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Groundwater trend analysis and salinity risk assessment for the south-west agricultural region of Western Australia, 2007–12

Resource management technical report 388

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Groundwater trend analysis and salinity risk assessment for the south-west agricultural region of Western Australia, 2007–12

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GP Raper, RJ Speed, JA Simons, AL Killen, AI Blake, AT Ryder, RH Smith, GS Stainer[1] and L Bourke[2]

1 Department of Agriculture and Food, Western Australia

2 Department of Parks and Wildlife

To the memory of Arjen Ryder

Arjen Ryder was a respected and long-standing member of the dedicated team that contributed to this hydrological research over many years. His attention to detail in data collection, verification and analysis, and his knowledge of landscape processes were evident in this work and throughout his 31-year career. Arjen was a respected colleague and loyal friend. We miss his enduring warm smile and friendly relaxed manner.

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Cover: Groundwater monitoring site beside a canola crop at Caren Caren Brook in the Dandaragan Plateau Hydrozone (photo: A Killen)

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Disclaimer

3 Baron-Hay Court, South Perth WA 6151

Telephone: (08) 9368 3333

Email: enquiries@agric.wa.gov.au

Website: agric.wa.gov.au

Contents

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Darren Farmer, Tiffany Fowler and Margaret Smith (Department of Parks and Wildlife [DPaW]) provided groundwater data for Lake Bryde and Lake Toolibin catchments, the Haddleton Nature Reserve and the Byenup Lagoon areas, respectively. Mal Graham (Australian Bush Heritage Fund) provided groundwater data around the Birdwood Nature Reserve, Kojonup. In most cases, bores were installed and monitoring initiated by DAFWA and monitoring responsibilities later assumed by DPaW.

We acknowledge the support of John Bruce for producing the maps in this report and Phil Goulding for preparing the data required for presenting the rainfall change maps.

We acknowledge the input of Don Bennett, Richard George and Angela Stuart-Street who provided both formal reviews of this document and informal guidance on its scope and context. Lastly, we thank Angela Rogerson for technical editing and her patient guidance through the process of producing a document of professional quality.

Summary

Dryland salinity is a hydrologically driven land degradation hazard in the south-west agricultural region of Western Australia (WA). Shallow-rooted annual crops and pastures transpire significantly less water than the native vegetation they replaced, leading to an increase in recharge, rising groundwater levels and the development of shallow watertables in areas where often none existed previously. Rising groundwater levels mobilise soluble salts, naturally stored at high concentrations in the regolith. These salts can be concentrated in the root zone of vegetation by evapotranspiration.

In addition to the clearing of native vegetation for agriculture, rainfall variability is a factor in determining groundwater trends in the region. Rainfall has been below the long-term average over most of the region since the mid-1970s. The change was most noticeable between 2001 and 2007, especially in the northern portion of the region. There are, however, areas in the far east of the region and in the eastern south coast where rainfall has consistently been above the long-term average.

Groundwater trends for 1500 surveillance bores were analysed to assess the salinity risk across the region. This analysis builds on previously reported analyses for the region (George et al. 2008) and this report compares three analysis periods: 1991–2000, 2000–07 and 2007–12. Between the 1991–2000 and 2000–07 periods, the proportion of bores with rising trends fell from 60 to 40% and the proportion of bores with falling trends increased from 6 to 29%. The changes in groundwater trends were most pronounced in the north of the region.

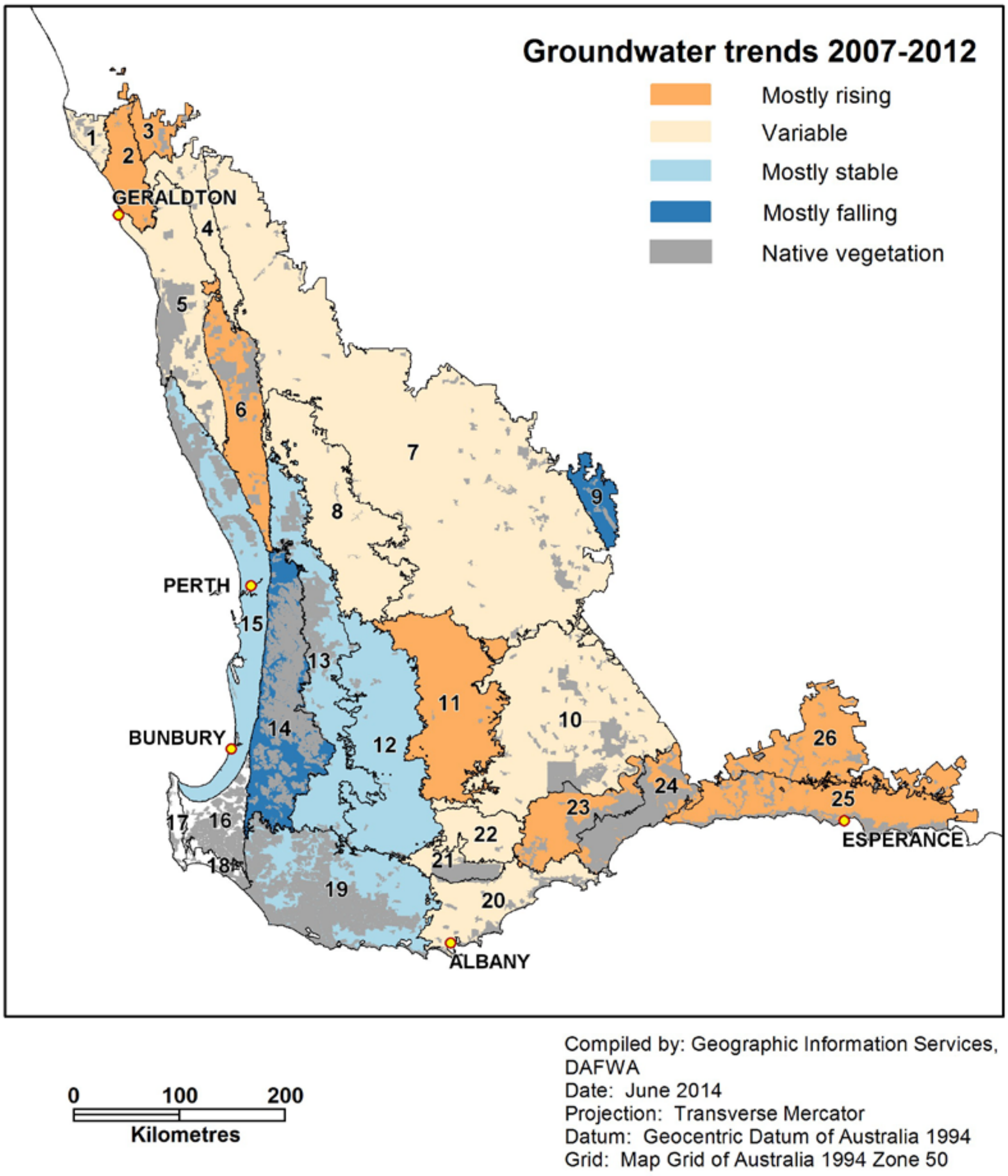
For the 2007–12 period, groundwater trends were reported on the basis of hydrozones, which are regions of similar hydrogeological, climate, landscape and farming system attributes. Hydrozones with variable groundwater trends covered half of the land area of the region. Hydrozones with predominantly rising or stable groundwater trends covered 21% of the region each. Hydrozones with mainly falling trends covered 6% and there is no data on which to base trends for 2% of the region (Figure 1).

Despite a general reduction in the proportion of bores with rising trends, groundwater levels have continued to rise in and adjacent to areas of salinity hazard in lower landscape positions over much of the region.

A salinity risk assessment for the region was performed using a risk matrix adapted from Spies and Woodgate (2005). The matrix combines likelihood and consequence factors to determine a salinity risk. Inputs to the risk assessment, additional to the groundwater trends and climate analyses, were the areas of salinity hazard and current extent, as determined by the Land Monitor project (Caccetta et al. 2010). The risk assessed was the expansion of dryland salinity and its consequence on agricultural land beyond its current extent.

The risk assessment revealed that 82% of the region has a moderate salinity risk, 10% has a high risk and only 8% has a low risk (Figure 2).

Over most of the region, the impact of rainfall variability on groundwater trends is still less than the impact of clearing. Climate variability, therefore, appears to be a secondary, rather than the driving factor in the risk of dryland salinity in the south-west agricultural region.



Hydrozone		Hydrozone		Hydrozone	
1	Kalbarri Sandplain	10	South-eastern Zone of Ancient Drainage	19	Warren–Denmark
2	Northampton Block	11	South-western Zone of Ancient Drainage	20	Albany Sandplain
3	East Binnu Sandplain	12	Southern Zone of Rejuvenated Drainage	21	Stirling Range
4	Irwin Terrace	13	Eastern Darling Range	22	Pallinup
5	Arrowsmith	14	Western Darling Range	23	Jerramungup Plain
6	Dandaragan Plateau	15	Coastal Plain	24	Ravensthorpe
7	Northern Zone of Ancient Drainage	16	Donnybrook Sunkland	25	Esperance Sandplain
8	Northern Zone of Rejuvenated Drainage	17	Leeuwin	26	Salmon Gums Mallee
9	Southern Cross	18	Scott Coastal Plain		

Figure 1 Dominant groundwater level trends (2007–12) within hydrozones in the south-west agricultural region

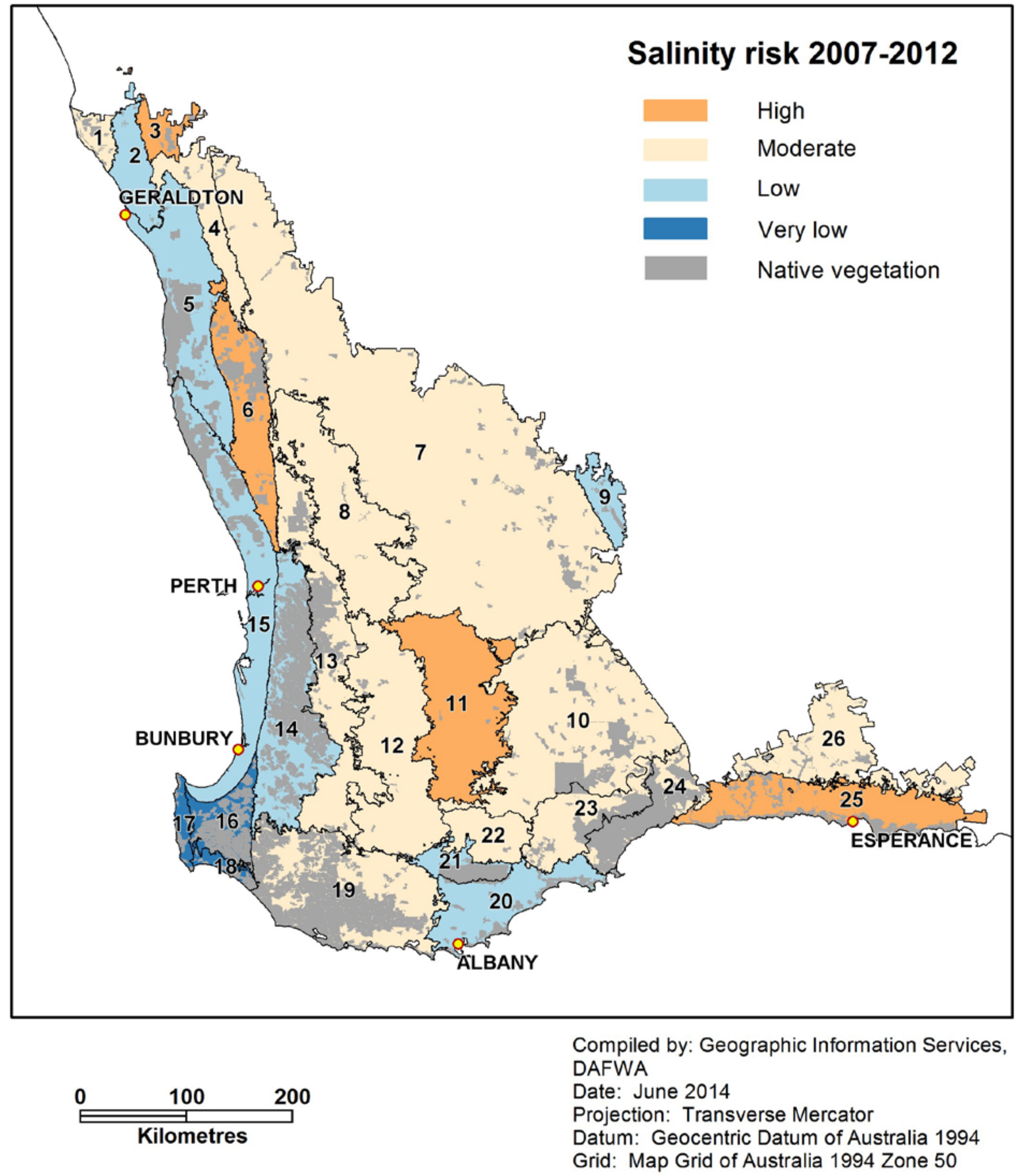


Figure 2 Salinity risk assessment for hydrozones in the south-west agricultural region, 2007–12

1 Introduction

Secondary salinisation within the south-west agricultural region of Western Australia (WA) is a form of hydrologically induced land degradation brought about by a change in the water balance caused either by clearing or by irrigation for agriculture. In dryland agricultural areas, shallow-rooted annual crops and pastures intercept and transpire significantly less water than the native vegetation they replaced, leading to an increase in recharge, rising groundwater levels and the development of shallow watertables in areas where often none existed previously (George et al. 1997). Rising groundwater levels mobilise soluble ions, primarily sodium and chloride, naturally stored at high concentrations in the regolith, particularly on the Yilgarn Craton. These salts accumulate within the root zone when watertables approach the soil surface and groundwater evaporates.

In addition to the effect of clearing on dryland agricultural areas, applying fresh to brackish irrigation water to areas of the coastal plain leads to salt accumulation in the root zone where subsoil drainage is poor. Parts of the irrigation area are also underlain by inherently saline, poorly drained soils (Bennett et al. 2004).

Soil salinisation not only reduces agricultural production but also damages rural and townsite infrastructure, renders water resources unusable and threatens native ecosystems (George et al. 1997). The *State of the Environment Report: Western Australia 2007* (EPA 2007) found that some 450 plant and 400 animal species are at risk of global or regional extinction because of salinisation and associated hydrological changes.

Land salinisation is considered one of WA’s most significant environmental issues. According to the Department of Environmental Protection (1997), salinity occurs over a significant part of the agricultural area and it has severely damaged the natural environment and reduced agricultural productivity.

The last salinity risk assessment undertaken in WA by George et al. (2005) concluded that salinity either currently affects or threatens large areas of agricultural land and many sites containing high value infrastructure. However, despite the extent and effects of salinity, the State of the Environment Committee (2011) noted that salinity was not a priority issue under the Caring for our Country program.

1.1 Purpose

The purpose of the work presented in this report is to:

- determine the dominant groundwater trends within the south-west agricultural region
- relate groundwater trends to spatial patterns of changes in rainfall
- assess the salinity risk for the region
- determine the suitability and capability of the available data to assess the salinity risk.

This report provides a brief overview of the physiography and climate of the south-west agricultural region, followed by a description of the method used to analyse groundwater trends and the hydrozones on which all analyses are summarised. The results of this groundwater trend analyses are compared to the results published by George et al. (2008) to provide a summary of groundwater trends in the region over the whole period (1975–2012) for which data is available. The results are then related to the rainfall observed in the region over the analysis periods and the salinity risk is assessed for each hydrozone. The suitability of the available data for assessing a salinity risk is also discussed.

1.2 Study area

For this analysis, the south-west agricultural region of WA is defined as the entire area south and west of the clearing line. The clearing line marks the boundary between freehold land that has been substantially cleared for broadacre agriculture and leasehold land that is used for pastoral grazing of native vegetation.

The region is bound to the west by the Indian Ocean and to the south by the Southern Ocean (Figure 1.1). Within the south-west agricultural region, there are large forested areas that include unallocated Crown land and areas managed for conservation, state forests and water catchment protection. The Perth metropolitan region is excluded from the region.

The region is about 25 million hectares and the cleared portion that is used for agricultural production is about 16 million hectares (64%).

1.3 Previous studies

1.3.1 Extent of dryland salinity in WA

One of the earliest estimates of the extent of dryland salinity in WA was made by Burvill (1950). He reported that in 1925, about 3% of the cleared area of "a number of farms in the older and wetter part of the wheat belt" was salt-affected. Burvill defined the wheatbelt as the land between the 635 and 300 millimetre per year (mm/y) rainfall isohyets.

The Australian Bureau of Statistics (ABS) have included questions aimed at determining the "area of salt-affected land which was previously used for crops and pasture" in census forms since 1955. However, only four surveys have included all agricultural shires and included the same question in comparable portions of the survey form. Ferdowsian et al. (1996a) reported that estimates derived from the ABS survey were gross underestimates, citing by way of example their estimate of 13% of land in the Upper Denmark Catchment being salt-affected whereas the ABS survey suggested only 2%. They attributed the difference to landholders reporting only bare areas in the ABS survey, whereas the Ferdowsian et al. (1996a) estimate included all land where the potential yield of salt-sensitive crops and pastures was reduced by at least 50%.

Besides critiquing the ABS estimates of the area of salt-affected land in the south-west, Ferdowsian et al. (1996a) estimated the salt-affected area of the region by extrapolating their own catchment-scale aerial photographic interpretations, landholder-mapped estimates, ground-based terrain conductivity surveys and satellite remote sensing estimates of salt-affected areas. Their estimate of the salt-affected area in 1994 was 1.8 million hectares (9.4%) of the area cleared for agriculture (Table 1.1).

Short and McConnell (2001) estimated the extent of dryland salinity in the south-west agricultural region for the National Land and Water Resources Audit (NLWRA). The audit process required a consistent analytical approach across all states and territories so only data consistent with the methodology was used. From Agriculture Western Australia (now DAFWA) and the Water and Rivers Commission (now Department of Water) groundwater databases, a selection of data from bores on cleared, agricultural land, with at least five years of time series data was used in the analysis. Groundwater depth and trend data were analysed to map the risk of shallow watertables and a salinity risk was inferred from the resultant map. A map of wet and waterlogged soils (Schoknecht 2000) was used to assist in interpreting the shallow watertable map.

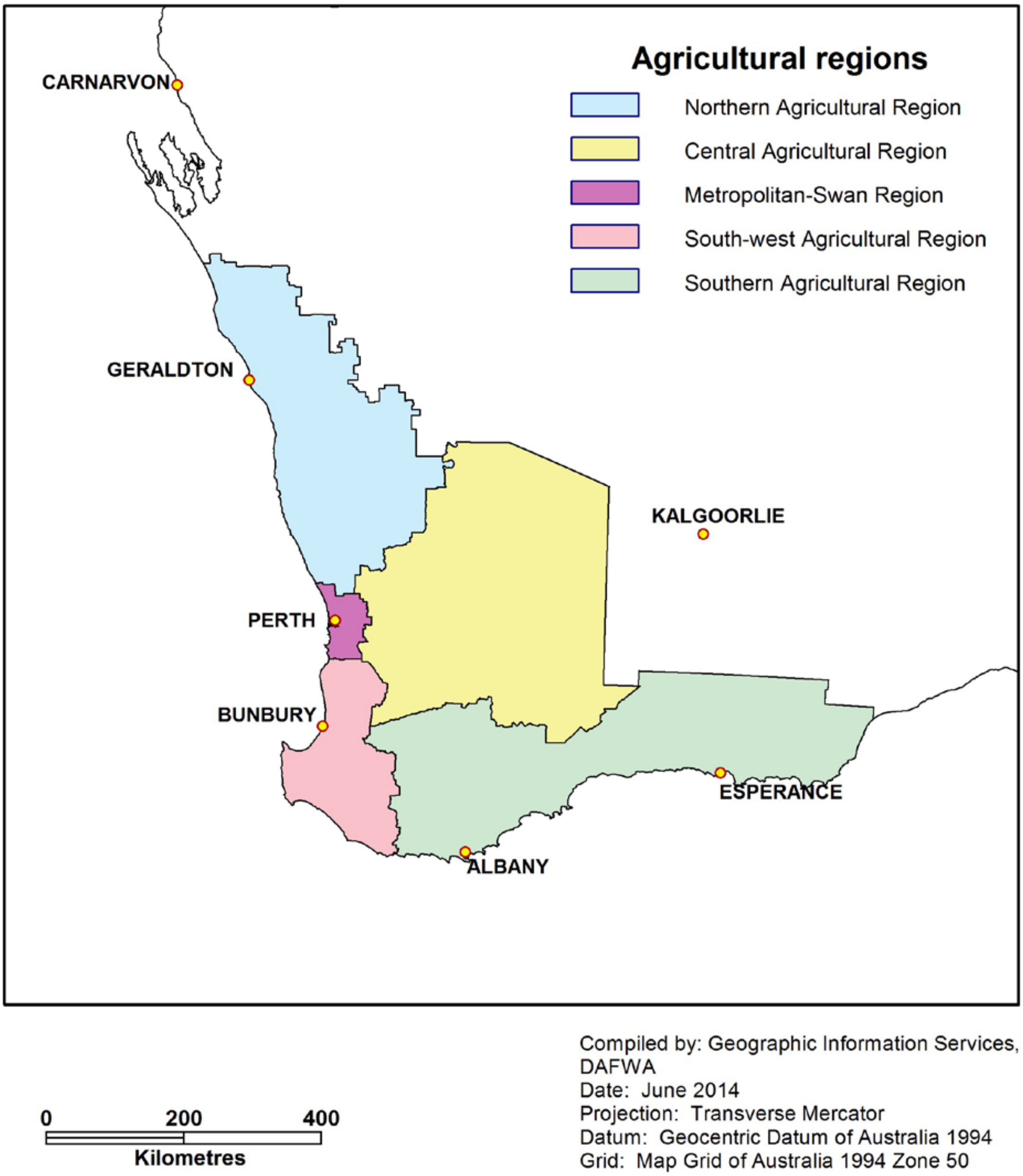


Figure 1.1 Study area location map

Short and McConnell (2001) performed their analysis at the soil-landscape system scale. Soil-landscape systems are spatial units based on landform patterns, soil parent material and soil associations. They are subdivisions of soil-landscape zones, which are differentiated by geomorphic and geological criteria (Schoknecht et al. 2004). The hierarchical method of defining soil-landscape zones and systems was based on a framework introduced by CSIRO (Commonwealth Scientific and Industrial Research Organisation 1983) and refined by DAFWA (Schoknecht et al. 2004). Short and McConnell (2001) analysed their data at the soil-landscape system scale but reported statistical results at the soil-landscape zone scale. They estimated that 3.55 million hectares (16%) of the south-west agricultural region, was at risk of being salt-affected in 2000 (Table 1.1). They stated that this methodology overestimated the area actually affected because not all of the area with a shallow watertable would experience salinity effects. They also estimated that 20% of the region would have a shallow watertable by 2020 and that by 2050 the area would have expanded to 33%.

The Land Monitor project was a multi-agency effort that assembled and processed sequences of Landsat Thematic Mapper (TM) data, a high resolution digital elevation model (DEM), and other spatial data to provide information on the area of salt-affected land and on changes in the area and status of perennial vegetation over the period 1988–2000 (Caccetta et al. 2000). Salt-affected land was mapped by interrogating successive spring Landsat TM images for areas of consistently low productivity (AOCLP). The map was then refined using landform information derived from the DEM to select the AOCLP most likely to be caused by salinity. Ground truthing was then undertaken to further refine and assess the accuracy of the AOCLP salinity map. The project also provided estimates of areas of salinity hazard, based on 1988 and 2000 salinity maps and a set of landform variables derived from the DEM. A third product was a set of maps of remnant native vegetation and vegetation change.

The results of the AOCLP analysis were distributed to land management agencies and landcare groups in digital or print form and summarised by Caccetta et al. (2010). The Land Monitor project estimated that almost 860 000 hectares (ha) was saline in 1989 and over the following seven years, the estimate increased to nearly 960 000ha (Table 1.1).The data was presented on a shire-by-shire basis in both absolute and proportional terms, and relative increases in areas affected between the assessment dates were determined.

In 2000, the State Salinity Council commissioned a Salinity Investment Framework (SIF) to identify, prioritise and guide investment in salinity abatement, recognising that current resources were only sufficient to protect a relatively small number of top priority assets (Sparks et al. 2006). The SIF analysis was undertaken using Land Monitor estimates of the extent of salt-affected land, which was revised and augmented by DAFWA hydrologists on a soil-landscape zone basis.

In addition to almost 1.05 million hectares of agricultural and public land affected by salinity in 1998 (Table 1.1), the SIF analysis also estimated that 250 kilometres (km) of highways and main roads (Sparks et al. 2006) and 3850km of local and unclassified roads were affected by salinity (George et al. 2005).

Table 1.1 Estimates of the area of salt-affected land within the south-west agricultural region of WA

Date	Area (ha)	Source	Comments
1955	73 500	ABS survey	
1962	123 500	ABS survey	
1979	167 000	ABS survey	
1984	254 500	ABS survey	
1989	446 500	ABS survey	
1989	859 500	Caccetta et al. (2010)	Land Monitor estimate from remotely sensed data.
1993	529 000	ABS, reported in Ferdowsian et al. (1996a)	Determined by Ferdowsian et al. (1996a) to be an underestimate of the actual salt-affected area.
1994	1 804 000	Ferdowsian et al. (1996a)	DAFWA estimate based on all available data.
1996–98	957 500	Caccetta et al. (2010)	Land Monitor estimate from remotely sensed data. Some Landsat scenes were processed with a nominal date of 1996; others were processed with a nominal date of 1998
1998	1 047 000	George et al. (2005), Sparks et al. (2006)	SIF, 1996 Land Monitor estimate from remotely sensed data, revised & augmented using expert panel approach
2000	3 553 000	Short & McConnell (2001)	NLWRA; area determined to be at risk of having a shallow watertable; overestimates the area salt-affected.
2002	932 500	ABS survey	

At a regional scale, Percy and Raper (2007) estimated the area of salt-affected land east of the 600mm/y isohyet to assist the South West Catchments Council set long-term resource condition targets for dryland salinity within their South-west Natural Resource Management Region. Estimates were made for each soil-landscape zone in the study area by considering the Land Monitor AOCLP estimate (Caccetta et al. 2000), the NLWRA estimate (Short & McConnell 2001), and the area of saline wet soils identified during regional soil-landscape mapping by DAFWA. In two of the four soil-landscape zones considered, catchment-scale estimates were also used to estimate the salt-affected area. The catchment-scale estimates included the Boree Gully Catchment in the Eastern Darling Range Zone and the Queerfellows Creek and Chain Gully catchments (Blackwood Focus Catchment Support Team 2000) in the Southern Zone of Rejuvenated Drainage. The estimates of the salt-affected proportion of each soil-landscape zone applied only to that part of the zone within the study area.

The Land Monitor AOCLP estimate was the lowest in three of the four soil-landscape zones considered and the NLWRA estimate for 2000 was higher than the estimates of Percy and Raper (2007) seven years later (Table 1.2). This supports the assertion of Short and McConnell (2001) that the NLWRA methodology tended to overestimate the salt-affected area relative to the other techniques.

Table 1.2 Proportions of soil-landscape zones within the South-West Natural Resource Management Region estimated to be salt-affected

Soil-landscape zone	Land Monitor AOCLP 1996–98 (%)	Saline wet soils (%)	NLWRA (%)	Percy & Raper (2007) (%)
South-eastern Zone of Ancient Drainage (250)	2.0	3.0	17.2	7
Eastern Darling Range Zone (253)	2.5	2.7	6.1	5
Southern Zone of Rejuvenated Drainage (257)	5.4	4.8	12.2	8
South-western Zone of Ancient Drainage (259)	7.5	12.0	17.2	>15

1.3.2 Groundwater trends

Analysing groundwater trends is fundamental to estimating the future extent of dryland salinity (Coram et al. 2001) and has been undertaken in the south-west agricultural region for that purpose since the 1990s.

Nulsen (1998) summarised the state of groundwaters in the agricultural areas of WA and reported rising groundwater trends through much of the area in most landscape positions under agricultural land uses, and some falling trends under revegetation. Nulsen (1998) clearly linked widespread rising trends with increased salinity risk.

George and Raper (2003) summarised the salinity effects, groundwater trends and potential for salinity management and mitigation within the South-west Natural Resource Management Region. This was followed by similar reports covering the Central Agricultural Region (Ghauri 2004), the Fitzgerald Biosphere region (Lillicrap 2004), the Kent-Frankland area (Ryder 2004) and the eastern south coast (Simons & Alderman 2004). In each report, groundwater trends were summarised for each soil-landscape zone within the area. Salinity risk was discussed in terms of the risk of shallow watertables using the same risk categories as Short and McConnell (2001). The technical feasibility of managing dryland salinity was also discussed for each soil-landscape zone.

George et al. (2008) analysed groundwater trends across the entire south-west agricultural region and Speed and Kendle (2008) undertook a similar exercise in the Northern Agricultural Region. Both reported that particularly dry conditions had prevailed in the north of the region since 2000 and of the eight growing seasons between 2000 and 2008, average rainfall occurred only in 2005. Prior to 2000, predominantly rising groundwater trends were observed; post-2000, the trends switched to predominantly falling throughout the north of the region, except in parts of the Perth Basin.

George et al. (2008) also reported that the relative proportions of bores with rising groundwater trends changed after 2000. They noted that this change was most pronounced in the Northern Agricultural Region and progressively reduced towards the eastern south coast where the pre- and post-2000 groundwater trends remained unchanged with an mean rate of rise of more than 0.2 metres per year (m/y). George et al. (2008) also observed that despite lower than average rainfall over much of the region since 2000, salinisation continued to expand. They inferred from this that land clearing is the dominant driver of hydrological imbalance and that climate would become more important as a driver of groundwater trends as a new equilibrium is approached.

Blake et al. (2012) argued that Speed and Kendle (2008) overestimated the decline in groundwater in the Northern Agricultural Region. They suggest that there was episodic groundwater rise because of very wet conditions in 1999 and the subsequent falling trends were an artefact of that spike. Blake et al. observed that in recent years (2008–11) rising groundwater trends in parts of the north-eastern portion of the region were similar to those prior to 2000.

Golder Associates (2008) determined groundwater trends in the south-west groundwater area between Bunbury and Augusta for the Department of Water. In contrast to most of the south-west agricultural region, significant groundwater abstraction takes place in the Bunbury to Augusta area. The aim of the work was to assist in groundwater allocation planning and the protection of groundwater dependant ecosystems. They determined groundwater trends for bores over two periods, 1985–2007 and 1995–2007 for each of the superficial, Leederville and Yarragadee aquifers. Mean groundwater trends for bores not affected by pumping over both time intervals were falling in the superficial aquifers, which are the aquifers relevant to salinity risk in the area.

1.3.3 Salinity hazard and risk assessments

Spies and Woodgate (2005) adopted definitions based on the Australian and New Zealand Risk Management Standard AS/NZS 4360:2004 (Standards Australia 2004). They define a hazard as “anything that can potentially cause harm to an asset”, and defined risk as “the chance of something occurring that will affect the achievement of objectives” (p. 24). Therefore, in the salinity context, hazard is a result of the inherent biophysical nature of the landscape including the soils, regolith and groundwater. That is, the attributes of the landscape that contributes to the potential for salinisation to develop. In this context, the objective is maintaining agricultural production, biodiversity and rural infrastructure. Salinity risk therefore includes the probability or likelihood, timing, consequence and severity of the salinity hazard being realised. It depends on the interaction between land use, climate and the physical attributes of the landscape that contribute to the potential for salinisation.

Spies and Woodgate (2005) point out that the consequence and severity of land salinisation will vary for different asset types and that salinity risk is most usefully assessed in relation to a particular class of asset. They suggest a matrix of likelihood and consequence to be used in a structured salinity risk assessment.

The Land Monitor project (Caccetta et al. 2000, McFarlane et al. 2004) provides one of only two quantitative estimates of the area of salinity hazard for the whole south-west agricultural region. Producing a map of salinity hazard involved using maps of the area predicted as likely to become salt-affected and DEM-derived variables to predict topographically low areas likely to accumulate water and become salt-affected. The water flow paths identified were truncated at the channel heads and all adjacent DEM pixels within a 2m vertical height tolerance were then determined to have a salinity hazard. This area was termed the average height above valley floor (AHAVF). All pixels within the AHAVF salinity hazard area were also assigned to one of four height classes: 0–0.5m, 0–1.0m, 0–1.5m and 0–2.0m above the flow path. The classes can be displayed separately and areas for each class calculated (McFarlane et al. 2004). The total 0–2.0m AHAVF for the south-west agricultural region was calculated as nearly 5.5 million hectares, which includes the 960 000ha estimated by Caccetta et al. (2010) to have already been salt-affected in 1996–98.

The second quantitative estimate of the area of salinity hazard was performed under the SIF project by George et al. (2005) and was a refinement of the Land Monitor estimate above. George et al. (2005) used the Land Monitor AHAVF map to define areas of salinity hazard and augmented it with an expert panel approach to define areas of salinity risk for soil-landscape zones in which the Land Monitor method failed.

Coram et al. (2001) list the key datasets they consider essential for determining salinity risk (pp. 6–7). The first dataset is the current extent of salinity effects on agricultural land, water resources and other assets. Other reviewers (Spies and Woodgate 2005, Gilfedder and Walker 2001) also list the datasets required in assessing a salinity risk but none specify a preferable or recommended methodology.

Gilfedder and Walker (2001) reviewed several geographic information system-based methods of assessing salinity risk. All are based on spatial indices or rule-based algorithms that require training or ground truthing against manually derived risk maps. This is also true for the automated generation of salinity hazard and extent maps derived under the Land Monitor project.

2 Characteristics of the study area

2.1 Geology

Much of the south-west agricultural region lies on Archean granitoid rock of the Yilgarn Craton (Figure 2.1). On the Yilgarn Craton, the regolith profile is typically 30–50m of gritty clay saprolite formed by in situ weathering of the crystalline basement rock. The weathered profile is occasionally covered by 10–30m of mixed sediments in sheets or palaeochannels (Beard 1999). The western edge of the Yilgarn Craton is defined by the Darling Fault, which extends some 700km north–south through the entire region.

West of the Yilgarn Craton, the Perth Basin is an elongate trough containing up to 12 000m of Permian to Early Cretaceous sediments (Mory & Iasky 1996). The Permian sediments are dominated by glacial tillite and shales. The Mesozoic sediments are dominated by felspathic sandstone and host extensive regional aquifers such as the Yarragadee.

In the northern-most extent of the Perth Basin within the region, the Northampton Complex is essentially a large outcrop of Proterozoic crystalline gneissic basement rock (Myers 1990b). It is partially capped in western areas by thin sequences of Jurassic sediments that form the flat-topped Moresby Range near Geraldton.

At the south-west tip of the region, the Leeuwin Complex is a narrow strip of Proterozoic granitic basement similar to the Northampton Block (Myers 1990b).

Along the south coast, the Albany–Fraser Orogen is exposed along the southern margin of the Yilgarn Craton and is characterised by high-grade gneisses and granitoid intrusions (Myers 1990a). Near the coast, the Albany–Fraser Orogen is partially capped by sediments assigned to the Bremer Basin. The Bremer Basin consists of numerous small depressions filled with Eocene sediments of the Plantagenet Group (Hocking 1990).

The Stirling Range Formation straddles a portion of the contact between the Yilgarn Craton and the Albany–Fraser Orogen, and its most obvious expression is the Stirling Range which runs from west of Cranbrook to Ellen Peak, south-east of Borden. The formation consists of a Middle Proterozoic sequence of metamorphosed sandstone and shale laid down in shallow water (Stuart-Street & Marold 2009).

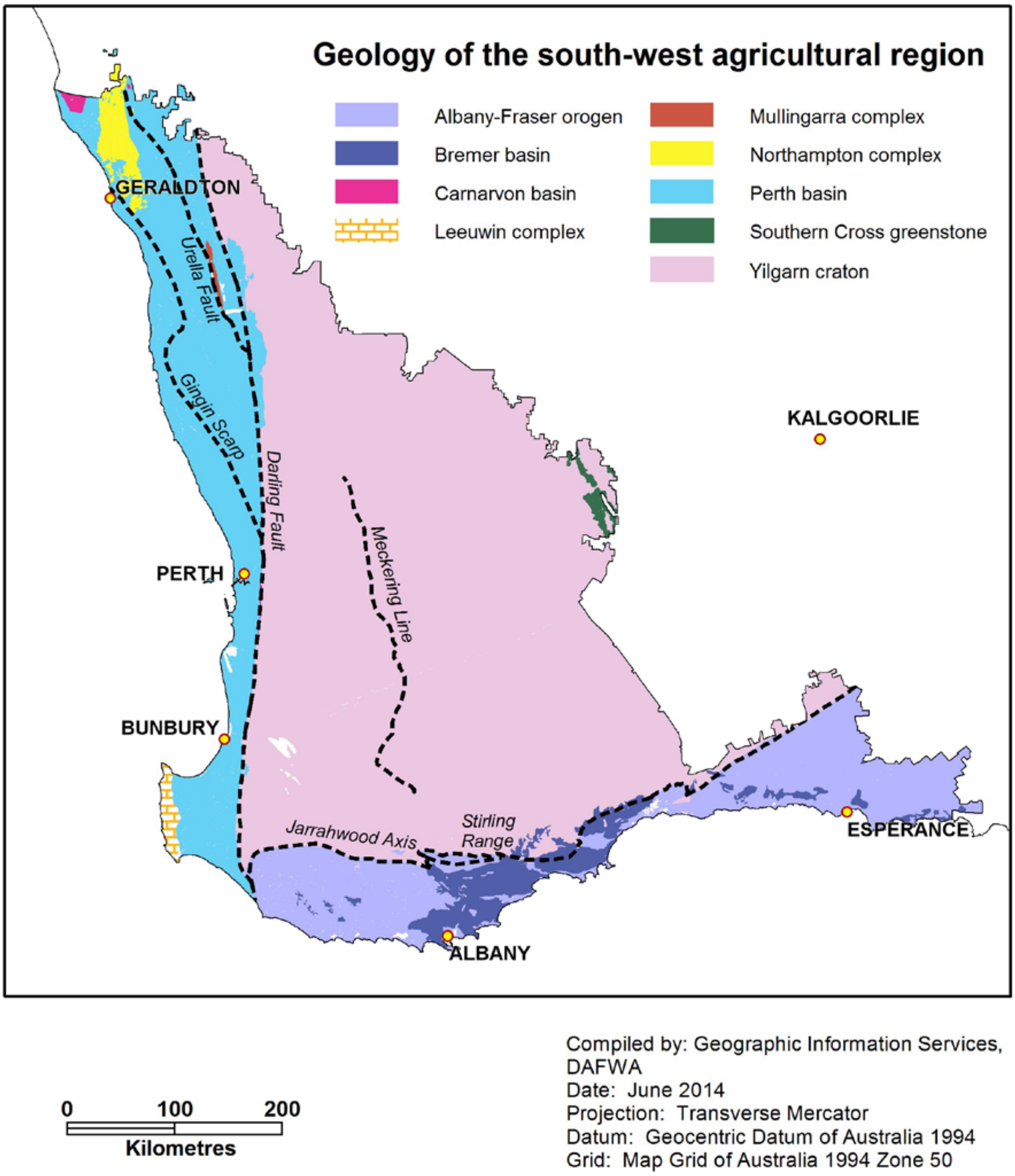


Figure 2.1 Geology and physiography of the south-west agricultural region

2.2 Landform

The region has generally subdued relief and the landscape is largely plateau with ranges of low hills (e.g. Darling Range, Stirling Range). There are low scarps that are surface expressions of geological faults, notably the Darling Scarp formed by the Darling Fault (Figure 2.1).

The Meckering Line, originally delineated by Jutson (1934), is a north-north-west to south-south-easterly trending zone marking a major transition in landform and drainage characteristics in the region (Figure 2.1). To the west of the Meckering Line, valleys are relatively narrow-floored and steep-sided with high gradients. To the east, valleys are much broader with flat floors, the drainage is generally sluggish and intermittent, and chains of salt lakes (playas) are common.

2.3 Soils

The soils of the Yilgarn Craton are formed mainly on laterite, truncated lateritic profiles, bedrock weathered in situ, colluvium and alluvium. On the catchment divides, soils are mainly Sandy gravels with some Pale deep sands. Grey sandy duplex soils, often with alkaline subsoils, are found on the valley slopes. Alkaline grey shallow loamy and sandy duplex soils, Calcareous loamy earths and Saline wet soils occur on the valley floors (Schoknecht & Pathan 2013).

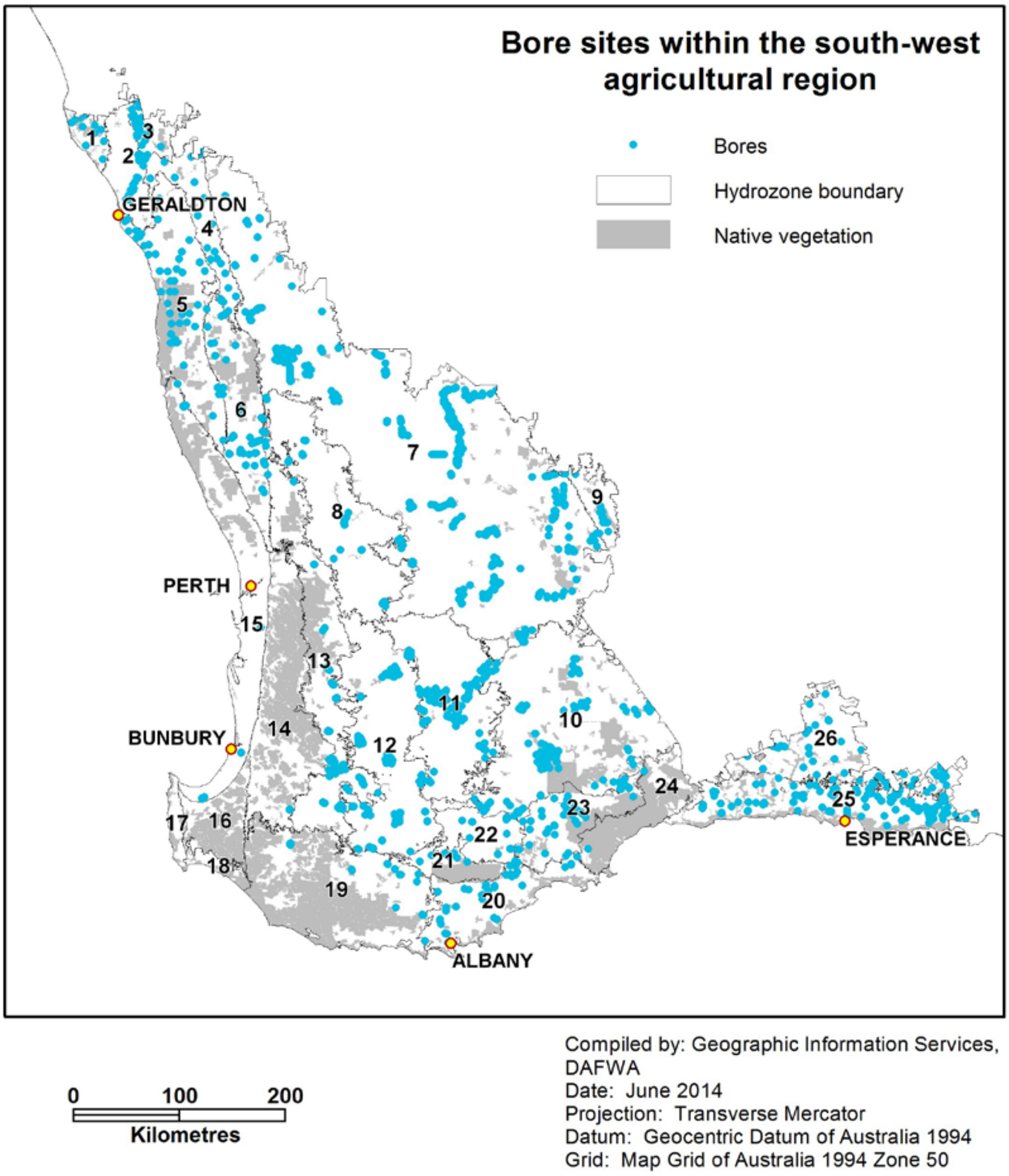
On the west and south coasts, the soils are derived from sedimentary sequences. They are often deep calcareous or alkaline sands or sandy duplex soils. Acid sands, clays and loams are common in low-lying coastal areas (Schoknecht & Pathan 2013).

The dominant soils and landforms of the region are discussed in more detail in Section 3.1.

2.4 Hydrozones

Previous studies of groundwater trends or salinity risk in the south-west agricultural region have used soil-landscape zones as the spatial unit for analyses. The Land Monitor project also used areas based on soil-landscape zones to develop the rules used to define areas of salinity hazard from Landsat TM data (Caccetta et al. 2010). Soil-landscape zones are areas defined on geomorphologic or geological criteria and are of the order of 10^3 to 10^4km^2, which is suitable for regional perspectives (Schoknecht et al. 2004). These zones reflect state-scaled regions with similar geomorphology, relief and farming system attributes. Furthermore, they align well with the gradient of mean annual rainfall (MAR) from the coast to the interior (Figure 2.3).

For this study, the concept of hydrozones is used as the spatial unit. Hydrozones are based on soil-landscape zones. However, there are several instances where adjacent soil-landscape zones are underlain by the same hydrogeological unit and where this occurs, soil-landscape zones are aggregated. In several cases, adjacent soil-landscape zones share contiguous distinct geological boundaries, such as major faults and, from a hydrological point of view, belong to the same functional unit. Hydrozones are therefore defined to coincide with soil-landscape zones, except where hydrogeological boundaries dictate that several soil-landscape zones belong to a contiguous hydrogeological unit.



Hydrozone		Hydrozone		Hydrozone	
1	Kalbarri Sandplain	10	South-eastern Zone of Ancient Drainage	19	Warren–Denmark
2	Northampton Block	11	South-western Zone of Ancient Drainage	20	Albany Sandplain
3	East Binnu Sandplain	12	Southern Zone of Rejuvenated Drainage	21	Stirling Range
4	Irwin Terrace	13	Eastern Darling Range	22	Pallinup
5	Arrowsmith	14	Western Darling Range	23	Jerramungup Plain
6	Dandaragan Plateau	15	Coastal Plain	24	Ravensthorpe
7	Northern Zone of Ancient Drainage	16	Donnybrook Sunkland	25	Esperance Sandplain
8	Northern Zone of Rejuvenated Drainage	17	Leeuwin	26	Salmon Gums Mallee
9	Southern Cross	18	Scott Coastal Plain		

Figure 2.2 Hydrozones in the south-west agricultural region and the location of bores used in this groundwater trend analysis

2.5 Climate

The climate of the south-west agricultural region ranges from temperate to arid, according to the updated Köppen-Geiger climate classification (Peel et al. 2007) (Figure 2.3).

The MAR ranges from more than 1200mm/y in the Darling Range south of Perth and on the far western south coast, down to 280mm/y in the east. About 80% of the rain falls between April and October over most of the region. Summer rainfall is highly variable and often associated with the southern passage of tropical cyclones (Indian Ocean Climate Initiative [IOCI] 2012).

Mean annual pan evaporation ranges from less than 1000mm/y in the far south-west, to more than 2800mm/y in the north-east. In the arid and much of the temperate areas, mean annual pan evaporation exceeds rainfall in most, if not all months (Figure 2.4 to Figure 2.7). Having evaporation in excess of rainfall is one of the factors that predispose the region to salt accumulation within the soil profile.

Mean monthly maximum summer air temperatures exceed 35°C in places and mean monthly minima are as low as 4°C (Figure 2.4 to Figure 2.7).

