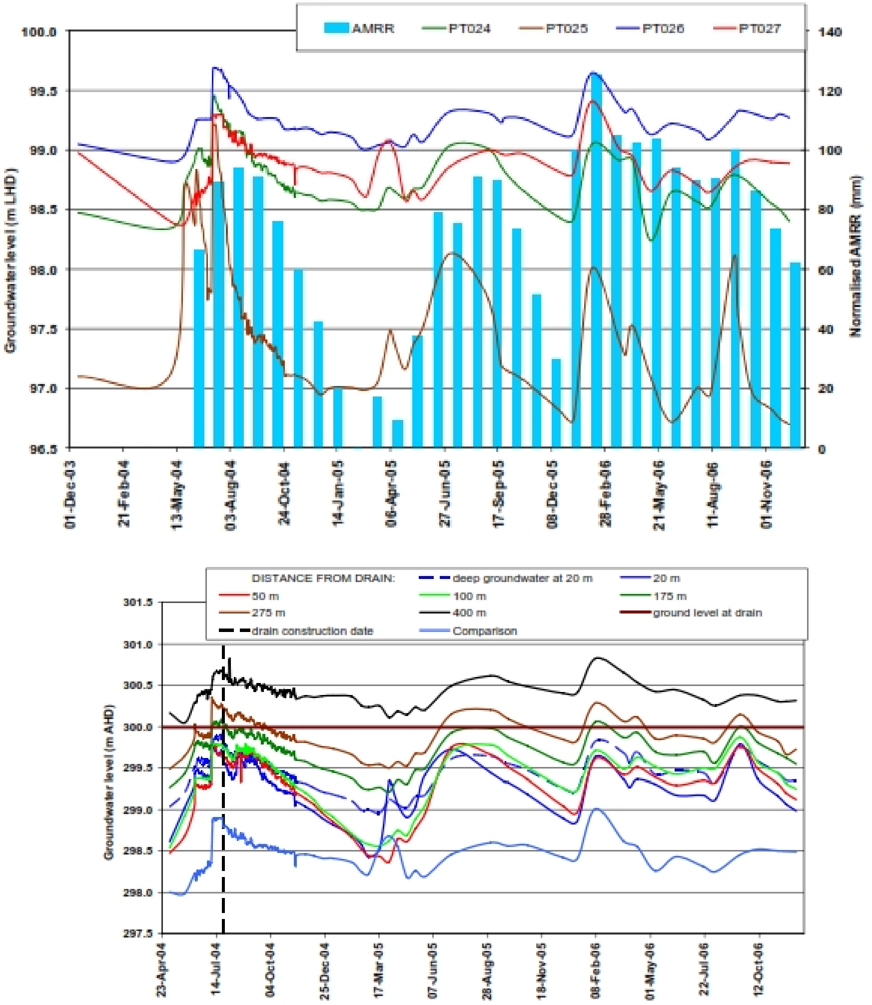

Figure 24 Pithara: hydrographs from comparison bores (top) and transect bores (bottom) show the same patter and are closely linked to AMRR (top) (from Cox, 2010)

Groundwater hydrographs from the Morawa single drain show similar results, with the comparison bores showing the same pattern as bores adjacent to the drain and groundwater levels all bores responding to changes in rainfall (Figure 25).

