Climatic influence on shallow fractured-rock groundwater systems in the Murray–Darling Basin, NSW

Department of **Environment & Climate Change** NSW

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Abstract

This document reports the findings of one of three studies undertaken to provide new evidence-based science to underpin the NSW Murray–Darling Basin (MDB) Salinity Audit update 2009. This latest research has revealed that climatic factors currently dominate water table and land-salinity trends, and mask the impacts of land use change.

In the Murray–Darling Basin Salinity and Drainage Strategy (1988–1990) and the previous MDB Salinity Audit (Beale *et al*. 2000), expansion of salt-affected land and rising stream salinity were seen as consequences of slowly rising groundwater as a response to increased recharge due to the massive vegetation clearing and changes in land-use practices, most of which were finalised by the end of the 19th century. Estimated trends were extrapolated to predict further potential increases in land and stream salinisation. However, rainfall drives the recharge process, and land use acts only as a tap that can be turned more or less on, increasing or decreasing the climatically driven signal. Australia is the land of floods and droughts, with huge climatic variations, and the major shift in climate in the late 1940s that brought substantial increases in rainfall could not but trigger higher recharge rates and affect the position of water tables.

The aims of this study were to discover and examine the historical trends in groundwater levels in fractured rocks in the NSW portion of the MDB over the period 1900–2003, and to re-examine the role of climate and land use changes as the major drivers of fluctuations in groundwater levels. As historical land use data are not readily available, the conclusions are based on comparison of groundwater and rainfall trends—their similarities and deviations from each other—followed by statistical analysis of annual datasets, to bring statistical rigour and to evaluate the findings. The statistical analyses used moving-average and residual mass curve techniques, followed by change-point, spectral, cross-correlation and multiple regression analyses and the building of statistical models.

The first bores with the purpose of monitoring water levels in NSW were drilled in fractured rock in 1987 within the framework of the MDB salinity and drainage strategy. However, more than 33000 production bores were drilled within the study area throughout the 20th century, and information about depth to water level in these bores, called standing water level (SWL), was recorded and stored in the NSW Groundwater Data Systems database. This study uses the drillers' SWL records to estimate the trends in groundwater over time. System behaviour is determined by agglomerating these point data over each section of the study area from all 5473 records held in the database that are genuinely derived from shallow fractured-rock groundwater systems.

The study area covers sections of the Lachlan Fold Belt and the New England Fold Belt. Bores within these fold belts are subdivided for analysis and presented by location within the major river basins. Thus, the results are presented for the Border Rivers, the Gwydir River Basin, the Namoi River Basin, the Peel River Basin, the Macquarie River Basin, the eastern, middle and western sections of the Lachlan River Basin, the eastern and western sections of the Murrumbidgee River Basin, and the eastern and western sections of the Murray River Basin. The study area corresponds closely to those areas analysed in the 1998 Murray Darling Basin Salinity Audit by Woolley *et al*. (1999) and Beale *et al.* (2000).

The most important conclusions arising from this study are the following:

1. Trends in SWL have been following trends in rainfall across the study area for the period of available SWL data, with a delay. The only noticeable deviation, consistent with the effects of clearing, was visible in the early records of Lachlan West section, before 1937.

2. Groundwater has been in dynamic equilibrium with rainfall inputs during at least the last four decades. Average annual rainfall increased after 1947, but in the last decade it has been decreasing in most areas. Groundwater levels in fractured rock have followed these trends: they rose, stabilised, and are currently falling in most areas.

3. Groundwater flow systems in fractured rock show much faster responses to changed recharge conditions than former estimates implicitly included in the previous MDB Salinity Audit and current estimates as conceptualised within the Groundwater Flow System framework (Coram 1998; Coram *et al.* 2000).

4. Lachlan West bore records demonstrate that even though the initial water table rise due to clearing could not be detected in other sections, the 19th century clearing permanently increased potential recharge and placed the water table at a shallower level than if there had been no clearing.

5. Dryland salinity worsened during the second half of the 20th century as the increased potential recharge due to clearing was superimposed on the long-term wet climatic phase. Together, both processes caused water tables to rise and intersect the landscape at many points, creating salt deposits on the surface as the water evaporated. This was happening at more points and in larger areas than when the water table was deeper during the first half of the century.

6. Climatic variation, which caused so many salinity outbreaks over the last half of the 20th century, was in fact very mild compared with variation over longer time scales. This suggests that the salt build-up in the landscape is not merely a consequence of a single, longer-term, wet climatic episode superimposed on the land use change, but has its origin in the long sequence of preceding hydrologic perturbations.

The pioneering work in this study can serve as a basis on which to build our knowledge about salinity, recharge and hydrologic processes. The information used here is very limited, so to ensure future progress it will be necessary to collect more data. It is therefore absolutely necessary for government to provide adequate funding for a centralised bore data custodian and, most importantly, to require the handing over of all groundwater information to this custodian. This should be done so that all existing data sources, such as parts of the DWE (former DIPNR) database that we did not use, data from other agencies and published papers, can be brought together in one place. We strongly recommend further data acquisition in the Border Rivers and Murray catchments, where insufficient data prevented detailed statistical analysis.

Data should be collected from monitoring bores at a frequency of at least one point per month. Methods used in this study can be further improved by replacing the moving-average technique with splines, choosing a 5-year time step as the basis for detailed statistical analysis, introducing an autoregressive component into the statistical models, and running the FLAG model at the appropriate resolution to produce UPNESS and WETNESS indices of the catchments in the study area. Those indices can then be used as co-variables in the statistical models. Further research, outside the scope of this study, would be beneficial for the understanding of salinity processes: collection and analysis of water quality bore data and exploring similarities and differences between electrical conductivity and SWL trends. This study shows that no long-term predictions of groundwater trends can be made without the ability to predict rainfall: a range of steps can lead to better understanding of energy transfer processes and climatic patterns, such as calculation of an index analogous to the Pacific Decadal Oscillation, but for the Southern Hemisphere, and relating this index to the rainfall on the east coast of Australia; recalculation of the L index; and extension and analysis of rainfall time series based on hydrologic analysis of Lake George levels.

1 Introduction

1.1 Background

Dryland salinity has been observed in some areas of the Murray–Darling Basin (MDB) in south-eastern Australia since the end of the 19th century (Wagner 2001). However, it was not until the 1970s that the community became aware that salinity posed a major threat to the MDB's land and water resources. The resources of the MDB are committed to a wide range of agricultural, urban and ecological uses, whose viability is at risk if water quality and catchment health decline.

To assess the impact of declining water quality on MDB communities, the Murray–Darling Basin Commission (MDBC) launched the first Salinity and Drainage Strategy in 1988. The strategy and associated works aimed at improving the quality of MDB water, controlling land degradation, ensuring the sustainable use of the resource, conserving the natural environment, and protecting sensitive ecosystems in the MDB (MDBC 1999).

By the 1980s, significant land and water salinisation was occurring across NSW. Salinity investigations increased as a result of widespread community concern at medium- and long-term salinity trend predictions. During this time, piezometers and groundwater monitoring bores (underlined terms are explained in the Glossary, page 73) were constructed across many upland catchments overlying fractured rock to help understand the underlying processes.

Fractured-rock zones are often exposed in the upper reaches of catchments. Water that enters the groundwater systems at higher elevations travels down the systems and discharges at lower positions in the landscape. Discharge can form seeps, be lost by evapotranspiration or enter rivers or alluvial systems.

Groundwater systems react to changes in recharge rates by adjusting the position of the water tables, resulting in changes in pressure and discharge rates. The time needed by a groundwater system to adapt to a new equilibrium depends on its storage size, pathway length and hydraulic conductivity (Domenico and Schwartz 1998). Different types of groundwater systems show different response times, and hence the relationship with rainfall of each system should be analysed separately. For example, groundwater in Palaeozoic fractured rock responds to changed recharge conditions faster than that in the vast regional Great Artesian Basin, but slower than that in highly conductive, local, Tertiary volcanic systems.

Groundwater pumping affects groundwater levels. Intensive pumping is possible in high-yielding volcanic and alluvial aquifers, which can be affected by river diversions, irrigation activities and regulation of river flows. In the NSW MDB, all these activities take place outside the fractured-rock fold belt areas, so their impact on the hydrology of the fractured-rock groundwater is minimal. Thus, fractured rock offers the advantage that groundwater levels are largely independent of effects other than those caused by rainfall and land use change.

1.2 Groundwater monitoring and analysis of groundwater trends in NSW

A lack of long-term fractured-rock groundwater monitoring data before the 1980s makes detailed analysis of salinity processes and the prediction of standing water level (SWL), electrical conductivity (EC) and areas of land salinisation difficult. In particular, the impact of longer-term climate changes on salinity processes and trends cannot be evaluated. Most previous analyses assessed trends on the basis of the average rate of change in SWLs among groups of bores located in specific areas. These methods relied on the comparison of SWL at the time of bore construction and some years later. Studies rarely involved multiple measurements of the same bore over time. For predicting trends, it was usually assumed that rates of groundwater would rise linearly, in perpetuity.

1.2.1 Reconnaissance groundwater surveys before 1999

No systematic surveys or analysis of registered bore data were conducted in NSW before the early 1980s. However, in the late 1980s and early 1990s, numerous groundwater reconnaissance surveys were undertaken (Gates and Williams 1988; Salas and Garland 1989; Williams 1990; Williams and Saunders 1990; Woolley and Bogoda 1992; Bish and Gates 1991; Hamilton 1992; Bish 1993; Lytton *et al.* 1993). Although most of these surveys did not make distinctions between bores based on the geology in which they were drilled, the authors generally concluded that water levels had risen significantly in the recent past. The influence of climatic factors on water level responses was not taken into consideration.

By revealing that there was considerable potential for further groundwater level rises, the reconnaissance surveys provided a new impetus to establish new bore monitoring programs, and a basis for undertaking more detailed studies of the possible development of salinity.

1.2.2 1999 Murray–Darling Basin Salinity Audit

The 1999 salinity audit (MDBMC 1999) aimed at predicting the salt load in MDB streams, on the basis of worst-case scenarios, in 2020, 2050 and 2100. Studies attempted to link the results of various groundwater reconnaissance surveys (Woolley *et al.* 1999) with predicted changes in water quality in upland tributaries (Jolly *et al.* 1997). This led to the general conclusion that in the absence of widespread land use change, the salt loads in the NSW streams were likely to continue to increase in response to the general rise of groundwater levels.

The first attempt at predicting the long-term salinity had two major limitations. Firstly, it assumed that changes in water levels over time were linear. Secondly, the lack of suitable landscape analysis tools did not allow the imposition of topographic constraints on the areas of potentially saline water discharge. Some distortion in the predictions also arose, because bores showing falling groundwater levels were excluded from the analysis, and no account was taken of the potential effects of increased groundwater usage by irrigators.

1.2.3 Developments since 1999

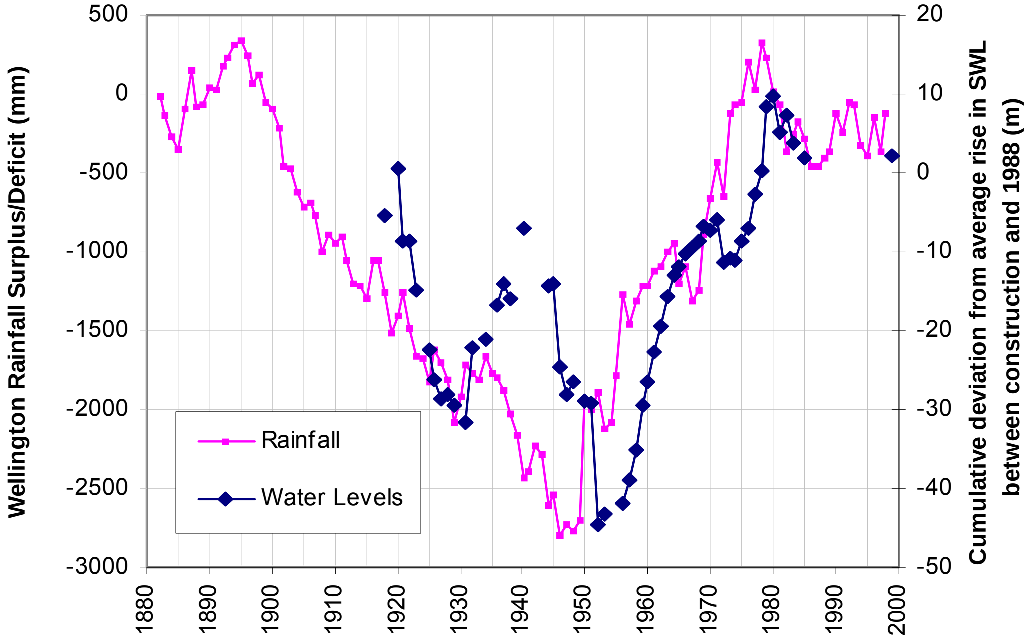
In response to the 1999 audit, in 2000 the NSW Government implemented the NSW Salinity Strategy, which supported additional investigations, including a salinity audit of the Hunter River (Beale *et al.* 2001) and of the other NSW coastal river basins (Beale *et al.* 2004).

A re-survey of bores in the Lachlan River valley upstream of Lake Cargelligo added a third water level measurement to the previous two-point dataset (Muller and Lennox 1999). Linear regression analysis was used to estimate trends in individual bores and thereby predict areas most at risk from shallow or rapidly rising groundwater. This analysis generally confirmed that water levels were rising.

The 2001 National Land and Water Resources Audit (NLWRA 2001) highlighted that monitoring and assessment methods presented significant limitations to evaluating the current and future extent of dryland salinity in Australia. Particular issues related to the spatial distribution and density of monitoring bores, their limited length of record, and data quality and availability. A partner report (Nulsen and Evans 2001) identified that in most areas where dryland salinity was a problem, the length of record of most monitoring bores was less than 15 years. This was identified as a major barrier to accurately predicting water table trends. The lack of long-term regularly monitored bores was also highlighted as a major issue in the 1990–2000 Murray–Darling Basin Groundwater Status: Summary Report (Ife and Skelt 2004).

Since the 1990s, there has been a gradual realisation that, in addition to land clearing and land use change, the occurrence of wet or dry periods of rainfall also had an important impact on the behaviour of groundwater systems (e.g. Cresswell *et al.* 2003; Ife and Skelt 2004).

Figure 1: Residual mass curve of SWL and rainfall presented by Salas and Smithson (2002)



To overcome problems related to the lack of long-term (>50 years) groundwater data, Salas and Smithson (2002) used a novel approach in their study of groundwater trends in the central west of NSW. They used the SWL data from 255 private water supply bores drilled between 1918 and 1985 to construct a long-term time series. For each sample of bores constructed each year, the median difference between the groundwater levels at the time of drilling and again in 1988 (ΔSWL) was plotted on a residual mass curve (Figure 1) to depict the cumulative sum of the deviations from the long-term average.

The ΔSWL curve followed a similar trend to the rainfall residual mass curve (Figure 1). This shows that groundwater levels were lower in the first half of the 20th century, when rainfall in the central west of NSW was generally lower than the long-term average, but rose in the second half of the century following the well-documented (e.g. Riley 1988) increase in rainfall since about 1947.

Salas and Smithson (2002) concluded that groundwater levels have not been rising constantly over the last 100 years, but rather that they have followed changes in the rainfall pattern. They also found a variable time lag (4 to 13 years) between annual rainfall changes and groundwater responses.

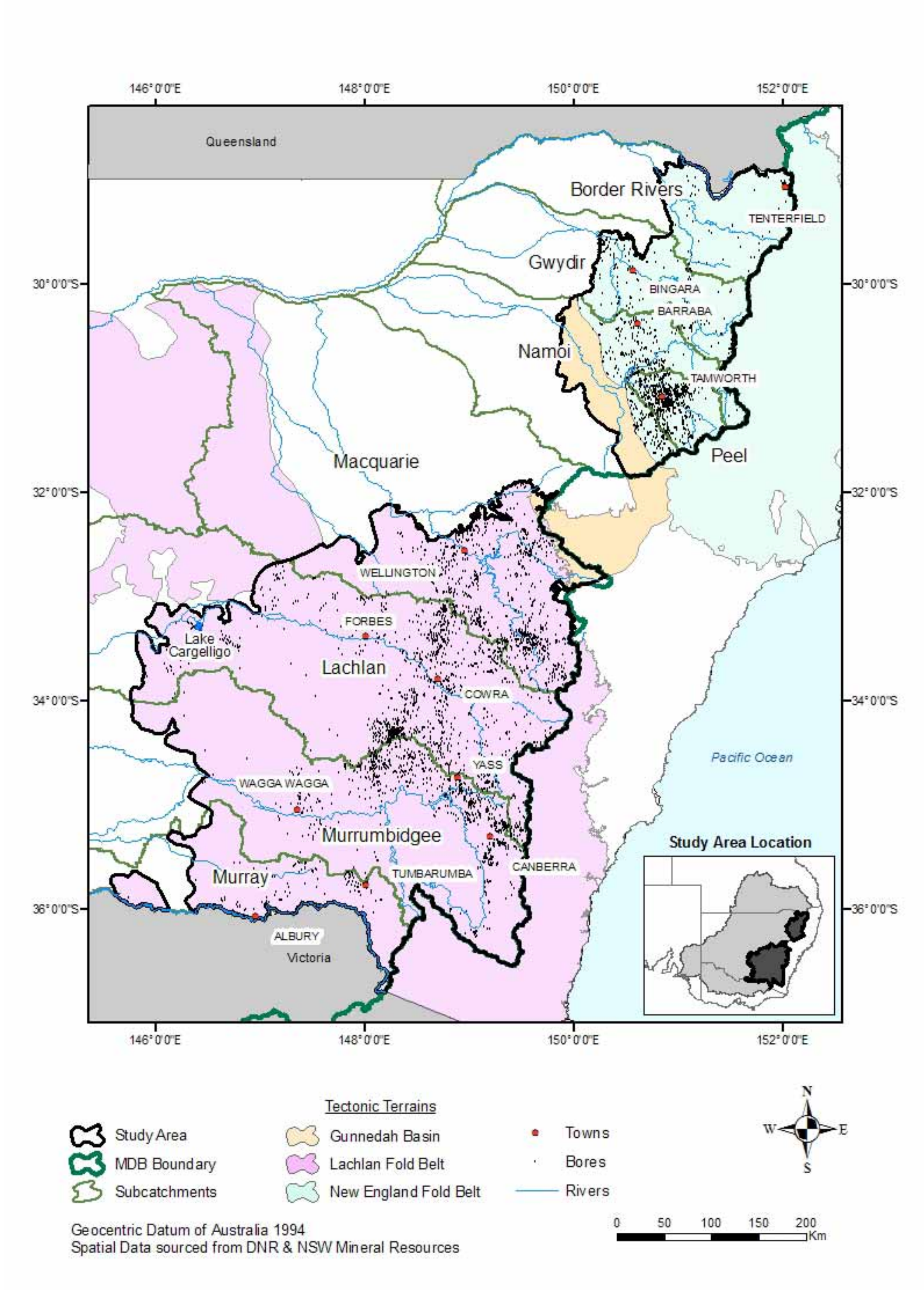
By developing a composite time series that combines many individual observations through time, Salas and Smithson (2002) overcame one of the most significant barriers in developing a greater understanding of salinity processes in NSW.

Their approach has been refined and extended here. The broad aim of this study is to analyse the effects of rainfall changes on groundwater behaviour over time in the fractured-rock areas within the NSW sector of the MDB.

2 Study area

The study area covers the western slopes of the Great Dividing Range and includes the New England Fold Belt, the Gunnedah Basin and the Lachlan Fold Belt (Figure 2).

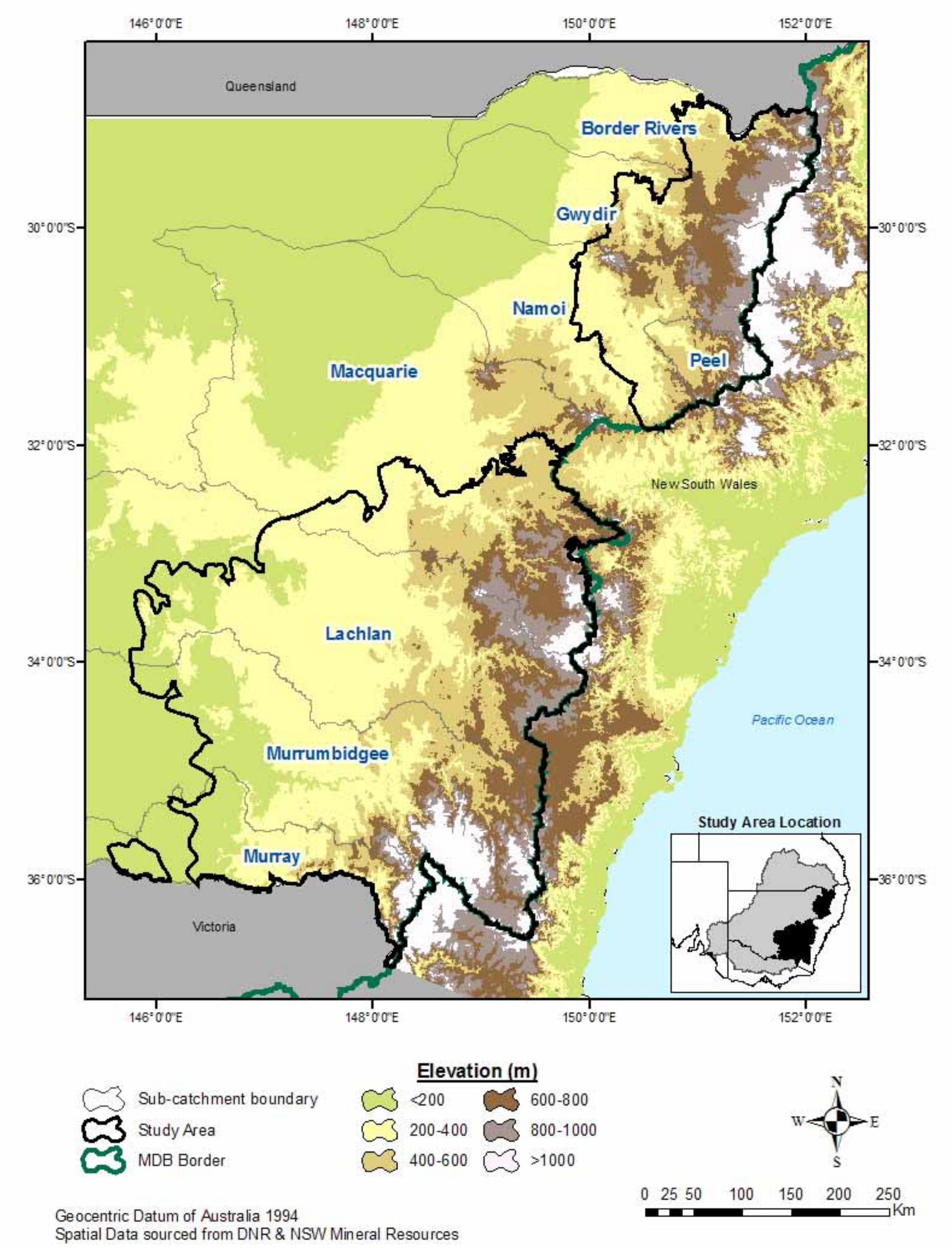
Figure 2: Study area



2.1 Topography

The western watershed of the Great Dividing Range includes mountainous to hilly erosive landscapes in the east, with some peaks exceeding 2000 m above sea level, grading westwards into depositional plains with low to gentle slopes and some protruding relict mountain ranges (Figure 3).

Figure 3: Topography



2.2 Climate

2.2.1 Rainfall

Rainfall decreases with the distance from the coast and increases with rising altitude. Hence, the elevated areas along the Great Dividing Range receive the highest average annual rainfall, over 800 mm/year (Figure 4). Rainfall declines to less than 400 mm/year in the west. However, from north to south it is possible to define three seasonal rainfall zones:

- **Summer rainfall zone**. The northern catchments (Border Rivers, Gwydir, Namoi and Peel) experience a dominance of summer over winter rainfall. Summer rains originate from troughs between the travelling anticyclones (high-pressure cells) that draw in moist, maritime airflows from tropical regions to the north (Gentilli 1971), as well as the remnants of tropical cyclones that come down from the north.
- **Uniform rainfall zone**. The central catchments (Macquarie, Lachlan, northern and upper Murrumbidgee, above Burrinjuck Dam) experience a non-seasonal rainfall pattern, with no more than 30% variation between summer and winter. The dominance of the winter rain-bearing westerlies over the summer rain-bearing troughs diminishes northwards.
- **Winter rainfall zone**. The southern catchments (south-western Murrumbidgee and Murray) experience a dominance of winter over summer rainfall. The weather in this region is dominated by eastward-moving anticyclones in summer, and rain-bearing westerly winds, low-pressure cells and associated troughs in winter (Dodson 1998).

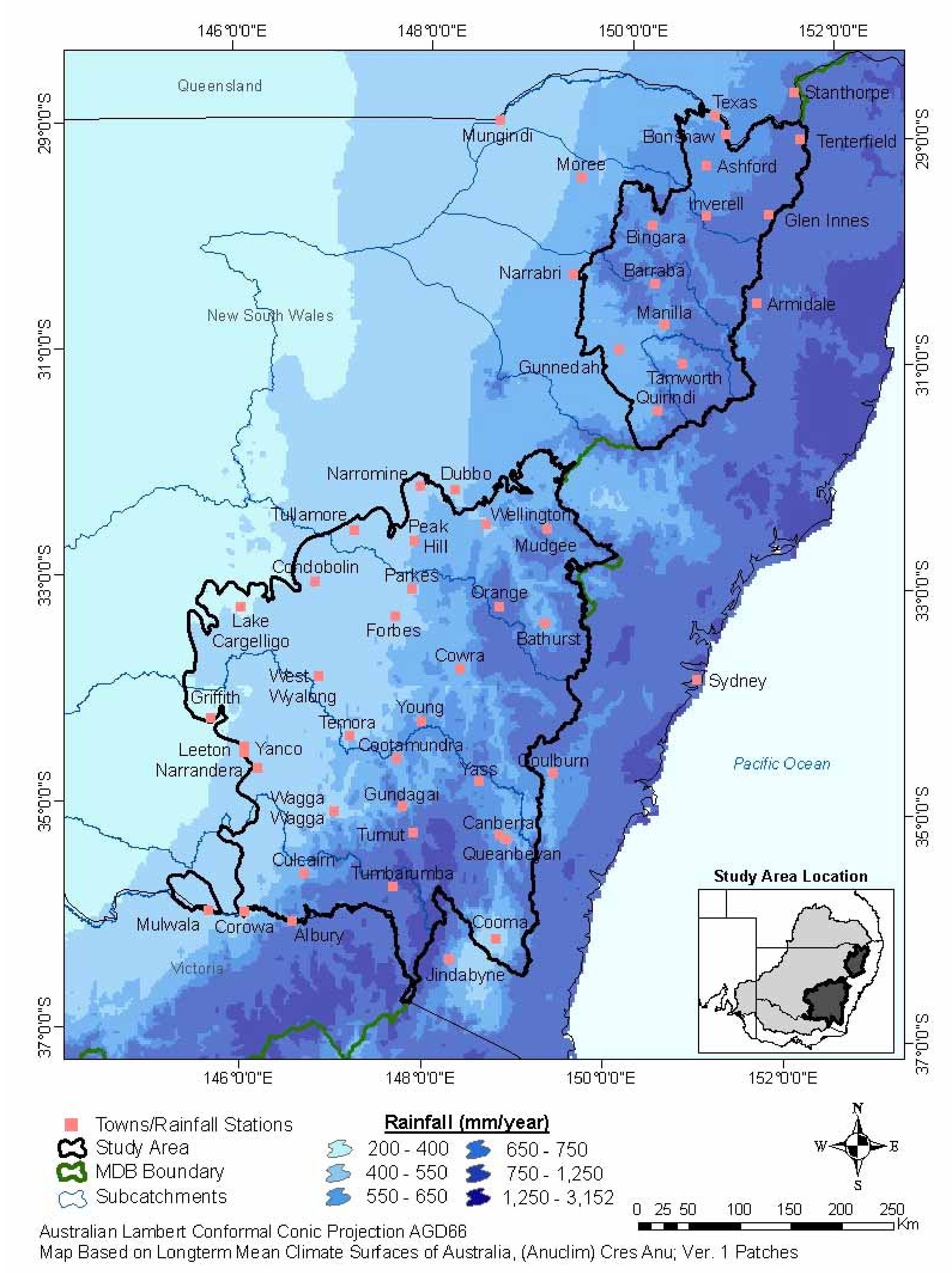
Differences in seasonal rainfall distribution between the north and south of the state are the result of the change in the average latitudinal position of the subtropical high-pressure ridge, which follows the Sun in its annual cycle. In summer, the Sun is over the Southern Hemisphere and the ridge passes to the south of mainland Australia. This exposes southern NSW to easterly winds, and northern areas to intrusions of warm, moisture-laden tropical cyclones. The easterly winds bring moisture onto the southern NSW coast and ranges, but the inland is generally dry. In winter, as the Sun moves to the Northern Hemisphere and the subtropical high-pressure systems also move north, southern Australia comes under the influence of mid-latitude cyclones, and predominantly westerly to south-westerly winds. This brings rain-bearing low-pressure cells and associated cold frontal systems across the inland of NSW, while areas such as the southern coastal strip and ranges receive little rain.

2.2.2 Temporal climatic variability, rainfall shifts and meridional energy transfer

Kraus (1955a) explained that the abrupt decrease of rainfall in eastern Australia from the end of the 19th century (1895–1946) was associated with the following interrelated factors:

- a reduction of the direct meridional circulation between the equator and temperate latitudes
- a weakening of the inter-tropical convergence zone
- a narrowing of the equatorial rain belt
- a shortening of the wet season
- the strong development and the equatorial displacement of the mean upper westerlies at 300 hPa and above

Figure 4: Average annual rainfall in the study area

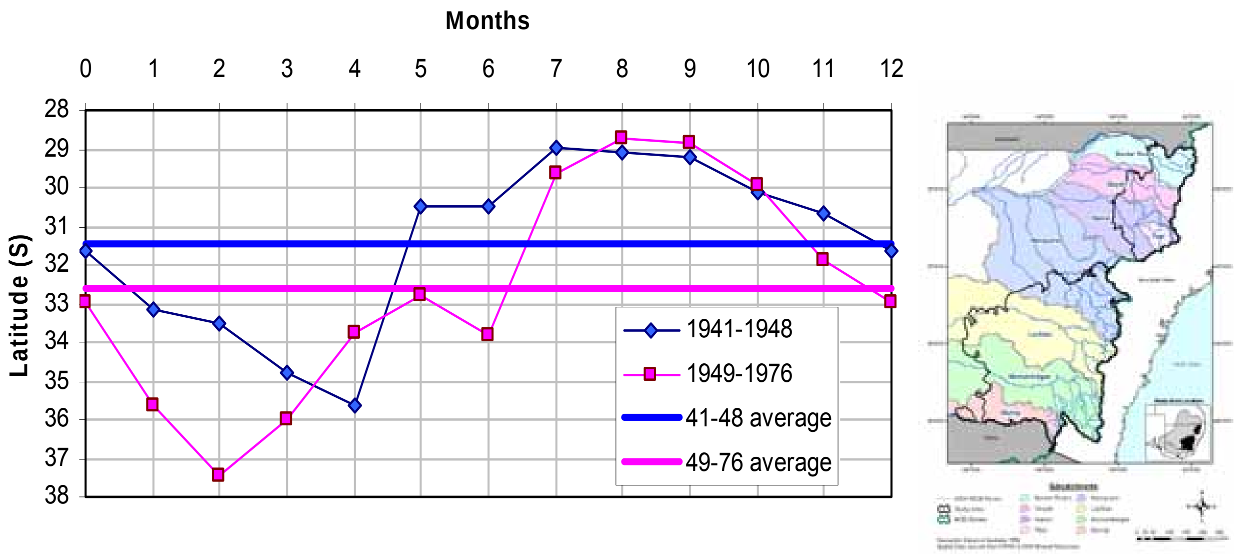


- an expansion of the subtropical pressure belt and its equatorial displacement
- a wider separation of the tropical and westerly rain belts
- the absence of east coast cyclones (a decline in mean rain intensity and a reduction in the number of rainy days and storminess), as heavy spring and autumn rainfalls in eastern Australia are often associated with east coast cyclones, which receive some energy from the westerlies, but also draw in moist tropical or equatorial air from the northern Tasman and Coral seas
- a major decline in spring and autumn rainfall in southern NSW.

The abrupt increase in rainfall in the late 1940s in eastern Australia was characterised by the opposite effects.

Figure 5 is based on an estimate of the L index by Pittock (1973). It illustrates pole-ward displacement of the high-pressure belt in the late 1940s and lengthening of the wet season. This lengthening is most pronounced between 31°S and 33°S, corresponding to the Macquarie and Lachlan sections of the study area, in the uniform rainfall zone.

Figure 5: Annual cycle of the mean latitude of the subtropical ridge along the east coast of Australia



As reported by Pittock (1973), and later extended by Pittock (courtesy of W. Drozdowsky, Bureau of Meteorology, Melbourne pers. comm., 2005) for 1941–1948 and 1949–1976, and the juxtaposed map of the study area in the same latitudes.

The displacements of the high-pressure belt and the related climate shifts are manifestations of a quasi-periodic process that is intimately linked to the attempt of the coupled ocean–land–atmosphere system to distribute solar energy in the meridional direction (Kraus 1955a; Pittock 1975). The frequency of this process reflects most likely the internal frequency of this system, which appears to have changed phase in this part of the world, and over the available record, twice per century: in the 1890s, the 1940s (Kraus 1955a; Pittock 1973) and possibly again in 2000 (Rakich *et al.* 2008; Vines 2008). The same type of process, strongly linked to meridional energy transfer, seems to have been pulsing at double speed in the North Pacific and is reflected through the change phases of the Pacific Decadal Oscillation

(PDO). Analysing the period from 1900 to 1996, Mantua *et al.* (1997) recognised PDO polarity reversals in 1935, 1947 and 1977.

A rainfall shift occurred in the 1940s in and around the Pacific and Indian oceans. It occurred at approximately the same time in both hemispheres, as well as in the equatorial Pacific, and has been reported and analysed by various authors (Kraus 1955a, 1955b; Hobbs 1971; Pittock 1975, 1983; Cornish 1977; Russell 1981; Allan *et al.* 1995; Mantua *et al.* 1997; Biondi *et al.* 2001; Gedalof and Smith 2001; Franks and Kuczera 2002; Vivès and Jones 2005; MacDonald and Case 2005; Verdon and Franks 2006; Verdon *et al.* 2006 and many others).

The ocean–land–atmosphere system also distributes its energy laterally, as manifested through the east–west Walker Circulation and associated El Niño – Southern Oscillation (ENSO). This process also has a strong influence on NSW rainfall. When the Walker circulation enters its El Niño phase, the Southern Oscillation Index becomes negative. This results in reduced rainfall, particularly during winter, spring and early summer in eastern and south-eastern Australia. El Niño events occur about every 4 to 7 years, and are related to the occasional inversion of pressure and wind direction in the Pacific Ocean. They typically last for around 12 to 18 months. Significant correlations have been demonstrated between rainfall distribution over the continent and the strength of the thermally driven east–west Walker Circulation (Pittock 1975).