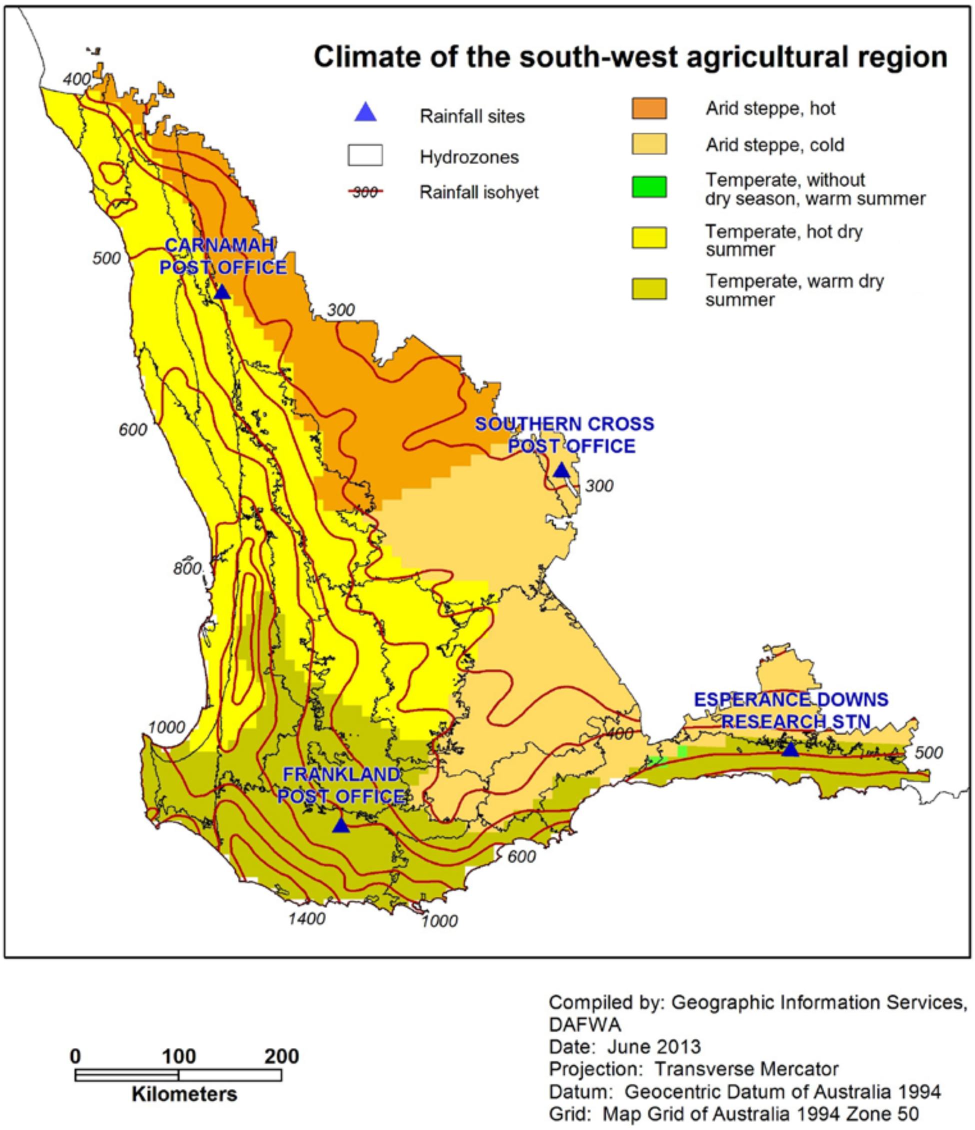


Figure 2.3 Climate map for the south-west agricultural region

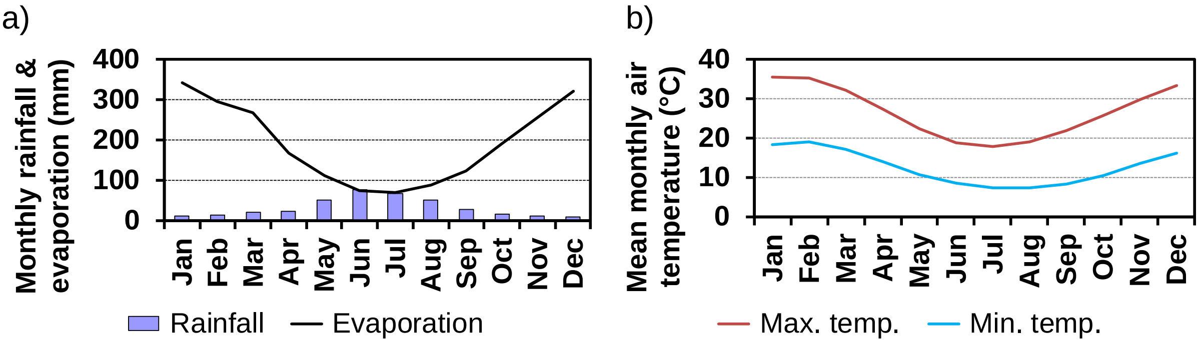


Figure 2.4 Carnamah climate (1898–2012): (a) mean monthly rainfall (MAR = 380mm) and mean monthly pan evaporation (mean annual pan evaporation = 2300mm); (b) mean monthly maximum and minimum air temperatures

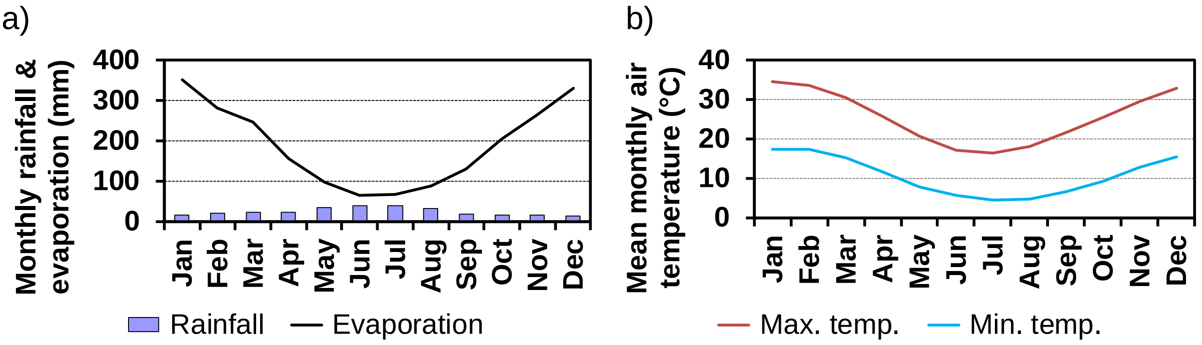


Figure 2.5 Southern Cross climate (1898–2012): (a) mean monthly rainfall (MAR = 290mm) and mean monthly pan evaporation (mean annual pan evaporation = 2280mm); (b) mean monthly maximum and minimum air temperatures

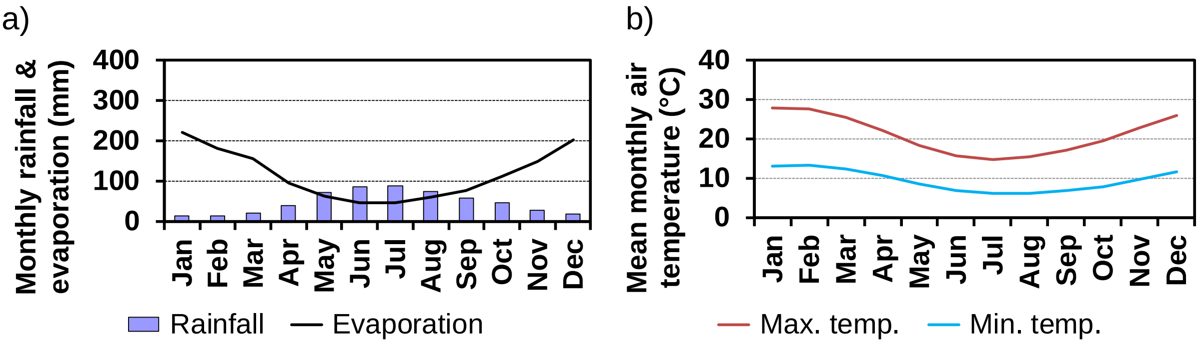


Figure 2.6 Frankland climate (1923–2012): (a) mean monthly rainfall (MAR = 560mm) and mean monthly pan evaporation (mean annual pan evaporation = 1410mm); (b) mean monthly maximum and minimum air temperatures

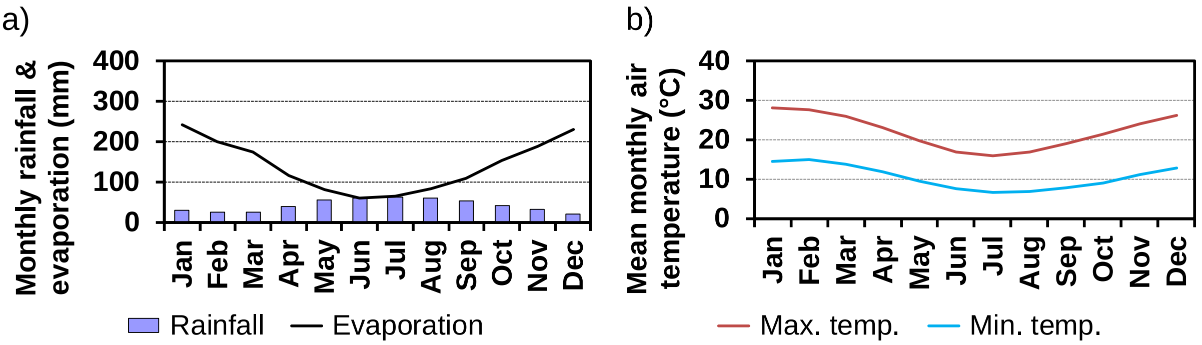


Figure 2.7 Esperance Downs Research Station climate (1951–2012): (a) mean monthly rainfall (MAR = 510mm) and mean monthly pan evaporation (mean annual pan evaporation = 1710mm); (b) mean monthly maximum and minimum air temperatures

2.5.1 Climate trends

According to the IOCI, the May to July rainfall in the western portion of the region has decreased since the 1970s and this rainfall reduction has intensified and expanded geographically over the past decade. This rainfall reduction is generally accepted to include both natural climate variability and anthropogenic components and is expected to continue (IOCI 2012).

Mean annual temperatures in the region have increased over the past 50 years; however, summer maxima have decreased along the south coast and in the east of the region (IOCI 2012).

The IOCI (2012) raises the issue of the appropriate period of the historical rainfall record to use as a baseline for comparing recent rainfall decline and the expected future decline. This question remains unresolved. The following summary is based on data accessed from the Patched Point Dataset, compiled by the Queensland Department of Science, Information Technology, Innovation and the Arts, and uses the period 1910–74 as a baseline period.

The MAR from 1975 to 1990 was below the long-term mean over much of the south-western portion of the region but there was an equivalent area with above average rainfall (Figure 2.8). This pattern was repeated in the 1991–2000 period, though the area with above average rainfall was larger. From 2001 to 2007, annual rainfall was much less than the long-term mean over most of the region; percentage decrease was highest and most widespread in the north. The exception was along the eastern fringe of the cleared agricultural area and along the eastern south coast where MAR remained above average. During 2008–12, the rainfall deficit (relative to the long-term mean) was lower in the north of the region and more pronounced in the central west and south-west. Although the distribution of areas with above average rainfall changed in the eastern portion of the region, most of the eastern south coast remained wetter than average.

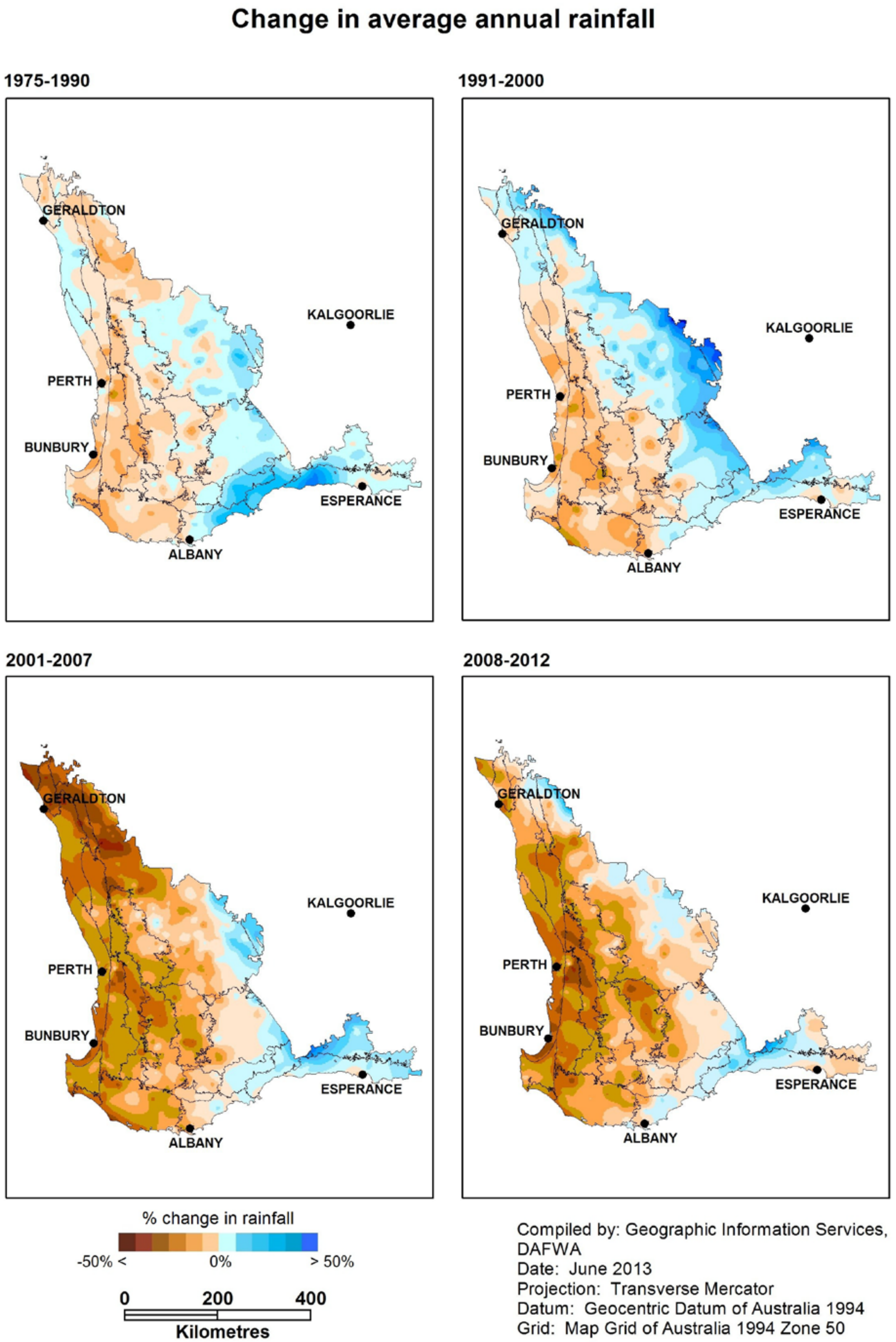


Figure 2.8 Percentage change in annual average rainfall 1975–90, 1991–2000, 2001–07 and 2008–12, compared to the long-term average of 1910–74

3 Groundwater trend analyses

Trend analysis for each bore site was undertaken for the period 2007–12, which complemented the analyses for pre-1990, 1991–2000 and 2001–07 performed by George et al. (2008). The analysis published by George et al. (2008) covered the 2000–07 period up to observations made up to mid-2007. The additional analyses presented here continued from that period, that is, mid-2007 to mid-2012. The rainfall change maps (Figure 2.8), however, are based on analysis of whole calendar year data.

To determine groundwater trends, lines of best fit were drawn through the data for the period of record and the gradient calculated. For bores with high variability between seasons, the line of best fit was aligned to the summer minima. Bores were included in the analyses if they were remote from any likely effects of salinity management treatments (drains, trees, perennial pastures) and met a minimum standard of five years duration with at least 20 monitoring observations. The criteria of a minimum of 20 observations was relaxed for some of the bores drilled during the 2007–08 program (DAFWA 2008) where a clear trend could be identified. Where nested bores exist at a monitoring site, the trend and depth for the deepest bore was reported, as it is most likely to reflect the status of the groundwater system responsible for mobilising salts stored within the regolith. To maintain a methodology consistent with the analyses reported by George et al. (2008), the effects of rainfall variability were not separated from linear trends in groundwater levels in this study.

Data for some bores monitored by DPaW, not included in the analysis by George et al. (2008), were available for inclusion in this study and rates of change in groundwater level for the 1991–2000 and 2001–07 periods were calculated for those bores. These results were then pooled with the results of George et al. (2008) for those analysis periods.

Groundwater trends were categorised as either rising, stable or falling. Low (less than ± 0.03m/y) calculated rates of change in groundwater level were assigned to the stable category. Groundwater levels at most bores are measured quarterly or biannually to the nearest 0.01 or 0.005m, and the 0.03m/y threshold was adopted to account for measurement error.

A representative hydrograph that matched the dominant trend and seasonal variability was selected for each hydrozone and plotted with the accumulated monthly residual rainfall (AMRR) for the closest rain gauge. AMRR is calculated as the cumulative sum of the difference between the observed monthly rainfall and the mean rainfall for that particular month (Weber & Stewart 2004, Ferdowsian et al. 2001). All monthly data from the first full year of record for each rain gauge was used to calculate the AMRR. An AMRR plot that covers the full period of record will always start and finish at zero. If AMRR is increasing, monthly rainfall is consistently exceeding the long-term mean, indicating above mean rainfall. If AMRR is decreasing, monthly rainfall is consistently below the long-term mean, indicating drier periods.

Rainfall data was accessed from the Patched Point Dataset compiled by the Queensland Department of Science, Information Technology, Innovation and the Arts.

3.1 Groundwater trends by hydrozone

The groundwater trends for 2007–12 are presented for each hydrozone. In each case, the results for earlier analysis periods (1991–2000, 2001–07), reported by George et al. (2008), are included in the summary tables. The results for the pre-1990 period reported by George et al. (2008) are not shown because of the relatively small number of bores for which data was available.

A brief description of each hydrozone is given which includes an overview of the geology, physiography and main groundwater flow systems (Coram 1998).

Groundwater trend by depth scatter plots are included to provide a complete picture of groundwater trends for the hydrozone over the full period of record. The scatter plots show the rate of change in groundwater level over each of the analysis periods, plotted against the depth to groundwater at the last observation date for each bore. Artesian bores plot above the abscissa on these graphs. The numbers of bores for which results are plotted are shown on each plot because the clustering of bores around the origin makes it difficult to differentiate individual results.

A representative hydrograph with AMRR is shown for each hydrozone. The AMRR provides site-specific, temporal information on rainfall variability compared to the long-term regional information in Figure 2.8. The AMRR plot on each graph does not start and finish at zero because the time series of rainfall observations is significantly longer than the time series of groundwater observations.

Maps showing the location of bores, classified by groundwater trend for the 1991–2000, 2001–07 and 2007–12 periods are presented for each hydrozone. Where appropriate, the Land Monitor AHAVF salinity hazard area is also shown to provide context on the location of bores in each of the trend categories.

3.1.1 Kalbarri Sandplain Hydrozone

The Kalbarri Sandplain Hydrozone is a combination of the southern parts of two soil-landscape zones: the Kalbarri Sandplain Zone (232) and the Port Gregory Coastal Zone (231). The northern portions of both soil-landscape zones remain uncleared. The hydrozone is a triangular wedge bounded to the north by Kalbarri National Park, to the east by the Northampton Block Hydrozone and in the west by the Indian Ocean. It covers an area of 144 000ha, 60% of which is cleared for agriculture.

This hydrozone is characterised by gently undulating plateau or sandplain with moderately dissected valleys and some gorges. Close to the coast, dunes and alluvial plains dominate the landscape and coastal cliffs fringe the western boundary.

The hydrozone occurs within the Carnarvon Basin. In this southern most extent of the Carnarvon Basin, the dominant geological unit is the Silurian-aged Tumblagooda Sandstone, which is well exposed in the cliffs of the Murchison River gorge near Kalbarri. Throughout the hydrozone, the Tumblagooda Sandstone is capped by Cretaceous sediments — Tamala Limestone along the coastal strip and aeolian (windblown) sandplain deposits in the east.

The Tumblagooda Sandstone contains an intermediate to regional groundwater flow system that discharges to the Indian Ocean. It is a good aquifer producing large quantities of water from nearly all wells and bores that intersect it (Playford et al. 1970, Hocking et al. 1982). Within the Kalbarri Sandplain Hydrozone, groundwater in the Tumblagooda Sandstone is predominantly fresh.

Where paired bores have been installed in the Tumblagooda Sandstone and the overlying surficial aquifer, the groundwater levels and responses in the two aquifers are similar. It appears therefore that the system behaves as a single aquifer. Groundwater levels and trends from either aquifer therefore provide a valid indicator of salinity risk for the location.

Groundwater monitoring and historical trends

Groundwater monitoring began in late 2007 when 11 sites were established during the Resource Condition Monitoring Project (DAFWA 2008). This report provides the first assessment of groundwater trends within the Kalbarri Sandplain Hydrozone.

Current situation

Falling, stable and rising groundwater trends are observed in the Kalbarri Sandplain Hydrozone (Table 3.1, Figure 3.1). Where groundwater is deep (>15 metres below ground level [m BGL]), the groundwater trends are falling or stable. Rising groundwater trends are observed in the north of the hydrozone, where the watertable is less than about 15m deep, despite below average rainfall. The hydrograph for bore 07KB2D is typical of this kind of response (Figure 3.2).

This hydrozone is characterised by a plateau where the Land Monitor algorithm computed an AHAVF area that included unacceptably large areas of commission error (areas judged ‘not at risk’ were mapped as ‘at risk’). The proportion of landscape occupying low-lying or valley floor positions that could be considered at risk of salinity is therefore not shown in Figure 3.3.

Table 3.1 Summary of groundwater trends in the Kalbarri Sandplain Hydrozone

	1991–2000			2001–07			2007–12		
Trend	**No. of bores**	**Proportion (%)**	**Mean RoC* (m/y)**	**No. of bores**	**Proportion (%)**	**Mean RoC* (m/y)**	**No. of bores**	**Proportion (%)**	**Mean RoC* (m/y)**
Falling							5	46	-0.15
Stable							2	18	
Rising							4	36	0.09

* Mean rate of change in groundwater level.

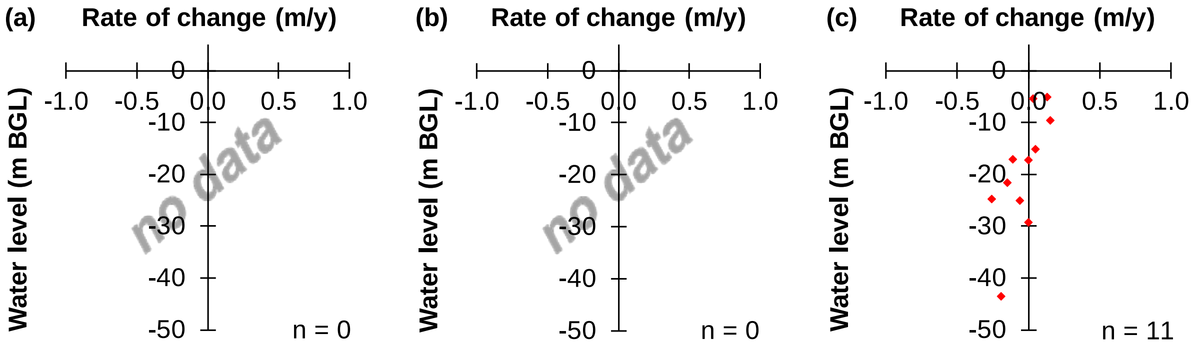


Figure 3.1 Rate of change in groundwater levels plotted against groundwater depth at the last observation date in the Kalbarri Sandplain Hydrozone for the 2007–12 analysis period (no data for the 1991–2000 and 2001–07 periods)

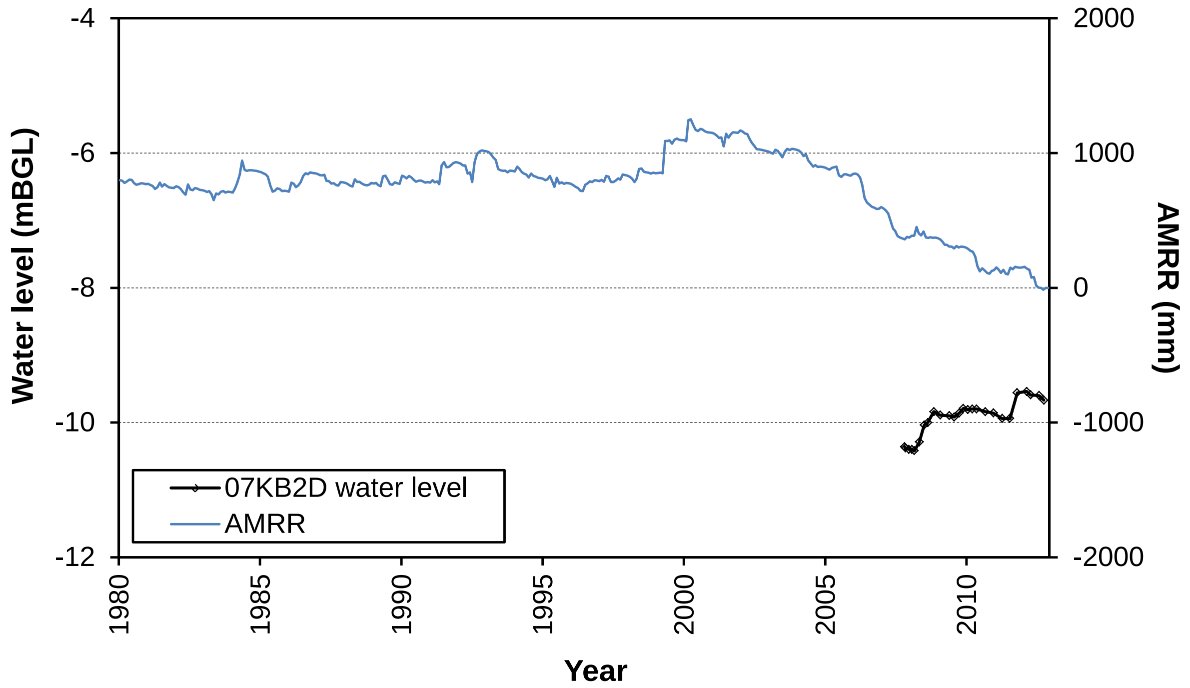


Figure 3.2 Hydrograph for bore 07KB2D with accumulated monthly residual rainfall for Balline

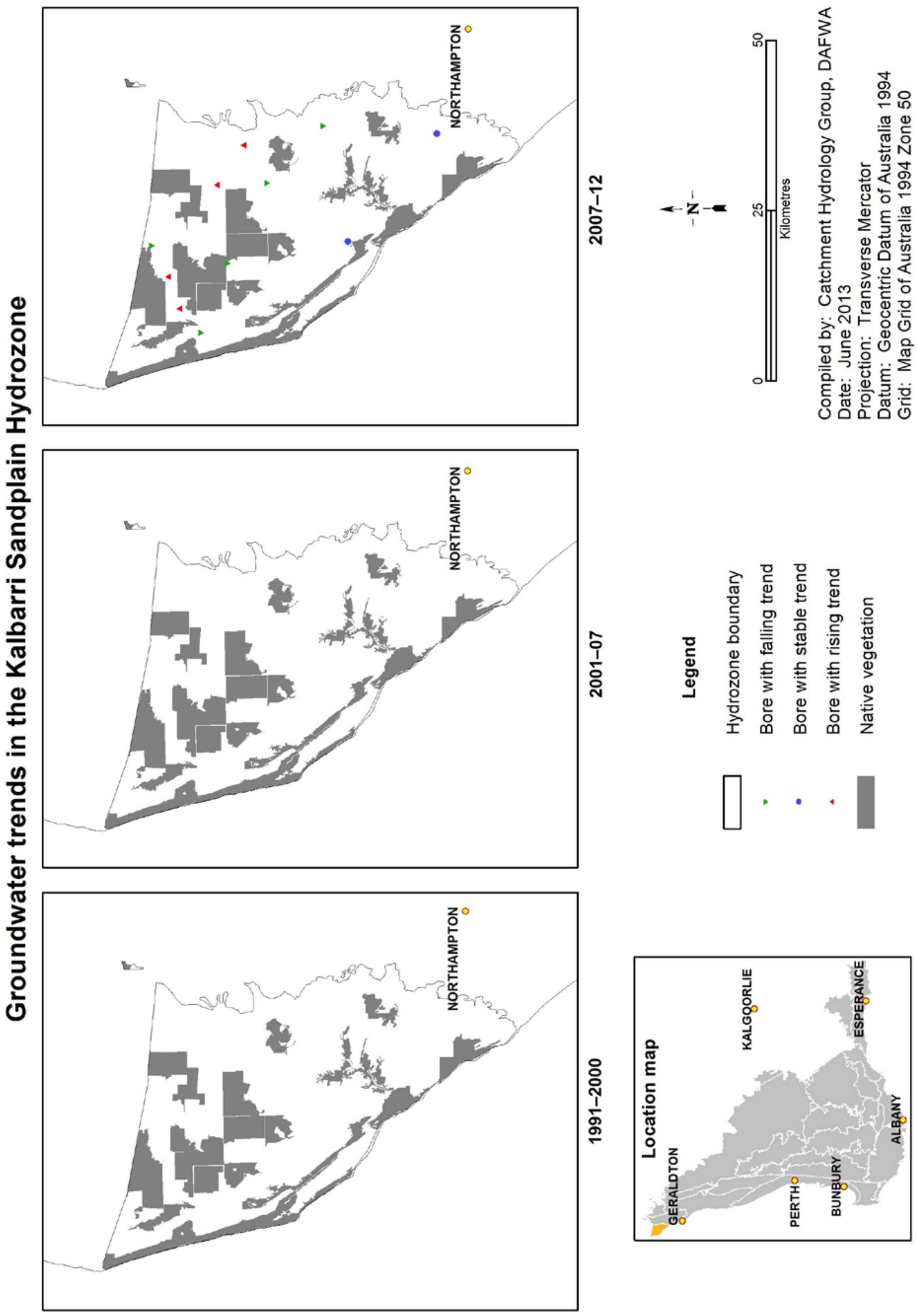


Figure 3.3 Groundwater trends in the Kalbarri Sandplain Hydrozone for each of the analysis periods (no data for the 1991–2000 and 2000–07 periods)

3.1.2 Northampton Block Hydrozone

The Northampton Block Hydrozone takes its name from the Northampton Block, which is a large outcrop of Proterozoic crystalline gneissic basement rock within the Perth Basin. It is partially capped in western areas by thin sequences of Jurassic sediments that form the characteristic flat-topped Moresby Ranges near Geraldton. The hydrozone covers an area of 348 000ha and is 80% cleared.

A mantle of gritty clay saprolite has formed over the Northampton Block. Groundwater yields from saprolite are limited, with useful yields generally only obtained from the basal saprolite grits or underlying fractured basement. Groundwater from the saprolite grits is generally of suitable quality for stock, except where the saprolite is covered by Jurassic sediments that may have restricted the flushing of salt from the underlying regolith (Speed 2002). The saprolite hosts local groundwater flow systems.

Groundwater and surface water discharge from the hydrozone via the Chapman River. A palaeochannel associated with the Chapman River contains up to 19m of alluvial channel sediments and contains useful, small-scale potable groundwater resources (Speed 2002). The Chapman River is directly connected to groundwater in the alluvial channel sediments in some sections where groundwater discharge maintains perennial flow. The alluvial channel sediments host an intermediate groundwater system.

The hydrozone is partially capped by numerous, minor perched aquifers within the Jurassic sediments. They are nearly all insignificant as water sources, except for limited stock supplies. Most of the bores monitored in the hydrozone have electrical conductivity (EC) values below 1000mS/m (5500mg/L). EC values above 3000mS/m (16 500mg/L or half as saline as seawater) have been observed but are rare.

Groundwater monitoring and historical trends

Groundwater monitoring began with 10 sites established in late 1991. The bore network was extended in early 1994 to investigate outbreaks of salinity and again in 1997 and 1998 during the investigation of Chapman Valley by the National Airborne Geophysics Project (George et al. 1998).

Before 2000, groundwater levels fluctuated in response to seasonal rainfall but there was no overall groundwater trend. This apparent equilibrium was attributed to well-defined surface drainage, enhanced topographic relief and groundwater discharge as baseflow in streams.

From 2001 to 2007, groundwater levels dropped significantly throughout the hydrozone as recharge reduced during an extended dry period and groundwater drained away. The mean rainfall for 2001–07 was 30–50% below the long-term mean for the hydrozone.

Current situation

Rising groundwater trends dominate throughout the Northampton Block Hydrozone (Table 3.2 and Figure 3.4). However, groundwater levels are generally still at least 2m below pre-2000 levels (Figure 3.5). Rainfall during 2008–12 was higher than during 2001–07 but still up to 30% below the long-term mean over most of the zone.

A very small area in the far south-west of the hydrozone received 30–40% below the mean rainfall during 2001–07.

Table 3.2 Summary of groundwater trends in the Northampton Block

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)
Falling	0			28	90	-0.18	1	3	-0.11
Stable	14	93		2	7		2	6	
Rising	1	7	0.54	1	3	0.07	29	91	0.19

* Mean rate of change in groundwater level.

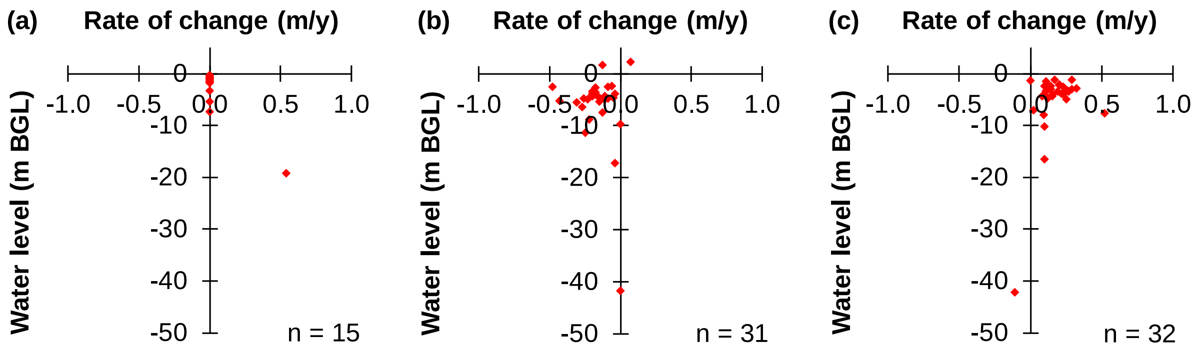


Figure 3.4 Rate of change in groundwater level plotted against groundwater depth at the last observation date in the Northampton Block Hydrozone for each of the analysis periods: (a) 1991–2000; (b) 2001–07; (c) 2007–12

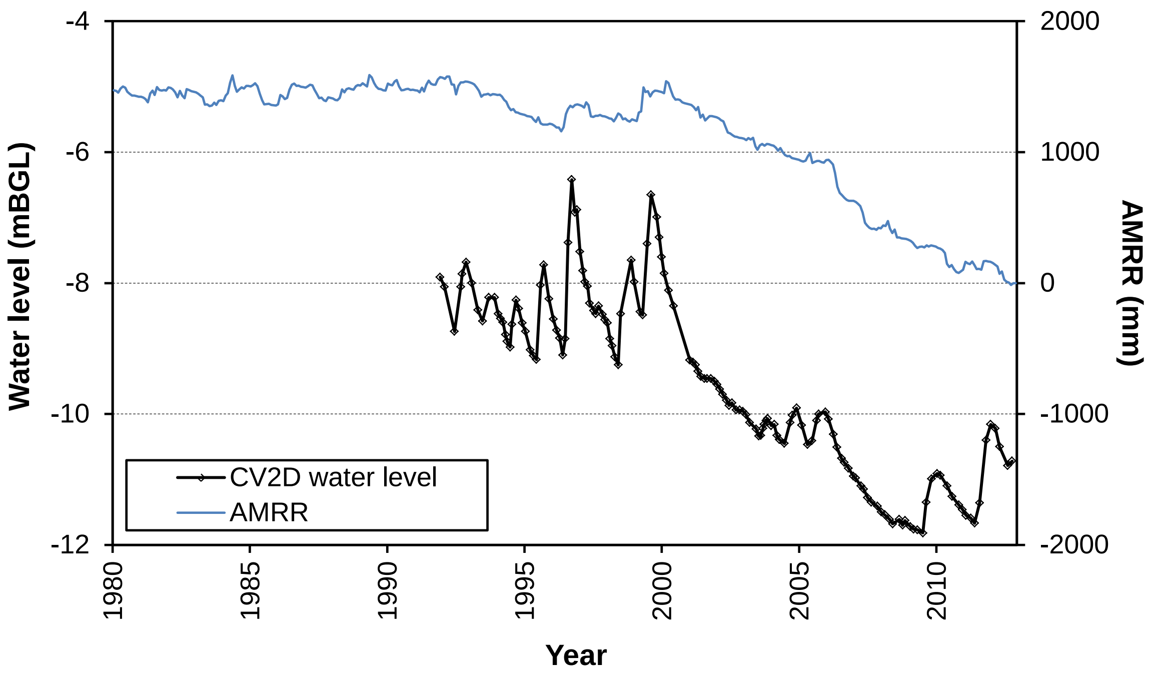


Figure 3.5 Hydrograph for bore CV2D with accumulated monthly residual rainfall for Chapman Valley

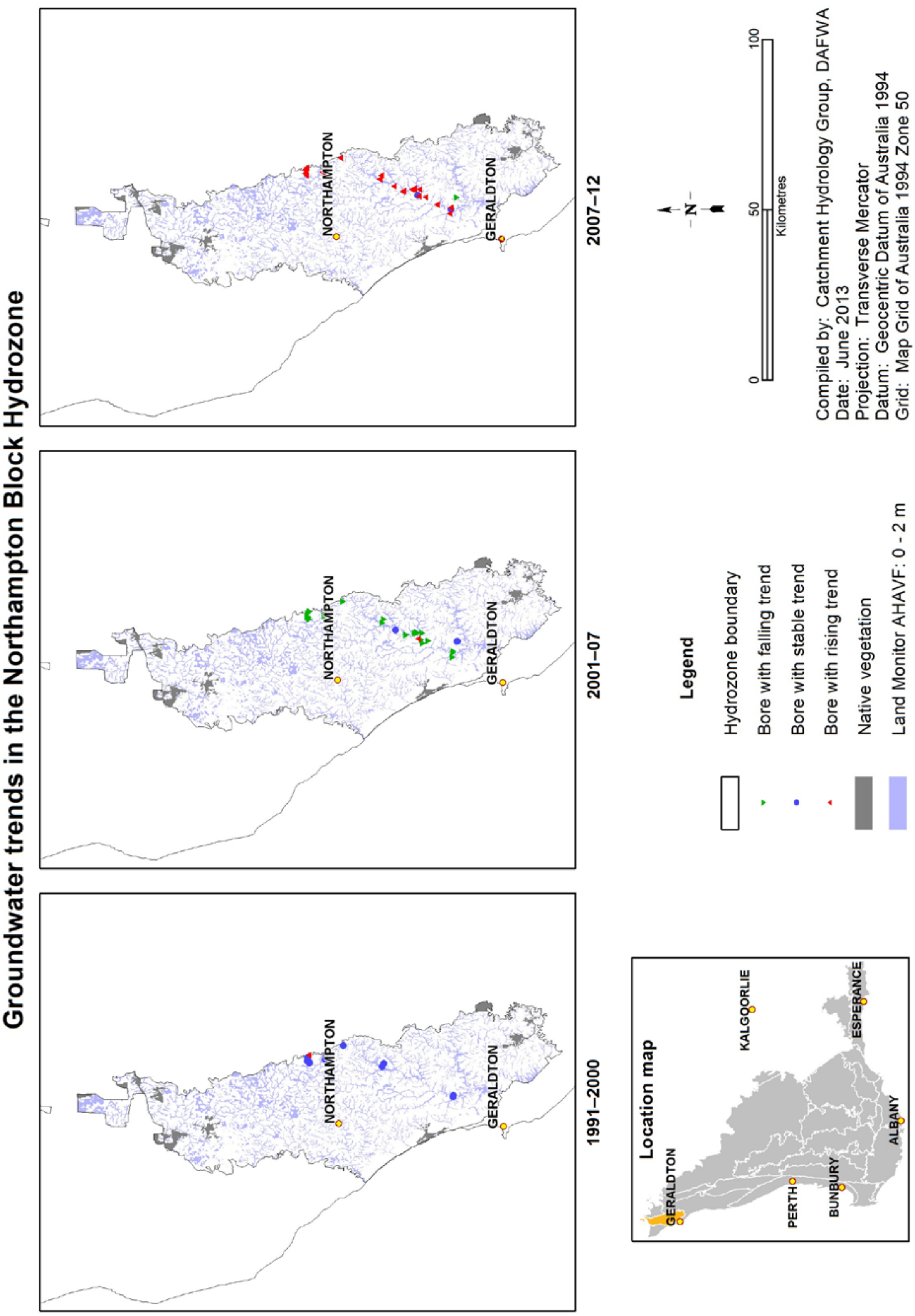


Figure 3.6 Groundwater trends in the Northampton Block Hydrozone for each of the analysis periods

3.1.3 East Binnu Sandplain Hydrozone

The East Binnu Sandplain Hydrozone coincides with the southern parts of two soil-landscape zones: the Northern Victoria Plateau Sandplain Zone (223) and the Victoria Red Sandplain Zone (234). It is characterised by a very gently undulating, internally draining, sandplain plateau extending from just north of the Chapman River near Yuna, northward to the Murchison River. It is bound to the west by the Northampton Block Hydrozone and to the east by the occurrence of Permian sediments that are a feature of the Irwin Terrace Hydrozone. The eastern boundary is poorly defined and is possibly structurally controlled by faulting. The hydrozone covers an area of 168 000ha, 73% of which is cleared for agriculture.

The East Binnu Sandplain Hydrozone occurs within the Coolcalalaya Sub-basin in the far north of the Perth Basin. It is occupied by a single geological unit, the Tumblagooda Sandstone, and there is substantial evidence that the overlying sandplain has formed by in situ weathering of the sandstone. The Tumblagooda Sandstone is Silurian age and is well exposed in the cliffs of the Murchison River gorge near Kalbarri.

The Tumblagooda Sandstone hosts an intermediate to regional groundwater system with predominantly brackish to saline groundwater (Playford et al. 1970). Any potential westward movement of groundwater is most likely blocked by the crystalline basement of the Northampton Block. Therefore, it appears that groundwater flow in the Tumblagooda Sandstone is northward and probably discharges to the Murchison River.

It appears from the similar responses of paired bores installed in the Tumblagooda Sandstone and the overlying surficial formation that the system behaves as a single aquifer. Groundwater levels and trends from either aquifer therefore provide a valid indicator of salinity risk.

Groundwater monitoring and historical trends

Groundwater monitoring began in 2004 with monitoring sites installed in response to investigations into unauthorised clearing. The investigations indicated that a significant salinity problem could be developing in the sandplain on the northern Perth Basin. This report is the first assessment of groundwater trends in the East Binnu Sandplain Hydrozone.

Current situation

Rising groundwater trends dominate throughout the East Binnu Sandplain Hydrozone, despite the reduced rainfall since 2000 (Table 3.3, Figure 3.7). Figure 3.8 shows a typical hydrograph with increasing groundwater levels despite continued low rainfall.

The hydrozone is characterised by an internally draining landscape where the Land Monitor algorithm computed an AHAVF area that included unacceptably large areas of commission error (areas judged ‘not at risk’ were mapped as ‘at risk’). The proportion of landscape occupying low-lying or valley floor positions that could be considered at risk of salinity is therefore not shown in Figure 3.9.

Table 3.3 Summary of groundwater trends in the East Binnu Sandplain Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	0			0			0		
Stable	0			1	100		4	16	
Rising	1	100	0.30	0			21	84	0.12

* Mean rate of change in groundwater level.

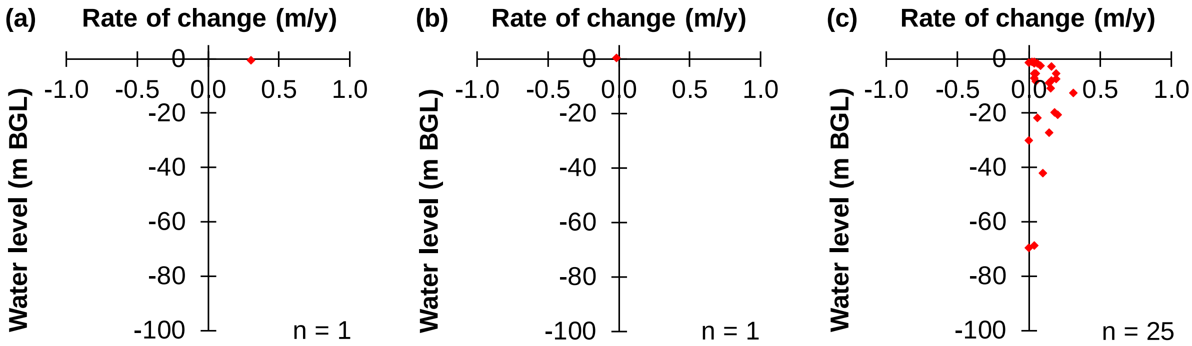


Figure 3.7 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the East Binnu Sandplain Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

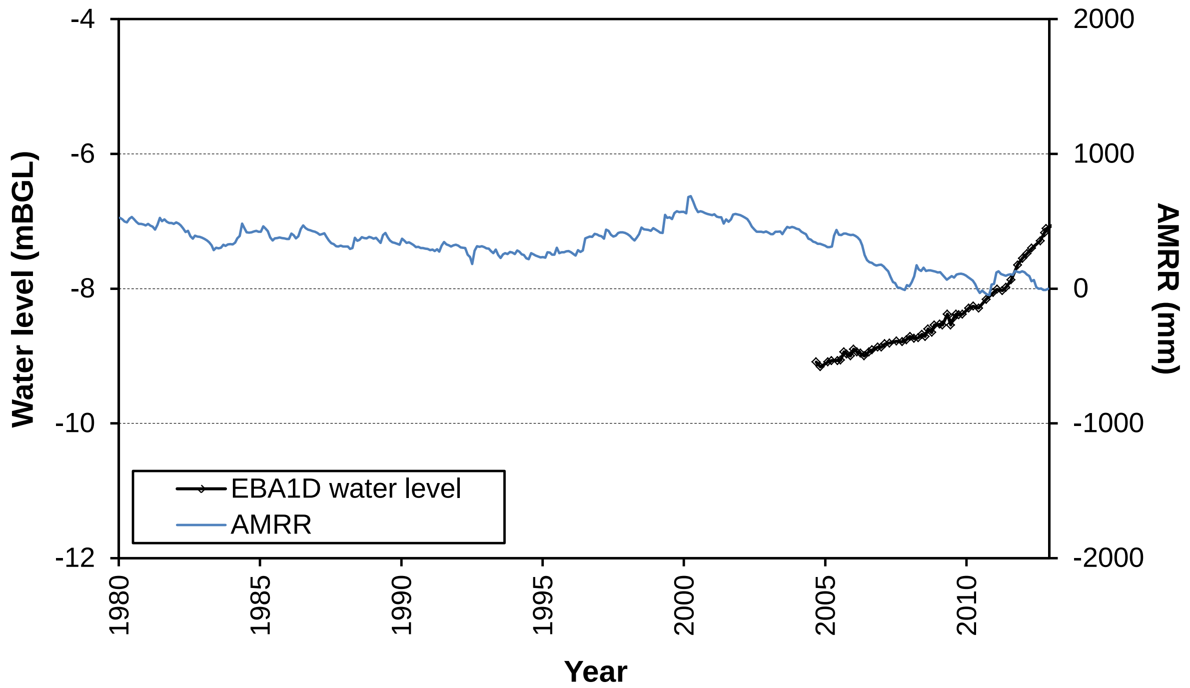


Figure 3.8 Hydrograph for bore EBA1D with accumulated monthly residual rainfall for Ajana

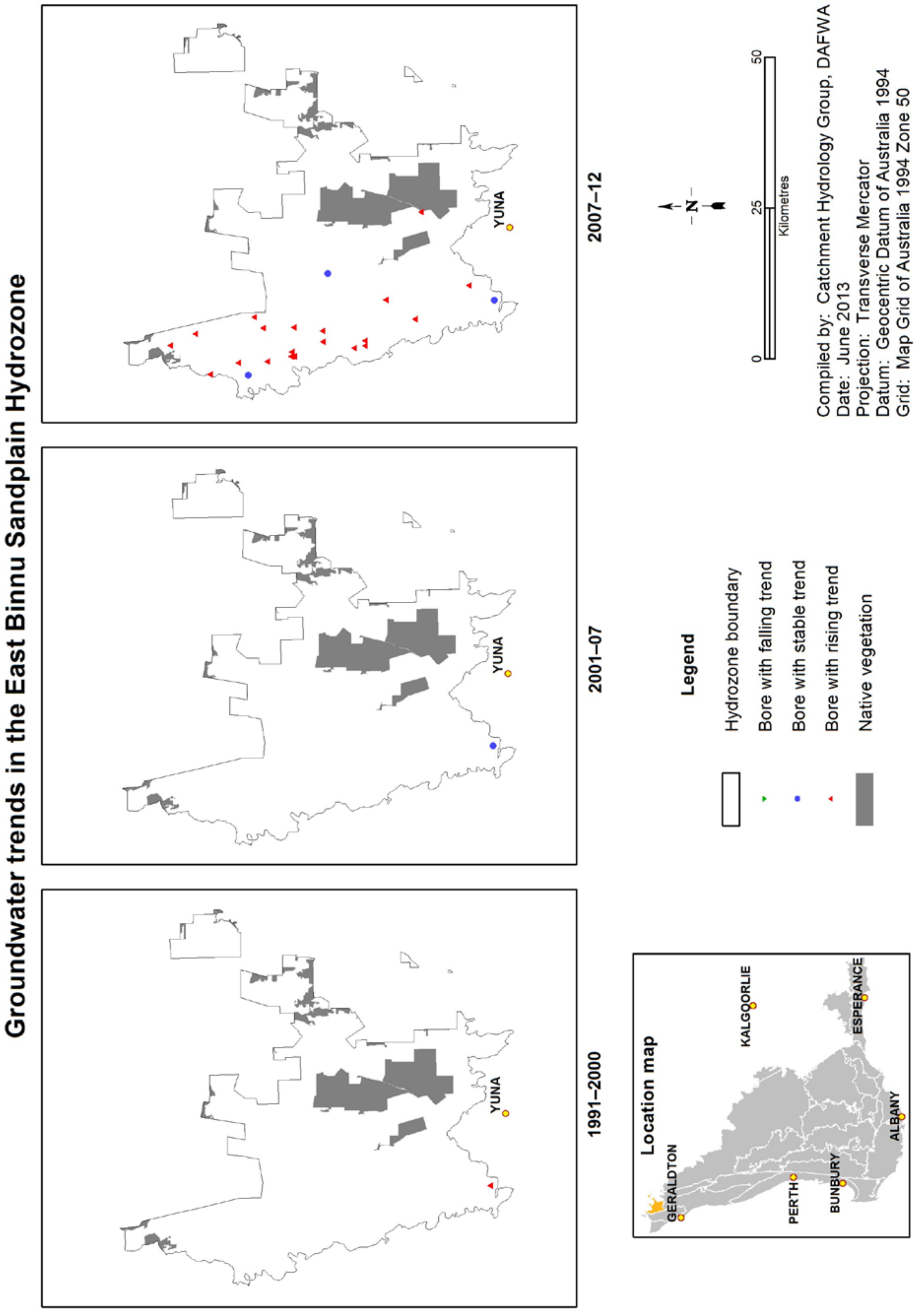


Figure 3.9 Groundwater trends for each of the periods analysed for the East Binnu Sandplain Hydrozone

3.1.4 Irwin Terrace Hydrozone

The Irwin Terrace Hydrozone covers two soil-landscape zones: in the south, it coincides with the Lockier Zone (226); in the north and west, it coincides with the Tenindewa Zone (227). The eastern boundary of the hydrozone is defined by the Darling Fault, which demarcates the western edge of the Yilgarn Craton. South of Mullewa, the western boundary is defined by the Urella Fault. North of Mullewa, the western boundary splays, forming a branch that extends westward along the upper catchment of the Chapman River to the Northampton Block Hydrozone. The hydrozone covers an area of 422 000ha and is 83% cleared for agriculture.