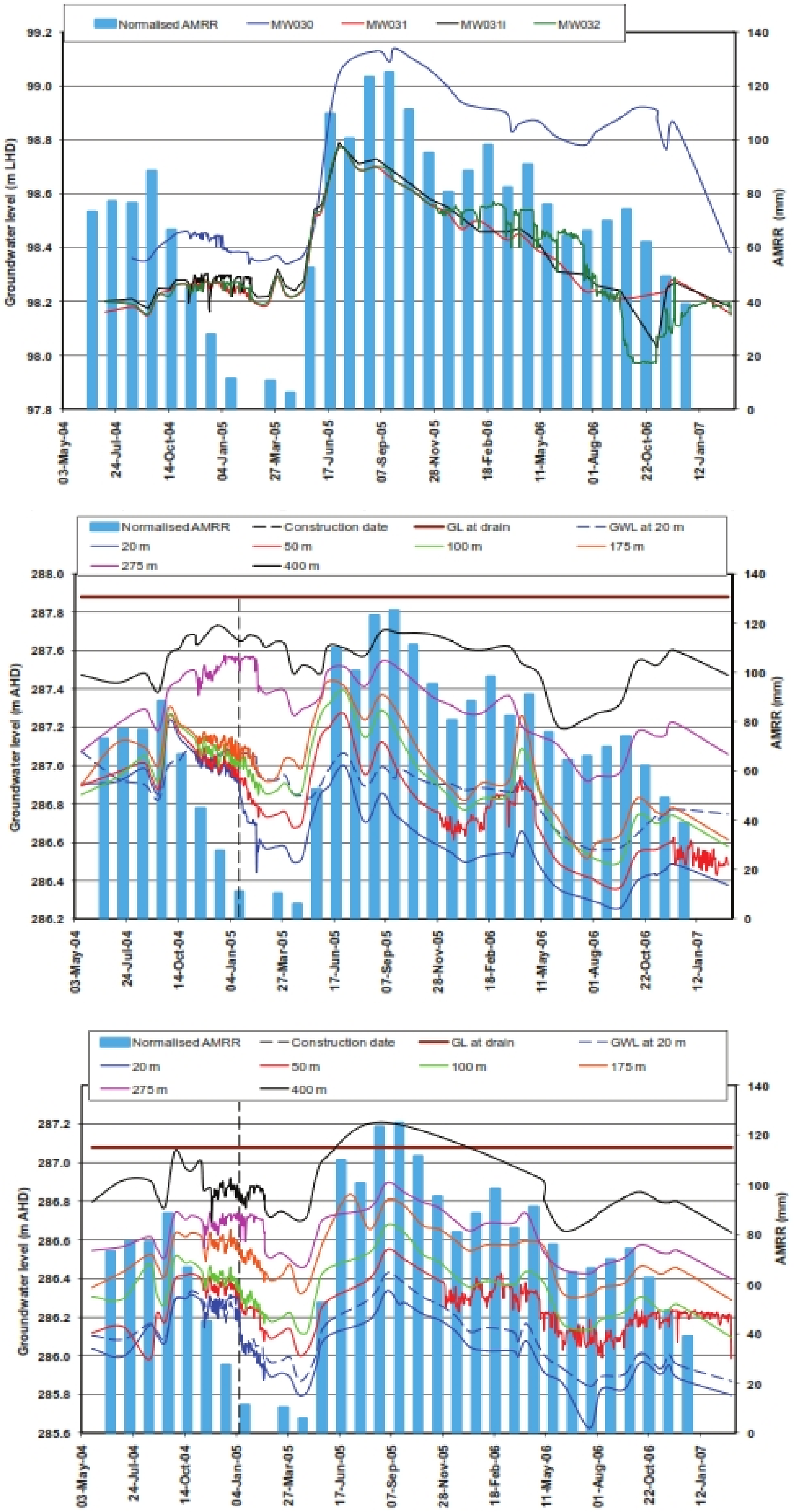

Figure 25 Morawa: hydrographs from comparison bores (top) and transect bores (middle and bottom) show the same patter and are closely linked to AMRR (from Cox, 2011)

Similar results were reported at Wallatin Creek where although the construction of the 2.5 m deep drain resulted in an initial 0.2 m decline in watertable levels, no further impact from the drain could be identified over the two-year monitoring period. The authors of that report attribute the decline in watertable and improvements to productivity at Wallatin Creek to climate (specifically declining rainfall) and not to the construction of the drain.

At Hillman River South, which is an area of higher rainfall than the Pithara and Wallatin Creek sites, a single deep drain had no measurable effect on waterlogging or watertable levels (which remained at or above ground level) because the recharge adjacent to the drain exceeded the capacity of the drain.

Ali et al. (2004) reported more success at Narembeen with claims that single deep drains effectively lowered and controlled watertables at depths of 2 m below ground surface for significant distances (200 m) either side of the drain. However, an assessment of the data presented in that paper suggests the impact of the drains at Narembeen is over-stated. The watertable at the control site (John Deluis site) showed similar declines as at the Latham site, where declines were attributed to the deep drain. Data presented in the paper shows the watertable at the Latham site rose to within 1 m of the surface at times during the monitoring period, which is too shallow for reliable cropping. Furthermore, the watertable fluctuations at the Narembeen sites appeared similar at drained and undrained sites.

The placement and spacing of monitoring bores is critical for the accurate determination of watertable drawdown and estimations of the zone of benefit caused by deep drains. If bores are too widely spaced, the zone of benefit will be over-estimated. Stuart-Street et al. (in prep.) suggests that the bore spacing used by Ali et al. (2004) to evaluate drains at Narembeen may have over-estimated the drawdown attributed to the drains.

Parallel deep drains may be effective in some instances

The results from the initial studies of parallel drains at Dumbleyung and Morawa suggest that deep drains constructed in parallel may be effective at lowering groundwater levels in some instances.

The Beynon drainage project demonstrated that parallel drains could lower and control groundwater levels more effectively than single drains (Cox and Tetlow, in prep.). At the Dumbleyung sites, an acceptable reduction in groundwater levels was only achieved within 50 m of the single drains, whereas the parallel drains demonstrated that groundwater levels could be effectively controlled over the 220 m distance between the drains. Subsequent analysis suggested that parallel drains at Beynon could have been effective at a spacing of 360 m.

Similar results were observed between parallel drains at Morawa and Beacon (Cox and Tetlow, 2014). Figure 26 shows groundwater hydrographs from bores installed to monitor the impact of single drains at Beacon and Morawa. The bores show that the single drains did not lower or control the watertable but that the subsequent construction of adjacent parallel bores produced resulted in a significant lowering of the watertable. The hydrographs also show the removal of significant fluctuations in groundwater levels after the installation of the parallel drain. Although the drain spacing at Beacon (400 m) was too wide to maintain groundwater levels below the critical depth (<1.5 m below ground level), the more closely spaced drains at Morawa (360 m) lowered and controlled groundwater levels at below the critical depth. The lowering of groundwater levels at Morawa allowed cropping on previously salt-affected land between the parallel drains. The success of the drains has encouraged the landowner to construct several further parallel drains at the site.