Pittock (1975) showed that the L-index and the Southern Oscillation Index are correlated with, respectively, the second and first components (Eigenvectors) determined by principal components analysis. These two Eigenvectors account for more than half of the variability in annual rainfall in Australia, and even more than that in eastern Australia. Drosdowsky (2005) also showed that these relationships changed slightly between the third and fourth quarters of the 20th century. Power *et al.* (1999) pointed out that the cycle of temperature changes in the equatorial Pacific, manifested through the Inter-decadal Pacific Oscillation and analogous to the North Pacific PDO, modulates the strength of the relationship between Australian rainfall and the ENSO. Although the Inter-decadal Pacific Oscillation and the PDO are highly correlated, the mid-Pacific related cycle of ocean warming and cooling is slower than the North Pacific cycle (Power *et al.* 1999), but apparently not as long as the cycle which manifests further south through the rainfall shifts of the east coast of Australia. Rainfall shift in the 1940s was, however, present in all three regions of the Pacific and beyond.

Lower-frequency processes, linked to the meridional energy transfer, cause sudden changes in the rainfall regime after rainfall shifts, and preserve the rainfall average between the shifts. Higher-frequency processes, which arise from latitudinal energy transfer, play a more important role in inter-decadal rainfall variability and short-term hydrologic fluctuations.

2.2.3 Evaporation

Throughout the study area, potential evaporation is highest in summer and lowest in winter, and the average evaporation declines from north to south and with increasing altitude. Although in southern Australia there is usually a surplus of rainfall over evaporation during winter, it is only in high-altitude, high-rainfall zones (generally where rainfall exceeds 850 mm) that there is an annual surplus.

2.2.4 Temperature

Daytime temperatures are generally mild to hot in summer, and mild to cool in winter. Throughout the area, frost is common in winter. Snowfalls are common in winter at elevations above 1500 m.

2.3 Surface water resources

Seven major river systems drain waters from the Great Dividing Range towards its west and north-west (Figure 2).

The Border Rivers system drains waters from Queensland and NSW primarily via the Macintyre River. The Queensland portion of the system is not included in the study area. Major rivers on the NSW side within the study area are the Dumaresq, Severn–Macintyre, and Beardy rivers. The most important impoundment storage on the NSW side is Pindari Dam, located on the Severn River, 22 km downstream of Ashford. Pindari Dam was only 1/10th of its current size when it was first built in 1969. It was greatly enlarged in 1995 and now has a total capacity of 312 GL.

The largest rivers in the Gwydir River system are the Gwydir, Rocky and Horton rivers. Copeton Dam, constructed on the Gwydir River near Inverell in 1976, with a capacity of 1364 GL, is the largest storage.

The Namoi River system includes the Namoi, Peel and Mooki rivers and their tributaries. There are three major storages: Split Rock Dam (387 GL; constructed in 1998) on the Manilla River, Keepit Dam (425.5 GL; 1978) on the Namoi River; and Chaffey Dam (61.8 GL; 1979) on the Peel River.

The major rivers of the Macquarie River system include the Talbragar, Bell, Macquarie, Cudgegong and Bogan rivers. The major storage, Burrendong Dam, with a capacity of 1188 GL, was constructed in 1967, and Windermere Dam, with a capacity of 368 GL, was constructed in 1984.

The Lachlan River system includes the Boorowa, Abercrombie, Belubula and Carcoar rivers among several others. Wyangala Dam, near Cowra, was constructed in 1936 and considerably enlarged in 1971 to a capacity of 1220 GL.

The Murrumbidgee River system includes rivers rising from the headwaters in the Snowy Mountains: the Tumut, Yass and Molonglo rivers, and Jugiong, Muttama, Kyeamba and Tarcutta creeks. Burrinjuck Dam was constructed in 1919 and enlarged in 1956 to 1026 GL. Blowering Dam, constructed in 1968, is the largest storage (1631 GL). Other storages include Tantangara Dam (254 GL), Talbingo Dam (160 GL) (which are part of the Snowy Mountains Scheme) and some smaller storages in and around the ACT (total of 100 GL). A proportion of water from the storages that are part of the Snowy Mountains Scheme is transferred to the Murrumbidgee River system.

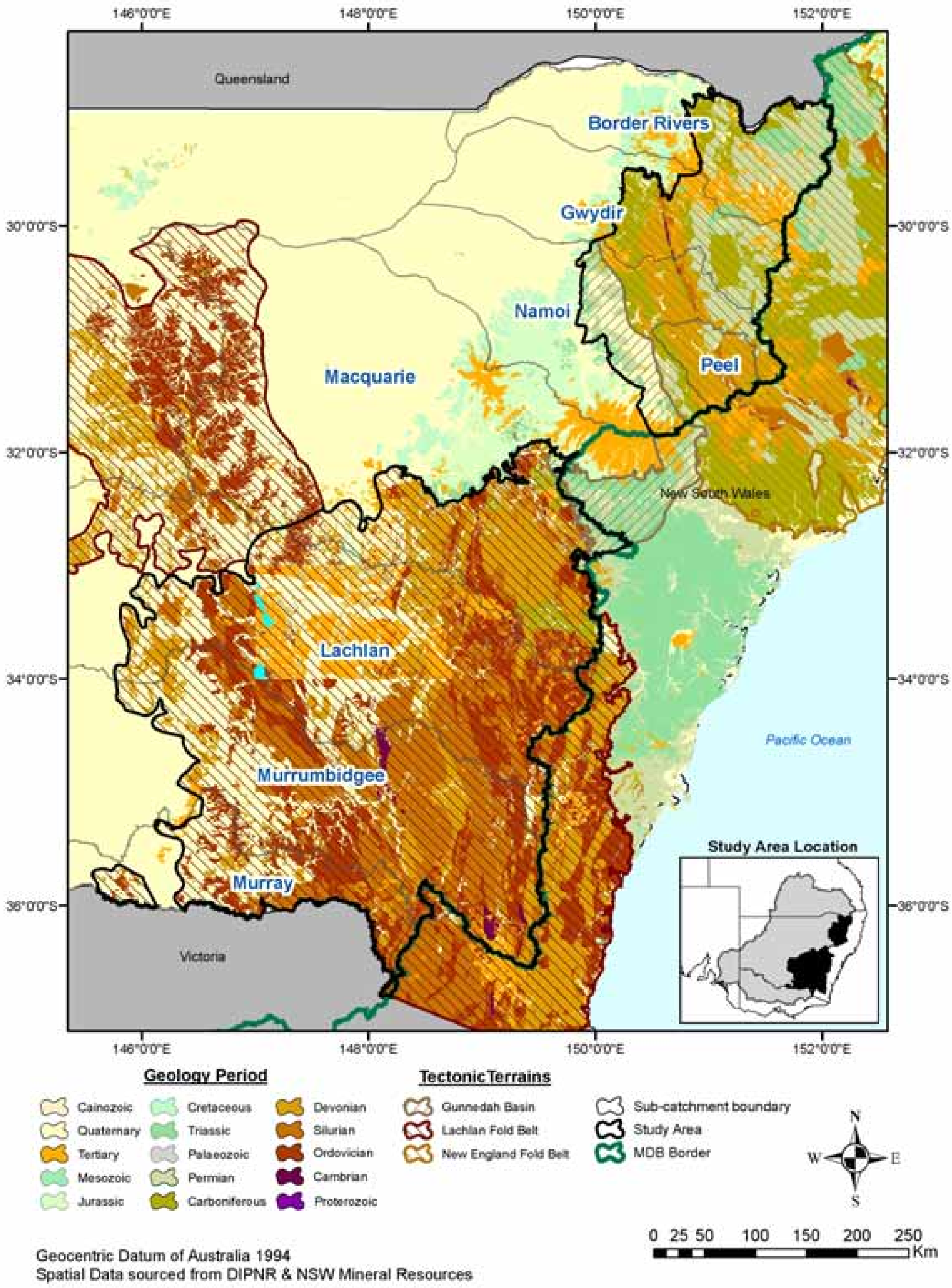
The only major NSW tributary in the Murray River system is Billabong Creek. The major storage is the Hume Dam, near Albury (3303 GL). It is the largest storage in the study area. Its construction started in 1919, and in 1924 the Commission agreed to enlarge it from its planned capacity of 1360 to 2470 GL. This was later reduced to 1540 GL owing to the Great Depression. When construction was finished in 1936, the Hume Dam was the biggest dam in the Southern Hemisphere and among the largest in the world. It was subsequently enlarged in 1961 to its current size. Some water is diverted into the Murray River from the Snowy Mountains Scheme.

2.4 Geology

Five major geological provinces occur in the study area (Branagan and Packham 2000), as shown in Figure 6:

- The Lachlan Fold Belt, a composite orogenic belt of Mid-Cambrian to Early Carboniferous age, consisting of meta-sediments, meta-volcanics and granites. Extension, compression and strike–slip deformation have resulted in a strongly faulted and folded north-north-west structural grain.
- The New England Fold Belt, also a composite orogenic belt, of Cambrian to Triassic age. It consists of meta-volcanics, meta-sediments and granites. The extension, compression and strike–slip deformation have resulted in a strongly faulted and folded north-north-west structural grain.
- The Sydney–Gunnedah Basin (part of Sydney–Bowen Basin), of Early Permian to Triassic age, consisting of consolidated marine and non-marine sediments and volcanics.
- The Late Cretaceous to Tertiary volcanics. Widespread volcanism associated with mantle plume activity produced (mainly basaltic) volcanic complexes, thick volcanic piles, lava fields, minor sills, dykes and laccoliths. (No bores associated with this geological province were selected for this study.)
- The Murray Basin and unconsolidated sediments in upland tributaries, of Tertiary and Quaternary age. (No bores associated with this geological province were selected for this study.)

Figure 6: Geology of eastern NSW



2.5 Hydrogeology

Under natural conditions, groundwater systems are primarily recharged by rainfall and river leakage. However, river regulation has substantially modified flooding and flow regimes, influencing groundwater level behaviour in adjoining connected groundwater systems.

Groundwater systems respond to changes in the water balance by hydraulic transmission of pressure changes (which can be very rapid), and as physical flow of water from areas of high to low hydraulic head. The time needed by a groundwater system to adapt to a new hydrologic equilibrium depends primarily on its storage size, length and hydraulic conductivity (Domenico and Schwartz 1998).

Depth to groundwater also varies within a catchment depending on topographical position and proximity to recharge or discharge areas. Upper-catchment recharge areas are characterised by deeper water table depths, larger vertical hydraulic gradients, and unconfined to weakly confined groundwater conditions. In discharge areas and lower parts of the catchment, groundwater is shallower, has an upward hydraulic gradient, and is often confined or semi-confined by materials of lower permeability. Between these two positional extremes depth to water table has a smaller range of values and vertical hydraulic gradients are less pronounced.

The margin between recharge and discharge areas does not stay constant with time. Hence, the same area can act as a discharge area under wet conditions, when the water table is above it, and as a recharge area under dry conditions, after groundwater recedes below it.

Confined (or semi-confined) groundwater conditions can occur in areas overlain by low-permeability (usually clay-rich) material. Saturated clay generally has a much lower permeability than unsaturated clay. Clays containing swelling minerals such as smectite, bentonite or montmorillonite form macropores or cracks, which act as preferential pathways for groundwater flow. Consequently, these clays exhibit extreme variations in hydraulic conductivity, which are dependent on their moisture content.

Three broad groundwater systems occur within the study area: fractured metamorphosed fold belt terrains, fractured late-Cretaceous–Tertiary volcanics and unconsolidated Cainozoic sediments.

2.5.1 Groundwater systems in the fold belt terrains

The fold belt terrains consist of Palaeozoic to Triassic metamorphosed sedimentary, volcanic and intrusive fractured rock. The hydrogeological characteristics of the terrain most pertinent to this study are greatly reduced primary porosity and permeability. Structural deformation, igneous intrusion, weathering and solution have created secondary fracture porosity and permeability. At the regional scale, bulk permeability is generally very low, but at the local scale it can be extremely variable depending on fracture frequency, size, asperity, connectivity and degree of mineral infill or dissolution. Saturated fold belt systems are generally in good hydraulic connection unless very poorly fractured. Large permeable fractures act as primary conduits between deeper and shallower groundwater systems.

The effects of weathering are usually limited to depths of 100 m. Below these depths, fractures tend to be closed by the weight of the overlying rock. Therefore, the permeability of these groundwater systems generally decreases with depth (Price 1985). However, water-yielding zones have been found even at depths of several hundred metres. Deeper water-bearing zones form the intermediate to regional groundwater systems that drain water beyond the local scale.

Owing to their much lower porosity, fold belt fractured-rock groundwater systems have a much smaller storage size than large sedimentary basins such as the Great Artesian Basin or the Murray Basin. Thus, they respond faster and with greater magnitude to changes in the water balance than large sedimentary basins do.

The bores used in this study are located in fold belt terrains, where they are rarely influenced by irrigation and other human activities.

2.5.2 Groundwater systems in the Cainozoic volcanics

The late-Cretaceous to Tertiary volcanics within the study area are generally well fractured and highly permeable owing to the formation of shrinkage cracks during lava cooling. These systems are characterised by relatively fresh groundwater, high fracture permeability (orders of magnitude greater than fold belt fractured rocks) and high storage capacity. Cainozoic volcanic fractured rocks often form productive groundwater supply systems, and in NSW many are managed as Groundwater Management Areas (GMAs). These systems were excluded from the study because of their vastly different hydrogeological characteristics from those of the older, more widespread fold belt fractured-rock terrains in which saline discharge and runoff are more common.

2.5.3 Groundwater systems in the unconsolidated Cainozoic sediments

The hydraulic and chemical characteristics of the unconsolidated sedimentary groundwater systems are highly variable, depending on environment of deposition and their location in the landscape. Some thick riverine plain sequences composed of sandy gravels have very high primary porosity, permeability and yield characteristics. Dryland salinity is more closely associated with the thinner, more variable upland valley-fill sediments that are anisotropic and inhomogeneous and often have much lower permeability. These characteristics result in the poor lateral and vertical drainage that exacerbates shallow perched water tables and salinity.

In valleys and riverine plains, the fold belt and Tertiary volcanic fractured-rock systems may be overlain by unconsolidated sediments of variable thicknesses. At these locations, the unconsolidated sediments generally control shallow groundwater characteristics and responses.

2.6 Clearing and land use within the study area

Across the rising country in the east of the study area, land is dominantly used for agriculture, mainly grazing by sheep and cattle on largely cleared natural pasture containing a range of annual and perennial grasses, annual legumes and broadleaved weedy species. Mixed farming involving integration of crop and livestock enterprises becomes increasingly important on flatter lands to the west (Figure 3).

During the early years of European settlement, self-sufficiency in agricultural production was a primary goal. As land was explored and opened up for settlement west of the Great Dividing Range, its woody vegetation was progressively cleared, both to allow agriculture to develop and for other purposes.

During the gold rush eras of the early to mid 1800s, timber was in demand for use in mine construction; as fuel; for fencing, dwellings, bridges etc. It was also used for major public construction works such as for railway bridges and sleepers. Two events triggered large-scale clearing after 1860: Crown Land Acts and wire fencing. Crown Land Acts, which sought to open up the selection of Crown Land and break the monopoly of the squatters, imposed so-called ‘improvement conditions’ on the purchase of land, triggering clearing. The introduction of wire fencing promoted sheep raising and the need to maximise fenced areas. Rates of clearing rose to accommodate rising sheep numbers, which increased in NSW from 5 to 63 million between 1860 and 1890. Sheep numbers declined after this during the dryer spells of the first half of the 20th century, ending the need for further massive land clearing.

Although forests and woodlands were features of the Australian landscape, they were not ubiquitous. Extensive areas of natural grassland also occurred. Although these did not require clearing, they were nevertheless changed by various practices, including grazing, cultivation and the introduction of foreign plants, including weeds.

A number of unrelated but parallel events helped shape the direction of ‘vegetational change’ within the NSW MDB: unrealistic stocking rate expectations of early settlers, the concurrent introduction and rapid spread of rabbits, prickly pear and other pests, and droughts (especially the long droughts between 1895 and 1946). In addition, closer (soldier) settlement after the ends of both World Wars, with associated requirements for settlers to fence and clear their holdings and the financial imperative for them to crop lands, largely unsustainably, also contributed to ‘vegetational change’. Economic pressures also contributed to this change. These included labour unavailability during the wars; the Great Depression (1929–1938), with the offer of ‘cheap’ rural labour; and cost–price issues that influenced the type, extent and profitability of farm enterprises. Technological advances also contributed to vegetation change: developments in farming implements; new crop and pasture varieties; new husbandry methods; fertiliser use; agricultural chemicals; and even innocuous inventions such as windmills, poly-pipe, and water troughs, which allowed water for livestock to be able to graze land that was previously ungrazable. However, changes in the 20th century were more pronounced outside rather than within fractured-rock recharge areas of NSW.

Although most broadacre clearing had been completed by the end of the 19th century, trees and other woody plants have regenerated in many areas since that time (notably in the western districts, the Pilliga, and ‘whipstick’ forest formations in the south-west of NSW). More subtle changes have also occurred in the species composition and function of expansive areas subject to a long grazing and cropping history.

Cropping involves destruction of the original perennial grassland, and its replacement with an annual-growing crop–pasture system. Although cropped land may be sown for short periods to perennial pastures, these pose serious cost–benefit challenges. Thus, most farmers who regularly sow crops generally do not sow perennial species during non-crop phases. Cropping exists mainly outside fractured-rock recharge area.

In pastures that are grazed and not cropped, the main change that has occurred in the northern summer rainfall zone is the predominance of relatively unpalatable perennial species, annual species including legumes, and less desirable weedy plants at the expense of the original tall summer-growing grasses. These pastures have retained the functions of the original grasslands, because of the recruitment of species that mimic the functional characteristics of the original vegetation.

In the uniform and winter rainfall zones, there has been widespread loss in the extent, density and health of tall, summer-growing grass communities. These communities have been displaced or considerably modified by grazing, fertiliser application and the accidental or deliberate introduction of winter-growing annuals or perennials. The general changes are that short winter-growing species or unpalatable or short summer-growing ones have replaced tall summer-growing grasses, and that the proportion of cool-season annual species occurring in pastures in spring has increased considerably.

Overgrazing of pastures during drought, and under-grazing during ‘good’ years, coupled with long-duration set-stocking, when animals graze the same areas longer than 6 months, has contributed to pasture modification. Thus, considerable variation in impacts may be observed between farms over time.

3 Methods

The primary data used in the study were long-term rainfall data and SWL data. Rainfall data were obtained from the Bureau of Meteorology (NRME 2004). SWL data were drawn from the former Department of Natural Resources (DNR) database and other sources.

3.1 Rainfall data

3.1.1 Data sources

Within the study area, a total of 343 Bureau of Meteorology rainfall stations recorded monthly Patched Point Data (PPD) between January 1880 and July 2004 (NRME 2004). The PPD dataset is a semi-synthetic dataset that combines the original record with gaps in data in-filled by using a trivariate thin-plate smoothing spline (described in Wahba and Wendelberger 1980), and latitude, longitude and elevation as independent variables.

3.1.2 Data selection, pre-processing and quality assurance

Inspection of residual mass curves and patterns obtained by smoothing annual rainfall data indicated that anomalous patterns often coincided with periods where data were estimated. To overcome potential bias resulting from data filling, a rigorous analysis of each individual rainfall station was carried out, and the rainfall stations with the most reliable data and the fewest missing data were selected for inclusion in the final dataset. After the selection was completed, data from each catchment (DIPNR 2004a) were spatially weighted to derive composite rainfall series.

The numbers of recorded and estimated (patched) rainfall station data were obtained from the SILO website (www.nrm.qld.gov.au/silo/). These numbers enabled stations to be ranked on the basis of the proportion of their records that had been patched since 1900. This procedure identified 92 long-term stations having fewer than 5% missing records. Three additional rainfall stations with a shorter length of record (>50 years) and a low proportion of missing data were included in the dataset to improve the spatial coverage in several catchments.

To ensure consistency in trends between stations, we visually compared the time-series graphs, the residual mass curves, the 7- and 21-year moving average filters, and implemented the cross-correlation analyses. Where rainfall stations were closely clustered, or when their data were inconsistent with the datasets of adjoining stations, stations were removed from the primary dataset. Stations were also removed during further checking for errors and, in the final selection, when they were not spatially representative of the study area.

These quality assurance procedures resulted in considerable attrition of the original dataset (Table 1). The procedures ensured, however, that the data used in the project were of verifiable high quality.

For each subdivision of the major basins (Figure 2), data from the verified rainfall stations were used to calculate a single, area-weighted dataset. The weighting coefficients were calculated as the ratio between number of bores located closest to each contributing station and the total number of bores in the subdivision.

The exception was the Gwydir catchment, where only 2 verified rainfall stations closely represented the rainfall near the recharge areas of most of the bores. These were at Bingara Post Office, in the centre of the catchment, and at Barraba Post Office, in the adjacent Namoi catchment, just outside the Gwydir catchment boundary. To provide a composite dataset for the Gwydir catchment in the study area, data for these stations were averaged.

In summary, the final rainfall dataset consisted of annual rainfall data-series for each of the selected PPD rainfall stations listed in Table 1, together with a composite area-weighted dataset (or averaged dataset in the case of Gwydir) for each catchment subdivision for which bore data were available.

Table 1: Selection of PPD rainfall stations

Catchment	Available PPD rainfall stations	More than 95% recorded data since 1900	Selected PPD stations
Border Rivers	17	6	1
Gwydir	25	9	2
Namoi (New England)	24	10	5
Peel	8	2	5
Macquarie	48	14	5
Lachlan	87	24	20
Murrumbidgee	108	20	15
Murray	31	10	2

3.2 Bore data

As outlined in section 1.2.3, the approach adopted in this work consisted of developing a composite SWL time series from the SWL that was recorded when each bore was constructed. Annual samples were derived for each year in each catchment or section.

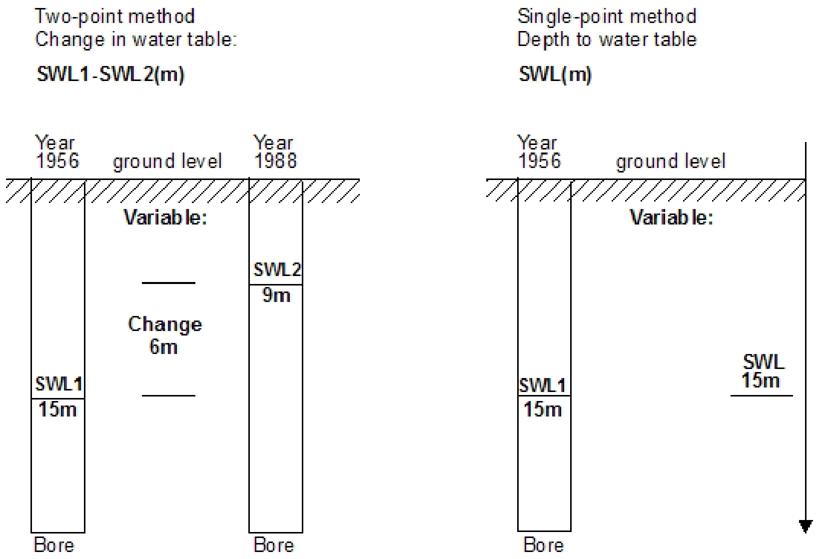
The main difference between this approach and that used in the Macquarie Valley study by Salas and Smithson (2002) is that their study was based on the difference in SWL between two points in time (date of construction and 1988; ∆SWL), whereas our study uses only SWL data recorded by the drillers when they constructed the bores. This approach, illustrated in Figure 7, does not require a second measurement of the SWL of each bore. Thus, it is more time-efficient, and it potentially provides a larger statistical sample.

3.2.1 Data sources

Data were primarily sourced from the Department of Water and Energy (DWE; formerly DNR and DIPNR) Groundwater Data Systems (GDS) database (DIPNR 2004b), which held data for a total of 33 104 bores in the study area. In addition to their date of completion and the SWL on that date, the database also contained information relating to the rock types and other features of the site in the form of drillers' reports. As some bores had several water-bearing zones, each with SWL data, the database provided a total of 40 599 data points. Additional data were available for 23 bores in the Murray East GDS (DIPNR 2005).

The GDS contained information about bores in different groundwater systems, but it did not have an attribute field that allowed data to be selected on that basis. A methodology was thus devised that identified fractured-rock bores on the basis of the GDS data and geographic information system (GIS) information. The digital spatial layers that were most useful for this purpose were NSW geology (Figure 6; base scale 1:250 000), the GMA map (DIPNR 2004c) and the topographic map (Figure 3).

Figure 7: The two-point (ΔSWL) method of detecting change in standing water level (Salas and Smithson 2002) vs single-point method adopted in this study



Note that SWL is measured relative to the ground surface. Decreasing SWL thus indicates rising water level; negative SWL value indicates water level above the ground surface (i.e. artesian flowing bore).

3.2.2 Data selection, pre-processing and quality assurance

The SWL data were analysed separately for each of the catchments in the study (Figure 2). As the goal was to select only true fractured-rock bores, shallow bores in unconsolidated material located within the fractured-rock areas had to be eliminated. Owing to some imprecision in the bore coordinates and maps, we found that a few fractured-rock bores were placed within the alluvial and Cainozoic volcanic areas, or vice versa. Some true Palaeozoic fractured-rock bores were also found within the alluvial and Cainozoic volcanic areas, but close to their edges. As the intention was not to leave these bores out, it was not sufficient to base the selection purely on the position of the bores within the mapped geology; it became necessary to look also at the water-bearing zone types and the geologic horizons, as described in the drillers' reports. This was approached in a systematic way. Bores were categorised and the selection rules were derived and implemented for each category. Finally, we decided to take out all those fractured-rock bores positioned close to alluvial areas in places where they could be influenced by the alluvial groundwater systems.

As presented in Table 2, the process of bore selection involved: (i) classification of bores based on the geological and GMA maps into 3 classes and further division into 7 groups based on description in the GDS; (ii) selection of bores that were in shallow fractured rock; and (iii) elimination of those fractured-rock bores which may have been influenced by alluvial groundwater systems.

3.2.2.1 Classifying bores into groups

The grouping of bores was based on the mapped geology and on the GDS description of the water-bearing zones (WBZ).

The latitude and longitude of each bore were projected onto the geological and GMA maps, and the bores were classified into three classes: unconsolidated sediments; Cainozoic volcanic rock; and fractured rock of the New England Fold Belt, Gunnedah Basin and Lachlan Fold Belt (Figure 2). Bores were classified as fractured-rock bores only if both the geological and GMA maps indicated this to be the case.

Table 2: Bore selection

Class		Uncosolidated sediments					Volcanics		Fractured rock							Additional SWL points	Total
Class No		I					II		III								
Group		FR	Unc	N/A	Total		WBZ	Bores	FR	Unc	N/A	Total		Total			
Group No		1	2	3	WBZ	*Bores*	4		5	6	7	WBZ	*Bores*	WBZ	*Bores*		
	Available	21	83	103	207	*151*	1001	*774*	60	9	91	160	*206*	1368	*1131*		
Border Rivers	Selected	0	0	0	0	*0*	15	*15*	29	4	36	69	*69*	84	*84*	0	84
	Available	18	18	61	97	*107*	354	*303*	298	48	201	547	*536*	998	*946*		
Gwydir	Selected	4	1	0	5	*5*	3	*3*	108	13	49	170	*170*	178	*178*	13	191
Namoi New	Available	131	334	332	797	*577*	31	*21*	670	181	518	1369	*1219*	2197	*1817*		
England FB	Selected	29	2	10	41	*41*	3	*3*	272	7	99	378	*378*	422	*422*	0	422
	Available	103	207	170	480	*612*	12	*6*	2330	397	1304	4031	*3145*	4523	*3763*		
Peel	Selected	43	0	4	47	*47*	1	*1*	811	3	167	981	*981*	1029	*1029*	28	1057
Namoi	Available	211	3936	1302	5449	*3217*	88	*99*	456	164	271	891	*801*	6428	*4117*		
Gunnedah B	Selected	64	4	14	82	*82*	1	*1*	127	6	34	167	*167*	0	*0*	0	0
	Available	440	846	623	1909	*1669*	848	*634*	2276	255	1470	4001	*3458*	6758	*5761*		
Macquarie	Selected	90	0	23	113	*113*	17	*17*	896	9	196	1101	*1101*	1101	*1101*	0	1101
	Available	795	2977	1153	4925	*4167*	397	*282*	2011	273	1231	3515	*3010*	8837	*7459*		
Lachlan	Selected	178	53	60	291	*291*	19	*19*	789	10	267	1066	*1066*	1376	*1376*	26	1402
	Available	460	1269	865	2594	*2269*	56	*45*	2210	225	2130	4566	*3877*	7216	*6191*		
Murrumbidgee	Selected	100	0	5	105	*105*	0	*0*	608	7	409	1024	*1024*	1024	*1024*	0	1024
	Available	225	1082	390	1697	*1420*	5	*5*	295	98	179	572	*494*	2274	*1919*		
Murray	Selected	14	1	1	16	*16*	0	*0*	90	1	34	125	*125*	141	*141*	51	192
	Available	2404	10752	4999	18155	*14189*	2792	*2169*	10606	1650	7395	19652	*16746*	40599	*33104*		
Total	**Selected**	268	57	75	400	*400*	41	*41*	3603	54	1257	4914	*4914*	5355	*5355*	118	5473

Selected bores shaded yellow.

Unconsolidated sediments and fractured-rock classes were further subdivided according to the description in the GDS of each water-bearing zone: fractured and consolidated water-bearing zones, which were treated as a single category (FR); unconsolidated (Unc); and unknown water-bearing zone (N/A) (Table 2). This resulted in seven groups of bores (three categories for areas defined by the geological map as unconsolidated sediments, three for fractured-rock areas, and a single remaining category for Tertiary volcanic areas).

3.2.2.2 Selection of bores for inclusion in the dataset

Bore selection within each of the seven groups was based on the depth of water-bearing zones and the zone position within the geologic sequence noted in drillers' reports.

Two depth rules were imposed. The minimum depth rule aimed to eliminate shallow bores whose water-bearing zones may occur in perched (unconsolidated) groundwater systems overlying the fractured rock. The maximum depth rule aimed to minimise SWL outliers (extreme values), which generally coincided with deep water-bearing zones and high vertical hydraulic gradients, typical of recharge zones near the top of ridges and discharge zones in catchment lowlands. Deep fractured-rock water-bearing zones are found in catchment lowlands on account of the thick deposits of unconsolidated materials there. The SWL is either a very small positive value, or more often a negative value representing an extreme value. Eliminating deeper bores also provided confidence that only the local and locally recharged groundwater systems were sampled.

Water-bearing zones were considered shallow if they were located within the top:

- 10 m, for bores located in fractured-rock areas: fractured-rock zone (group 5 in Table 2)
- 16 m, for bores in fractured-rock areas: unknown and unconsolidated zone (groups 6 and 7)
- 20 m, for bores located in unconsolidated sediments (groups 1, 2 and 3).

Bores within these categories were eliminated unless a driller's report indicated that the water-bearing zone was fully contained within fractured rock.

Water-bearing zones were defined as deep if the top of the zone occurred below 60 m, and eliminated. Bores remained in the dataset if their water-bearing zones were fully contained within the top 45 m.

Remaining bores (i.e. water-bearing zones deeper than 45 m, but not starting below 60 m) were not eliminated, provided drillers' reports indicated that they were fully contained within a single fractured rock starting at a depth shallower than 30 m:

- For highland fractured-rock recharge areas, we assumed that 30 m was the depth of considerable weathering. Water-bearing zones that were fully contained within a single rock material, which includes the weathering zone, would most likely be recharged locally, and thus be representative of the shallow fractured-rock groundwater system. Where the profile consisted of series of layered rock materials, some materials could limit the water-bearing zone capacity to being recharged locally.
- For lowland areas, the 30 m depth constraint ensured less than 30 m of unconsolidated overburden, which means that the selected bore was not deep in the alluvial flats, but outside or just at the alluvial–fractured-rock boundary, reducing the possibility of the water-bearing zone being influenced by water in the alluvial systems.

As indicated by drillers' logs, the water-bearing zones of some bores in groups 2 and 6 (unconsolidated material; Table 2) were likely to have represented weathered fractured-rock zones. Provided the other criteria were met, these bores were included in the final dataset.

Bores in Tertiary volcanic areas (class 2, group 4) were also included if the driller's report showed that the associated rock material was not related to the Tertiary volcanic rocks. In addition, the bore had to satisfy the same criteria as the other fractured-rock bores.

Bores with multiple water-bearing zones were processed individually.

In the first half of the 20th century, bores were drilled using a cable tool with simultaneous progressive sinking of the screen (drill and drive method). Drillers using this technique were able to record SWL in each water-bearing zone. Where this was the case, we used the SWL data for the shallowest fractured-rock water-bearing zone. With the introduction of rotary mud drilling, pumping tests were generally performed after the bore was drilled, and the resulting SWL was not representative of a particular zone. These data were not included unless the topmost water-bearing zone in the fractured rock was the only zone that was screened.

While stock and domestic bores generally have a single pipe running down the borehole, monitoring bores may have multiple pipes. If the information was available, construction details and drillers' reports were used to select appropriate water-bearing zones.

Bore data for the Border Rivers and Murray catchments were sparsely represented in the GDS, having either not been entered or gone missing. In the Murray catchment, water level data were recorded in the Boremaster database, but the drillers' records and other bore construction information remained in its original paper form. Thus, additional water level data for 23 bores selected from the GDS were extracted from the Boremaster database.

Bore selection analysis was automated in Excel to achieve efficiency and objectivity. The features of the deepest logged horizon (upper and lower margins and geological material) were easily accessible in Excel. Suspicious water-bearing zone data was tagged for additional checking against the driller's log sequence. These procedures resulted in three possible outcomes: data were rejected, selected or nominated for further investigation. Some bore records, especially early records, that needed further investigation were checked individually, taking into account the full driller's record, proximity to streams (DIPNR 2004d) and records of nearby bores in addition to already mentioned sources.

3.2.2.3 Screening for the influence of alluvial groundwater

A small number of fractured-rock bores were selected from areas mapped as unconsolidated sediments (Table 2). These bores were close to the border between fractured rock (with water-bearing zones) and alluvial flats. They either had a shallow alluvial layer or were entirely in the fractured rock, but owing to the imprecise mapping or to scale problems, they appeared as mapped in unconsolidated sediments. The final step in bore selection was to compare trends in SWL between these bores and adjacent bores located in mapped fractured-rock areas. This precautionary step ensured that the behaviour of fractured-rock bores mapped within unconsolidated geology was not influenced by nearby alluvial groundwater systems. Groups of bores whose SWL trends diverged from those known to be in mapped fractured-rock areas were removed from the dataset (Murrumbidgee, Macquarie).

3.3 Data analysis

There were 3 phases in data analysis:

- rainfall analysis to define wet and dry periods in the long-term record
- SWL data analysis to define periods of high and low groundwater level independent of rainfall
- analysis of the relationship between the time series of rainfall and SWL to determine whether changes in SWL could be explained by the changes in rainfall, and if so, to gain some understanding of the processes involved.

3.3.1 Rainfall data analysis

Statistical analysis was performed on individual, selected rainfall station data, as well as on the composite (area-weighted) rainfall datasets for each catchment section (see section 3.1.2). The rainfall series consisted of long-term (Jan 1800 to Jul 2004) monthly rainfall data, transformed into annual (1880–2003) rainfall data.