In the south, the hydrozone is characterised by dissected terrain with breakaways and plateau remnants. In the north, it is characterised by wash plains surrounded by gently undulating sandplain.

The hydrozone is characterised by Permian sediments, which are predominantly heavy clay rich. North of Mingenew, the Permian sediments are partially blanketed by sandplain.

The heavy clay of the Permian sediments has extremely low hydraulic conductivity and while there are sandier zones and deeper sandstone layers in some areas, the lateral connectivity and distribution of these is poorly understood. Where clay soils, which are derived from Permian sediments, are exposed in drainage lines, they are typically severely salt-affected.

Groundwater quality in the Permian sediments ranges from brackish (500mS/m, 2750mg/L) to hypersaline (7000mS/m, 38 500mg/L).

Groundwater monitoring and historical trends

Groundwater monitoring began in 1995 with the installation of five monitoring sites. Prior to 2000, when rainfall was above average, high rates of groundwater rise were observed beneath the red earth flats north-east of Mingenew and widespread salinity appeared inevitable (Figure 3.10). The drier conditions that have prevailed since 2000 have resulted in less recharge and falling trends at those sites (Figure 3.11).

Several groundwater monitoring sites close to the south-western edge of the hydrozone were installed in 1998 and 2001 to gain a better understanding of why salinity was developing east of the Urella Fault in this hydrozone and not down gradient in the adjoining Dandaragan Plateau Hydrozone, as may have been expected.

Another 10 groundwater monitoring sites were installed in late 2007 and 2008 as part of the Resource Condition Monitoring Project (DAFWA 2008) and this report is the first assessment of groundwater trends at these sites.

Current situation

Variable groundwater trends are observed throughout the Irwin Terrace Hydrozone (Table 3.4, Figure 3.10, Figure 3.12). Rising trends are associated with sites located within areas of sandplain soils. Falling trends tend to be associated with sites located in areas of heavier soil types (Figure 3.11). Stable trends are observed where groundwater is shallow (<2m) and the sites are affected by salinity.

The hydrozone is characterised by an internally draining landscape where the Land Monitor algorithm computed an AHAVF area that included unacceptably large areas of commission error (areas judged 'not at risk' were mapped as 'at risk'). The proportion of landscape occupying low-lying or valley floor positions that could be considered at risk of salinity is therefore not shown in Figure 3.12.

Table 3.4 Summary of groundwater trends in the Irwin Terrace Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	0			8	62	-0.14	5	20	-0.13
Stable	3	50		3	23		9	36	
Rising	3	50	0.21	2	15	0.15	11	44	0.12

* Mean rate of change in groundwater level.

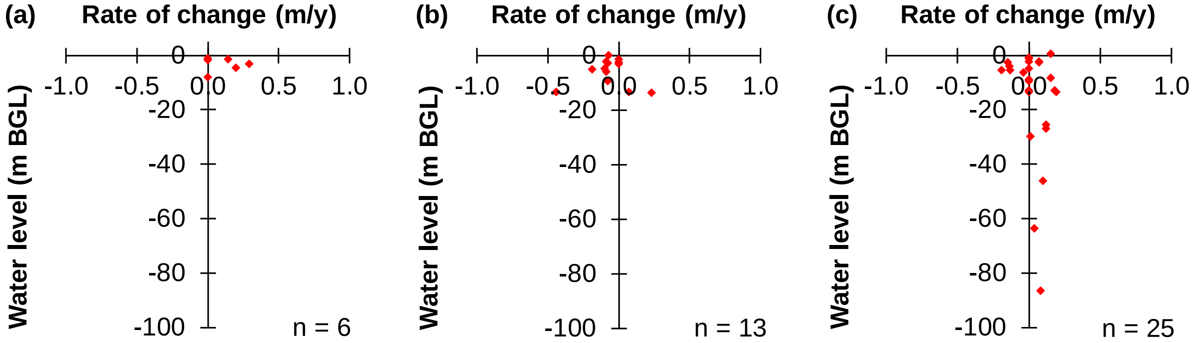


Figure 3.10 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in the Irwin Terrace Hydrozone for each of the analysis periods: (a) 1991–2000; (b) 2001–07; (c) 2007–12

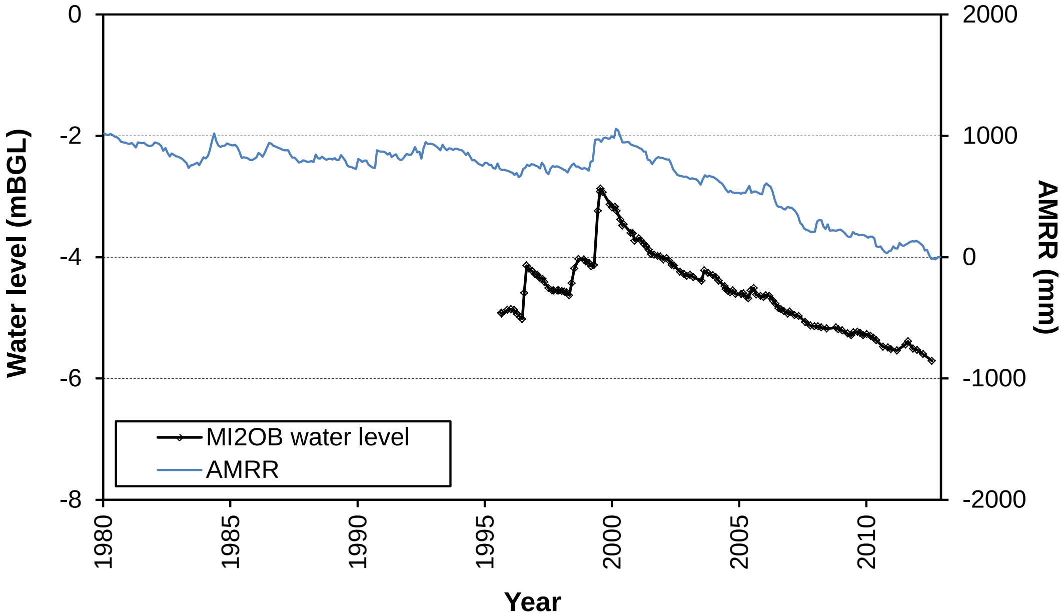


Figure 3.11 Hydrograph for bore MI2OB in the Irwin Terrace Hydrozone, with accumulated monthly residual rainfall for Mingenew

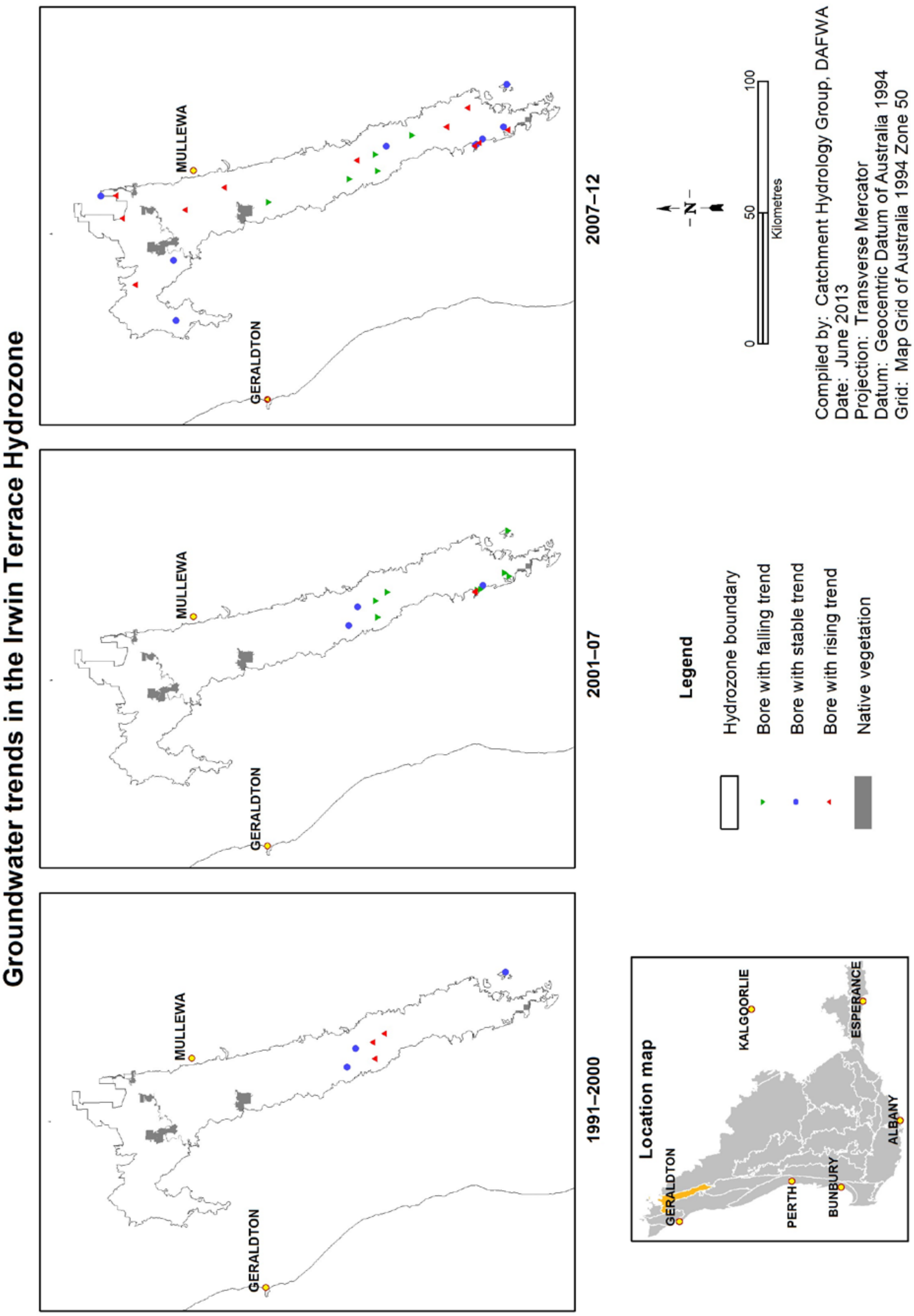


Figure 3.12 Groundwater trends for each of the periods analysed for the Irwin Terrace Hydrozone

3.1.5 Arrowsmith Hydrozone

The Arrowsmith Hydrozone coincides with three soil-landscape zones: the Southern Victoria Plateau Sandplain Zone (220), Geraldton Coastal Zone (221) and Arrowsmith Zone (224). It is characterised by gently undulating sandplain and sandy alluvial fans on the Eneabba Plain. It extends from Muchea to Geraldton in the western portion of the West Midlands and is bound to the west by the Indian Ocean from Leeman to Geraldton. The hydrozone covers an area of 1.08 million hectares, 63% of which is cleared for dryland agriculture.

The dominant soil types are Yellow or Pale deep sands, Yellow/brown shallow sands, Deep sandy gravel and Grey deep sandy duplex. Minor areas of lateritic duricrust also exist.

The Arrowsmith Hydrozone occurs within the Perth Basin. It is dominated by Jurassic sediments, principally the Yarragadee Formation. The Yarragadee Formation consists of interbedded felspathic sandstone, siltstone and claystone with minor conglomerate and coal (Mory & Iasky 1996). In this hydrozone, the Yarragadee Formation forms a mostly unconfined aquifer hosting a significant, low salinity, regional groundwater system. Groundwater flow is generally westward, discharging to the Indian Ocean.

Groundwater monitoring and historical trends

Groundwater monitoring began in 1991 with monitoring sites installed at Bibby Springs near Cervantes. In 1996, bores installed by the then Water and Rivers Commission (Greenough Shallows and Leeman Shallows) were monitored to assess the salinity risk in the lower-lying western portion of the Arrowsmith Hydrozone.

In March 1999, groundwater monitoring sites were installed in and around Lake Logue, just prior to the flooding that occurred that year. Another eight groundwater monitoring sites were installed throughout the hydrozone in 2007 and 2008 as part of the Resource Condition Monitoring Project (DAFWA 2008).

There are bores in the Arrowsmith Hydrozone screened in both the surficial aquifer and in the Yarragadee Formation. Where paired bores have been installed, the groundwater levels and responses in the two aquifers are nearly identical and it appears that the system behaves as a single aquifer. Groundwater levels and trends from either aquifer therefore provide a valid indicator of salinity risk for the location.

Prior to 2000, most sites had rising groundwater trends and there was an episodic rise in groundwater levels at most sites in response to very wet conditions in 1999. From 2001 to 2007, significantly drier than average conditions prevailed and there was a switch from mostly rising to mostly falling groundwater trends (Table 3.5, Figure 3.13).

Current situation

Since 2007, mostly falling groundwater trends have prevailed in western areas of the Arrowsmith Hydrozone because rainfall has remained below the long-term mean (Figure 3.14). Rising groundwater trends in the regional groundwater system are observed in central and eastern parts of the hydrozone, generally where localised perched watertables overlie the regional aquifer. The greatest rates of rise are observed where watertables are deepest (Figure 3.13).

The Arrowsmith Hydrozone is characterised by a gently undulating sandplain where the Land Monitor algorithm computed an AHAVF area that included unacceptably large areas of commission error (areas judged 'not at risk' were mapped as 'at risk'). The proportion of landscape occupying low-lying or valley floor positions that could be considered at risk of salinity is therefore not shown in Figure 3.15.

Table 3.5 Summary of groundwater trends for the Arrowsmith Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	3	11	-0.04	30	73	-0.14	24	44	-0.12
Stable	6	22		8	20		14	26	
Rising	18	67	0.19	3	7	0.24	16	30	0.25

* Mean rate of change in groundwater level.

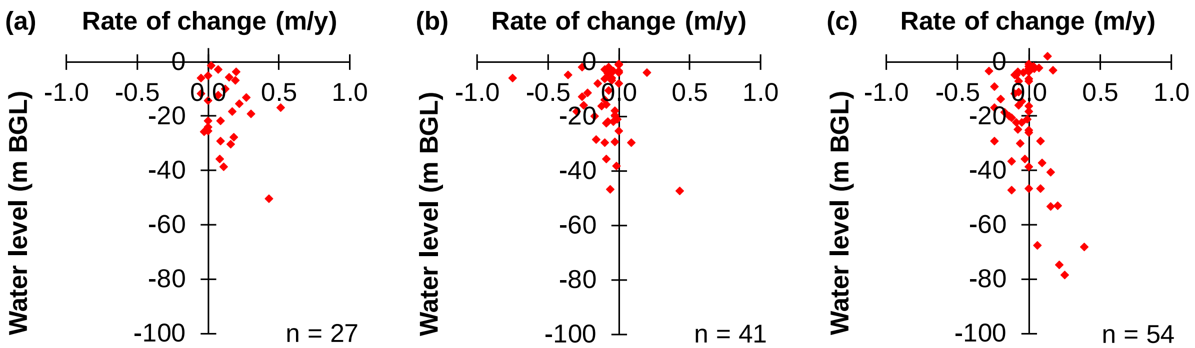


Figure 3.13 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Arrowsmith Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

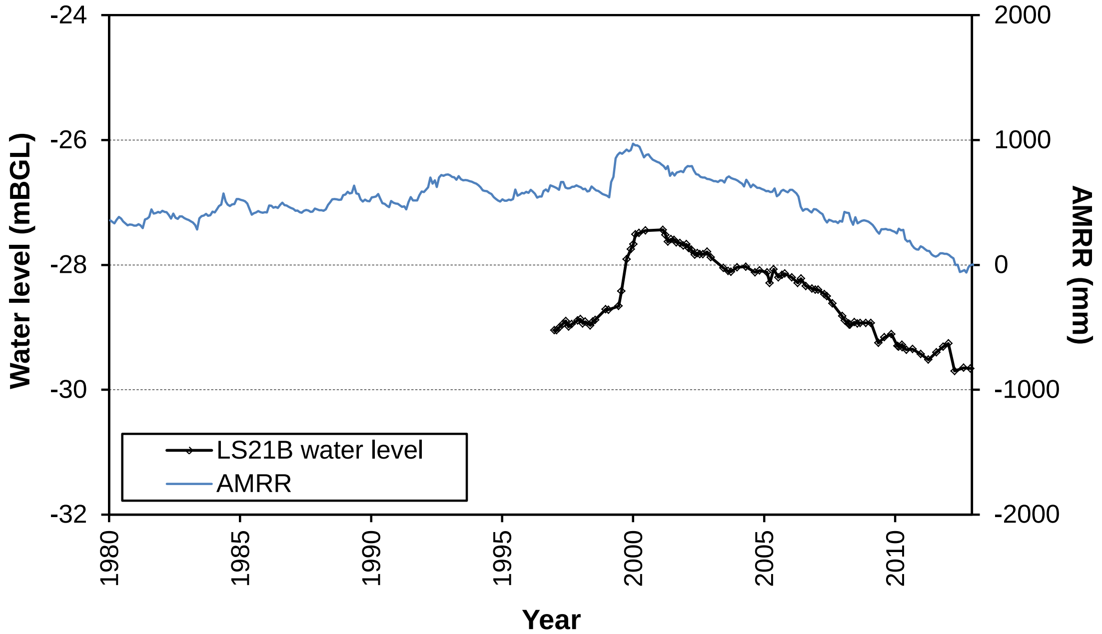


Figure 3.14 Hydrograph for bore LS21B with accumulated monthly residual rainfall for Eneabba

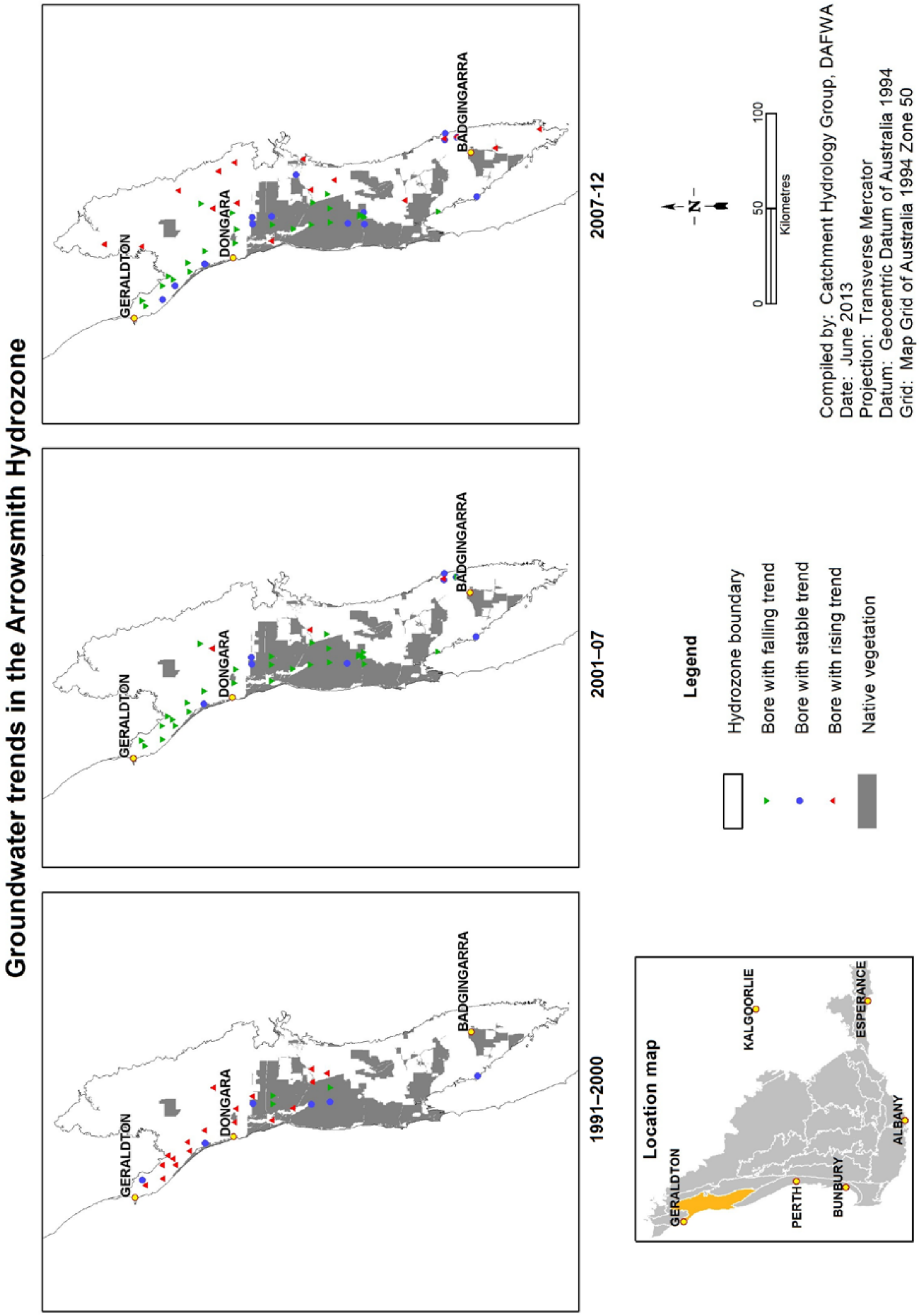


Figure 3.15 Groundwater trends for each of the periods analysed for the Arrowsmith Hydrozone

3.1.6 Dandaragan Plateau Hydrozone

The Dandaragan Plateau Hydrozone is characterised by gently undulating sandplain extending from Gingin in the south to Yandanooka in the north. It is bounded to the east by the Darling Fault south of Coorow and the Urella Fault north of Coorow. It extends west to the Gingin Scarp in the south and to the outcrop of the Otorowiri Member in the north-west. It covers an area of 715 000ha and is 60% cleared.

The hydrozone falls within the Perth Basin and is dominated by Cretaceous sediments, principally the Parmelia Formation which consists of felspathic sandstone, with minor siltstone and claystone (Mory & Iasky 1996). The Parmelia Formation is a significant unconfined aquifer hosting a low salinity regional groundwater system. Groundwater flow is generally westward, discharging as seeps and springs over the shales and siltstones of the Otorowiri Member. Localised, perched aquifers occur throughout the hydrozone but are not widespread.

Groundwater monitoring and historical trends

Groundwater monitoring in the Dandaragan Plateau Hydrozone began in 1988 in the west Gillingarra area in response to rapidly spreading salinity. In 1993, monitoring sites were installed south of Dandaragan. In 1998 and 2001, more sites were installed to determine why salinity was developing east of the Urella Fault in the adjoining Irwin Terrace Hydrozone, yet not down gradient in the Dandaragan Plateau Hydrozone as may be expected.

Groundwater monitoring sites were installed in Dandaragan townsite under the Rural Towns Program in 2006. Another 28 sites were installed throughout the hydrozone in 2008, as part of the Resource Condition Monitoring Project (DAFWA 2008), collaborative work with the Forest Products Commission, and on behalf of the Moore Catchment Council.

Historically, rising groundwater trends have been observed throughout the hydrozone, albeit from sparsely located monitoring sites (Table 3.6, Figure 3.16).

Current situation

Consistently rising groundwater trends are dominant and recurring throughout the Dandaragan Plateau Hydrozone (Figure 3.17). The proportion of bores with rising trends halved between the 1991–2000 and the 2001–07 periods. In 2007–12, the number of bores analysed increased to 39 and three-quarters of these showed rising trends because of increased rainfall (Table 3.6).

The Dandaragan Plateau Hydrozone is characterised by an internally draining landscape where the Land Monitor algorithm computed an AHAVF area that included unacceptably large areas of commission error (areas judged ‘not at risk’ were mapped as ‘at risk’). The proportion of landscape occupying low-lying or valley floor positions that could be considered at risk of salinity is therefore not shown in Figure 3.18.

Table 3.6 Summary of groundwater trends for the Dandaragan Plateau Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)
Falling	0	0		2	16	-0.05	3	8	-0.12
Stable	1	13		5	42		6	15	
Rising	7	88	0.27	5	42	0.32	30	77	0.18

* Mean rate of change in groundwater level.

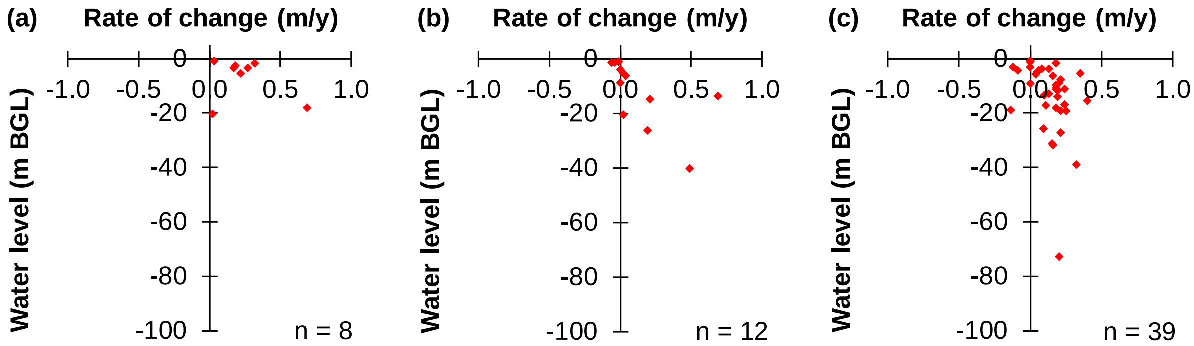


Figure 3.16 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Dandaragan Plateau Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

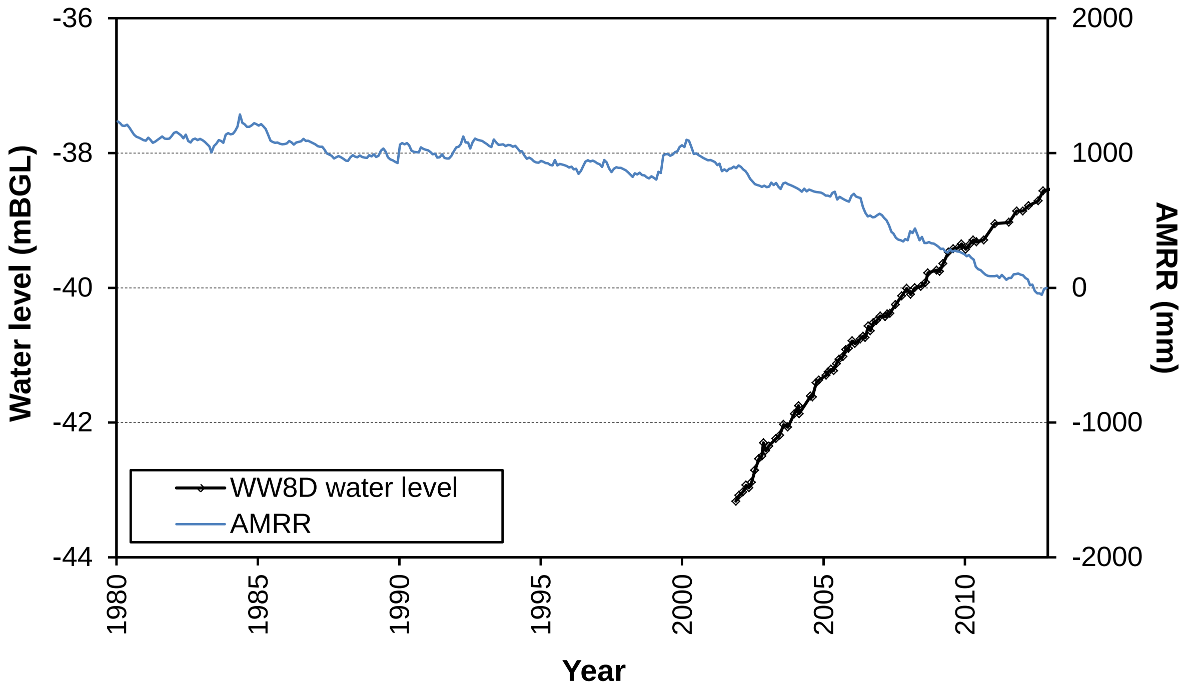


Figure 3.17 Hydrograph for bore WW8D with accumulated monthly residual rainfall for Carnamah

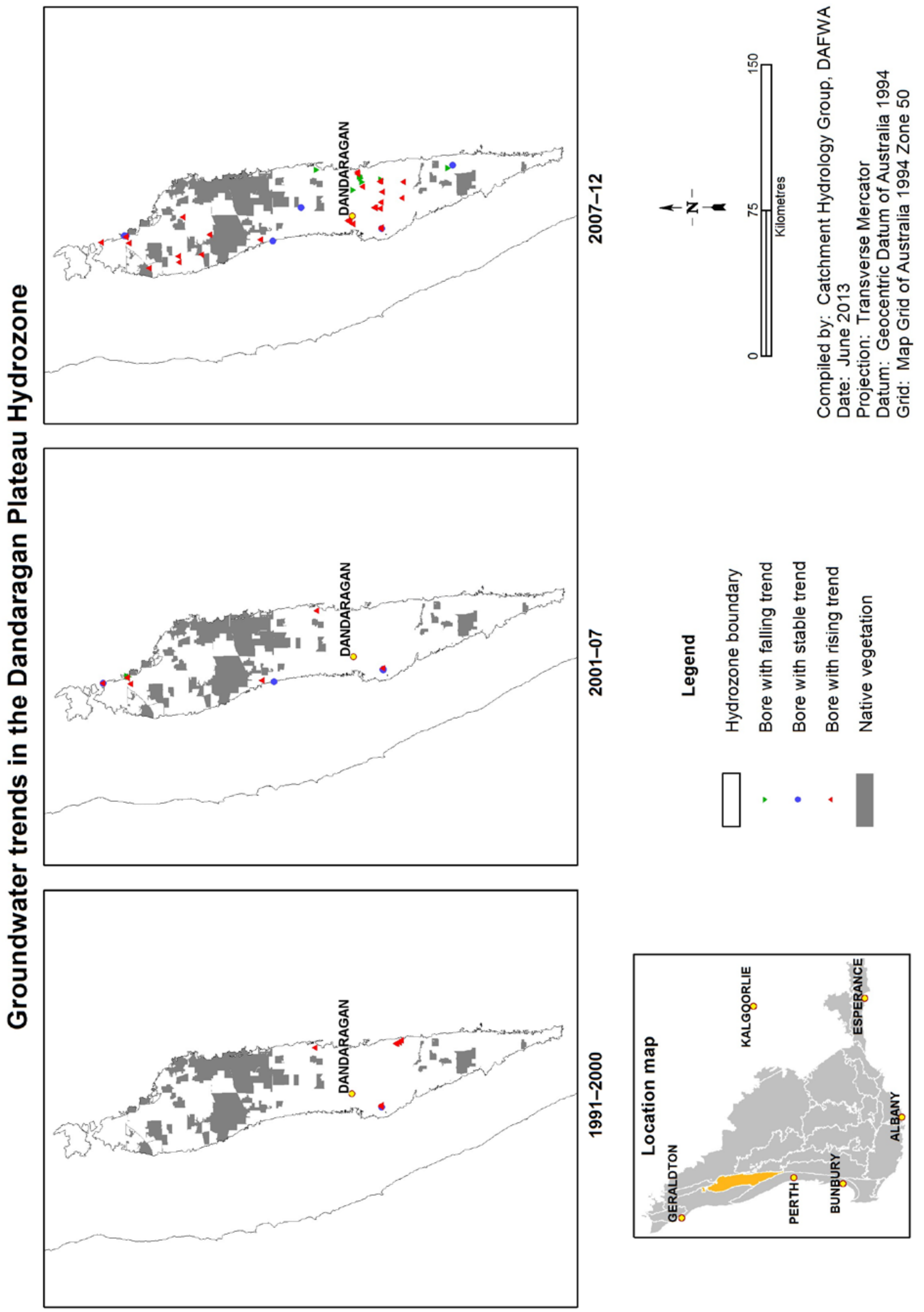


Figure 3.18 Groundwater trends for each of the periods analysed for the Dandaragan Plateau Hydrozone

3.1.7 Northern Zone of Ancient Drainage Hydrozone

The Northern Zone of Ancient Drainage Hydrozone is located on the Yilgarn Craton, which is a large raft of Archean continental granitoid rock. It coincides with three soil-landscape zones: the Irwin River Zone (271), Karara Hills, Lakes and Plains Zone (270) and Northern Zone of Ancient Drainage Zone (258). It is characterised by subdued relief with broad valley floors that have dominantly red or brown loamy to clay soils and coarser textured loamy to sandy soils in upland areas. It is bound to the west by the Darling Fault, to the east by the clearing line and the edge of pastoral activities, and to the south by the South-western and South-eastern Zones of Ancient Drainage. It covers an area of 6.2 million hectares and is 82% cleared.

Regolith profiles in the Northern Zone of Ancient Drainage Hydrozone are typically up to 30m of gritty clay saprolite formed by in situ weathering of the crystalline basement rock. The gritty clay saprolite hosts local groundwater systems where the yields are generally low and the majority of groundwater, particularly in valley floors, is saline. Most of WA’s existing dryland salinity occurs on the Yilgarn Craton.

There are extensive areas of primary salinity on the Yilgarn Craton in salt lake systems that are rarely connected by surface flows. Palaeochannels of deep sediment, up to 80m thick, are known to occur within the salt lake systems, which can provide high yielding but hypersaline groundwater resources.

Perched aquifers in deep sands on hillslopes are common and often contain small supplies of fresh groundwater that are suitable for stock and that can be accessed via soaks or low-yielding windmills. Saline hillside seeps often occur at the downslope end of perched aquifers where the groundwater comes close to the soil surface and salts are concentrated by evaporative discharge.

Groundwater monitoring and historical trends

Prior to 2000, rainfall was above the long-term mean over much of the hydrozone. Rising groundwater trends dominated and were widespread in both weathered granite and palaeochannel aquifers (Table 3.7, Figure 3.19). The exceptions tended to be at sites located within large blocks of remnant native vegetation or where salinity was well advanced and a post-clearing equilibrium had become established. There was significant episodic rise in groundwater at all the sites in the northern part of the hydrozone in response to very wet conditions in 1999 (Figure 3.20).

From 2001 to 2007, rainfall was well below average over most of the hydrozone and there was a change from predominantly rising groundwater trends to equal proportions of falling and stable groundwater trends, with rising trends in the minority (Table 3.7). The magnitude of the falling trends was probably amplified by recessions from the episodic peak in 1999. Subsequently, there was a particularly dry spell that persisted for much of 2001–07.

Current situation

Since 2007, rainfall has been close to, or above the long-term mean over much of the hydrozone (Figure 2.8), resulting in a return to more widespread rising groundwater trends, although falling and stable trends remain in some areas (Table 3.7, Figure 3.19, Figure 3.21).

Bores in upland sandplain locations exhibit rising groundwater trends, probably because these areas experience higher recharge rates than on the loam and clay soil types that predominantly occur in lower landscape positions.

Table 3.7 Summary of groundwater trends for the Northern Zone of Ancient Drainage Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	14	8	-0.10	156	42	-0.14	137	29	-0.09
Stable	53	30		144	39		183	39	
Rising	112	62	0.14	69	19	0.15	148	32	0.10

* Mean rate of change in groundwater level.

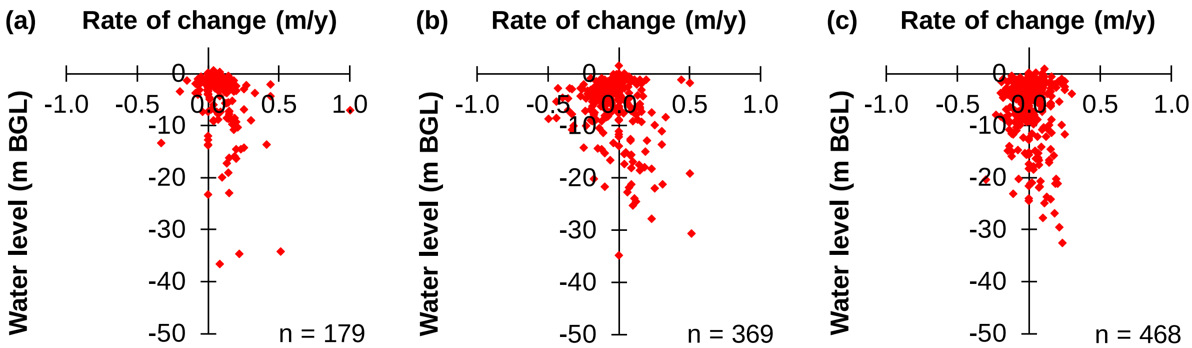


Figure 3.19 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Northern Zone of Ancient Drainage Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

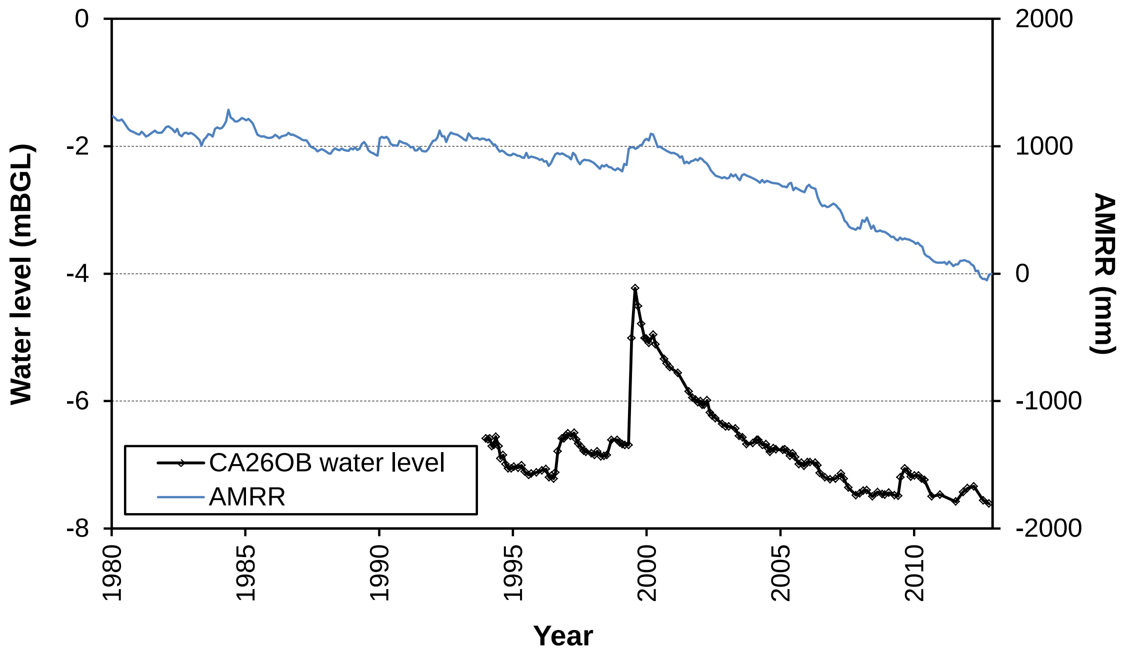


Figure 3.20 Hydrograph for bore CA26OB with accumulated monthly residual rainfall for Carnamah

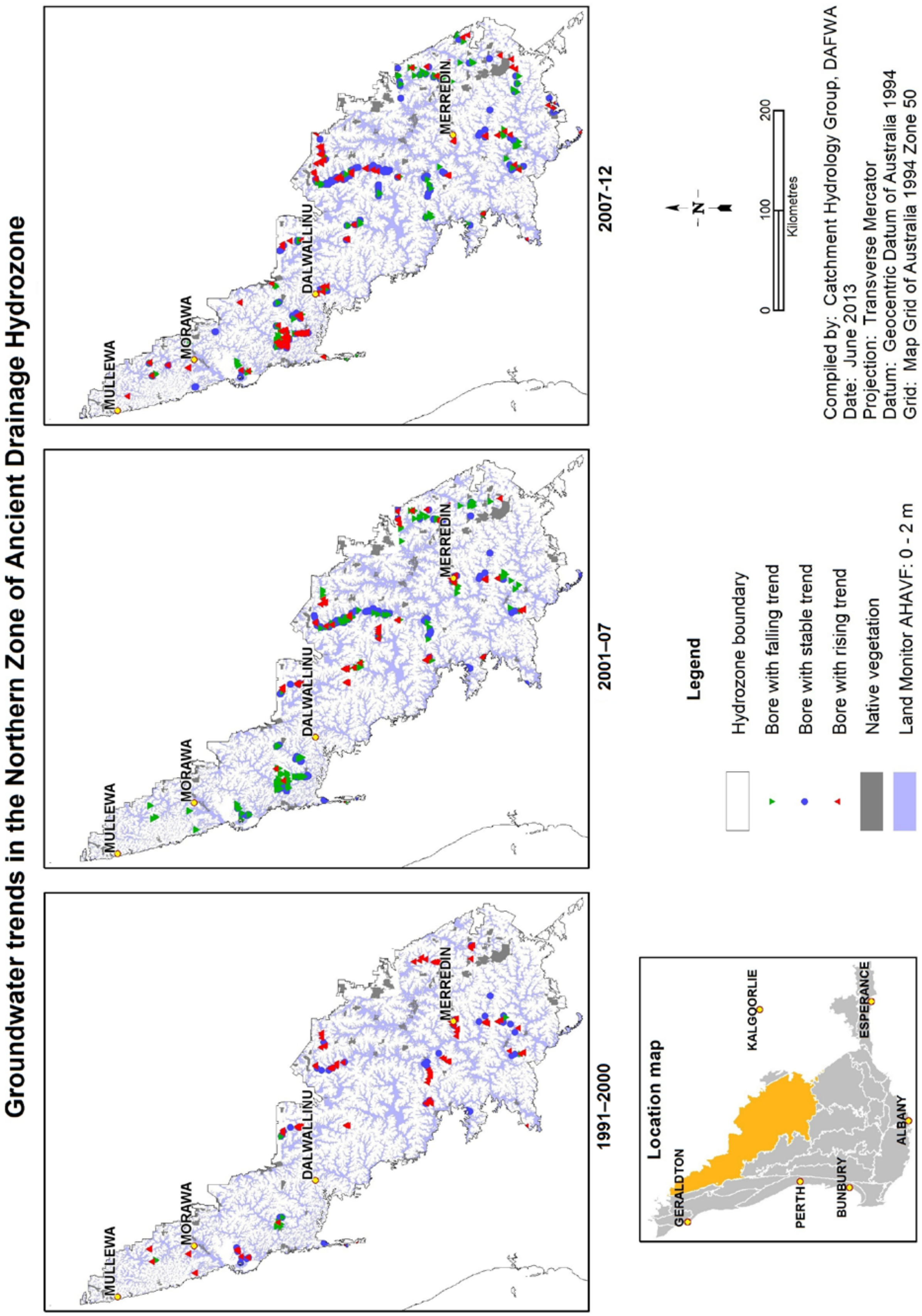


Figure 3.21 Groundwater trends for each of the periods analysed for the Northern Zone of Ancient Drainage Hydrozone

3.1.8 Northern Zone of Rejuvenated Drainage Hydrozone

The Northern Zone of Rejuvenated Drainage Hydrozone lies on a basement of granitoid rock at the western edge of the Yilgarn Craton. The hydrozone is predominantly an erosional landscape (Ghauri 2004) with uplands mainly comprised of lateritic gravelly grey sandplain, red loams around dolerite intrusions and rocky outcrops (Galloway 2004). Flat valley floors are usually covered by sandy duplex soils rather than clays. Creeks and streams flow regularly to the Avon and other westward flowing rivers. It covers an area of 1.28 million hectares, 87% of which is cleared for dryland agriculture.

Saprolite aquifers at the interface between the strongly weathered profile and the basement form local groundwater flow systems throughout the hydrozone. Generally, groundwater is more saline close to drainage lines. Perched aquifers containing low salinity water suitable for livestock are common but are of very limited supply and volume. Groundwater salinities range in EC from 500–5500mS/m (2750-30 250mg/L).

Groundwater monitoring and historical trends

There was relatively little variation from the long-term mean rainfall over most of the hydrozone during 1991–2000.

There is a network of piezometers and shallow observation wells across the hydrozone. The network encompasses a range of landscape positions in the Morbinning Catchment (installed in 1989), Goomalling Shire (installed in 2000) and the Western Australian No-Tillage Farmers Association (WANTFA) Meckering trial site (installed in 2005). During the 1990s, groundwater levels in all but one of the bores were rising regardless of landscape position (Table 3.8, Figure 3.22). Waterlogging was prevalent in lower landscape positions across the zone.

In response to below average rainfall during 2001–07, groundwater trends were mostly stable, with equal proportions rising or falling (Table 3.8, Figure 3.22).

Current situation

Most bores in low landscape positions have shallow, stable groundwater levels that fluctuate seasonally in response to rainfall and evaporation (Figure 3.23). However, one-third of bores still display rising groundwater trends (Table 3.8, Figure 3.24). In mid to upper landscape positions, most bores with groundwater levels deeper than 5m have falling or stable trends (Figure 3.24).

Overall, relative to the 2001–07 period, there is a small increase in the proportion of bores with rising groundwater trends and a decrease in the proportion with stable trends, despite continued below average rainfall.

Table 3.8 Summary of groundwater trends for the Northern Zone of Rejuvenated Drainage Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	0	0		10	21	-0.11	14	25	-0.12
Stable	1	4		25	53		24	42	
Rising	24	96	0.11	12	26	0.12	19	33	0.09

* Mean rate of change in groundwater level.

