3 Beyond hydrogeologic evidence: challenging the current assumptions about salinity processes in the Corangamite region, Australia.

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3.1 Abstract

In keeping with the standard scientific methods, investigations of salinity processes focus on the collection and interpretation of contemporary scientific data. However, using multiple lines of evidence from non-hydrogeologic sources such as geomorphic, archaeological and historical records can substantially add value to the scientific investigations. By using such evidence, the validity of the assumptions about salinity processes in Australian landscapes is challenged, especially the assumption that the clearing of native vegetation has resulted in rising saline groundwater in all landscapes. In the Corangamite region of south-west Victoria, salinity has been an episodic feature of the landscapes throughout the Quaternary and was present at the time of the Aboriginal inhabitants and the first pastoral settlement by Europeans. Although surface water salinity has increased in some waterways and the area of salinised land has expanded in some landscapes, there is no recorded evidence found which supports significant rises in groundwater following widespread land-use change. In many areas salinity is an inherent component of the region's landscapes, and sustains world-class environmental assets that require appropriate salinity levels for their ecological health. Managing salinity requires understanding the specific salinity processes in each landscape.

Key words: Salinisation, saline wetlands, conceptual models, Corangamite, Australia.

3.2 Introduction

The common conception for the salinisation of land and water resources in Australian dryland agricultural regions is that of evaporative concentration of salts from shallow watertables that have risen following the clearing of native vegetation for agriculture (Peck and Williamson 1987; George et al. 1997; Salama et al. 1999). This paper argues a major shift away from that notion, by linking evidence from the fields of geomorphology, archaeology and environmental history. Using data sources beyond the usual hydrogeologic evidence (such as groundwater hydraulics, hydrochemistry, isotopes, modelling etc.) has developed more empirically accurate conceptualisations for salinity processes that are occurring in the Corangamite region of south eastern Australia. Examining the salinity processes over an extended timeline can provide a context for the current day observations and lead to a different conclusion than that based on short-term monitoring and prediction. It is contended that supplementing hydrogeological research with multiple lines of evidence from non-scientific sources can substantially add value to such scientific investigations.

Dryland salinity impacts on the water quality, agricultural land, environmental assets, urban and rural infrastructure, and cultural heritage assets of the Corangamite region in south west Victoria. The most urgent threats are to the urban water supplies of the region's two major provincial cities – Ballarat and Geelong, and to wetlands of international significance listed under the Ramsar Convention and habitats for migratory birds subject to international treaties. In the 1.3 million hectares of the Corangamite region over 17 thousand hectares of salt-affected land have been mapped and the area continues to expand (Nicholson et al. 2006).

The Corangamite regional population is approximately 400,000 persons and is growing at 5.2 % per year, with manufacturing, tourism, agriculture and forestry as major industries. The climate is generally warm temperate, with winter/spring dominant rainfall that varies from 400 mm to 2000 mm annually across the region. Four drainage basins – the Barwon, Moorabool, Lake Corangamite and Otway Coast – cover the region and the major drainage systems are those of the Barwon, Woady Yaloak, Moorabool, Leigh, Gellibrand and Curdies rivers. Over 1500 lakes and wetlands are a feature of the region, including the internationally significant Lake Corangamite, Lake Gnarpurt, Lake Connewarre, Lake Murdeduke, Lake Colac, Lake Colongulac, Lake Beeac and Lake Martin (Figure 3.1).

In 2001 the National Land and Water Resources Audit released the Australian Dryland Salinity Assessment 2000 (NLWRA 2001). The predictions for the Corangamite region were dire; with the worst-case scenario suggesting that 48.5 % of agricultural land is at risk from shallow water tables by 2050, costing the region AUD$ 29 million per year and with over 40 % of the region's wetlands threatened by 2050. Based on the predictions of increasing salinity, the

Corangamite region is nominated as one of the priority regions in Australia, under the National Action Plan for Salinity and Water Quality (CoAG 2000).

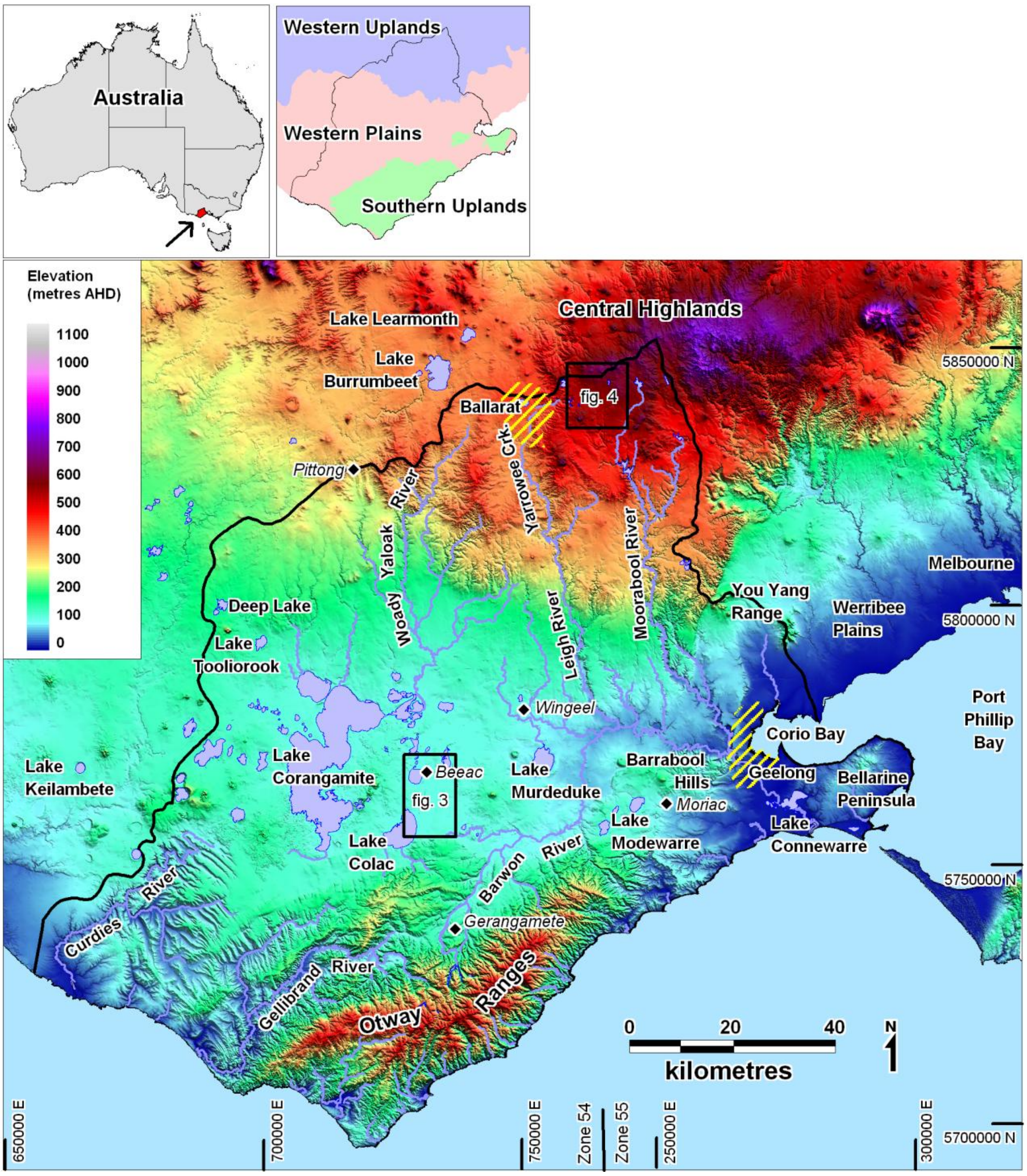


Figure 3.1 Location of the Corangamite region.