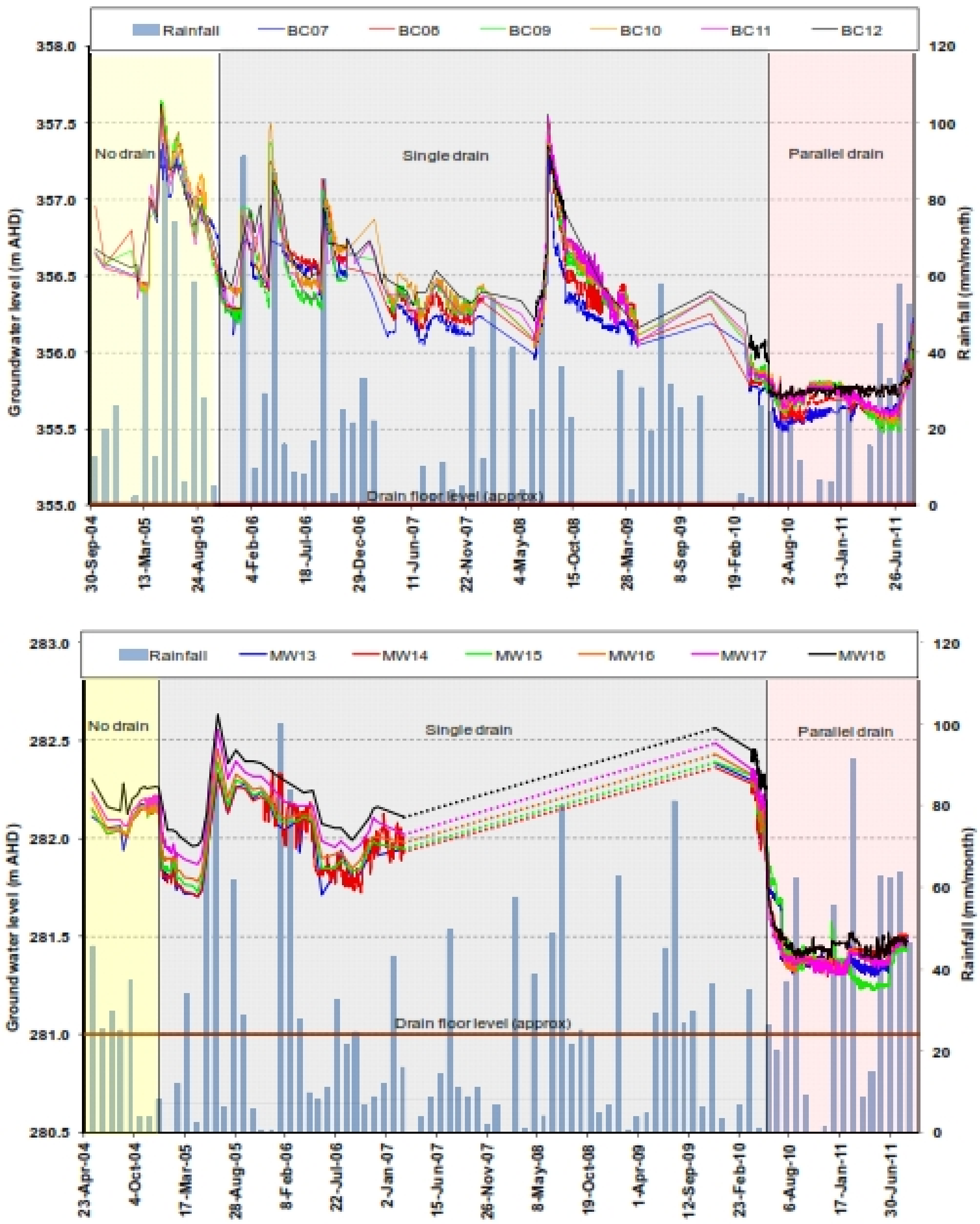

Figure 26 Watertable response to parallel drains: hydrographs from monitoring transect bores at Beacon (top) and Morawa (bottom) show very different watertable response at the same site following the construction initially of single drains (2004-2005) and later a parallel drain (2010) (from Cox and Tetlow, 2015)

Internationally, most agricultural drainage schemes comprise of a network of parallel lateral drains connected to a main drain and most agricultural drainage theory and design tools have been developed for these parallel drainage networks. Drain spacing, or drainage intensity, is a key design parameter for these systems.

Previous deep drainage designs in the wheatbelt have misinterpreted drainage theory and the accompanying tools, which were generally developed for parallel drains and assume a no-flow boundary at some distance. When the theory was applied to the Beynon parallel drains it was found to be consistent with the monitoring results, but when it was applied to single drains it underestimates the drainage discharges and overestimates the groundwater drawdown

Importance of soil permeability

The performance of deep drains is partly determined by the soils in which they are excavated. Highly transmissive soils will lead to greater groundwater discharge to the drain and can lead to a wider zone of benefit (although permeability alone is not sufficient to deliver a wider zone of benefit).

In the Narembeen drains (Ali et al., 2004), the high groundwater discharge (5-10 ML/day) was associated with porous ferricrete and sand seams intercepted by the drain. Conversely, the drainage efficiency at the Pithara site (Cox, 2010) was limited by the low permeability of the clay subsoils.

However, soil permeability alone is not sufficient to ensure that a deep drain will lower and control the adjacent water table. Deep drains at the Hillman River South site were excavated through highly transmissive soils but had no significant impact on the adjacent water table because the recharge adjacent to the drain exceeded the capacity of drain.

Soil and crop response

The key objective of most deep drainage systems is to return salt-affected land to agricultural production. Lowering and controlling groundwater levels below a critical depth prevents upward migration of salts by capillary rise and allows accumulated salts to leach from the upper soil profile.

Most of the projects reviewed in this study focussed on watertable response to the construction of deep drains. Predicting watertable response to drains is critical in determining the feasibility of deep drainage, is relatively simple to measure (although attention to bore spacing, monitoring period and frequency and an understanding of climate and other factors is important) and can be investigated in the timeframes typically allowed for the projects reviewed (1-3 years).

However, the focus on watertable response is an over-simplification of the challenge of restoring salt-affected land. The processes and timescales for the leaching of salt from the soil profile, the importance of soil solution salinity, the impact of occasional high-watertable events on soil and soil solution salinity, the recovery of soil structure and soil organic matter and the crop response to these processes are less well understood.

The need to examine crop productivity, soil salinity and soil moisture data was a recommendation for further work from the early EEI workshops (Dogramaci and Degens, 2003). Some studies have investigated the impacts of drainage on soils (e.g. Bell and Mann, 2004; Bell et al., 2009), the importance of soil and soil solution salinity on various crops (Setter et al., 2016; Rengasamy, 2016) and the effects of depth to watertable and soil salinity (Barrett-Lennard, Bennett and Altman, 2013). Those studies highlighted the complex interaction between soil chemistry, soil moisture content and plant response. Furthermore, the seasonal nature of plant germination, growth and flowering means the timing of rainfall events affects the impacts of salinity on crop productivity.