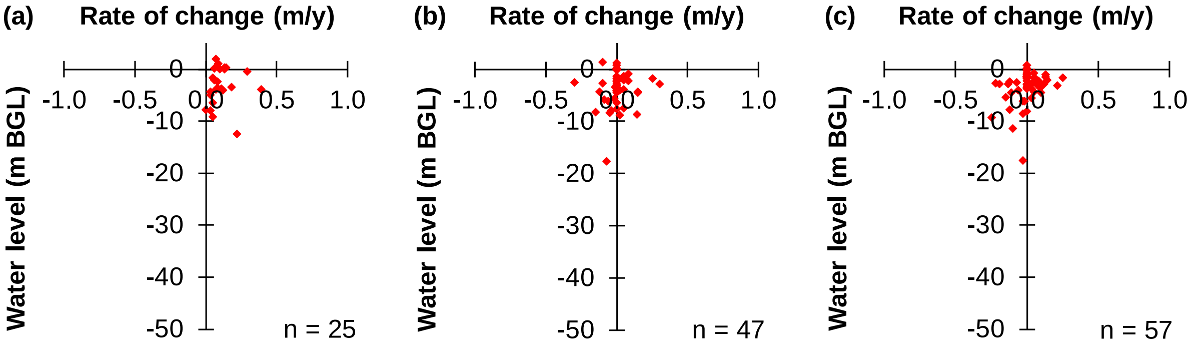


Figure 3.22 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Northern Zone of Rejuvenated Drainage Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

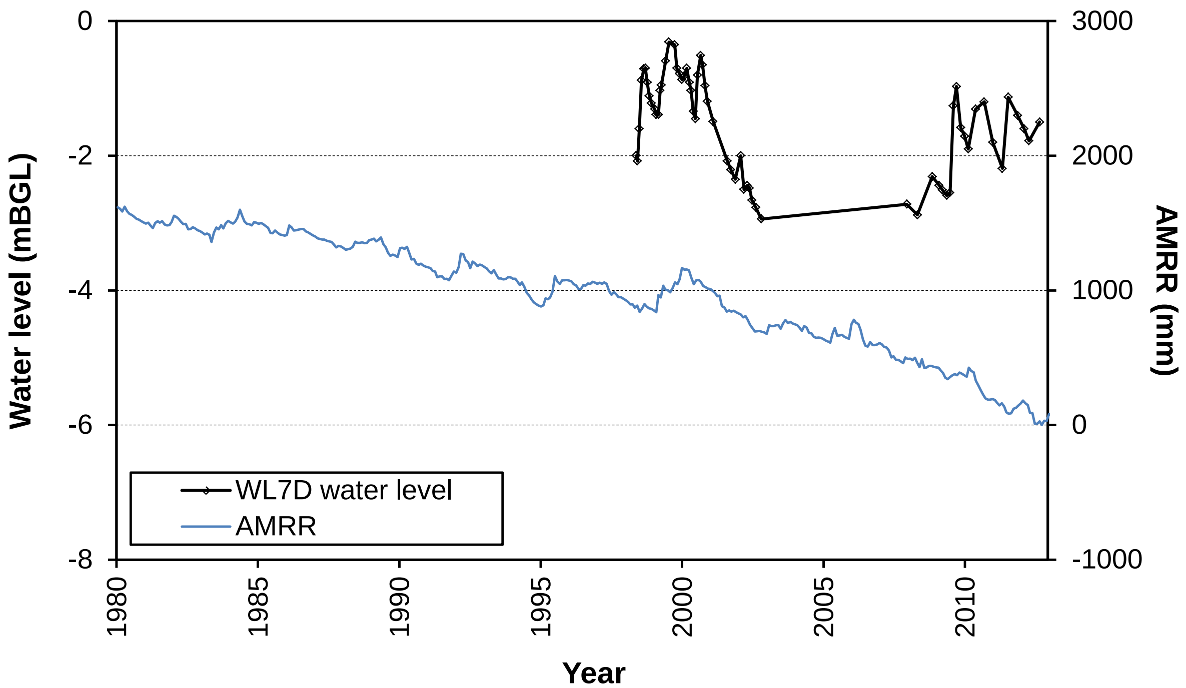


Figure 3.23 Hydrograph for bore WL7D with accumulated monthly residual rainfall for New Norcia

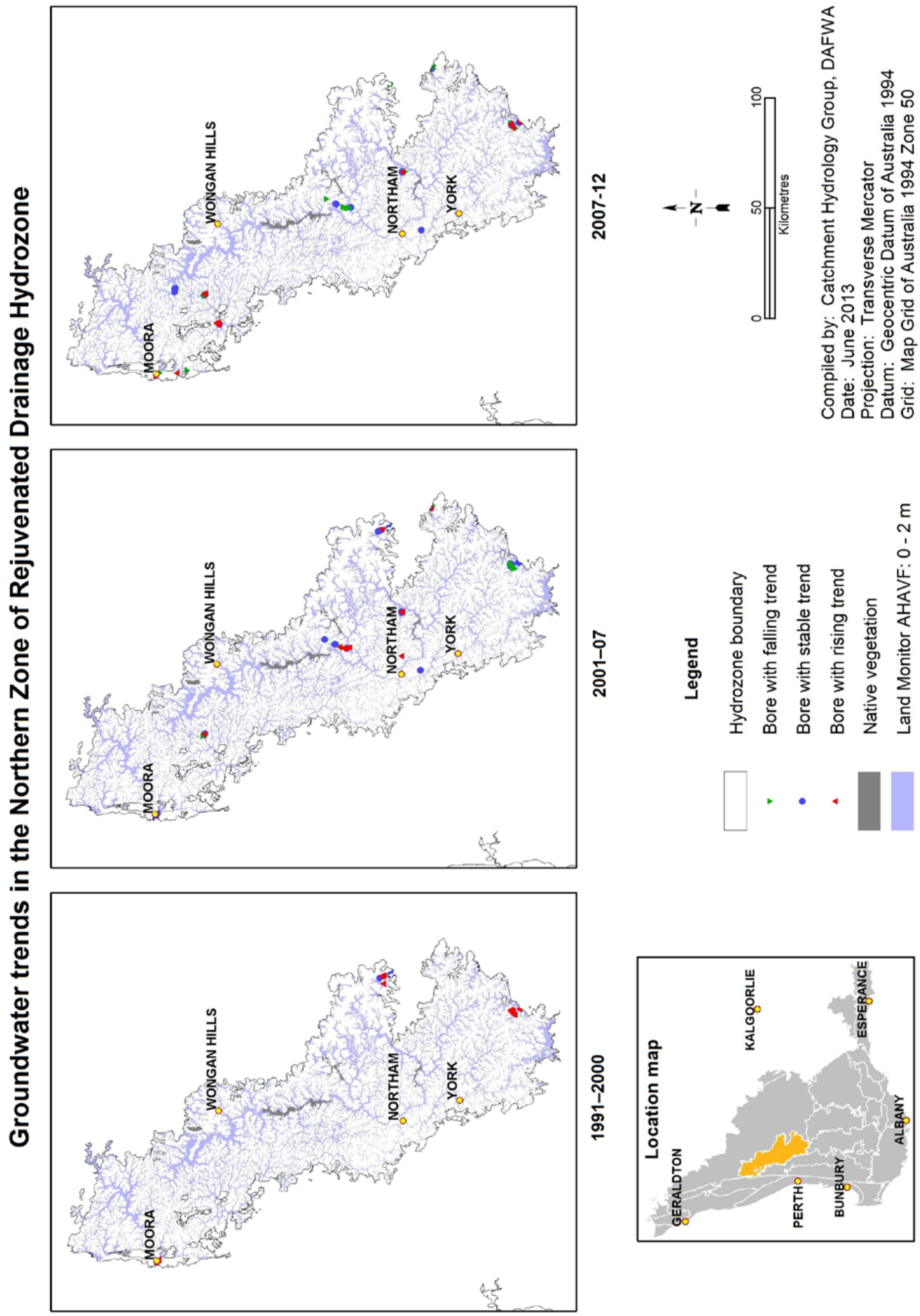


Figure 3.24 Groundwater trends for each of the periods analysed for the Northern Zone of Rejuvenated Drainage Hydrozone

3.1.9 Southern Cross Hydrozone

The Southern Cross Hydrozone is defined by an area of internally draining saline plains and rises on Archaean greenstone (Gee 1981). Local relief is about 80m and the broad valley systems lack defined watercourses. Southern Cross greenstone is a combination of near-vertically dipping mafics and metasediments appearing as linear islands between the mining settlements of Marvel Loch and Bullfinch (Mackie Martin and Associates 1987). Regolith profiles on the mafic basement are weathered up to 100m deep. Northerly-trending granitoids and gneisses occur on either side of the mafic belts. Tertiary sandplain and gravel cover some of the upland areas. Soils on the greenstone are alkaline red loams and clays. The hydrozone covers an area of 216 000ha and is 72% cleared for agriculture.

Groundwater within the greenstone is saline to hypersaline and is found at depths of 10 to 40m. Within areas of granite geology, groundwater is found at similar depths but is not as saline. Some of the tertiary sand deposits contain perched aquifers, which contain generally brackish to saline groundwater. Groundwater is neutral to slightly alkaline.

Groundwater monitoring and historical trends

In 2007, 15 groundwater monitoring sites were established in weathered greenstone aquifers in the Marvel Loch Catchment in the southern part of the hydrozone. Prior to this, only one monitoring bore existed in the far north-west of the hydrozone in a location more typical of the hydrogeology of the Northern Zone of Ancient Drainage Hydrozone. During 2001–07 this bore exhibited a falling trend.

Current situation

Rainfall was above average across the whole hydrozone and 20–30% above average over the northern half of it during 2001–07, following the wettest year on record at several sites in the hydrozone in 1999. During 2007–12, rainfall was between average and 20% below the long-term average over most of the hydrozone.

Since monitoring started in 2007, falling groundwater trends are evident in all lower-catchment bores (Figure 3.27). Variable groundwater trends are observed in mid and upper catchment locations; one bore has a rising trend, two bores have a falling trend and two bores have a stable trend (Table 3.9, Figure 3.25, Figure 3.26). Although all bores are in the same surface water catchment, there are anomalies in the piezometric heads, indicating compartmentalisation of the greenstone area and potentially very different permeabilities of the various greenstone components.

Table 3.9 Summary of groundwater trends for the Southern Cross Hydrozone

	1991–2000			2001–07			2007–12		
Trend	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling				1	100	-0.14	7	70	-0.09
Stable				0			2	20	
Rising				0	0		1	10	0.11

* Mean rate of change in groundwater level.

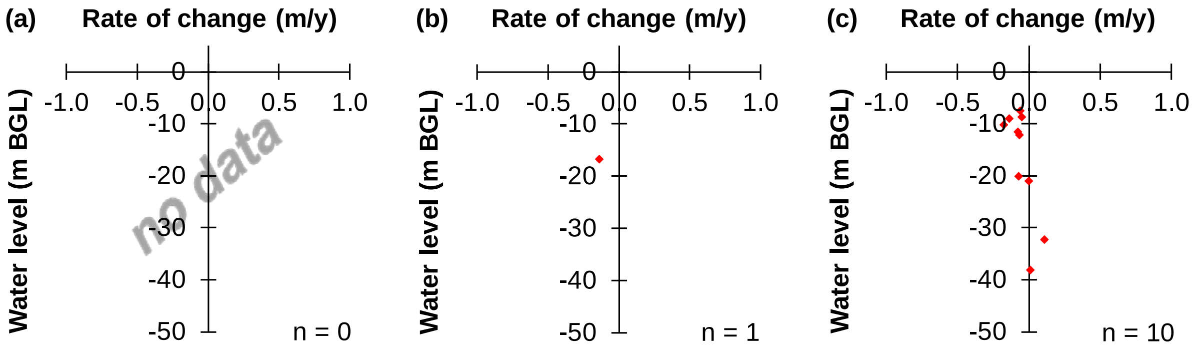


Figure 3.25 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Southern Cross Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

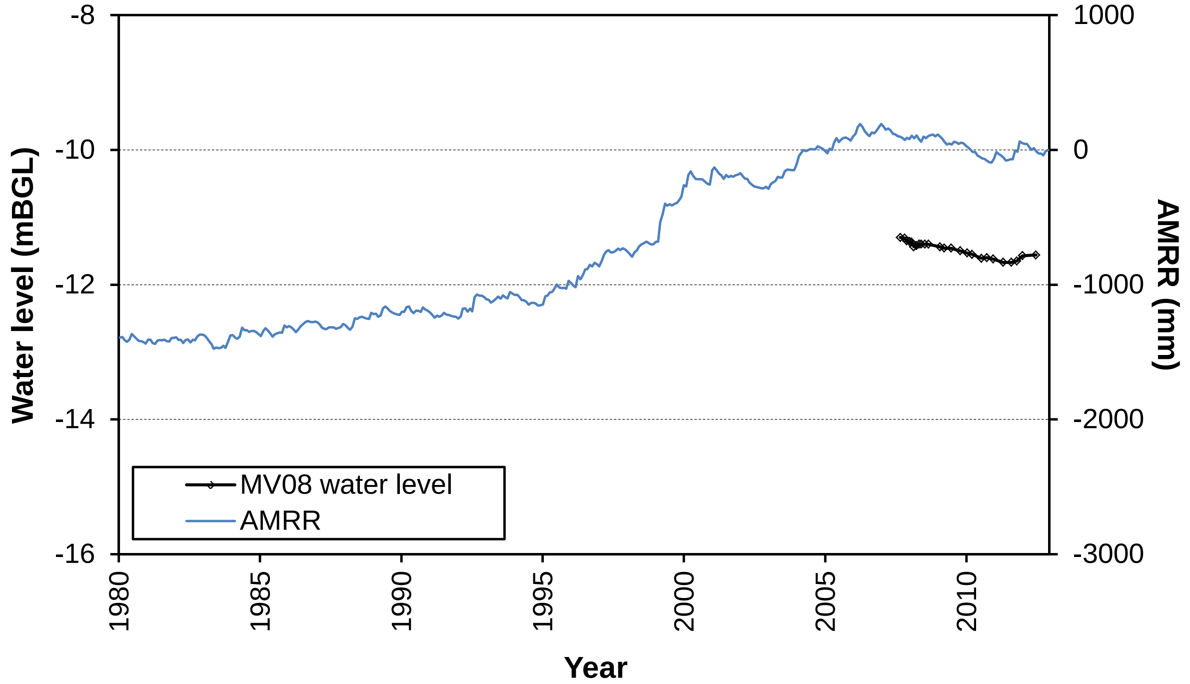


Figure 3.26 Hydrograph for bore MV08 with accumulated monthly residual rainfall for Southern Cross

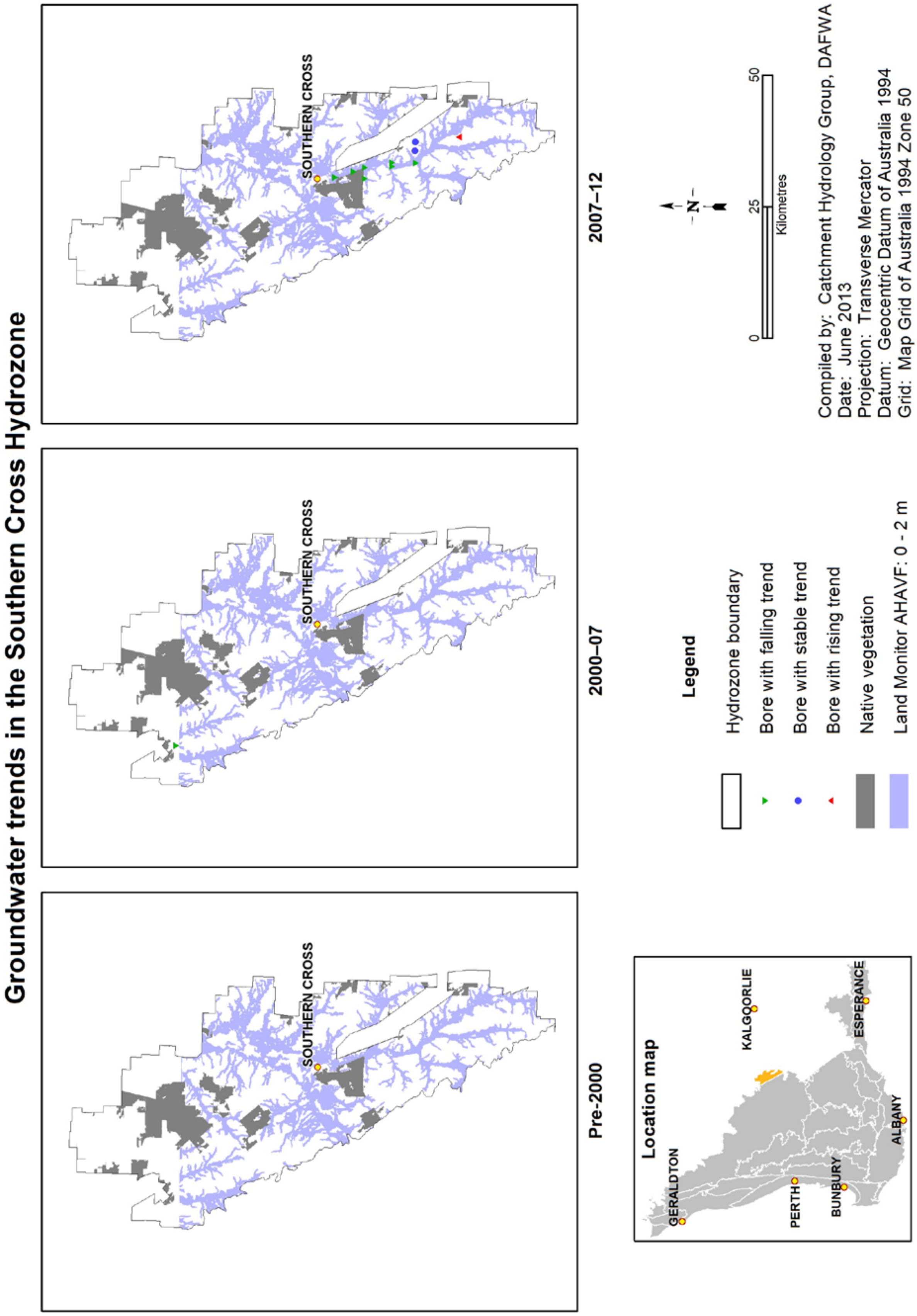


Figure 3.27 Groundwater trends for each of the periods analysed for the Southern Cross Hydrozone (no data for the pre-2000 period)

3.1.10 South-eastern Zone of Ancient Drainage Hydrozone

The predominant feature of the South-eastern Zone of Ancient Drainage Hydrozone is the extensive palaeodrainages through broad, flat valley floors (5–8km wide). Salt lakes in these palaeodrainage lines often form surface water sinks for many internally drained catchments. Upper slopes and crests are typically gravelly sandplain and sandy earths (Galloway 2004), while mid-slopes to valley floor areas phase from loamy duplex to loamy earths to calcareous clays. The regolith of these long-weathered granites is typically 30m thick. The hydrozone covers an area of 2.18 million hectares and 69% is cleared.

Low-yielding saprolite aquifers are widespread across the hydrozone. Groundwater is saline with a neutral pH, trending towards acid in the north. Groundwater in palaeochannels is also low yielding, because of fine quartz sediment, and is of poor quality (saline to hypersaline). Local factors influencing groundwater include dolerite dykes and aeolian sandplain around lake systems. Groundwater flow systems are local to intermediate, even in palaeochannels.

Groundwater monitoring and historical trends

Groundwater monitoring in the South-eastern Zone of Ancient Drainage Hydrozone has occurred since the mid-1990s at a small number of sites (37 sites in three catchments). The number of sites monitored was increased in 2000 and again in 2007 to monitor groundwater trends over a more comprehensive range of landscape positions and soil types (DAFWA 2008).

During the 1990s, rising groundwater trends were observed at all sites with only a few bores in low landscape positions showing stable trends or equilibrium behaviour (Figure 3.28, Table 3.10). In 2001–07, rising trends were still observed in bores in mid and upper landscape positions but in some lower-catchment bores, falling trends, in direct response to reduced rainfall over most of the hydrozone, were apparent.

Current situation

Dry conditions have prevailed in the western portion of the South-eastern Zone of Ancient Drainage Hydrozone during 2001–07 and 2008–12. Lake Grace, in the central west of the hydrozone, recorded its three driest years on record during this time and the MAR was 10–40% below the long-term mean. The rest of the hydrozone received only slightly lower than average or slightly above average rainfall over the same period. For example, at Lake King, in the east of the hydrozone, the mean rainfall during 2001–07 and 2008–12 was roughly equal to the long-term mean, despite the 2010 rainfall being the lowest on record.

The proportion of bores in the hydrozone with stable groundwater trends rose from 24% in 2001–07 to 44% in 2007–12. However, continually rising trends are still observed in many upland areas, especially in the east and south where rainfall has been close to average over the period 2008–12. Although the rate of groundwater rise has fallen in some bores, the mean rate of rise has remained constant (Table 3.10, Figure 3.29). While strongly influencing shallow groundwater levels, episodic events, both dry and wet, have had little to no effect on deeper groundwater levels in upland bores. The highest rates of rise occur in bores with deep groundwater levels, regardless of landscape position (Figure 3.28, Figure 3.30).

Table 3.10 Summary of groundwater trends for the South-eastern Zone of Ancient Drainage Hydrozone.

Trend	1991–2000 No. of bores	1991–2000 Proportion (%)	1991–2000 Mean RoC* (m/y)	2001–07 No. of bores	2001–07 Proportion (%)	2001–07 Mean RoC* (m/y)	2007–12 No. of bores	2007–12 Proportion (%)	2007–12 Mean RoC* (m/y)
Falling	3	10	-0.20	16	26	-0.13	11	16	-0.09
Stable	7	22		15	24		31	44	
Rising	21	68	0.11	31	50	0.12	28	40	0.11

* Mean rate of change in groundwater level.

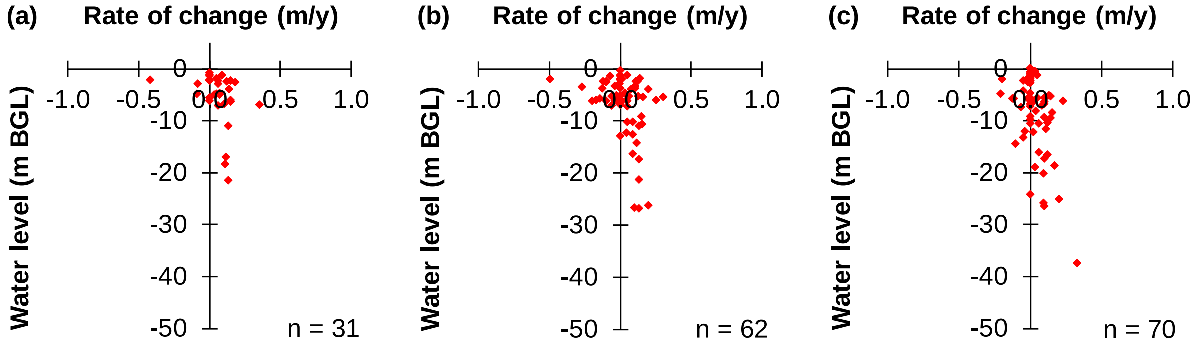


Figure 3.28 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the South-eastern Zone of Ancient Drainage Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12.

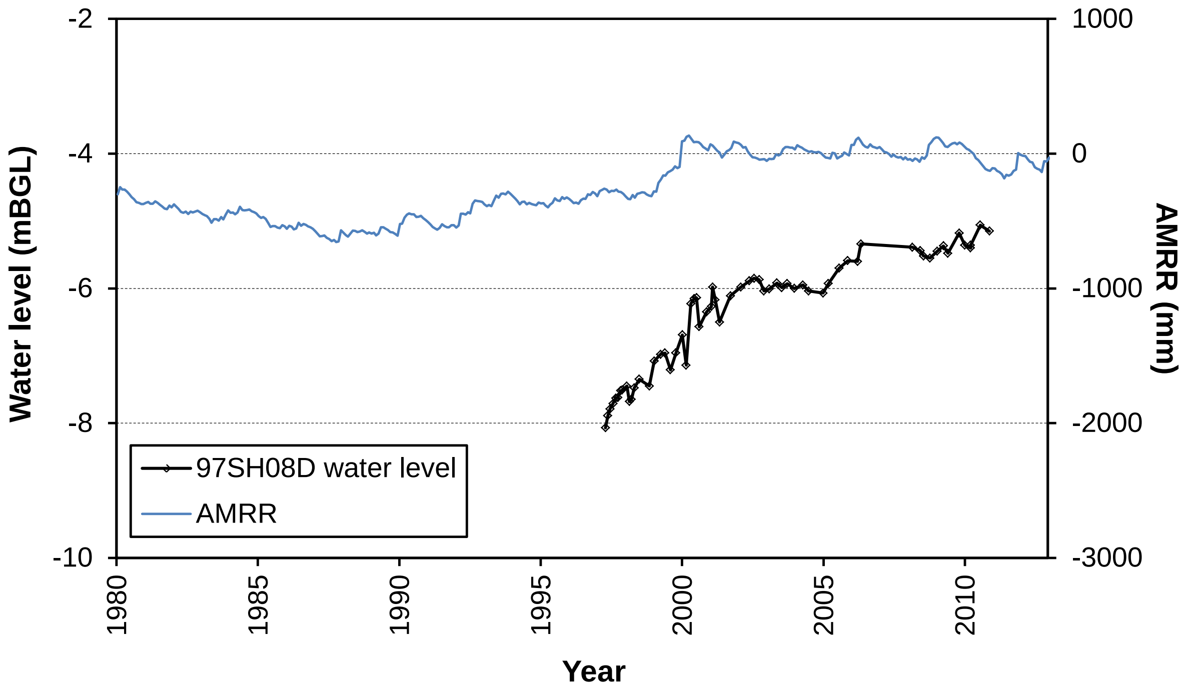


Figure 3.29 Hydrograph for bore 97SH08D in the South-eastern Zone of Ancient Drainage Hydrozone and accumulated monthly residual rainfall for Hyden

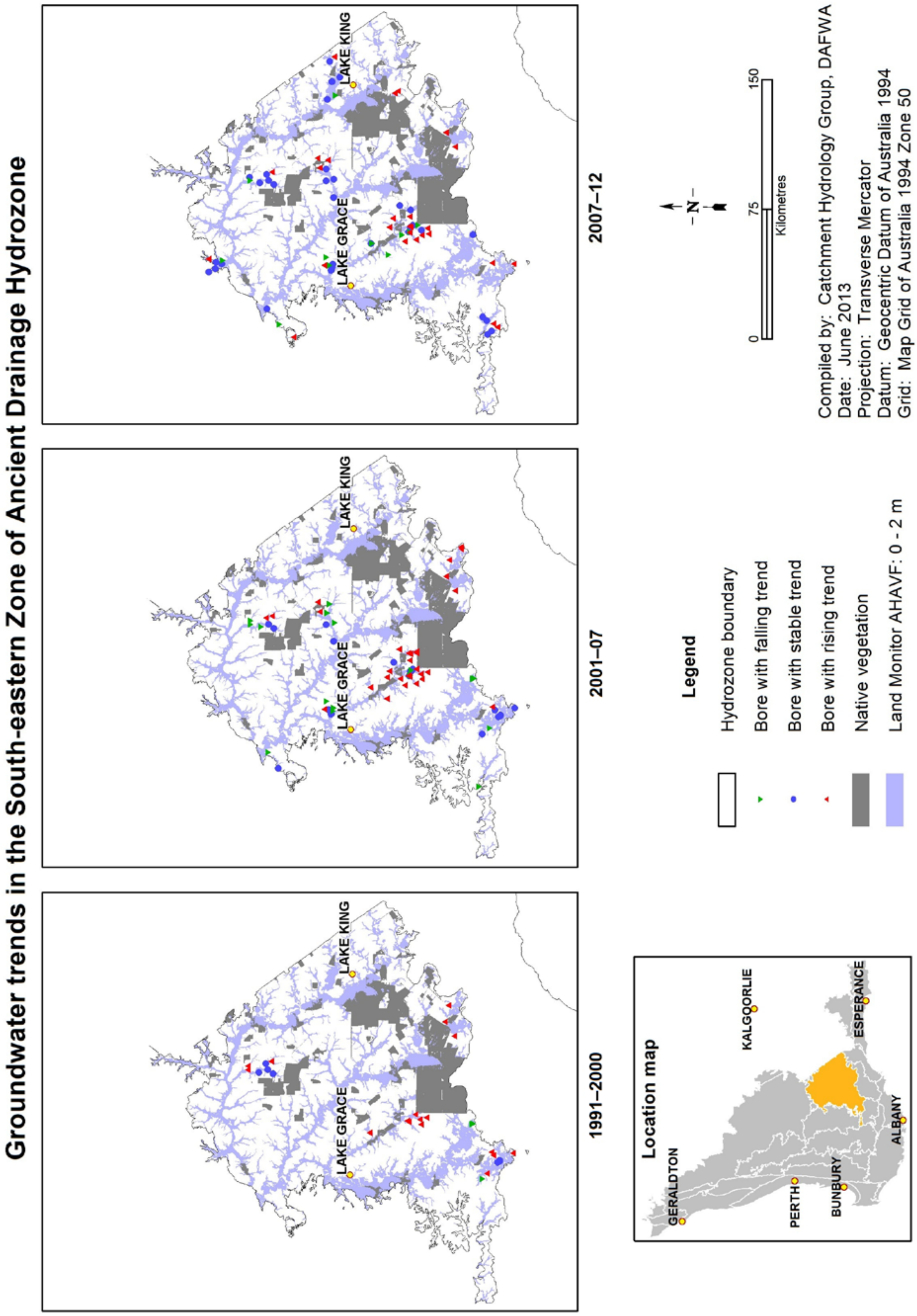


Figure 3.30 Groundwater trends for each of the periods analysed for the South-eastern Zone of Ancient Drainage Hydrozone

3.1.11 South-western Zone of Ancient Drainage Hydrozone

The South-western Zone of Ancient Drainage Hydrozone lies east of the Meckering Line and encompasses most of the upper Blackwood River Catchment and adjacent parts of the Avon River Catchment. It is an ancient, gently undulating plateau with sluggish drainage systems that only flow in very wet years (Tille et al. 2001, Percy 2003). Local relief is typically 10–40m and it covers an area of 1.2 million hectares, 86% of which is cleared.

The soils are mostly shallow sandy or loamy duplex soils with uplands dominated by sandy gravels. Reddish brown to red loamy duplex soils, loams and clays are common on weathered gneissic rocks. Soils on the broad alluvial and lacustrine plains of the Coblinine, Avon and Lockhart rivers and their tributaries are sandy and loamy duplex soils and are mainly salt-affected (Percy 2003).

Groundwater occurs in low-permeability saprolite and palaeochannel aquifers and groundwater flow systems are mainly local scale. Palaeochannels occur in many of the larger valleys and the flow paths tend to be of the order of tens of kilometres, terminating in playas. Salt lake chains are common because of the sluggish drainage (George & Bennett 1998).

Capillary rise on the broad alluvial plains and valleys is the most common groundwater discharge process in this hydrozone. This process is prevalent in the Coblinine soil-landscape system and is often associated with palaeochannels (e.g. Toolibin Catchment). These areas are also prone to waterlogging or inundation throughout winter (Brockman 2001). Groundwater discharge in drainage lines accounts for most of the remaining salinity in this hydrozone.

A number of processes cause mid-slope and seep discharges in this hydrozone, including discharge over dolerite dykes and break-of-slope seeps. Discharge from perched aquifers occurs in deep sands and sandplain seeps in gravelly uplands in the Kukerin, Dongolocking and East Katanning soil-landscape systems and on dunes and lunettes within the Coblinine soil-landscape system.

Groundwaters in both the saprolite and palaeochannel aquifers are mainly saline (1000–5000mS/m, 5500–27 500mg/L).

Groundwater monitoring and historical trends

During the 1975–90 and 1991–2000 analysis periods, variations from the long-term mean rainfall were relatively minor in this hydrozone. Most bores on valley floors and alluvial plains had rising groundwater trends (0.2m/y), though a significant number had stable trends. In the valleys of the upper Toolibin and Fence Road catchments, where significant clearing was still occurring during the early 1970s, groundwater levels were deep but exhibited high rates of rise. Bores in upland locations generally had rising groundwater trends (Table 3.11, Figure 3.31, Figure 3.32, Figure 3.33).

The Kulin monitoring network was established in 2000 with 13 sites installed in the mid to lower catchment. Another 15 sites were installed in 2007 in the mid to upper catchment. Post-2000 monitoring showed that all shallow and intermediate bores with piezometric heads between 0 and 5m BGL were falling (Ghauri 2004). This incidence was strongly influenced by groundwater recession in the run of dry seasons that followed the Lockhart River flood in January 2000, which greatly elevated groundwater levels. Rising groundwater trends were observed in upper catchment bores.

Current situation

Since 2007, rainfall has been significantly below the long-term mean in the northern and central portions of the hydrozone. There has been an increase in the number of bores with stable groundwater trends, though many in valley floor areas still have rising trends, as do bores in upland positions (Figure 3.33).

In the southern (Blackwood) portion of the hydrozone, bores in and adjacent to areas of salinity hazard continue to rise, despite below average rainfall. Figure 3.32 shows the hydrograph for bore SS9701D in the Land Monitor AHAVF valley hazard area of the Lake Toolibin Catchment, which typifies this kind of response.

Most mid and lower-catchment bores in the north-eastern portion of the hydrozone have rising groundwater trends in 2007–12 (Figure 3.33). Some valley floor bores have sharp groundwater rises caused by local flooding in 2006, followed by gradual recessions in response to below average rainfall. In the north-western portion, many bores have stable trends because of below average rainfall since 2007.

Table 3.11 Summary of groundwater trends for the South-western Zone of Ancient Drainage Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	0	0	0.00	7	8	-0.12	6	7	-0.11
Stable	13	29		20	24		36	41	
Rising	32	71	0.18	57	68	0.17	45	52	0.17

* Mean rate of change in groundwater level.

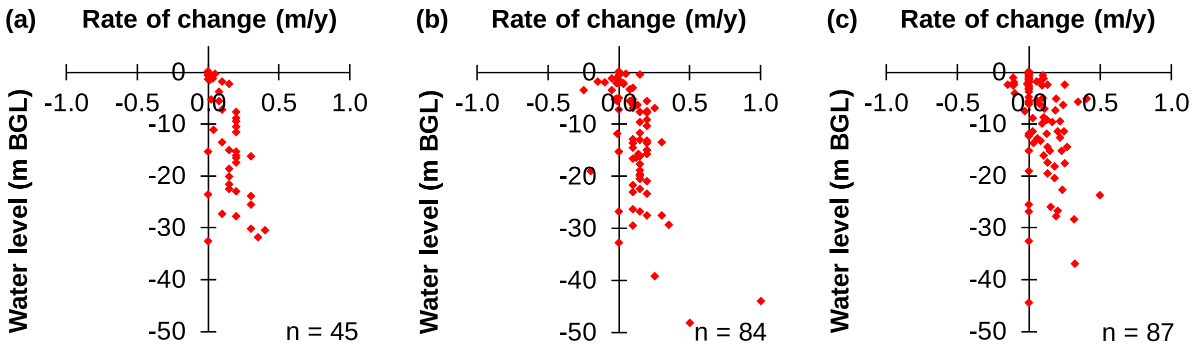


Figure 3.31 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the South-western Zone of Ancient Drainage Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

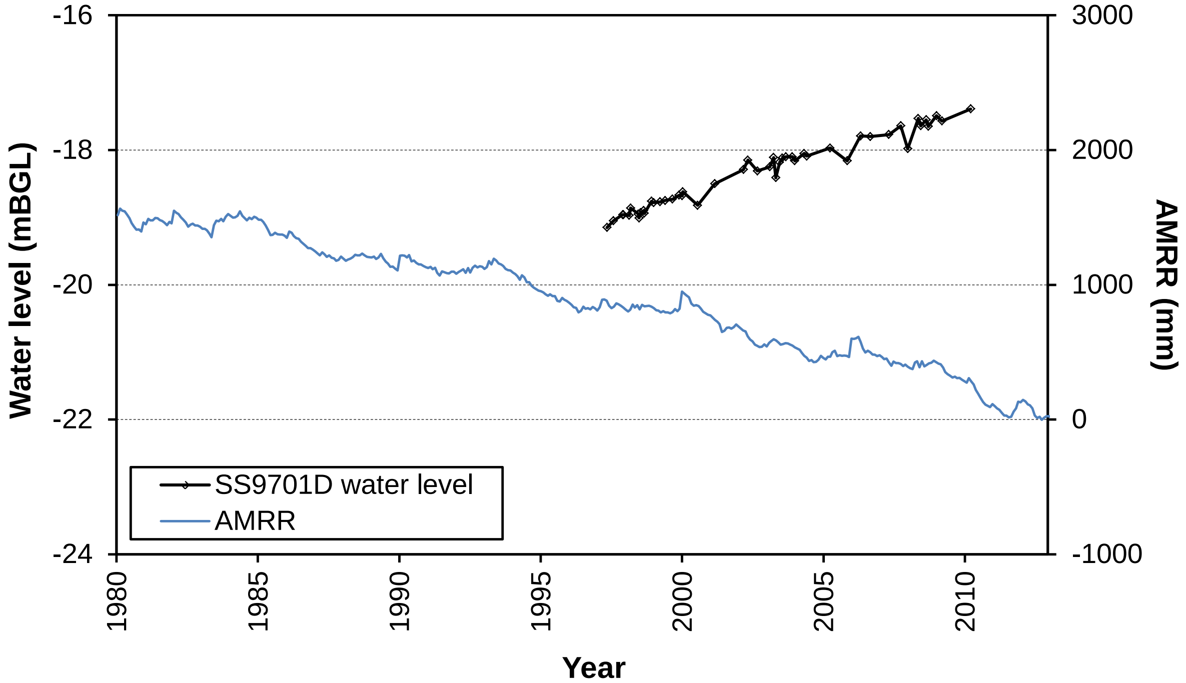


Figure 3.32 Hydrograph for bore SS9701D, within the South-western Zone of Ancient Drainage Hydrozone and accumulated monthly residual rainfall for Dudinin.

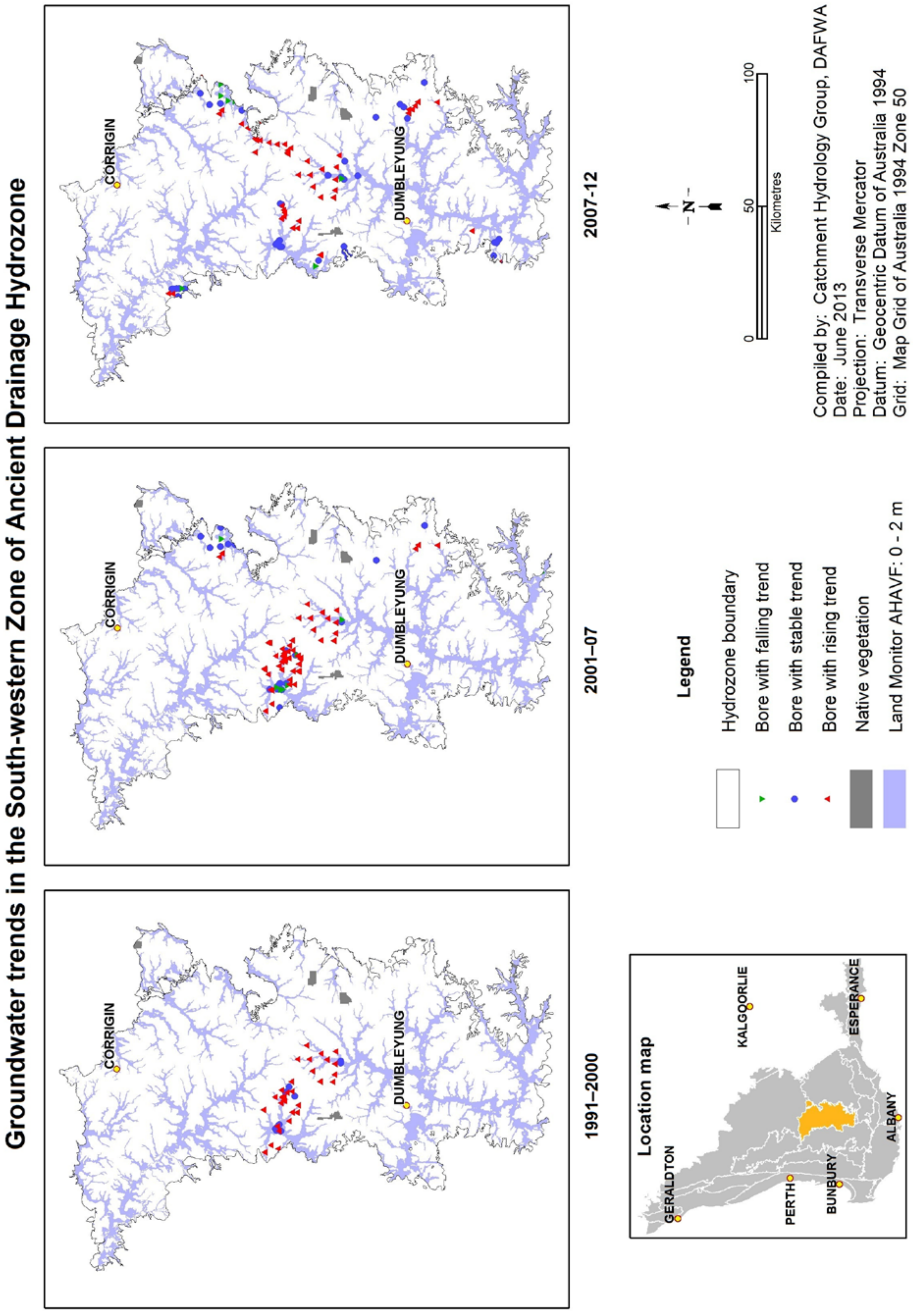


Figure 3.33 Groundwater trends for each of the periods analysed for the South-western Zone of Ancient Drainage Hydrozone

3.1.12 Southern Zone of Rejuvenated Drainage Hydrozone

The Southern Zone of Rejuvenated Drainage Hydrozone lies to the west of the Meckering Line and is characterised by gently undulating rises to low hills. The valley floors are broad with lakes and associated dune systems, and the main stream channels are continuous and flow in most years. The hydrozone covers an area of 1.4 million hectares and 78% is cleared.

Basement in the hydrozone is mainly even-grained granitoid rock of the Yilgarn Craton, intruded by prevalent, north-easterly trending dykes. Duplex sandy gravels, Loamy gravels and Pale deep sands occur on upper slopes and crests on lateritic remnants (Tille et al. 2001). Grey deep sandy duplex soils dominate the slopes and valley flats, although loamy duplex soils formed on dolerite or gabbro are common. Valley floor soils are predominantly Grey deep sandy duplexes, often affected by salinity (Percy 2000).

Groundwater flow systems are mainly local or intermediate scale, even in the palaeochannels. A high degree of landscape incision in the hydrozone has compartmentalised the groundwater systems, except for those in the palaeochannels. Groundwater quality is mainly brackish to saline (300–5500mS/m, 1650–30 250mg/L).

Groundwater monitoring and historical trends

The proportion of bores with rising groundwater trends fell between the 1991–2000 and 2001–07 analysis periods in response to below average rainfall; the proportion with falling or stable trends increased (Table 3.12, Figure 3.34).

Percy and Raper (2007), who analysed rates of groundwater rise by landscape position in the Blackwood River Catchment portion of the hydrozone, reported that rates of rise were higher in upper- and mid-slope landscape positions. Sixty per cent of the bores they analysed had rising trends, despite the low rainfall, and most of the bores with stable or falling trends were on lower-slopes or valley floors.

Groundwater trends in the Beaufort zone of the Blackwood River Catchment were analysed in 2002 (Blackwood Catchment Appraisal Team 2002). The Beaufort zone covers 339 000ha, of which about 224 000ha (66%) falls within the Southern Zone of Rejuvenated Drainage Hydrozone. This zone constitutes 16% of the southern portion of the hydrozone. Bores with rising groundwater trends were found in all landscape positions but the greatest rates of rise, up to 1.5m/y, were found in bores on upper slopes and ridges. Not many bores had stable trends and most of these were located on valley floors or lower-slopes. No bores had falling trends.

Current situation

The proportion of bores with rising groundwater trends continued to fall in 2007–12 because of ongoing low rainfall. However, there is a small but significant group of bores within and adjacent to areas of Land Monitor AHAVF salinity hazard with rising trends, most notably in the East Yornaning and Doradine catchments (Figure 3.36). The Junction Brook Catchment in the central west of the hydrozone, where clearing took place early and annual rainfall is more than 500mm/y, appears to have reached a new hydrological equilibrium (Figure 3.35). The Queerfellows Creek, Chain Gully and Byenup Hill catchments also appear to be close to equilibrium; however, a reduced monitoring effort since 2007 may be masking continued groundwater rises.

Prior to 2007, no monitoring sites were present in the Avon portion of the hydrozone. Two of the 10 bore sites drilled in the Woodebulling Catchment in 2007 are located in the far north-east of the hydrozone and these bores have stable groundwater trends.

Table 3.12 Summary of groundwater trends for the Southern Zone of Rejuvenated Drainage Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	1	2	-0.05	13	16	-0.09	9	7	-0.17
Stable	19	48		41	51		79	65	
Rising	20	50	0.21	26	33	0.14	34	28	0.23

* Mean rate of change in groundwater level.

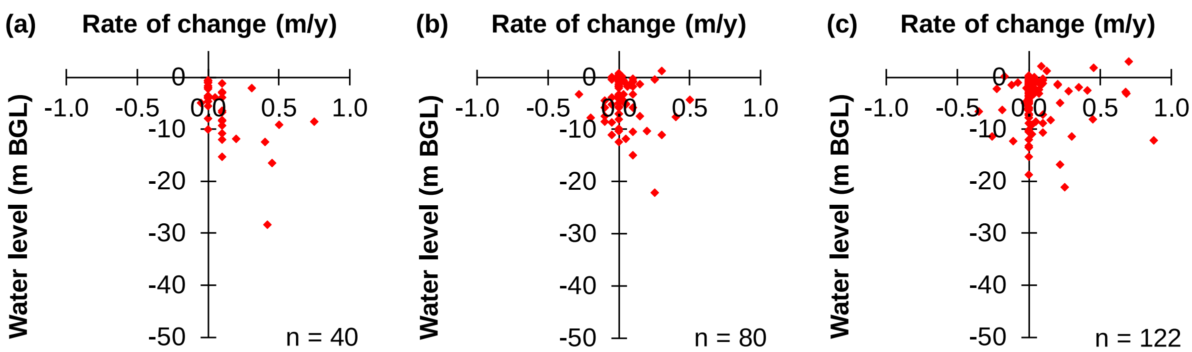


Figure 3.34 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Southern Zone of Rejuvenated Drainage Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

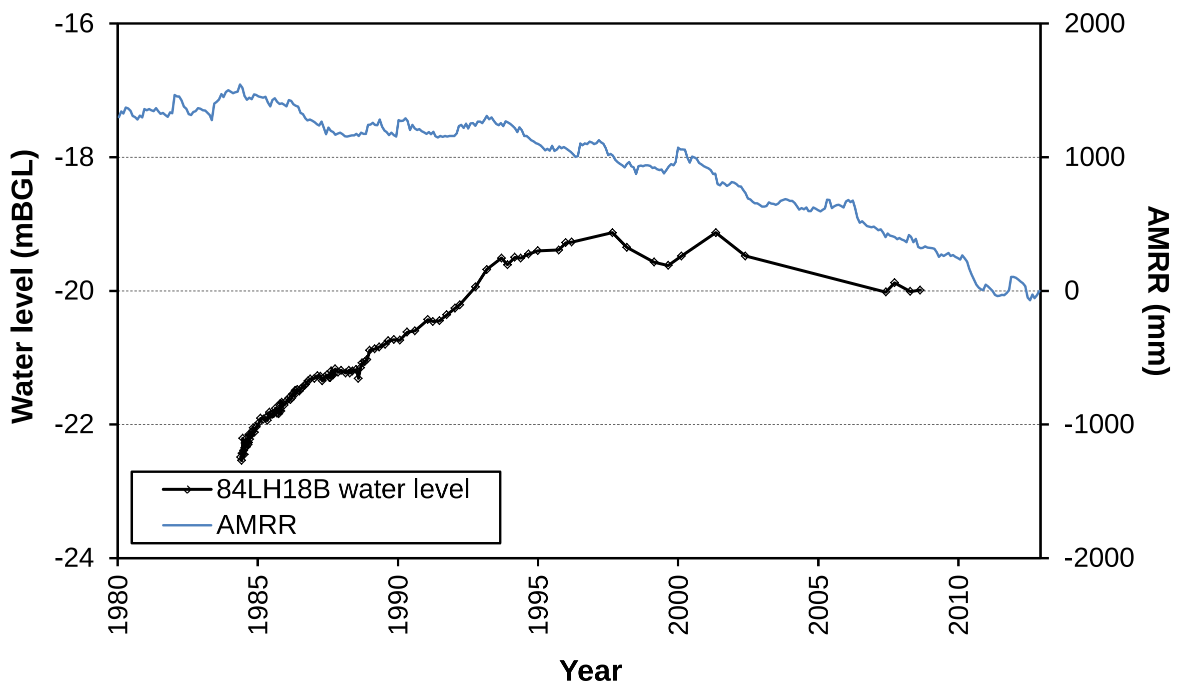


Figure 3.35 Hydrograph for bore 84LH18B, within the Southern Zone of Rejuvenated Drainage Hydrozone and accumulated monthly residual rainfall for Wonnaminta

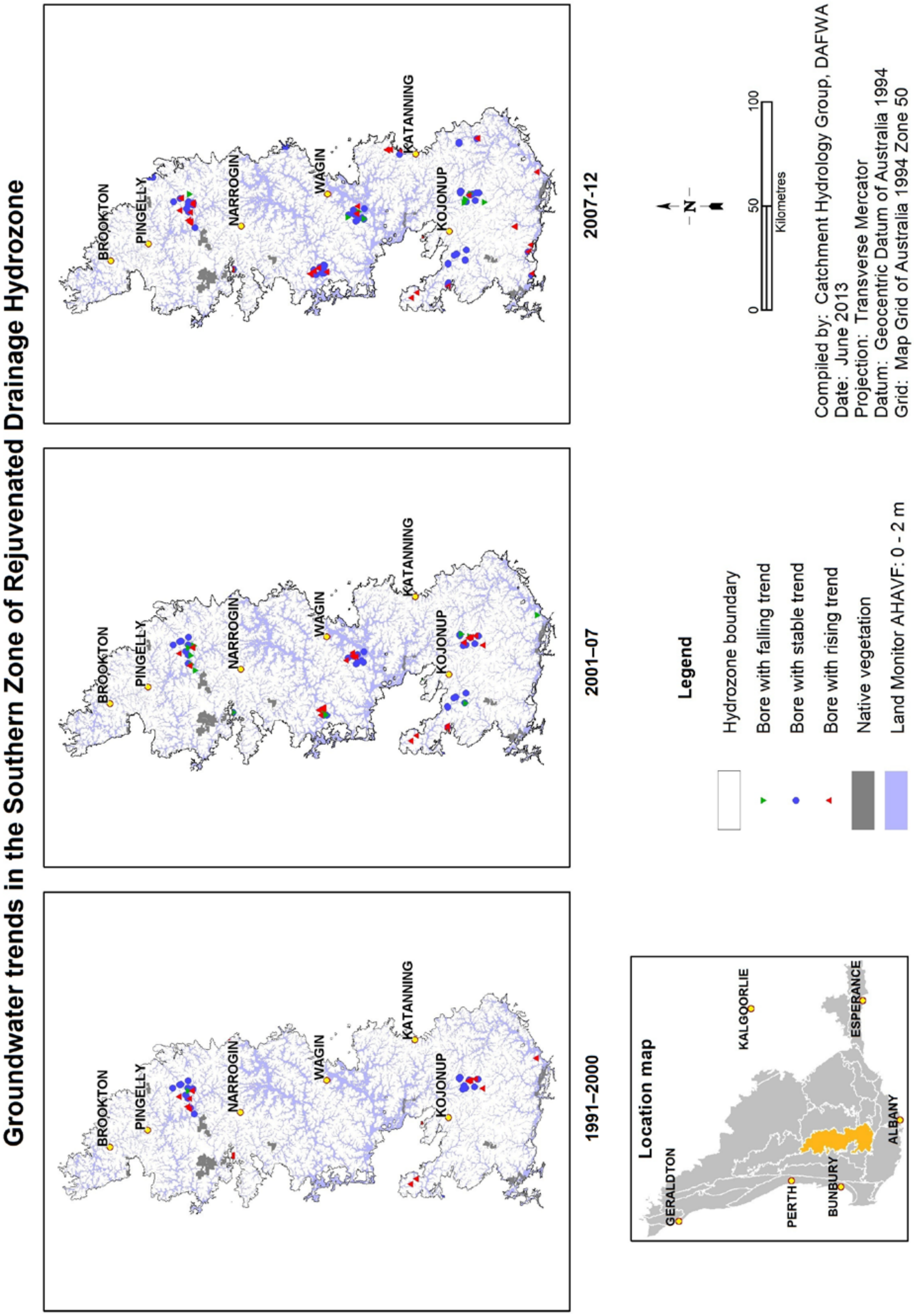


Figure 3.36 Groundwater trends for each of the periods analysed for the Southern Zone of Rejuvenated Drainage Hydrozone

3.1.13 Eastern Darling Range Hydrozone

The Eastern Darling Range Hydrozone consists of undulating to rolling terrain formed by the dissection of a lateritic plateau and local relief is 20–100m. Many of the narrow valley floors are incised into the underlying granitic basement rocks of the Yilgarn Craton (Tille et al. 2001). The streams in broad (1–3km), shallow valleys often flow eastward through poorly drained flats on ancient (Eocene) sediments (Tille 1996). The hydrozone covers an area of 1.24 million hectares, 55% of which is cleared for agriculture.