The main cause of the salinity is assumed to be rising saline groundwater following widespread clearing of native vegetation in the mid to late 19th century for pastoral settlement, agriculture and mining (NLWRA 2001). Since the first regional salinity strategy in 1992 approximately AUD$ 50 million dollars of government funding has been provided to the region for salinity management, and many millions of dollars in landholder, industry and community contributions.

This funding has been provided to establish over 5,000 ha of trees, treat around 1,500 ha of salt affected land, establish over 500 groundwater monitoring bores and support several major research programs (Nicholson et al. 2006).

This paper reviews the evidence for salinity in the Corangamite region during the Quaternary Period and time since first European settlement. The validity of the current assumption that the clearing of native vegetation has resulted in rising saline groundwater in all landscapes throughout the region is challenged. Although the cause (land clearing) and effect (salinisation) has been well established in other areas of Australia (Ghassemi et al. 1995) it is not universally applicable in this region. The implications for the current salinity management actions are discussed.

3.3 Geological, geomorphic and hydrogeologic framework

Three broad-scale geomorphic components make up the Corangamite region: the Victorian Western Uplands in the north; the Victorian Western Plains in the centre; and the Victorian Southern Uplands in the south (Joyce et al. 2003).

The basement rocks of the Corangamite region are prominent in the undulating hills and broad valleys which characterise the landscapes of the Western Uplands. These Cambrian and Ordovician age sedimentary rocks formed as deep-marine turbidite sediments, resulting in sequences of quartz-rich arenites and black shales. Tectonic activity from the Late Ordovician to Early Silurian periods folded and faulted the rocks, metamorphosing the shales into phyllite and quartz-mica schists, and injecting quartz veins (some of which were auriferous). A number of granite bodies were intruded during the Late Devonian and the associated contact metamorphism formed aureoles of hornfels. The granites have been subsequently exposed by the extensive erosion during the Palaeozoic and Mesozoic eras that removed several kilometres of overlying sedimentary rocks.

Uplift and erosion during the Palaeogene resulted in the widespread deposition of gravels and sands over much of the Western Uplands. These are now sporadically distributed as ferruginised and silicified gravel caps at various elevations. Deep weathering during the Neogene formed a thick regolith of bleached shales, sandstones and kaolinised granite. A marine transgression and regression during the Pliocene deposited sands which now fringe the Palaeozoic rocks as a dissected tableland. During the Pliocene and Pleistocene, volcanic eruptions filled the broad valleys to form elongate basalt plains and a variety of other volcanic landforms. The placer deposits of gold in the buried stream sediments, termed deep leads, were later mined.

The Western Plains, the largest of the three geomorphic units, comprise gently undulating plains formed on both volcanic and sedimentary rocks. Volcanic plains of Pliocene and Pleistocene age basalt make up the majority of the geomorphic unit. These basalts are less than 50 m thick and are younger than 4.6 million years, with the largest volume emplaced around 2 million years ago (Price et al. 2003). The youngest eruption points are represented by cinder cones, maars, lava shields and stony basalt barriers, some of which are less than 100,000 years old. The basalts unconformably overlie extensive sand plains of Pliocene age. These sands, which are generally less than 20 m thick, are exposed in places where they were not covered by the volcanic lavas. Beyond the volcanic plains to the south west, the sand plains have been dissected, exposing the underlying limestone and marl of Miocene age.

The southern portion of the Corangamite region is dominated by the Southern Uplands, comprising the deeply dissected Otway Ranges, moderately dissected Barrabool Hills and low hills of the Bellarine Peninsula. All three landscapes have been formed by the uplift of structurally controlled blocks of lithic sedimentary rocks of the Lower Cretaceous age (i.e. the Otway Group rocks). The Barrabool Hills and Bellarine Peninsula are smaller fault-bounded uplift blocks at lower elevations than the Otway Ranges, and are generally more planar and less deeply dissected. The northern flanks of the Otway Ranges are fringed by gravels, sands and fine-grained sedimentary rocks of Palaeogene age.

3.3.1 Groundwater flow systems

Seventeen groundwater flow systems (GFS) were delineated in the Corangamite region (Figure 3.2) consistent with the National Land and Water Audit framework for dryland salinity management in Australia (NLWRA 2001). The GFS characterise similar landscape-groundwater systems which give effect to similar salinity issues, and where similar management options may apply. The boundaries of the systems are based on the region's geological units which have been grouped according to their hydrogeological characteristics, as determined by consensus of opinion reached at a 3 day GFS workshop with 55 regional experts who have conducted numerous investigations over the past decades (Dahlhaus et al. 2002a). The flow systems do not represent a traditional hydrogeological map, but rather they are a tool for assessing hydrological responsiveness of a catchment. They are characterised by their hydrological responses and flow paths into dominantly local, intermediate and regional systems, *viz:*

Local systems: Groundwater flows over distances of less than 5 km within the confines of surface water sub-catchments. Watertables rise rapidly and saline discharge typically occurs within 30 to 50 years of widespread land-use changes such as clearing native vegetation for agricultural development. These systems can respond rapidly to salinity management practices, and afford opportunities to mitigate salinity at a local scale.

Intermediate systems: Groundwater flows over distances of 5 to 30 km and may occur across sub-catchment boundaries. They have a greater storage capacity and generally higher permeability than local systems and take longer to 'fill' following increased recharge. Increased discharge typically occurs within 50 to 100 years of widespread clearing of native vegetation. The extent and responsiveness of these systems present greater challenges for salinity management.

Regional systems: Groundwater flow occurs over distances exceeding 50 km at the scale of river basins. They have a high storage capacity and permeability and they take much longer to develop increased groundwater discharge than local or intermediate flow systems – probably more than 100 years after widespread clearing of native vegetation. The scale of regional systems makes locally-based catchment management options ineffective and these systems will require widespread community action and major land-use change to secure improvements in water balance.