To understand the feasibility of deep drainage as a tool for restoring salinized land to agricultural production requires a better understanding of the impacts of drainage on soil productivity, the effects of soil and soil solution salinity on crops and of methods to improve the recovery of salt-affected land after drainage. These processes are more difficult to measure than watertable response, more difficult to isolate and require longer-term research programs.

9.3 Groundwater and drainage discharge water quality

The characteristics of water discharged from deep drains are closely linked to the surrounding groundwater. In many parts of the wheatbelt the groundwater is saline, particularly under the flat valley floors, and commonly, although not always, acidic with elevated metal concentrations (Shand and Degens 2008; Degens and Shand 2010).

Acid groundwater is naturally occurring across the wheatbelt. It is typically found between 5-10 m depth but it is highly variable spatially, with acid and non-acid bores occurring within hundreds of metres of each other (Lillicrap and George, 2010). For example, in the Fence Road Drainage System, the groundwater varies from almost neutral in the upper catchment to acidic in lower catchment (Seewraj, 2010). Over a larger scale, groundwater in the southern part of the Yarra Yarra catchment (Xantippe, Jibberding and Mongers 55) is generally strongly acidic (pH 2.5-3.7), while to the north (Mongers 16, Bowgada, Merkanooka and Canna-Gutha) groundwater is neutral to slightly alkaline (pH 7.6-8.3) (Fordyce, 2012).

The origins of acid groundwater appear to be long-term biologically mediated processes (Lillicrap and George, 2010). Vegetation type can explain about one third of the variability, with the occurrence of acid groundwater being strongly correlated with Eucalyptus woodlands and shrublands and subsoil alkalinity. Based on soil mapping of subsoil alkalinity, acid groundwater is predicted to be more widespread than previously thought, although mainly confined to valley floors of palaeo drainage lines (Lillicrap and George, 2010).

The hydrolysis of dissolved iron in the groundwater (when it is exposed to oxygen in the drain) sometimes results in lower pH in the drainage discharges than in the surrounding groundwater (Cox and Tetlow, in prep.). Consequently, groundwater pH alone is a poor indicator of the acidity and potential pH of the discharge from the drainage system and total acidity is a much better indicator of the final pH of drainage discharge. In the absence of national guidelines for inland saline ecosystems, Degens (2013) has proposed a maximum net acidity of 10 mg $CaCO_3$/L for drainage discharges to waterways and lakes. Where drainage discharges exceed these values it may be necessary to treat acidic water before discharge (Degens, 2009).

The salinity of drainage discharges also reflects the salinity of the surrounding groundwater but shows a strong seasonal variation due to the effects of dilution by rainfall in the winter and evapo-concentration over the summer. For example, the salinity of the discharge from the Beynon drain near Dumbleyung varied from 5,000 mg/L to 95,000 mg/L (Cox and Tetlow, in prep.).

Deep drains do not change salinity or pH of the surrounding aquifer. Deep groundwater in particular is very stable, although some fluctuations in salinity occur in shallow groundwater.

Planning for any deep drains should consider the water quality of the surrounding groundwater. Preliminary desktop investigations could consider predictive mapping based on subsoil alkalinity (Lillicrap and George, 2010). Site investigations should be undertaken to characterise the groundwater, noting the recommendation to use total acidity, rather than pH, as an indicator of potential pH of drainage discharge.

9.4 Downstream impacts

A key concern regarding the excavation of deep drains is the potential adverse impacts on downstream receiving environments due to the increased salinity, acidity and nutrient concentrations in the drainage discharge.

Potential downstream impacts were only evaluated for four of the deep drainage sites: Hillman River South, Fence Road, Beynon Road, Morawa and the Yarra Yarra Catchment Regional Drainage Program.

The construction of the Hillman River South drainage system increased surface water flows and salinity in the river within a kilometre of the discharge point but did not change pH (McDougall, 2012). No changes in water quality could be detected 10 km downstream, so it is unlikely that the discharge from the Hillman River South drain is detrimental.

In contrast, acidic saline discharge from the Fence Road arterial drainage system was generally detectable 13 km downstream to the junction with Doradine Creek and occasionally up to 30 km downstream (Seewraj, 2010). Further downstream, streamflow pH continued to increase and was generally above pH 8 before it entered Lake Dumbleyung. The drainage discharge had a measurable impact on aquatic ecology of the receiving waterway for a distance of at least 15 km downstream, with lower macroinvertebrate diversity, different macroinvertebrate community composition and visibly less healthy in-stream flora.

Discharges to some salt lakes and playas, such as the Yarra Yarra wetlands, may have a limited and acceptable environmental impact. Many salt lakes and playas in the wheatbelt are already degraded with limited biodiversity and are exposed to naturally saline and sometimes acidic groundwater. Evaporation of the drainage discharges usually limits the area impacted and some salt lakes have natural buffering capacity, which can mitigate the impact of low pH drainage discharge. However, if some salt lakes or playas are accepted as sacrificial disposal sites it is important to identify and protect those systems with high environmental values.

The YYCMG supported a range of ecological monitoring activities, including an assessment of the effect of deep drains on the ecology of the Yarra Yarra playas and wetlands (WRC, 2008). That study found that the Yarra Yarra catchment continues to support a moderately rich aquatic invertebrate fauna. The macro-invertebrate community structure in the Yarra Yarra wetlands is primarily influenced by salinity, with species richness declining with increasing salinity. The micro-invertebrate communities are primarily affected by acidity and secondarily by salinity (many wheatbelt species are naturally salt-adapted). Most naturally saline systems are alkaline, so that acidic saline wetlands represent extreme environments. Acidification poses a substantial threat to the biodiversity of wheatbelt playas and wetlands. Most of the study sites had elevated concentrations of dissolved metals and the dissolved metals in acidic drainage water may have an impact on invertebrate fauna.