3.3.1.1 Exploratory analysis of rainfall data

The rainfall shift which occurred in the 1940s in and around the Pacific and Indian oceans has been reported and analysed by various authors (Kraus 1955a; Kraus 1955b; Hobbs 1971; Pittock 1975; Cornish 1977; Russell 1981; Pittock 1983; Allan *et al.* 1995; Mantua *et al.* 1997; Biondi *et al.* 2001; Gedalof and Smith 2001; Franks and Kuczera 2002; MacDonald and Case 2005; Verdon and Franks 2006; Verdon *et al.* 2006). We further explored and analysed rainfall data to examine whether the climate shift affected all parts of the study area equally, to pinpoint the timing of this shift more precisely, to examine similarities and differences in rainfall patterns across the study area and to derive long-term rainfall trends so they can be later compared with the long-term trends in SWL.

The exploratory analysis used residual mass curves and the moving-average technique. Residual mass curves were constructed from monthly and annual rainfall data to explore the existence and precise timing of the rainfall shift across the study area. Trends in rainfall were explored using moving-average filters. Residual mass curves and moving-average graphs were plotted for all selected rainfall stations. Both techniques represent low-pass filters, which smooth the data, attenuate short-term variability and accentuate underlying trends.

Definition and interpretation of residual mass curves

A residual mass curve represents the cumulative sum of deviations from the long-term average:

$$\sum(X_i - m)\cdot\Delta t,$$

where Δt is the time step or time interval (year, month, day, hour, minute, second …); X_i is the ith element of the series, representing the average value over time interval Δt (mm/year, mm/month …); and m is the long-term average (mean), expressed in the same units as X_i.

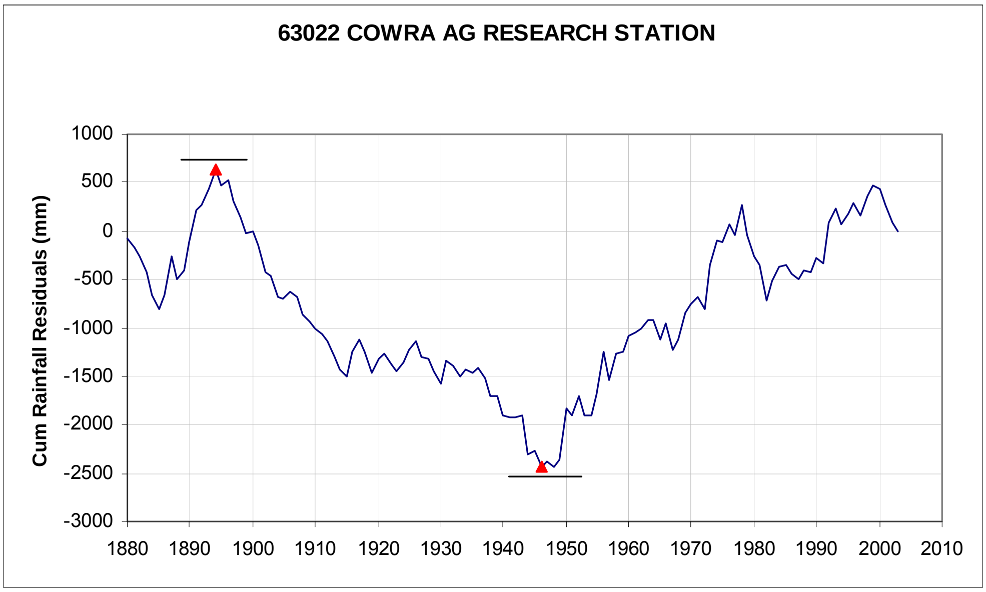
The residual mass curve is an approximation of an integral of deviations from the average (the sum becomes an integral when the time-step approaches zero):

$$\int(X(t) - m)\mathrm{d}t.$$

The extremes of the residual mass curves are used to detect and illustrate abrupt changes in the mean (Figure 8). Slopes of the segments between the extremes (first derivative of the integral) correspond to the values of the mean preserved during each segment. A positive slope (rising trend) indicates that the period is characterised by the mean being greater than the long-term mean, and a negative slope (falling trend) indicates the opposite. If the residual mass curve shows a pointy ‘V’ shape (discontinuity of the first derivative), the system abruptly changed from one regime (mean) to another. A smooth ‘U’-shaped curve (continuity of the first derivative is preserved) indicates a smooth transition.

The residual mass curve (Figure 8) was constructed from annual rainfall data (mm/year) covering the period 1880–2003. Note that the units of the residual mass curve are mm. A similar curve could be constructed from the monthly data, or data collected over any smaller time-step, and the mm units would be preserved.

Figure 8: Example of residual mass curve (in blue) with extremes (red triangles) which show the timing of two major changes in rainfall regimes



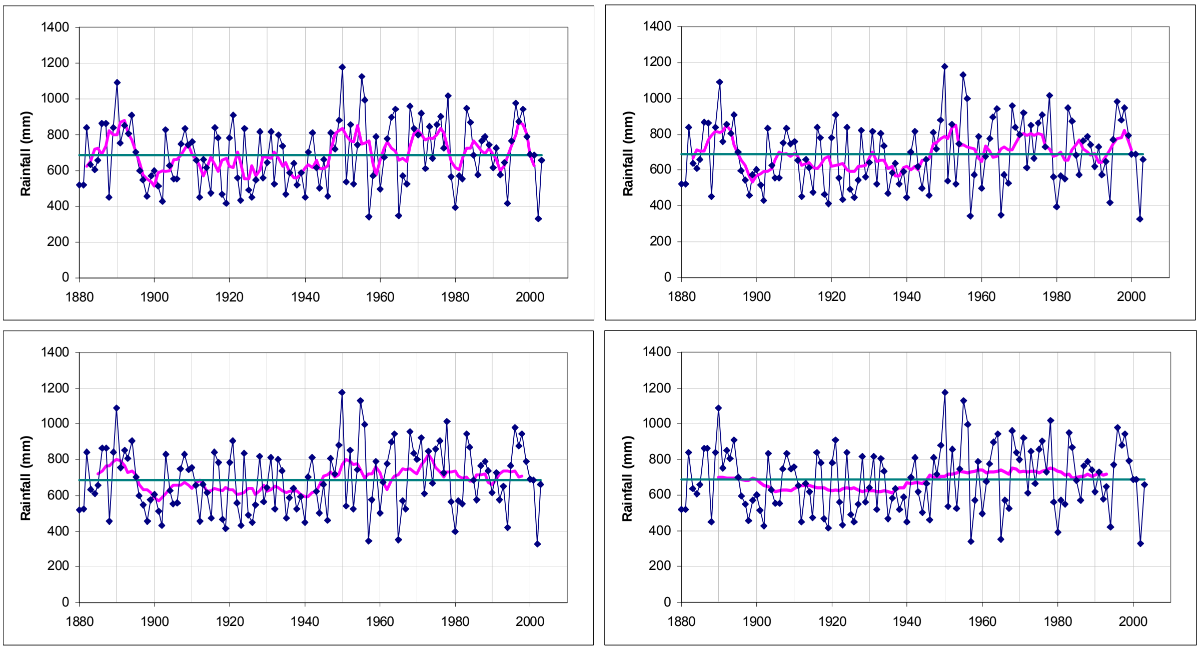
The graph shows an initial wet period (rising trend to 1894), then a dry period (falling trend from 1895 to 1946), followed by a wet period (rising trend) from 1947. The period 1895–1946 was dryer than the long-term average by about 60 mm/year (calculation based on approximately 3000 mm difference accumulated over five decades: 3000 mm / 50 years = 60 mm/year). The period 1947–2000 was wetter than the long-term average by approximately 60 mm/year. The increase in the mean annual rainfall after 1947 is therefore about 120 mm/year. The change in hydrologic regime was abrupt ('V' shape). A dry 1895–1946 period shows extremely dry conditions (steep downward slope) at the beginning (Federation Drought until 1915) and at the end (World War II droughts), while the middle of the period (1916–1936) is characterised with more average conditions (flatter slope). The wet period after 1947 was initially wetter than in later years, as seen from a steeper upward slope that gradually changed to an oscillatory pattern around a horizontal line from the late 1970s, signalling a return to average conditions.

Choice of the 21-year moving-average filter

Time series with moving averages ranging from 5 to 31 years were tested to find the most appropriate one that would adequately describe long-term rainfall trends and accentuate the difference in rainfall regime caused by the mid-century rainfall shift.

It can be seen from Figure 9 that the short-interval moving averages (5 and 7 years) accentuate short-term variability, medium-interval averages (11 years) are more useful for identifying medium trends, and the longer-interval averages (21 years) depict long-term trends and major changes in rainfall regime. In Figure 9 the oscillations of the 5-, 7- and 11-year moving averages repeatedly cross the long-term average, both before and after 1947, while the 21-year moving average clearly distinguishes the change in rainfall after 1947, clearly illustrating average long-term rainfall values during two distinct rainfall regimes. The powerful 21-year moving-average filter proved to be ideal in removing high-frequency signals and revealing the low-frequency signal of the process that changes phase at 50-year intervals. An odd number (21) follows the convention of plotting the average at the mid point.

Figure 9: Curves illustrating the filtering effect of applying (left to right, top row) 5-year, 7-year, (bottom row) 11-year, and 21-year moving averages (red trace) to annual rainfall data (—•—) for Forbes; green horizontal line indicates the long-term average rainfall of 687 mm



Comparison of Figure 8 and Figure 9 suggested that the 21-year moving average attenuated the short-term rainfall fluctuations to a similar degree as when a residual mass curve was used. This confirmed that the length of the moving-average filter was appropriate, and that the low-frequency signal associated with climate shift was clearly exposed.

The choice of a long interval for the moving average was even more crucial for reliable representation of the SWL trends, as early bore records had very few observations and large gaps. There were often only one or two SWL points within any 12-month period, from which the annual median was derived. Such a small sample size inevitably resulted in a large scatter, a wide range of values and a high variance of the early annual SWL records. Many sources cause this dispersion of SWL values, but local position in the landscape (water table being much deeper at the top of a hill than in a valley) is the primary cause. There were often only 5 to 7 years in which these noisy SWL data were recorded over any two decades in the period before 1950. Even in the period 1950–1970 the SWL data often had a large number of gaps. A long interval, spaning 21 years, meant that a sufficient number of SWL data were used for the calculation of the average and that the trend estimates were reliable.

We also found that the 21-year moving average applied to SWL data produced very similar, but delayed, trends to those obtained by the rainfall. This had two advantages: it allowed for a simple visual estimate of the groundwater response time; and any significant effect that was unrelated to climate would be clear, as it would cause the trends to deviate after the effect until the new equilibrium in SWL was reached. For example, a significant increase in recharge not related to rainfall would cause the SWL trend-line to rise more (or fall less) than the rainfall trend-line.

Therefore, we chose the 21-year moving average to represent rainfall and SWL trends.

3.3.1.2 Change-point analysis of rainfall data

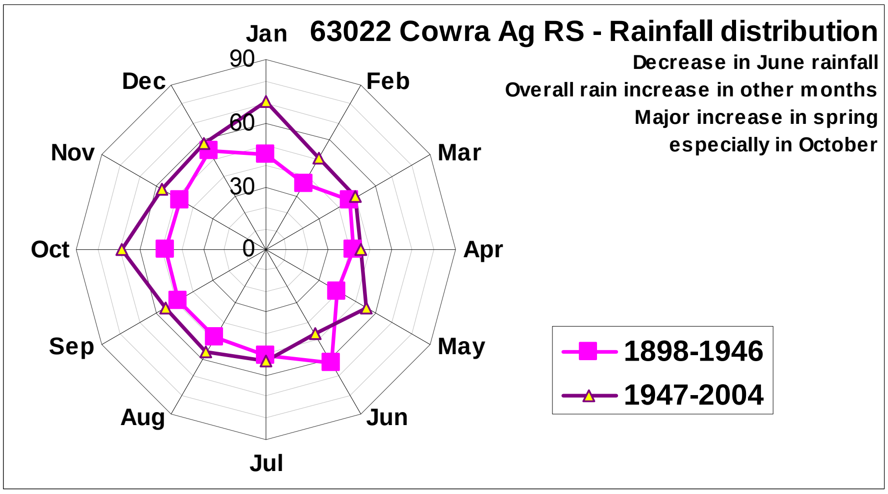
Change-point analysis was undertaken using the software package Change-Point Analyser v. 2.3 (Taylor 2000), which is specifically designed to detect abrupt changes in mean values as well as abrupt changes in variability in time-ordered data. The package has several advantages, including that it automatically verifies assumptions, checks for outliers and guides the user in handling such cases. It is also capable of detecting subtle changes that may be missed by control charts, and it provides confidence levels and confidence intervals for change points.

The approach uses residual mass curves to detect change points by identifying the extremes in residual mass curves (Figure 8), and bootstrap analysis to assign confidence levels. Bootstrapping is a distribution-free approach. The only assumption for a bootstrap is that the resampled data are independent and identically distributed. Once a change has been detected, the data are segmented each side of the change, and the analysis is repeated for each segment. The procedure is iteratively repeated until all abrupt changes with a confidence level above the set limit (minimum 90%) have been accounted for.

Changes in variation within the data over time are also examined by performing change-point analysis on the difference between consecutive data pairs (i.e. data corresponding to (X_1, X_2), (X_3, X_4), (X_5, X_6) etc., where X_i (i = 1, n) is an element of the time series).

An abrupt change in rainfall regime is also known as a rainfall shift. A change point in rainfall regime is also known as the timing of a rainfall shift. Change points were analysed for all selected rainfall stations and for the composite rainfall for each section of the study area (defined in Table 3). The average monthly rainfall was calculated for the periods before and after the rainfall shift for all selected rainfall stations. This was done to examine whether changes in the seasonal distribution of rainfall accompanied the rainfall shift. The results of this analysis were plotted as radar graphs (Figure 10).

Figure 10: Example of radar graph, showing change in monthly rainfall (mm) associated with the change in rainfall regime in 1947 (analysis based on recorded monthly rainfall data only, and does not include estimates before 1898)



3.3.2 Bore data analysis

The bore dataset included the year of construction, the SWL, and the latitude and longitude, which allowed individual bores to be allocated to basin catchments (Figure 2). Time-series data from the same bore are usually required for analyses which investigate trends in groundwater data. However, as previously stated, the data that were available for use in this analysis came from different bores, in which SWL was sampled only once, at the time each bore was drilled. This resulted in confounding of the spatial and temporal variations. The data selection procedure described in section 3.2.2 was designed to minimise the possibility of including non-fractured-rock bores, or bores whose SWL data may be suspect, in the final dataset. The procedure was also designed to maximise the bore data in the dataset.

3.3.2.1 Development of composite SWL time series

Although the rainfall data represented a true time series, the bore data consisted of a variable number of SWL points for each year up to August 2004. SWL data were not available for every year. Data were sparse in the early records, and were geographically clustered in some years, thus potentially giving rise to spatial-temporal confounding.

Of the possible approaches that we investigated for deriving data values for the composite SWL time series (such as using arithmetic means, spatially weighted averages or medians) we found annual medians to give the most convenient and robust measure of central tendency. For each catchment (Figure 2) and subsection (Appendix, Figure 26), composite SWL time series were thus constructed using the median annual SWL values.

Using the latitude and longitude of individual bores, we obtained additional information, including altitude, FLAG UPNESS and WETNESS indices (Roberts *et al.* 1997), land use and land capability, from the various GIS layers available within former DNR. These data were appended to the SWL data files.

3.3.2.2 Exploratory analysis of bore data

The initial exploratory analysis highlighted the need to subdivide the three southern, longer catchments (Appendix, Figure 26), resulting a in total of 12 catchment sections:

- Border Rivers
- Gwydir catchment
- Namoi catchment
- Peel catchment
- Macquarie catchment
- Lachlan catchment: East, Mid, West
- Murrumbidgee catchment: Murrumbidgee East, also known as the Upper Murrum-bidgee, the entire catchment area upstream of Burrinjuck Dam; and Murrumbidgee West, the catchment downstream of Burrinjuck Dam within the Lachlan Fold Belt
- Murray catchment: East and West.

These 12 sections were further examined using exploratory analysis routines in S-Plus 7 software (Insightful Inc., 1995).

The exploratory data analysis aimed to maximise insights into the data, to uncover their underlying structure, to extract important variables, to detect outliers and anomalies, and to test underlying assumptions. Histograms, scatter plots, LOESS plots and three-dimensional surface splines were used. The summary statistics of the number of data points available for analysis each year were also calculated.

The specific details sought in the exploratory phase of data analysis were:

- the number of data points available for analysis
- the relationship between SWL and elevation
- issues such as confounding of SWL by elevation over time
- the spatial confounding of SWL data by years
- the spatial confounding of SWL data by land use
- whether geographic variables (UPNESS, WETNESS and elevation) were useful co-variables in explaining relationships between SWL and rainfall
- the spatial distribution of UPNESS and WETNESS
- the nature of the relationships between SWL and UPNESS.

3.3.2.3 Refining catchment subsections for analysis

In response to the outcome of exploratory analysis, the large areas of Lachlan West and Murrumbidgee East and West were further subdivided with the aim of creating more homogeneous datasets and reducing possible effects of spatial/temporal confounding. Murrumbidgee East was split into northern and southern parts. The areas which contained the majority of bores in the eastern parts of Lachlan West and Murrumbidgee were named Lachlan Inner West and Murrumbidgee Inner West. This resulted in a total of 16 subsections (Table 3 and Appendix, Figure 26).

SWL data for 10 out of these 16 subsections were subject to detailed statistical analysis. The Border Rivers and both sections in the Murray catchment were excluded from the detailed statistical analysis owing to data sparsity. Trends in the Lachlan Inner West and Murrumbidgee Inner West showed similar patterns to those in the entire western subsections, indicating that spatial/temporal confounding was not a major issue, and eliminating the need to perform separate detailed statistical analysis for the Inner West subsets (Table 3 and Appendix, Figure 26).

Table 3: Sections subject to SWL analysis

Section/subsection	Trend and residual mass curve analysis	Exploratory analysis in S-Plus 7	Detailed statistical analysis	Approximate geographic limits
Summer rainfall zone				
Border Rivers	Yes	Yes	No	East of the boundary with the Great Artesian Basin to the crest of the Great Dividing Range
Gwydir River	Yes	Yes	No	East of the boundary with the Great Artesian Basin to the crest of the Great Dividing Range
New England portion of Namoi River	Yes	Yes	Yes	East of the boundary with the Gunnedah Basin to the crest of the Great Dividing Range
Peel River	Yes	Yes	Yes	Entire catchment of the Peel River
Uniform rainfall zone				
Macquarie	Yes	Yes	Yes	South-east from near a line between Dubbo and Narromine to the crest of the Great Dividing Range
Lachlan East	Yes	Yes	Yes	East of 149°E (~40 km west of Cowra) to the crest of the Great Dividing Range
Lachlan Mid	Yes	Yes	Yes	Between about 148.5°E and 149°E (from ~20 km west to 40 km east of Cowra)
Lachlan West	Yes	Yes	Yes	West of 148.5°E
Lachlan Inner West	Yes (additional)	No	No	Portion of Lachlan West between 148.5°E and 146.8°E (near Kacatoo)
Murrumbidgee East	Yes	Yes	No	Murrumbidgee catchment upstream of Burrinjuck Dam
Murrumbidgee South-East	Yes (additional),	No	Yes	Southern portion of Murrumbidgee East (south of 35.3°S), including areas around Canberra and Cooma
Murrumbidgee North-East	Yes (additional)	No	Yes	Northern portion of Murrumbidgee east, north of 35.3°S—Yass river catchment and surrounding area
Winter rainfall zone				
Murrumbidgee West	Yes	Yes	Yes	Entire contributing catchment within the study area downstream of Burrinjuck Dam
Murrumbidgee Inner West	Yes (additional)	No	No	Subset of Murrumbidgee west between Burrinjuck Dam and 147.8°E (~5 km east of Tarcutta) and north of 35.1°S (near South Gundagai)
Murray East	Yes	Yes	No	Upper Murray catchment, east of 147°E (near Hume Dam)
Murray West	Yes	Yes	No	Lower Murray catchment, west of 147°E (Hume Dam) to the border with Mesozoic rocks of the Murray Basin

(additional) - additional subsection in which only a part of already formed section is analysed: Lachlan Inner West is part of Lachlan West; Murrumbidgee East is split into South East and North East and Murray Inner West is part of Murray West.

3.3.2.4 Trend analysis of bore data

Residual mass curves and 21-year moving-average charts were produced for all 16 sections listed in Table 3. The moving average was plotted on the central year (*Y*): for year *Y* it is the arithmetic average of all median annual SWL values from 10 years before to 10 years after year *Y*.

3.3.2.5 Change-point analysis of bore data

The composite bore datasets for catchment sections chosen for detailed statistical analysis (Table 3) were subject to change-point analysis using the same approach outlined for the analysis of rainfall data (see section 3.3.1.2).

3.3.3 Relationship between rainfall and standing water level

The main aim of the analysis was to investigate the relationship between SWL and rainfall. In the initial phase, exploratory graphical techniques were used to compare trends in each.

The moving averages and residual mass curves cannot be used for regression analysis, as consecutive data points are not independent. In general, the cross-correlation of filtered data results in auto-correlated error terms, so the correlation cannot be assessed. Thus, even though a relationship between trends in rainfall and SWL can be obvious when the plots are overlaid (see Appendix, Figure 22), this relationship cannot be quantified using regression. Therefore, we investigated the relationship between annual rainfall and SWL.

The data were subjected to spectral analysis and cross-correlation analysis, followed by multiple regression analysis.

3.3.3.1 Trends in rainfall and SWL and residual mass curves

The differences in response time (lag) between rainfall and SWL were examined by comparing plots of the 21-year moving average of rainfall with the 21-year moving average of SWL (see Appendix, Figure 22) and the corresponding residual mass curves. This gave initial estimates of the time-delay response of groundwater to rainfall and identified the sections and time-segments in which a clear relationship between rainfall and SWL was visible (SWL pattern replicated the rainfall pattern, with a delay) or missing (SWL pattern diverged from the rainfall pattern).

3.3.3.2 Statistical analysis of the relationships between annual rainfall and SWL

This section deals with the analysis of the mean annual rainfall time series and the median annual SWL time series. Our objective was to see whether the annual SWL could be explained by the annual rainfall data, assuming a simple temporal displacement relationship.

Statistical complexities

We used the cross-spectral analysis and the cross-correlation analysis to look at the relationship of the two time series. We did the spectral analysis to see whether there were any simple periodicities that we could use to improve our regression models. Although the data were very complex, the simple models were used to get a handle on the various components that could be important.

There were three basic statistical problems in quantification of the periodic components of physical process:

1. Non-stationary properties had to be removed from the data before spectral analysis, as their presence might have masked periodicities in the data. The rainfall and SWL data were generally non-stationary, as the expected values of the mean and the variance were not constant throughout the data set. The variance was stabilised using a log-transformation. The log-transformed values of rainfall and SWL were detrended by fitting splines with three degrees of freedom, with time as the independent variable and rainfall and SWL as the dependent variables.

2. The periodicities in rainfall and SWL data could be non-sinusoidal. The spectral and cross-spectral analysis methods assume that the periodic processes may be fitted with

a sine or cosine wave. This confounds the interpretation of the analyses by distributing the harmonic variances at frequencies higher than the true periodic process.

3 The rainfall and SWL data were complex and possibly contained more than one periodic component.

Other issues concerned the quality and availability of data. For most catchment sections, the SWL data before 1950 were very patchy. There may also have been spatial confounding of SWL with the temporal data. The results of the analysis should be interpreted with these complexities in mind.

Spectral analysis

Spectral analysis explores cyclical patterns in data. The purpose of this type of analysis is to decompose a complex time series with cyclical components into a few underlying sinusoidal (sine and cosine) functions of particular wavelengths. The term ‘spectrum’ provides an appropriate metaphor for the nature of this analysis, since performing spectrum analysis on a time series is like putting the series through a prism in order to identify the wavelengths and importance of underlying cyclical components. As a result of a successful analysis one might uncover just a few recurring cycles of different lengths in the time series of interest, which at first may have looked more or less like random noise. For a more detailed discussion of spectral analysis see Bohrer and Porges (1982), Chatfield (1975) or Gottman (1981).

Log-transformed and detrended rainfall and SWL time-series values were used for the spectral analysis, to make sure that the periodogram and density spectrum were not ‘overwhelmed’ by a very large value for the first cosine coefficient (for frequency 0). Proc SPECTRA in SAS V. 9.1 (SAS Institute Inc., 2006) was used for the detection of periodicity. The Parzen kernel was used to smooth the periodogram.

The complete time series were needed only for spectral analysis. Data analysis was carried out from a year when the SWL data did not have lots of missing points. For example, in Gwydir it began in 1954. If there were one or two missing data points in the SWL record, they were interpolated using splines (Proc EXPAND in SAS).

Cross-spectral analysis

The purpose of cross-spectral analysis is to uncover the correlations between two series at different frequencies. Detailed discussions of this technique can be found in Bloomfield (1976), Jenkins and Watts (1968), Brillinger (1975), Brigham (1974), Elliott and Rao (1982), Priestley (1981), Shumway (1988) or Wei (1989). Cross-spectral analysis generates a coherence function. Coherence is the square of the correlation between the two processes at a specific frequency. The coherence at any specific frequency is the square of the cross-spectral density divided by the product of the spectral densities of each series at the specific frequency. This is similar to the calculation of the squared correlation coefficient (i.e. the coefficient of determination). The cross-spectral density parallels the squared cross-products, and the spectral densities parallel the variances. Conceptually, the coherence may be thought of as a time series analogue of η (eta), or the proportion of variance accounted for by the influence of one series on the other at each specific frequency.

The cross-spectral analysis also generates the phase, which measures the time lag between two time series. The phase shift estimates are computed as tan-1 of the ratio of the quad density estimates over the cross-density estimate. The phase shift estimates (usually denoted by φ, phi) are measures of the extent to which each frequency component of one series leads the other.

Cross-correlation analysis

Cross-correlation is the correlation of one time series with a time-lagged version of a second time series. The cross-correlation function provides information on the statistical dependence of one series on another, assuming simple temporal displacement. If the two time series are identical, the peak value of the cross-correlation function will be unity at the lag that makes the two series identical and less than unity at all other lags. In most cases, since the second series is not simply a time-shifted version of the first series, the peak value of the cross-correlation will be less than unity. Cross-correlation techniques lose their effectiveness and sensitivity at assessing the communality between two series when the difference between the series is more than a temporal displacement.

3.3.4 Steps in analysis

For model fitting with cyclic terms the assumption is that the cycles or a seasonal component is known. In this case the nature of cycles was not known. Spectral analysis was carried out to get an idea of the cyclic nature of the time series. The data are often detrended before spectral analysis. Proc GAM in SAS was used to fit a spline with 3 degrees of freedom to the log-transformed SWL and rainfall data. The residuals from the model were used for further analysis. Spectral analysis was done on both the SWL and rainfall series to look at the periodicity in the individual series. The periodicity in these series was estimated by spotting the peaks in the spectral density plots.

Cross-spectral analysis of the two series followed the spectral analysis. The purpose of the cross-spectral analysis was to uncover the correlation between two series at different frequencies. High amplitude for any frequency or period gives us the periodicity in the SWL series, which is 'in sync' with the rainfall series. Significant cross-correlation values and the corresponding lags give the strength of the relationship between the two series and the lag between them. Proc ARIMA in SAS was used for the cross-correlation analyses.

As these are annual series, the autocorrelation is fairly small. Regression models were fitted to the log-transformed SWL values with lag terms for the log-rainfall series. Trigonometric functions of time with period estimated from the spectral analysis were used to remove the cyclic effects. Elevation and quadratic time functions were also included in the model. If there was a significant correlation coefficient for time in the regression analysis, it could be inferred that even after the contribution of the rainfall was removed from the SWL data, there is still some time trend, although the assumption is that the entire trend in the SWL data is explained by the rainfall data.

A dummy variable was included for the step change model (as found from the change-point analysis). A trend was then fitted to each of these time periods to see whether any of these time periods still have a time trend left in them after the step change.

Only the change points with confidence limits of ≥95% were used.

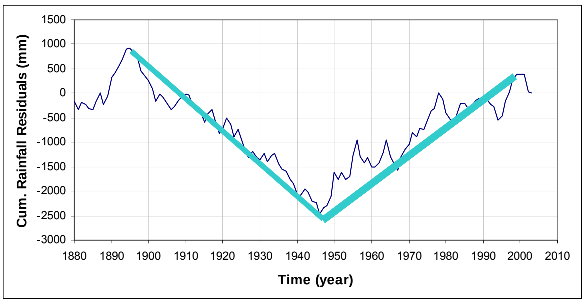
4 Results

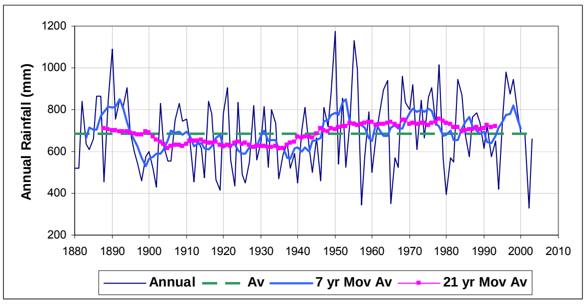
4.1 Rainfall

4.1.1 Exploratory data analysis

Exploratory data analysis for all verified rainfall stations confirmed the existence of two abrupt climatic changes in the mid 1890s and the late 1940s in most of the study area, as illustrated in Figure 11, Figure 12 and Figure 15. The first change marked the switch from a wet to a dry hydrologic regime, and the second back to wet. The most pronounced droughts occurred at the beginning and at the end of the five-decadal dry spell, which started in 1895 and lasted until 1947. Although the second part of the 20th century was wet, the climate dried slightly and slowly towards the end of the century. The year 2000 was the last year with an above-average rainfall at most stations, indicating the possibility of another phase reversal at the turn of the century and a return to dryer conditions that could prevail until the middle of the 21st century.

Figure 11: Clear rainfall shift in the summer rainfall zone: residual mass curve (left) and time-series graph (right) with two degrees of filtering (7- and 21-year moving averages) for the 54003 Barraba Post Office rainfall station



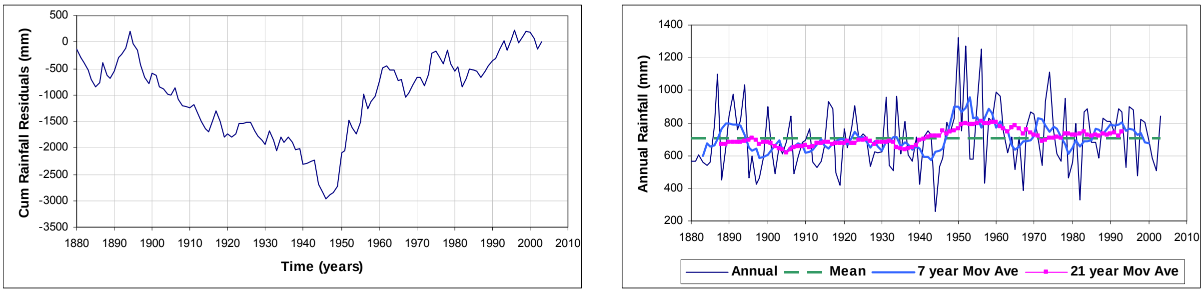


The most pronounced extremes in the residual mass curve mark the rainfall shifts, which delineate five-decadal phases of wetter and dryer climate.

We investigated the timing of the mid-century switch from dry to wet separately in all of the catchments within the study area, as various timings (from 1944 to 1949) had been reported in literature by different authors. More precise timing of the rainfall shift across the study area was necessary for accurate evaluation of the delay in the response of groundwater systems. Residual mass curves, based on monthly data, were constructed for the period 1880–2003, and the minimum, which indicated the transition from dry to wet regime, was recorded. More than 50% of the stations from every catchment showed that the transition happened in 1947, and the catchments in the uniform rainfall zone exhibited the smallest scatter.

The 1947 climate shift was most pronounced in the uniform rainfall zone (Macquarie, Lachlan, Murrumbidgee East, upstream of Burrinjuck Dam, and the narrow northern belt of Murrumbidgee close to the border with Lachlan). The rainfall increased by more than 20% at most stations. The residual mass curves typically exhibited a distinct ‘V’ shape, clearly delineating the dry from the wet phase. The 21-year moving-average graphs illustrated a long-term rainfall average that characterised each phase. Shorter-term climatic oscillations linked to the higher-frequency signals were visible, but were not the dominant feature seen in the residual mass curves.

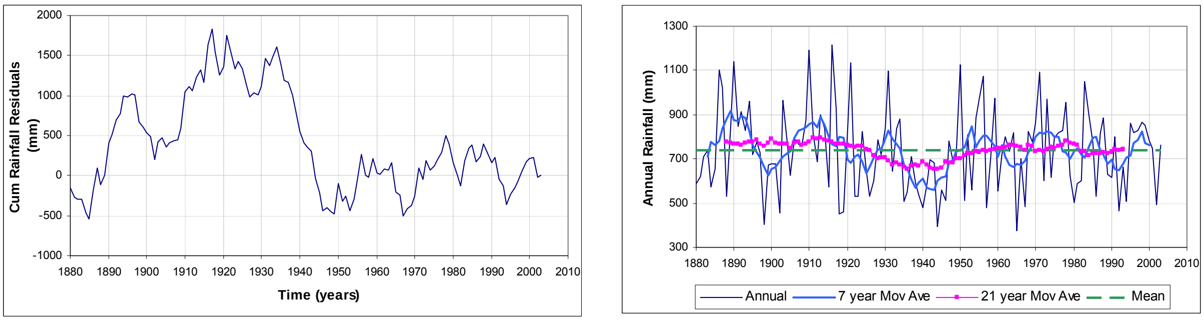
Figure 12: Clear rainfall shift observed across entire uniform rainfall zone



Residual mass curve (left) and annual time series (right) with two degrees of filtering (7- and 21-year moving averages) for the 70028 Yass (Derringullen) rainfall station.

The Murrumbidgee catchment upstream of Burrinjuck Dam represents the southern extension of the uniform rainfall zone, as the Snowy Mountains guard this area from the south-west, partially blocking the southern winter rainfall. Rainfall in this area shifted abruptly in 1947, after which it fell mildly (Figure 12).

Figure 13: Unclear signal observed in some stations in summer rainfall zone, such as 54004 Bingara Post Office (Gwydir)

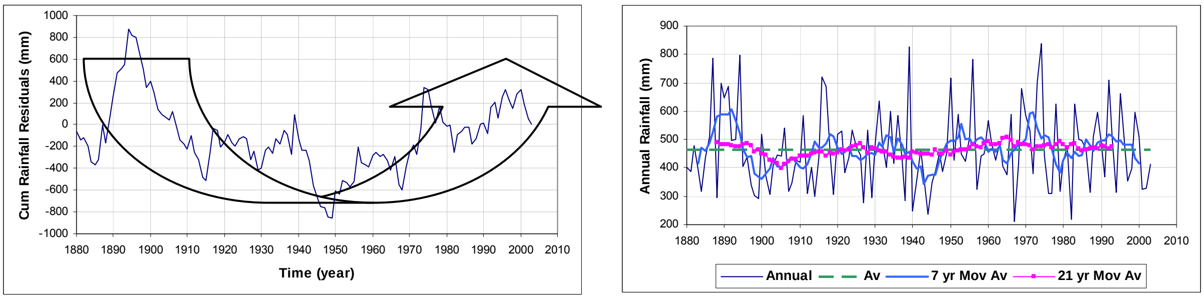


Residual mass curve (left) and annual time series (right) with two degrees of filtering (7 and 21-year moving averages). Note the unusually wet spell registered at this station between 1900 and 1920, and average conditions during the second half of the century.