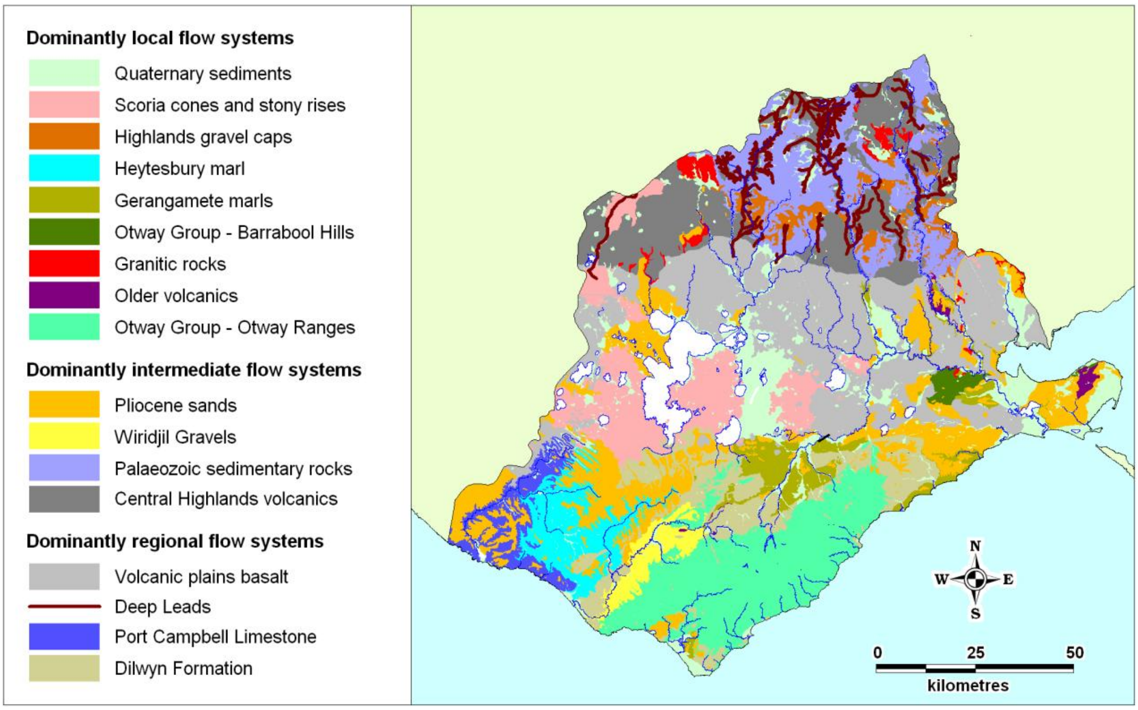


Figure 3.2 Groundwater flow systems of the Corangamite region.

In accord with the national and state policies, the salinity management actions in the Corangamite region are based on the response of the GFS implicated in the salinity process (Dahlhaus 2004). This is mainly achieved through the establishment of vegetation in areas targeted for recharge or discharge management (Nicholson et al. 2006).

3.4 Salinity during the Quaternary Period

Evidence of salinity in the Corangamite landscapes throughout the Quaternary Period is provided by both the geomorphic features and the archaeological evidence of human occupation.

3.4.1 Salinity in the Pleistocene (2.5 Ma – 11 ka)

The Western Plains, which cover approximately 40 % of the Corangamite region, are noted for their shallow lakes and wetlands, many of which are saline. The majority of the lakes are bordered by lunettes, crescentic dune-like landforms that record the hydrologic conditions of the adjacent lake (Bowler 1983). Clay lunettes are associated with saline conditions, as the salt efflorescence causes the near surface clays to form a soft fluffy pelletal layer which is then deflated by wind. Sand lunettes are formed as beach deposits by both wave and aeolian accumulation during lake-full conditions, and are associated with low-salinity water.

Dating and stratigraphic studies of the lunettes in the Colac-Beeac area has been undertaken by Dimmer (1992) and Tickell and King (1992) and compiled by Edwards et al. (1996). Their research confirms a broad scale transition from low salinity conditions associated with high lake levels, increased surface runoff and high watertables around 30,000 – 20,000 years B.P. followed by high salinity conditions associated with lower lake levels and lower watertables during the last glacial 20,000 – 10,000 years B.P. This observation correlates well with the record of climatic oscillations in southern Australia (Wasson and Donnelly 1991; Williams et al. 1993).

Further evidence for the varied lake levels is provided by a recently acquired high-resolution digital elevation model in the region (Figure 3.3). The successive episodes of lunette building are shown by the truncation of larger lunettes (Figure 3.3, arrow A) as lake levels have risen and nesting of smaller lunettes within larger ones as the lake levels have dropped (Figure 3.3, arrow B). The geomorphology fits with the general observations on changing lake typology during the changes from maximum lake level (megalake stage) to a drier phase in which the lake sediment composition is increasingly influenced by groundwater (Williams et al. 1993).

It is likely that humans have inhabited the Corangamite region for at least 35,000 years (Mulvaney and Kamminga 1999) although little is known of the early inhabitants. An important study of Aboriginal land-use and demographics of the Lake Corangamite Drainage Basin has been published by McNiven (1998), who contends that only four lakes in the drainage basin have seasonal salt-levels within the range tolerable for human consumption (<4000 ppm); *viz:* lakes Logan, Tooliorook, Deep and Colac. Other sources of seasonal low salinity water are the Woady Yaloak River and the Pirron Yallock Creek. Based on the correlation of the locations and number of artefact sites and salinity of the lakes around which they are found, he convincingly argues that the availability of freshwater is the singularly most important limiting factor for past Aboriginal land-use of the drainage basin. McNiven (1998) proposes a model in which the development of a closed drainage basin has slowly increased the salinity of the lakes since the Late Pleistocene, and the Aboriginal settlement patterns were restructured in response to individual water sources becoming too saline to drink. Commencing with a sporadic occupation concentrated around the fresher water sources during the Late Pleistocene, Aboriginal occupation probably declined during the Last Glacial Maximum as drier conditions prevailed.