On the uplands, sandy and loamy gravels are dominant. On the valley slopes, there are a range of soils, depending on whether the soils are formed on truncated laterite (Sandy gravels, Grey deep sandy duplex soils, Pale deep sands) or weathered granite or dolerite (Brown loamy duplex soils, Red deep sandy duplex soils) (Percy 2000).

Groundwater flow systems are local or occasionally intermediate, with flow paths of only a few kilometres. Flow paths may be longer in the eastern portion of the hydrozone.

Groundwater discharge may occur in drainage lines and on valley floors in cleared catchments within the hydrozone (George & Bennett 1998). Discharge associated with dolerite dykes is the dominant discharge process in mid- to upper-slope landscape positions. Regional-scale faults and discharge from alluvial channel sequences are also responsible for salinity in parts of the hydrozone.

Winter discharge from perched aquifers is usually associated with deep sands and occurs in the Boscabel Soil-landscape System (Stuart-Street 2003). Groundwaters in these aquifers are relatively fresh and can provide stock water during periods of low rainfall (South-west Natural Resource Management Region Appraisal Team 2005).

Groundwaters are generally brackish to saline, with marginal quality groundwater found occasionally.

Groundwater monitoring and historical trends

Groundwater level data are available for more than 100 bores in the southern half of the Eastern Darling Range Hydrozone and about 40% of them are sited within areas of Land Monitor AHAVF (Figure 3.39). A large portion of the central section of the hydrozone is forested, but two catchments — Yalanbee and Westdale — have been monitored since 1972 and 1992, respectively. In the northern portion of the hydrozone, the Newdale Catchment contains the only bores for which time series data are available and these bores have been monitored since 1988.

Prior to 2000, rainfall was just below average over most of the hydrozone. About half of the bores had rising groundwater trends and most of the remaining bores, which were located within areas of Land Monitor AHAVF salinity hazard, had stable trends (Table 3.13).

Between 2001 and 2007, the proportion of bores with rising groundwater trends fell in response to below average rainfall. The proportion of bores with stable trends remained the same and the proportion with falling trends increased.

Current situation

Since 2007, the proportion of bores with rising groundwater levels has decreased in response to continued and more widespread below average rainfall. However, there are still bores within and adjacent to areas of Land Monitor AHAVF salinity hazard with rising trends (Figure 3.38). There is also a high proportion of bores within or adjacent to areas of Land Monitor AHAVF salinity hazard with artesian heads. In fact, the Eastern Darling Range Hydrozone contains the highest proportion of bores with artesian heads of any hydrozone.

In the northern portion of the hydrozone, where the rainfall reduction has been the most severe, all bores have stable or falling groundwater levels (Figure 3.39). Where groundwater is shallow (<3m BGL), stable trends have persisted during 2001–07 and 2007–12. Areas with groundwater levels deeper than 5m have falling trends as high as 0.2m/y. Seasonal fluctuations have been less pronounced in all bores.

Table 3.13 Summary of groundwater trends for the Eastern Darling Range Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	2	2	-0.13	22	17	-0.13	12	9	-0.25
Stable	52	43		55	44		96	73	
Rising	66	55	0.28	49	39	0.24	24	18	0.27

* Mean rate of change in groundwater level.

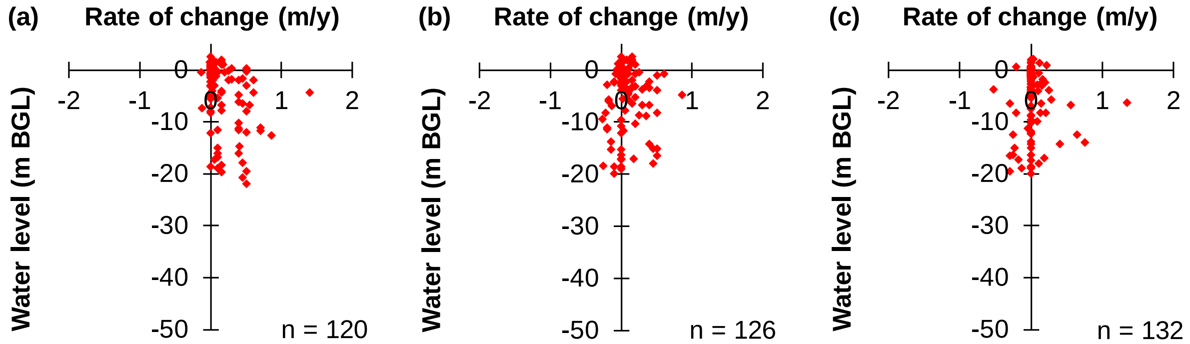


Figure 3.37 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Eastern Darling Range Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

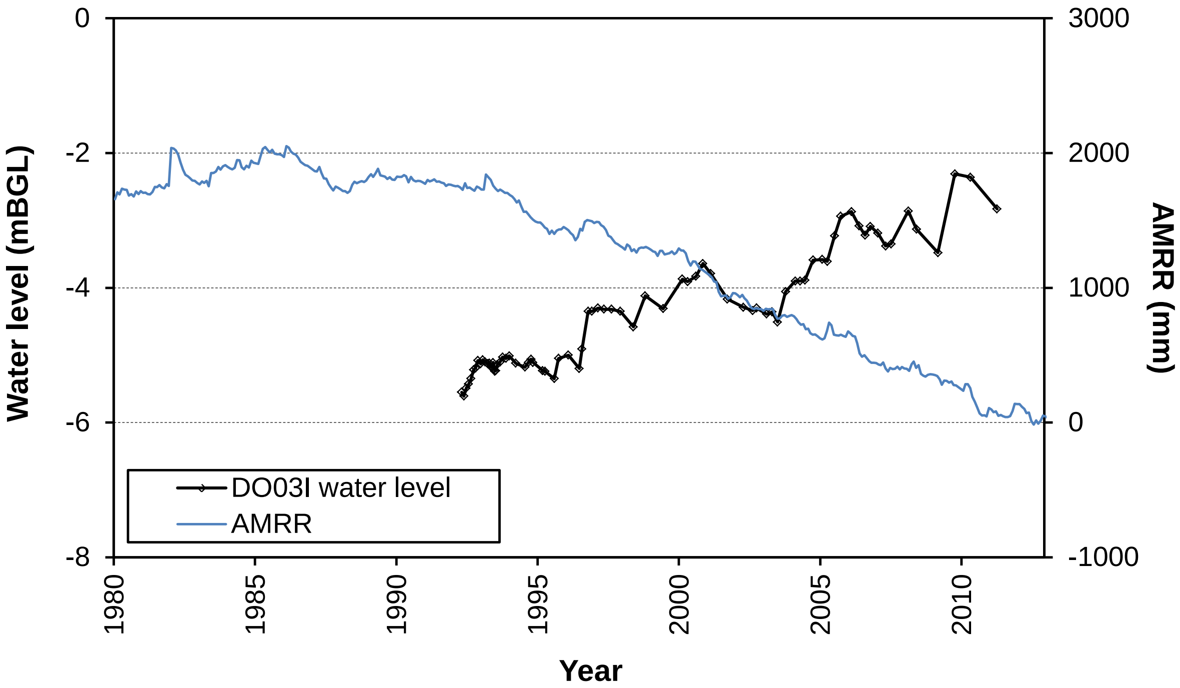


Figure 3.38 Hydrograph for bore DO03I, within the Eastern Darling Range Hydrozone and accumulated monthly residual rainfall for Duranillin

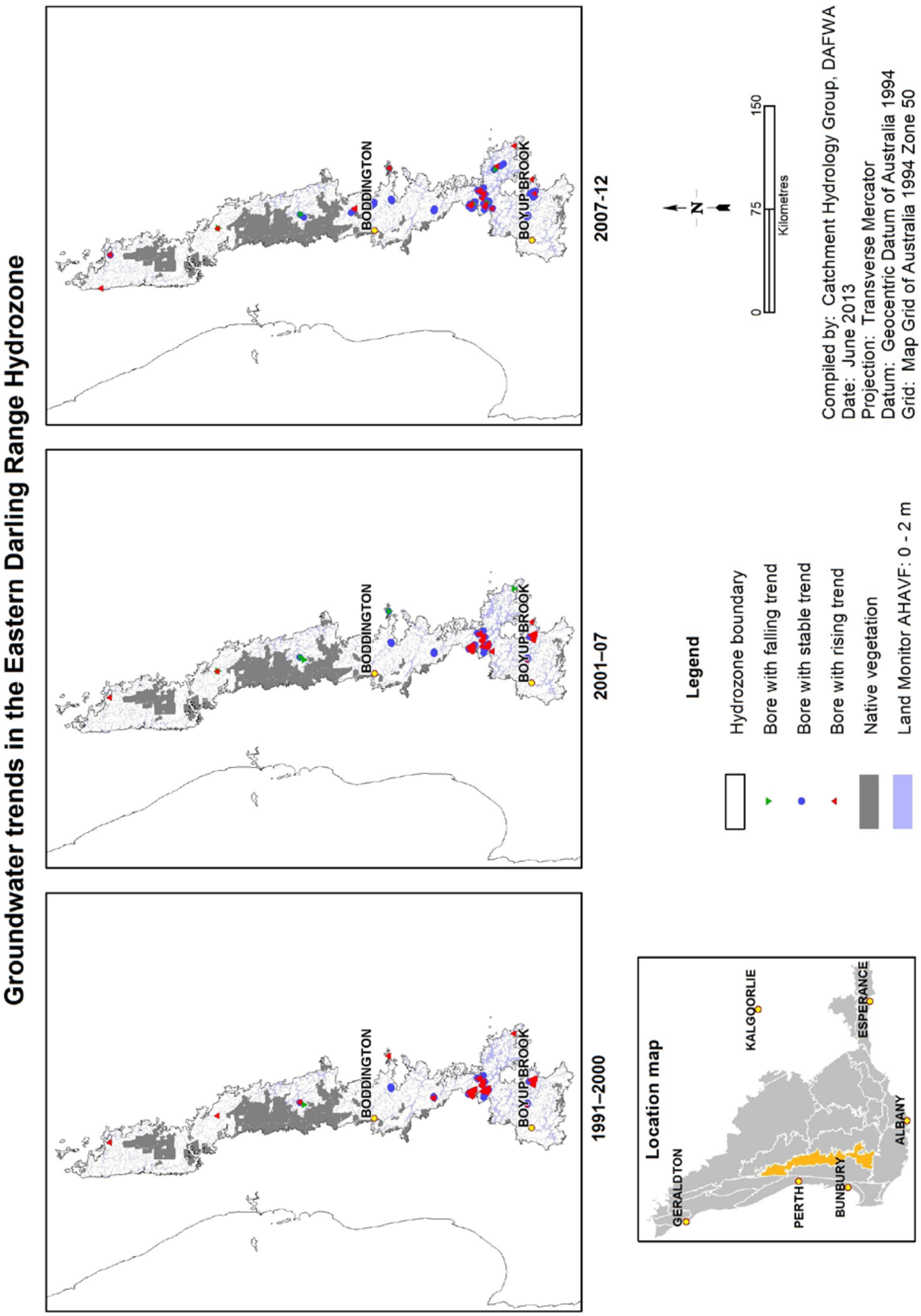


Figure 3.39 Groundwater trends for each of the periods analysed for the Eastern Darling Range Hydrozone

3.1.14 Western Darling Range Hydrozone

The Western Darling Range Hydrozone is 30–80km wide and extends from north of the Avon River to the Blackwood River in the south, covering an area of 1.18 million hectares. Seventy-eight per cent of the hydrozone is native forest and an unknown proportion of the cleared area is forestry plantations.

The hydrozone is an undulating lateritic plateau derived from the granitic and gneissic basement rocks of the Yilgarn Craton. Major river systems, such as the Avon, Blackwood, Murray and Collie, have eroded the plateau, forming deeply incised valleys and stripping the lateritic profile to expose fresh rock on valley slopes (Percy 2000).

The soils are mainly loamy and sandy gravels with small areas of Yellow and Pale deep sands. There are also significant areas of red-brown and yellow-brown loams grading to clays and Grey deep sandy duplex soils formed on weathered granite, dolerite or gneiss (Percy 2000).

Aquifer systems are local or occasionally intermediate with flow paths of only a few kilometres. Groundwaters in the hydrozone range from fresh to saline but are predominantly brackish.

Groundwater discharge may occur in drainage lines and on valley floors in cleared catchments within the hydrozone (George & Bennett 1998). Geological features, such as dolerite dykes, bedrock highs and fractured bedrock, may also cause groundwater to discharge in mid- to upper-slope landscape positions in the cleared catchments. These processes may occur in winter when groundwater recharge is greatest, or perennially depending on the hydrogeological characteristics of the area. Seepages at the break of slope are less common.

Groundwater monitoring and historical trends

Five surveillance bores are monitored in the far south of the hydrozone. Four of the five bores are located east of Greenbushes, high in the Hester Brook Catchment, and have had stable groundwater trends since they were completed in 1992 (Figure 3.42). The fifth bore is high in the catchment of the Collie River East, close to the divide between the Collie Basin and the Blackwood River Catchment, and has had groundwater rising at 0.3m/y since completion in 1994 (Table 3.14).

Current situation

In 2007–12, groundwater levels fell in the four bores in the Hester Brook Catchment (Figure 3.40, Figure 3.41). This trend may be because of below average rainfall, especially since 2010; the effect of nearby revegetation undertaken in 2006; or a combined effect of the two. The bore in the Collie River East continued to rise since 2007, but at a reduced rate.

Table 3.14 Summary of groundwater trends for the Western Darling Range Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	3	60	0.00	4	80	0.00	4	80	-0.41
Stable	1	20		0	0		0	0	
Rising	1	20	0.30	1	20	0.30	1	20	0.26

* Mean rate of change in groundwater level.

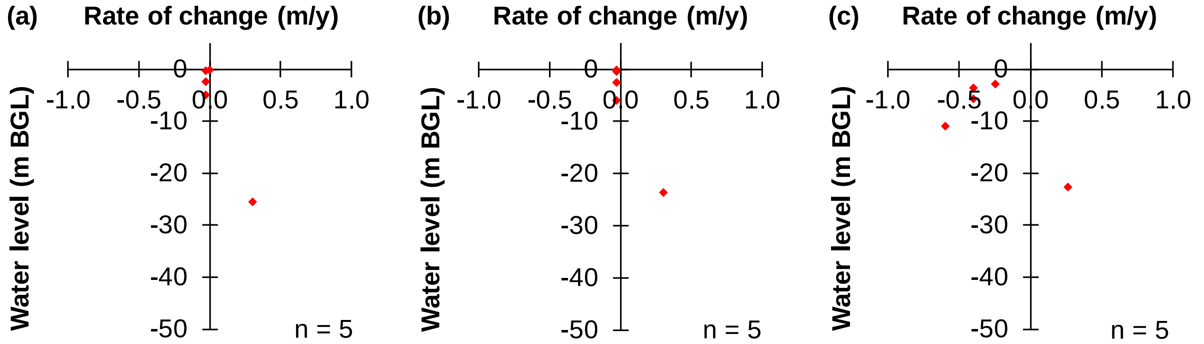


Figure 3.40 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Western Darling Range Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

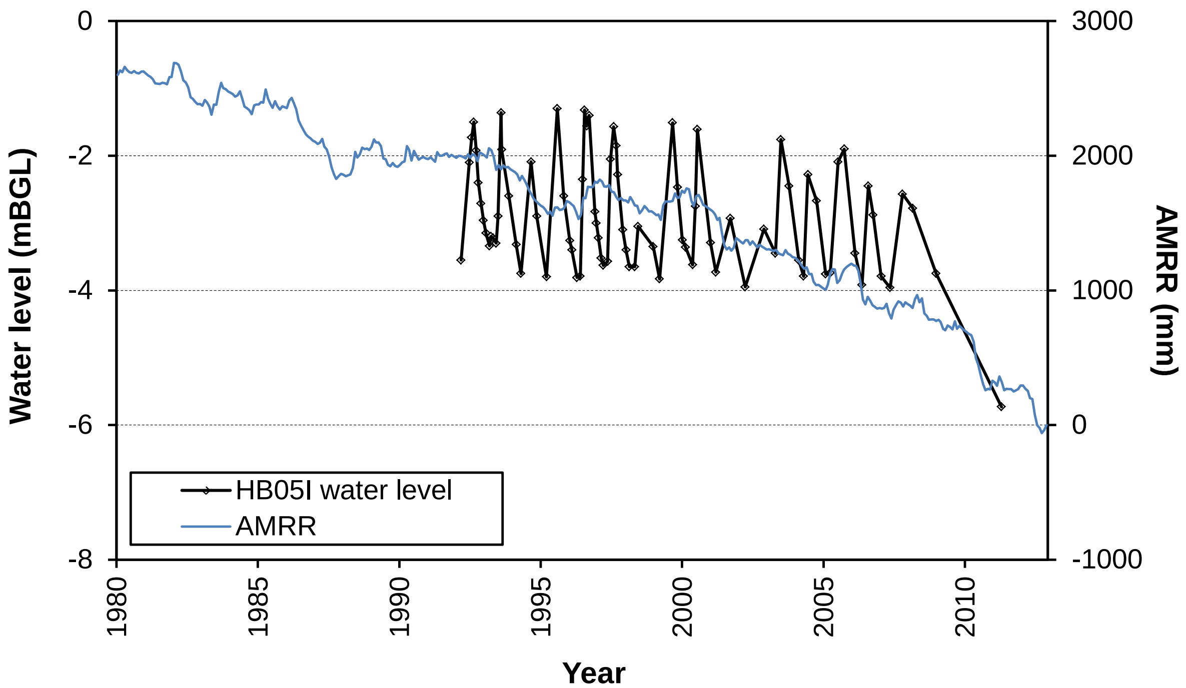


Figure 3.41 Hydrograph for bore HB05I, within the Western Darling Range Hydrozone and accumulated monthly residual rainfall for Greenbushes

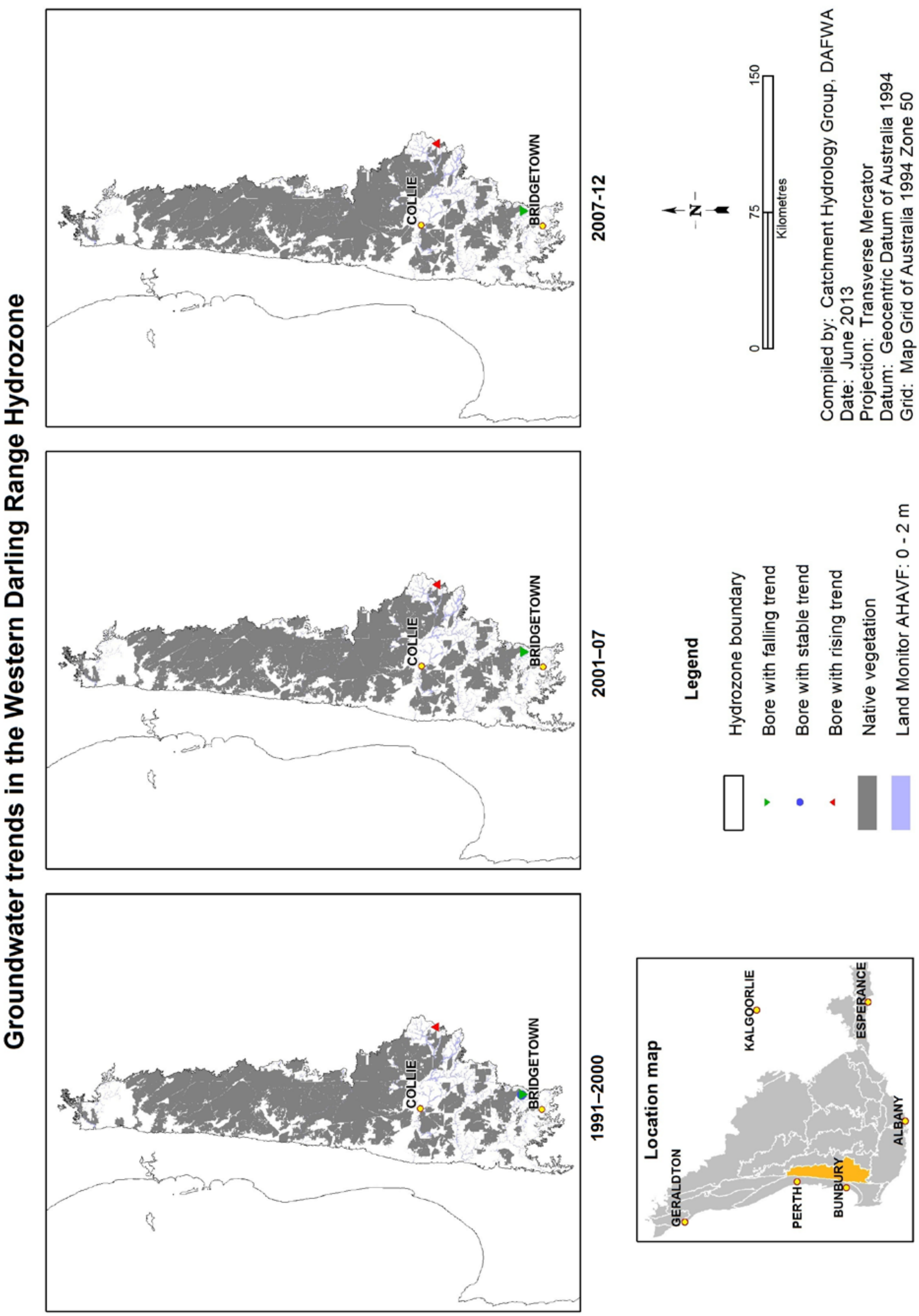


Figure 3.42 Groundwater trends for each of the periods analysed for the Western Darling Range Hydrozone

3.1.15 Coastal Plain Hydrozone

The Coastal Plain Hydrozone incorporates the Perth Coastal Dune (211), Bassendean (212) and Pinjarra (213) soil-landscape zones. It is characterised by fixed dunes immediately inland from the coast, and a flat to gently undulating plain with low-lying wet areas further from the coast. The hydrozone extends from Cape Naturaliste in the south to Jurien Bay in the north. It is bounded to the west by the Indian Ocean, to the east by the Darling Fault and by the Gingin Scarp, north of Bullsbrook. The hydrozone covers an area of 1.08 million hectares, 36% of which is cleared, for either dryland or irrigated agriculture.

The hydrozone occupies part of the onshore, western portion of the Perth Basin. The hydrogeology of the plain is dominated by unconsolidated sediments and limestone over sedimentary rocks. The Perth Basin sediments range from highly permeable to impermeable. Many of the surficial deposits in the hydrozone are highly permeable sands. Major aquifers are located in the sandstones of the Leederville, Yarragadee and Cockleshell Gully Formations, with deposits of clay and shale acting as confining layers. The Yoganup Formation, which lies along the inland boundary of the hydrozone, is a major recharge area for these aquifers. Groundwater flow is generally east to west to the Indian Ocean.

The dominant soils are Yellow deep sands, Pale deep sands, Calcareous deep sands and Yellow/brown shallow sands in the Coastal Dune Soil-landscape Zone; Pale deep sand, Semi-wet soils and Wet soils in the Bassendean Soil-landscape Zone; and Semi-wet and Wet soils, Grey deep and shallow sandy duplexes (sometimes alkaline), Pale deep sands and loams in the Pinjarra Soil-landscape Zone.

Groundwater quality ranges from fresh to saline, with the fresher groundwaters found in the main sedimentary aquifers.

Groundwater monitoring and historical trends

The Department of Water has primary responsibility for groundwater resources and monitoring in the Coastal Plain Hydrozone. However, DAFWA has monitored bores around Bunbury and Vasse, in the southern portion of the hydrozone since the mid-1980s. Most of the bores are screened in the surficial aquifer, which is the aquifer most likely to be associated with any future salinity risk. Groundwater is shallow over much of the hydrozone but groundwater trends are stable, responding to seasonal rainfall.

DAFWA's groundwater monitoring in the northern portion of the hydrozone began in 1991 with monitoring bores installed across a low-lying area east of Cervantes (Figure 3.45). Groundwater was generally less than one metre below the surface and groundwater quality ranged from fresh to saline (<100 to >2600mS/m) (Figure 3.44). This part of the hydrozone is a groundwater discharge zone and it has progressively degraded over time.

The Coastal Plain Hydrozone was not included in the groundwater trend analysis performed by George et al. (2008). Furthermore, shallow groundwater is widespread in the south-west irrigation areas but these areas are not included in this analysis. The Land Monitor AHAVF product is not considered a suitable reflection of salinity hazard in this hydrozone because of the permeability of the aquifers and the gentle undulating topography and therefore it is not shown in Figure 3.45.

Current situation

Groundwater remains less than one metre below the surface in low-lying areas in the northern portion of the hydrozone, despite continued below average rainfall, particularly since 2001 (Figure 3.44).

The bores in the southern portion of the hydrozone have not been monitored since 2007 at which time groundwater levels were either within a metre of the ground surface or artesian and displaying stable trends (Table 3.15, Figure 3.43, Figure 3.45).

Table 3.15 Summary of groundwater trends for the Coastal Plain Hydrozone

	1991–2000			2001–07			2007–12		
Trend	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	0	0		2	17	-0.12	0	0	
Stable	21	88		10	83		3	100	
Rising	3	12	0.07	0	0		0	0	

* Mean rate of change in groundwater level.

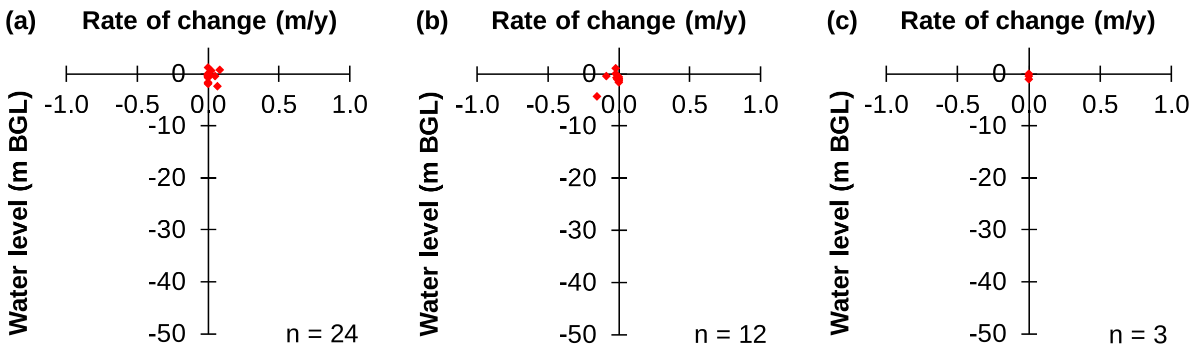


Figure 3.43 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Coastal Plain Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

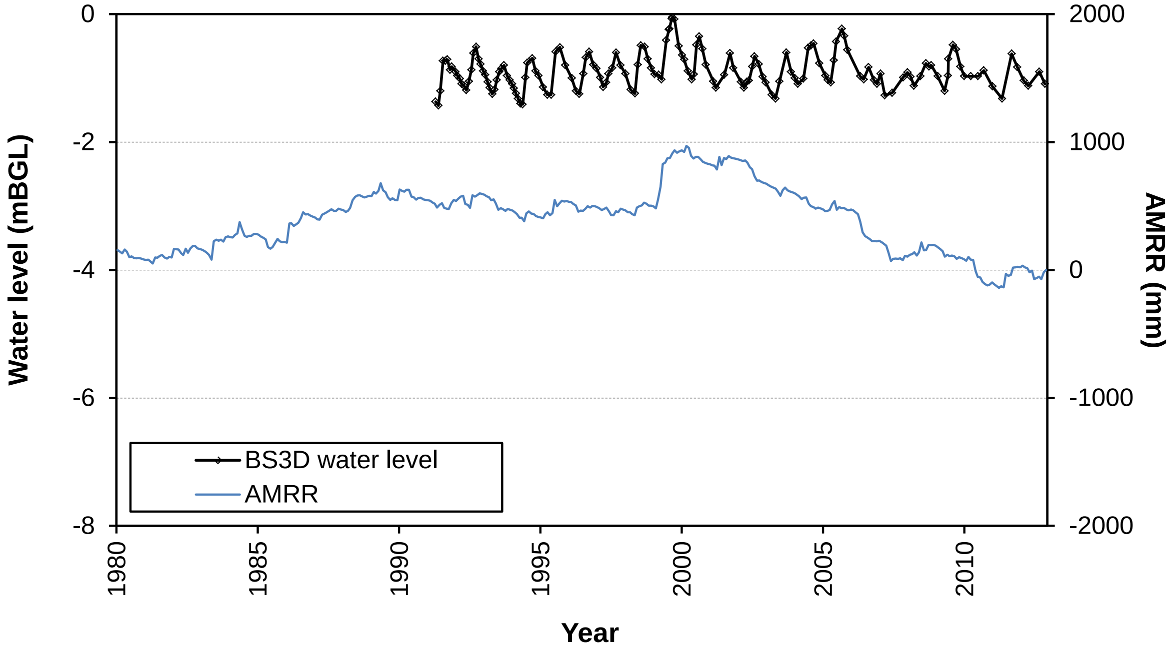


Figure 3.44 Hydrograph for bore BS3D, within the Coastal Plain Hydrozone and accumulated monthly residual rainfall for Jurien

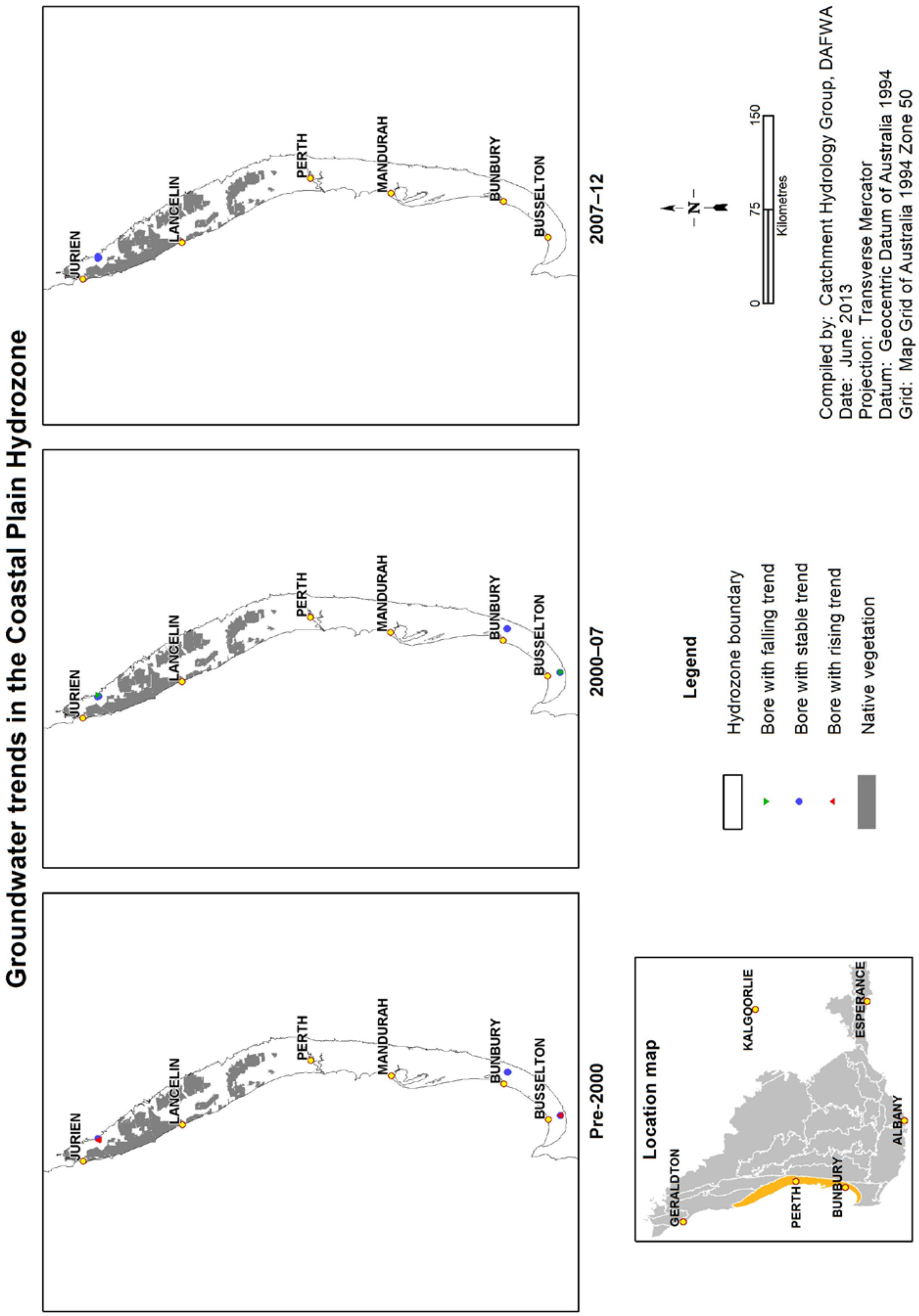


Figure 3.45 Groundwater trends for each of the periods analysed for the Coastal Plain Hydrozone

3.1.16 Donnybrook Sunkland Hydrozone

The Donnybrook Sunkland Hydrozone is a moderately dissected lateritic plateau of deeply weathered mantle and colluvium over Perth Basin sedimentary rocks. The Blackwood Plateau land system occupies 67% of the hydrozone and the term is often used to describe the whole area (Irwin 2006, Golder Associates 2008). It covers an area of 371 000ha, 13% of which is cleared for agriculture (Figure 3.46).

Soils in the hydrozone are formed in lateritic colluvium, weathered in situ sedimentary rocks and alluvium. Duplex sandy gravels, Wet and Semi-wet soils, deep sands and loamy gravels dominate (Tille 1996).

Less than 10% of the hydrozone has been cleared.

Groundwater monitoring and historical trends

DAFWA does not monitor any bores in this hydrozone and it was not included in the groundwater trend analysis performed by George et al. (2008).

Current situation

Land salinity in the Donnybrook Sunkland Hydrozone is limited to very small areas adjacent to drainage lines.

3.1.17 Leeuwin Hydrozone

The Leeuwin Hydrozone consists of coastal sand dunes and a moderately dissected lateritic plateau over granitic bedrock. On the western margin, the granite is overlain by Tamala Limestone and some coastal dunes. The dominant soils are Loamy gravels, Duplex sandy gravels, Wet and Semi-wet soils, Calcareous deep sand and loams. It covers an area of 102 000ha and less than 44% is cleared for agriculture (Figure 3.46).

Groundwater monitoring and historical trends

DAFWA does not monitor any bores in this hydrozone and it was not included in the groundwater trend analysis performed by George et al. (2008).

Current situation

Land salinity in the Leeuwin Hydrozone is limited to very small areas adjacent to drainage lines and small areas on the Whicher Scarp.

3.1.18 Scott Coastal Plain Hydrozone

The Scott Coastal Hydrozone is separated from the Blackwood Plateau of the Donnybrook Sunklands Hydrozone by the Barlee Scarp and from the Leeuwin Hydrozone by the Leeuwin–Naturaliste Ridge (Irwin 2006). The western portion of the hydrozone is drained by the Blackwood and Scott rivers and the eastern portion is drained by the Donnelly River. The central portion is largely internally drained and subject to seasonal inundation. Lakes Jasper and Quitjup are in this portion in a flat-lying area east of the coastal dunes. The hydrozone covers an area of 89 000ha and 64% is native vegetation (Figure 3.46).

The hydrozone consists of coastal sand dunes and plain with swamps. The hydrogeology is characterised by limestone and unconsolidated sediments over sedimentary rocks. Acidic, non-calcareous sands dominate the low-lying wet areas. The dunes consist of Calcareous deep sands.

Groundwater monitoring and historical trends

DAFWA does not monitor any bores for assessing salinity risk in this hydrozone and it was not included in the groundwater trend analysis performed by George et al. (2008).

Current situation

There are no significant areas of land salinity in the Scott Coastal Plain Hydrozone.

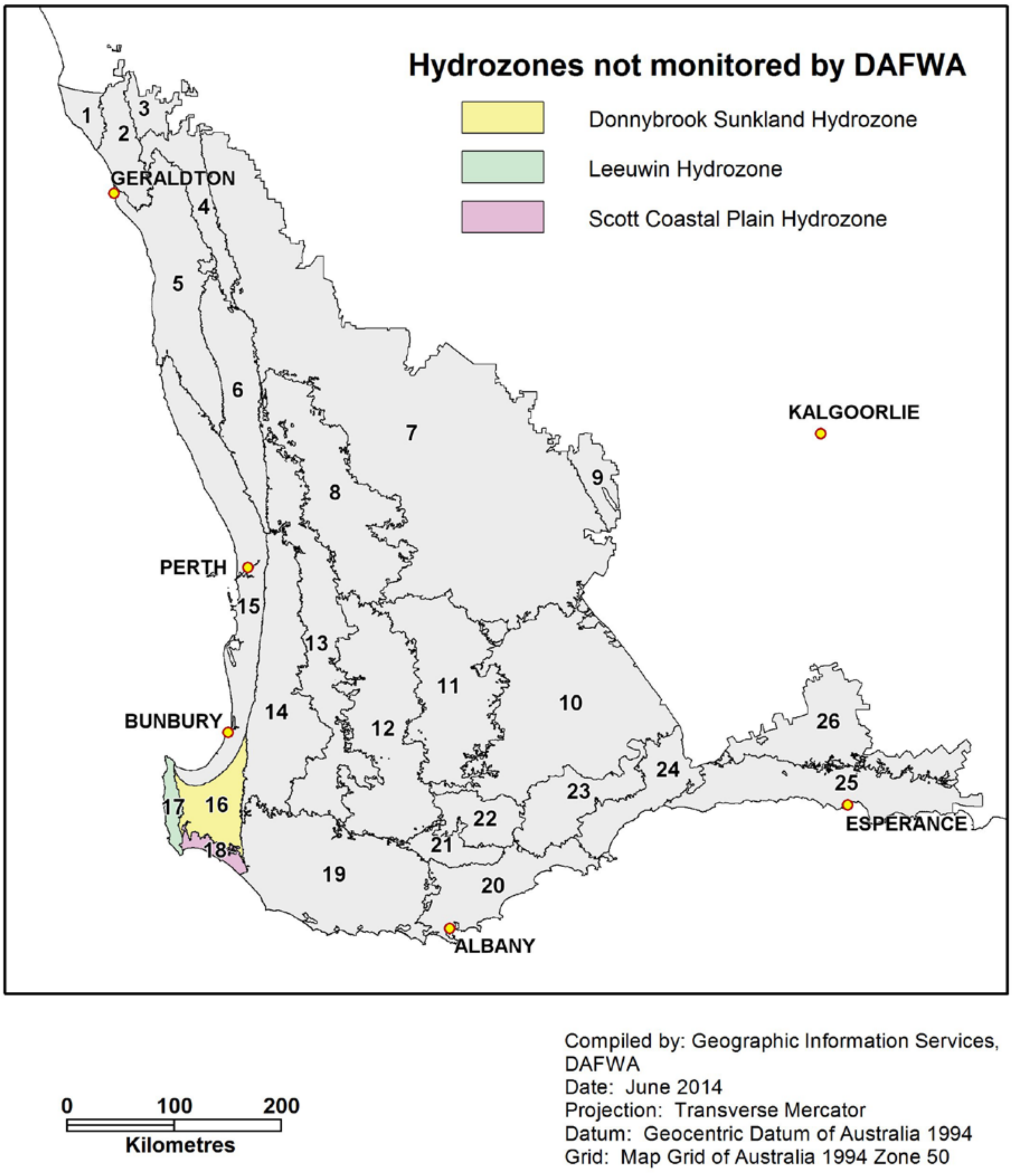


Figure 3.46 Location of the Donnybrook Sunkland, Leeuwin and Scott Coastal Plain hydrozones within the south-west agricultural region of WA

3.1.19 Warren–Denmark Southland Hydrozone

The Warren–Denmark Southland Hydrozone is characterised by a topography that rises in a series of broad benches from the Southern Ocean north to the Blackwood Valley catchment divide. Drainage near catchment divides can be sluggish because of the flat landscape, resulting in swampy areas and a number of lakes, such as Unicup, Muir, Poorrarecup and Kwornicup. The hydrozone has a number of southward-flowing rivers that provide good drainage, including the Kent, Hay, Denmark, Frankland, Warren and Shannon rivers. It covers an area of 1.56 million hectares, 25% of which has been cleared for agriculture. About 45% of the cleared area is occupied by private forestry plantations.

The profile is deeply weathered granite and gneiss overlain in the south by Tertiary and Quaternary sediments. Occasional swarms of dolerite dykes and shear zones result in groundwater systems that are local and compartmentalised. When groundwater rises occur, localised hillside seeps and salinity become evident. The dominant soils are Loamy gravel, Duplex sandy gravel, Wet and Semi-wet soil, shallow and Deep sandy gravel and Grey deep sandy duplexes. Groundwaters are generally low quality, ranging from brackish to saline.

Groundwater monitoring and historical trends

In 1989, 15 bores were installed in and around early trial plantings of blue gums in the catchments of the Hay and Denmark rivers to monitor groundwater trends.

Between 1990 and 2000, more than 125 monitoring bores were installed in the Denmark River, Kent River and Frankland catchments and most of these were installed in or adjacent to revegetated areas. In 2008, two additional sites (8 bores) were drilled as part of the Resource Condition Monitoring Project (DAFWA 2008).

In 1991–2000, rainfall was marginally below average across the entire hydrozone but half of the bores had rising groundwater trends. The proportion of bores with falling trends was 16% and 32% had stable trends (Figure 4.49, Table 4.16).

In 2001–07, the proportion of bores with rising groundwater trends fell to 30%, the proportion of bores with falling trends almost doubled to 30%, and 40% had stable trends. During this period, the rainfall deficit relative to the long-term mean was greater than during 1991–2000.

Current situation

In 2007–12, below average rainfall continued across most of the hydrozone. Only 16 bores continue to be monitored. The proportion of bores with rising groundwater trends has continued to fall to 25%. Bores with stable trends now make up 56% of the total and 19% have falling trends (Table 3.16, Figure 3.47). The main change from previous trend analyses is the reduced proportion of bores with rising trends and the reduced rate of rise over time, from 0.2 to 0.12m/y (Figure 3.48). The proportion of bores with stable trends has been steadily increasing (Figure 3.49).

Table 3.16 Summary of groundwater trends for the Warren–Denmark Southland Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	3	16	-0.12	6	30	-0.08	3	19	-0.10
Stable	6	31		8	40		9	56	
Rising	10	53	0.20	6	30	0.14	4	25	0.12

* Mean rate of change in groundwater level.

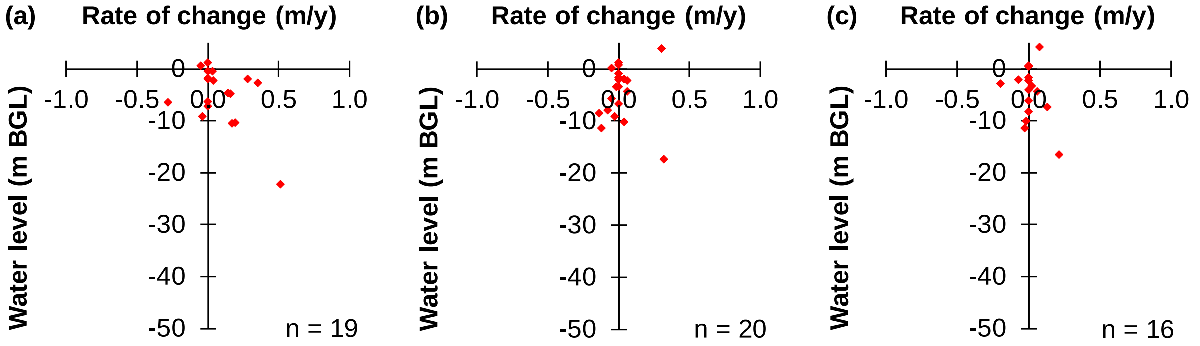


Figure 3.47 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Warren–Denmark Southland Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

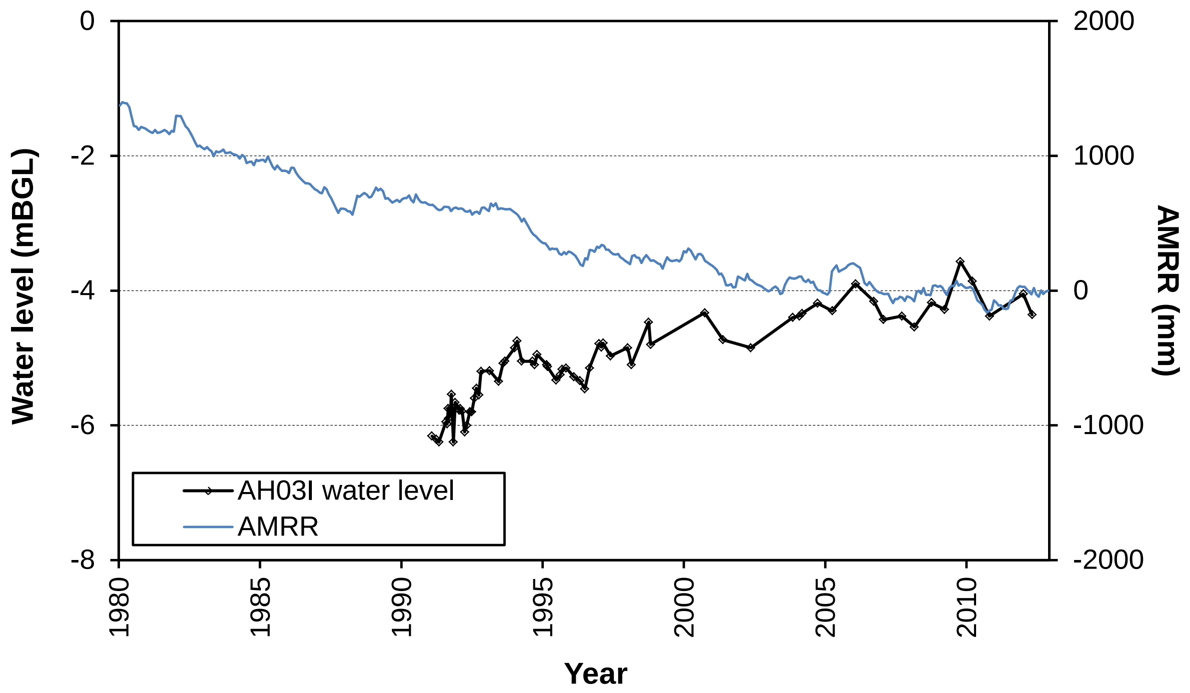


Figure 3.48 Hydrograph for bore AH03I, within the Warren–Denmark Southland Hydrozone and accumulated monthly residual rainfall for Frankland

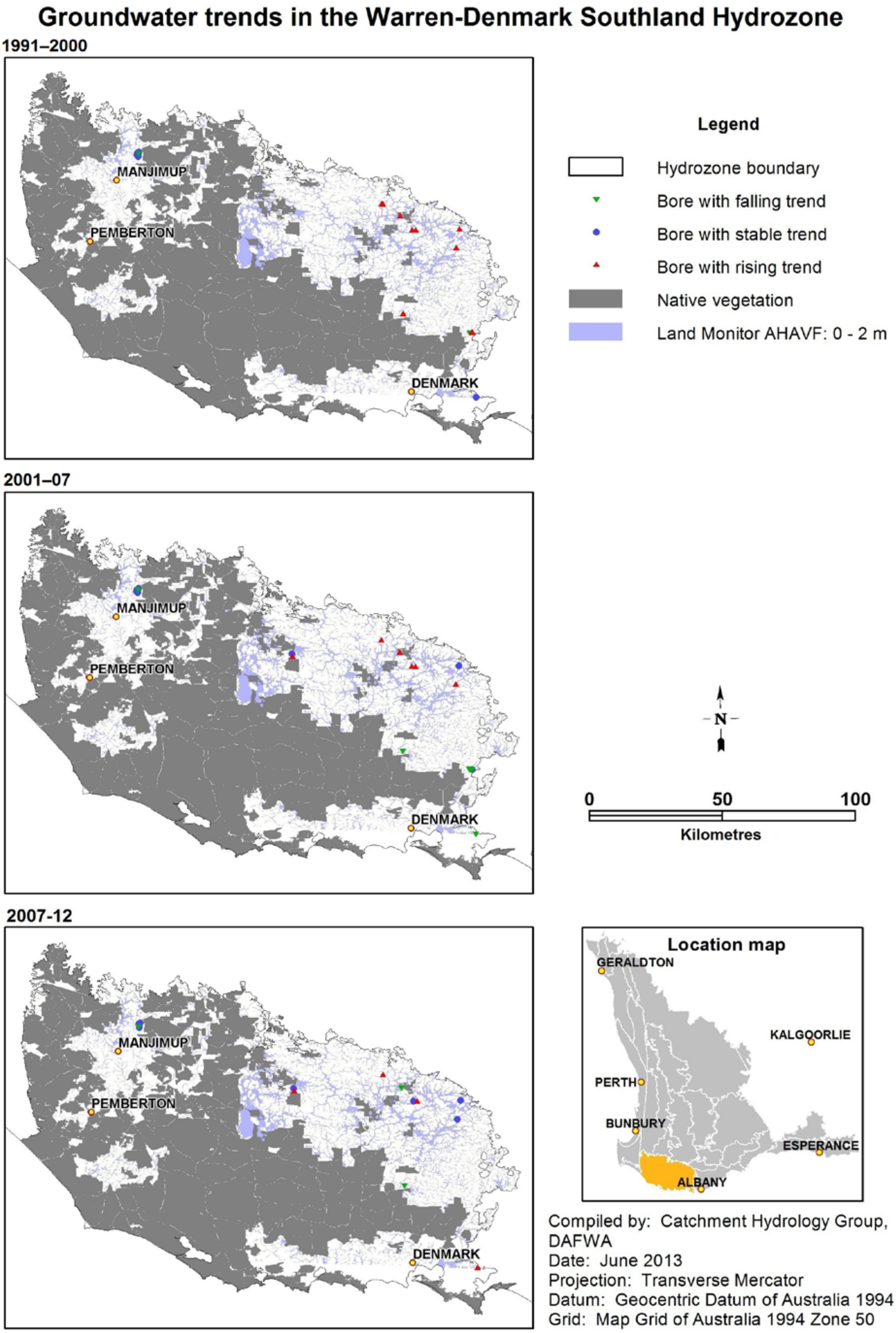


Figure 3.49 Groundwater trends for each of the periods analysed for the Warren–Denmark Southland Hydrozone

3.1.20 Albany Sandplain Hydrozone

The eastern part of the Albany Sandplain Hydrozone is a gently undulating plain dissected by a number of short, southward-flowing rivers. Most of the area consists of broad plains with numerous lakes and depressions that become seasonally inundated. The Pallinup River cuts through the Tertiary plain and acts mainly as a conduit to drain the Pallinup Hydrozone located to the north of Albany Sandplain Hydrozone. The western part of the hydrozone contains the Kalgan, King and Napier rivers and consists of a moderately dissected sandplain with hills. The hydrozone is underlain by Tertiary marine sediments overlying Proterozoic granitic and metamorphic rocks. Soils are sandy duplexes, often alkaline and sodic, with some sands and gravels. The hydrozone covers an area of 663 000ha, 51% of which is cleared.