Salinity and pH appear to provide good predictors of biodiversity and offer cost effective proxies to more expensive invertebrate fauna monitoring. Monitoring programs should adopt sampling and analysis methods that allow the speciation of metals to provide better estimates of bioavailable metal concentrations where metal concentrations are expected to exceed the guideline trigger values.

Potential downstream impacts can be mitigated by discharging drainage water to constructed evaporation basins such as at Morawa (Cox, 2011). Leakage from the evaporation basin at Morawa was greater than anticipated and up to 79% of the water pumped into basin was lost to leakage through the uncompacted base. The resulting groundwater plume extended over approximately 60 ha downgradient of the basin, increasing soil salinity across this area and resulting in visible salt crust at the surface. However, the impact of the leakage from the Morawa basin was significant, due to the salt-effected condition of the area before the construction of the basin.

9.5 Construction costs

The cost of construction is a function of several factors including: location, soil type, depth of the drain, side slopes, levees and crossings. In the reports reviewed, construction costs were provided for seven sites (Table 10).

Table 10 Summary of drainage costs (depth is 2.5 m and side slopes are 1(H):0.5(H) unless noted).

Site	Year	Drain	Culverts/ crossing	Report
Pithara	2004	$6,453/km	$1,819 ea	Cox (2010)
Morawa	2005	$6,944/km	$6,000 ea	Cox (2011), Cox & Tetlow (2015)
Dumbleyung	2002	1 m: $1,800/km 2 m: $6,100/km 3 m:$14,600/km	-	Cox & Tetlow (2015)
Wubin	2006	1(V):0.5(H): $6,500/km 1(V):1(H): $12,500/km stepped: $10,800/km	-	Cox & Tetlow (2009)
Hillman River South	2009	2 m; 1(V):1(V): $13,500/km	-	McDougall (2012)
Yarra Yarra	2008-2009	$8,000-9,000/km	-	YYCMG (2010)
		$16,727 (incl. culverts and crossing)		
Northern Agricultural Region	2006-2009	$2,000-8,000/km	$3,000 ea	Beattie & Stuart-Speed (2008)

The cost of drain construction increases nonlinearly with depth due to the combined effects of the nonlinear increase in excavation volume and the decreased excavation efficiency with increasing depth (increased cycle time). At Dumbleyung the excavation cost almost doubled for each 1 m increase in depth, increasing from $1,800/km at 1 m depth, to $6,100/km for 2 m depth to $14,600/km for 3 m depth (Cox and Tetlow, in prep.).

A similar impact is caused by side slope. At Wubin, the cost of excavating a 2.5 m deep drain increased from $6,500/km for 1(V):0.5(H) to $12,500/km for 1(V):1(H). This increase is consistent with the cost of excavating a 2 m deep drain at Hillman River South with a side slope of 1(V):1(H), which was $13,500 (McDougall, 2012).

To account for the effect of inflation over the time since construction, the Australian Bureau of Statistics Consumer Price Index calculator (Cat. No. 6401.0) was used to convert the cost in the year of construction of four drains to indicative 2016 cost (Table 11). The equivalent average 2016 cost of 2.5 m deep drain with 1(V):0.5(H) side slopes was $8,673/km (say $8,000-9,000/km). Although there is a range of drains excavation costs, the costs for similar drains are relatively consistent, possibly driven by the limited number of drainage contractors.

Applying the same technique to escalate the all in costs (excavation of deep drain, levees, surface water drains and crossings) from the Yarra Yarra Regional Drainage Program (YYCMG, 2010) suggests a total arterial drainage cost of approximately $20,000/km (2016).

Table 11 Indexed construction costs for 2.5 deep drain with 1(V):0.5(H) side slopes

Site	Construction year	Construction cost	2016 cost
Beynon	2002	$6,100/km	$8,648/km
Pithara	2004	$6,453/km	$8,695/km
Morawa	2005	$6,944/km	$9,130/km
Wubin	2006	$6,500/km	$8,218/km
Average (mean)			**$8,673/km**

9.1 Economic evaluation

Although there is some construction cost information available in the reports reviewed, only one of the reports presented any benefit-cost analysis (Cox and Tetlow, in prep.), or other economic evaluation of the construction of deep drains.

At Beynon, the superior performance of the 3 m deep parallel drain out-weighed its increased cost. A 30-year benefit cost analysis concluded that the 3 m deep parallel drains produced a consistently high enough benefit/cost ratio (1.8) to be considered financially viable. This compared with 2 m deep parallel drains with a benefit/cost ratio of 1.2 (financially marginal). Single deep drains were not considered financially viable at any depth, with the 3 m deep single drain producing a benefit/cost ratio of 0.74 and a 2 m deep single drain a benefit/cost ratio of 0.13. Some caution must be applied when making investment decisions on the limited data presented. Although the cost of drain construction appears well understood, the economic benefit will depend on the increased crop yield achieved and the market price.

Although only one of the reports included in this review presented any economic or benefit-cost analysis, other studies have attempted to investigate the economic benefits and costs of salinity in the wheatbelt (Hardy and Ryder 2013, Herbert 2009) and use benefit-cost analysis to inform selection of deep drainage options (URS 2006). In a more practical form, DrainLogic is a computer-based tool designed to assist landholders assess the feasibility of deep drains and which includes an economic assessment tool that considers construction costs, area of land affected and the predicted crop response (George, Abadi and Raper 2009).

Where deep drains are unable to return salt-affect land to agricultural production, they may still have sufficient impact to slow the rate of salinisation or to allow some revegetation. These intangible benefits were not considered in the economic evaluation and may be sufficient to influence some landowners to install deep drains.