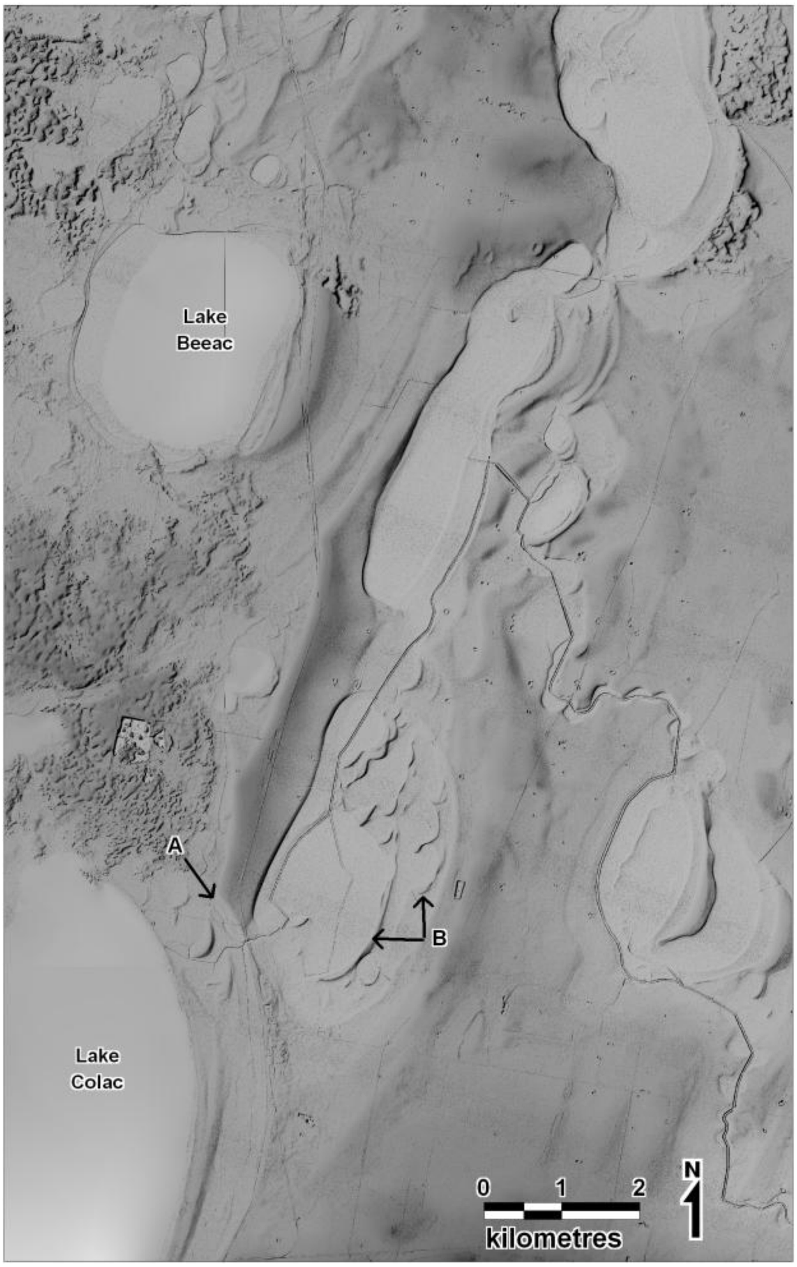


Figure 3.3 High resolution terrain model showing the history of lunette development associated with the hydrologic changes of the lakes

(A - truncated lunette indicating increased lake development; B – nested lunettes indicating diminishing lake development).

3.4.2 Salinity in the Holocene (11 ka – present)

Warmer and wetter conditions prevailed during the early Holocene as shown by the return to slightly higher lake levels (Dimmer 1992) and more favourable conditions for Aboriginal settlement (McNiven 1998). Archaeological excavations at Lake Colac in which the earliest cultural materials have been dated to around 7000 years B.P. are correlated to a sandier horizon in the lunette, indicating more surface flow into the lakes and thus fresher water conditions. Evidence that the population increased significantly during the late Holocene is given by the increase in artefacts and charcoal, dated to around 2000 years BP, which correlates to higher lake levels in the region. The archaeological evidence of the variations in lake levels and salinity (McNiven 1998) is supported by the palaeoecological and sedimentological research at Lake Keilambete by Mooney (1997), who concluded that there was a period of higher rainfall from 2000 to 1800 years BP, then decreased rain from 1750 to 1425 years BP. Higher rainfalls in the periods between 1415 and 1320 years BP and 1150 and 800 years BP (which equates with Medieval Warm Period) are contrasted with a general drying of the climate during the past 130 years of recorded history (Jones et al. 1993).

3.5 The early historical record of European settlement

On the Western Plains of the Corangamite region, McNiven (1998) suggests that the late Holocene settlement patterns were seasonal. People moved out across the landscapes during winter and spring (wet) to take advantage of the diverse food and water supplies, and during summer and autumn (dry) remained close to the permanent fresher water bodies. This pattern of land-use is broadly supported by the early ethno-historical observations, which suggest that the region was a rich diverse area which supported an indigenous population estimated to be between 2500 and 4000 persons (Clark 1990). The grassy plains, rivers and wetlands provided an ample supply and variety of food. In particular, shellfish were gathered from the coast; fish and eels were hunted and trapped in the rivers, lakes and estuaries; land mammals and reptiles were hunted on the plains; and birds were taken from the lakes and estuaries.

A record of Aboriginal life is provided by escaped convict William Buckley, who lived with the region's Aboriginal community from 1803 to 1835 (Morgan 1852).

The territory of the *Wathaurong* community with whom Buckley lived extended from the Bellarine Peninsula to Lake Corangamite and from the Otway Ranges to the Central Highlands (Clark 1990). Buckley's account indicates that water quality determined where camps were made and food was sourced. Frequent mention is made of fresh water 'wells', and fresh water, brackish and salt lakes. Buckley refers to the Western Plains as treeless landscapes, and recalls a time camping beside Lake Murdeduke as follows: *"There we made our huts with reeds and stones, there being no wood; so bare was it indeed, that we had to go nearly three miles [about 4 - 5 km] for fuel to cook our food with."* (Morgan 1852).

This observation of sparsely treed landscapes is confirmed in early records and maps of the Western Plains. Among the earliest historical accounts of the Corangamite landscapes are those of Charles Grimes, who surveyed Port Phillip Bay in January 1802 (Fleming 1802), and Matthew Flinders (1814), who described the country around Port Phillip Bay in late April and early May 1802. Grimes records the Werribee Plains as a mosaic of equal parts grass, stone and earth and notes features indicating that water frequently lies on the surface. Flinders traversed the volcanic plains from Corio Bay to the You Yang Range across *"…a low plain, where water appeared frequently to lodge; it was covered with small bladed grass, but almost destitute of wood, and the soil was clayey and shallow."* From the peak he described the country as *"…low, grassy, and very slightly covered with wood…"*, and even on the Bellarine Peninsula *"…the wood was so thinly scattered that one might see a considerable distance."*

These grassy plains were an attraction to the first pastoral settlers who arrived in 1835 and quickly established sheep runs on the extensive open plains to the west of Geelong and the grassy hills of the Bellarine Peninsula (Todd 1835; Rusden 1872). By 1840 the squatters had ventured over all of the Corangamite region, many parts of which were immediately available for agriculture without the need to remove trees and were well watered with rivers, *"…everlasting waterholes, and many fine and valuable springs"* (Fyans c.1853, in Bride 1898).