The hydrology is strongly influenced by the Plantagenet Group of sediments, which is comprised of the Pallinup and Werillup formations. Spongolite, siltstone, sandstone and silt are found in the Pallinup Formation and the Werillup Formation contains lignite in various stages of formation. Sand and rounded gravel aquifers at the base of the Werillup Formation can provide good yields of groundwater with a high potential for fresh water resources close to the coast.

The western part of the hydrozone is reasonably well drained by the Kalgan and King rivers, resulting in local and intermediate groundwater flow systems discharging into the surface drainage. The eastern part is not as well drained and has many lakes, resulting in intermediate to regional groundwater flow systems with very little lateral flow.

Groundwater monitoring and historical trends

Salinity investigations began in 1987 with the establishment of 10 bores around Lake Chillinup and a broad saline valley floor south of the Stirling Ranges. These bores are no longer monitored but historical data to 2000 was available for analysis by George et al. (2008).

In the early 1990s, 40 bores were installed throughout the Wellstead area to investigate the impact of agriculture on rising groundwater and to determine the groundwater connection between the Pallinup River and the lake systems, and the Stirling Range to the coast (Ferdowsian et al. 1996b). In 2001, the Wellstead Catchment Group agreed to a plan to drain Lake Chillinup and 10 bores were installed around the lake to measure the effect. These bores are still monitored by the landholder. In 2008, two additional sites (4 bores) were drilled as part of the Resource Condition Monitoring Project (DAFWA 2008) and these continue to be monitored.

Prior to 2000, 65% of bores had rising groundwater trends, 23% had a falling trend and 13% had stable trends (Table 3.17, Figure 3.50). During this period, rainfall was close to average across most of the hydrozone and this persisted into the 2001–07 analysis period. There was very little change in groundwater trends in 2001–07.

Current situation

Forty-three bores are still monitored in the hydrozone. The proportion of bores with rising groundwater trends has fallen from 65% to 47%. These bores are concentrated in the central and eastern parts of the hydrozone, where rainfall was slightly above the long-term mean during 2008–12.

The proportion of bores with falling groundwater trends increased from 19 to 30% and 23% of bores now have stable trends (Figure 3.52). Most of the bores with falling trends are located in the western third of the hydrozone.

The hydrograph for bore SH1D90 shows three distinct groundwater responses: 1990–96 has a steep rise; 1996–2007 has a reduced rate of rise; and 2007–12 has a stable trend (Figure 3.51). MAR has decreased over the past 20 years and is likely to be the reason for this response.

Table 3.17 Summary of groundwater trends for the Albany Sandplain Hydrozone

	1991–2000			2001–07			2007–12		
Trend	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)
Falling	7	23	-0.12	6	19	-0.09	13	30	-0.11
Stable	4	13		5	16		10	23	
Rising	20	64	0.12	21	65	0.11	20	47	0.09

* Mean rate of change in groundwater level.

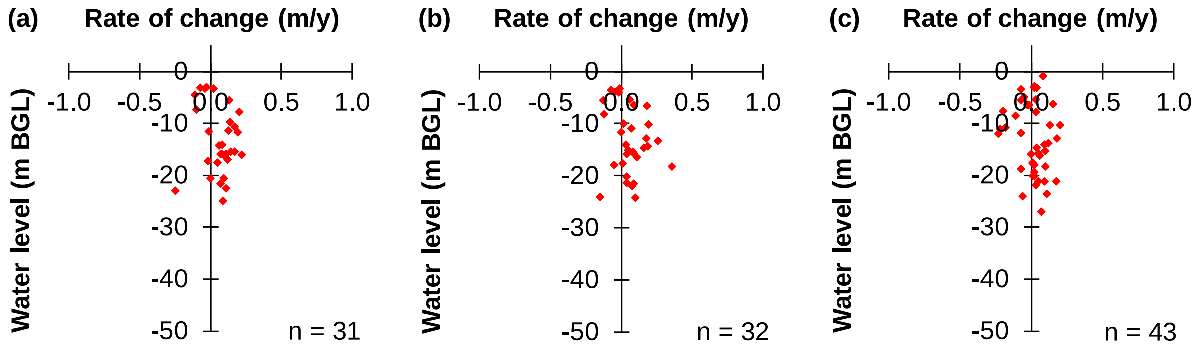


Figure 3.50 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Albany Sandplain Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

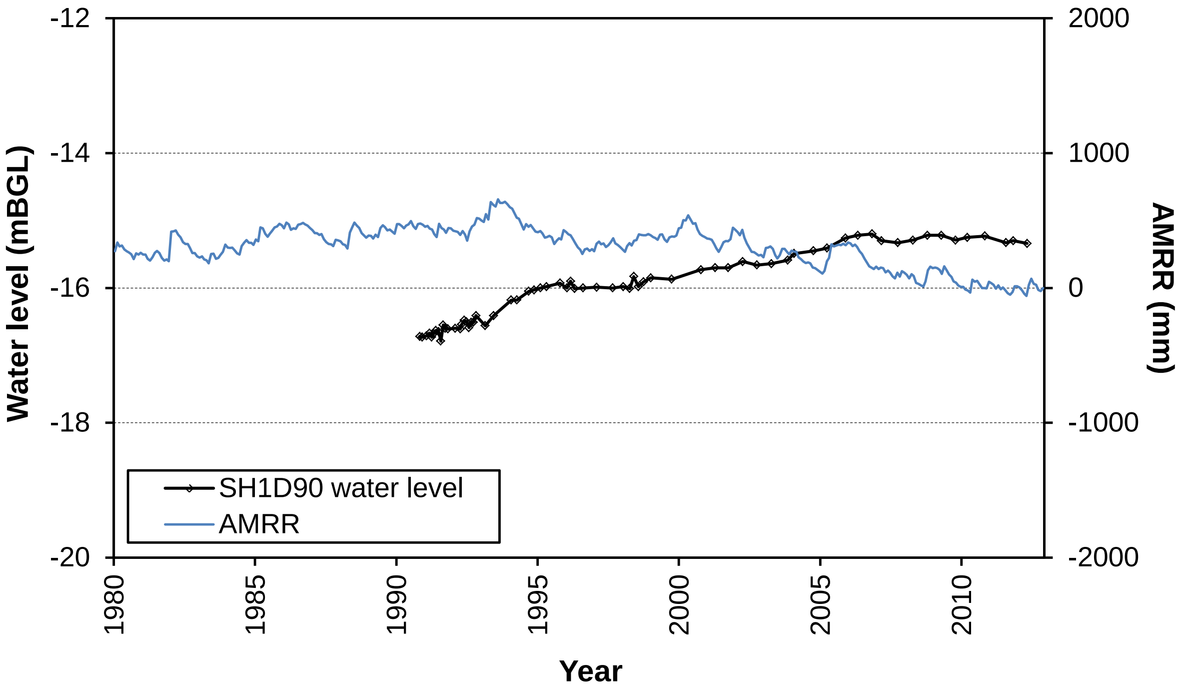


Figure 3.51 Hydrograph for bore SH1D90, within the Albany Sandplain Hydrozone and accumulated monthly residual rainfall for Cape Richie

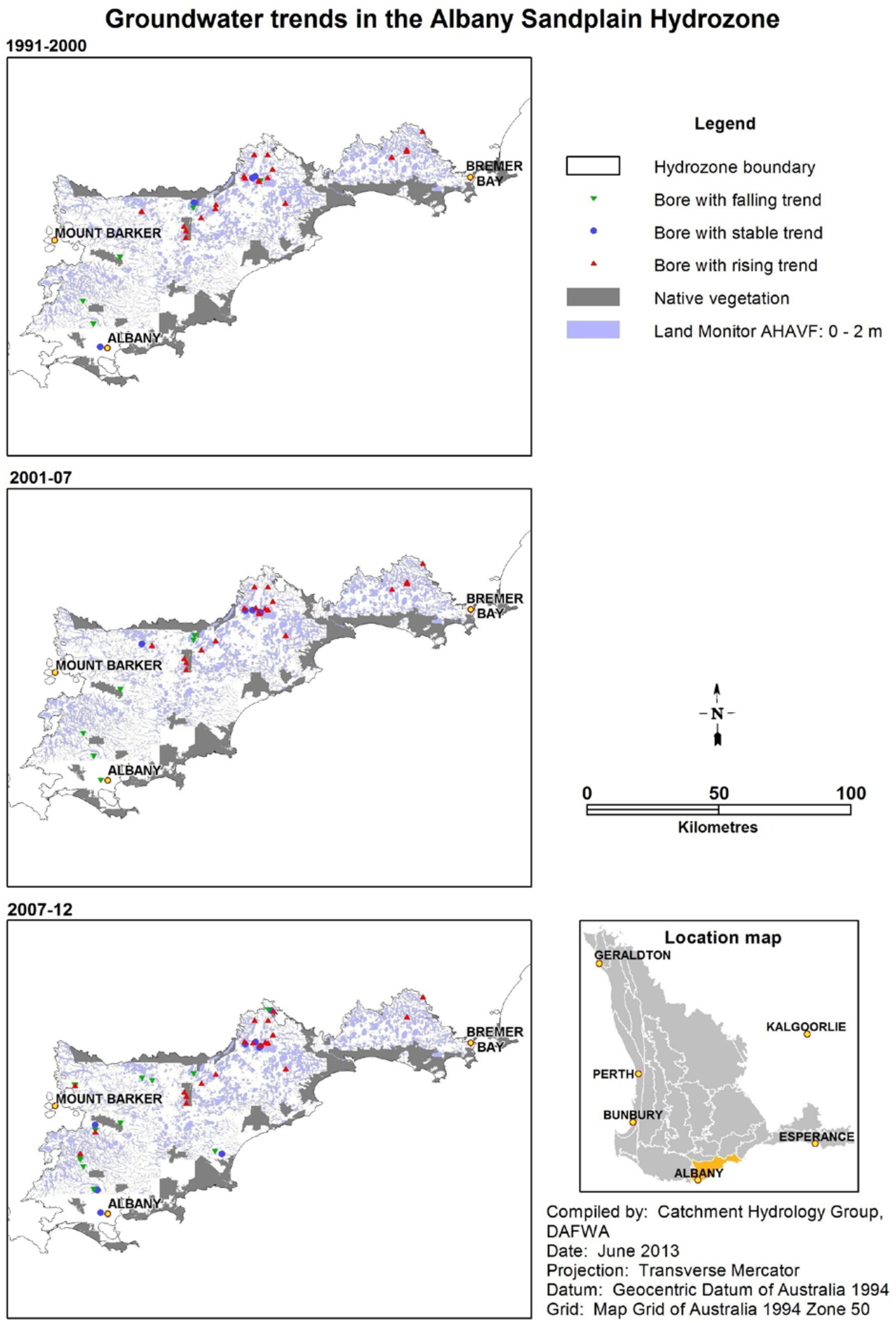


Figure 3.52 Groundwater trends for each of the periods analysed for the Albany Sandplain Hydrozone

3.1.21 Stirling Range Hydrozone

Landscape features within the Stirling Range Hydrozone include the steep mountains of the range itself, undulating rises with granitic outcrops immediately to the north of the range, plus the broad, poorly drained plains of the North Stirling Basin that contains many salt lakes. The Stirling Range itself consists of metamorphosed sandstone, slate and phyllite (Muhling & Brakel 1985). Rocky and gravelly soils occur on the Stirling Range and Alkaline grey sandy duplexes occur on the rises and plain. Shrublands dominate the mountains and woodlands dominate the rises. The hydrozone covers an area of 210 000ha and is 40% cleared.

The mountainous Stirling Range National Park is a large feature of the hydrozone. The footslopes to the north consist of Quaternary sediments sitting on top of the Yilgarn Craton. Many large lakes occur at the base of the footslopes, with very little run-off leaving the area because of the broad, flat landscape. The internally drained area has aquifers that tend to be stagnant and nearly one-dimensional because of the low gradient and low hydraulic conductivity of the regolith. One of the few known sources of groundwater discharge from the basin is via fractures in the basement rock at the eastern end, which apparently contributes to soil salinity in the adjacent Six Mile Creek (Lewis 1992). A consequence of the stagnant aquifers is that groundwaters are saline to extremely saline (900 to >16 000mS/m). The regolith is more than 100m thick in portions of the North Stirling Basin.

Groundwater monitoring and historical trends

In 1986, the National Soil Conservation Program funded a project to investigate groundwater flow conditions and geology of the North Stirling area. Sixty-five bores were drilled in conjunction with the Geological Survey of Western Australia. The main reason for these investigations was the increasing area of secondary salinity and the threat of large increases, particularly given that the area is relatively flat and internally drained.

Rainfall across the western half of Stirling Range Hydrozone has remained slightly below average since 1975. In the eastern half of the hydrozone, rainfall was slightly above average during 1975–1990 and 1991–2000, but has been below average since (Figure 2.3).

In 1991–2000, 63% of bores had rising groundwater trends, 13% had falling trends and 25% had stable trends (Table 3.18, Figure 3.53, Figure 3.55).

In 2001–07, only one bore had a rising trend, 38% had a falling trend and 50% had stable trends. Groundwater levels were no longer rising near discharge sites (saline flats, swamps and lakes) where the depth to groundwater was less than 2m. In these areas, groundwater levels fluctuated seasonally with annual rainfall (Ferdowsian & Crossing 2004).

Current situation

Six bores are monitored in the hydrozone with equal numbers having rising and falling groundwater trends (Table 3.18, Figure 3.53). The main change from the 2007–12 analysis period, is an increase in the proportion of bores with rising trends. The hydrograph for bore NS11D86 shows a typical groundwater response for the zone (Figure 3.54).

Table 3.18 Summary of groundwater trends for the Stirling Range Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)
Falling	1	13	-0.06	3	38	-0.05	3	50	-0.07
Stable	2	25		4	50		0	0	
Rising	5	62	0.10	1	12	0.03	3	50	0.06

* Mean rate of change in groundwater level.

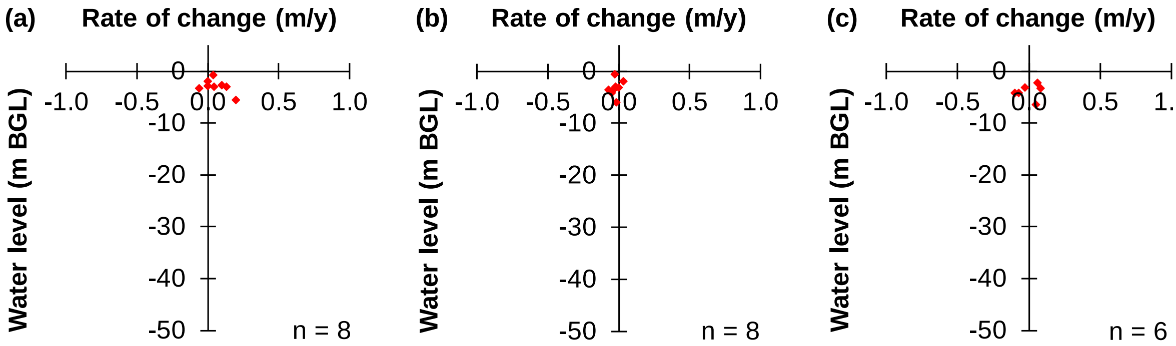


Figure 3.53 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Stirling Range Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

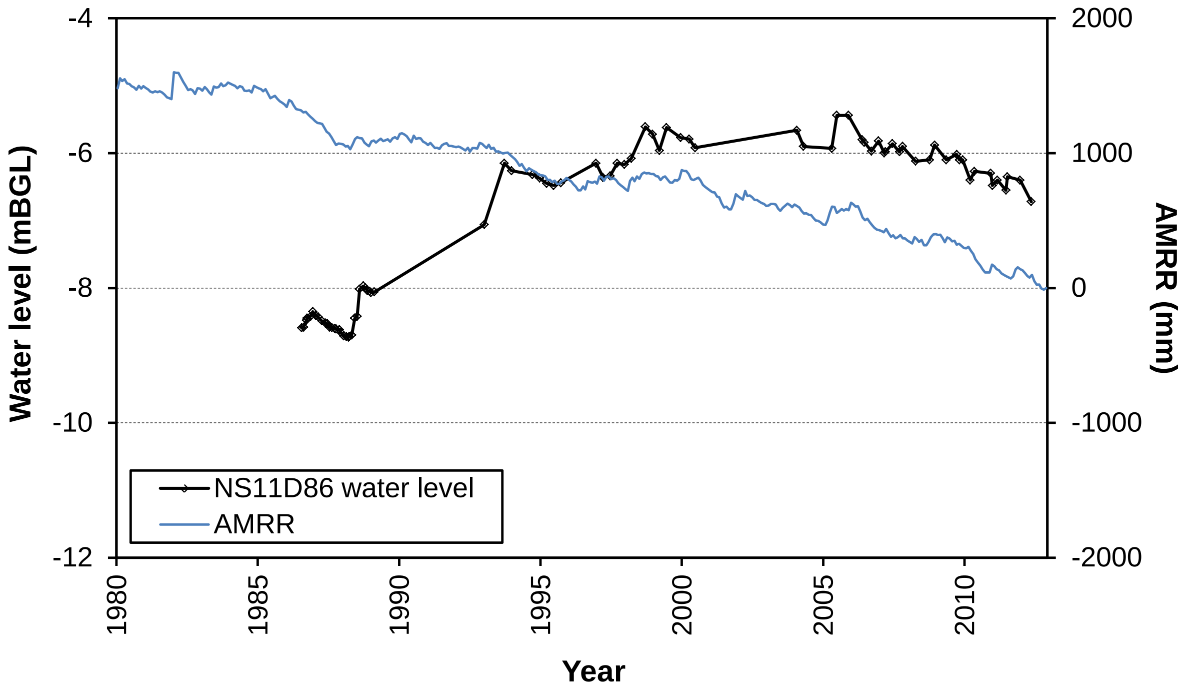


Figure 3.54 Hydrograph for bore NS11D86, within the Stirling Range Hydrozone and accumulated monthly residual rainfall for Tambellup

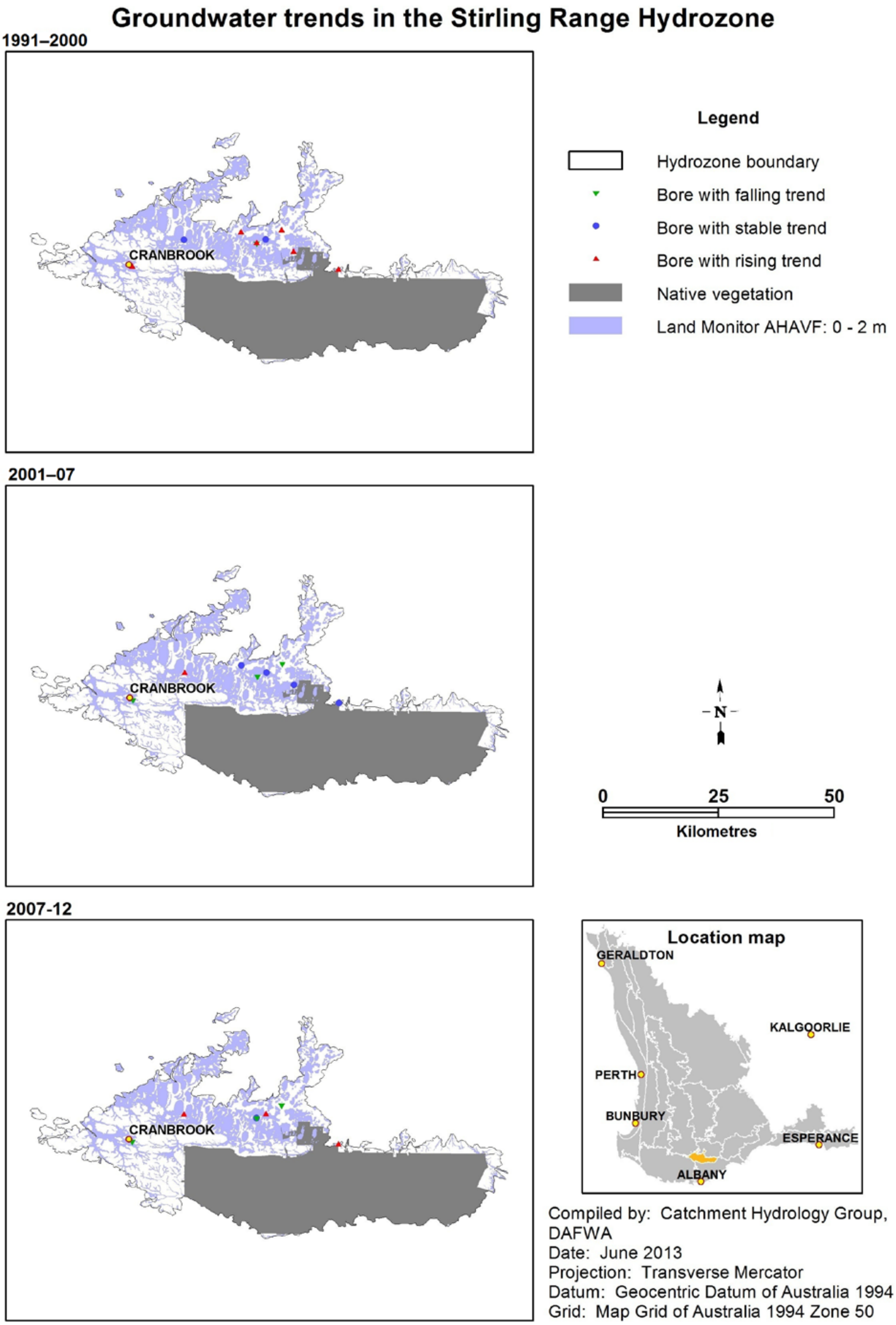


Figure 3.55 Groundwater trends for each of the periods analysed for the Stirling Range Hydrozone

3.1.22 Pallinup Hydrozone

The Pallinup Hydrozone is located in the Upper Pallinup River Catchment and contains gently undulating rises and low hills on Archaean basement rocks on the southern margin of the Yilgarn Craton. It has a weathered lateritic profile that has been eroded, forming well-defined creeklines. The hydrozone is extensively intruded by the Gnowangerup dyke swarm, with rock outcrops occurring on some ridges and slopes. The shallow basement rocks and dolerite dykes can partially obstruct groundwater flow and cause hillside seeps. Common soils are Grey shallow sandy duplex (0.1–0.4m) and red soils associated with dykes. Many of the subsoil clays are sodic and alkaline. The hydrozone covers an area of 327 000ha and is 85% cleared for agriculture.

The main drainage line running through the hydrozone is the Pallinup River, which discharges into the Wellstead Estuary and then into the Southern Ocean. The aquifers are local to intermediate, discharging into surface drainage and tributaries.

In areas of low hills, groundwater gradients towards discharge areas tend to be higher than in the rest of the hydrozone, which facilitates groundwater flow to creeklines and valley floors. Faults and shear zones also affect groundwater movement by restricting groundwater flow, although in some cases they can also be carriers of groundwater.

The shallow to moderate (5–20m) regolith thickness results in aquifers that have lower thresholds for storage, accentuating the effect of variable recharge on groundwater levels. Groundwaters are mainly saline (900–5500mS/m). The extent of salinity is limited to creeklines and hillside seeps (Ferdowsian & Crossing 2004), the occurrence of which is often linked to dolerite dykes or bedrock highs.

Groundwater monitoring and historical trends

The Pallinup Landcare Group installed 70 bores throughout this hydrozone from 1995 to 1998 to gain an understanding of hydrology and groundwater trends. The bores were monitored by the landholders for five years but there has been limited monitoring since. Five bores continue to be monitored.

In 2008, four sites (10 bores) were drilled under the Resource Condition Monitoring Project (DAFWA 2008) to infill gaps in the bore network.

Rainfall across the Pallinup Hydrozone has remained within 20% of the long-term mean since the mid-1970s. During the 1991–2000 analysis period, one bore had a rising groundwater trend, three (38%) had a falling trend and five (50%) had a stable trend. In 2001–07, no bores had a rising trend, 63% had falling trends and 38% had stable trends.

Current situation

Seventeen bores are currently monitored. With the additional bores installed during 2007–12, the proportion of bores with rising groundwater trends increased from 12% in 1991–200 and nil in 2001–07 to 35% (Table 3.19, Figure 3.56), even though rainfall across the hydrozone remained relatively close to the long-term mean. In this analysis period, the geographic spread of bores provides a clearer picture of groundwater trends compared to previous analysis periods where most of the data was obtained from bores installed on one property in the north-east of the hydrozone (Figure 3.58). Forty-one per cent of bores still have falling trends but this is a significant reduction relative to 2001–07. There is a small reduction in the proportion of bores with stable trends. Figure 3.57 shows the gradual rise in groundwater as well as the seasonal variation that is typical of rising or stable groundwater trends in the hydrozone.

Table 3.19 Summary of groundwater trends for the Pallinup Hydrozone

	1991–2000			2001–07			2007–12		
Trend	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)	No. of bores	Pro-portion (%)	Mean RoC* (m/y)
Falling	4	50	-0.09	5	62	-0.13	7	41	-0.08
Stable	3	38		3	38		4	24	
Rising	1	12	0.05	0	0		6	35	0.19

* Mean rate of change in groundwater level.

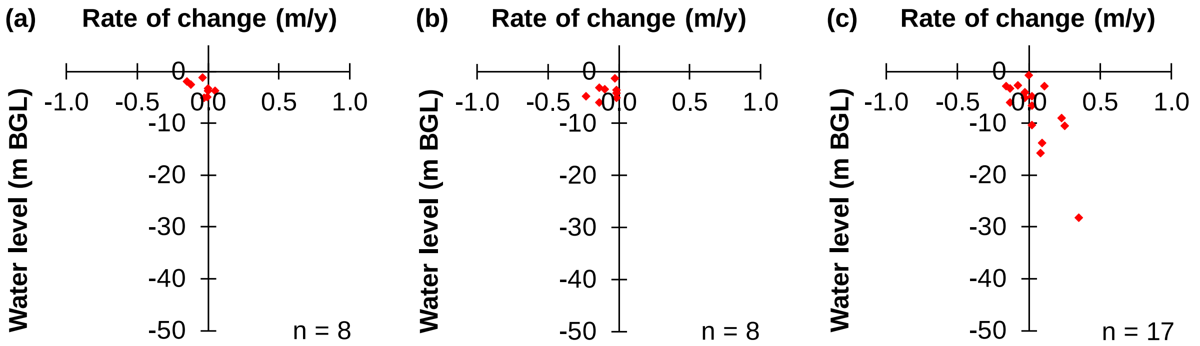


Figure 3.56 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Pallinup Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

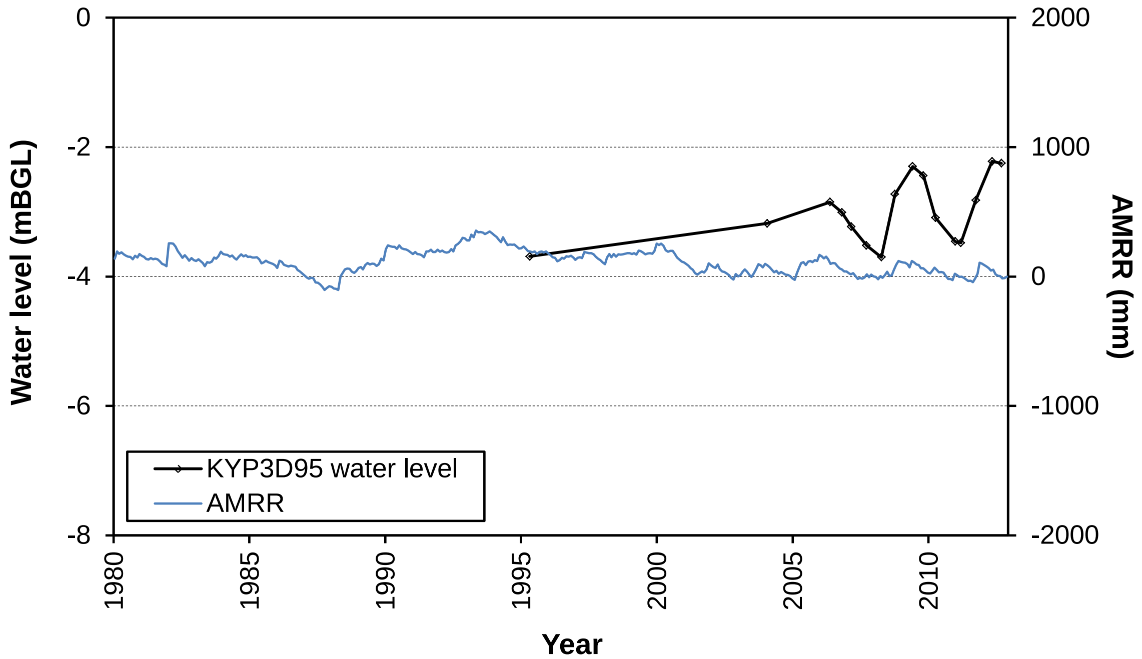


Figure 3.57 Hydrograph for bore KYP3D95, within the Pallinup Hydrozone and accumulated monthly residual rainfall for Borden

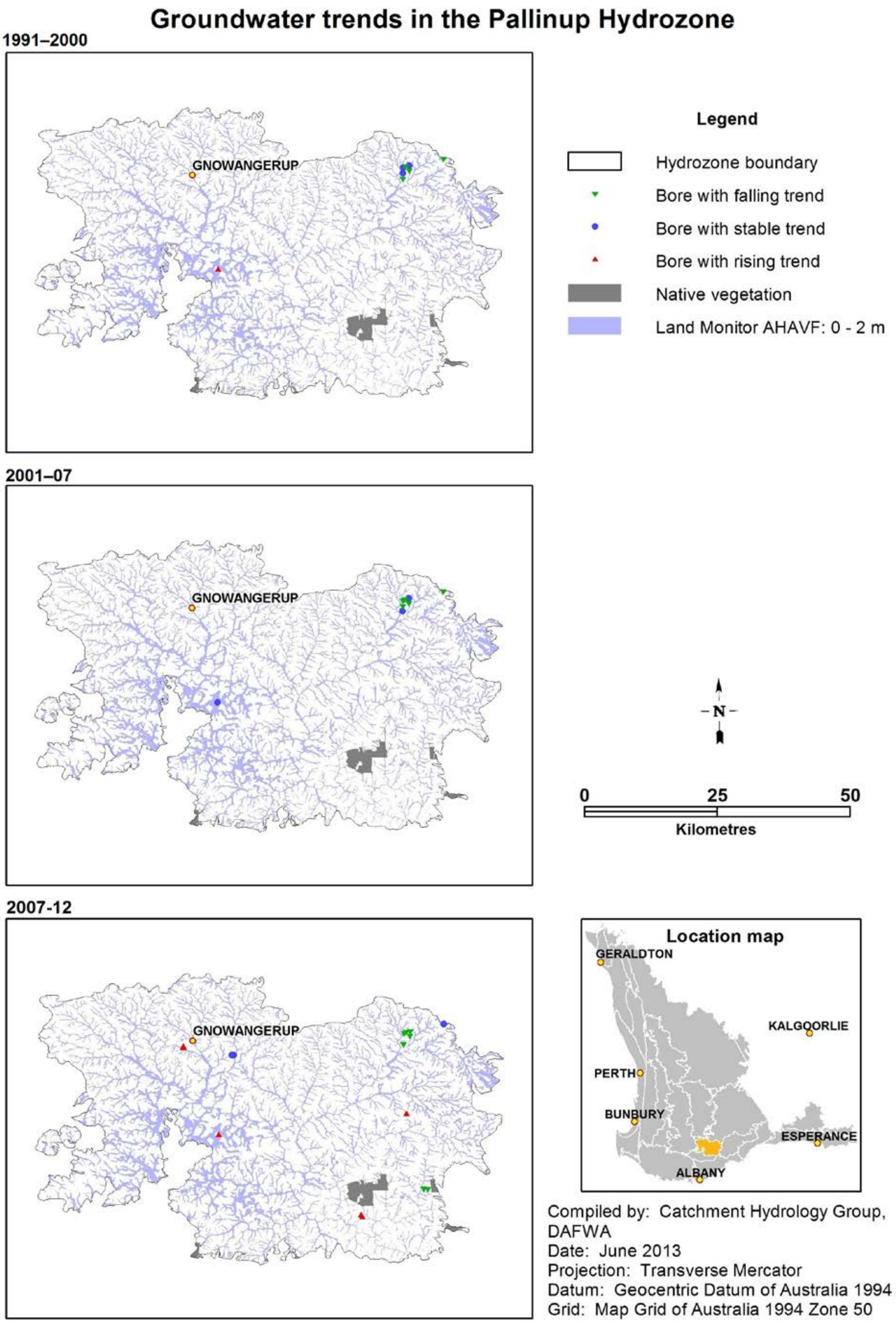


Figure 3.58 Groundwater trends for each of the periods analysed for the Pallinup Hydrozone

3.1.23 Jerramungup Hydrozone

The Jerramungup Hydrozone is a level to gently undulating plain dissected by a number of short, southward-flowing rivers. The main rivers draining the area are the Gairdner, Fitzgerald and Jacup. The hydrozone covers an area of 541 000ha and it is 61% cleared.

Most of the Jerramungup Hydrozone overlies Archean granitic basement of the Yilgarn Craton. Along the southern boundary, Cainozoic sedimentary rocks of the onshore Bremer Basin Plantagenet Group overlie the granitic basement where the Jarrahwood Axis divides the tilted Ravensthorpe Ramp from the Yilgarn Craton (Dodson 1999). The hydrozone is underlain by granites and gneiss, which are intruded by numerous dolerite dykes. The Bremer sediments occur as lenses over the basement rock and range in thickness from 5 to 50m. Weathering of the granitic basement has produced a lateritic profile of gravels and pallid white clays. Soils are Alkaline sandy duplexes (0.3–0.5m deep) with profiles of sand over clay or sand over gravel over clay.

In the dissected (>3% slope) valleys where rivers have been rejuvenated through uplift and cut through the sedimentary profile, shallower (5–12m) regolith is common, with local groundwater flow systems. In many sections of the rivers, rejuvenation has caused erosion to the basement, exposing granite along the beds. In the broader valleys, with gently inclined (1–3%) slopes and moderate regolith thickness (10–30m), groundwater flow systems are local to intermediate and mostly align with the direction of the surface drainage. Groundwaters are predominantly saline.

Groundwater monitoring and historical trends

Between 1989 and 1990, 110 bores were drilled on farms throughout the Jerramungup Hydrozone to examine groundwater flow and geology (Martin 1992). Nineteen of these bores are still monitored by DAFWA. In 2004, the Fitzgerald Biosphere Group (FBG) was selected to participate in the Catchment Demonstration Initiative and a further 49 bores were drilled.

In 2008, five sites (12 bores) were established as part of the Resource Condition Monitoring Project to fill in the gaps in the monitoring network (DAFWA 2008) and these continue to be monitored.

Rainfall across the Jerramungup Hydrozone has been above the long-term mean since 1975. During 1975–90, rainfall was up to 40% above average over the southern central portion the hydrozone (Figure 2.8).

The 110 FBG bores were analysed annually from 1993 to 1998 and presented at the Jerramungup Expo. Of the 110 bores, 86 were monitored regularly and had sufficient data to calculate trends. In 1990–93, 91% of bores had rising groundwater trends and the remainder had falling trends. By 1997, the proportion of bores with rising or falling trends had not changed but the mean rate of change in groundwater levels had increased in bores with rising trends. By 2007, the proportions of bores with rising or falling trends were again similar but the mean rate of change in groundwater levels had almost halved in bores with rising trends (Table 3.20).

Table 3.20 Groundwater trends for bores installed in 1989–90 for the Fitzgerald Biosphere Group

Trend	1990–93			1993–97			1997–2007		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	8	9	-0.12	8	9	-0.07	2	11	-0.15
Stable	0	0		0	0		0	0	
Rising	78	91	0.14	78	91	0.19	17	89	0.10

* Mean rate of change in groundwater level.

Long-term trend analyses, using bores with data from 1990 to 2012, are shown in Table 3.21. During 1991–2000, 75% of bores had a rising groundwater trend, 10% had a falling trend and 15% had a stable trend. In 2001–07, 68% of bores had rising trends, 10% had a falling trend and 23% had a stable trend.

Current situation

During 2008–12, the western third of the hydrozone had marginally below average rainfall and the remainder continued to receive above average rainfall.

Thirty-three bores were monitored: 52% have rising groundwater trends, 30% have falling trends and 18% have stable trends. The main change from the previous analysis is the decrease in bores with rising trends — from 75% to 52% — and the reduced rate of rise — from 0.18m/y to 0.09m/y (Table 3.21, Figure 3.59, Figure 3.61). Figure 3.60 shows a typical groundwater response for the hydrozone.

The proportion of bores with falling groundwater trends has increased since 2007 in response to decreasing annual rainfall, but the mean rate of fall has remained consistent since 1990.

Table 3.21 Summary of groundwater trends for the Jerramungup Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	2	10	-0.11	3	10	-0.13	10	30	-0.10
Stable	3	15		7	22		6	18	
Rising	15	75	0.18	21	68	0.11	17	52	0.09

* Mean rate of change in groundwater level.

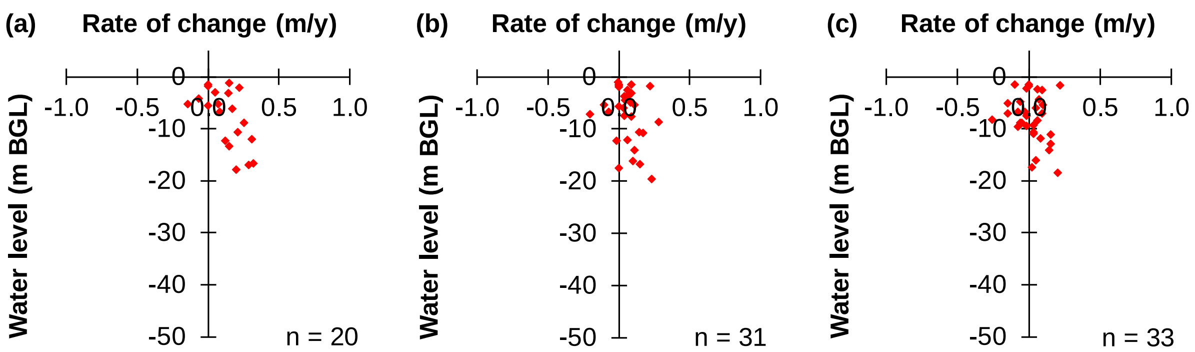


Figure 3.59 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Jerramungup Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

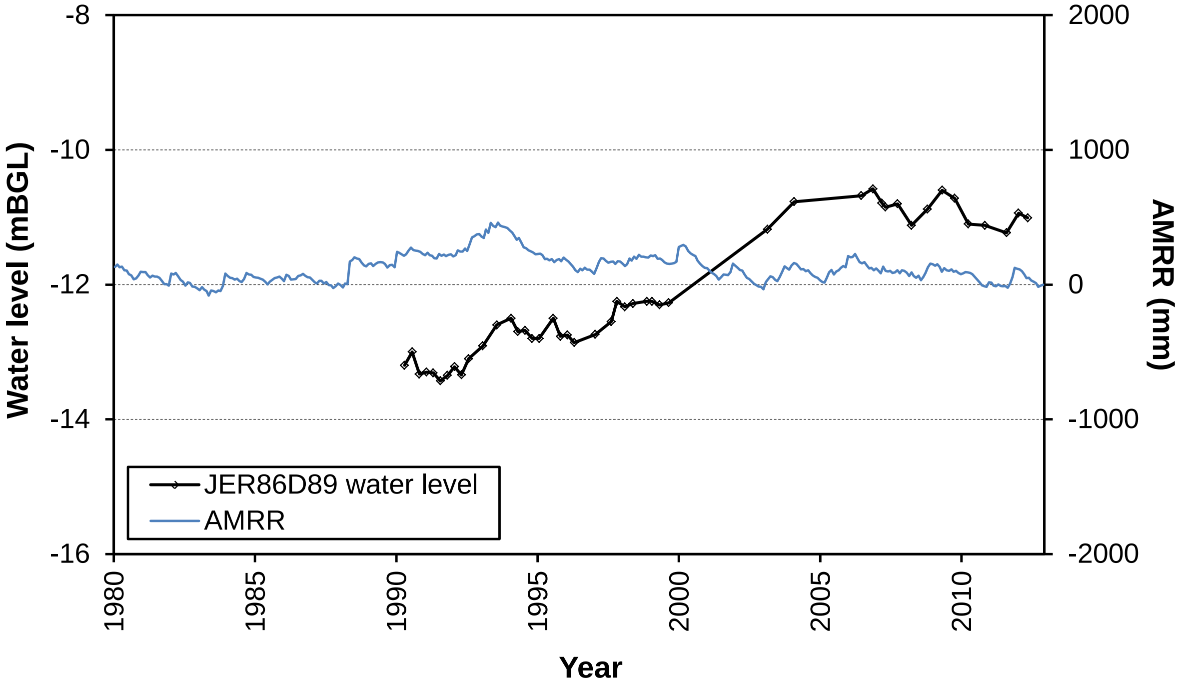


Figure 3.60 Hydrograph for bore JER86D89, within the Jerramungup Hydrozone and accumulated monthly residual rainfall for Jerramungup

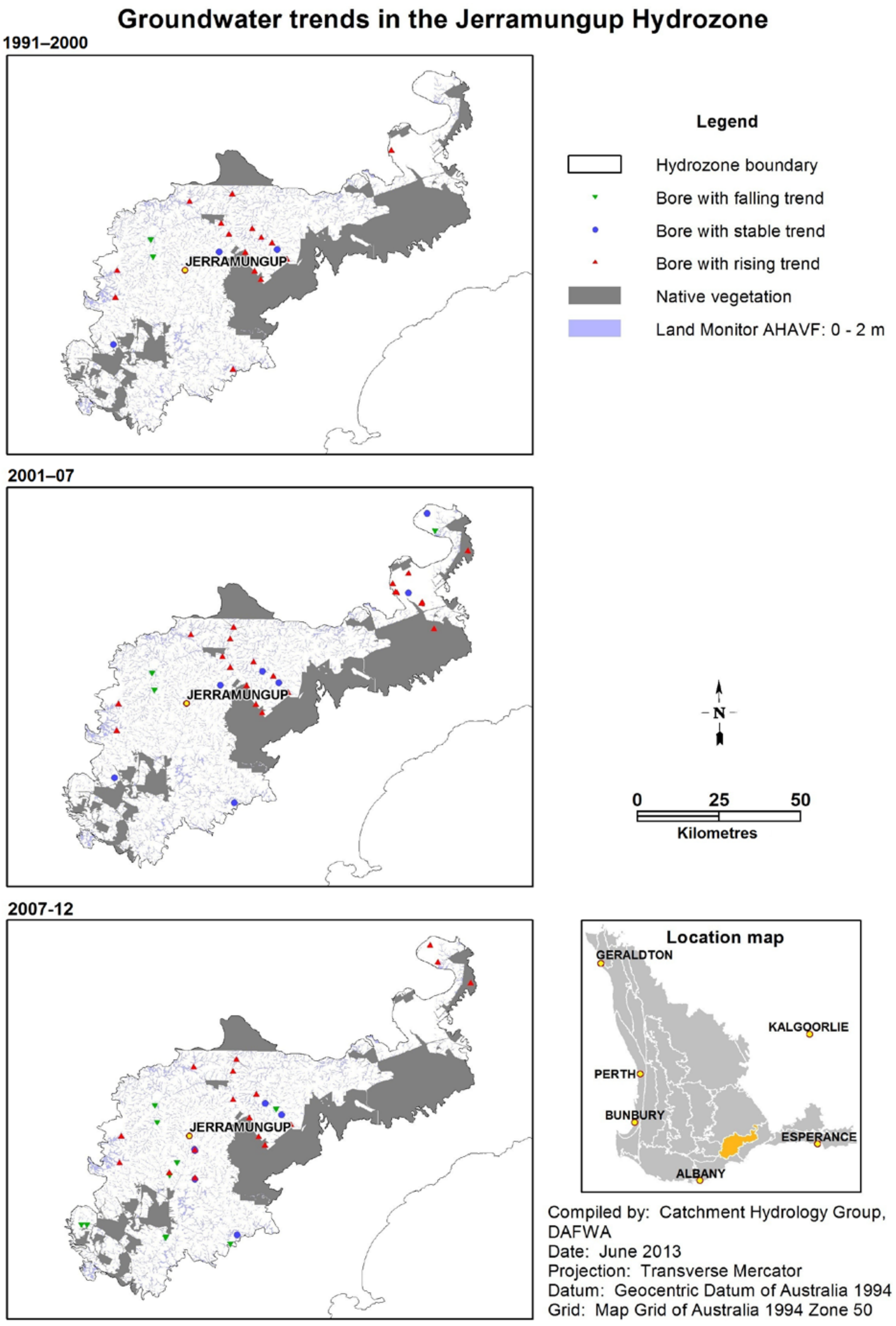


Figure 3.61 Groundwater trends for each of the periods analysed for the Jerramungup Hydrozone

3.1.24 Ravensthorpe Hydrozone

The Ravensthorpe Hydrozone consists of rolling to undulating low hills formed on the fractured and weathered basement rocks. A thin cover of Cainozoic surficial deposits form a level to gently undulating sandplain containing swamps and plains with headwaters of the dissected tributaries. Soils are predominantly Alkaline sandy duplex soils with some sands and gravels. Incised rivers, such as the Fitzgerald, West and Phillips, drain the hydrozone and flow south through the Fitzgerald River National Park to discharge into coastal estuaries. The hydrozone covers an area of 494 000ha, of which about 20% (100 000ha) is allocated for agriculture and the rest is predominantly native vegetation in nature reserves (Figure 3.64).

The Ravensthorpe Hydrozone straddles the boundary between the Yilgarn Craton and Albany-Fraser Orogen. It is underlain by Precambrian basement rocks. In the north-east, the basement rocks comprise Archaean gneiss, granites and enclosed greenstone belts of the Yilgarn Craton. These basement rocks are extensively intruded by Proterozoic mafic dykes of the Widgiemooltha Dyke Swarm and have numerous north-east and east-trending faults (Thom et al. 1977). In the south and south-west, the basement rocks comprise Proterozoic granite and gneiss of the Albany-Fraser Orogen, which also includes sedimentary rocks of the Mount Barren Group (Thom et al. 1977).