9.2 Stakeholder evaluation

Farmers who have installed drains in the Northern Agricultural Region generally support drains and believed their drains were effective in reducing waterlogging and improving productivity (Beattie & Stuart-Street, 2008). This is a very similar result to a survey of farmers' attitudes in the Avon, Yilgarn and Lockhart catchments (Kingwell and Cook, 2007), suggesting that a belief in the efficacy of deep drains is widely held across the wheatbelt of Western Australia. Indeed, the landowners met during site visits undertaken for this review in May and June 2016 were almost all supportive of deep drains. The only landowner to publicly express some concern about deep drains was from the downstream end of a drainage system and his concerns were linked to adverse impacts from flooding due to poor maintenance of the drain and its levees.

Most landholders also felt their drains provided value for money, although these views are not generally based on any detailed analysis (Beattie & Stuart-Street, 2008; Kingwell and Cook, 2007). This is in contrast to the results of benefit-cost analyses that suggest single deeps drains in the wheatbelt are unlikely to be financially viable (e.g. Cox and Tetlow, in prep.). The ongoing construction of private drains constructed at some of the sites is evidence of landowners' satisfaction with and confidence in the value of deep drains.

In discussions during site visits in June 2016, it was learnt that landowners did not rely on groundwater data in forming an opinion regarding the performance of deep drains, but were more likely to rely on cropping data, waterlogging and adjacent vegetation health. Some farmers were uncertain whether the observed improvements were due entirely to the drains or to climate, but they were still supportive of deep drains.

Both landholder surveys found the most common source of advice used by landholders before deciding to install deep drainage was neighbouring landholders and drainage contractors. If neighbouring landholders generally believed their drains are effective (as the landholder surveys have also shown), the support for further deep drainage will continue.

Landholders do not appear to access technical advice available from government agencies, which is considered too broad, not specific to individual farms and not providing clear guidance on actions. They want face-to-face information about their particular situation.

Landholders met during the site visits for this study were keen for further government support for deep drain construction – especially arterial drainage for discharge from private drains. In the landholder survey for the Northern Agricultural Region, external funding for the construction of their drains influenced their decision to install drains and some landholders would not have installed drainage without external financial assistance.

The results of the landholder surveys are valuable for development and delivery of information regarding the performance of deep drains.

9.3 Governance

Although governance arrangements were not reported in any of the documents reviewed in this study it emerged as an issue in stakeholder conversations during visits to several of the sites in May and June 2016.

The policy framework for inland drainage (Department of Water, 2012) recommended strategies to ensure appropriate governance procedures are in place before drainage construction commences. In particular the policy framework identified the need to clearly define roles, responsibilities and structures for project planning, implementation and management.

Although the projects reviewed in this report pre-date that policy framework it is useful to consider the effectiveness of the governance arrangements in place for those projects.

Fence Road Drainage Scheme

The original governance arrangements for the Fence Road Drainage Scheme (Department of Water, 2007) clearly described specific responsibilities of the Shire of Dumbleyung, landowners and the Local Land Drainage Advisory Committee (LLDAC). However, discussions with landowners and other stakeholder during a visit to the Fence Road Drainage Scheme in May 2016 suggested some of the original arrangements were no longer in place.

The Shire is responsible for the management of the scheme. Memoranda of Understanding were executed between the Shire and landowners, which described responsibilities and governance arrangements for the drainage scheme. An easement was registered over the length of the drainage corridor to enable access to the drain and annual rates are paid to the Shire by landowners through whose land the arterial drain passes. The rates are intended to meet the costs of ongoing maintenance and management of the drainage scheme. Rates are not charged on private spur drains that discharge to the Fence Road Drainage Scheme. The governance arrangements for the scheme (Department of Water, 2007) allows landowners to establish new connections for private benefit but required those landowners to be responsible for the costs of construction and ongoing maintenance.

Maintenance of the drain has presented the Shire and landowners with challenges. During the site visit in May 2016 some landowners expressed concern that no maintenance was undertaken on the drain in the 2015/16 financial year. It is understood that some maintenance is scheduled for 2016/17.

The governance arrangements for the scheme require landowners to undertake weed control within the easement boundary on a regular basis but there are reports of declared weeds not being controlled in sections of the drain.

The LLDAC was formed as an advisory committee to the Shire to provide feedback from stakeholders, develop management policies and resolve potential disputes. It consisted of representatives from the drainage area, including landowners, the Shire and State government representatives. It is understood that the LLDAC has not met since October 2013.

Narembeen drainage system

In contrast to the Fence Road Drainage Scheme, the Narembeen drainage system was constructed without any formal governance arrangements in place.

At the time of the site visit in May 2016, the Narembeen district was recovering from a period of heavy rainfall and the drainage system appeared to be in disrepair. Surface water had breached levees and entered the drainage system in several places. Whether these failures were the result of poor design, poor construction or poor maintenance is uncertain. However, the failure of the drainage system at one location can lead to flooding and damaged land and infrastructure. In the absence of any clear governance structure, it is unclear who is responsible for ongoing maintenance and repair and who is liable for damage costs.

Local government road crossings are an example where poorly designed or maintained deep drains have flooded road crossing causing damage (Figure 27).

Figure 27 Flooded road crossing at Narembeen (27 May, 2016)

Yarra Yarra Regional Drainage Program

The Yarra Yarra Catchment Management Group (YYCMG) secured funding for the construction of the first stage of the Yarra Yarra Regional Drainage Program in 2006. To address long-term governance issues for the implementation and ongoing management of the drainage program, the YYCMG worked with the Shires of Dalwallinu, Morawa, Three Springs, Koorda, Perenjori and Wongan-Ballidu to establish the Yarra Yarra Catchment Regional Council (YYCRC) in 2007 as a regional local government under the *Local Government Act 1995*.

Under a similar arrangement to the Fence Road Drainage Scheme, the YYCRC was responsible for the construction and maintenance of the Yarra Yarra arterial drains. It is understood that the YYCRC leased the drainage corridor from landowners and collected a service fee from landowners connected to the arterial drainage system.