3.5.1 *Historical records of groundwater levels*

Groundwater discharges into many of the shallow saline lakes and wetlands of the Western Plains (Dickinson 1995; Coram et al. 1998; Blackam 1999). Research by Coram et al. (1998) indicate that the groundwater flow to some lakes (e.g. Lake Beeac) is terminal and others (e.g. Lake Murdeduke) are groundwater throughflow lakes. The presence of lunettes, the archaeological sites and the early historic record provide evidence that the groundwater levels were close to the surface of the plains during the wetter periods of the Quaternary. The observations of the early pastoral settlers record water in most of the lakes across the plains, with varying depths related to the climatic conditions of the time (e.g. Bonwick 1858; Brough-Smyth 1869; Hebb 1888; Bride 1898).

Following the discovery of gold in the northern Corangamite region (Western Uplands) in 1851, many areas of the landscapes were transformed from forests of native vegetation to mining settlements within a decade. Mining Registrar Wood (in Brough-Smyth 1869) meticulously documented the earliest mining at Ballarat from 1851 and recorded that many of the earliest mines, some as shallow as 3 to 5 m, were abandoned because of inflows of groundwater. Examples include:

- Golden Point: This is the site of the first discovery of gold at Ballarat. The gold was found in a small watercourse (now Canadian Creek) in late August 1851. By late 1852, shafts were sunk higher up the hill and many were abandoned at 7.5 m depth (25 feet) because of the groundwater inflows.
- White Flat: Mining commenced in April 1853. Shafts were sunk 3 m to 5 m deep (10 to 16 feet), but encountered "*a great deal of water*".
- Canadian Gully: Mining commenced August 1853. Wood noted that a large quantity of groundwater was encountered at a depth of 3 m to 4 m which required three or four men continuously bailing with buckets for mining to continue.
- Red Hill Lead: The mining commenced in shallow ground at the end of 1852, but sinking was very difficult because of "*the great quantity of water*".
- Eureka Lead: Mining commenced in July 1852. In the vicinity of the Yarrowee Creek, the quantity of water encountered was about 0.25 litres per

second (200 gallons per hour) and increased as mining progressed, with some miners bailing with an 82 litre (18 gallon) bucket for 6 to 8 months before they could reach bottom.

- Gravel Pits Lead: Mining commenced in June 1853. In one shaft the quantity of water was so great that it became impossible to continue sinking until an engine driven pump was installed. This was one of the first engines on the goldfields.

By 1856 the deep leads were being worked under the basalt and the volume of water was so immense that the style of claim was changed. One shaft sunk in 1856 through 60 m (200 feet) of basalt into the Gravel Pit Lead experienced water rising 46 m (150 feet) up the shaft. The water encountered in the Ballarat West goldfield was, on occasion, overwhelming to the miners. New pumps were imported and worked at rates of up to 13 megalitres per day (2,000 gallons per minute) until the mines had been dewatered.

Records of the water quality are scarce. Selwyn (1857) reported to the Victorian Legislative Assembly on the potential for fresh water supply by artesian wells. He made the point that surface water runoff is *"invariably purer"* than groundwater and that *"…this appears to be especially the case in Victoria, where … the very numerous brackish springs which occur in all parts of the Colony where wells have been sunk, and in nearly all formations…"*. In his report Selwyn gives the assurance that data on water would be included on the geological maps being completed at the time (i.e. the Quarter Sheets of the Geological Survey of Victoria).

Only a dozen Geological Quarter Sheets for the Corangamite region were published, most covering the eastern portion of the Western Plains. The published sheets document 15 wells, 8 springs and 16 waterholes, mostly associated with the pastoral settlements and villages. Information on these features is scarce, but it can be implied by the presence of springs and wells that shallow groundwater was present in some areas of the sparsely populated landscapes of the Corangamite region in 1860.

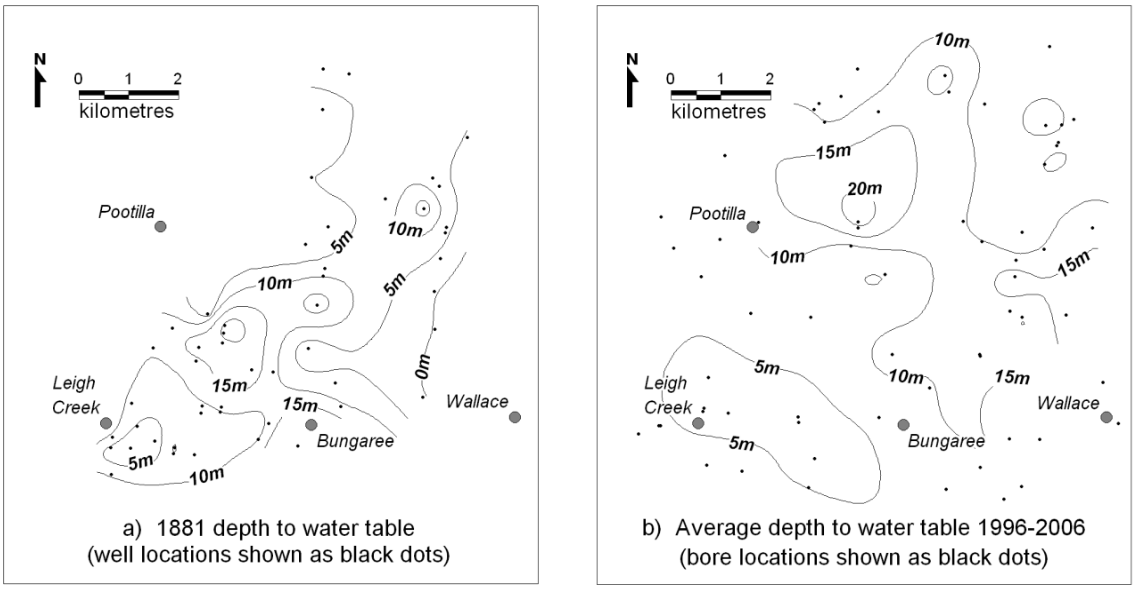
During 1870 and 1871 Ferdinand Krause, the water engineer for Ballarat (and Professor of Geology, Metallurgy and Mining at the Ballarat School of Mines), surveyed and geologically mapped the upper West Moorabool River catchment and the upper Leigh (now Yarrowee) River catchment in the Western Uplands. On the four maps of the proposed water supply area for Ballarat, Krause mapped groundwater discharge in the form of springs and recorded some details of 15 water wells (Table 3.1). The majority of groundwater levels recorded in 1870 or 1871 are within the range of the average groundwater levels recorded in the 1996 – 2006 period.

At the time that Krause's maps were completed the catchment was sparsely inhabited and covered in native vegetation. An 1860 survey report records the Moorabool River catchment as *"almost entirely wooded"* and the Leigh River catchment as *"entirely wooded"* (Nathan 2004). Recent mapping of native vegetation Ecological Vegetation Community estimates that these pre-settlement (nominated as 1750 AD) landscapes were mostly vegetated with plains grassy woodland and herb-rich foothill forest. The plains grassy woodland is described as open eucalypt woodland with approximately 15 large trees (to 15 m tall) per hectare among grasses and small shrubs. Herb-rich foothill forest is a medium to tall (to 25 m tall) open forest or woodland with a density of approximately 20 large trees per hectare and a sparse to dense shrub layer over a ground cover of grasses and herbs (DSE 2004a).