A shift was also clearly pronounced in the summer rainfall zone, although the signal was clearer in the Namoi catchment (including Peel) than in the northern catchments. More stations in the Gwydir and Border Rivers catchments deviated from the typical patterns, showing a somewhat different timing of the shift and a smaller increase in rainfall, than in the Namoi catchment (Figure 13).

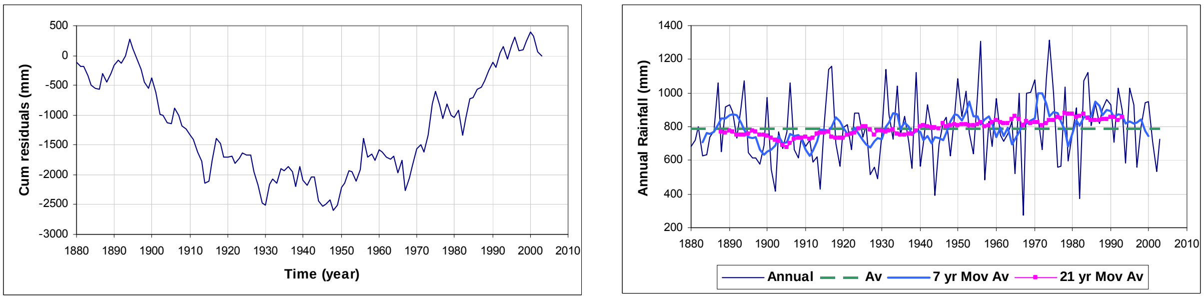
The rainfall shift was least pronounced in the winter rainfall zone (the entire Murray River catchment and most of the Murrumbidgee catchment downstream of Burrinjuck Dam, except the northern-most belt). The winter rainfall zone experienced a much milder rise in rainfall of around 5% from the first to the second part of the 20th century. The increase in rainfall in this area was not so abrupt, with only a few stations conforming to the standard rainfall shift pattern (Figure 15), and most showing the oscillatory pattern superimposed on a continuously rising trend throughout the century (Figure 14). The year 1947 generally marked only the local minimum in residual mass curves in this area. The last of the higher-frequency oscillations peaked around 1994 at most stations, after which dryer conditions prevailed.

Figure 14: Unclear rainfall shift observed across the winter rainfall zone, such as at 74008 Grong Grong (Berembed) rainfall station in Murrumbidgee West



Even though the minimum of the function is clearly visible on the residual mass curve (left), the accumulated departures from the average are relatively small, and the curve resembles more the parabolic 'U' shape than the 'V' shape. The annual time series (right), with two degrees of filtering (7- and 21-year moving averages), indicates a small but steady rainfall increase over the 20th century, culminating in the mid 1990s.

Figure 15: Reasonably clear rainfall shift observed at a very small number of stations in the winter rainfall zone, such as Adelong (Gundagai), (Murrumbidgee West, west of Snowy Mountains).



Residual mass curve (left) indicates that the accumulated departures from the mean rainfall in both parts of the century are more than 3 times the average rainfall; but the annual time series (right), with two degrees of filtering (7- and 21-year moving averages), shows that this change was more gradual than in the uniform rainfall zone.

The stations in dryer areas exhibited larger variability in patterns and deviated more from the typical rainfall shift signal than the stations from the high-rainfall zones.

We can conclude that the entire study area was affected by the rainfall shift, but the extent of the effect was variable: It declined with distance from the central latitude of the uniform rainfall zone, with the decline more pronounced to the south than to the north. It also declined, to some extent, with aridity.

4.1.2 Statistical analysis of rainfall data

The results of the change-point analysis of the weighted-average annual rainfall time series are given in Table 4 for each catchment section. The minima of the residual mass curves underpin the change-point analysis. Some of these residual mass curves are plotted against the residual mass curves of the SWL data in the Appendix in Figure 23. The results of the time-series change-point analysis are given further on in Table 6. The results of the analyses of individual rainfall stations that were used in the study are shown in the Appendix in Table 13 and Table 14.

A statistically significant (>90%) step-point change was detected in all the sections except Gwydir, Murrumbidgee West, and Murray East and West (Table 4). The change-point, which occurred in 1947, was associated with an abrupt increase in the average rainfall of between 72 and 143 mm (Murrumbidgee East and Peel respectively). The rainfall shift was most pronounced in the uniform rainfall zone and at higher altitudes. Its influence diminished in the northern portion of the summer rainfall zone, in the winter rainfall zone and at lower altitudes.

Table 4: Results of change-point analysis of the weighted-average annual rainfall series in each catchment section

Section/subsection	Year change occurred	Confidence level	Pre-change average rainfall (mm/year)	Post-change average rainfall (mm/year)
Border Rivers	1947	>99.5%	794.8	900.3
Gwydir	no significant change			
Namoi	1947	97%	647.8	726.7
Peel	1922	98%	673.9	556.6
	1947	98%	556.6	699.9
Macquarie	1947	98%	607.0	705.0
Lachlan East	1947	99%	668.6	775.4
Lachlan Mid	1895	99%	650.9	568.5
	1947	98%	568.5	668.7
Lachlan West	1947	97%	569.9	648.3
Murrumbidgee East (North)	1947	96%	638.0	720.9
Murrumbidgee East (South)	1947	>99.5%	562.7	635.5
Murrumbidgee West	1895	96%	625.7	508.7
	1916	94%	508.7	632.4
Murray East	no significant change			
Murray West	no significant change			

Confidence level of >90% was used to indicate a significant change. The results of analysis of individual rainfall stations are given in the Appendix in Table 13.

In every section in which the analysis of the composite annual rainfall detected the 1947 shift in average rainfall, there were some stations where the shift was not detected with a 95% confidence level (see Appendix, Table 13). In the Gwydir, the shift was not detected in the composite rainfall data, but it was detected at two stations that were used to calculate the composite rainfall (Glen Innes Post Office and Tingha, Crystal Hill). It was the same in Murrumbidgee West. The rainfall shift was not detected with a 95% confidence level at any of the rainfall stations in the Murray (Appendix, Table 13).

The data in Table 4 and Table 13 together confirmed all the conclusions of exploratory analysis, presented in section 4.1.1.

In most cases where an abrupt rainfall increase was detected, it was accompanied by a statistically significant increase in rainfall variability (Table 5). Figure 11 to Figure 15 show that the bulk of this increase in variability occurred after the disturbance brought on by the rainfall shift. A significant increase in variability was not detected in the Border Rivers, Namoi and Lachlan West catchments, where significant changes in variability were detected only at some of the contributing rainfall stations (Appendix, Table 14).

Table 5: Significance of changes in rainfall variability within the weighted-average annual rainfall series in each catchment section

Section/subsection	Year change occurred	Confidence level	Pre-change rainfall standard deviation	Post-change rainfall standard deviation
Border Rivers	No significant change			
Gwydir	No significant change			
Namoi	No significant change			
Peel	1946	95%	109.6	447.7
	1958	93%	447.6	158.6
Macquarie	1944	91%	125.1	236.6
Lachlan East	1944	97%	95.3	229.1
Lachlan Mid	1944	98%	130.4	182.1
Lachlan West	No significant change			
Murrumbidgee East (North)	1950	93%	130.4	213.8
Murrumbidgee East (South)	1950	98%	104.7	209.5
Murrumbidgee West	No significant change			
Murray East	No significant change			
Murray West	No significant change			

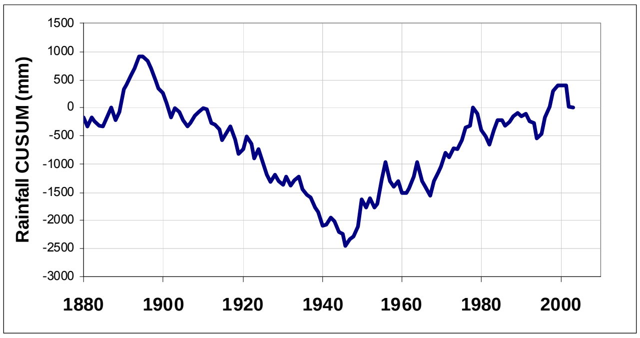
Confidence level of >90% was used to indicate a significant change. The results of analysis of individual rainfall stations are shown in Appendix, Table 14.

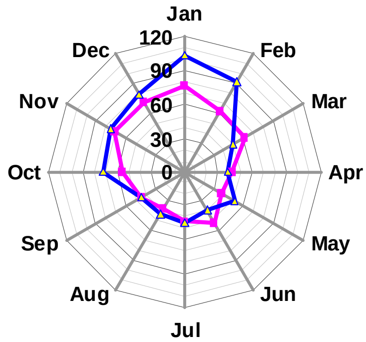
An additional perspective on the impact of the abrupt rainfall change is given in Figure 16, which shows radar graphs of pre- and post-1947 monthly rainfall, accompanied by the residual mass curves for the Barraba Post Office, Forbes and Tumbarumba. The residual mass curves for Barraba Post Office and Forbes show a typical, strong, single ‘V’ shape, which corresponded to the significant change-point in 1947. In contrast, that for Tumbarumba indicated 7 to 9 break-points over the period of record, none of which were strong enough to be detected as significant.

Analysis of monthly rainfall before and after 1947 (Figure 16) indicated that the 1947 rainfall shift was accompanied by changes in rainfall distribution and by increased spring, summer and autumn rainfall and decreased winter rainfall across the study area. The increase in autumn rainfall was the smallest. The increase in spring rainfall was highest in the uniform and winter rainfall zones, while the increase in summer rainfall was the most pronounced in the summer rainfall zone. The decrease in winter rainfall was due primarily to a decrease in June rainfall.

The residual mass curves of June rainfall within the study area (not presented in this report) had centrally located maxima, in contrast to the centrally located minima captured by the residual mass curves based on annual data. June rainfall also consistently failed to show any influence of the 1895 rainfall shift across the study area. The June rainfall pattern was generally characterised as wet until 1930, average between 1930 and 1960, and dry following 1960.

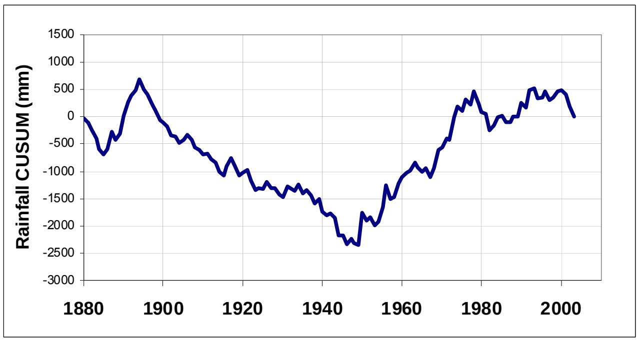
Figure 16: Residual mass curves of rainfall, and radar graphs showing pre-1947 and post-1947 average monthly rainfalls at Barraba PO, Forbes and Tumbarumba

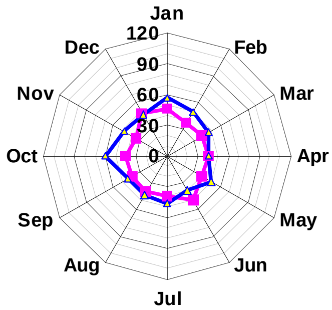




Summer rainfall zone – Barraba (CBM 54003)

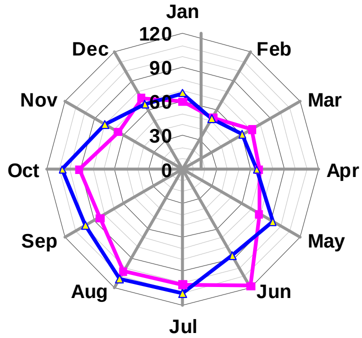
(Border Rivers; Gwydir; Namoi; Peel)





Uniform rainfall zone – Forbes (CBM 65016)

(Macquarie; Lachlan; Murrumbidgee east)



Winter rainfall zone – Tumbarumba (CBM 72043) Before 1947 After 1947

(Murrumbidgee west; Murray)

CBM – Commonwealth Bureau of Meteorology

4.2 Bore data

4.2.1 Exploratory data analysis

The availability of data for developing composite SWL time series was variable between catchments and over time (Appendix, Table 15). In general, before 1950, data were sparse, i.e. containing gaps and with few observations per year. Even in some years after 1950, data were missing. Years when there were few data points caused considerable apparent variability within the time series, as the small sample size leads to an estimate of a median that diverges substantially from the population median, therefore artificially introducing variability in the time series. The exploratory analysis of the SWL data also found that there was insufficient data in Border Rivers and Murray catchments to allow detailed statistical analysis to be undertaken.

Bore data from each section were categorised into time periods (pre-1950, 1951–1970, 1971–1990 and post-1990), as this allowed for the examination of temporal and spatial distribution (Appendix, Figure 24). Scatter plots of bore elevation and SWL against time in each catchment section (Appendix, Figure 25) were drawn to evaluate uniformity: Non-uniform spatial bore spread can prevent us from knowing whether a change in SWL over time is due only to processes that operated over the time period, or whether the difference in bore position within the landscape also played a role in the calculated SWL values. This inability to distinguish between the influence of two variables (such as space and time) on the third variable (SWL) is called spatial/temporal confounding.

Analysis showed a certain degree of non-uniformity in the Gwydir, Peel, Macquarie and Murray East sections, as before 1950 most bores were drilled in the lower elevations, whereas later in the century the spread was more equal and wider, encompassing some bores from higher elevations. This phenomenon was only marginally present in the Namoi catchment, where the elevation range of early bores captured the distribution of a majority of the later bores. In the Border Rivers and in both the northern and southern portions of Murrumbidgee East (upstream of Burrinjuck Dam), only a few bores were drilled before 1950, so that the relative uniformity between the first and second halves of the century was not possible to judge. A dissection of the Lachlan, Murrumbidgee and Murray catchments had already been done to eliminate and minimise non-uniformity. A further dissection of the catchments in which some non-uniformity was detected would have resulted in insufficient bore numbers and would have prevented further bore analysis. In all of the Lachlan and Murrumbidgee West sections, there were only a few bores at higher altitudes, outside the range captured by the early bores, so non-uniformity was not an issue. In other sections the bores providing SWL over time were fairly uniformly distributed across all elevations.

LOESS plots of SWL and elevation indicated weak, inverse relationships in most catchments (i.e. at the regional scale, bores in the upper parts of catchments tended to have shallower groundwater) (Appendix, Figure 25), indicating that for the final analysis their elevation may be a useful covariate.

In all of the study catchments the calculated UPNESS and WETNESS indices were close to zero and did not vary markedly across bore locations in any of the study catchments. Two reasons contributed to this:

- Indices were calculated for the entire MDB, and therefore a coarse grid was used. Thus, the study area represented a small and peripheral portion of the largely smoothed surface, which forced calculated values to converge to zero.

- Although originally calculated as a double precision, values were truncated to a single precision, so that even the negligible variation originally captured by this information was lost. Therefore, the indices were not considered further in the analysis.

The exploratory analysis of the SWL data found that of all the variables examined, only elevation was likely to be a useful covariate.

4.2.2 Change-point analysis of bore data

The results of change-point analysis of SWL and of the variability in SWLs are given in Table 6 and Table 7, respectively. The description of the methodology used can be found in section 3.3.1.2. There were insufficient data in the Border Rivers and Murray (east and west) catchments to allow meaningful change-point analysis. No significant change-points were detected in the Gwydir catchment. However, reducing the level of significance to a confidence level of 90% revealed change-points in the remainder of the catchments.

Variability in the SWL data of the Namoi and Macquarie catchments was due to a high proportion of single data points per year during the early years of the bore records (see Appendix, Table 15). The preliminary statistical analysis indicated the presence of outliers in the data for Lachlan East. Therefore, the analysis was repeated with ranked data (non-parametric). The non-parametric analysis did not show a significant change in variance.

Table 6: Change-point analysis of SWL data, confidence level >90%; bootstraps = 1000

Section/subsection	Year change occurred	Confidence level	From (m)	To (m)
Border Rivers	insufficient data			
Gwydir	no change			
Namoi	1949	>99.5%	23.2	15.9
	1955	95%	15.9	11.6
Peel	1952	>99.5%	20.5	11.3
Macquarie	1953	>99.5%	18.1	10.3
Lachlan East	1952	92%	14.5	6.9*
Lachlan Mid	no change			
Lachlan West	1937	>99.5%%	26.2	16.9
	1963	>99.5%	16.9	9.2
	1993	97%	9.2	14.6
Murrumbidgee East	1965	93%	4.7	8.3
	1997	>99.5%	8.3	13.6
Murrumbidgee West	1937	94%	21.1	11.4
Murray East	insufficient data			
Murray West	insufficient data			

* Analysis of ranked data (non-parametric) showed no significant change.

Table 7: Change-point analysis of SWL variability, confidence level > 90%; bootstraps = 1000

Section/subsection	Year change occurred	Confidence level	Variance from	Variance to
Namoi	1920	98%	23.483	3.145
Macquarie	1954	93%	5.897	2.542

4.3 Relationships between rainfall and standing water level

The relationships between rainfall and SWL were studied using three methods:

- a comparison of smoothed rainfall and SWL series
- a change-point analysis of rainfall and SWL time-series data
- the building of a statistical model that establishes the relationship between the annual rainfall data and the annual SWL data-series.

The annual SWL data-series were composed from the median SWL for all bores constructed in each particular year.

4.3.1 Exploratory analysis

Exploratory analysis examines the relationship between rainfall and SWL. Two techniques were applied: (1) comparison between trends in SWL and rainfall; trends are in a form of 21 year moving average (running mean) filter and (2) comparison of residual mass curves of SWL and rainfall. Both techniques were used to smooth variability in rainfall. Residual mass curves also demonstrated the change-points in the climate regime. The graphs on which the analysis was based are presented in the Appendix in Figure 22 and Figure 23. The following conclusions were drawn from the analysis:

- The trends in SWL are very similar to the trends in rainfall across the study area, with the exception of the initial period in Lachlan West.
- The trends in SWL lag variably behind the trends in rainfall.
- Lags estimated by trend analysis match well with lags deducted from the minima in residual mass curves.
- Patterns of residual mass curves of SWL and rainfall are very similar.
- Observed lags are short close to the Great Dividing Range and increase down the catchment in a westerly direction.
- Although lags are variable across the study area, their values are much smaller than currently conceptualised response times of groundwater systems (Coram *et al.* 2000).
- Similarity of rainfall and SWL patterns indicate that the recharge was not substantially altered by the non-climatic effects during the period of observation.
- Diverging patterns in Lachlan West indicate additional recharge in the initial period due to a cause unrelated to climate.
- Short response times of groundwater systems and completion of most clearing by the end of the 19th century are together responsible for the absence of an expected water table rise due to clearing across the study area, except in Lachlan West.
- Diverging patterns between SWL and rainfall in the slowly responding Lachlan West are consistent with the effects expected from clearing.
- Unusually long response times are observed in both sections of the Murray catchment.

4.3.2 Change-point analysis

As change-point analysis uses the extremes of the residual mass curves to detect change-points, these points are already known from the exploratory analysis phase. The change-point analysis brought in the statistical rigour that allowed for the calculation of the confidence intervals; i.e. it evaluated the probability of these changes being random.

Graphs of residual mass curves on which the analysis was based are presented in the Appendix in Figure 23, and the summary of change-points and lags is presented in section 5.2, in Table 12.

4.3.3 Detailed statistical analysis

Detailed statistical analysis aimed at exploring the relationship between rainfall and SWL by multiple regression analysis. Various steps were involved, including:

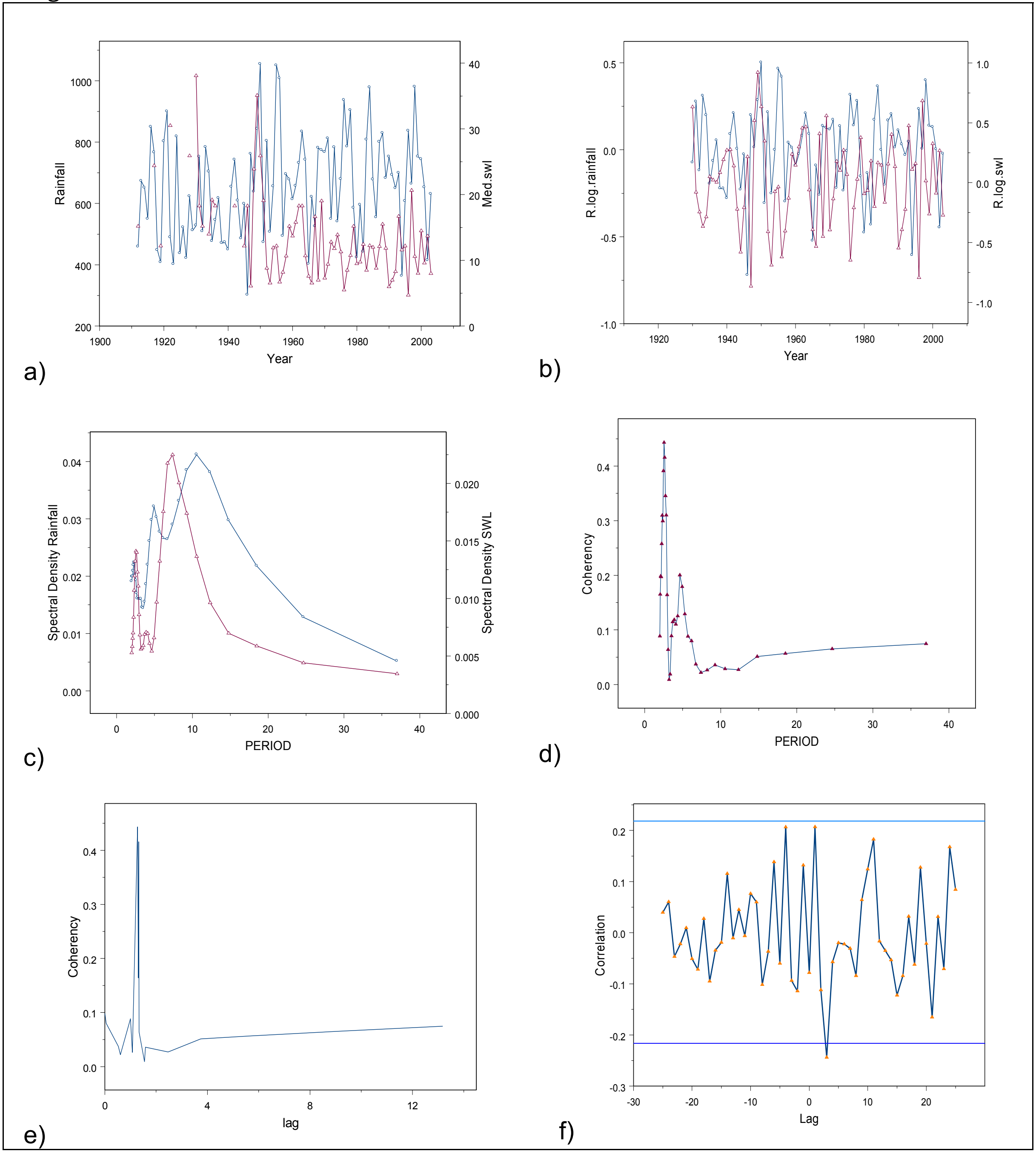
- spectral analysis, to account for cyclical patterns in data
- cross-spectral analysis, to examine correlations between data at different frequencies
- cross-correlation, to explore the statistical dependence of SWL on lagged rainfall
- multiple regression analysis, to provide a model that could be used to predict SWL responses to rainfall changes.

The various steps undertaken to analyse relationships between rainfall and SWL are illustrated in Figure 17, using data for the Peel catchment. Figure 17a plots raw SWL and rainfall data against time. As already deduced from the trend and change-point analyses, the data are not stationary, showing a trend over time. The data are also heterogeneous, as the distributions of bores in space and time are not the result of carefully planned data collection, but were responses to economic and technological development. Figure 17b shows the log-transformed and detrended SWL and rainfall data that were used for further analysis. After removal of the trend and transformation, the residuals data in Figure 17b appear to be stationary. Figure 17c is a spectral density plot of log-transformed and detrended SWL and rainfall data. There is a peak at about 10 years in SWL and at about 7 years in rainfall. This means that there are cycles of these periods in each respective series. A cross-spectral plot of SWL and rainfall is shown in Figure 17d. A peak at about 4 to 5 years corresponds to the period when the periodicity in SWL is 'in sync' with rainfall cycles. This is an indication that the oscillation in rainfall with a frequency of 4 to 5 years is passed on to, and therefore mirrored in, the SWL data, and that it represents a part of the detectable relationship between rainfall and SWL. Figure 17e is a plot of the coherency value (or coherence, defined in Cross-spectral analysis in section 3.3.3.2) from the cross-spectral analysis and lag values. The coherency value has a peak at lag 1, which means that the rainfall data lead the SWL data by 1 year. Figure 17f is a cross-correlation plot of SWL and rainfall. The statistically significant correlation ($P > 95\%$, represented by a light blue horizontal line in Figure 17f) between the two series is at lag 3 with a correlation value of –0.24. This means there is a weak but significant negative correlation between the two series, with rainfall leading SWL by 3 years.

As these are annual series, the autocorrelation is fairly small. The regression model was fitted to the log-transformed SWL values with lag terms for the log-rainfall series. Trigonometric functions of time, with period (duration of a full cycle) estimated from the spectral analysis, were used to remove cyclic effects. Elevation and quadratic time function were also included in the model. If there is a significant coefficient for time in the regression analysis, it could be inferred that even after the contribution of the rainfall is removed from the SWL data, there is still some time trend that cannot be explained by a simple temporal displacement relationship between rainfall and SWL on an annual time-step.

The results of the spectral and cross-spectral analyses for catchment sections are presented in Table 8, and those of the cross-correlation analysis are presented in Table 9.

Figure 17: Example of the procedures used in analysing relationships between rainfall and SWL, using data for the Peel section



(a) Plot of raw data: both SWL (red) and rainfall data (blue) are plotted against time. (b) Log-transformed and detrended SWL and rainfall data used for further analysis. (c) Spectral density plot of log-transformed and detrended SWL and rainfall data. (d) Cross-spectral plot of SWL and rainfall data. (e) Plot of coherency values from the cross-spectral analysis and the phase values (converted to lags). (f) Cross-correlation plot of SWL and rainfall; dotted lines are 95% confidence bands.

Table 8: Results of spectral and cross-spectral analyses

	Spectral analysis		Cross-spectral analysis		
Section/subsection	**Periodicity in SWL (yrs)**	**Periodicity in rainfall (yrs)**	**Coherency**	**Periodicity at peak coherency (yrs)**	**Lag at peak coherency (yrs)**
Gwydir	no clear periodicity	no clear periodicity	–	no clear periodicity	–
Namoi	2, 3, 7	7	0.28	7	1
Peel	10	7	0.45	3	1
Macquarie	7, 17	no clear periodicity	0.41	7	2
Lachlan East	no clear periodicity	no clear periodicity	–	no clear periodicity	–
Lachlan Mid	no clear periodicity	no clear periodicity	0.48	3	0
Lachlan West	5	no clear periodicity	0.44	4	0
Murrumbidgee East—Northern sector	no clear periodicity	no clear periodicity	–	no clear periodicity	–
Murrumbidgee East—Southern sector	10	no clear periodicity	–	no clear periodicity	–
Murrumbidgee East Combined	4	no clear periodicity	–	no clear periodicity	–
Murrumbidgee West	no clear periodicity	no clear periodicity	–	no clear periodicity	–

These two methods identify any periodic features in the SWL and rainfall series.

Except for the Macquarie catchment, spectral analysis shows that the groundwater data showed 2–3- and 4–5-year cycles. There were also longer-term cycles of 7 and 17 years observable in the Macquarie catchment and 10 years in Peel and southern section of Murrumbidgee East. Some catchments did not show significant periodicities. Cycles longer than 17 years could not be detected from groundwater records because of the short period for which observations were available. This means that the existence of longer-term cycles, such as a century-long cycle, could not be investigated.

The coherency analysis indicates the degree to which rainfall and SWL cyclical behaviour are related. Peak coherency in the Peel, Lachlan Mid and Lachlan West sections corresponded to a periodicity of 3-4 years, lagged from 0 to 1 year; it was greater in the Namoi and Macquarie (7 years, lagged 1 or 2 years) (Table 8).

The results of the cross-correlation analysis (Table 9) indicate that with the exception of Gwydir and Lachlan East, there were significant correlations between rainfall lagged to varying extents and SWL. The longest lag times were 19 years in Lachlan Mid and Murrumbidgee West, followed by Lachlan West (16 and 17 years), and Macquarie, Namoi and Peel (1–7, 1–10 and 3 years respectively).

Table 9: Results of cross-correlation analysis showing the statistically significant correlation values and the corresponding lags

Section/subsection	Cross-correlation *R*	Corresponding lag (years)
Gwydir	not significant	
Namoi	–0.25	1
	–0.24	7
	–0.26	10
Peel	–0.24	3
Macquarie	–0.24	1
	–0.21	2
	–0.21	7
Lachlan East	not significant	
Lachlan Mid	–0.38	19
Lachlan West	–0.23	1
	–0.27	16
	–0.23	17
Murrumbidgee East (northern sector)	–0.26	0
	–0.23	1
Murrumbidgee East (southern sector)	–0.26	3
Murrumbidgee East	–0.30	0
	–0.26	1
Murrumbidgee West	–0.29	19

The results of the multiple regression analysis of SWL and lagged rainfall are summarised in Table 10. Only the significant predictors are shown. Both the sine and cosine terms are included in the model if one of them was significant.

Values of the coefficients used in the model are presented in the fourth column ('Coeff. (±SE)'). For example, in the Namoi, the derived relationship can be read as:

$$\ln(SWL) = 9.52 - 0.52 \cdot \ln[Rain(t-1)] - 0.41 \cdot \ln[Rain(t-10)] - 0.00077 \cdot Altitude - 0.00479 \cdot Time + Re,$$

where Re represents residuals, or the random component.

The probability associated with the coefficients is presented in the third column (Pr < |t|.) A small Pr indicates that the coefficient is very statistically significant.

A statistical model should contain both a deterministic part (the relationship) and a random component (noise). Serial correlation of residuals is a sign that residuals are not random, and therefore more work is needed to separate the deterministic component out of the residuals to leave only the random component behind. Durbin Watson statistics, presented in Table 10, tell us about the degree of correlation between residuals. The Durbin Watson test statistic is calculated from the estimated residual, $\hat{e}_t$, as:

$$d = \sum_{t=2}^{N} (\hat{e}_t - \hat{e}_{t-1})^2 \Big/ \sum_{t=1}^{N} \hat{e}_t^2$$

The *d*-statistic has values in the range [0,4]. Low values of *d* are in the region for positive autocorrelation. High values of *d* are in the region for negative autocorrelation.

The fifth column presents R^2 and adjusted R^2. R^2 is the square of the coefficient of determination. A high R^2 indicates a strong relationship (and a low R^2 indicates a weak relationship) between the analysed variables. Adjusted R^2 adjusts for the number of explanatory terms in a model. Unlike R^2, the adjusted R^2 increases only if the new term improves the model more than would be expected by chance. The adjusted R^2 can be negative, and will always be less than or equal to R^2.

Statistically significant predictors that accounted for between 8.5% and 55% of the total variance ($R^2 \times 100$) were detected in all catchments except Lachlan East and Gwydir. The remaining variability is a consequence of a small time-step (year) chosen for the analysis, which inevitably caused small SWL data samples in the early bore record, and resulted in large noise. The noise was highest where the annual sample size was small and therefore inadequate to capture the overall system behaviour. Variability in SWL of individual bores originates mainly from the bore position in the landscape and the annual groundwater cycle oscillation. The smaller the sample size, the more chance the calculated annual median value has of deviating from the true system median. Some variability might also have been introduced by land use change and other anthropogenic local influences, which affect the water table and the water balance.

A choice of the step-change function over the quadratic function to represent the underlying trend also reduced the unexplained variability, resulting in R^2 close to or above 0.4 for Namoi, Peel and Macquarie – all three catchments where it was applied (Table 10). A weak autocorrelation indicated in the Macquarie was reduced by replacing the quadratic trend with the step-change trend in the model. As seen in Table 10, the first-order auto-correlation in residuals decreased from 0.39 to 0.21, and the Durbin Watson statistic increased from 1.21 to 1.56, also indicating a reduction in first-order auto-correlation.

Splitting of the Murrumbidgee East into northern and southern sectors was based on the different rates of mild rainfall decline observed during the second part of the century, following the abrupt rainfall increase in 1947 (compare observed rainfall and SWL trends in Appendix, Figure 22, continued) and the different lengths of the postulated groundwater flow path. SWL showed a positive trend with time in both the northern and southern sectors (deepening water table). Analysis of Murrumbidgee East as a single subdivision showed a similar positive trend with time. Log(rainfall) with a lag of 1 was a significant predictor.

A linear relationship between log-transformed SWL and time means that the time coefficient should be transformed exponentially to indicate average change of SWL per year. As seen in Table 10, SWL showed an average decrease (indicating an exponential rise of groundwater table) during the period of observation at a rate of 0.5% per year in the Namoi, 0.8% in the Peel, 2.96% in the Macquarie and 5.82% in Lachlan West. In Murrumbidgee East and Lachlan Mid, where analysed SWL data started after 1947 and the rainfall fell mildly after the rainfall shift, SWL increased (indicating exponential deepening of groundwater table) of 9.42% and 3.05% per year respectively. An average exponential increase of SWL (representing decline of groundwater table) of 2.43% per year was observed in the northern division of this section. An average SWL rise of 3.67% per year was observed since 1965 in the southern division of Murrumbidgee East.