The YYCRC was dissolved in 2014 and funds transferred to the Shire of Perenjori and held in trust by the Shire of Perenjori for use by the YYCMG for drainage maintenance and monitoring. During a visit to the Yarra Yarra drainage sites in June 2016, stakeholders were uncertain of ongoing roles and responsibilities and arrangements for payment of service fees following the dissolution of the YYCRC.

Wallatin Creek

The deep drain at Wallatin Creek is smaller in scale that the drains at Fence Road, Narembeen or the Yarra Yarra catchment. There is no formal governance structure in place. The neighbouring farmers through whose land the drain is constructed work collaboratively to maintain the drain. Although this arrangement seemed very effective it relies on the ongoing relationship and goodwill between farmers. Any breakdown in that relationship represents a significant risk to the ongoing maintenance of the drain.

10. Conclusions

The following conclusions can be drawn from the reports reviewed for this study. Although these reports and papers address the key issues of drainage performance, they do not represent the full extent of inland drainage research in Western Australia and so this review should not be taken to represent the full current understanding of deep drainage in Western Australia.

Drainage design

Most of the drains reviewed for this study were 2-3 m deep, with 2.5 m being the most common depth. This depth appears to have been chosen as a pragmatic depth, arrived at on the advice of drainage contractors and based on their experience and the available plant and equipment. The Beynon Road study (Cox and Tetlow, in prep.) found that 3 m deep drains were more cost-effective than 2 m deep drains. Although that assessment did not include 2.5 m drains, it suggests the widely used 2.5 m depth may not be the optimum depth for deep drains.

Although drainage theory and design tools are available, these tools were rarely used to design the depth of deep drains in the wheatbelt. Noting the substantial investment that deep drains represent, it is surprising that greater value is not placed on optimising performance through design.

Most of the drains in studies included in this review had side slopes of 0.5(H):1(V). This slope has been largely determined by the experience of the drainage contractors who have developed excavator buckets to efficiently construct drains of this profile. Based on the batter trials at Wubin (Cox and Tetlow, 2009) the drain with 0.5(H):1(V) batter slope had a lower combined construction and maintenance cost that drains with 1(H):1(V) batter slope or a stepped batter.

The impact of climate on groundwater levels

In the decade leading up to 2000, rainfall in the northern parts of the wheatbelt was above average, resulting in rising groundwater levels and increasing salinity risk, which was a key driver in the increased construction of deep drains. From 2001-2007, rainfall was well below average and groundwater trends in many valleys were mostly falling or stable. Since 2007 rainfall has been closer to the long-term average and rising groundwater trends are returning to some areas.

The monitoring periods for all the drainage sites reviewed in this study fall within this period of declining rainfall after 2000. When a groundwater monitoring period coincides with a period of declining rainfall, declining groundwater levels (as well as observations of crop productivity, soil salinity and vegetation health) can be incorrectly attributed to the construction of a deep drain. The absence of good pre-drainage groundwater level data and appropriate control or comparison bores makes it difficult to clearly identify the impact of drainage on the watertable.

Single deep drains are unlikely to effectively lower and control groundwater

The results from the studies reviewed show that single deep drains were not effective at lowering and controlling the watertable at the levels required to recover land for agricultural production. Comprehensive monitoring programs at Pithara (Cox, 2010), Morawa (Cox, 2011), Wallatin Creek (George and Stainer, 2009) and Hillman River South (McDougall, 2012) all concluded that single deep drains were unable to lower and control groundwater at the critical depth (Nulsen 1981) necessary to return the land to reliable agricultural production. An earlier assessment of deep drains at Narembeen (Ali et al., 2004) concluded that deep drains were effective. However, an assessment of the data presented in that paper suggests the impact of the drains at Narembeen is over-stated.

Parallel deep drains may be effective in some instances

The results from the two studies of parallel drains at Dumbleyung (Cox and Tetlow, in prep.) and Morawa (Cox and Tetlow, 2014) suggest that deep drains constructed in parallel may be effective in some instances.

Parallel deep drains are more effective than single deep drains because they are able to provide a hydrological boundary to the drainage area, reducing groundwater inflow from the surrounding aquifer to the area between the parallel drains.

Internationally, most agricultural drainage schemes comprise of a network of parallel lateral drains connected to a main drain and most agricultural drainage theory and design tools have been developed for these parallel drainage networks. Drain spacing, or drainage intensity, is a key design parameter for these systems.

Soil and crop response to deep drainage

The lowering of groundwater by deep drains is intended to lead to a reduction in soil salinity and the restoration of soil productivity. However, the processes and timescales for the leaching of salt from the soil profile, the importance of soil solution salinity, the impact of occasional high-watertable events on soil salinity, the recovery of soil structure and soil organic matter and the crop response to these processes have not been adequately considered in relation to the effectiveness of deep drainage.

To understand the feasibility of deep drainage as a tool for restoring salinized land to agricultural production requires a better understanding of the impacts of drainage on soil productivity, the effects of soil and soil solution salinity on crops and of methods to improve the recovery of salt-affected land after drainage. These processes are more difficult to measure than watertable response, more difficult to isolate amongst the complex dataset collected from field experiments and require longer-term research programs.

Financial viability of deep drains

Parallel deep drains may be financially viable in some situations but single drains are unlikely to be financially viable because of their narrower zone of benefit (Cox and Tetlow, in prep.). Although the cost of drain construction is well understood, the economic benefit from drains is less certain and will depend on the area of land reclaimed, the increased crop yield achieved and the market price at the time.

Where deep drains are unable to return salt-affect land to agricultural production, they may still have sufficient impact to slow the rate of salinisation or to allow some revegetation. These intangible benefits were not considered in the economic evaluation and may be sufficient to influence some landowners to install deep drains.