Much of the forest had been cleared by 1881 when Ballarat Water Commissioner, Mr Thompson, recorded the depth of 74 wells and their groundwater levels in the upper West Moorabool catchment (Nathan 2004). He also recorded 14 surface springs, assumed to be groundwater discharge. Thompson's list records the property owner, but not the precise location of the wells and springs. The watertables in the wells varied from 0.9 m to 12.2 m, with an average of 3.2 m. Dunn (1888) also noted that the wells sunk in the basalt in and around the upper West Moorabool water reserve yielded a supply of good quality water, with seasonally fluctuating watertables generally less than 10 m (30 feet) deep. Although only the approximate locations of the wells are known, the 1881 watertable is generally within the range of the average depth to the watertable in the 1996-2006 period (Figure 3.4), and comparable to those recorded by Krause (1870, 1871; Table 3.1).

Table 3.1 Krause's 1870 & 1871 well depths and water levels compared with the average water levels from 1996-2006.

Location details (Map Grid of Australia, 1994)			1870 & 1871 Geological map data					average SWL 1996-2006
			Feature	Description	Well depth		standing water level (SWL)	
Zone	Easting	Northing			feet	metres	metres	metres
54	763220	5840980	Well	Permanent water. Exceedingly hard.	14	4.3		6.7
54	763220	5840990	Well	Softer water. Liable to run dry in summer.	18	5.5		6.7
54	763260	5840980	Well	Plentiful supply. Tolerably sweet. Liable to run dry in summer.	20	6.1		6.6
54	760220	5838880	Well	Water standing at 14 feet (4.3m).	30	9.1	4.3	6.1
54	761220	5839180	Well	Good water.	25	7.6		4.2
54	761220	5839190	Well	Brackish water.	22	6.7		4.2
54	761220	5838380	Well	Hard water. Standing at 23 feet (7m).	29	8.8	7.0	6.9
54	761320	5838280	Well	Partly surface water. Standing at 21 feet (6.4m).	35	10.7	6.4	7.2
54	760920	5838380	Well	Good water.	47	14.3		6.6
54	762120	5837180	Well	Good water. Standing at 33 feet (10m).	39	11.9	10.0	7.0
54	759620	5837180	Well	Brackish water.	unknown			4.5
55	235910	5846980	Well	Good permanent water.	29	8.8		9.7
55	236610	5836180	Well	Permanent water.	30	9.1		7.2
55	236610	5843680	Well	Permanent water. Standing at 18 feet (5.5m).			5.5	9.5
55	236610	5843380	Well	Good water.	32	9.75		9.5
54	761420	5838780	Spring	Flowing 468 gallons per hour (0.6 l.s-1)	surface?			5.3
55	236610	5844680	Shaft	Abandoned because of water inflows	20	6.1		9.5



a) 1881 depth to water table
(well locations shown as black dots)

b) Average depth to water table 1996-2006
(bore locations shown as black dots)

Figure 3.4 Depth to water tables in 1881 compared to the average for 1996-2006 in the Upper Moorabool River catchment.

The historical evidence indicates that water tables in the unconfined volcanic aquifer of the West Moorabool River catchment were reasonably shallow even under the forest cover of 1870, and that subsequent clearing of the landscape for agriculture has not resulted in higher watertables. The current land-use is mixed farming of grazing and cropping, with potatoes as the dominant crop. The groundwater is used for summer irrigation of the crops and the groundwater levels in the unconfined aquifer recover rapidly following drawdown (Evans 2006).

3.5.2 *Hydrologic change linked to land-use change*

Within the first three decades of pastoral settlement (from 1835) hydrological changes were observed which were linked to the land-use change. Contrary to the present axiom, the impacts of these changes attributed to clearing and agriculture were generally regarded as having a positive impact.

The most commonly made observation on the Western Plains was that the introduction of pastoral agriculture had resulted in compacted soils, increasing runoff (Bonwick 1858; Brough-Smyth 1869; Hebb 1888). In the general district around Lake Colac, Hebb (1888) reports that in the 1840's the soil was "*damp, marshy and springy*" being "*too moist and damp for sheep*", such that they had difficulty walking over the "*soft and porous*" soil, even in the uplands. This observation was made when the pastoral settlement was relatively sparse: in 1845 the (non-indigenous) population of south western Victoria was approximately 2998, with 2286 acres in cultivation and over one million sheep.

Bonwick (1858), a school inspector with a great interest in geography and geology, documented the state of the environment during his educational tour of south western Victoria in 1857. Bonwick's hydrological observations include numerous references to swamps, waterlogged soils, salt water and fresh water lakes, streams and rivers. As a part the narrative account of travel just south of Lake Burrumbeet, Bonwick writes:

"*I was interested with accounts of the change of climate, as it was said by some, since the occupation of the western country by the Whites. Formerly the drought was greatly to be dreaded. The creeks soon dried up, and the water-holes were few and shallow. Now, water is abundant. Once huge trees grew in hollows in the bed of the stream; now these holes contain twenty and thirty feet of water. The simple truth is, that continual treading of the soil by the hoof of the stock forms a surface, from which the rain water falls into hollows of creeks. Water holes, moreover, are able to retain the precious liquid, better than formerly, because the cattle have by pressure puddled, as it were, the bottom into retentive clay.*" (Bonwick 1858).

This observation is probably made in relation to the water levels and water quality of the lakes, particularly Lake Burrumbeet. Learmonth (1853, in Bride 1898), the first European settler to visit Lake Burrumbeet, records the water as brackish in August 1837. When the lake was next visited in January 1838 it was *"…a few inches deep of intensely salt water*" and unrecognisable from the previous visit. Withers (1887) notes that the following year (1839) the lake was dry and remained so for several successive summers.

The influence on the hydrology attributed to first pastoral settlers by Bonwick (1858) accords with an observation made by Brough Smyth (1869), the Secretary for Mines in the Colony of Victoria. The note by Brough Smyth is quoted in its entirety:

"*Large swamps, which in the memory of settlers have been dry lands for several years in succession, have by tillage and drainage of the adjacent slopes been* *converted into lakes which have in a brief period increased in depth and area, and inundated large tracts of fertile land. Lake Learmonth, Lake Burrumbeet, and notably Lake Modewarre, are instances of this kind of action.*

From records made by the Land Surveyors it appears that in 1841 the bed of Lake Burrumbeet was quite dry and overgrown with fine silky grass, and mussel shells were abundant on the surface. When the lake was full the water was said to be salt. In 1849 there was fresh water to the depth of four and six feet. At the present time there is a great depth of water, and the lake is a conspicuous feature in the landscape; and, when I visited it in October, 1868, there were boats on it, and the proprietor of them told me that he was about to purchase a small steam vessel to ply between the northern and southern shores.