The hydrogeology is complex with compartmentalised and generally disconnected aquifers (Simons 2006). Consequently, groundwater flow systems are predominantly local in scale, with saline water qualities. The aquifers either discharge into low-lying areas, such as waterways and wetlands, or form hillside seeps. The hillside seeps are located either on geological features, such as basement highs that impede groundwater flow, or in areas where perched aquifers formed on silcrete benches discharge groundwater originating from upslope areas of deep sands.

Groundwater monitoring and historical trends

Groundwater monitoring in the western part of the hydrozone started in 1990 with a monitoring bore (JER94D89) installed near Bremer Bay. Groundwater monitoring in the eastern part has been intermittent and began in 2001 with monitoring sites established in the Moolyall–Woodenup Creeks and Phillips River catchments. Ravensthorpe Land Conservation District Committee (RLCDC) project staff and landholders initially monitored these bores but by 2003, the monitoring had ceased. In 2004 and 2009, DAFWA undertook bore censuses to update groundwater levels and qualities (EC and pH) and to determine their status and potential to be incorporated into DAFWA's groundwater monitoring network.

Rainfall in the Ravensthorpe Hydrozone was up to 40% above average during 1975-90. Rainfall has remained above average since, apart from the far south-west of the hydrozone, which received below average rainfall during 2001–07.

All bores with shallow (<2m BGL) groundwater levels that fluctuated seasonally with rainfall between 2001 and 2002, still had shallow groundwater levels in 2004. Three of the four bores with deeper (>10m BGL) groundwater levels had groundwater trends rising at a mean rate of 0.28m/y (Table 3.22, Figure 3.62, Figure 3.63).

Current situation

During 2007–12, all monitored bores with groundwater levels deeper than 10m had rising trends of 0.05 to 0.20m/y, with an mean rate of 0.14m/y. Bores with shallow groundwater levels in 2001–07, still had stable trends during 2008–12. The bore distribution is shown in Figure 3.64.

Table 3.22 Summary of groundwater trends for the Ravensthorpe Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	0	0		0	0		0	0	
Stable	0	0		4	57		3	43	
Rising	1	100	0.18	3	43	0.28	4	57	0.14

* Mean rate of change in groundwater level.

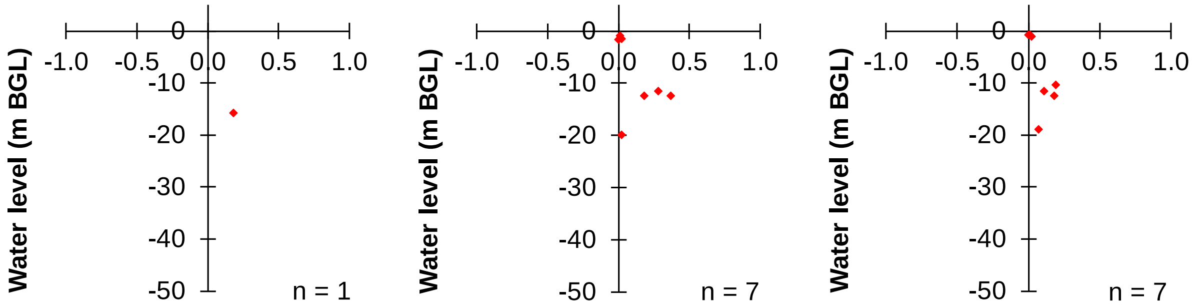


Figure 3.62 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Ravensthorpe Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

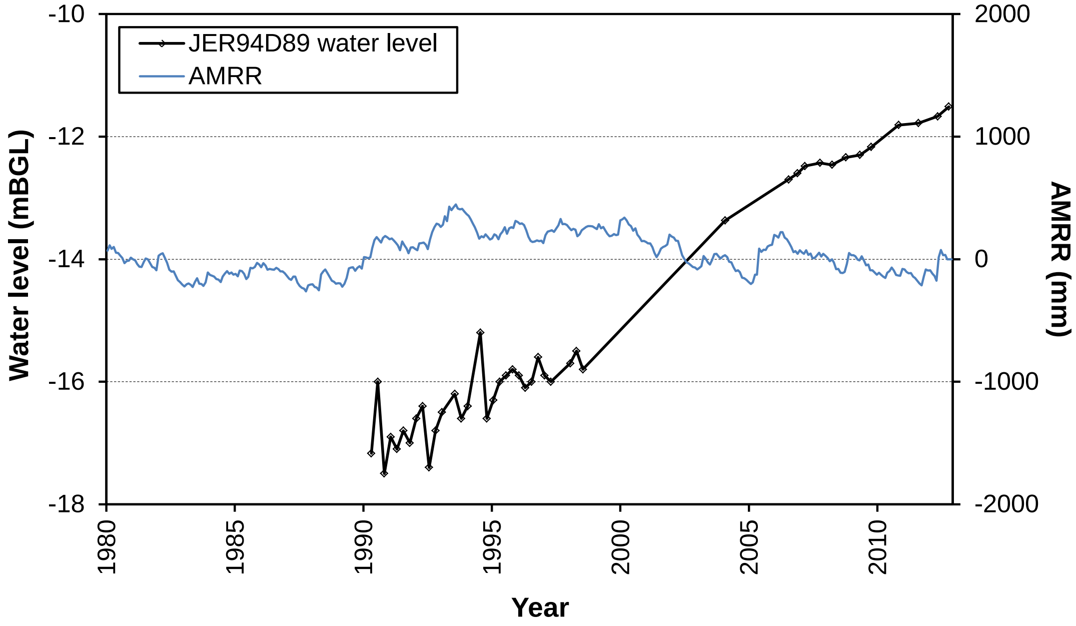


Figure 3.63 Groundwater hydrograph for bore JER94D89, within the Ravensthorpe Hydrozone and accumulated monthly residual rainfall for Bremer Bay

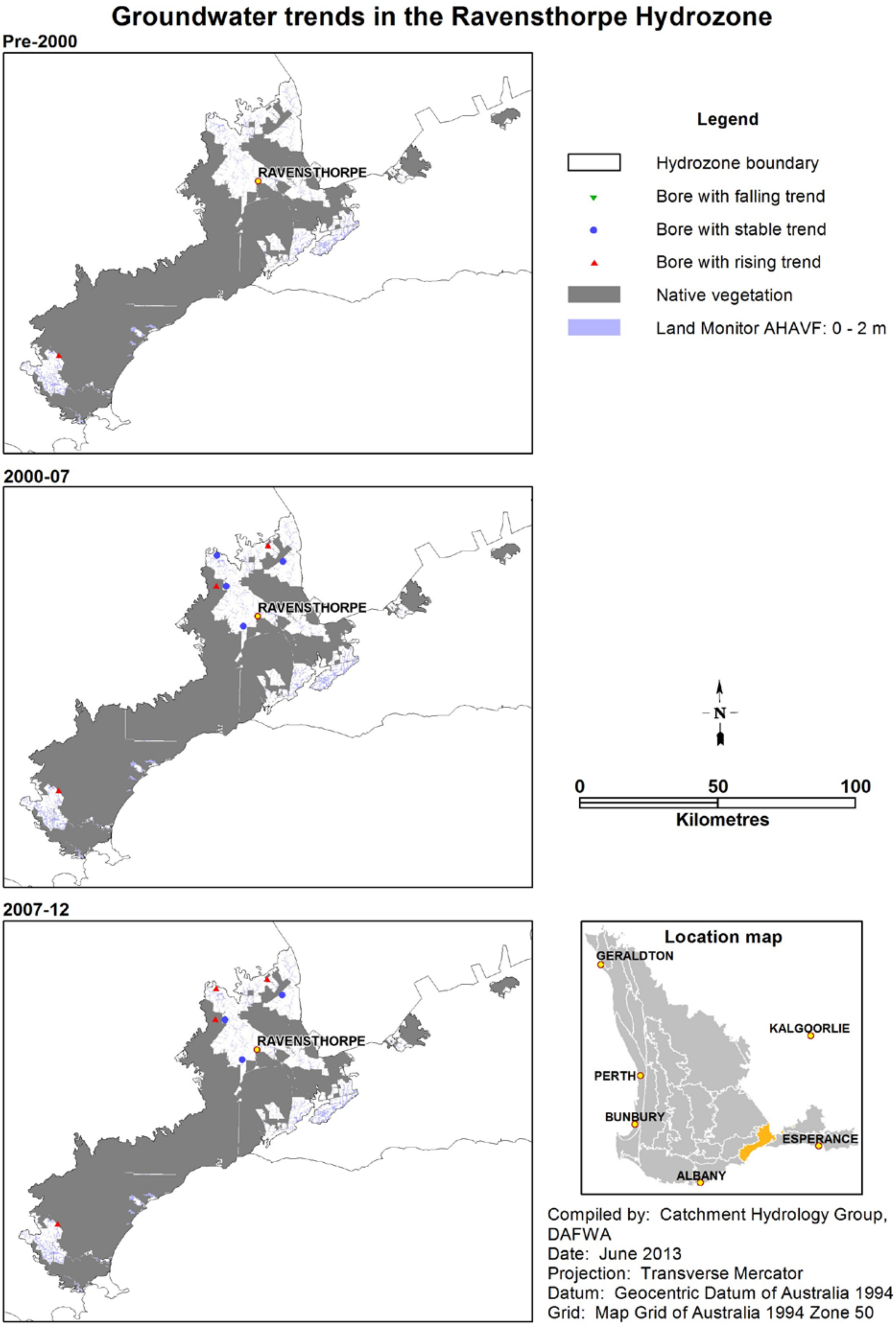


Figure 3.64 Groundwater trends for each of the periods analysed for the Ravensthorpe Hydrozone

3.1.25 Esperance Sandplain Hydrozone

The Esperance Sandplain Hydrozone is characterised by a level to undulating sandplain that forms a 40–60km wide strip along the coast. It consists of a sheet of fine sand of varying thickness (0.1–5m) overlying gravel or clay. It covers an area of 955 000ha and is 65% cleared for agriculture.

West of Esperance, the landscape is externally drained through a number of well-defined rivers (Oldfield, Munglinup, Young, Lort, and Dalyup) and creeks (Coobidge, Kateup, Coramup and Bandy) that flow into mostly saline wetlands and estuaries on the coast. East of Esperance, the landscape is internally drained. Poorly defined drainage systems lead into freshwater, paperbark (*Melaleuca* spp.) and yate (*Eucalyptus occidentalis*) swamps.

Proterozoic crystalline rocks of the Albany-Fraser Orogen form the basement rock that underlies the area (Morgan & Peers 1973). Tertiary sediments from the Plantagenet Group of the western Eucla Basin unconformably overlie the weathered basement. Quaternary surficial sediments form a veneer overlying both the weathered basement and Tertiary sediments.

The undulating basement topography influences the hydrogeology of the area (Berliat 1952). In areas west of Esperance that have well-defined external drainage, groundwater flow systems are local to intermediate, separated by basement highs and ridges. To the east, where drainage is internal and poorly defined, the groundwater flow systems are intermediate to regional. Groundwater flow within the weathered basement and overlying sediments is typically sluggish, principally because they have low groundwater gradients (<1%). Areas with deep sands can have perched, localised aquifers that overlie intermediate or regional, brackish to saline, groundwater flow systems.

Groundwater salinity increases away from the coast (Short 1997) with fresher water generally occurring south of Gibson (Berliat 1952) in the higher rainfall coastal areas (Johnson & Baddock 1998). Perched aquifers in the deep sandsheets also contain fresh (<90mS/m) to marginal (90–270mS/m) water. The groundwater salinity in the monitoring bores ranges from fresh (40mS/m) to saline (9800mS/m), with over 60% of bores having an EC of 2000mS/m or less.

Groundwater monitoring and historical trends

Groundwater monitoring in this hydrozone began in the late 1970s on the Esperance Downs Research Station where secondary salinity developed a few years after clearing began in the mid-1950s (McFarlane & Ryder 1990). However, more widespread groundwater monitoring did not start until the early 1990s, when a number of hydrological studies began.

Rainfall across most of the hydrozone has been above average since the mid-1970s. In the central west, rainfall was as much as 50% above average during 1975–90. The area immediately around Esperance and the eastern third of the hydrozone are the exceptions, receiving below average rainfall during at least part of that period.

Before 2007, rising groundwater trends were observed throughout most of the hydrozone (Figure 3.66, Figure 3.67). Between 2001 and 2007, 67% of bores had rising trends, 25% had stable trends and less than 10% had falling trends. Generally, shallow (<2m BGL) groundwater levels fluctuated seasonally, while bores with deeper (>5m BGL) groundwater had levels that were rising at rates from 0.03 to 1.0m/y, with a mean rate of 0.15m/y (Table 3.23, Figure 3.65).

Current situation

Since 2007, about half of the bores have rising groundwater trends of about 0.14m/y (Table 3.23). Bores with a rising trend are either located west of Esperance in the Munglinup area, or north and east of Condingup in the east of the hydrozone (Figure 3.67). About half of the bores with a rising trend also have groundwater levels that are more than 10m BGL (Figure 3.65).

Since 2007, the number of bores that have falling groundwater trends has doubled and most of these sites are located to the north-east of Esperance (Figure 3.67). This area coincides with the portion of the Esperance Sandplain Hydrozone that has had below average growing season rainfall since 2009.

Generally, bores with a stable or falling groundwater trend have either shallow (<3m BGL), seasonally fluctuating groundwater levels, or slightly deeper (3–5m BGL) groundwater levels that rise or fall over a number of concurrent years in response to above or below average annual rainfall or episodic rainfall events. However, the whole of record (1993–2012) trend in most of these bores is a rising trend because the aquifers are still filling and have not yet reached a new hydrological equilibrium (Figure 3.66).

The Esperance Sandplain Hydrozone is characterised by level to undulating sandplain where the Land Monitor algorithm computed a 0–2m AHAVF area that over-predicted the area judged to have a salinity hazard. The 0–1m AHAVF area is considered a more accurate reflection of the salinity hazard area and is shown in Figure 3.67.

Table 3.23 Summary of groundwater trends for the Esperance Sandplain Hydrozone

	1991–2000			2001–07			2007–12		
Trend	**No. of bores**	**Pro-portion (%)**	**Mean RoC* (m/y)**	**No. of bores**	**Pro-portion (%)**	**Mean RoC* (m/y)**	**No. of bores**	**Pro-portion (%)**	**Mean RoC* (m/y)**
Falling	5	4	-0.09	8	8	-0.08	16	20	-0.14
Stable	25	20		24	25		22	27	
Rising	95	76	0.13	65	67	0.15	43	53	0.14

* Mean rate of change in groundwater level.

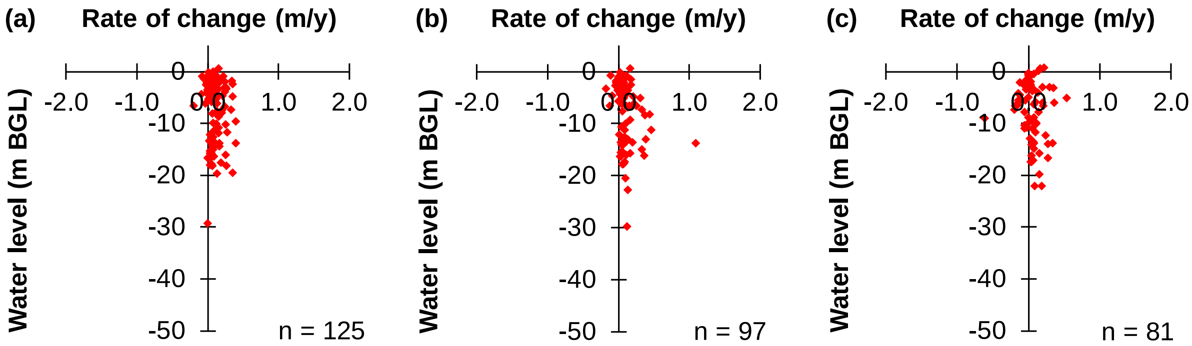


Figure 3.65 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Esperance Sandplain Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

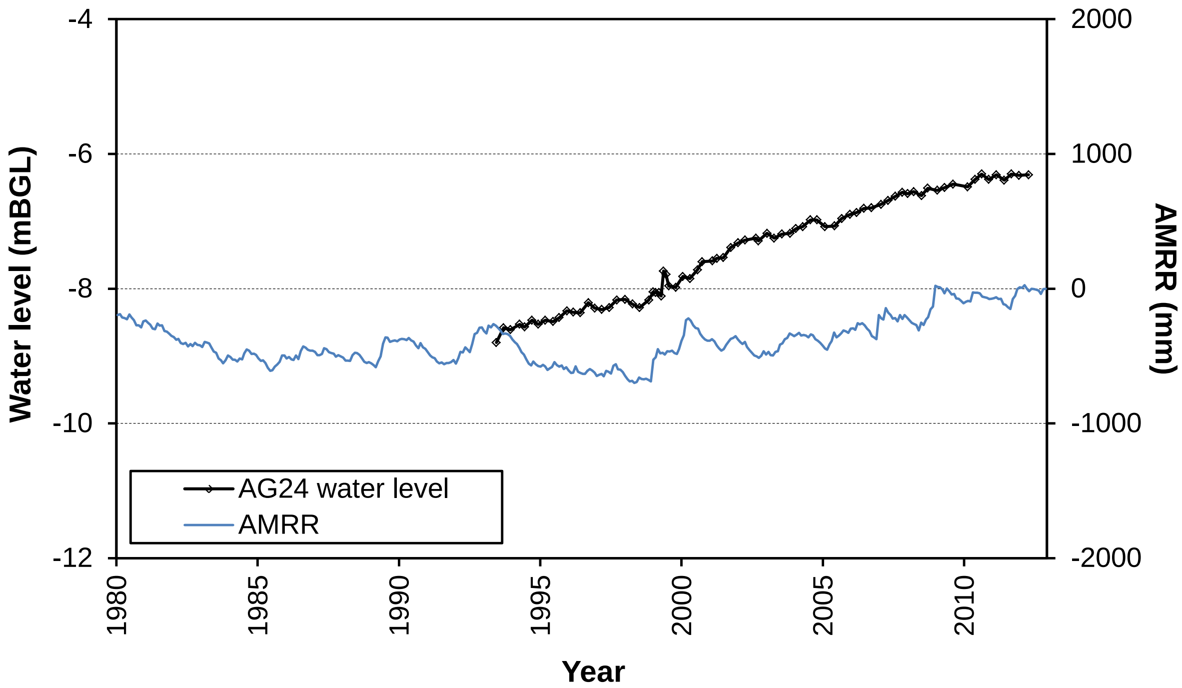


Figure 3.66 Hydrograph for bore AG24, within the Esperance Sandplain Hydrozone and accumulated monthly residual rainfall for Esperance Downs Research Station

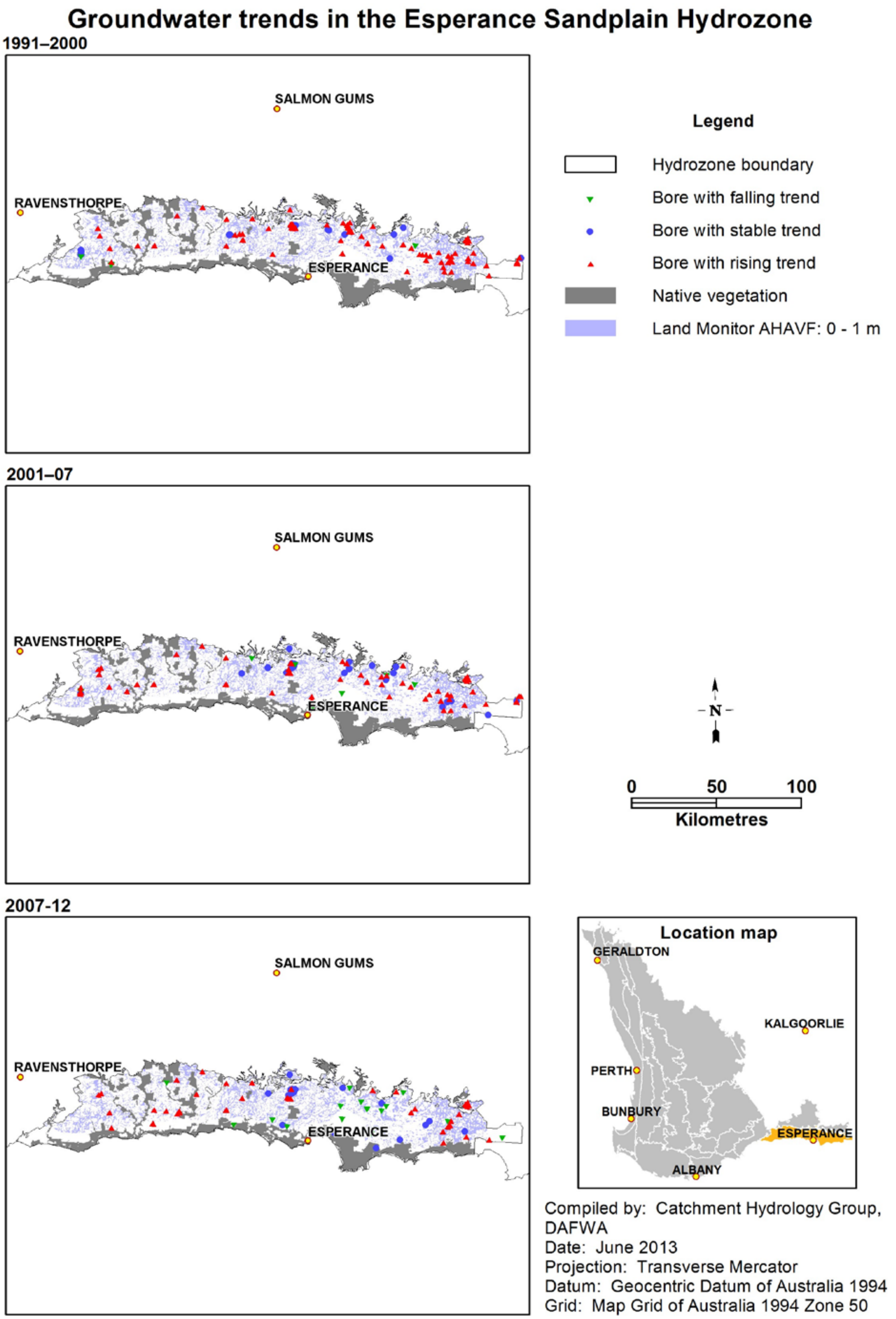


Figure 3.67 Groundwater trends for each of the periods analysed for the Esperance Sandplain Hydrozone

3.1.26 Salmon Gums Mallee Hydrozone

The Salmon Gums Mallee Hydrozone is characterised by its mallee vegetation and contains a level to gently undulating plain with numerous salt lakes. The dominant soils are Alkaline grey sandy duplexes that overlie predominantly marine sediments. The western portion of the hydrozone is drained by southward-flowing rivers and the eastern and northern areas drain internally into salt lakes. The hydrozone covers an area of 867 000ha, 79% of which is cleared.

Precambrian basement rocks underlie the entire hydrozone. In the west, they consist of Archaean granites of the Yilgarn Craton, and in the east, they consist of Proterozoic granite, gneiss and migmatite from the Albany-Fraser Orogen (Morgan & Peers 1973). Tertiary sediments from the Plantagenet Group of the western Eucla Basin form a discontinuous cover over the basement rocks (Johnson & Baddock 1998). The sediments consist of two distinct formations: the Werillup Formation and the Pallinup Siltstone. The Werillup Formation consists of dark coloured siltstone, sandstone, claystone and lignite, and is restricted to the depressions and valleys (palaeochannels) in the basement rocks (Cockbain 1968). The Pallinup Siltstone is more widespread and consists of siltstone and spongolite overlying either the Werillup Formation sediments or weathered basement rock (Morgan & Peers 1973). Quaternary sediments occur as a thin (<10m) surface veneer overlying the Tertiary sediments.

The hydrogeology of the hydrozone can be divided into four distinct units that correspond with the major soil-landscape systems (Simons 2006). The hydrogeology of the eastern parts (Halbert System) is dominated by palaeodrainages and the multitude of salt lakes that can be characterised as windows to the shallow watertable. In the north-western part (Salmon Gums System), the basement is more elevated and groundwater occurs in isolated pockets (Morgan and Peers 1973). In the south-western (Scaddan System) and far north-eastern (Buraminya System) parts, the basement is generally deeper, the sediments are thicker and the watertable forms a continuous surface, except in a few areas of elevated basement.

The groundwater flow systems are predominantly intermediate, except in the north-west (Salmon Gums System) which has localised groundwater flow systems occurring in areas of undulating basement. Groundwaters are saline to extremely saline throughout the hydrozone.

Groundwater monitoring and historical trends

Groundwater monitoring began in the late 1980s when DAFWA requested the Geological Survey of Western Australia establish monitoring bores in two areas north of Cascade and Condingup (Mt Beaumont) that were proposed for land release. Since their installation, groundwater levels have been rising at a rate of 0.20m/y in the Cascade bore and 0.10m/y in the Mt Howick bore, north of Condingup.

Widespread groundwater monitoring started in the early 1990s, when a number of hydrological studies began, the last being in 2008 when gaps in the monitoring network, particularly north of Salmon Gums, were filled (DAFWA 2008).

The Salmon Gums Mallee Hydrozone received above average rainfall across most of the hydrozone for most of the period since 1975: during 1991–2000, rainfall was up to 50% above average in the far north; during 2008–12, rainfall in the east was marginally below average.

Prior to 2007, rising groundwater trends were observed throughout most of the zone, except in the north of Salmon Gums where groundwater levels were stable (Figure 3.68, Figure 3.69, Figure 3.70). In 2001–07, 68% of bores had rising trends, 29% had stable trends, and only 3% had falling trends (Table 3.24). The watertable in this hydrozone is typically between 5 and 10m BGL; however, groundwater levels less than 2m BGL are common in areas with shallow basement, at the headwaters of the rivers and creeks, and in low-lying areas adjacent to the salt lakes (Figure 3.68, Figure 3.69).

Current situation

Groundwater levels in the north of this hydrozone still have stable groundwater trends (Figure 3.70). Groundwater levels in the east are either stable or have been falling, on average by 0.09m/y, because of below average annual rainfall and the absence of episodic events which historically (1989, 1992, 1999, 2000, 2005 and 2007) have caused increases in groundwater levels. Conversely, groundwater trends in the west are rising, predominantly because this area had up to a 20% increase in annual rainfall in 2008–12, compared to the long-term mean.

The Salmon Gums Mallee Hydrozone is characterised by a gently undulating plain where the Land Monitor algorithm computed a 0–2m AHAVF area that over-predicted the area judged to have a salinity hazard. The 0–0.5m AHAVF area is considered a more accurate reflection of the salinity hazard area and is shown in Figure 3.70.

Table 3.24 Summary of groundwater trends for the Salmon Gums Mallee Hydrozone

Trend	1991–2000			2001–07			2007–12		
	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)	No. of bores	Proportion (%)	Mean RoC* (m/y)
Falling	1	2	-0.08	2	3	-0.07	10	17	-0.08
Stable	17	37		17	27		19	31	
Rising	28	61	0.12	44	70	0.12	31	52	0.12

* Mean rate of change in groundwater level.

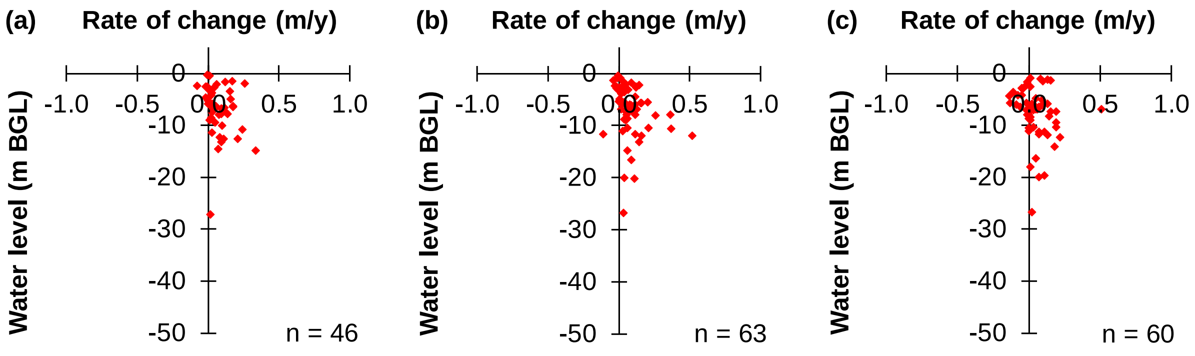


Figure 3.68 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for the Salmon Gums Mallee Hydrozone: (a) 1991–2000, (b) 2001–07, (c) 2007–12

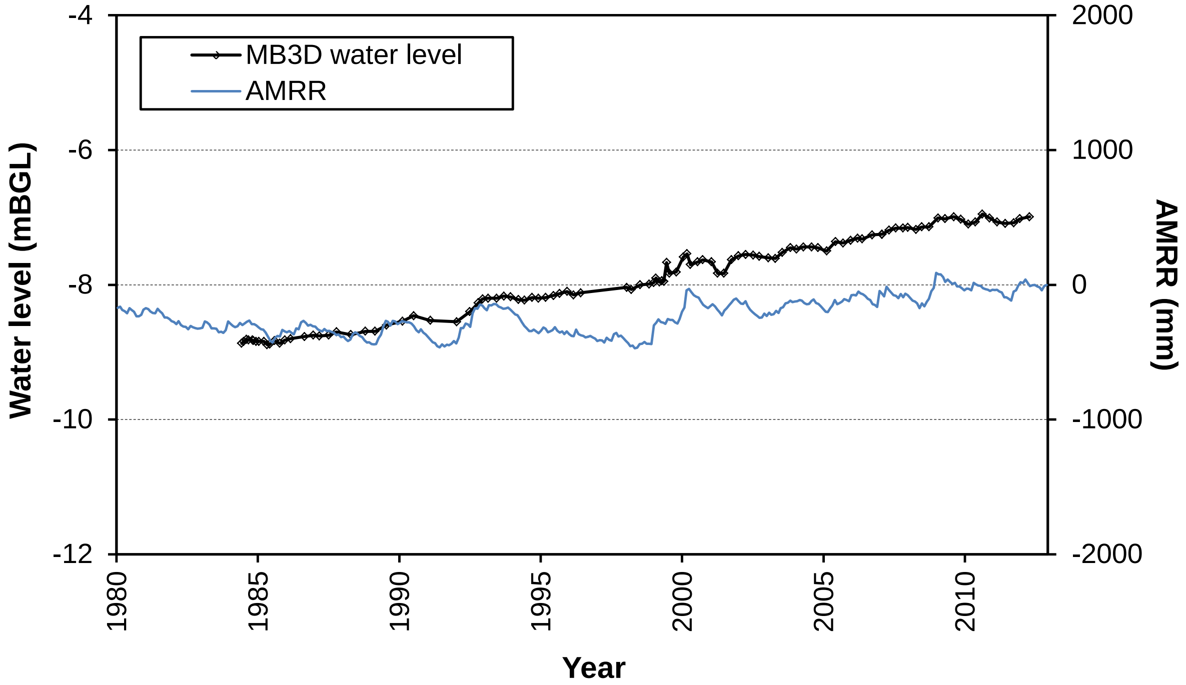


Figure 3.69 Hydrograph for bore MB3D, within the Salmon Gums Mallee Hydrozone and accumulated monthly residual rainfall for Scaddan

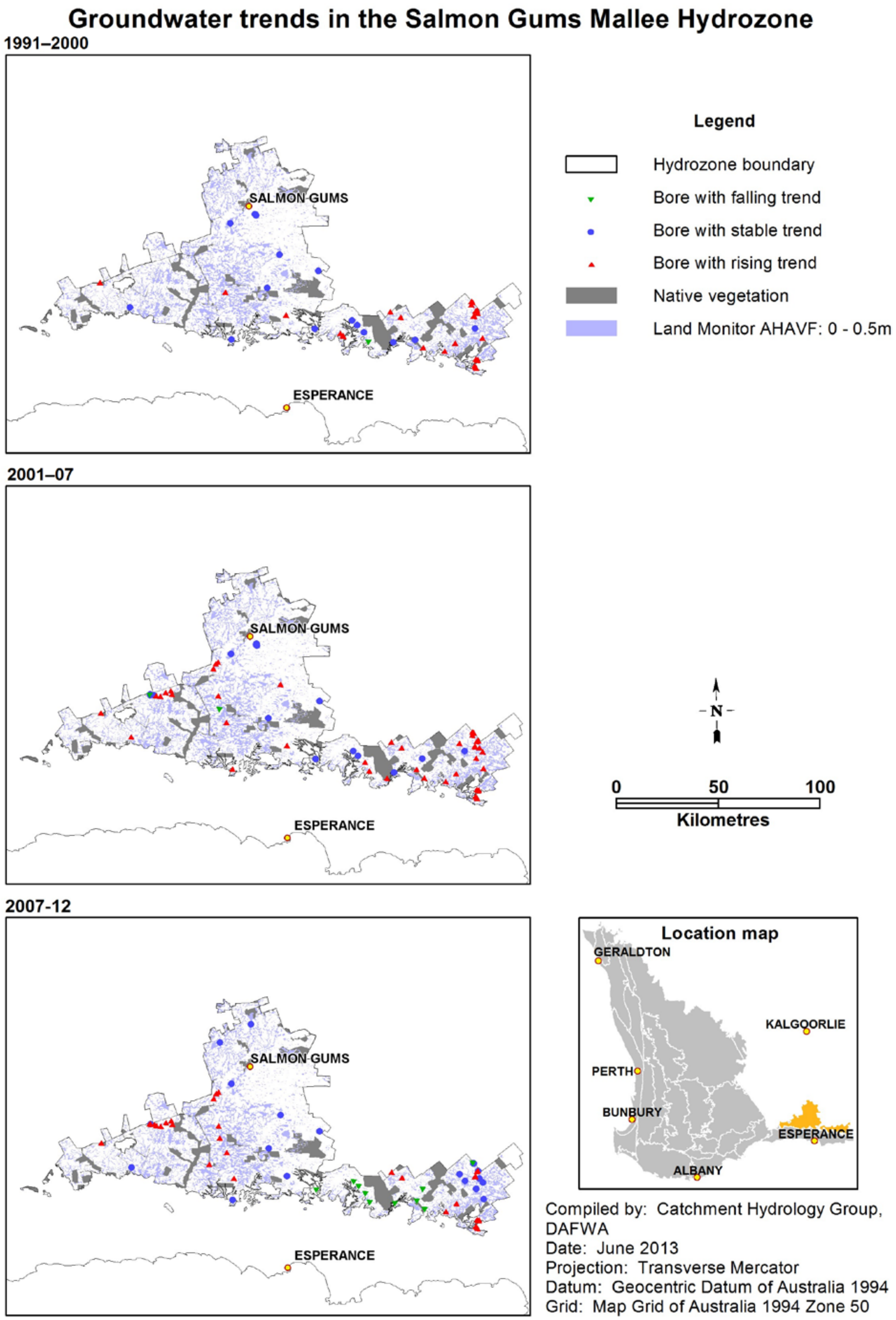


Figure 3.70 Groundwater trends for each of the periods analysed for the Salmon Gums Mallee Hydrozone

3.2 Groundwater trends summary

A summary of groundwater trends by hydrozone for the 2001–07 and 2007–12 analysis periods is presented in Appendix A. The dominant groundwater trends (Table 3.25) are displayed spatially in Figure 3.71.

During 2007–12, groundwater levels were mostly rising (i.e. at least 50% of bores had rising trends) in the Northampton Block, East Binnu Sandplain and Dandaragan Plateau hydrozones in the Northern Agricultural Region; the South-western Zone of Ancient Drainage Hydrozone in the Central Agricultural Region; and the Jerramungup, Ravensthorpe, Esperance Sandplain and Salmon Gums Mallee hydrozones in the Southern Agricultural Region. Only in the northern hydrozones did the proportion of bores with rising trends significantly exceed 50%: Northampton Block, 91%; East Binnu, 84%; Dandaragan Plateau, 77%.

In the Stirling Range Hydrozone (Southern Agricultural Region), 50% of bores had rising groundwater trends during 2007–12 and the other half had falling trends.

Groundwater levels were mostly falling in the Southern Cross and Western Darling Range hydrozones and mostly stable in the Eastern Darling Range, Coastal Plain and the Northern and Southern Zones of Rejuvenated Drainage hydrozones.

Trends in groundwater levels were variable (i.e. bores within the hydrozone have roughly equal numbers of falling, rising and stable groundwater trends) in the remaining hydrozones.

DAFWA does not monitor groundwater levels in the Donnybrook Sunklands, Leeuwin or Scott Coastal Plain hydrozones and therefore groundwater trends were not assessed.

Table 3.25 Definition of groundwater trend categories

Category	Summary	Description
F	Mostly falling	Groundwater levels in most (>50%) of the bores in the hydrozone were falling. Remaining bores could have stable or rising trends.
S	Mostly stable	Groundwater levels in most (>50%) of the bores in the hydrozone were stable. Remaining bores could have falling or rising trends.
R	Mostly rising	Groundwater levels in most (>50%) of the bores in the hydrozone were rising. Remaining bores could have stable or falling trends.
V	Variable trend	There were roughly equal numbers of bores with falling, stable and rising groundwater trends.

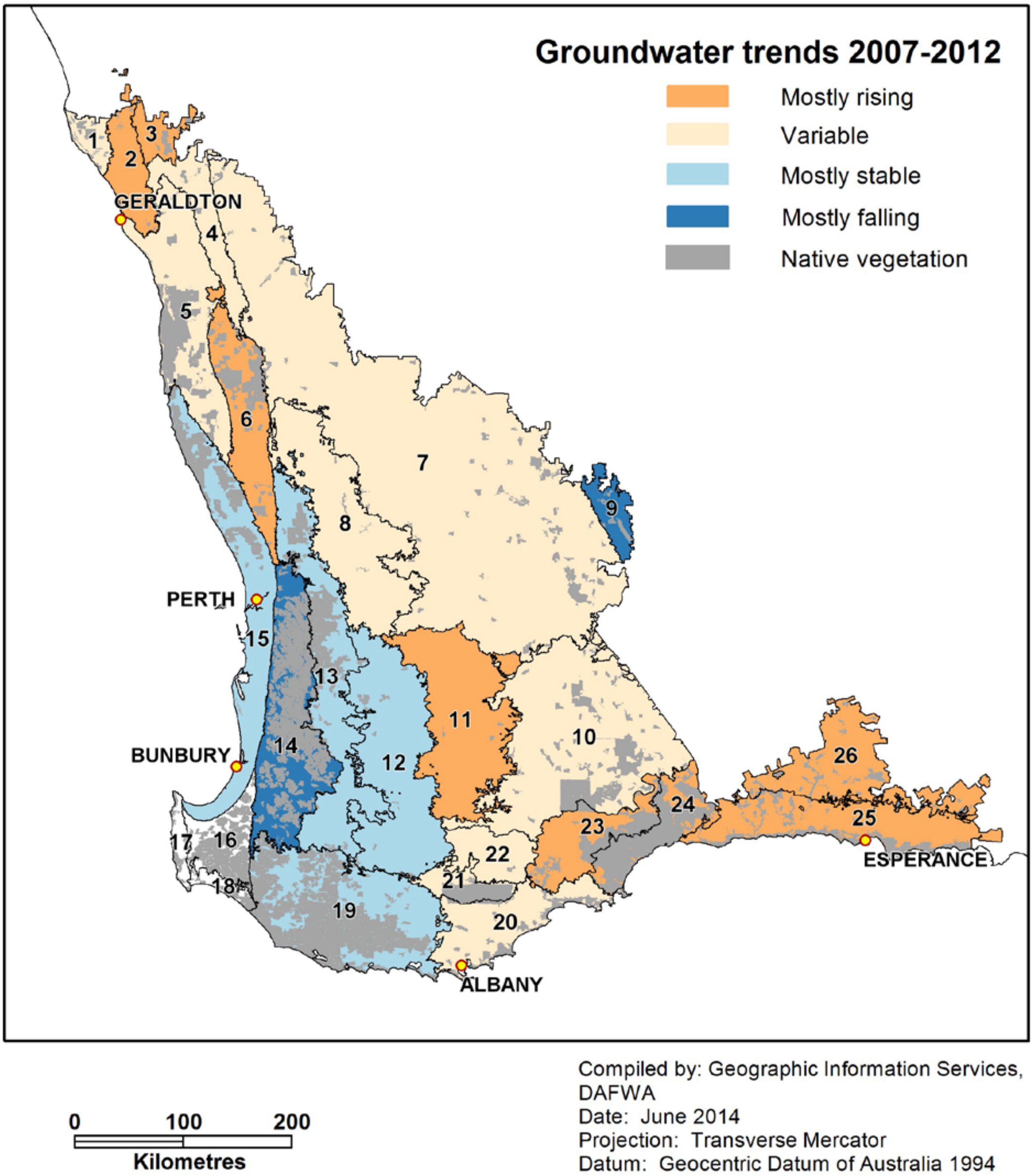


Figure 3.71 Dominant groundwater level trends (2007–12) within hydrozones in the south-west agricultural region

3.3 Regional changes in groundwater trends since 2007

Groundwater level data from 1532 bores within 23 hydrozones covering the south-west of WA were analysed to categorise the dominant trends in groundwater levels. This study analysed 117 more bores than the analysis undertaken by George et al. (2008). The total number of bores used to compare groundwater trends in each of the analysis periods in this study and the proportions in each trend class are shown in Figure 3.72. The numbers of bores reported for the 1991–2000 and 2001–07 periods includes results reported by George et al. (2008).

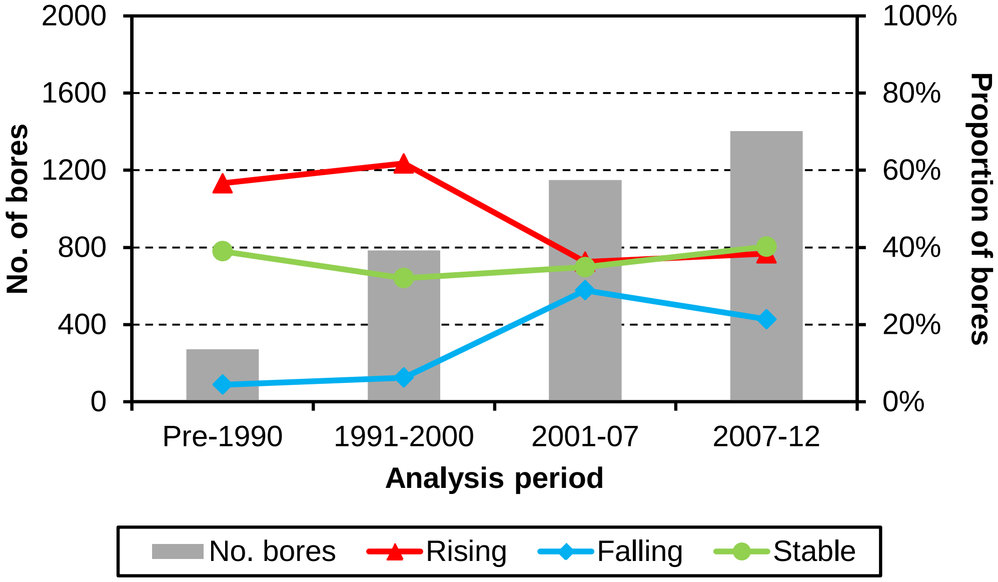


Figure 3.72 Change in groundwater trends between analysis periods for the south-west agricultural region

Between 1991–2000 and 2001–07, the proportion of bores exhibiting rising groundwater trends fell from 60% to 36%. During 2001–07, there were approximately equal proportions with falling, stable and rising trends. The proportion of bores exhibiting stable trends has been consistent since 1975–90, varying between 32 and 40%. The proportion of bores with falling trends peaked in 2001–07 at 29% and has since fallen to 21% (Figure 3.72).

The number of bores with rising groundwater trends decreased after 2000, with the effect most pronounced in the Northern Agricultural Region. In the north, 63% of bores had rising trends in 1991–2000 but in 2001–07, only 18% of bores had rising trends. During 2007–12, the proportion of bores with rising trends increased to 40% in the north in response to a marked increase in rainfall, despite totals still being below the long-term mean (Figure 2.8). In the rest of the region, the proportion of bores with rising trends fell relative to 2001–07 in all but two hydrozones. This fall is directly related to below average rainfall in the Central and South-west agricultural regions in 2008–12 (Figure 2.8).

The hydrozones in which rising groundwater trends dominated in 2007–12 are the Northampton Block, East Binnu Sandplain, Dandaragan Plateau, South-western Zone of Ancient Drainage, Jerramungup Plain, Ravensthorpe, Salmon Gums Mallee and Esperance Sandplain. The soils in three of these hydrozones, East Binnu Sandplain, Dandaragan Plateau and Esperance Sandplain, are predominantly sands, suggesting that the high infiltration and low water-holding capacity of these soils contributes to groundwater recharge being higher than aquifer discharge capacity. Furthermore, of all the hydrozones in which rising groundwater trends dominated in 2007–12, three in the Northern Agricultural Region, Northampton (91% rising), East Binnu Sandplain (84% rising) and Dandaragan Plateau (77% rising), were the highest (Table A1). In these hydrozones, rainfall was below average during both the 2001–07 and 2007–12 analysis periods.

High mean rates of groundwater rise appear to be strongly associated with the occurrence of high mean annual rainfall (MAR) and the dominance of permeable soil types. The hydrozones with the highest rates of groundwater rise in 2007–12 are:

- Arrowsmith (0.25m/y, MAR = 550–325mm/y)
- Eastern Darling Range (0.27m/y, MAR = 700–425mm/y)
- Western Darling Range (0.26m/y, MAR = 900–600mm/y)
- Southern Zone of Rejuvenated Drainage (0.23m/y, MAR = 550–375mm/y).

Deep sands or loamy soils are prominent over large portions of all these hydrozones. However, not all hydrozones with high MAR and permeable soils have high mean rates of groundwater rise. In the Warren–Denmark Southland Hydrozone, where the MAR ranges from 1225 to 475mm/y, the mean rate of groundwater rise in 2007–12 was 0.12m/y (Table 3.16).

In some hydrozones, there were a significant differences between the mean ($\bar{x}$) and median (M) rates of groundwater rise in 2007–12. These were the Arrowsmith ($\bar{x}$ = 0.25m/y, M = 0.14m/y), Eastern Darling Range ($\bar{x}$ = 0.27m/y, M = 0.15m/y), Esperance Sandplain ($\bar{x}$ = 0.14m/y, M = 0.10m/y), and Southern Zone of Rejuvenated Drainage ($\bar{x}$ = 0.23m/y, M = 0.11m/y) hydrozones. The differences between the mean and median rates of groundwater rise indicate that the mean rates are affected by outliers; that is, these hydrozones had the greatest range in rates of groundwater rise. All these hydrozones receive relatively high MAR, up to at least 550mm/y, in some portion of the hydrozone (Figure 2.3).

Based on the high proportion of bores, widespread falling groundwater trends represent a risk to groundwater resource use and allocation in the Arrowsmith Hydrozone because the hydrozone hosts important regional groundwater resources that are used to supply many towns and an extensive reticulated supply system (Table 3.5).

In the Northern Zone of Ancient Drainage Hydrozone, rising groundwater trends appear to be influenced by episodic rainfall events, particularly in the lower rainfall, eastern parts of the hydrozone that experienced above average rainfall in 2001–07 and 2007–12.

In 2001–07, there was an increase in rainfall, compared to the long-term mean, across most of the Esperance Sandplain and all of the Salmon Gums Mallee hydrozones mean. In 2007–12, only the north-western portion of the Esperance Sandplain and western half of the Salmon Gums Mallee hydrozones had increased rainfall (Figure 2.8). In the Esperance Sandplain, the proportion of bores with rising trends decreased from 67% in 2001–07 to 53% in 2007–12 (Table A1). In the Salmon Gums Mallee, the proportion of bores with rising trends decreased from 70%

in 2001–07 to 52% in 2007–12. These changes result from both a reduction in the spatial extent of above average rainfall and a reduction in unseasonal (summer/autumn) episodic rainfall in the eastern parts of these hydrozones.

Conversely, the area of the Albany Sandplain Hydrozone receiving above average rainfall increased from 2001–07 to 2008–12 (Figure 2.8), but the proportion of bores with rising groundwater trends fell from 66% (2001–07) to 47% (2007–12). This unexpected result may be an artefact of where the bores are located within the hydrozone. It may reflect long delays in groundwater response as recharge slowly infiltrates through the Pallinup Siltstone. Alternatively, the hydrozone may be approaching hydrological equilibrium.

3.4 Factors affecting groundwater trends at the hydrozone scale

3.4.1 Native vegetation

The South-eastern Zone of Ancient Drainage Hydrozone is the only hydrozone for which a significant number of bores have been monitored in nature reserves and other uncleared areas. Sufficient groundwater data for about 55 bores in the Lake Bryde and Lake Magenta Nature Reserves and other uncleared areas were available to determine groundwater trends for the 2001–07 and 2007–12 analysis periods (Table 3.26, Figure 3.73).

Bores with rising groundwater trends in 2007–12 are mostly located on hillslopes and uplands but some are located within areas of Land Monitor AHAVF salinity hazard. Bores with stable trends are all located within or very close to areas of Land Monitor AHAVF, though only two are within obviously salt-affected areas. About 80% of bores with falling trends are sited within areas of Land Monitor AHAVF.