Table 10: Summary of multiple regression analysis of rainfall and SWL (P < 0.10)

Section/ Subsection	Variables	Pr < |t|.	Coeff. (±SE)	R^2 (adj. R^2)[1]	1st order autocorrel. in residuals	Durbin Watson statistic
Gwydir[2] (n = 45) 1954–2003	No significant predictor					
Namoi (n = 75) 1907–2003	Intercept $Lag1Log_eRain$ $Lag10Log_eRain$ Altitude Time	<0.0001 0.005 0.023 0.0015 0.008	9.52 (1.69) –0.52 (0.18) –0.41 (0.18) –0.00077 (0.000233) –0.00479 (0.00175)	0.41 (0.37)	–0.11	2.17
Namoi (with step change) (n = 75) 1907–2003	Intercept $Lag1Log_eRain$ $Lag10Log_eRain$ TimeCode Altitude	0.0001 0.14 0.092 <0.0001 0.1035	6.92 (1.71) –0.256 (0.171) –0.300 (0.175) –0.500 (0.103) –0.00069 (0.00042)	0.44 (0.41)	–0.166	2.28
Peel (n = 71) 1912–2003	Intercept $Lag3Log_eRain$ Time	<0.001 0.013 <0.001	6.14 (1.12) –0.45 (0.176) –0.008 (0.001)	0.29 (0.27)	0.05	1.89
Peel (with step change) (n = 71) 1912–2003	Intercept $Lag3Log_eRain$ TimeCode	<0.0001 0.059 <0.0001	5.05 (1.09) –0.331 (0.170) –0.521 (0.101)	0.37 (0.35)	–0.033	2.06
Macquarie (n = 79) 1918–2003	Intercept $Lag1Log_eRain$ $Lag2Log_eRain$ $Lag7Log_eRain$ Time $(Time)^2$	<0.0001 0.013 0.054 0.029 0.0005 0.015	8.40 (1.38) –0.30 (0.12) –0.23 (0.12) –0.26 (0.12) –0.03 (0.01) 0.0002 (0.0001)	0.48 (0.44)	0.39	1.21
Macquarie (with step change) (n = 73) 1914–2003	Intercept $Lag1Log_eRain$ $Lag2Log_eRain$ $Lag7Log_eRain$ TimeCode Sin(t) Cos(t)	<0.0001 0.020 0.219 0.030 <0.0001 0.0514 0.614	7.28 (1.46) –0.291 (0.122) –0.143 (0.115) –0.260 (0.118) –0.481 (0.075) –0.0979 (0.0493) –0.0247 (0.0488)	0.55 (0.51)	0.211	1.56
Lachlan East[2] (n = 38) 1945–2003	No significant predictor					
Lachlan Mid (n = 35) 1950–2003	Intercept $Lag19Log_eRain$ Time $(Time)^2$	<0.001 <0.001 0.029 0.052	4.30 (1.18) –0.59 (0.14) 0.09 (0.04) –0.001 (0.0005)	0.51 (0.46)	–0.05	2.07
Lachlan West (n = 65) 1922–2003	Intercept $Lag16Log_eRain$ $Lag17Log_eRain$ Time $(Time)^2$	<0.001 0.001 0.005 0.001 0.002	11.09 (1.73) –0.61 (0.18) –0.53 (0.18) –0.06 (0.02) 0.0005 (0.0002)	0.38 (0.33)	–0.04	2.08
Murrumbidgee East (northern sector) 1949–2003	Intercept Time	ns <0.001	 0.024(0.0066)	0.21 (0.20)	0.04	1.88

Table 10: Summary of multiple regression analysis of rainfall and SWL (P < 0.10) (continued)

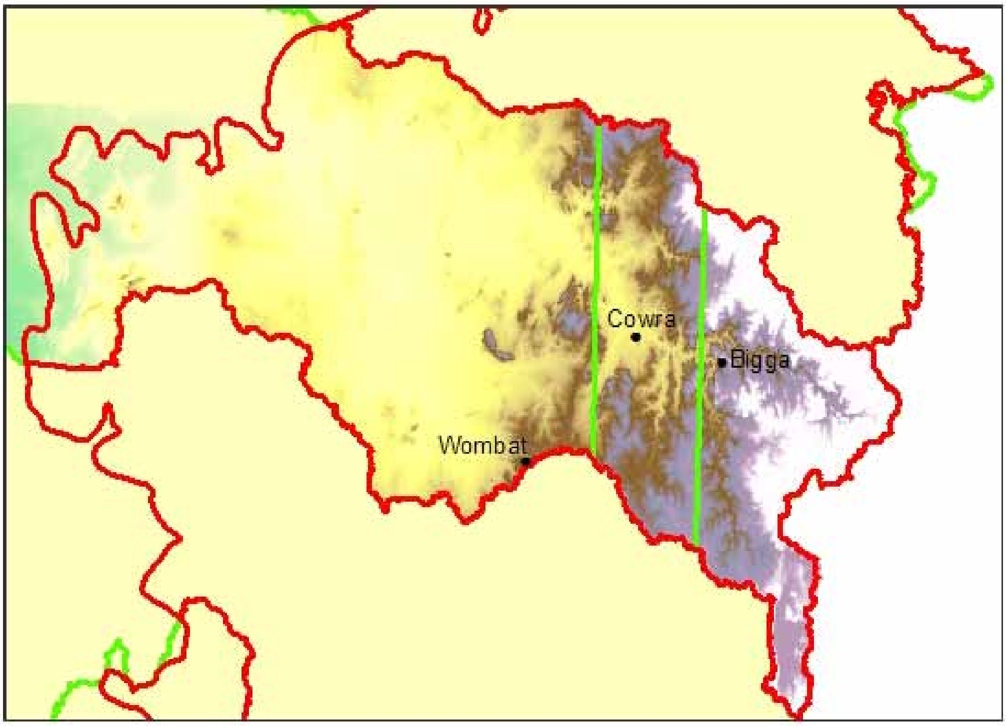
Section/ Subsection	Variables	Pr < |t|.	Coeff. (±SE)	R^2 (adj. R^2)[1]	1st order autocorrel. in residuals	Durbin Watson statistic
Murrumbidgee East (southern sector) 1965–2003	Intercept Time	ns 0.006	 0.036(0.007)	0.44 (0.43)	0.29	1.4
Murrumbidgee East (combined) (n = 49) 1949–2003	Intercept Log_eRainfall Lag1Log_eRain Time	0.004 0.045 0.041 <0.001	9.36 (3.08) –0.63 (0.31) –0.65 (0.31) 0.03 (0.006)	0.50 (0.44)	0.21	1.49
Murrumbidgee West (n = 65) 1920–2003	Intercept Lag19Log_eRain	<0.0001 0.019	5.39 (1.27) –0.48 (0.20)	0.085 (0.07)	–0.179	2.26

n: number of observations
[1] (adj. R^2) – adjusted R^2
[2] no significant predictor – no model could be derived

5 Discussion

Water levels in fractured-rock groundwater systems reflect a state of dynamic equilibrium between the rates of water movement into and out of the systems (recharge and discharge). More water enters these groundwater systems at high elevations, near the headwaters of the basin catchments, than at low elevations. At high elevations, along the ridges, rainfall is high and soils are thin. These thin, highly permeable soils are quickly saturated, resulting in a high proportion of rainfall recharging vertically into the fractured rocks. At mid slopes, recharge is more limited owing to the buffering effect of the deeper soil layers. The lower slopes and alluvial flats are predominantly discharge areas. A high proportion of the groundwater found in the middle and lower slopes in fractured rock originates from recharge that occurs at the ridges and propagates down-slope, and is not local, vertical recharge. Thus, as distances down-catchment increase, the lag between rainfall and the response of the groundwater system also increases.

Figure 18: Lachlan catchment sections and topography



Perhaps the most interesting finding in this study is that the lag between rainfall and the groundwater system response increases down-catchment not only at a local scale, but also at a regional scale. This was exemplified most strongly in the Lachlan catchment, where there were sufficient bores, well distributed over time, to allow the catchment to be subdivided into 3 sections, delineated by lines running in north-south direction: East (containing Bigga), Mid, (containing Cowra), and West, (containing Wombat) (Figure 18). The SWL response in Lachlan East lagged about 5 years behind the rainfall, while in Lachlan Mid and West the lag times increased to a maximum of 19 years (Table 12). Possible causes of such lag distribution are further discussed in section 5.2.

The aim of this study was to relate the behaviour of water levels in fractured-rock groundwater systems to rainfall, and in particular to investigate the influence of significant changes in rainfall through time on SWLs.

5.1 Rainfall analysis

Individual rainfall station data, as well as composite rainfall data for each section, were analysed to determine whether significant abrupt changes in the mean rainfall could be detected in the long-term record.

The statistical analysis of the annual rainfall data showed that, with the exception of the Gwydir, at most stations and sections north of the Murrumbidgee Valley, the average annual rainfall showed a significant abrupt increase after 1947. This was caused by an increased spring and summer rainfall in the summer rainfall zone (rainfall zones are described in section 2.2.1, Rainfall, on page 7), and by an increased spring, summer and autumn rainfall in the uniform rainfall zone (Table 11).

Table 11: Rainfall average (mm) before and after 1947 and percentage change

	Average monthly rainfall												Average seasonal rainfall				
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Spring	Summer	Autumn	Winter	Annual
Barraba - summer rainfall zone																	
Pre-1947	75.0	55.4	61.2	41.5	32.9	50.4	45.5	36.5	40.5	49.6	65.2	73.2	155.28	203.6	135.7	132.5	627.0
Post-1947	103.1	91.7	49.6	37.8	50.3	38.8	45.1	43.1	43.9	72.2	75.5	79.2	191.5	270.2	137.8	127.0	730.3
% change	37.3	65.6	-19.0	-8.8	52.8	-23.0	-0.9	18.0	8.4	45.5	15.8	8.3	23.3	32.7	1.6	-4.1	16.5
Forbes - uniform rainfall zone																	
Pre-1947	45.5	33.1	37.5	35.6	35.0	49.1	40.4	40.9	37.9	37.3	33.1	44.0	108.2	122.5	108.2	130.4	469.3
Post-1947	57.0	49.7	46.5	40.8	50.1	37.7	46.2	44.4	43.4	59.5	47.1	45.9	149.9	153.8	137.4	128.3	568.2
% change	25.3	50.3	24.1	14.5	43.0	-23.2	14.3	8.6	14.6	59.5	42.4	4.3	38.6	25.5	27.0	-1.6	21.1
Tumbarumba - winter rainfall zone																	
Pre-1947	59.8	53.2	70.5	67.0	75.9	117.2	98.3	103.8	83.1	90.2	62.2	73.3	235.5	186.4	213.4	319.2	954.4
Post-1947	67.0	51.6	61.2	65.4	91.8	87.9	109.5	111.1	98.4	106.2	79.1	66.7	283.6	197.7	218.4	308.5	995.8
% change	12.0	-3.0	-13.3	-2.4	21.0	-25.0	11.4	7.1	18.4	17.8	27.1	-9.0	20.5	6.1	2.3	-3.4	4.3

Pre-1947, 1895–1946; post-1947, 1947 to the end of observed record; estimated data not included in analysis.

In the winter rainfall zone (Murrumbidgee West and Murray), the significance and extent of the abrupt rainfall changes diminished. Nevertheless, spring rainfall increased markedly, and there was also a small increase in autumn rainfall (Table 11).

The percentage change in Table 11 illustrates that the winter rainfall declined after 1947. This was due mainly to a markedly reduced occurrence of rainfall in June. At some stations there was an increase in rainfall variability after 1947 (Table 14).

The largest increase in rainfall happened after 1947 in the uniform rainfall zone. This area also experienced the largest changes in the seasonal rainfall patterns. The largest changes happened here because the average annual position of the subtropical high-pressure belt was centred in this zone during the 20th century, and the southward movement occurred within this zone after 1947, as presented in Figure 5. This behaviour was consistent with changes in the atmosphere linked to the slight displacement of the subtropical high-pressure ridge towards the South Pole and its weakening, described by Kraus (1955a) and Drosdowsky (2005) and presented in more detail in section 2.2.2.

The cause of the anomalous June rainfall pattern is unclear. It may be linked to the June anomaly, described by Van Loon (1967) and Pittock (1971), in the high-pressure belt's annual cycle. The June anomaly manifests in a temporary return of the high-pressure belt back south, from the cold continental mass towards a still-warm ocean mass, as a consequence of slower cooling of the ocean than of the continental crust in winter. The mechanism of the connection between these two phenomena, however, remains unknown. Even more intriguing is that if the displacement of the high-pressure ridge in 1947 was the cause of the change in June rainfall, the absence of the 1895 phase-change in June rainfall remains unexplained. Inconsistency between June and annual rainfall patterns, discussed in section 4.1.2, implies that the origin of the process behind the June rainfall temporal fluctuations could be different from the origin of the process that had driven both the noted 1895 and 1947 rainfall shifts. A single phase-change in June rainfall during the 1880–2003 period suggests a possibly lower frequency of this process than of the two phase changes of the process captured in the annual rainfall around 1895 and 1947.

5.2 Standing water level analysis and the relationship with rainfall

The groundwater flow system responses captured by this study (Table 12) are much shorter than, and in large disagreement with, the currently conceptualised responses within the Groundwater Flow System (GFS) framework (Coram *et al.*, 2000), and being evidence (data) driven, offer paradigm shifts in the areas of GFS and salinity.

Table 12: Abrupt changes and lags in groundwater response to rainfall

Section/subsection	Year of shift in		Delay	Moving	Cross
	Rainfall	SWL	(years)	average fit	correlation
Gwydir	(NS)	(NS)	(-)	8	(NS)
Namoi	1947	1949, 1955	2, 8	4 - 5	1*, 7, 10*
Peel	1947	1952	5	3	3*
Macquarie	1947	1953	6	5 - 6	1*, 2*, 7*
East Lachlan	1947	1952	5	5	(NS)
Mid Lachlan	1947	(NS)	(-)	11	19*
West Lachlan	1947	1963	16	16	1, 16*, 17*
M'bidgee NE	1947	1991	#	N/A	0*, 1*
M'bidgee SE	1947	1988	#	N/A	3*
M'bidgee East	1947	1965, 1997	#	N/A	0*, 1*
M'bidgee West	(NS)	1937	-	11	19*
Murray East	(NS)	(NS)	-	14	(-)
Murray West	(NS)	(NS)	-	27-30	(-)

* Lags significant in the multiple regression analysis.
# The delay between shift in rainfall and shift in SWL was not calculated for the Murrumbidgee, as the shifts indicated a decrease in SWL, which was unrelated to the rainfall behaviour.
NS – Not statistically significant.

The high level of agreement within the results of various methods and across the study area provides confidence that the findings of this study are reliable.

5.2.1 Change-point analysis and trend analysis

The SWL change-point analysis detected significant abrupt decreases in SWL (from deep to shallow water table) everywhere where rainfall had a significant abrupt increase in 1947, except for the Gwydir, Lachlan Mid and Murrumbidgee. As indicated in Table 12, the years these were detected lagged behind the time of the abrupt increase in rainfall average.

In the Namoi, Peel, Macquarie, and Lachlan East and West, the abrupt changes were detected in both rainfall and SWL, and there was close agreement between the various independent estimates of the lagged groundwater–rainfall response.

In the Gwydir section, the change in rainfall and groundwater was detected after 1947 but with a confidence level lower than 90%, so it was not considered significant. This can be considered as a match between negative results, and the goodness of fit between rainfall and SWL can be judged from the moving-average graphs and residual mass curves, presented in the Appendix in Figure 22 and Figure 23.

In Lachlan Mid, the abrupt increase in rainfall in 1947 was not matched by a significant abrupt change in SWL. This is very likely the consequence of very few bore data in the early Lachlan Mid record, on which the system estimate was based. System estimates based on insufficient points can deviate substantially from the true values. However, the residual mass curve (Figure 23), the moving-average fit (Figure 22) and the cross-correlation of rainfall and SWL data indicated a lagged groundwater response. The residual mass curve of the SWL (Figure 23) showed a trapezoidal shape and distinguished three periods:

1 before 1947, when the SWL was deeper than average (falling arm)

2 1947–1966, when the SWL hovered around the average (very wide, 19-year stretched minimum of the residual mass curve, forming a base of the trapezium) the centre of the trapezium base falls around 1957

3 shallow SWL after 1966; (steeply rising arm).

This roughly corresponds to the 11-year lag depicted from the moving-average graphs (Figure 22). The 19-year lag was reflected in the cross-correlation analysis (Table 12) and the zero-year lag in the cross-spectral analysis (Table 8).

A fast response in Murrumbidgee East, of up to a year in the northern section and up to 3 years in the longer, southern section, was deduced from the cross-correlation analysis. In the eastern subdivisions of the Murrumbidgee catchment, the SWL data record starts in 1949 in the northern section and in 1965 in the southern section (Table 12), and does not reach far back in the past to capture the rise in groundwater levels, due to the fast system response, triggered by the increase in rainfall in 1947. The first abrupt deepening of groundwater levels was detected in 1965 in the combined Murrumbidgee East section. Thus, the detected abrupt change in the combined dataset could be due to spatial–temporal confounding imposed by the combination of the southern portion of the record with a slightly deeper average SWL from 1965 with the shallower northern portion of the record from 1949. The abrupt deepening in the groundwater table was detected in 1988 in the northern subdivision and in 1991 in the southern subdivision of Murrumbidgee East. When the SWL data from the southern and northern sections were combined, the abrupt change was detected not in 1988 or in 1991, but in 1997. This indicates that the change in SWL occurred gradually, over a longer timeframe, with the water table getting very slowly deeper and deeper, and that the detected abrupt changes were most likely a consequence of the small annual data samples that resulted in extreme values in the annual datasets. Monitoring bore data in four salinity sites situated within the Yass catchment (in the Jinchilee, Opening Site and Quarry Lake, within the Dicks Creek catchment and in the Williams Creek catchment) provide strong supporting evidence of mild gradual deepening of the water table during the period of observation across the Yass catchment, which constitutes the majority of the northern portion of the Murrumbidgee East. These records (not presented) show a mild, temporary rise of water table in the first 2 years after construction (1988–1990), which could be attributed to groundwater fluctuations due to the short-term rainfall variability, followed by the mild, gradual deepening of water table, becoming steeper since 2000, as an immediate reaction to the dryer hydrologic regime of the past 9 years. Although groundwater levels in Murrumbidgee East initially followed the rainfall trend, the drawdown in the past decade appears to be a bit steeper. This mild difference could be due to compound effects of:

- incomplete data
- an eruptive increase in the number of on-farm storages that could have altered the catchment water balance
- an increased number of bores that resulted in more extensive groundwater pumping.

Even though the bore datasets for the Border Rivers and Murray had gaps and only a small number of records per year, and therefore were not suitable for regression analysis, the records were still sufficient to provide some indication of general system behaviour through trend analysis. The moving average (Figure 22) and the residual mass curves (Figure 23) for the short SWL record of the Border Rivers matched closely the corresponding graphs for Tenterfield rainfall data. The delay of SWL behind the rainfall was not noticeable, indicating a very fast groundwater system response. In the Murray catchment, groundwater levels showed a prolonged gradual rise until the 1990s (Figure 22), which was consistent with rainfall behaviour. The lags in this catchment deduced from the trend analysis were extremely long compared with those in the other sections (14 years in Murray East and 27–30 years in Murray West). Such long response times combined with the general north-western slope of regional topography suggest a possible link with the Victorian groundwater systems. The small sample size on which the analyses for the Border Rivers and Murray were based means that these estimates are not as reliable as the response times derived for other sections.

5.2.2 Regression analysis

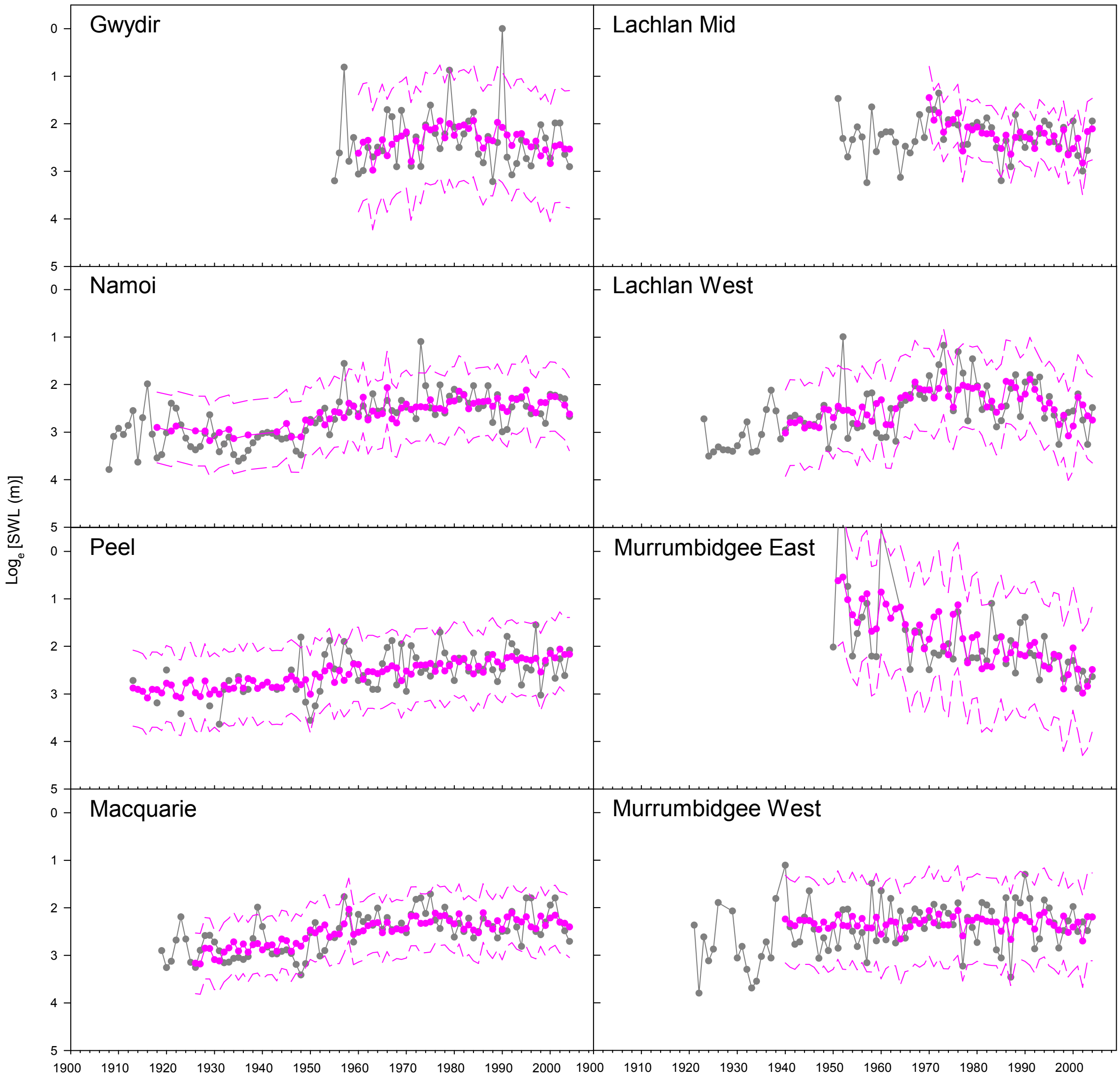
The results of the regression analysis confirmed the link between the lagged rainfall and the SWL response in the Namoi, Peel, Macquarie, Lachlan Mid and West, and Murrumbidgee East and West. For these catchments, the predicted SWL response and the 95% confidence bands were compared with the measured data in Figure 19.

As a regression analysis cannot capture relationships other than temporal displacement, and as the position of an SWL is a consequence of a long sequence of preceding annual rainfall volumes, only a portion of the complex rainfall–SWL relationship could be explicitly expressed through the regression of the annual SWL and rainfall. The remaining portion of the relationship (which was not a simple temporal displacement) remained hidden in the co-variable time. The underlying trend can be expressed through different functions, such as a linear, quadratic or a step-change function.

The variable ‘time’, through which the trend is described in the statistical model, was not statistically significant in Murrumbidgee West; that is, trends could not be described by assuming a linear or quadratic function.

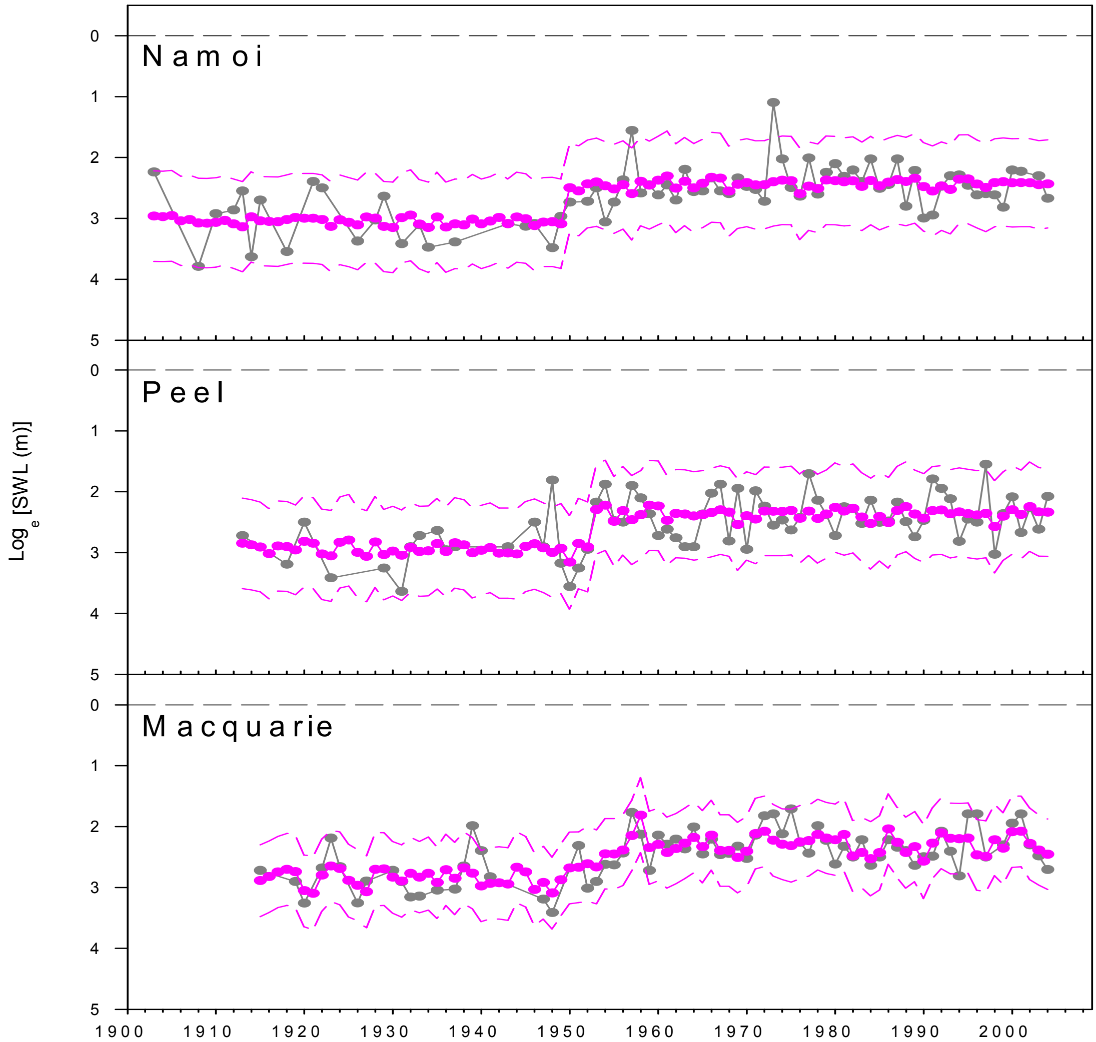
In the Namoi, Peel and Macquarie, where sufficiently long and complete bore records allowed detection of significant abrupt changes both in rainfall and SWL regimes, the step-change function was tested against the quadratic function to see which one better described the underlying trends in the SWL.

Figure 19: Predicted (solid pink line) and measured (grey line) SWL data, together with 95% confidence intervals (dashed pink line); Prediction made using a linear or quadratic trend function. (In the case of the Gwydir the relationship was not statistically significant.)



The step-change function model (Figure 20) showed no remaining time-trends left, apart from those captured by the step-change function and the lagged portion of the rainfall (Table 9). This implies that the strongest influence of rainfall on the SWL behaviour in these three catchments was expressed through the abrupt change in the long-term rainfall average. The significant but not as successful relationships were obtained by using linear and quadratic trend functions. These functions can be understood as an approximation of the step-change function. They confirm that the groundwater had risen from the first to the second part of the century. As the change-point analysis showed, it is misleading to interpret the results as an indication of a gradual groundwater rise. In all three sections where the step-change model was tested, it better reflected underlying process.

Figure 20: Predicted (solid pink line) and measured (grey line) SWL data, together with 95% confidence intervals (dashed pink line), for catchment sections with detected abrupt change in rainfall and SWL data; prediction made using step-change trend model

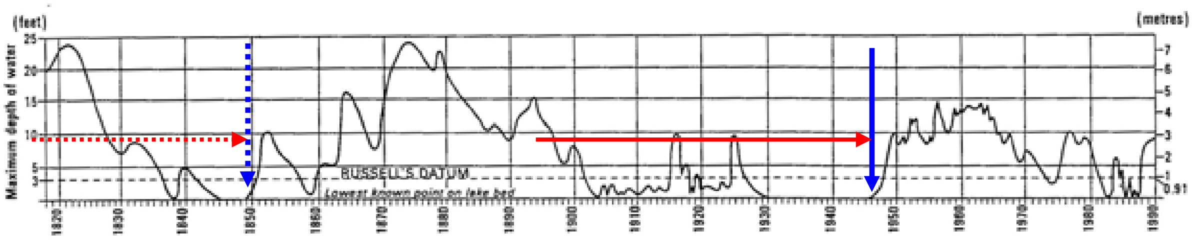


5.2.3 SWL relationship with climate

It is widely accepted that the groundwater acts as a reservoir, routing and attenuating the incoming hydrologic signal, in a similar way as the low-pass filter acts on the incoming signal attenuation. With a response time of several years to decades, it therefore attenuates to a larger extent the incoming signals that have higher frequency, such as ENSO, which is linked to latitudinal energy transfer, than the lower-frequency signals, manifested as climate regime shifts, which appear to be linked to the meridional energy transfer. Therefore, it would be most beneficial for our ability to predict the groundwater fluctuations if we devote our scientific efforts to understanding processes involved in the meridional energy transfer, so we can improve our ability to predict the low-frequency component of the climate.

When looking at the relative importance of land use change and climate on the current position of a water table, it is important to look at the problem from a wide historical perspective, and acknowledge that climate changes, and has always been changing, and that stationary climatic mode, that can allow development of hydrologic equilibrium is exceptional and short-lived. The record of levels of Lake George (Jacobson *et al.* 1991) is one of the longest Australian hydrologic records, and it vividly illustrates (Figure 21) that the climatic variation that caused so many salinity outbreaks over the last half of the century was in fact very mild. Lake George levels fluctuated in the previous century almost twice as much (0–7.5 m) as in the last one (0–4.5 m). This range is again negligible when compared with relatively recent history—the times from 27000 to 21000 years ago when its level reached 37 m and when water spilled over Garrys Gap. The high of 37 m represents about nine times the height reached in the 20th century. To better understand the time perspective, we can condense the age of the Palaeozoic rocks of the Lachlan and New England fold belts into a year. Last century is then equivalent to no more than the last 10 seconds of the imaginary year, and the time when Lake George was spilling would be within the last 40 to 50 minutes of New Year's Eve. It is therefore unrealistic to imagine that the salt that came out after 1947 accumulated only in last 10 seconds of our imaginary year. It is more likely that the shallow water table experienced during the last wet spell, clearly recognisable in the Lake George graph (vertical blue arrows), naturally occurred many times in history, and that it released salt that had been accumulating in the landscape owing to various processes over a much longer period of time.

Figure 21: Fluctuations in water level in Lake George, 1819–1990



Reprinted from Jacobson *et al.* (1991)
The blue solid vertical arrow on the right represents the 1947 cut-off point between a dry and a wet phase in climatic regime. The red horizontal solid arrow indicates a dry climatic phase that lasted from 1895 to 1947. A long-term dry spell can be recognised in falling lake levels up to 1849. The dry spell is marked with the dotted red horizontal arrow on the left, followed by the blue vertical dotted arrow, which marks the cut-off point between the dry and wet regimes of the 19th century. The five decades between 1850 and 1894 are characterised by very wet episodes that kept the water table of Lake George high.

5.3 Interpretation of the observed lags

We postulate that the observed lags between SWL and rainfall consist of up to three components:

- *Tr*, the time needed for **recharge** to infiltrate and reach fractured-rock groundwater.
- *Te*, the time needed for the portion of the storage that recharges mainly via vertical flux to reach **equilibrium**. If a storage that had maintained a balance between inflow and outflow suddenly starts receiving additional inflow, it reacts by increasing its level until the outflow matches the new inflow and a new level is achieved. *Te* is not a constant, as the system needs more time to adapt to a large change than to a small one.

- *Tl*, the time needed for the pressure impulse to **laterally** propagate down the system, from the highest recharge point to the lowest discharge point. This component is pronounced in complex systems (intermediate or regional), where recharge areas are spread over several hills.

Each of the three components can contribute to the highly variable lags within the study area. Shorter lags characterise uplands, close to the Great Divide, and longer lags are observed further west.

The eastern portion of the system has a thinner layer of unconsolidated sediments than further west. Therefore, the recharge response happens faster and *Tr* is smaller in the eastern highlands than in the western lowlands.

The size of the system is reflected through the *Te* component, as small systems move to a new equilibrium faster than large systems, which have more inertia.

The longer lag times in the west might be a consequence of the larger, intermediate systems found in these areas. In the complex intermediate or regional systems the flux propagates laterally through a sequence of unconfined and confined units. The unconfined units underlie the hilltop recharge areas, whereas confined and semi-confined units prevail in the fractured-rock systems underlying the discharge areas in the river valleys. The storage in the fractured rock underneath the top of the highest hill in this sequence receives flux only from recharge, and discharges partially locally, and passes part of the flux underneath the local valley to the next storage. The arrival of this flux at the second storage is delayed compared with the local recharge. The SWL in each of the consecutive storages is a consequence of the superposition of two signals, local recharge and lateral flux.

This study showed that what is currently conceptualised as a small local system might need several seasons to move to a new equilibrium after a significant change in rainfall regime, such as that in 1947. In any intermediate system, this delay must be prolonged, owing to the delay of the lateral flux arriving at each of the consecutive storages in the sequence.

The lag times suggested by the trend analysis are indicative of time-lag for the groundwater system as a whole, behind rainfall. There is a substantial variation between the different parts of the catchments in response times. Trend analysis (moving average) captures the overall system lag, whereas the spatial diversity is more obvious from the regression analysis and, in some cases, from the change-point analysis. For instance, in the Namoi catchment, the moving-average method indicates a system lag of 4 to 5 years; cross-correlation analysis finds that the lags significant in multiple regression analysis are 1 and 10 (the average being 5½); and change-point analysis shows delays of 2 and 8 years (average of 5, very close to the result of the simple moving-average method).

Lags that are presented in this study should be seen as approximate and informative, not as accurate values. Even so, they are no more than one fifth of the lags that are currently conceptualised under the GFS framework (Coram *et al.* 2000):

- 30–50 years for local GFS (flow path between recharge and discharge area <5 km)
- 50–100 years for intermediate GFS (flow path 5–50 km)
- more than 100 years for regional GFS (flow path >50 km).

This implies the need to revise the currently assumed concepts.

Such short response times are in agreement with some anecdotal evidence, dating back to the time of clearing (Abbot & Glengarry 1880), in which three streams in the Hunter Valley that used to run only seasonally became permanent in 1871 after ringbarking in 1869 and 1870.

Fast groundwater response times observed following the 1947 rainfall shift disagree with the currently assumed slow-reacting groundwater flow system concept, but agree with the findings of Wagner (2001) about expansion and reduction in salinity expression over the Yass catchment between 1943 and 1986, based on aerial photography and site inspections (Appendix, Table 16); and the SWL records from the monitoring bores after 1987.

5.4 Implications for dryland salinity

Observed groundwater response times across the fractured rocks of the New England and Lachlan fold belts are substantially shorter than the response times that are currently postulated within the GFS framework (Coram *et al.* 2000). This implies that the salinity outbreaks from the second half of the 20th century that prompted the overall concern and government action in the 1980s were a consequence of two hydrologic phenomena:

- the 1947 climate shift (direct consequence)
- the land clearing during the 19th century (indirect consequence).

The effects of the clearing on outbreaks of salinity were masked during the dry phase from 1895 to 1947, and resurfaced during the following wet phase all over the study area.