Mr. John Steavenson, the Assistant Commissioner of Roads and Bridges, informs me that, twelve years ago, he was well acquainted with the features of Lake Modewarre. Then the waters were salt – quite unfit for domestic purposes, or even for cattle, and characterised by that peculiar, almost foetid, odour and taste which belong to the waters of many of the salt lakes. Of late years, since the adjoining lands have been cultivated, roads and drains made, and the natural surfaces of the drainage area in many parts denuded of timber and grass, he has tasted the water and found it quite sweet and wholesome. The lake is now from ten to twelve feet above its original level; and many farms have been submerged."

It should be noted that many of the lakes in the Corangamite region, including lakes Burrumbeet and Learmonth, have been dry for the past few years. The low lake levels are attributed to the prolonged period of below average rainfall and human activity such as the extraction of groundwater (Adler and Lawrence 2004).

By 1887, the supply of timber for mining had become an issue in the areas where forests were being rapidly cleared (Langtree 1887). The following year, in a geological report on the Ballarat water supply, Dunn (1888) noted that the flow of springs which had continuously supplied excellent water had diminished since the forests had been cleared. These springs were those recorded by Krause in 1871 and Thompson in 1881 and both sources refer to their abundance and suitability as a permanent water supply for Ballarat. Dunn (1888) recommended replanting trees around the heads of the springs and "*the vegetation usually found naturally growing along the course of runnels from springs*." Ironically, this recommendation – that trees should be planted to restore groundwater discharge – is contrary to that of contemporary salinity management practice which advocates planting trees to reduce groundwater recharge (and therefore, discharge). Nevertheless it does accord with observations elsewhere in the higher rainfall landscapes of south west Victoria (Fawcett 2004).

3.6 The salinity problem

The management of salinity in the Corangamite region dates back to the very earliest days of pastoral settlement, when breakwaters were constructed across the Barwon River in 1840 and 1898 to prevent tidal salt reaching the new town of Geelong and secure river water for irrigation (Rosengren 1973). This established the precedent that salinity was primarily a water quality issue in the Corangamite region, and as such was the responsibility of the various water authorities.

An example is given by the 1860 proposal to drain Lake Corangamite and convert it from a saltwater lake to fresh water storage for irrigation of the plains and as an urban water supply for Colac (Hebb 1888). The idea gained prominence when a series of wet years caused the lake to rise and several adjoining properties were submerged. It was proposed to construct a channel to divert flows from the Woady Yaloak River to the Barwon River via Lake Murdeduke. Remarkably, this idea persisted for a century, and a diversion channel which more or less followed the route proposed in 1860 was constructed following a series of wet years during the 1950s which caused the lake level to rise and inundate several farm properties. Since the diversion commenced in 1960, the salinity of the lake has dramatically increased and now threatens the ecological values of the asset. It is now proposed to close the diversion channel to restore the lake to its unregulated state (Nicholson et al. 2006).

It was not until the Soil Conservation Authority (SCA) was founded in 1939 that soil salinity emerged as an issue, initially as a process in soil erosion and land degradation. From the outset, soil salinisation was related to land clearance, although the existence of some pre-settlement salinity was acknowledged

(Holmes et al. 1939). The relationship of salinity to land clearing had been previously established in the West Australian literature (Wood 1924). Soil salinity in the Corangamite region was first surveyed in 1952 (Cope 1955) and a landmark study published in 1958 by the SCA recorded over 4,000 ha (10,000 acres) of salted land in Victoria, including 10 locations in the Corangamite region (Cope 1958). This study clearly related salinity to the water-balance and identified rainwater as the main source of salt. It was argued that before European settlement, the rainwater was used by trees where it fell, although it was acknowledged that some saline discharge took place prior to settlement.

During the mid 1970s salinity emerged as a separate issue from soil erosion and by 1978 rising groundwater was seen as the dominant cause of salinity (SCA 1978). Salt and land salinisation were attributed to groundwater discharge and the increase in salinity was attributed to the several metres of recharge that had been added to the aquifers since settlement. Hydrogeology replaced agricultural science as the most appropriate research base from which to investigate dryland salting (Jenkin 1983) and observation bores were installed to monitor the rising watertables.

In 1983 the first comprehensive survey of soil salinity was completed for the Corangamite region (Duff 1983). The survey used the presence of several salt-tolerant plant species, aerial photo interpretation, field observations and soil analyses to conclude that approximately 1.2 % of the region was affected by dryland salinity. This investigation distinguished between primary and secondary salinity and made the point that distinction between the two is not clear. The total area affected by both primary (natural) and secondary (induced) soil salinity was 8,298 ha. This detailed investigative study was the first in the region that attempted to relate the salinity to a cause, concluding that rising groundwater levels following the clearing of the native vegetation was to blame. Duff (1983) argued that the ultimate control of secondary soil salinisation is the prevention of groundwater recharge.

The growing concern over salinity resulted in the establishment of the Victorian Government Task Force on salinity in 1985, and the first Victorian Salinity Strategy – *Salt Action: Joint Action* - in 1988. The strategy established the

Corangamite Salinity Control Region and initiated the development of the first regional salinity strategy for the Corangamite region – *Restoring the Balance* – which was launched in December 1992 (Nicholson et al. 1992b). According to the strategy, the single cause of salinity in the Corangamite region is the rising watertables caused by the imbalance in water use following the clearing of native vegetation. The strategy distinguished between local and regional groundwater systems based on the distance from recharge to discharge. Salinity management focussed on recharge control in local groundwater systems.

The implementation of this initial salinity strategy attracted more than AUD$9 million in State and Federal funding and many millions in landholder, industry and community contributions. Key achievements included the establishment of almost 3,500 ha of trees, more than 16,000 ha of perennial pasture and the treatment of 1,130 ha of saline land. Awareness of salinity in rural communities rose from 35 % to 65 % of the population, and 10,000 school students were engaged in the Saltwatch program. Many research programs were undertaken and establishment of an extensive monitoring network that included 580 bores and 14 surface water monitoring stations.

A comprehensive review of Restoring the Balance in 2002 (Nicholson 2002) concluded that there was little evidence that recharge control had achieved the expected outcomes. The validity of the original simple assumption was questioned and it was acknowledged that the salinity processes are much more complex than the original 'cause – effect models'. In particular the understanding of hydrogeology at the scale required to target on-ground works was inadequate, which has implications for the investment of resources in salinity management. Despite the best intentions, few of the salinity works resulted in a reduction in land and water salinisation (although they may have resulted in other positive benefits).

The Victorian Government launched the second generation salinity management framework in August 2000 – *Restoring our Catchments* – which recognises that although much has been achieved in the past decade, the 'best practice' agricultural systems in grazing and cropping cannot reduce recharge in high rainfall areas. It proposes that large-scale revegetation may represent the only prospect of halting or reversing water tables in these areas (e.g. much of the Corangamite region).