Drainage discharge water quality is variable and can be acidic

The characteristics of water discharged from deep drains are closely linked to the surrounding groundwater. In many parts of the wheatbelt the groundwater is saline, particularly under the flat valley floors, and commonly, although not always, acidic with elevated metal concentrations.

Acid groundwater is naturally occurring across the wheatbelt. It is typically found between 5-10 m depth but it is highly variable spatially. Based on soil mapping of subsoil alkalinity, acid groundwater is predicted to be mainly confined to valley floors of palaeo drainage lines (Lillicrap and George, 2010).

The hydrolysis of dissolved iron in the groundwater (when it is exposed to oxygen in the drain) sometimes results in lower pH in the drainage discharges than in the surrounding groundwater

(Cox and Tetlow, in prep.). Consequently, total acidity of groundwater is a much better indicator of the final pH of drainage discharge than groundwater pH alone.

Drainage discharges can have downstream impacts but those impacts can be managed

Drainage discharge can have a detrimental impact on downstream receiving environments due to the increased salinity and concentrations of metals and nutrients in the drainage discharge, particularly when the drainage discharge is acidic.

Acidic saline discharge from the Fence Road arterial drainage system had a measurable impact on aquatic ecology of the receiving waterway for a distance of at least 15 km downstream, with lower macroinvertebrate diversity, altered macroinvertebrate community composition and visibly less healthy in-stream flora (McDougall, 2012).

Discharges to some salt lakes and playas, such as the Yarra Yarra wetlands, may have limited and acceptable environmental impacts. However, if some salt lakes or playas are accepted as disposal sites it is important to identify and protect those systems with high environmental values. Most naturally saline systems are alkaline, so that acidification poses a threat to the biodiversity of wheatbelt playas and wetlands.

Farmers support deep drainage and rely on other farmers rather than technical advice

Farmers who have installed drains generally believe their drains are effective in reducing waterlogging and improving productivity and are value for money. Landholders do not rely on groundwater monitoring data in forming an opinion regarding the performance of deep drains, but are more likely to rely on qualitative cropping data, waterlogging and adjacent vegetation health.

Landholders do not appear to access technical advice available from government agencies, which is considered too broad, not specific to individual farms and not providing clear guidance on actions (Beattie and Stuart-Street, 2008). They want face-to-face information about their particular situation.

Appropriate governance arrangements must be in place before drain construction

The policy framework for inland drainage (Department of Water, 2012) recognises the need for effective governance structures and processes to be in place to manage deep drains over the long term and recommends strategies to deliver appropriate governance.

Of the drainage systems reviewed in this study, the Fence Road Drainage Scheme had an appropriate ongoing governance structure in place. The drainage system is managed by the Shire of Dumbleyung and the necessary access arrangements and funding arrangements are in place. However, the Local Land Drainage Advisory Committee has been less active since 2013 and some landowners expressed concern about weed management and drain maintenance.

The Yarra Yarra Regional Drainage Program has an active catchment management group in the YYCMG and was previously managed by a regional local government in the Yarra Yarra Catchment Regional Council. However, the recent dissolution of the Yarra Yarra Catchment Regional Council has created uncertainty regarding ongoing responsibilities and arrangements that needs to be resolved by stakeholders.

Governance arrangements at Wallatin Creek rely on the collaborative relationship between neighbouring farmers and a breakdown in that relationship represents a significant risk for the long-term management of the drainage system.

The Narembeen deep drainage system has no governance structure and sections of the drain are in poor condition and need of maintenance, potentially resulting in flooding and damage to land and infrastructure with no obviously accountable body.

The implementation of appropriate governance arrangements remains a significant challenge for the successful construction and management of deep drainage systems in the wheatbelt. It is critical that government ensures that appropriate long-term governance arrangements are in place before the construction of further deep drainage systems in Western Australia.

Recommendations for further work

- The Department of Water prepare a brief information note presenting the conclusions from this review. An information note would provide landholders and other stakeholders with an update of the current knowledge of deep drainage in Western Australia and key recommendations for implementation. Noting the results from the stakeholder evaluation, landholders are unlikely to access the information in this report but may be more inclined to read a more concise and accessible summary available through agency websites. The information note should draw attention to the need for feasibility assessment using tools such as the GRDC-funded DrainLogic and the benefits of rigorous engineering design.
- The Department of Water prepare a revised list of research priorities. The Department of Water should prepare a more complete list of the projects addressing the research priorities identified in Dogramaci and Degens (2003). Table 2, Table 3 and Table 4 in section 2 have listed the reports reviewed in this study and include other relevant studies known to the author. However, that list represents only some of the research projects completed under programs such as the Engineering Evaluation Initiative and the Wheatbelt Drainage Evaluation Project. It would useful to prepare a more complete list of research completed since 2003 to confirm which previously identified research priorities have been addressed and to identify any remaining research questions. A list of any remaining research questions would be a useful guide for investment by government and research institutions.
- Understand soil and crop response to deep drainage. The processes and timescales for the leaching of salt from the soil profile, the importance of soil solution salinity, the impact of occasional high-watertable events on soil salinity, the recovery of soil structure and soil organic matter and the crop response to these processes have not been adequately considered in relation to the effectiveness of deep drainage. These warrant further investigation but are more difficult to measure than watertable response, more difficult to isolate amongst the complex dataset collected from field experiments and require longer-term research programs.
- No further watertable monitoring required (or funded) unless for compliance or for specific research objectives. Based on the most recent reports reviewed for this study, there is now a broad consensus on the ability of deep drains to lower and control groundwater levels. Unless monitoring is needed to demonstrate compliance with a condition of approval, to investigate soil and crop response to drainage or monitoring data are required for a specific research objective, there is no further need for performance monitoring of deep drains in Western Australia.

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