The wetter climate forced groundwater levels in fractured rock to rise during the second half of the 20th century across the study area. The higher position of the groundwater table allowed the groundwater systems to reach the local depressions in the terrain and to discharge at a larger number of points. Where evaporation exceeded discharge, salt became concentrated, forming saline patches on the surface of the land. This increased both the number of salinised areas and their total size.

However, the clearing that took place a century ago changed the hydrologic properties in the study area, allowing higher recharge than if the previous land use had remained intact. The dry climatic phase between 1895 and 1947 and the cleared terrain had opposing effects on the recharge rate and on the hydrologic balance. After 1947, the effects of clearing and the wetter climate on recharge were superimposed. If the clearing had not taken place, the water table would have been deeper, the overall effect of the rainfall shift would have been smaller, and dryland salinity would have been less prominent.

Clearing also greatly increased soil erosion. Both processes enhanced the exposure of fractured rock and increased the recharge of aquifers. This recharge caused the water table rises that play an important role in land salinisation, particularly during and after times of high rainfall.

The increase in recharge due to the land use changes that occurred immediately after World War II could have been superimposed on the increase in recharge due to the rainfall shift, and would therefore be undetectable, but nevertheless would not alter any of the findings related to the speed of the groundwater system response. However, we expect that these land use changes would not significantly alter the deep drainage to groundwater flow systems in fractured rock, as the change from pasture to cropping occurred primarily on the flatter areas, which are not high-recharge, deep-drainage areas, but are mainly discharge areas (or shallow recharge areas), from which the shallow flux drains laterally towards the stream or the drainage line. Thus, the overall recharge contribution to the groundwater flow systems in fractured rock would have been either negligible or small, and therefore could not have had a substantial effect on the position of the water table and on salinity.

The link between the behaviour of groundwater in fractured rock and stream salinity is more complex than its link with land salinisation. The delayed peak of EC along streams described in the Stream-EC Trend Analysis Report (Harvey *et al.* 2009) has similarities with the lagged response of groundwater in fractured rock to climatic variation. The investigation of the link between stream salinity and the behaviour of groundwater in fractured rock is, however, outside of the scope of this report. An approach to this type of analysis is suggested in the Recommendations (section 5.6). It is very important to distinguish chemical equilibrium, expressed through the stream salinity, from hydrological (physical) equilibrium, which affects land salinisation. We can conceptualise what is happening in the system by imagining the following scenario:

1 An unplugged bathtub is being filled from the tap at the same rate as the water is draining from the plughole, so the water level is maintained. The flow from the tap is analogous to the recharge, the water level in the bathtub is analogous to the groundwater level, and the leak from the plughole is analogous to the discharge.

2 Someone adds bath salts to the water in the bathtub. The bath salts slowly dissolve: this is analogous to the process of weathering.

3 The tap is turned on slightly more. Time is needed for the new level in the leaking bathtub to rise and stabilise. When this happens, the system is in a new state of hydrologic equilibrium.

4 Additional bath salts are added to the water while the water level is rising. This is analogous to the process of salt wash-off.

5 All this time water is draining from the bathtub, and time is needed for the chemical concentration of the water that drains to stabilise. This is analogous to the chemical equilibrium in the stream.

Obviously, steps 3 and 5 represent two related but different processes, and the lag time after the hydrological, physical change in groundwater cannot be expected to be identical with the lag time of the chemical change in the stream.

5.5 Conclusions

This study introduces new knowledge about the speed at which the groundwater flow systems in fractured rock react to changes in rainfall, and a new paradigm in the way we should perceive the history of dryland salinity in NSW. The most important conclusions arising from this study are as follows:

- Trends in SWL have been following trends in rainfall across the study area for the period of available SWL data, with a delay. The only noticeable deviation, consistent with the effects of clearing, was visible in the early records of Lachlan West before 1937.
- Groundwater has been in dynamic equilibrium with rainfall inputs during at least the last four decades. Average annual rainfall increased after 1947, but in the last decade it

has been decreasing in most areas. Groundwater levels in fractured rock have followed these trends: they rose, stabilised, and are currently falling in most areas.

- Groundwater flow systems in fractured rock show much faster responses to changed recharge conditions than former estimates implicitly included in the previous Salinity Audit and current estimates as conceptualised within the GFS framework (Coram 1998; Coram *et al.* 2000), which was used in the National Land and Water Resource Audit and the Australian Dryland Salinity Assessment 2000 (Natural Heritage Trust 2001).
- Lachlan West bore records demonstrate that even though the initial water table rise due to clearing could not be detected in other sections, the 19th century clearing permanently increased potential recharge and placed the water table at a shallower level than if there had been no clearing.
- Dryland salinity worsened during the second half of the 20th century as the increased potential recharge due to clearing was superimposed on the long-term wet climatic phase. Together, both processes caused water tables to rise and intersect the landscape at many points, creating salt deposits on the surface as the water evaporated. This was happening at more points and in larger areas than when the water table was deeper during the first half of the century.
- Climatic variation, which caused so many salinity outbreaks over the last half of the 20th century, was in fact very mild compared with variation over longer time scales. This suggests that the salt build-up in the landscape is not merely a consequence of a single, longer-term, wet climatic episode superimposed on the land use change, but has its origin in the long sequence of preceding hydrologic perturbations.

Other important conclusions also arise from this study:

- The increase in rainfall in about 1947 in many parts of the MDB caused a rise in groundwater levels over the following years and played an important part in the outbreaks of salinity in the regions covered by this study.
- The abrupt and statistically significant change in rainfall happened in 1947 in the uniform rainfall zone (Macquarie, Lachlan and Murrumbidgee East) and in the southern portion of the summer rainfall zone (Namoi and Peel). A less abrupt increase in rainfall occurred outside these areas: in the Border Rivers and Gwydir (northern part of the summer zone) and in Murrumbidgee West and Murray (winter zone).
- Phase changes in the rainfall regime that took place around 1895, 1947 and possibly 2000 (Vivès and Jones 2005):
    - are consistent with the displacement of the high-pressure ridge to the north and south (Kraus 1955b; Pittock 1973)
    - are linked to the meridional energy transfer of the coupled ocean–atmosphere–continent system in the Southern Hemisphere
    - appear to capture periodicity equal to the two periods of the PDO registered in the northern Pacific (Mantua *et al.* 1997).
- The June rainfall pattern is in disharmony with the annual rainfall patterns, being above average between 1880 and 1930, average between 1930 and 1960, and below average since. This had an important influence on dissipation of the rainfall shift signal across the winter rainfall zone.

- The response times increase with distance from the Great Dividing Range. Groundwater levels respond to recharge changes in approximately half a decade in the upper catchments: Border Rivers <1 year, Gwydir 8 years, Namoi 2–8 years (average 5 years), Peel 3–5 years, Macquarie 5–6 years, Lachlan East 5 years, Murrumbidgee East 1–3 years). The responses may take longer further west, down the groundwater path: Lachlan Mid 11 years, Lachlan West 16–17 years, Murrumbidgee West 11–19 years, and possibly Murray West 27–30 years.
- The ENSO phenomenon represents a less important climatic driver of water table behaviour and land salinisation than the longer-lasting, persistent signal captured by changes in rainfall regime.
- An explicit effect of massive clearing on the water table could not be detected across the study area, except in Lachlan West, owing to:
    - the short groundwater response times
    - the late start of the bore record in the 20th century
    - the completion of most clearing by the end of 19th century.
- The initial rise in the water table in Lachlan West was consistent with the rise expected after clearing. It was possible to capture this rise as the bore record started early enough and the groundwater response in this section was slow.
- The effects of clearing on outbreaks of salinity were masked during the dry phase from 1895 to 1947, but resurfaced during the following wet phase.
- The data from bores in Murray West reveal a long-term rise of 0.5 m/year in the bores running north from the Hume Dam, suggesting a possible local groundwater rise linked to the changes in the groundwater regime caused by the dam construction.
- Coarse groundwater data coverage prevented detection of possible minor, temporary or local effects of human influence on recharge, such as localised changes in vegetation cover or land management practices, minor groundwater pumping, dam construction and river regulation, which occurred throughout the 20th century.
- The increase in recharge due to the land use changes that occurred immediately after World War II could have been superimposed on the increase in recharge due to the rainfall shift, and therefore be undetectable, but would not alter any of the above findings, including the fast groundwater flow response.
- The analysed climatic variability of the 20th century captures only a small portion of the overall climatic variability. So even though the situation is currently stable, the water table is generally falling and the salinity-affected catchments are recovering, if and when the climate of the 19th century repeats, it will have enormous effects on recharge and will trigger salinity outbreaks much more severe than those we experienced during the second half of the 20th century.
- Much wetter long-term spells and much higher recharge occurred in the recent history and prehistory of NSW and Australia, so it is very likely that NSW experienced times of high water tables and severe dryland salinity in the past, and that with every new long-term wet spell, existing accumulated salt stores are remobilised and replenished.
- Lag times and processes addressed in the Stream Salinity Report (Harvey *et al.* 2009) are linked to time needed to establish chemical (salt) equilibrium in streams. They are different from the lag times and processes analysed here, which are related to time

needed for the groundwater storage to move to a new state of hydrologic (physical, pressure-related) equilibrium. Every groundwater flow system has therefore (at least these) two independent lag times.

5.6 Recommendations

Two major groups of recommendations arise from this work. Group A is related to data acquisition, and group B deals with suggestions for further research and analysis, which should be done to improve our knowledge about groundwater flow systems and the phenomena that affect salinity, land use change and climate.

All existing data sources listed below could be brought together to further expand the pioneering work done in this study, and shed more light on the processes that drive the movement of water tables and dryland salinity:

A1 Data used in this study represent only a small portion of the existing data, which are scattered around NSW and held by various organisations, such as councils, universities and the CSIRO.

A2 Future investigation should include records in the ‘Water level’ and ‘Pumping test summary’ portions of the DWE database which could not be incorporated in this study owing to time limitations.

A3 Some information in published papers needs further processing before it can be used. Often, bore numbering systems differ from the DWE recording system.

A4 Further data acquisition is absolutely necessary in the Border Rivers catchment, where a detailed statistical analysis was not possible, and in the Murray catchment. The Murray has experienced groundwater rises up until recently, owing to the gradual and prolonged increase in rainfall in the winter rainfall zone, and with very limited bore data we are faced with uncertainty about whether the water table rise across the Murray catchment has truly ended, or whether there are some regions where the water table is still rising and therefore expanding salinisation is still a risk.

A5 Even though DWE is the NSW groundwater data custodian, other organisations that collect groundwater data are not obliged to pass their data to the DWE database. In addition to this, a series of consecutive reorganisations and staff cuts in Government departments have resulted in insufficient, almost non-existent, resources to run and maintain its databases. Groundwater in fractured rock is an integral part of the available water resources. The recording of its changing levels and behaviour is an important step in understanding the history and mechanisms of dryland salinity in NSW. For this and other reasons, such as the need for protecting the future of all land and water resources and the environment, it is essential to adequately fund a centralised data custodian and to require all groundwater information to be handed over to this custodian.

A6 Most SWL data are currently collected only once or twice a year at monitoring sites. This is insufficient for any type of serious analysis. Data should be collected at least monthly, and at least one bore at highest altitude within the monitoring site should be equipped with the probe and continuously monitored.

A7 Bores drilled in the first half of the 20th century close to monitoring sites should also be monitored at least monthly to provide sufficient data for statistical analysis. This would enable the change in SWL near the monitoring sites caused by the abrupt increase in rainfall in 1947 to be better estimated, as it would tell us the total rise in the water table level caused by the rainfall phase change at that particular site, which we can link and correlate with the information from the existing monitored bores and use to estimate the rise in the water table across the catchment. The results could support reliable groundwater model calibration: models that can be calibrated over a sufficiently long period that encapsulates large climatic variability are much more reliable than those that use a small temporal window, such as from 1988 onwards, during which period the bore monitoring records show relatively small hydrologic variation. Calibrated models can in turn be used as reliable tools to evaluate impacts of historical land use changes on groundwater levels, investigate possible hydrologic scenarios, and predict areas salinised under these scenarios.

A8 Recent SWL records in the Murray catchment, which were stored in the Boremaster database, should be incorporated in DWE's GDS. Victorian data should be used to supplement the NSW Murray data.

A9 Existing data on Lake George levels should be tracked down, and monitoring of levels should be continued, as the Lake George record has the oldest hydrologic record in Australia. The funding necessary for its monitoring is negligible compared with the scientific value it already provides and will provide in hydrology, meteorology, climatology and salinity studies.

B1 Statistical methods that were used in this study can be further improved by replacing the moving-average technique with splines, choosing a 5-year time step as the basis for detailed statistical analysis, and introducing the autoregressive component into the statistical model.

B2 The FLAG model should be run with an appropriate, high resolution to explore whether the WETNESS and UPNESS indices could be used as co-variables in the multiple regression analysis between SWL and rainfall to reduce the effects of spatial variability in SWL and to eliminate possible effects of heterogeneity and spatial–temporal confounding. For more details about problems with FLAG model implementation see section 4.2.1.

B3 Existing fractured-rock water quality data should be collected and, if possible, analysed.

B4 Harvey *et al.* (2009) grouped together and colour coded catchments drained by streams with common properties and behaviour doing Salinity Audit Stream-EC trend analysis. This grouping was based on how much catchements might be problematic in the future:

- The most problematic catchments were those that experienced rising trend in EC. These so-called 'bad-boy' catchments were generally situated in the west, in the regions of lower rainfall and flatter slopes.
- The least problematic were those catchments that had a falling EC trend and those that were in an oscillatory state of dynamic equilibrium, such as the Upper Murrumbidgee, Snowy and Lachlan mountainous catchments. These were

generally close to the Great Divide, or in the highlands of the Snowy Mountains, in the high-rainfall zone and characterised by steep slopes and good drainage.

- There were other categories in between, each coded in a different colour.

Bore information should be re-collated to reflect these groupings. It would then be possible to derive SWL information for these new bore groupings and to look at relationships between SWL, stream EC, rainfall, stream salt flux and bore EC. This would help us to better understand links between the behaviour of groundwater in fractured rock and stream salinity.

B5 Further research is recommended to explain the highly variable lags observed in the study area. This should include:

- analysis of information obtained from the monitoring sites
- testing whether the propagation of the lateral pressure signal happens within the deep, regional groundwater flow system, the hypotheses alternative to the current concept of the GFS Framework
- collection and analysis of data from mining history and accidents, such as the accident in Browns Creek gold and copper mine, 8 km west of Blayney, in 1999, in which the deep drilling encountered a major fracture, water flooded the mine, and the sudden depressurisation caused successive oscillations in all groundwater flow systems within at least a 5-km radius. Information collected during such natural hydrologic experiments should be used to improve our understanding of the basic concepts of groundwater flow systems.

B6 We need further research and analysis of historical land use changes in NSW, as our current knowledge is more qualitative than quantitative. We know that vegetation clearing happened, but systematic information about land use changes over the State and over time is not readily available. Accurate, digital spatial–temporal information is necessary for the analysis of the effects of land use changes on recharge, groundwater tables and salinity. This can be achieved through funding for:

- interpretation of historical aerial photographs and transformation of the information into GIS-type spatial data; this would demystify the extent of land use changes from pasture to cropping in the high-recharge areas of fractured rock since World War II
- bringing together all the information collected through past and current research and transforming it into useful spatial data
- future research to fill the remaining gaps in our knowledge.

B7 Further research in climatology and meteorology, with emphasis on physical processes, is needed to improve our abilities to predict rainfall regimes, groundwater behaviour and salinity. We suggest the following topics to be covered:

- An index analogous to the PDO should be calculated, and its link with eastern Australian rainfall should be analysed.

- Long-term, historical, high-pressure-belt movement on the east coast of Australia should be reconstructed using existing data and methods based on Pittock's and Drosdowsky's work, with additional parameters for determination of multiple maxima in the case that they are encountered.

- Historical rainfall patterns back to 1820 should be reconstructed using the Lake George historical record as a basis for the hydrologic analysis. This record can then be subjected to frequency analysis and change-point analysis and compared with other possibly related hydrologic records in which the 1895 and 1947 rainfall shifts were noted.

- Investigation of the reasons for the overlap of two phases of the PDO in the Northern Hemisphere with a single phase of climatic regime in the study area.

- Investigation of the reasons behind the anomalous behaviour of June rainfall, the associated energy transfer process, and the frequency of this process.

B8 The SWL trend around the Hume Dam should be derived and compared with historical lake oscillations to verify whether the Hume Dam contributed to the high water table rise north of the lake. All bores (not just the fractured-rock bores) should be used in this exercise. Bores should be grouped into concentric rings. The SWL in bores on the segment towards Billabong Creek that experienced a high historical SWL rise (GW006742, GW0025573, GW027752, GW055384 and GW056102) should be monitored.

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7 Glossary

Adjusted R^2—A modification of R^2 that adjusts for the number of explanatory terms in a model. Unlike R^2, the adjusted R^2 increases only if the new term improves the model more than would be expected by chance. The adjusted R^2 is defined as:

$$R^2 = 1 - (1 - R^2)((n - 1)/(n - p))$$

where p is the total number of regressors in the linear model and n is sample size.

Alluvial—Material transported and deposited by running water.

Aquifer—Geological formation which is sufficiently permeable to allow water to move within it and to be extracted. Aquifers generally occur in porous materials such as sands, gravels, limestone with solution cavities, sandstone or well-fractured rocks.

Artesian bore—Bore in which the water level rises above the top of the aquifer or groundwater system intercepted.

Artesian flowing bore—Bore in which the water level rises above the ground surface.

Autocorrelation—correlation between a series X_i and the same series lagged by one or more elements X_{i-k}.

Climate shift—Abrupt change in climatic regime.

Confounding variable—See ‘Spatial–temporal confounding’.

Detrending—removing trend.

FLAG model—The ‘Fuzzy Landscape Analysis GIS’ is a CSIRO-developed spatial model that uses topographic information in the form of a digital elevation model, and includes UPNESS and WETNESS indices.

High-pressure belt—See ‘Subtropical high-pressure ridge’.

High-pressure ridge—See ‘Subtropical high-pressure ridge’.

Low-pass filters—Mathematical functions that eliminate high-frequency signals from the data. A similar device can be found in a stereo, where it eliminates or filters out high-pitched noise (low-pass filter) or deep tones (high-pass filter).

Monitoring bore—A bore designed and constructed with the purpose of measuring SWL, pressure or water quality.

Noise—Input that consistently causes variation in the output measurement that is random and unexpected and, therefore, not controlled. Also called white noise, random variation. This term originates from acoustics.

Noisy data—It is hard to understand speech in noisy places, such as parties, as our brain has to separate and decode (filter out) the speech signal from the background noise. A ‘noisy’ radio signal has higher variance and a larger random component than a ‘clean’ radio signal. In statistics, data that similarly have a pronounced random component are therefore called ‘noisy’ (also see ‘Noise’).

Non-stationary time series (opposite of ‘Stationary time series’)—A time series with a variable mean, variance or autocorrelation through time.

Outlier—In statistics, an outlier is a data point that is located far from the rest of the data. Given a mean and standard deviation, a statistical distribution expects data points to fall within a specific range. Those that do not are called outliers and should be investigated.

Periodogram— an estimate of the spectral density of a signal. The term was coined by Arthur Schuster in 1898.

Production bore—A bore designed and constructed with the purpose of water extraction.

Rainfall shift—Abrupt change in rainfall regime.

Regressor—independent variable in regression.

Spatial–temporal confounding—Inability to differentiate between the effect of space and the effect of time on a particular variable.

Stationary time series—A time series $x(t)$; $t = 1, \ldots$ is stationary if its statistical properties do not depend on time t. A time series may be stationary in respect to mean, variance or autocorrelation.

Step-change analysis—A type of statistical analysis used to discover the existence of abrupt changes, to study their timing and to evaluate the probability of these changes occurring at random. The mean (and median) of a process that has undergone a step change generally abruptly increases or decreases from one value to a very different value. Graphs of step-changes resemble two consecutive steps in a staircase: __|¯¯.

Subtropical high-pressure ridge—A region of high-pressure air that separates a wet and warm equatorial weather system from a colder and dryer mid-latitude weather system.

SWL—Standing water level = natural level of water in the bore (not affected by pumping), measured from the surface of the land, with the axes pointing downwards (illustrated in Figure 7, page 20).

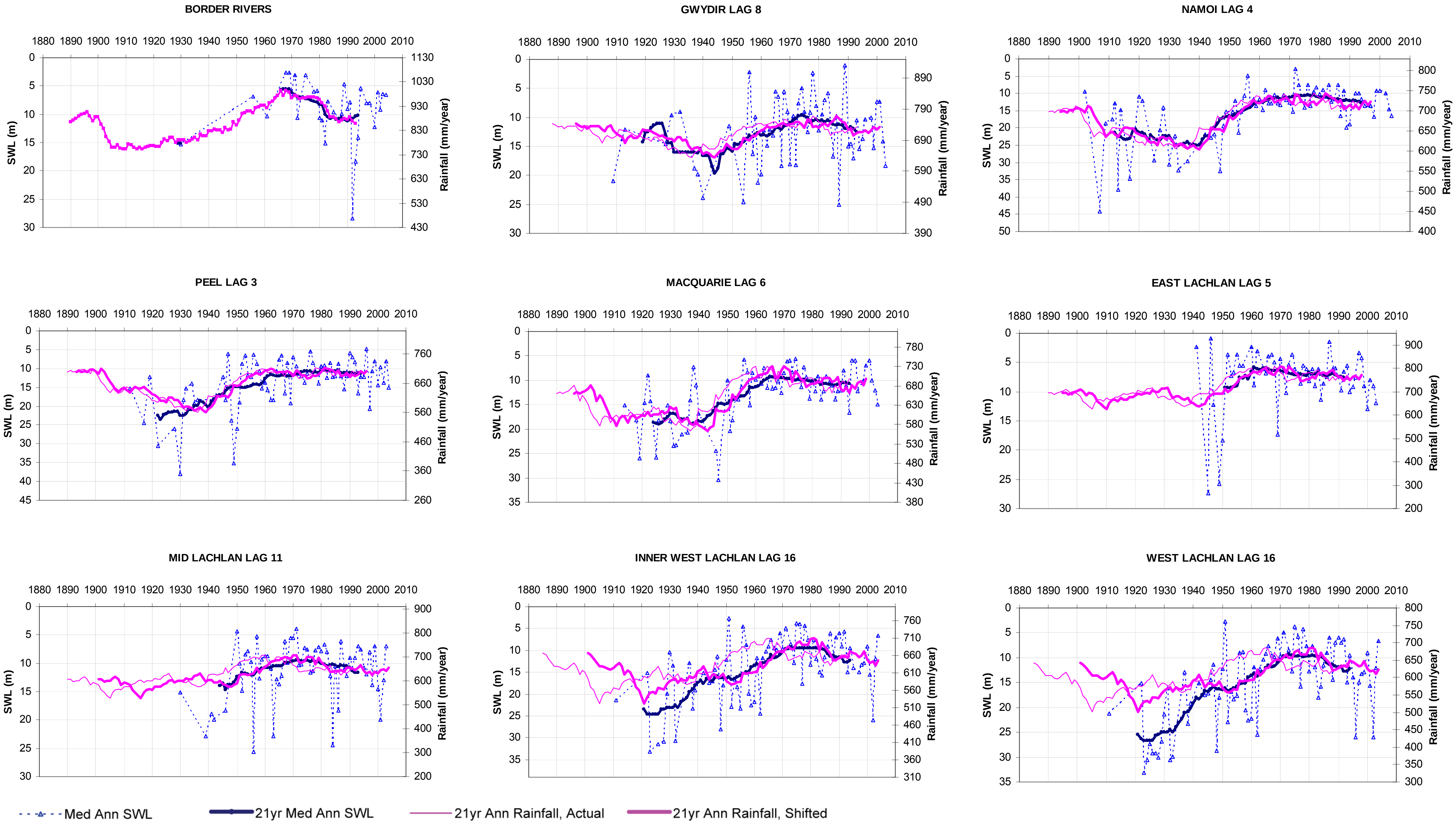
UPNESS index—An index evaluating surface and shallow subsurface water accumulation. It varies from 0 (at ridges) to 1 (in lowlands).

WETNESS index—An index associated with water accumulation and probability of discharge. It is used in the FLAG model. High values (close to 1) identify areas in a catchment where water accumulates and the probability of discharge is high.

White noise—A stationary time series or a stationary random process with zero autocorrelation. In white noise $N(t)$, any pair of values $N(t_1)$ and $N(t_2)$ taken at different moments t_1 and t_2 are not correlated—i.e. the correlation coefficient $r(N(t_1), N(t_2))$ is 0.

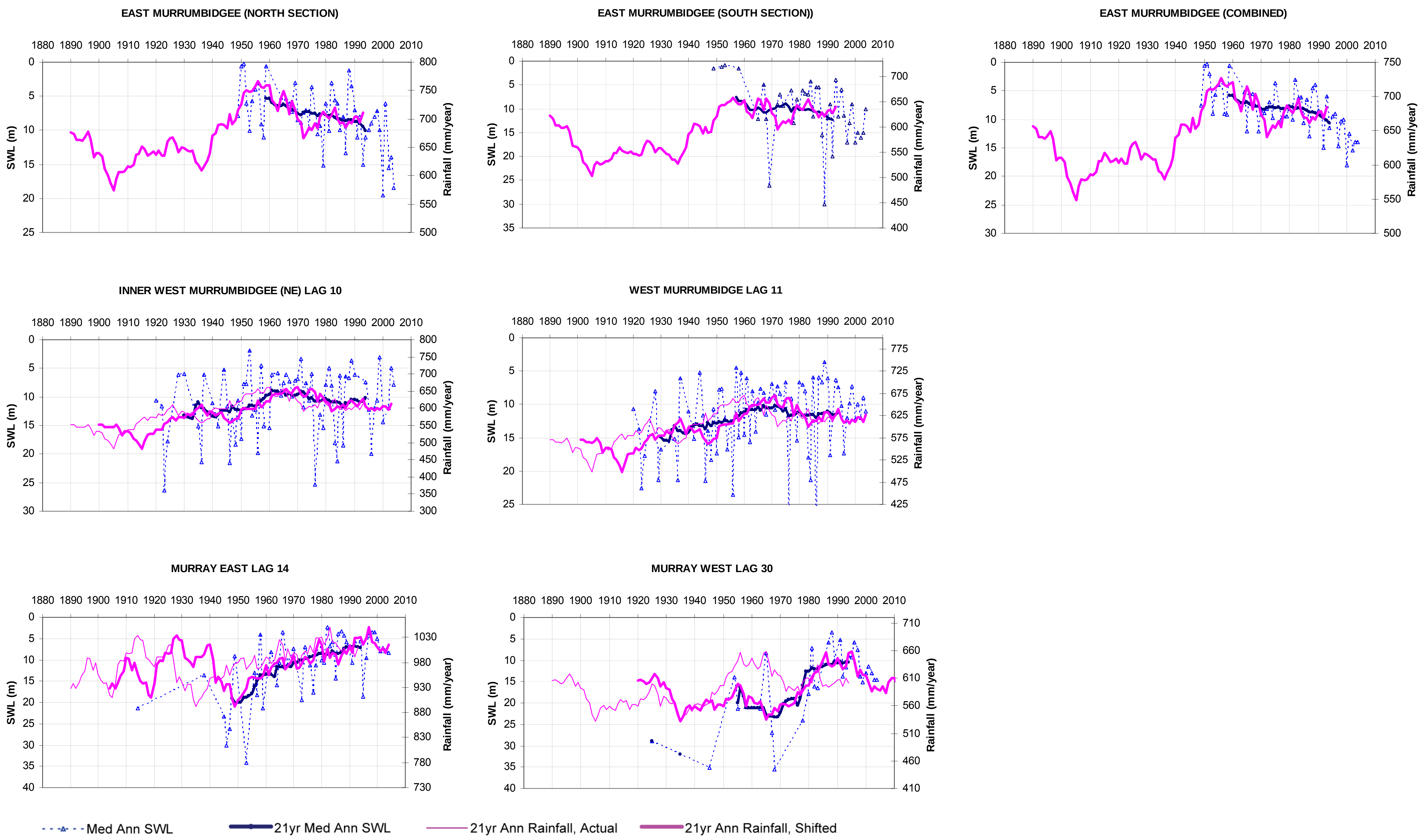
Appendix

Figure 22: Trends in rainfall and standing water levels in the form of the 21-year moving average



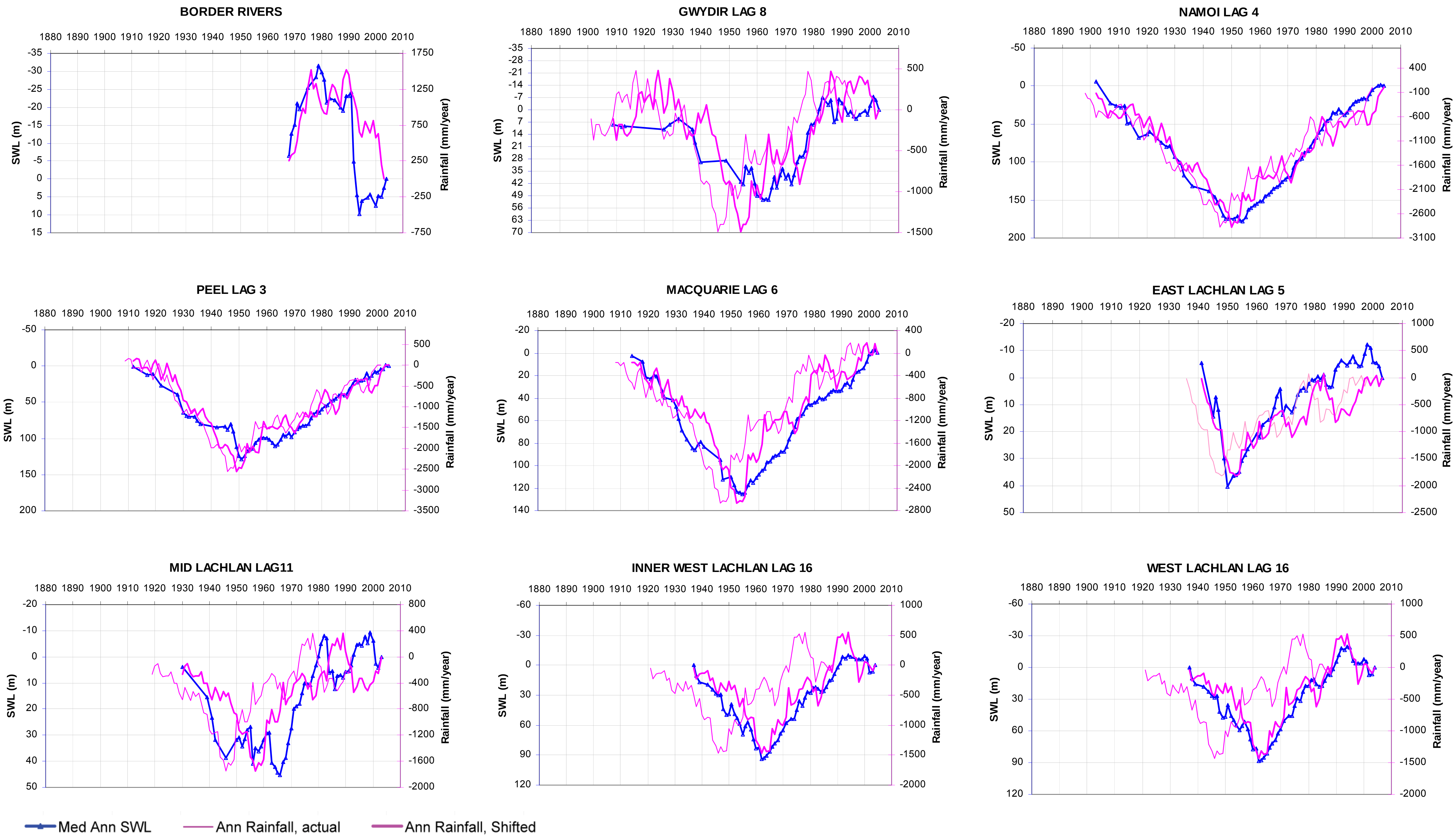
Rainfall is spatially averaged except in Border Rivers (Tenterfield 56032), Murray East (Tumbarumba 72043) and Murray West (Culcairn 74188).

Figure 22: Trends in rainfall and standing water levels in the form of the 21-year moving average (continued)



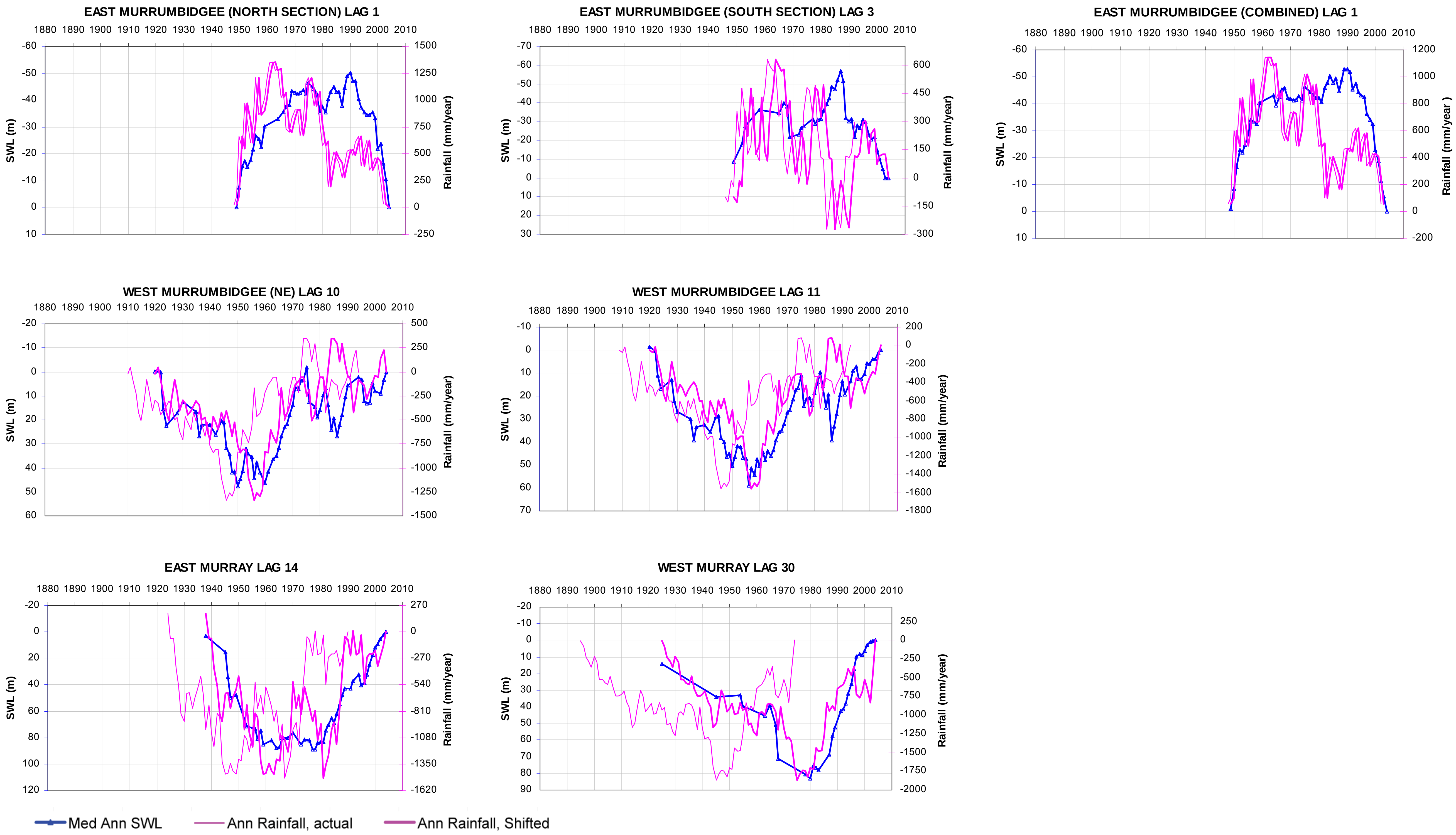
Rainfall is spatially averaged except in Border Rivers (Tenterfield 56032), Murray East (Tumbarumba 72043) and Murray West (Culcairn 74188).