The comparison between groundwater trends for bores in cleared and uncleared areas is confounded by the fact that 90% of the bores in uncleared areas fall within the Land Monitor AHAVF, whereas only 60% of bores in cleared areas fall within areas of AHAVF. This challenge can be overcome to some degree by comparing the change in the proportion of bores with different trends between the 2001–07 and 2007–12 analysis periods.

In 2001–07, the annual rainfall was within ±10% of the long-term mean across most of the hydrozone (Figure 2.8). A small area in the south-east of the hydrozone received 10–20% above average rainfall and the far south-west received 10–20% below average rainfall. In 2007–12, a larger proportion of the hydrozone received below average rainfall and only a very small area received above average rainfall.

With the reduction in rainfall from 2001–07 to 2007–12, the proportion of bores with rising groundwater trends in uncleared areas fell from 50 to 18% and the proportion of bores with falling trends increased from 17 to 45% (Table 3.26). In cleared areas, the most significant change in groundwater trends between 2001–07 and 2007–12 was the proportion of bores with stable trends increasing from 24 to 44%. This difference implies that the reduction in rainfall from 2001–07 to 2007–12 had a greater impact on groundwater trends in uncleared areas than in cleared areas, which is to be expected because deep-rooted, perennial vegetation allows less recharge than shallow-rooted agricultural species.

Table 3.26 Summary of groundwater trends for bores in cleared and uncleared areas of the South-eastern Zone of Ancient Drainage Hydrozone

Trend	Cleared areas				Uncleared areas			
	2001–07		2007–12		2001–07		2007–12	
	No. of bores	Pro-portion (%)	No. of bores	Pro-portion (%)	No. of bores	Pro-portion (%)	No. of bores	Pro-portion (%)
Falling	16	26	11	16	9	17	25	46
Stable	15	24	31	44	18	33	20	36
Rising	31	50	28	40	27	50	10	18

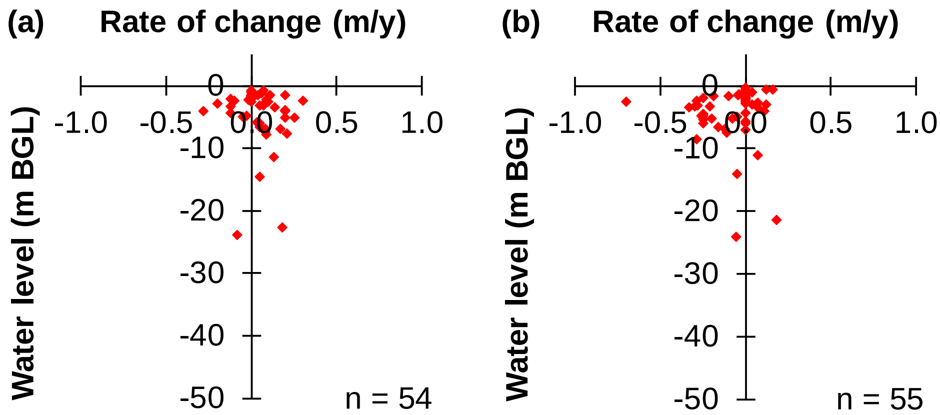


Figure 3.73 Rate of change of depth to groundwater plotted against groundwater depth at the last observation date in each of the periods analysed for bores in uncleared areas of the South-eastern Zone of Ancient Drainage Hydrozone: (a) 2001–07, (b) 2007–12

3.4.2 Land use impacts

The Denmark River Catchment occupies about 4% (67 100ha) of the Warren–Denmark Southland Hydrozone. Revegetation and monitoring carried out under the Denmark River Integrated Catchment Management project was recently reviewed by Ward et al. (2011). The results show that the river salinity has fallen from more than 700mg/L (130mS/m) in 1980–95 to 540mg/L in 2009 and that it is projected to fall to potable levels within the next decade. One of the main reasons for this fall is that 66% (5200ha) of the previously cleared catchment area (7800ha) has been revegetated with blue gum plantations, resulting in groundwater recessions and reduced salt export to the surface drainage.

In 2008, private plantations were estimated to occupy about 176 000ha (45%) of the 389 000ha of cleared land in the Warren–Denmark Southland Hydrozone (Department of Environment and Conservation 2008). Furthermore, comparing the mapped plantations and recent aerial photography reveals that the plantation area has since expanded. Given the reduction in stream salinity achieved through revegetating with plantations, as demonstrated in the Denmark River Catchment, any significant reduction in the area of plantations would be expected to increase groundwater levels and the area with shallow watertables in the Warren–Denmark Southland Hydrozone.

Within the Frankland, Kent and Hay River catchments, the area of blue gum plantations has peaked. However, it is likely that many blue gum plantations in these catchments will revert to broadacre agriculture over the next five to 10 years because blue gums have become less profitable because of a combination of low prices for woodchips and lower than expected yields in some areas (G Ellis [Ellis and Hewett Plantation Forestry] pers. comm., May 2013).

3.4.3 Hydrological equilibrium

Despite half of the bores within the Stirling Range Hydrozone having rising groundwater trends in 2007–12 (Table 3.18), it is likely that the hydrozone is approaching a post-clearing hydrological equilibrium.

One-quarter of the hydrozone falls within the Land Monitor 0–2.0m AHAVF and another 50% is the Stirling Range National Park (Figure 3.55), within which areas of AHAVF could not be determined. The quarter of the hydrozone mapped as AHAVF therefore represents half the cleared portion of the hydrozone.

The hydrozone has stagnant aquifers and a mean depth to groundwater of 2.2m (Figure 3.53). The hydrograph for bore NS11D86 (Figure 3.54) demonstrates a strong relationship between groundwater level and AMRR since the mid-1990s. This response is typical for the hydrozone and indicates that evaporation and rainfall now play a more significant part in the aquifer response than clearing for agriculture.

This hydrozone already contains large areas of severely salt-affected agricultural land and over the past 15 years, many hectares of salt-affected land have been planted to saltland pastures. The Stirling Range Hydrozone is probably the closest to a post-clearing hydrological equilibrium of all the hydrozones and it will be characterised by large areas of shallow watertables that respond slowly to seasonal rainfall because of the low topographic and hydraulic gradients of the area, limited groundwater discharge via fractures in the basement, and stagnant groundwater systems.

4 Salinity risk assessment

4.1 Determining salinity risk from groundwater trends

An assessment of salinity risk for each hydrozone was based on the likelihood of the salt-affected area expanding **beyond its current extent** and the consequence of that expansion. The primary asset at risk in this assessment is agricultural land, though other asset classes were considered. A salinity risk matrix (Table 4.1) was adapted from Spies and Woodgate (2005, p. 29) to meet the requirements of DAFWA's reporting of the condition and trend of the natural resources in the south-west agricultural region (DAFWA 2013). The consequence categories in Table 4.1 are based on economic, environmental and social impacts and are defined in Table 4.2, which is also adapted from Spies and Woodgate (2005, p. 28). Groundwater trend and salinity timing categories used in compiling the salinity risk assessments are summarised in Table 3.25 and Table 4.3, respectively.

The likelihood assessment for each hydrozone is based on the proportion of bores with rising groundwater trends, the mean rates of change in groundwater levels and where those bores are located in relation to areas of Land Monitor AHAVF and currently salt-affected land. For example, a high proportion of bores with rising groundwater trends, located within Land Monitor AHAVF that is not currently salt-affected, indicates that the salt-affected area is either 'likely' or 'almost certain' to expand. In some hydrozones, the Land Monitor AHAVF did not provide a reliable estimate of the area of salinity hazard and so the assessment relied solely on local knowledge. The dataset used to map currently salt-affected land was the 1996–98 Land Monitor AOCLP (areas of consistently low productivity), which is now more than 16 years out of date. It was augmented by local knowledge where possible.

The consequence assessment is based on the extent of salinity hazard and currently salt-affected land within each hydrozone, the productive value of the agricultural land within the hazard area and potential off-site impacts on rural infrastructure, water resources and biodiversity. However, unlike the SIF process reported by George et al. (2005) and Sparks et al. (2006), these impacts were estimated subjectively without detailed geographical information system (GIS) based assessment of the rural infrastructure affected or quantitative economic analyses.

Table 4.1 Salinity risk matrix (adapted from Spies & Woodgate 2005). Colours in the table cells relate to the legend of the salinity risk map in Figure 4.1

Likelihood	Insignificant consequence	Minor consequence	Moderate consequence	Major consequence	Catastrophic consequence
Almost certain	Moderate	Moderate	High	High	Very High
Likely	Low	Moderate	Moderate	High	High
Possible	Low	Low	Moderate	Moderate	High
Unlikely	Very Low	Low	Low	Moderate	Moderate
Rare	Very Low	Very Low	Low	Low	Moderate

Table 4.2 Definition of consequence categories used in the salinity risk matrix (Table 4.1)

Consequence	Socioeconomic loss	Environmental impact	Economic cost
Insignificant	low	negligible	not measurable
Minor	small	little	low
Moderate	higher	some	high
Major	major	extensive	major
Catastrophic	enormous	widespread and severe	massive

Table 4.3 Categories of timing of expected salinity expansion (source: George et al. (2005))

Category	Time (years)
Short term	<20
Medium term	20–75
Long term	>75

4.2 Salinity risk for hydrozones

Table 4.4 details the salinity risk assessment and rationale for each hydrozone. The salinity risk assessments are mapped in Figure 4.1. Figure 4.2 shows the expected time required to reach a new hydrological equilibrium for each hydrozone.

Table 4.4 Salinity risk assessments for hydrozones (numbers in parentheses relate to hydrozone numbers in Figure 4.1)

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Kalbarri Sandplain (1)	<1	n.a.	variable	possible	moderate	medium term	moderate	Variable groundwater trends occur throughout this hydrozone. Rising trends occur where groundwater is less than 15m deep. Falling and stable trends occur where groundwater is deep (>15m). The salinity risk is moderate because of the extensive areas of flat plains.
Northampton Block (2)	n.a.	17	mostly rising	unlikely	minor	short term	low	Prior to 2000, this hydrozone appeared to be in hydrological equilibrium. In 2001–07, drought led to significant groundwater decline. Since 2007, groundwater levels have been rising but generally remain below pre-2000 levels. Salinity is unlikely to expand, the consequences will be minor because the incised topography would restrict the extent.
East Binnu Sandplain (3)	<1	n.a.	mostly rising	almost certain	moderate	medium term	high	Rising groundwater trends dominate. Consistent rising groundwater and extensive areas where groundwater is less than 10m deep make it almost certain that salinity will continue to spread with moderate consequences, as there are extensive low-lying areas with salinity hazard.

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Irwin Terrace (4)	4	10	variable	possible	moderate	medium term	moderate	Variable groundwater trends occur in this hydrozone. Rising trends are associated with areas of sandplain soils. Falling trends are associated with heavier soil types and stable trends occur where groundwater is shallow (<2m). The salinity risk is moderate because further salinity could develop with moderate consequences because of the high quality of the agricultural land at risk.
Arrowsmith (5)	1	n.a.	variable	possible	minor	medium term	low	Rising groundwater trends occur in central and eastern parts of this hydrozone, where localised perched watertables overlie the regional groundwater system. West of Eneabba, where extensive areas of salinity have developed, mostly falling trends now prevail. Salinity will possibly expand with minor consequence because the areas at risk are largely Pale deep sands of low productivity.
Dandaragan Plateau (6)	1	n.a.	mostly rising	likely	major	long term	high	Rising groundwater trends occur throughout this hydrozone. At many sites, groundwater is less than 10m deep. Salinity is actively spreading in an area south-west of Moora (west Gillingarra). It is likely

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
								that salinity will continue to spread with major consequences in the long term. As well as high quality agricultural land, there are high value biodiversity assets at risk.
Northern Zone of Ancient Drainage (7)	6	30	variable	likely	moderate	medium term	moderate	The salinity risk is moderate because rising groundwater trends continue to occur throughout the hydrozone. Therefore, it is likely that salinity will continue to spread. The development and spread of salinity is slow and incremental with moderate consequences.
Northern Zone of Rejuvenated Drainage (8)	6	24	variable	likely	moderate	medium term	moderate	Most bores in low landscape positions have shallow, stable groundwater levels, fluctuating seasonally in response to rainfall and evaporation. In mid to upper landscape positions, most bores with groundwater deeper than 5m have falling or stable trends. Salinity is likely to expand with moderate consequences, although timing of salinity may be extended because of changes in rainfall pattern.

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Southern Cross (9)	2	26	mostly falling	possible	insignificant	long term	low	Groundwater levels within the greenstone ranges are deep (10–40m). Falling groundwater trends occur in all lower-catchment bores, with variable trends in mid and upper catchment bores. Depending on climate, the time to a post-clearing hydrological equilibrium may be decades away. The salinity risk is low because salinity could possibly occur in the future but with insignificant consequences.
South-eastern Zone of Ancient Drainage (10)	6	26	variable	likely	moderate	medium term	moderate	A large number of bores in the hydrozone now have stable groundwater trends. However, rising trends still occur in upland areas and in areas of AHAVF hazard in the south of the hydrozone where rainfall is highest. Salinity is likely to continue to develop, albeit at a reduced rate because of reduced rainfall. Future salinity development is expected to have moderate consequences in the north-east of the hydrozone, and major consequences in the south.

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
South-western Zone of Ancient Drainage (11)	9	22	mostly rising	likely	major	medium term	high	Most of the currently salt-affected land within the hydrozone occurs on broad valley floors. Salinity is likely to expand as groundwater levels continue to rise, particularly in areas of AHAVF hazard, with major consequences because there are large areas within the AHAVF hazard not currently salt-affected. The expected timing for future salinity development is 50 years or more.
Southern Zone of Rejuvenated Drainage (12)	8	24	mostly stable	likely	moderate	short term	moderate	Most monitored catchments appear to be approaching hydrological equilibrium but there are some bores adjacent to AHAVF hazard areas with rates of rise in excess of 0.5m/y. The area affected by salinity is likely to expand with moderate consequences, as fresh to brackish groundwater resources may be impacted. The salinity risk is likely to be realised within the next 20 years.

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Eastern Darling Range (13)	2	3	mostly stable	almost certain	minor	medium term	moderate	Stable groundwater trends have persisted for the last decade and much of the hydrozone appears to be approaching a new hydrological equilibrium. However, 20% of bores in areas of AHAVF hazard have rising trends, despite below average rainfall. Many bores in or adjacent to areas already salt-affected have artesian heads, indicating high rates of groundwater discharge. It is almost certain that the area affected by salinity will expand, though the area, in addition to that already salt-affected, will not be great and hence the consequence is minor.
Western Darling Range (14)	1	4	mostly falling	possible	minor	short term	low	Groundwater monitoring is minimal in this hydrozone because it is mostly forested or reafforested. As a result, groundwater levels are falling at most sites. The salinity risk is low and the likelihood of salinity expanding is possible at a local scale with minor consequences.
Coastal Plain (15)	n.a.	n.a.	mostly stable	possible	minor	short term	low	Groundwater is shallow across much of the hydrozone but trends are stable, responding to seasonal rainfall. Salinisation is limited to

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
								poorly drained areas on the Pinjarra Plain and coastal swales. The salinity risk is low because the likelihood of salinity expanding is possible with minor consequences, unless high intensity land uses move into poorly drained areas. Salinity is likely to increase in surficial aquifers. Widespread soil salinity occurs in the south-west irrigation areas but is not included in this analysis.
Donnybrook Sunkland (16)	n.a.	n.a.	Not monitored	unlikely	insignificant		very low	There are few areas of salinity within this hydrozone, hence DAFWA does not monitor groundwater levels. The salinity risk is very low because salinity is unlikely to expand and consequences are insignificant. Brackish groundwater seepages into water supplies occur and may be locally or seasonally relevant.
Leeuwin (17)	n.a.	n.a.	Not monitored	unlikely	insignificant		very low	There are few areas of salinity within this hydrozone, hence DAFWA does not monitor groundwater levels. The salinity risk is very low because salinity is unlikely to expand and consequences are insignificant.

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Scott Coastal Plain (18)	n.a.	n.a.	Not monitored	unlikely	insignificant		very low	Most of the hydrozone is forested or recently cleared and there are no large areas of salinity, hence DAFWA does not monitor groundwater levels. The hydrozone is probably close to hydrological equilibrium; therefore, the salinity risk is very low because salinity is unlikely to expand with insignificant consequences. Salinity associated with private irrigation systems has not been assessed.
Warren–Denmark Southland (19)	1	11	mostly stable	possible	moderate	short term	moderate	Aquifers in this hydrozone respond to changes in recharge and depending on land use and/or seasonal rainfall, groundwater can rise or fall accordingly. With many blue gum plantations being converted back to annual farming systems, the salinity risk has increased and in some instances, groundwater levels have already begun to rise. The salinity risk is moderate because it is possible salinity will expand (because of changes in land use) with moderate consequences, particularly if streamflow salinity increases and river water quality falls below potable limits.

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Albany Sandplain (20)	1	24	variable	possible	minor	medium term	low	The low percentage of salt-affected land can be attributed to deep groundwater levels. The western part of the hydrozone has isolated areas of salinity, many of which have been stabilised by plantations. The eastern sandplain has steadily rising groundwater trends and salinity may expand in the medium to long term. The salinity risk is low because there is potential that salinity will expand but with minor consequences.
Stirling Range (21)	5	24	variable	unlikely	minor	short term	low	This hydrozone contains large areas of severely salt-affected agricultural land and over the past 15 years, many hectares have been converted to saltland pastures. It appears that the hydrozone is approaching a new hydrological equilibrium. Salinity is unlikely to expand with minor consequences because large areas already have groundwater levels at or near the surface.

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Pallinup (22)	3	22	variable	likely	minor	medium term	moderate	The salinity risk is moderate because it is likely to expand but with minor consequences, and will mostly be confined to drainage lines and hillside seeps. The effect on agricultural productivity depends on where the salinity develops in the landscape; it will be minor in areas with incised topography and moderate in areas of broad, flat valley floors with extensive areas of AHAVF hazard.
Jerramungup Plain (23)	3	15	mostly rising	likely	moderate	short term	moderate	The risk of salinity developing is moderate, because deep groundwater levels are rising, causing existing discharge areas to expand, with moderate consequences. Though the potential downstream effect on drainage lines that flow through the Fitzgerald Biosphere Reserve has not been determined, reduced water quality is likely to lead to ecosystem change and loss of riparian vegetation.
Ravensthorpe (24)	<1	12	mostly rising	likely	minor	medium term	moderate	Most of the salinity in this hydrozone is caused by hillside seeps or groundwater baseflow to river channels and some tributaries. The salinity risk is

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
								moderate because salinity is likely to expand with minor consequence because the area of agricultural land at risk is small. However, the off-site impacts could be considerable in relation to biodiversity, especially along the waterways in the Fitzgerald Biosphere Reserve.
Esperance Sandplain (25)	1	21	mostly rising	almost certain	moderate	medium term	high	The area of salt-affected land has expanded since the 1990s because of a series of above average seasonal and annual rainfall years. Groundwater levels are either shallow and fluctuate seasonally, or where they are deep (>5m), they are rising. The salinity risk is high as salinity will almost certainly expand with moderate consequences because of the extensive (>20%) areas of agricultural land within the AHAVF hazard area and the off-site impacts on the biodiversity assets, particularly those within the coastal reserves (e.g. Ramsar wetlands and national parks).

Hydrozone	% of zone within AOCLP in 1996–98	% of zone within AHAVF	Dominant groundwater trend	Likelihood of future salinity	Consequence of future salinity	Timing of future salinity	Salinity risk	Comments
Salmon Gums Mallee (26)	4	22	mostly rising	possible	moderate	long term	moderate	Groundwater levels in the north of this hydrozone have stable trends. In the east, groundwater levels have been falling over the last few years because of below average rainfall. In western areas, where rainfall has not declined, groundwater levels continue to rise. The salinity risk is moderate; expansion of salinity is possible with moderate consequences.

n.a. not applicable because the Land Monitor mapping product did not produce a reliable estimate for this hydrozone.

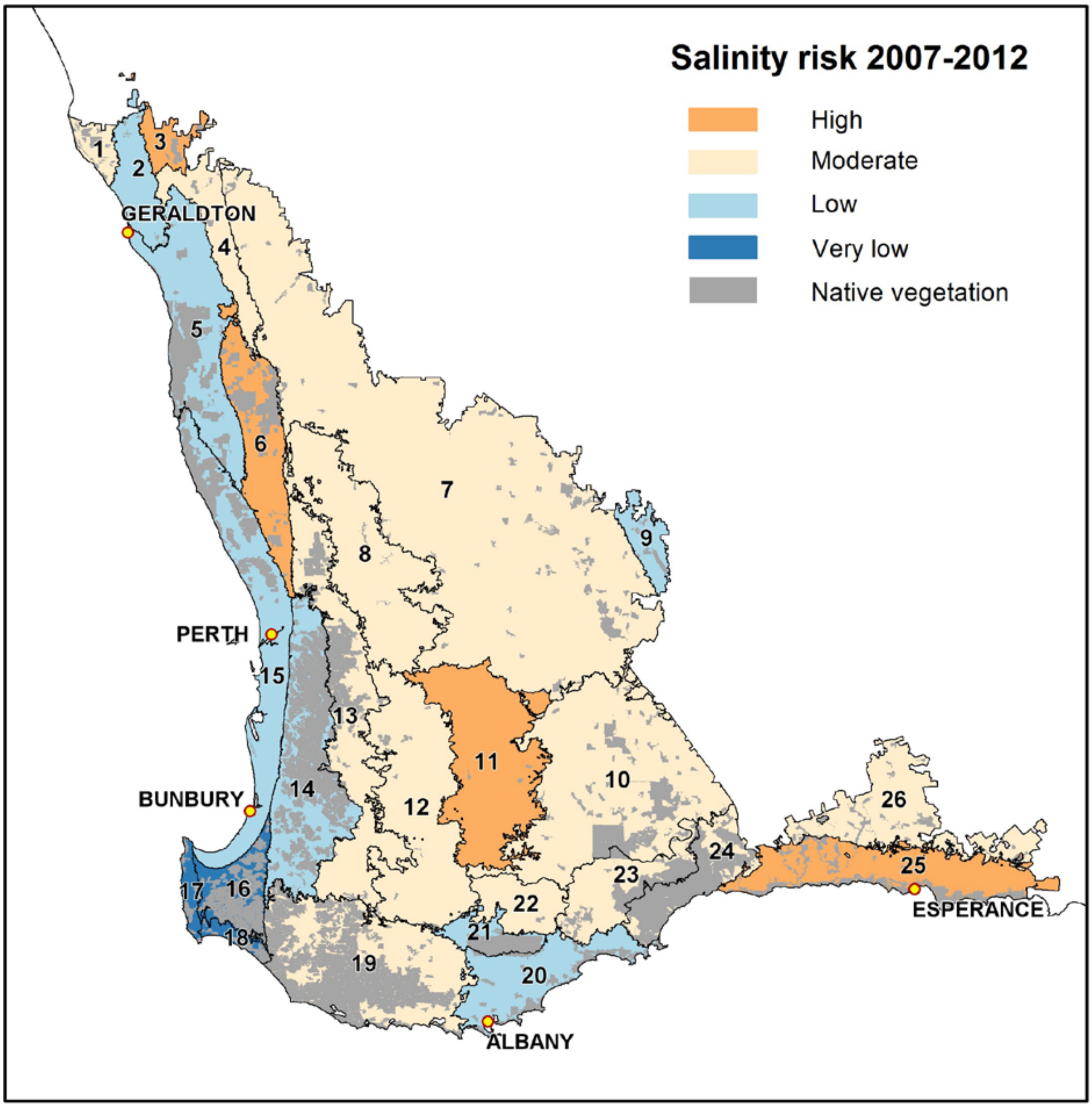


Figure 4.1 Salinity risk assessment for hydrozones in the south-west agricultural region, 2007–12

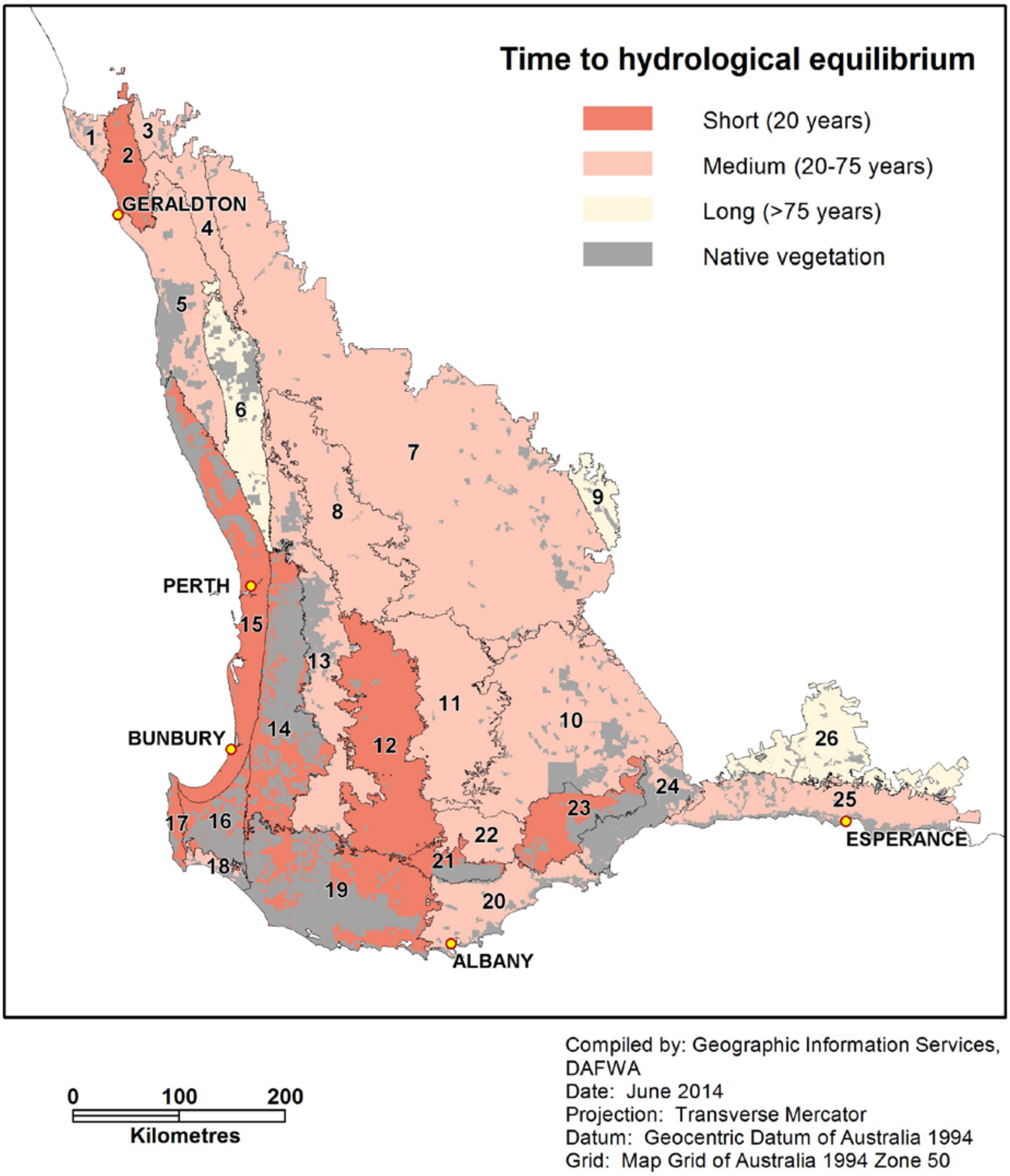


Figure 4.2 Expected time until the hydrozones in the south-west agricultural region reach hydrological equilibrium

4.3 Salinity risk summary

The estimated area of Land Monitor AHAVF salinity hazard that falls within each salinity risk class was calculated by assigning the salinity risk class for each hydrozone (Table 4.4) to the entire area of AHAVF that falls within each hydrozone. This calculation assumes that the salinity risk is uniform throughout each hydrozone, which is not the case, but it allows a first order estimate of the AHAVF area within each risk class. The calculation also ignores the proportion of AHAVF that is already salt-affected in each hydrozone. Table 4.5 shows that the vast majority of the AHAVF hazard area falls within the moderate salinity risk class.

Table 4.5 Area of Land Monitor AHAVF salinity hazard classified by the salinity risk of the hydrozone in which it falls

Salinity risk	AHAVF (ha)	AHAVF (%)
High	478 000	10
Moderate	3 733 000	82
Low	372 000	8
Very low	n.a.	n.a.

n.a. Hydrozones with this hazard area were not assessed by AHAVF

Four of the 26 hydrozones — East Binnu Sandplain, Dandaragan Plateau, South-western Zone of Ancient Drainage and Esperance Sandplain — which represent 10% of the mapped AHAVF in the region, have a high risk of dryland salinity (Table 4.4).

In the East Binnu Sandplain and Esperance Sandplain hydrozones, the high salinity risk assessments resulted from an 'almost certain' likelihood of salinity expanding. This likelihood is based on predominantly rising groundwater trends and the mean rates of rise, even though the rates were moderate (0.12 and 0.14m/y, respectively), as well as the current depth to groundwater and knowledge of the hydrogeology. Both hydrozones are characterised by sedimentary aquifers, subdued topographic relief and internal surface drainage over at least a portion of the zone. Furthermore, in the East Binnu Sandplain Hydrozone, westward groundwater flow is blocked by the crystalline basement of the Northampton Block, limiting groundwater discharge and increasing the likelihood of shallow watertables.

In the South-western Zone of Ancient Drainage and Dandaragan Plateau hydrozones, the high salinity risk assessment was based on the 'likely' spread of salinity and the 'major' consequences of the expected increase in the salt-affected area. In the South-western Zone of Ancient Drainage, the 'likely' expansion of salinity is based on predominantly rising groundwater trends, particularly within areas of AHAVF hazard (60% of bores in AHAVF have rising trends), and a moderate mean rate of groundwater rise (0.17m/y) in 2007–12 when rainfall was significantly below average across most of the hydrozone. The 'major' consequences arise from the large area of AHAVF within the hydrozone that is not currently salt-affected and the high proportion of bores within the AHAVF with rising trends.

In the Dandaragan Plateau Hydrozone, which is internally drained, the Land Monitor AHAVF could not be derived (section 3.1.6) and therefore the salinity risk is assessed without the benefit of a mapped area of salinity hazard. The 'high' salinity risk was based on the 'likely' spread of salinity, which was based on the high proportion (77%) of bores with rising groundwater trends, the relatively high mean rate of groundwater rise (0.18m/y), subdued relief of the hydrozone and the observed actively spreading salinity. The 'major' consequence of salinity expanding was based on local knowledge and a subjective assessment of the productivity of the agricultural land and biodiversity assets at risk.

Twelve hydrozones, representing 82% of the mapped AHAVF in the region, have a 'moderate' risk of dryland salinity expanding. In all but one of these hydrozones, this assessment was based on a 'possible' or 'likely' likelihood of salinity expanding with 'moderate' consequences. The exception is the Eastern Darling Range Hydrozone, where salinity expansion is considered 'almost certain' despite the fact that the hydrozone appears to be approaching a new hydrological equilibrium, which means that the area of salinity expansion is ‘low’ and of ‘minor’ consequence relative to the area already salt-affected. The undulating terrain and incised natural drainage contribute to the expected limited extent of any salinity expansion. In this hydrozone, a small proportion of bores within and adjacent to areas of AHAVF had rising trends with mean rates of groundwater rise as high as 0.27m/y in 2007–12. Even though rainfall has been well below average, especially in the north of the hydrozone, MAR is high (700–425mm/y). This hydrozone also has the highest proportion of bores with artesian heads (32%).

In the Ravensthorpe Hydrozone, dryland salinity is confined to either localised hillside seeps or groundwater baseflow within waterways. Any expansion of the salt-affected area is expected to remain confined to these relatively small areas and the area of agricultural land at risk is small. However, the off-site impacts could be considerable in relation to biodiversity, especially along the waterways in the Fitzgerald Biosphere Reserve.

Seven of the remaining hydrozones, representing 8% of the mapped AHAVF, have a low risk of salinity expansion. In most of these hydrozones, it is ‘possible’ the area of salinity will expand, but the consequences are ‘minor’.

In the Northampton Block Hydrozone, it is ‘unlikely’ that the area affected by dryland salinity will expand, despite the high proportion (91%) of bores with rising groundwater trends in 2007–12. Prior to 2000, groundwater levels were fluctuating seasonally, with 93% of bores having stable trends. In 2001–07, groundwater levels dropped significantly in response to an extended dry period. Rainfall in 2008–12 has been slightly higher, but still below average, and groundwater levels have risen, though they have generally not reached pre-2000 levels. The hydrozone is characterised by incised topography and a permeable aquifer with significant hydraulic gradients, discharging as baseflow to the local surface drainage, which is unique in the south-west agricultural region. These factors are expected to restrict the expansion of the salt-affected area and the hydrozone is considered to be at, or close to, a post-clearing hydrological equilibrium.

The Albany Sandplain Hydrozone currently has a low percentage of salt-affected land, which can be attributed to deep groundwater levels. The western section has isolated areas of salinity, many of which have been stabilised by the establishment of plantations. The eastern sandplain section has steadily rising groundwater trends and salinity may possibly develop in the medium to long term but the consequence is ‘minor’.

The Stirling Range Hydrozone already contains large areas of severely salt-affected agricultural land and over the past 15 years, saltland pastures have been established on much of that land. It appears that the hydrozone is approaching a post-clearing hydrological equilibrium as large areas have groundwater levels at or near the surface (section 3.4.3). Therefore, salinity expansion is ‘unlikely’ with ‘minor’ consequences.

Three hydrozones have a low salinity risk, the Donnybrook Sunkland, Leeuwin and Scott Coastal hydrozones. The Land Monitor project did not estimate AHAVF for these hydrozones and the most recent review of groundwater levels is provided by Golder Associates (2008). They report that groundwater levels fell under the southern portion of the Donnybrook Sunkland during 1995–2007, in the absence of groundwater abstraction, and attribute the fall to below average rainfall, which is consistent with the rainfall declines in Figure 2.8. They also report falling groundwater trends under two-thirds of the Scott Coastal Plain, the northern portion of the Donnybrook Sunkland and the portion of the Coastal Plain covered by their analysis. However, groundwater levels in these latter areas were affected by abstraction.

As part of the NLWRA, Short and McConnell (2001) identified parts of the Scott Coastal Hydrozone as having a high salinity risk. They noted, however, that groundwater in the area was fresh to marginal (200mS/m), implying that the 'high' risk assessment may be an over-statement.

4.3.1 Timing of salinity

Eight (32%) of the 23 hydrozones that were assessed are expected to reach hydrological equilibrium in the short term (<20 years): Northampton Block, Southern Zone of Rejuvenated Drainage, Jerramungup Plain, Western Darling Range, Coastal Plain, Warren–Denmark and Stirling Range (Table 4.4). These hydrozones receive the highest mean annual rainfall and are among those cleared earliest, except for the Western Darling Range, where the small area of agriculture was recently cleared.

In the Northampton Block and Stirling Range hydrozones, hydrogeology influences the short time frame to expected equilibrium. The Northampton Block is relatively well drained, with incised stream channels in hydraulic connection with a permeable aquifer and a high degree of topographic relief. Groundwater is therefore responsive to changes in rainfall and a dynamic equilibrium appears to have been established. The Stirling Range Hydrozone is hydrogeologically the opposite, with low topographic relief and stagnant groundwater systems that are approaching capacity. In this hydrozone, hydrological equilibrium is much less dynamic and is characterised by large areas with shallow groundwater.

More than half (56%) of the hydrozones are expected to reach hydrological equilibrium in the medium term (20–75 years). These areas have undergone staged clearing and most have received well below average rainfall over the past 20 years.

Three hydrozones — Dandaragan Plateau, Southern Cross and Salmon Gums Mallee — are expected to take longer than 75 years to reach a new hydrological equilibrium. The Southern Cross and Salmon Gums Mallee hydrozones are among the last to be cleared. Furthermore, the Southern Cross Hydrozone is one of the driest in the region.

There are two important, contrasting issues to appreciate when considering the time to hydrological equilibrium. First, the area of groundwater discharge in a catchment may reach its maximum extent before groundwater levels in elevated areas stop rising. In this case, the rate of discharge will continue to increase to accommodate the increased hydraulic gradient generated by rising groundwater levels. This phenomenon is referred to as 'effective equilibrium' (George et al. 2005, p. 8). Second, it may take years for the areal extent of dryland salinity in a catchment to reach a maximum because salts will continue to accumulate in the topsoil long after a shallow groundwater has reached equilibrium. Furthermore, the severity of salinity impacts will be dependent on seasonal conditions and land management and may not be stable even once the salt-affected area has reached equilibrium.

4.4 Uncertainty in salinity risk assessment

There are uncertainties in the salinity risk map in Figure 4.1 and the main sources are:

- within each hydrozone, it is assumed that all areas of salinity hazard have a uniform level of salinity risk, which is not the case
- within each hydrozone, the distribution of bores may not represent the factors affecting groundwater levels that influence most of the area of salinity hazard
- the risk assessment methodology is not completely objective and relies on local hydrogeological knowledge. No economic analysis of the effects of dryland salinity was undertaken to derive the consequence rating for each hydrozone
- the Land Monitor AOCLP current extent of salt-affected land mapping product is out of date by more than a decade.

Using hydrozones for determining and reporting salinity risk is a compromise in terms of scale and the degree to which they represent areas of uniform salinity risk. Alternatively, using surface water catchments as a basis for salinity risk assessment and reporting is superficially appealing; however, there are overriding impediments to their use. For example, many surface water catchments in the south-west agricultural region cross major hydrogeological boundaries, in particular the boundary between the Yilgarn Craton and the sedimentary basins that lie between it and the coast. The mechanisms governing groundwater trends are therefore not consistent within surface water catchments.

DAFWA's groundwater monitoring network has evolved from a collection of bores specifically established for hydrological process investigations to support salinity research and to monitor salinity treatment trials, into a regional groundwater monitoring network. During 2007 and 2008, DAFWA installed more than 400 bores at 343 sites (DAFWA 2008) in soil-landscape zones (upon which the hydrozones are based) not previously represented in the network. Bores were sited in and adjacent to areas of salinity hazard in these landscapes with the express intention of providing information for assessing salinity risk. Although there are many soil-landscape systems still unrepresented, the network now covers all soil-landscape zones in the south-west agricultural region. Furthermore, the network now covers soil-landscape sub-systems that represent 56% of the total land area within the region. Therefore, although the number and distribution of bores in the network is not optimum for determining salinity risk, it does represent the areas of highest known salinity risk and is an appropriate compromise given the resources available for installing and monitoring a regional groundwater monitoring network.

The level of objectivity inherent in the salinity risk assessment methodology used here is broadly consistent with the documented alternatives applicable to the scale of the south-west agricultural region. Gilfedder and Walker (2001), for example, describe composite index methods of salinity assessment that use spatial datasets combined in a GIS. Spatial layers of salinity risk factors are weighted during the process and the weights are determined by the operator and are dependent on operator experience and process understanding. Gilfedder and Walker (2001) also discuss a class of salinity risk assessment methods they call strongly inverse methods, which they consider to be more objective than composite index methods.

Strongly inverse methods relate the weights of salinity risk factors to the proximity to mapped areas of currently salt-affected land. However, these methods do not account for salinity risk factors not explicitly included in the datasets used to determine the weightings. For example, Robinson et al. (2010) report that in a catchment in the Northern Zone of Ancient Drainage Hydrozone, more than half of the patches of salt-affected land that appeared between 1996–98 and 2006 were not on the valley floors adjacent to existing salt-affected areas. This observation highlights that proximity to salt-affected areas may not always be a determining factor in the expansion of dryland salinity.

The Land Monitor AHAVF and AOCLP map products (Caccetta et al. 2010) are also generated using a process that relies on spatial training data to generate rules. The training data is reliant on the skill and process understanding of operators in interpreting salt-affected areas from aerial photography, for example, or in defining areas of salinity hazard from their knowledge of landscape form and processes.

The third class of salinity risk assessment methods discussed by Gilfedder and Walker (2001) are trend-based methods that combine objective spatial data with trend data. The methodology used in this analysis clearly falls into this class, despite the spatial data and groundwater trend data not being combined in a structured, formal way. Although this methodology lacks the structural rigour of combining and weighting datasets in a GIS, as discussed by Gilfedder and Walker (2001), it does allow the local knowledge and judgement of the individuals making the assessments to be used to maximum advantage. Spies and Woodgate (2005) suggest that this class of salinity risk method, which combine spatial and temporal information, is capable of providing assessments with the highest level of confidence.

Spies and Woodgate (2005) discuss using remote sensing techniques applicable to regional-scale salinity hazard and risk assessment, in particular airborne electromagnetics (AEM). When processed and interpreted along with other spatial data, AEM is capable of mapping the 3-dimensional distribution of salts stored in the profile under a target area, which can be used to produce high resolution salinity hazard and risk maps (Lawrie et al. 2010). Despite the obvious advantages of AEM, it is generally not applied to large areas, such as the south-west agricultural region (25 million hectares), because of the cost.

Spies and Woodgate (2005, p. 75) list remotely sensed estimates of the distribution of salinity as an essential element of any regional salinity risk assessment. Coram et al. (2001, p. 6) also list the current extent of salinity impacts on agricultural land, water resources and other assets as the first dataset required to make a salinity risk assessment. In this analysis, the most recent estimation of the area of salt-affected land available was the 1996–98 Land Monitor assessment (Caccetta et al. 2010), which is now 14 years out of date.

There is little data available that allows any estimate of the expansion of salinity over the whole of the south-west agricultural region since 1998. Robertson et al. (2010) report that by 2006, the area of salt-affected land in the Wallatin and O’Brien catchments (combined area 44 500ha) in the Northern Zone of Ancient Drainage Hydrozone had expanded by 60% relative to the 1996–98 AOCLP estimate. This expansion occurred during a period when half of the bores monitored in the catchments had rising groundwater trends and 80% of those bores were located in or adjacent to areas of salinity hazard.

A study in the Date Creek Catchment in the Eastern Darling Range Hydrozone also provides some insight into the expansion of dryland salinity in the south-west agricultural region (van Wyk & Raper 2008). In 2000, the catchment landholders mapped salinity on their individual properties and the combined area was 245ha (3% of the 7 800ha catchment) compared to the 1996–98 Land Monitor estimate of 150ha (2%). The reported accuracy of the AOCLP product for the Collie and Pemberton scenes, which cover the catchment, was 99% for bare salt-affected land and 70% for marginally salt-affected land (Evans 2001). In 2008, landholders again mapped salinity and the combined area was 470ha (6%) but this estimate did not include salinity on properties owned by landholders not participating in the exercise. The participating landholders then estimated the total salinity to be 790ha (9%) but this figure could not be validated. Disregarding the difference between the landholder's 2000 estimate and the 1996–98 AOCLP estimate, the area of salt-affected land in the catchment expanded by 222% between 2000 and 2008, during which rainfall was consistently 10–20% below the long-term mean. If the salt-affected area actually mapped by the participating landholders is assumed to be a more accurate estimate of the 2008 extent, the proportional increase relative to their 2000 estimate was still 92%.

Within the south-west agricultural region, the area mapped by the Land Monitor project as salt-affected expanded by 11% between 1989 and 1996–98 (Caccetta et al. 2010). The reported increases for individual shires ranged from 7 to 98%. Given the large variations in the reported increases and in the two catchment studies above, it is reasonable to expect that the salinity expansion between 1996–98 and 2012 would be equally as variable. Furthermore, the large spatial and temporal variability in rainfall across the region reinforces the likelihood that salinity expansion will depend on climate, hydrogeology, landform and land management. The lack of an explicit, current map of the salt-affected area is therefore likely to be the most significant source of subjectivity and uncertainty in the salinity risk assessment presented here. The two viable options for producing an explicit, current map of the salt-affected area in the region are another Land Monitor AOCLP estimate using current Landsat TM data, or an extrapolation of catchment-scale aerial photograph interpretations, landholder-mapped estimates and ground-based terrain conductivity surveys, as performed by Ferdowsian et al. (1996a).

5 Conclusions

Groundwater trends were determined for 1500 surveillance bores distributed across the south-west agricultural region of WA. The objective of the analysis was to update the last groundwater trend assessment made in 2007 (George et al. 2008) and to make a salinity risk assessment for the region at the most appropriate scale for the available data. Agricultural land was the principal asset considered in the risk assessment.

The proportion of bores exhibiting rising trends underwent a reduction between the 1991–2000 and 2001–07 assessment periods due to lower than average rainfall over much of the region. Conversely, the proportion of bores exhibiting falling trends increased between 1991–2000 and 2001–07.

Trends in groundwater levels are variable (i.e. bores within the hydrozone have roughly equal numbers of falling, rising and stable groundwater trends) in nine of the 23 hydrozones, which make up 50% of the area of the south-west agricultural region.

Groundwater levels were mostly rising in most hydrozones in the Northern Agricultural Region, the South-western Zone of Ancient Drainage Hydrozone in the Central Agricultural Region and the, Jerramungup, Ravensthorpe, Esperance Sandplain and Salmon Gums Mallee Hydrozones in the Southern Agricultural Region. The hydrozones in which rising trends dominated make up 21% of the land area of the region.

Stable groundwater trends dominate the Eastern Darling Range Hydrozone, the Northern and Southern Zones of Rejuvenated Drainage Hydrozones and the Coastal Plain Hydrozone on the west coast. Together these hydrozones make up 21% of the region. Groundwater levels are mostly falling in two hydrozones that constitute 6% of the south-west agricultural region.

Despite an increase in the proportion of bores exhibiting falling trends during 2007–12, groundwater levels have continued to rise in, and adjacent to, areas of salinity hazard in lower landscape positions over much of the region.

The results of the groundwater trend analyses were the primary input into a salinity risk assessment for the south-west agricultural region. The salinity risk assessment also relied on the Land Monitor (Caccetta et al. 2010) AHAVF salinity hazard map and AOCLP salt-affected area map for 1996–98, and an understanding of the local hydrogeology. The risk assessment methodology was based on a matrix of likelihood and consequence adapted from Spies and Woodgate (2005).

The groundwater trends and salinity risk assessments are reported for hydrozones that are regions of similar hydrogeological, climate, landscape and farming system attributes. The risk assessments are presented in Table 4.4.

The salinity risk map is shown in Figure 4.1 and shows that the highest salinity risk occurs in:

- portions of the Northern and Central Agricultural Regions of the region, where groundwater levels have continued to rise, despite several decades of below average rainfall

- in the east of the Southern Agricultural Region, where rainfall has been above average for the past decade and watertables are already shallow.

The significant proportion of bores with rising trends in and adjacent to areas of salinity hazard, indicates that, over most of the region, the impact of reduced rainfall on groundwater trends is still less than the impact of clearing. Climate variability therefore appears to be a moderating, rather than driving factor in the risk of dryland salinity in the south-west agricultural region.

Appendix A Summary of groundwater trends by hydrozone

Table A1 Summary of groundwater trends in each hydrozone in the 2001–07 analysis period (George et al. 2008) and the 2007–12 analysis period

Hydrozone	No. of bores		% with falling trend		% with stable trend		% with rising trend	
	2001–07	2007–12	2001–07	2007–12	2001–07	2007–12	2001–07	2007–12
Kalbarri Sandplain	n.a.	11	n.a.	45	n.a.	18	n.a.	36
Northampton Block	31	32	90	3	6	6	3	91
East Binnu	1	25	n.a.	0	100	16	n.a.	84
Irwin Terrace	13	25	62	20	23	36	15	44
Arrowsmith	40	53	75	45	18	25	8	30
Dandaragan Plateau	12	39	17	8	42	15	42	77
Northern Zone of Ancient Drainage	369	468	42	29	39	39	19	32
Northern Zone of Rejuvenated Drainage	44	54	23	22	50	44	27	33
Southern Cross	1	10	100	70	n.a.	20	n.a.	10
South-eastern Zone of Ancient Drainage	62	70	26	16	24	44	50	40
South-western Zone of Ancient Drainage	84	89	8	7	24	42	68	52
Southern Zone of Rejuvenated Drainage	80	122	16	7	51	65	33	28
Eastern Darling Range	126	132	17	9	44	73	39	18
Western Darling Range	5	5	80	80	0	0	20	20
Coastal Plain	7	4	14	0	86	100	0	0
Donnybrook Sunkland	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Hydrozone	No. of bores		% with falling trend		% with stable trend		% with rising trend	
	2001–07	2007–12	2001–07	2007–12	2001–07	2007–12	2001–07	2007–12
Leeuwin	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Scott Coastal	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Warren–Denmark	20	16	30	19	40	56	30	25
Albany Sandplain	32	43	19	30	16	23	66	47
Stirling Range	8	6	38	50	50	0	13	50
Pallinup	8	17	63	41	38	24	0	35
Jerramungup	31	33	10	30	23	18	68	52
Ravensthorpe	7	7	0	0	57	43	43	57
Esperance Sandplain	97	81	8	20	25	27	67	53
Salmon Gums Mallee	63	60	3	17	27	32	70	52

n.a. not assessed.

Shortened forms

Shortened form	Full name
AEM	airborne electromagnetics
AHAVF	average height above valley floor; Land Monitor product mapping salinity hazard. See sections 1.3.3 and 4
AMRR	accumulated monthly residual rainfall
AOCLP	areas of consistently low productivity; Land Monitor product mapping salt-affected land. See sections 1.3.1 and 4
BGL	below ground level
DEM	digital elevation model
EC	electrical conductivity
ha	hectare
km	kilometre
m, m/y, mm/y	metre, metres per year, millimetres per year
m BGL	metres below ground level
MAR	mean annual rainfall
NLWRA	National Land and Water Resources Audit
SIF	Salinity Investment Framework
y	year

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