Figure 23: Residual mass curves (cumulative deviation from the mean) of the median annual SWL, actual annual rainfall and lagged annual rainfall



Rainfall is spatially averaged except in Border Rivers (Tenterfield 56032), Murray East (Tumbarumba 72043) and Murray West (Culcairn 74188).

Figure 23: Residual mass curves (cumulative deviation from the mean) of the median annual SWL, actual annual rainfall and lagged annual rainfall (continued)



Rainfall is spatially averaged except in Border Rivers (Tenterfield 56032), Murray East (Tumbarumba 72043) and Murray West (Culcairn 74188).

Table 13: Change-point analysis of annual rainfall for individual rainfall stations within catchment sections

Section/subsection	Year change occurred	Confidence level	Pre-change average rainfall	Post-change average rainfall
Border Rivers				
Glen Innes Post Office	1942	98%	806.1	909.4
Emmaville (Strathbogie)	1895	96%	899.6	762.2
Tenterfield (Federation Park)	1898	94%	895.4	767.9
	1945	100%	767.9	908.9
Tingha (Crystal Hill)	1947	100%	791.3	938.3
Weighted-average rainfall	1947	100%	794.8	900.3
Gwydir				
Glen Innes Post Office	see Border Rivers			
Warialda Post Office	no change			
Bingara Post Office	no change			
Barraba Post Office	1947	97%	650.4	730.1
Tingha (Crystal Hill)	1947	100%	791.3	938.3
Bundarra Post Office	no change			
Uralla (Dumaresq St)	no change			
Weighted-average rainfall	no change			
Namoi				
Gunnedah Pool	1897	94%	675.3	536.7
	1947	100%	536.7	661.2
Goonoo Goonoo Station	no change			
Barraba Post Office	see Gwydir			
Wallabadah (Woodton)	1889	95%	653.4	980.0
	1895	98%	980.0	694.0
	1949	100%	694.0	834.0
Manilla Post Office	no change			
Weighted-average rainfall	1947	97%	647.8	726.7
Peel				
Gunnedah Pool	see Namoi			
Goonoo Goonoo Station	see Namoi			
Barraba Post Office	see Gwydir			
Wallabadah (Woodton)	see Namoi			
Weabonga (Stoneleigh)	1947	97%	776.2	853.2
Carroll (The Ranch)	no change			
Attunga (Garthowen)	1889	96%	613.1	911.3
	1895	96%	911.3	631.5
	1922	90%	631.5	514.3
	1947	100%	514.3	680.0
Weighted-average rainfall	1922	98%	673.9	556.6
	1947	98%	556.6	699.9
Macquarie				
Mudgee (George Street)	1947	96%	618.3	732.9
Millthorpe (Inala)	1947	99%	729.3	861.7
Gulgong Post Office	1886	92%	475.2	874.5
	1895	98%	874.5	572.1
	1947	99%	572.1	698.8
Peak Hill Post Office	1947	98%	519.1	615.4
O'Connell (Stratford)	1949	96%	559.6	635.8
Weighted-average rainfall	1947	98%	607.0	705.0

Table 13: Change-point analysis of annual rainfall for individual rainfall stations within catchment sections (continued)

Section/subsection	Year change occurred	Confidence level	Pre-change average rainfall	Post-change average rainfall
Lachlan East				
Golspie (Ayrston)	1949	92%	694.2	774.9
Bungendore (Gidleigh)	1948	94%	583.0	665.8
Bigga (Woolbrook)	1890	95%	592.6	958.6
	1895	97%	958.6	537.4
	1900	90%	537.4	723.6
	1947	99%	723.6	864.9
Millthorpe (Inala)	1947	99%	729.3	861.7
Weighted-average rainfall	1947	99%	668.6	775.4
Lachlan Mid				
Manildra (Hazeldale)	1947	93%	618.3	714.5
Yass (Derringullen)	see Murrumbidgee East (North)			
Cowra Ag Research Station	1886	91%	476.3	769.6
	1895	100%	469.7	550.8
	1947	98%	550.8	652.8
Murringo (Windermere)	1895	100%	679.3	509.6
	1915	93%	509.6	696.1
	1977	96%	696.1	601.5
Canowindra (Canowindra Street)	1947	97%	552.3	644.6
Cudal Post Office	no change			
Boorowa Post Office	1895	94%	629.7	421.0
	1903	95%	421.0	625.8
Weighted-average rainfall	1895	99%	650.9	568.5
	1947	98%	568.5	668.7
Lachlan West				
Grenfell (Quondong Rd)	1886	92%	455.1	820.2
	1895	97%	820.2	508.4
	1916	97%	508.4	635.8
Wombat (Tumbleton)	1947	93%	653.1	738.7
Trundle (Murrumbogie)	1895	98%	580.2	399.2
	1947	100%	399.2	524.3
Condobolin Retirement Village	1895	95%	509.2	391.5
	1947	100%	391.5	482.5
Lake Cargelligo Airport	1947	97%	392.0	461.6
Goonumbla (Coradgery)	1895	96%	594.6	465.0
	1947	98%	465.0	565.5
Manildra (Hazeldale)	1947	93%	618.3	714.5
Forbes (Camp Street)	1886	96%	408.0	678.9
	1895	100%	678.9	469.0
	1950	99%	469.0	568.2
Warroo (Geeron)	1895	97%	511.0	388.1
	1948	100%	388.1	474.9
Barmedman Post Office	no change			
Weighted-average rainfall	1947	97%	569.9	648.3
Murrumbidgee East (North)				
Canberra Airport	1895	97%	729.0	541.3
	1947	97%	541.3	639.5
Fairlight Station	1895	99%	829.6	621.3
	1915	100%	621.3	844.2
Hall (Lochleigh)	1895	100%	729.4	560.2
	1915	94%	560.2	711.0
Yass (Derringullen)	1947	91%	662.2	758.8
Weighted-average rainfall	1947	96%	638.0	720.9

Table 13: Change-point analysis of annual rainfall for individual rainfall stations within catchment sections (continued)

Section/subsection	Year change occurred	Confidence level	Pre-change average rainfall	Post-change average rainfall
Murrumbidgee East (South)				
Canberra Airport	see Murrumbidgee East (North)			
Fairlight Station	see Murrumbidgee East (North)			
Hall (Lochleigh)	see Murrumbidgee East (North)			
Michelago (Soglio)	1895	98%	626.0	448.9
	1913	100%	448.9	633.2
Cooma (Kiaora)	1948	95%	484.0	558.9
Yass (Derringullen)	see Murrumbidgee East (North)			
Weighted-average rainfall	1947	100%	562.7	635.5
Murrumbidgee West				
Tarcutta Post Office	1895	98%	687.3	548.6
	1915	93%	548.6	682.6
Mundarlo (Yabtree)	no change			
Old Junee (Millbank)	1950	94%	479.0	546.4
Grong Grong (Berembed)	no change			
Leeton Caravan Park	no change	92%	402.6	456.3
Adelong (Gundagai Street)	no change	90%	662.2	758.8
Henty Post Office	no change			
Bethungra (Retreat)	1895	97%	539.7	440.4
	1916	94%	440.4	565.4
Boorowa Post Office	1895	93%	629.7	421.0
	1903	96%	421.0	625.8
Weighted-average rainfall	1895	96%	625.7	508.7
	1916	94%	508.7	632.4
Murray East				
Holbrook (Bowler Street)	no change			
Culcairn Bowling Club	no change			
Tumbarumba Post Office	no change			
Weighted-average rainfall	no change			
Murray West				
Urana (Butherwah)	no change			
Jindera (Wadicock)	no change			
Corowa Airport	no change			
Bungowannah (Roseleigh)	no change			
Burrumbuttock (Holyrood)	no change			
Culcairn Bowling Club	no change			
Lockhart (Osborne St)	no change			
Weighted-average rainfall	no change			

Confidence level = 90%, bootstraps = 1000. Some rainfall stations were used in two adjoining catchment sections (e.g. Glenn Innes PO in Border Rivers and Gwydir) to determine average rainfall for the section.

Table 14: Change-point analysis of rainfall variability for individual rainfall stations within catchment sections

Section/subsectiion	Year change occurred	Confidence level	Pre-change variability	Post-change variability
Border Rivers				
Tenterfield (Federation Park)	1944	96%	143.5	286.2
Peel				
Gunnedah Pool	1946	91%	145.4	410.2
	1958	95%	410.2	119.2
Barraba Post Office	1924	94%	113.9	196.3
Weabonga (Stoneleigh)	1924	96%	81.9	243.1
Attunga (Garthowen)	1946	95%	130.7	483.4
	1958	95%	483.4	184.1
Average	1946	95%	109.6	447.7
	1958	93%	447.7	158.6
Namoi				
Barraba Post Office	from above			
Tingha (Crystal Hill)	1978	98%	193.1	455.0
	1988	98%	455.0	128.8
Macquarie				
Mudgee (George Street)	1924	92%	118.5	242.1
Millthorpe (Inala)	1950	96%	165.0	298.6
	1980	97%	424.2	136.1
Peak Hill Post Office	1944	95%	109.8	182.1
Average	1944	91%	125.1	236.6
Lachlan East				
Golspie (Ayrston)	1904	100%	220.3	77.5
	1944	99%	77.5	242.2
Bungendore (Gidleigh)	1950	91%	129.1	344.2
	1984	98%	344.2	121.5
Bigga (Woolbrook)	1944	97%	134.4	263.0
Millthorpe (Inala)	1950	93%	165.0	298.6
Average	1944	97%	95.3	229.1
Lachlan Mid				
Manildra (Hazeldale)	1944	100%	107.1	227.3
Yass (Derringullen)	same as above			
Cowra Ag Research Station	1944	99%	122.7	225.9
Canowindra (Canowindra St)	1944	93%	84.7	216.0
Cudal Post Office	1944	97%	134.3	204.4
Average	1944	98%	130.4	182.2
Lachlan West				
Grenfell (Quondong Road)	1926	93%	90.8	221.4
Condobolin Retirement Village	1950	91%	120.9	156.4
Lake Cargelligo Airport	1896	91%	179.6	50.6
	1926	99%	50.6	162.4
Goonumbla (Coradgery)	1972	93%	121.1	424.2
	1980	98%	424.2	136.1
Manildra (Hazeldale)	1944	100%	107.1	227.3
Forbes (Camp Street)	1934	98%	87.9	223.4
Warroo (Geeron)	1944	98%	116.7	191.4
Barmedman Post Office	1928	99%	80.1	196.4
Murrumbidgee East (North)				
Yass (Derringullen)	1908	99%	160.2	85.1
	1930	92%	85.1	221.6
Average	1950	93%	130.4	213.8

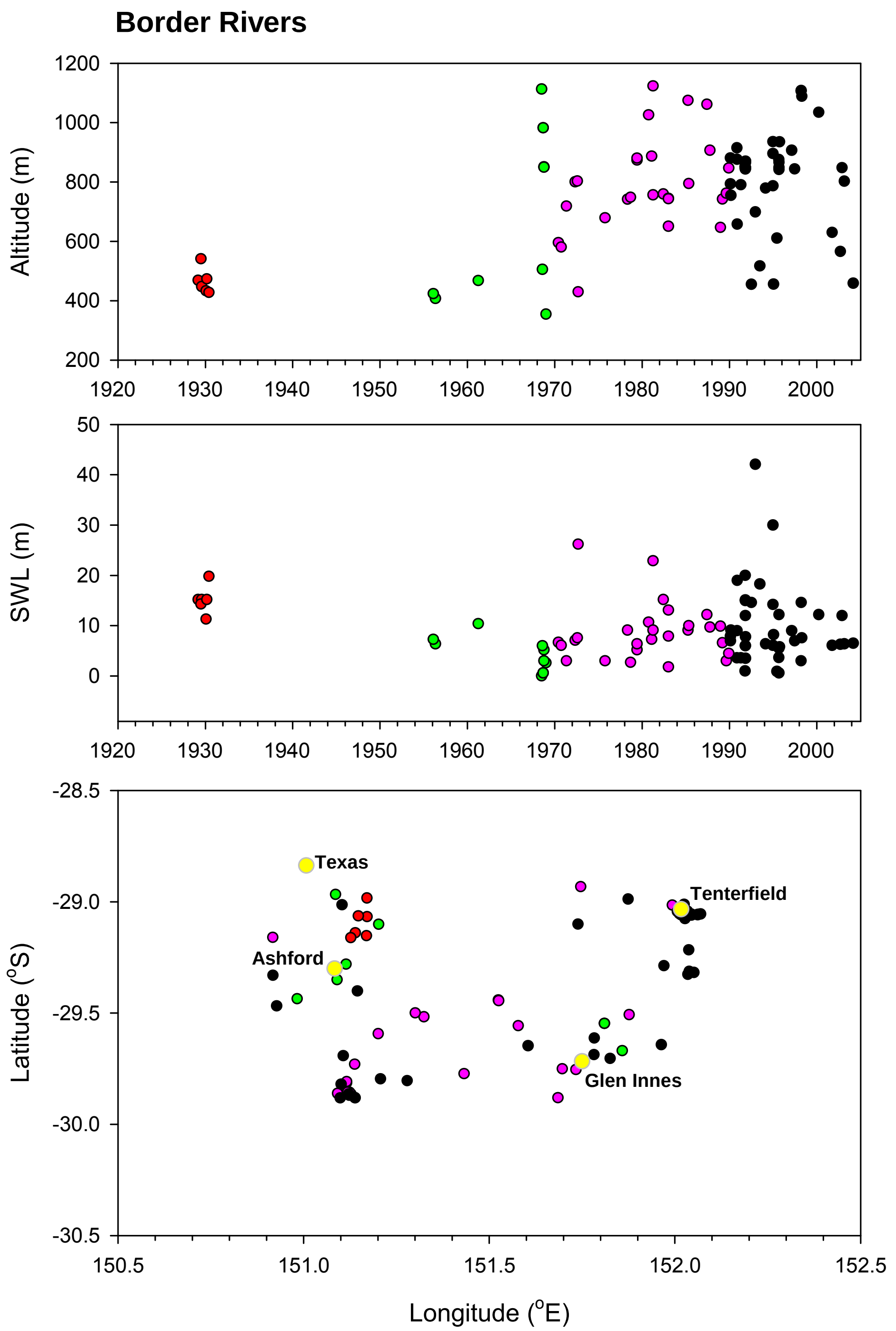
Table 14: Change-point analysis of rainfall variability for individual rainfall stations within catchment sections (continued)

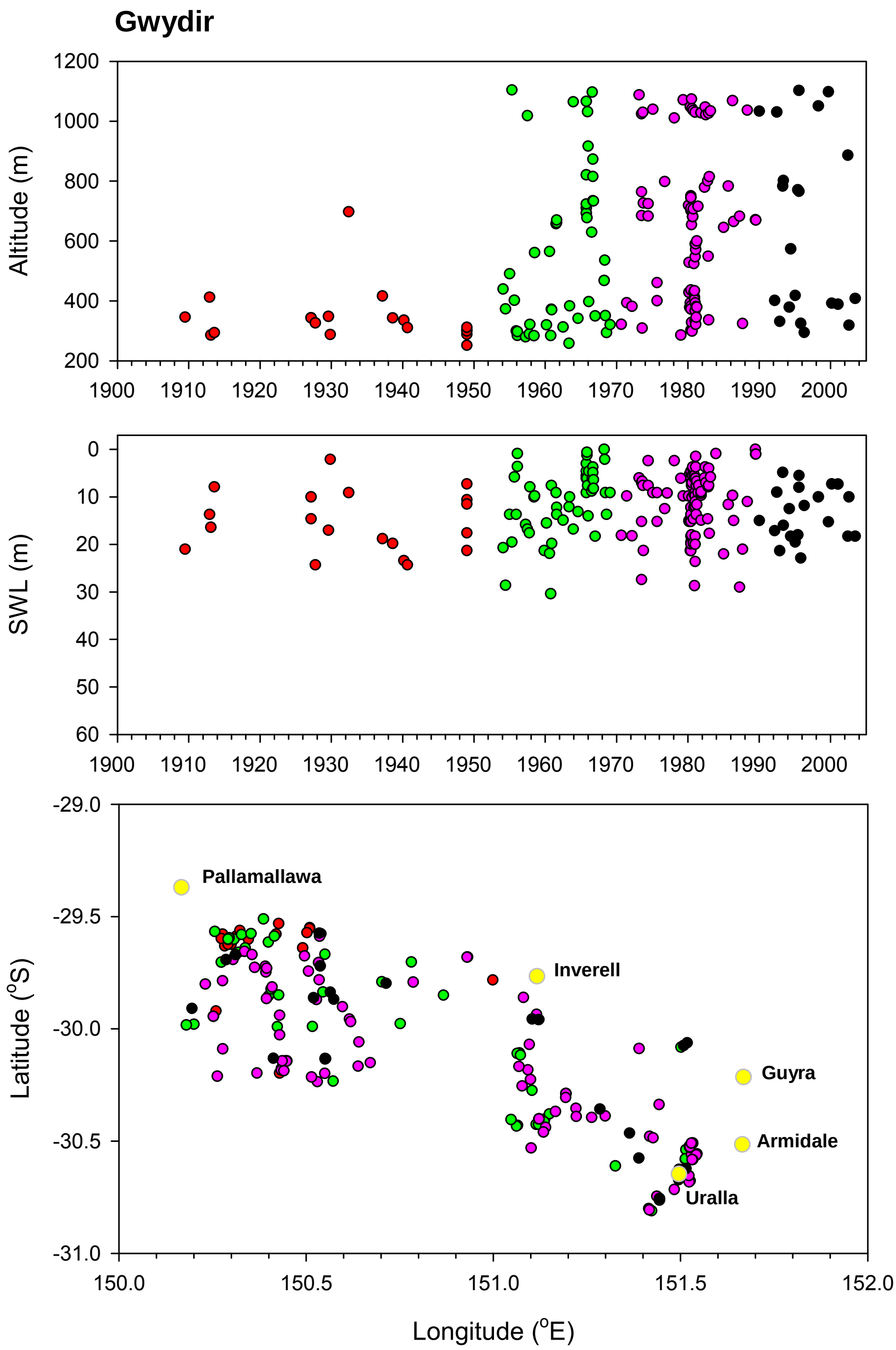
Section/subsectiion	Year change occurred	Confidence level	Pre-change variability	Post-change variability
Murrumbidgee East (South)				
Michelago (Soglio)	1904	95%	192.6	61.3
	1950	100%	61.3	212.7
Yass (Derringullen)	same as above			
Average	1950	98%	104.7	209.5
Murrumbidgee West				
Bethungra (Retreat)	1934	92%	96.4	190.8

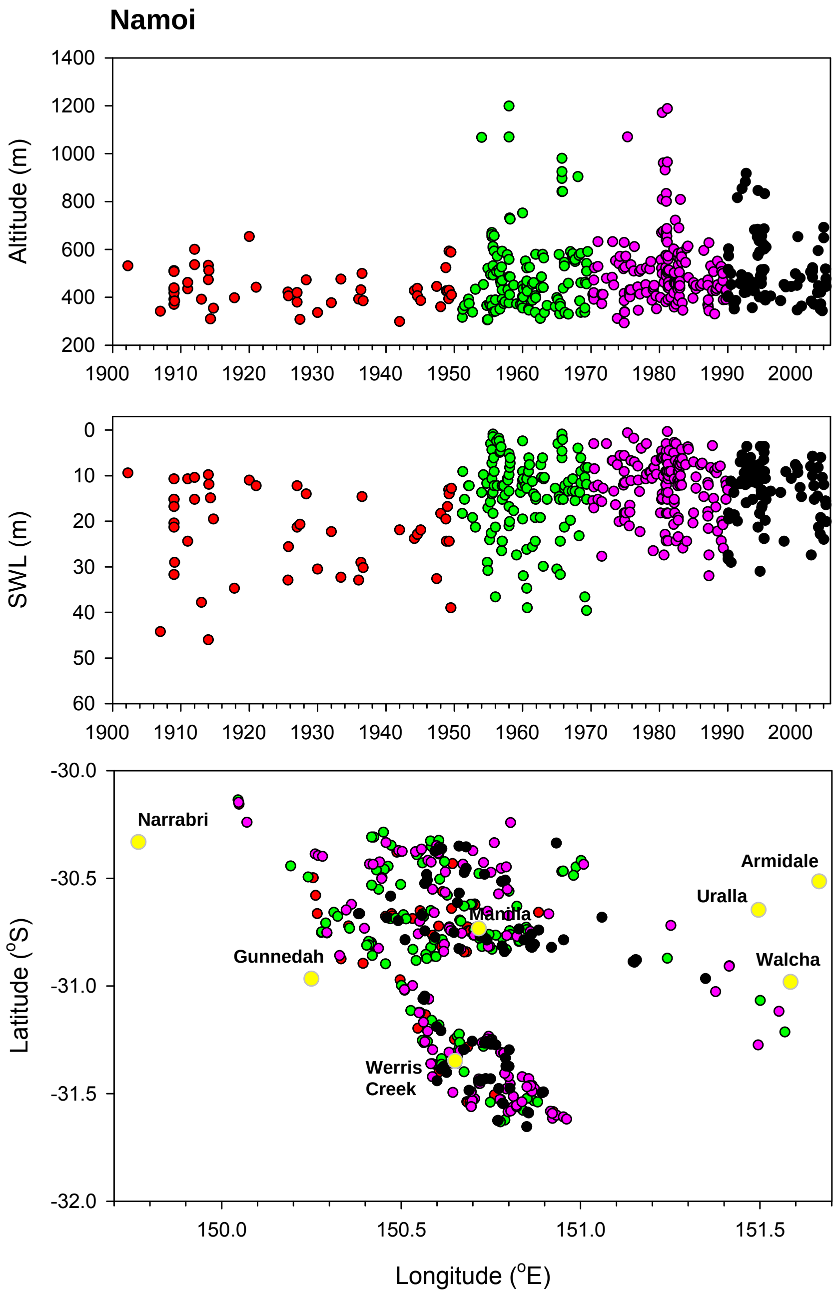
Confidence level = 90%, bootstraps = 1000. Data are shown only for stations where change was detected with a confidence level > 90%.

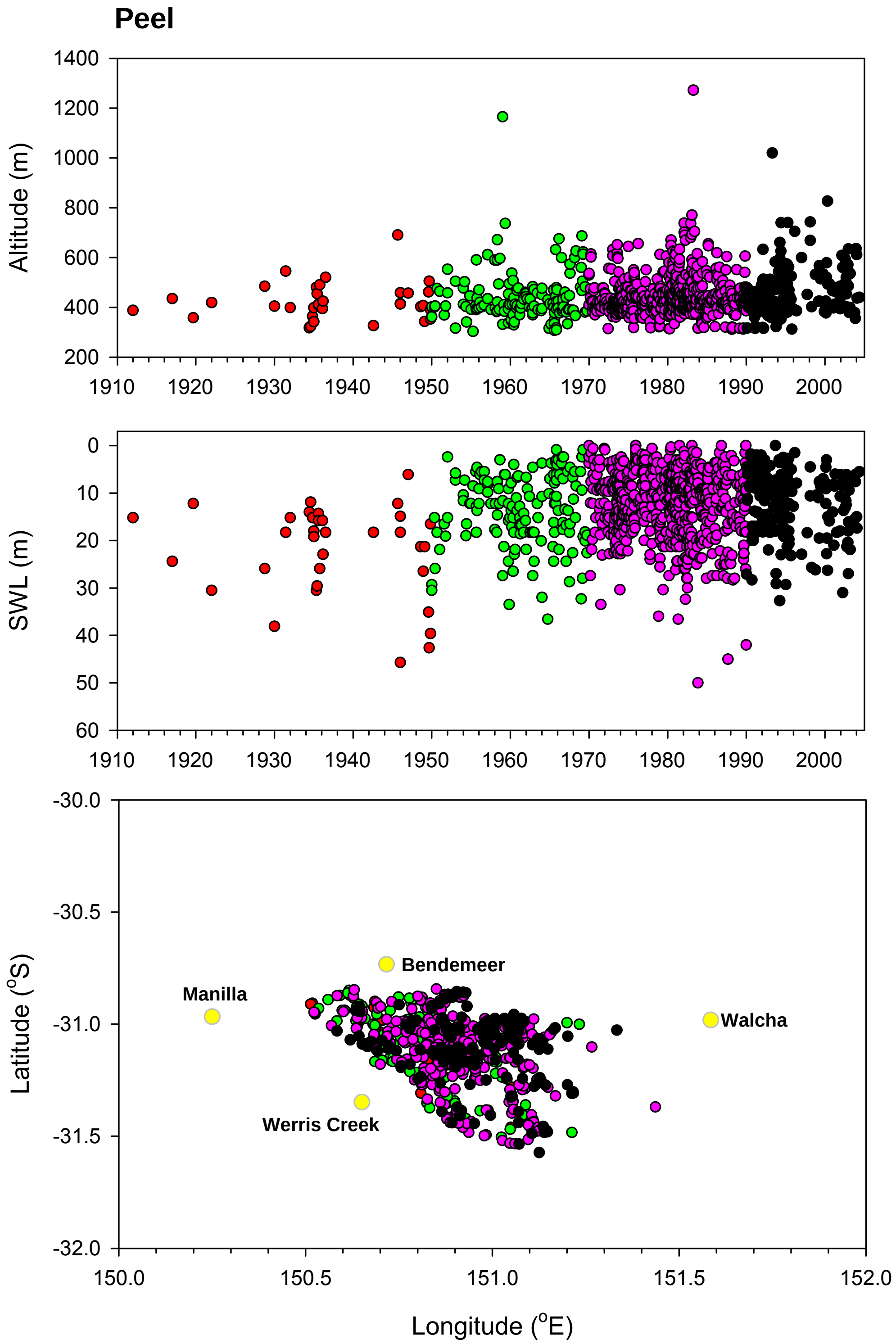
Figure 24: Scatter plots of bore elevation, SWL and position (latitude and longitude) for the main catchments in relation to time of construction

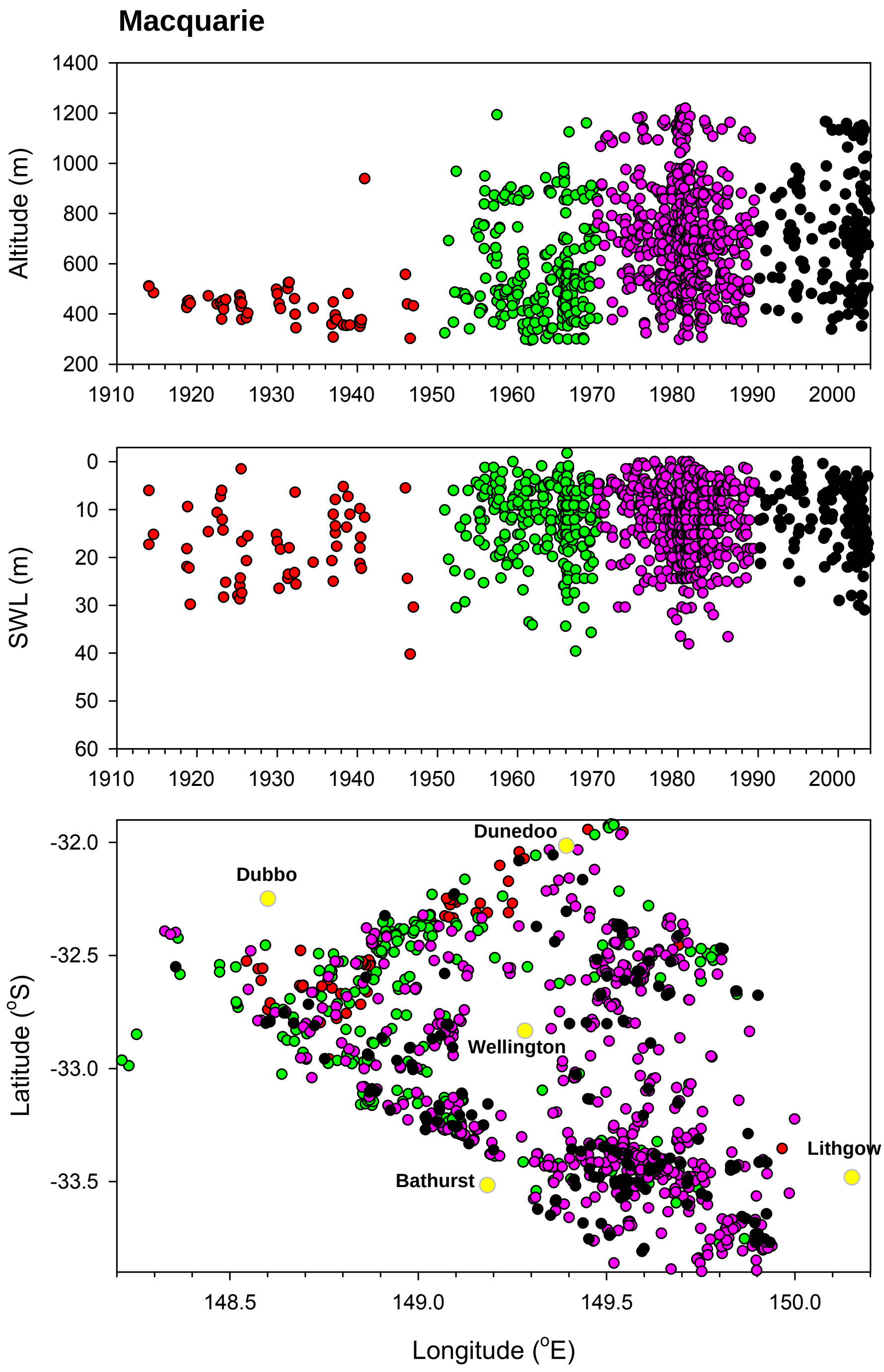
Red, before 1950; green, 1951–1970; pink, 1971–1990; black, after 1990. X axis represents time (year) if not labelled differently.

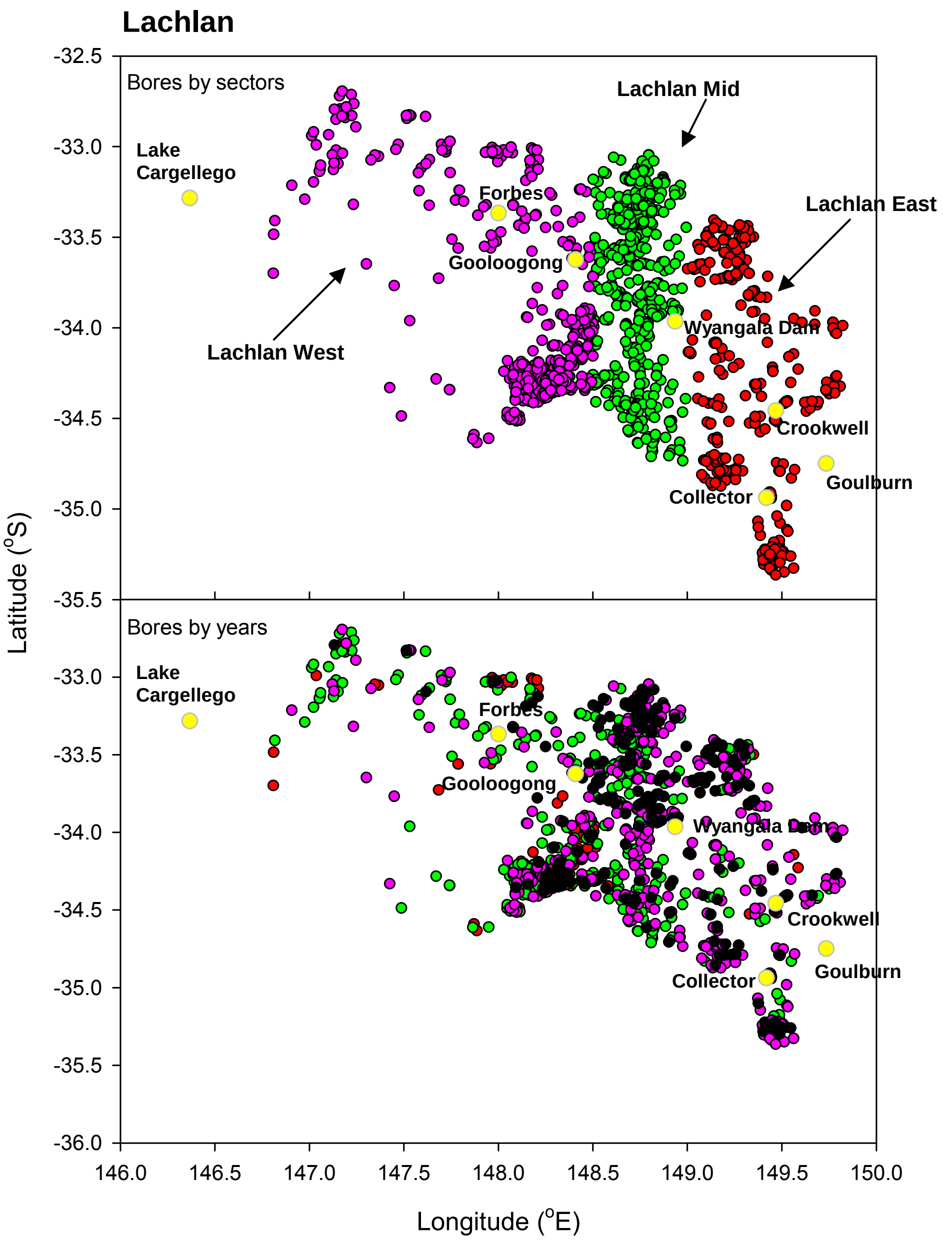


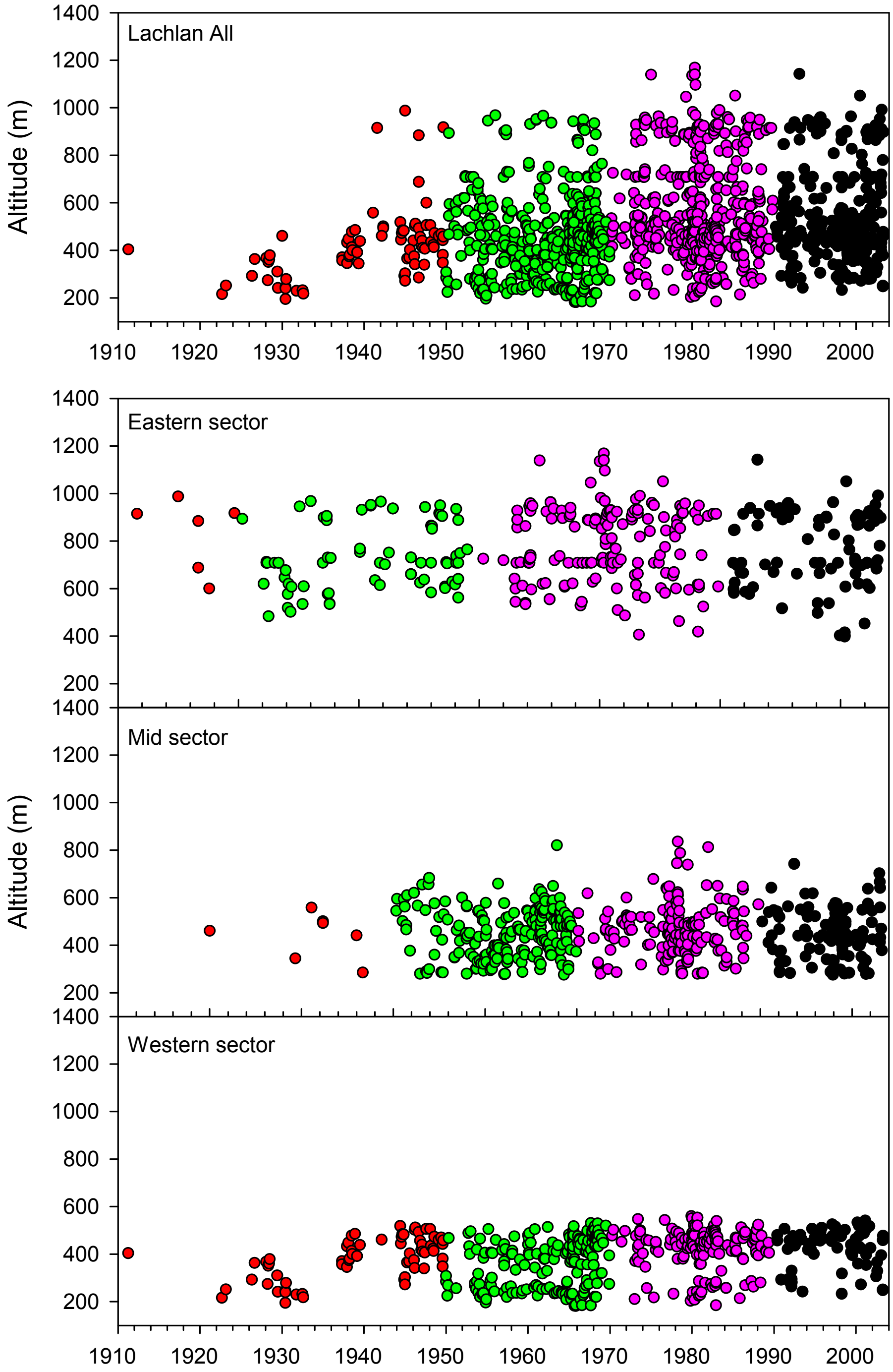

Gwydir
Altitude (m)
1200
1000
800
600
400
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
SWL (m)
0
10
20
30
40
50
60
Latitude (°S)
-29.0
-29.5
-30.0
-30.5
-31.0
150.0
150.5
151.0
151.5
152.0
Longitude (°E)
Pallamallawa
Inverell
Guyra
Armidale
Uralla

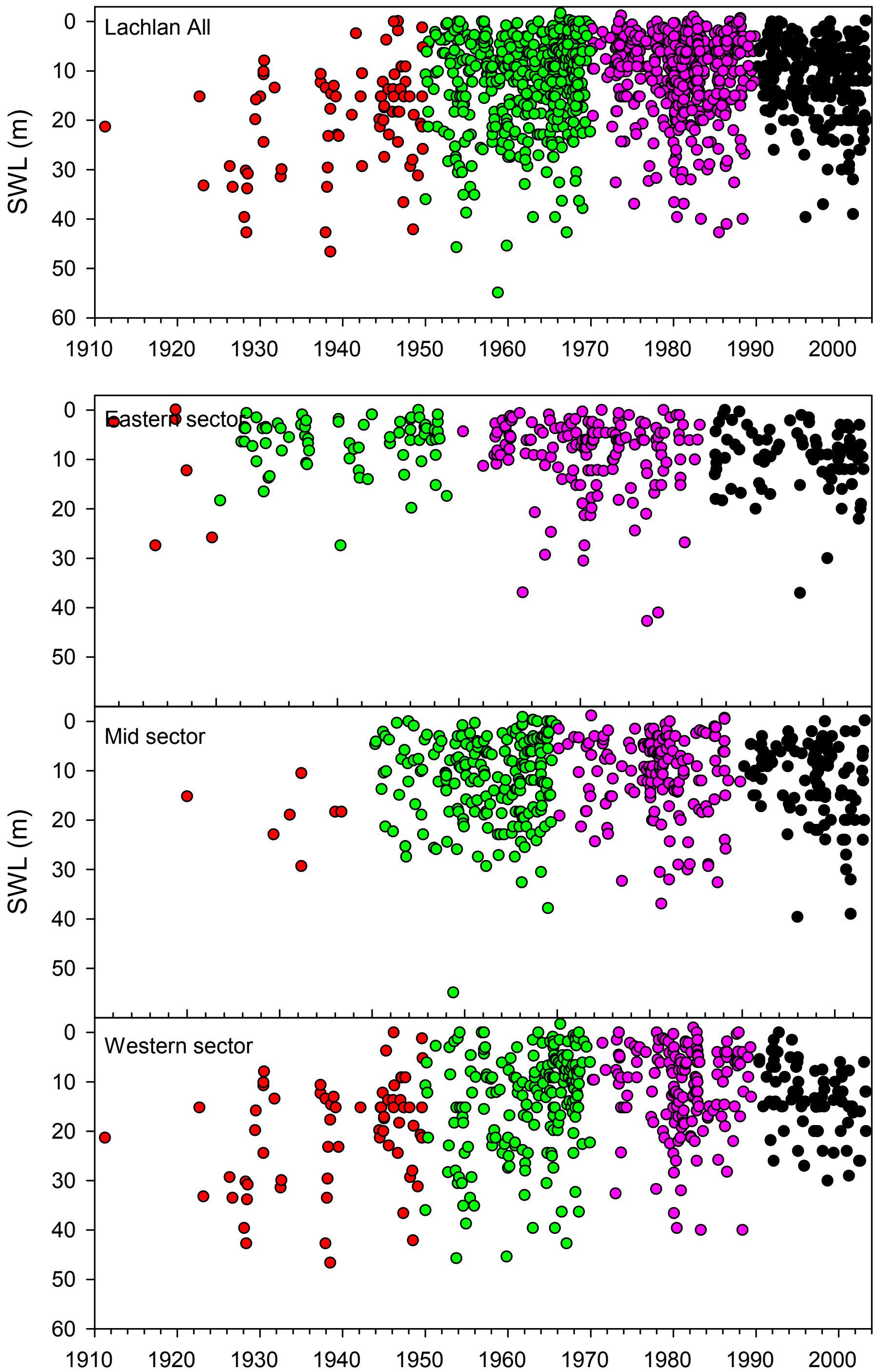

Namoi
Altitude (m)
1400
1200
1000
800
600
400
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
SWL (m)
0
10
20
30
40
50
60
Latitude (°S)
-30.0
-30.5
-31.0
-31.5
-32.0
Narrabri
Armidale
Uralla
Manilla
Gunnedah
Walcha
Werris Creek
150.0
150.5
151.0
151.5
Longitude (°E)

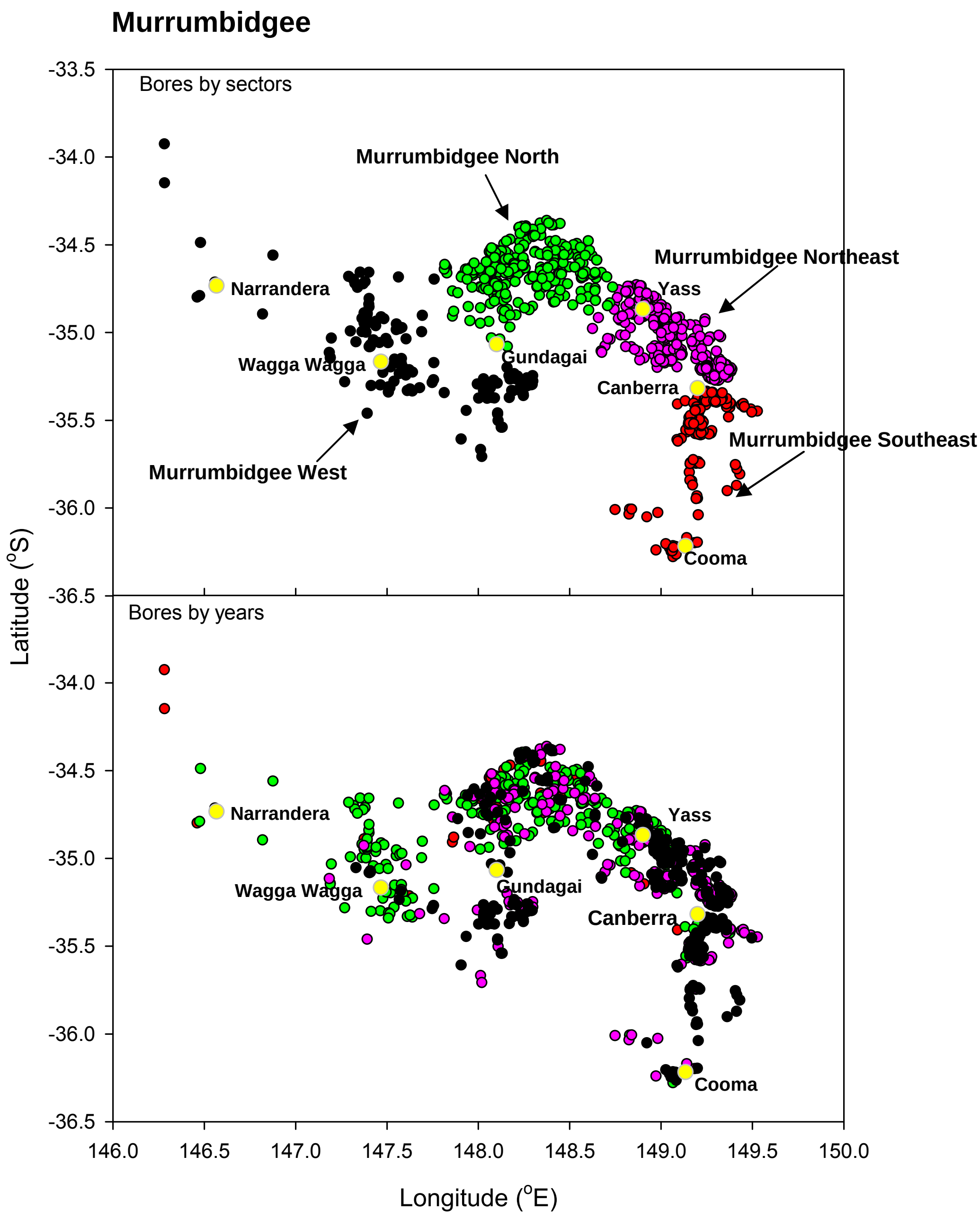

Peel
Altitude (m)
1400
1200
1000
800
600
400
200
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
SWL (m)
0
10
20
30
40
50
60
Latitude (°S)
-30.0
-30.5
-31.0
-31.5
-32.0
Bendemeer
Manilla
Walcha
Werris Creek
150.0
150.5
151.0
151.5
152.0
Longitude (°E)

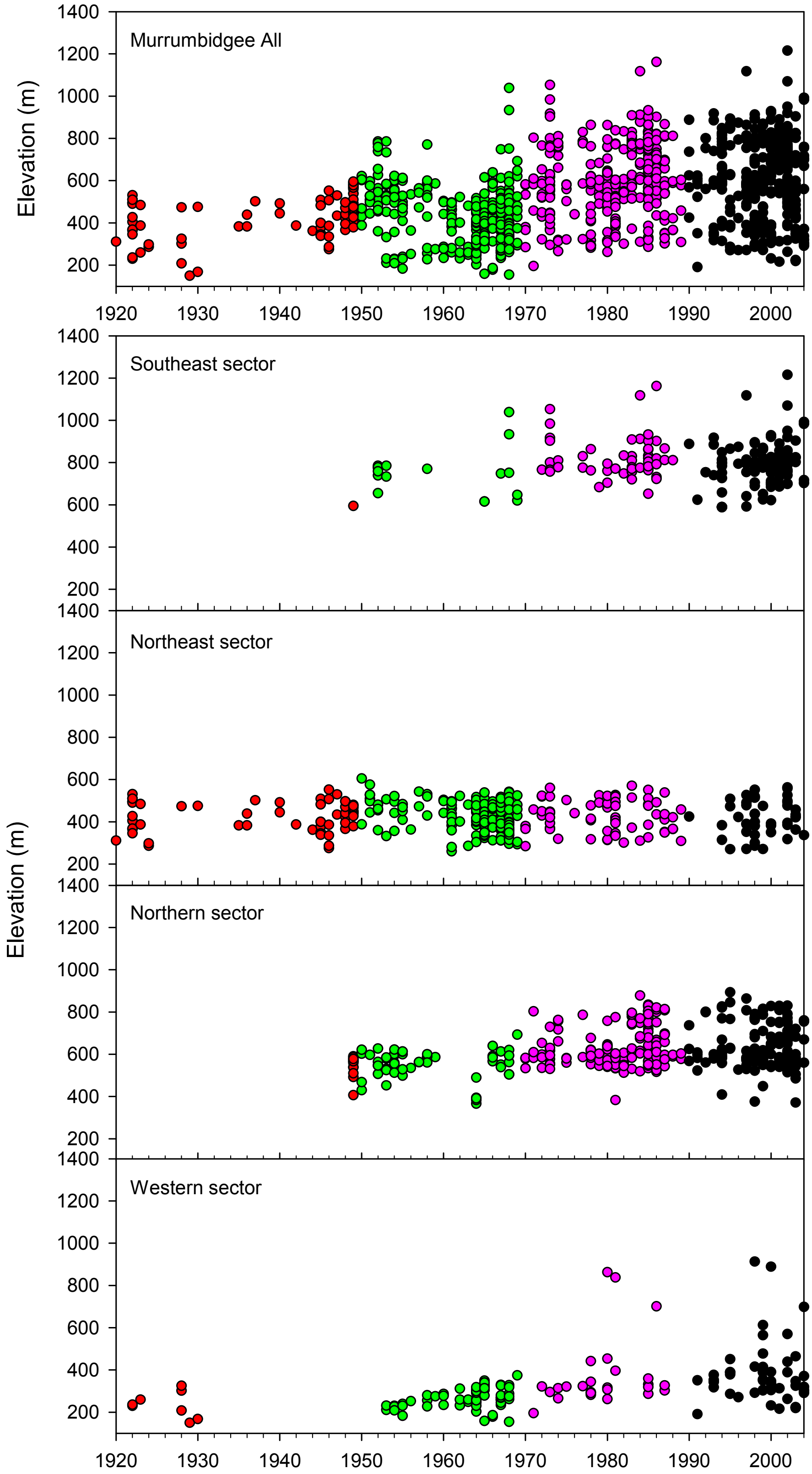

Macquarie
Altitude (m)
1400
1200
1000
800
600
400
200
1910 1920 1930 1940 1950 1960 1970 1980 1990 2000
SWL (m)
0
10
20
30
40
50
60
1910 1920 1930 1940 1950 1960 1970 1980 1990 2000
Latitude (°S)
-32.0
-32.5
-33.0
-33.5
Dunedoo
Dubbo
Wellington
Lithgow
Bathurst
148.5 149.0 149.5 150.0
Longitude (°E)


Lachlan
Bores by sectors
Lachlan Mid
Lachlan East
Lachlan West
Lake Cargellego
Forbes
Gooloogong
Wyangala Dam
Crookwell
Goulburn
Collector
Bores by years
Latitude (°S)
Longitude (°E)
-32.5
-33.0
-33.5
-34.0
-34.5
-35.0
-35.5
-36.0
146.0
146.5
147.0
147.5
148.0
148.5
149.0
149.5
150.0

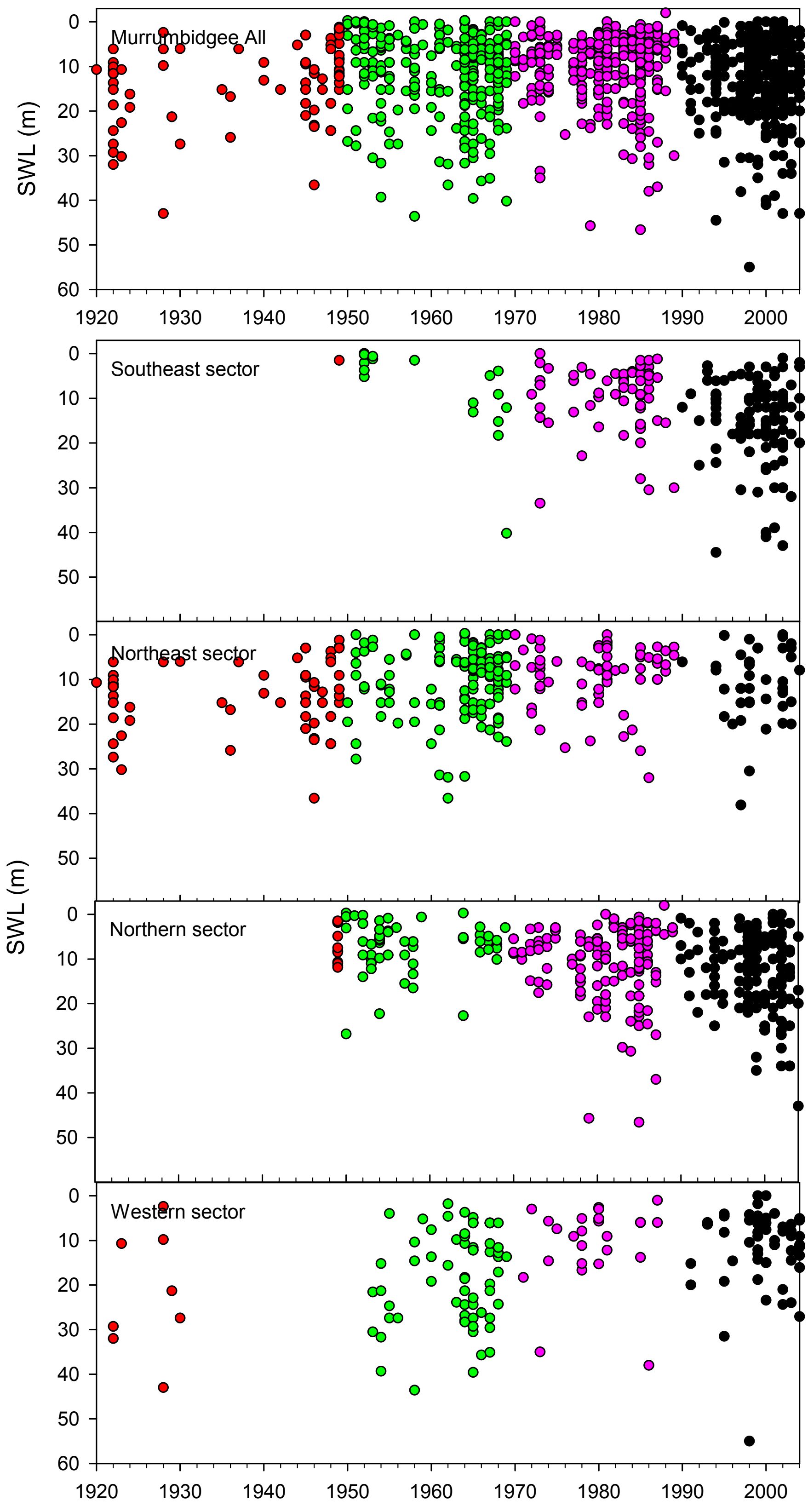

Lachlan All
Altitude (m)
1400
1200
1000
800
600
400
200
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Eastern sector
Mid sector
Western sector


Lachlan All
Eastern sector
Mid sector
Western sector
SWL (m)
SWL (m)
0
10
20
30
40
50
60
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000


Murrumbidgee
Bores by sectors
Murrumbidgee North
Murrumbidgee Northeast
Murrumbidgee Southeast
Murrumbidgee West
Narrandera
Wagga Wagga
Gundagai
Yass
Canberra
Cooma
Bores by years
Latitude (°S)
Longitude (°E)
-33.5
-34.0
-34.5
-35.0
-35.5
-36.0
-36.5
146.0
146.5
147.0
147.5
148.0
148.5
149.0
149.5
150.0



Murrumbidgee All
Southeast sector
Northeast sector
Northern sector
Western sector
Elevation (m)
1400
1200
1000
800
600
400
200
1920
1930
1940
1950
1960
1970
1980
1990
2000


Murrumbidgee All
Southeast sector
Northeast sector
Northern sector
Western sector
SWL (m)
0
10
20
30
40
50
60
1920
1930
1940
1950
1960
1970
1980
1990
2000

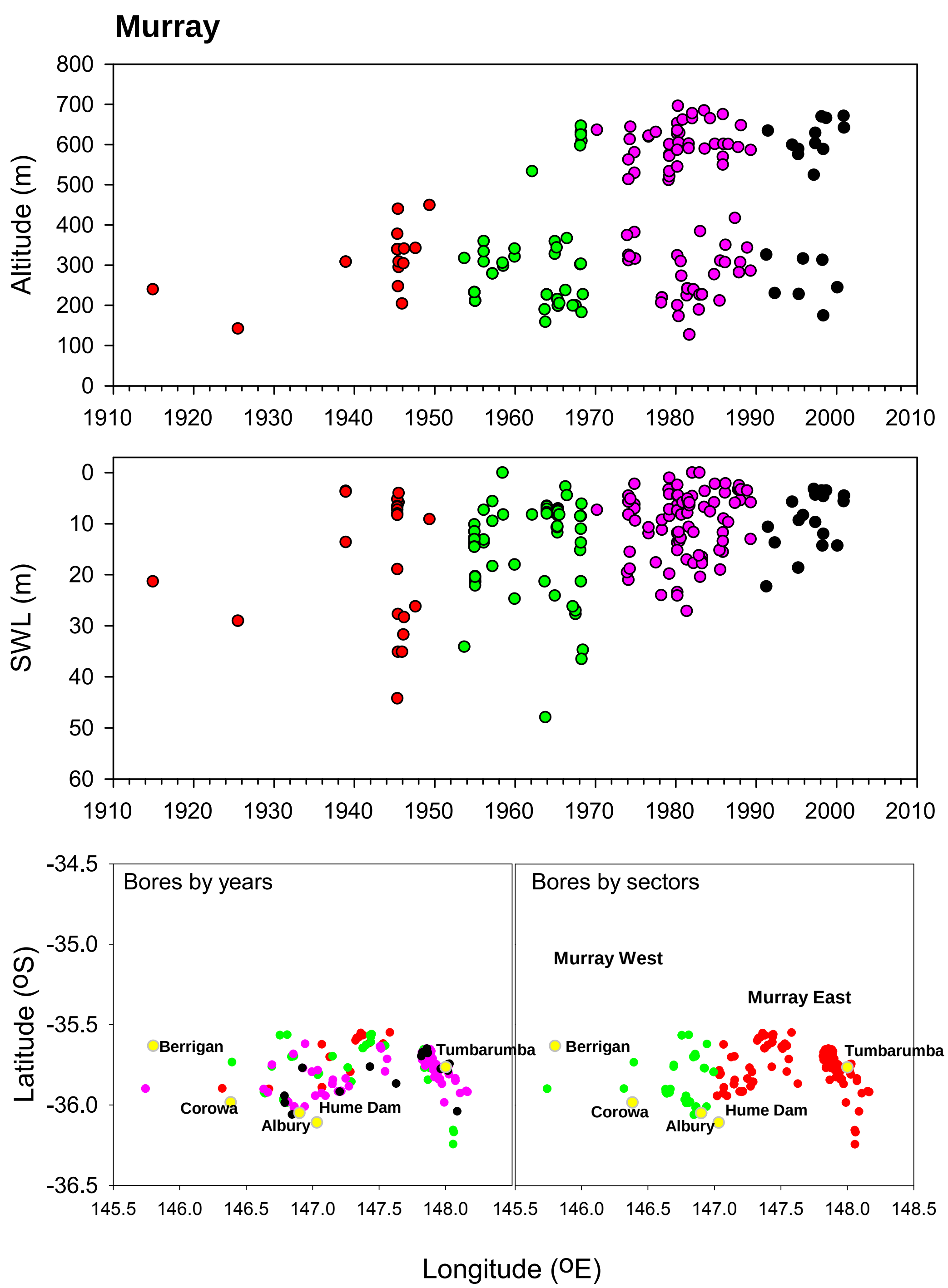

Murray
Altitude (m)
800
700
600
500
400
300
200
100
0
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
SWL (m)
0
10
20
30
40
50
60
Latitude (oS)
-34.5
-35.0
-35.5
-36.0
-36.5
Bores by years
Bores by sectors
Murray West
Murray East
Berrigan
Corowa
Albury
Hume Dam
Tumbarumba
145.5
146.0
146.5
147.0
147.5
148.0
148.5
Longitude (oE)

Figure 25: LOESS plots indicating relationships between SWL and altitude

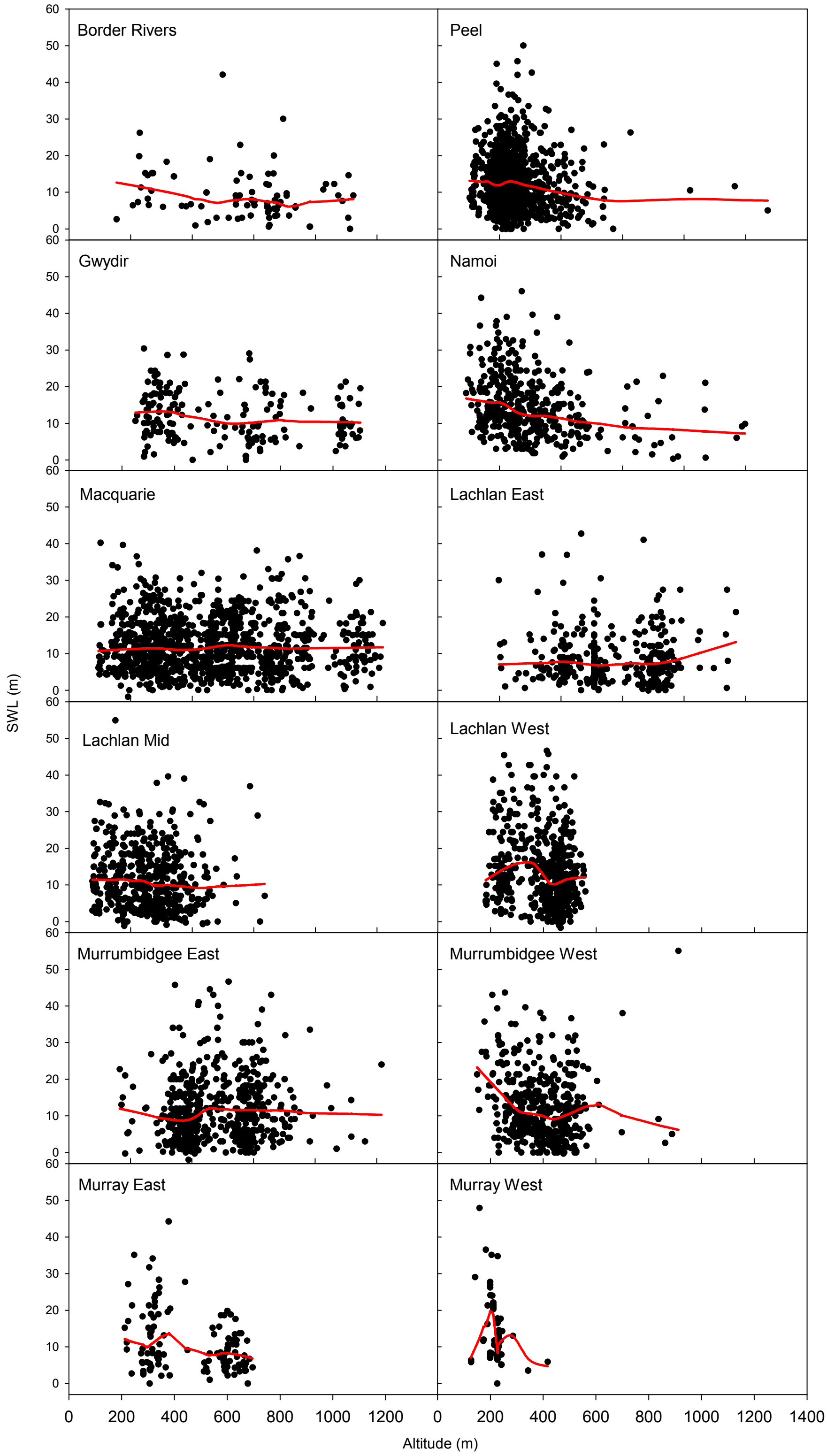


Table 15: Number of data points by year in each catchment section

Border Rivers

1929	1930	1956	1961	1968	1969	1970	1971	1972	1975	1978	1979	1980	1981	1982	1983	1985
3	4	2	1	6	1	2	1	3	1	2	2	1	3	1	3	2

1987	1988	1989	1990	1991	1992	1993	1994	1995	1997	1998	2000	2001	2002	2003	2004
2	1	3	6	10	2	1	4	7	2	3	1	1	2	1	1

Gwydir

1909	1912	1913	1927	1929	1932	1937	1938	1940	1949	1954	1955	1956	1957	1958	1959	1960
1	1	2	3	2	1	1	1	2	5	2	4	2	4	2	1	5

1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
3	1	3	1	9	9	1	4	1	1	1	1	7	2	3	1	2

1978	1979	1980	1981	1982	1983	1985	1986	1987	1988	1989	1990	1992	1993	1994	1995	1996
1	2	35	22	7	3	2	3	2	1	3	1	3	2	2	5	1

1998	1999	2000	2001	2002	2003
1	1	1	1	2	1

Namoi

1902	1907	1909	1911	1912	1913	1914	1917	1920	1921	1925	1927	1928	1930	1932	1933	1936
1	1	8	2	2	1	5	1	1	1	2	3	1	1	1	1	4

1942	1944	1945	1947	1948	1949	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
1	3	1	1	3	6	3	3	1	6	15	10	8	10	3	14	8

1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
4	4	1	12	5	5	6	7	5	5	1	5	9	8	4	3	6

1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
5	15	27	21	11	4	4	3	10	6	9	8	4	11	6	15	11

1996	1997	1998	1999	2000	2002	2003	2004
1	1	2	2	5	7	7	5

Peel

1912	1917	1919	1922	1928	1930	1931	1932	1934	1935	1936	1942	1945	1946	1947	1948	1949
1	1	1	1	1	1	1	1	3	7	3	1	1	3	1	2	5

1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
5	3	2	2	6	7	6	6	10	11	13	11	10	5	5	18	12

1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
10	6	10	18	19	21	69	42	31	17	33	24	27	54	58	60	36

1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
32	23	23	31	14	34	21	25	22	18	28	29	2	2	5	6	10

2001	2002	2003	2004
8	13	7	3

Macquarie

1914	1918	1919	1921	1922	1923	1925	1926	1929	1930	1931	1932	1934	1936	1937	1938	1939
3	3	2	1	2	5	7	2	1	3	3	3	1	1	6	3	1

1940	1946	1947	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
6	3	1	1	1	4	4	2	14	2	19	9	8	18	13	7	14

1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
8	37	50	15	22	14	10	9	5	18	10	30	18	24	29	42	136

1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1998
99	45	59	15	33	16	14	17	4	6	2	6	2	13	9	3	11

1999	2000	2001	2002	2003
10	7	25	30	25

Lachlan East

1941	1945	1946	1947	1949	1950	1952	1953	1954	1955	1956	1957	1960	1961	1962	1964	1965
1	1	2	1	1	1	6	5	5	3	1	10	3	6	4	3	4

1966	1967	1968	1969	1970	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
9	5	9	1	1	2	11	10	8	6	8	6	10	24	14	7	12

1984	1985	1986	1987	1988	1989	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
6	8	14	3	9	3	11	5	4	7	6	2	2	8	6	7	13

2002	2003
13	5

Lachlan Mid

1930	1939	1941	1942	1946	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961
1	1	1	2	2	2	7	3	8	3	7	3	5	10	14	11	11

1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
16	5	11	15	24	17	26	11	3	2	3	9	4	11	1	4	4

1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
10	24	28	16	11	5	8	5	9	9	1	3	5	9	3	6	8

1996	1997	1998	1999	2000	2001	2002	2003
3	15	24	10	4	13	4	7

Lachlan West

1911	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1937	1938	1939	1942
1	1	1	1	3	4	2	14	7	8	3	2	1	4	7	2	1

1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
6	5	6	6	6	6	5	1	3	8	11	8	3	10	8	5	11

1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1973	1974	1975	1976	1977	1978
9	9	12	9	32	15	23	25	7	2	2	14	5	5	2	8	8

1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
9	27	15	26	7	5	6	9	11	6	4	3	7	12	4	6	10

1996	1997	1998	1999	2000	2001	2002	2003	2004
1	9	6	4	9	6	3	7	4

Murrumbidgee East

1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1964	1965	1966	1967	1968	1969
13	6	1	11	7	8	5	1	3	6	1	5	2	4	4	9	3

1970	1971	1972	1973	1974	1975	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
3	3	5	17	6	3	5	13	6	16	12	9	18	12	43	20	11

1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
3	3	4	5	5	5	24	6	3	16	34	31	29	34	46	15	9

Murrumbidgee West

1920	1921	1922	1923	1924	1928	1929	1930	1932	1935	1936	1937	1940	1942	1944	1945	1946
1	2	13	3	2	4	1	2	1	1	2	1	2	1	1	8	6

1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
2	7	8	2	6	4	4	8	8	2	2	6	1	6	13	5	4

1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
23	33	15	30	26	7	3	2	5	10	3	2	1	1	9	2	12

1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1993	1994	1995	1996	1997	1998
13	1	3	1	10	3	7	3	2	1	2	4	2	8	2	7	14

1999	2000	2001	2002	2003	2004
12	10	3	13	11	9

Murray East

1914	1938	1945	1946	1947	1949	1953	1956	1957	1958	1959	1962	1964	1965	1966	1968	1970
1	3	12	2	1	1	1	3	3	2	2	1	2	1	2	7	1

1973	1974	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1991
1	11	2	1	2	6	14	4	2	3	3	6	3	5	2	1	2

1994	1995	1997	1998	2000
1	3	3	4	2

Murray West

1925	1945	1954	1955	1963	1965	1967	1968	1978	1980	1981	1982	1983	1987	1988	1989	1992
1	1	9	8	12	8	3	2	1	2	5	4	3	1	1	1	1

1995	1998	2000
1	1	1

Table 16: Development of dryland salinity sites across the South East Region, NSW 1941–43 to 1986 (total of 94 sites), reprinted from Wagner 2001

Period	Nil salinity	Minor salinity	Significant salinity	Degrading	No apparent change	Regenerating*	Nil observations
1941–1944	30	45	10	55**	30**	nil**	11
1950–53	18	53	19	66	20	4	4
1960–63	4	25	61	73	12	5	4
1970–73	2	32	57	53	25	13	3
1982–85	7	38	49	47	22	25***	
1986	7	40	47	48	17	29***	–

* Regeneration is relative.
** Initial observations
*** Includes 7 sites showing no salinity where full regeneration has taken place.

Figure 26: Subsections of the Lachlan, Murrumbidgee and Murray river basins