The Corangamite Salinity Action Plan (Nicholson et al. 2006) is the second-generation salinity management program for the Corangamite region, developed in the context of the National Action Plan for Salinity and Water Quality (CoAG 2000), the Victorian Salinity Management Framework (DNRE 2000) and the Corangamite Regional Catchment Strategy 2003 – 2008 (CCMA 2003). In line with the rationale for investment adopted by the State and regions for natural resource management projects, an asset-based approach was used to identify twelve target locations and priorities for salinity investment. These twelve areas encompass more than 83 % of the salinity in the Corangamite region, including 87 % of the saline wetlands and 72 % of the saline land.

3.7 Current condition

Salinity appears in the Corangamite Region as either saline land, saline wetlands or as changes in the salinity of surface water. Of the 63,000 ha of mapped salinity in the Corangamite region, 73 % occurs as semi-permanent or permanently saline wetlands and the remaining 27 % as land salinity.

However, land salting is the most obvious manifestation of salinity in the Corangamite Region. Assembling and rationalising all previous mapping indicates there are 17,250 ha of land salting, occurring at 1,500 locations in the landscape. This estimate is confounded by the presence of both primary (natural) and secondary (induced) salinity. In some locations the separation between natural and induced land salting has been made at the time of mapping on the basis of the indicator plants present. However, in many other areas the distinction is less clear. Based on the details provided in the original mapping and the historical record of salinity at the site, it is estimated that just over half the mapped land salinity is primary in origin (Figure 3.5). If the integrity of this natural salting is intact, these areas need to be viewed as environmental assets.

3.7.1 Current trends in land salinity

The area of land salinised in the Corangamite region has been assessed at various times over the past 30 years. A review of the most recent salinity mapping indicates that the area of land salinised is increasing in some areas of the Corangamite region.

A reassessment of 15 % of the previously mapped land salinity was undertaken by the Department of Natural Resources and Environment (Gardiner 2001). The project mapped 156 sites, of which 133 were previously mapped and 23 were new additions to the database. The 156 sites represented 17 % of the land salinity sites mapped at the time. The review found that the 2006.6 ha of land salinity previously mapped had increased 11 % to cover 2242.9 ha. The new additions to the mapped land salinity covered 137.4 ha in the regions mapped. The severity of the land salinity at the reassessed sites had changed considerably, with a 36 % increase in severity 1 (low salinity), 24 % decrease in severity 2 and a 0.9 % decrease in severity 3 (high salinity).

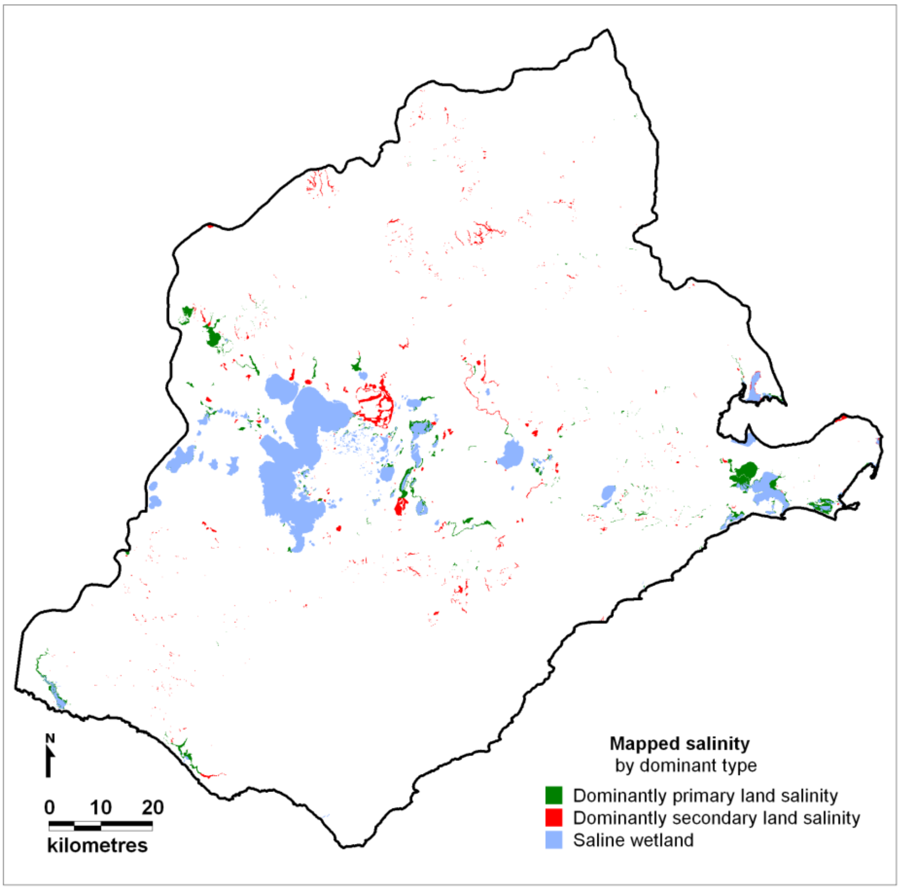


Figure 3.5 Distribution of salinity in the Corangamite region.

Gardiner's survey was the first attempt to achieve a statistically significant reassessment of land salinity in the Corangamite region. Although the results are valuable, the timing of the survey – January to March 2001 – was not ideal for the accurate identification of saline vegetation indicators and came at a time when rainfall had been below average for the antecedent 5 years. This highlights the fact that visual monitoring of land salinity is only useful as an indicative measure.

In August 2004, Primary Industries Research Victoria (PIRVic) reported on the re-assessment of six discharge sites in the Corangamite region which are part of the Victorian Dryland Salinity Monitoring Network (Clark and Hekmeijer 2004). A summary of their findings are tabulated in Table 3.2.

Table 3.2 Summary of discharge monitoring at the six State discharge monitoring reference sites

(summarised from Clark and Hekmeijer 2004).

Location	Beeac	Gerangamete agroforestry	Gerangamete control	Moriac	Pittong	Wingeel
Year established	1996	1994	1994	1995	1996	1995
Year reassessed	2000	1999	1999	2000	2000	1999
Change in total salt-affected area	13% decrease	7% increase	25% decrease	7% decrease	8% increase	18% decrease
Change in groundwater levels	1 m lower	0.5 to 1.5 m lower	stable	0.6 m lower	Slightly lower	0.4 m lower

The results of the monitoring indicate the difficulty in linking cause and effect at an individual site. As an example, at the Gerangamete agroforestry site, recharge control treatment (planting of tree belts) commenced in 1993. Since that time, the area of land affected by salinity has increased by at least 7 % and the water tables have dropped 0.5 to 1.5 m. During the same period at the control site at Gerangamete, where no treatment has been undertaken, the area of land affected by salinity has decreased 25 % and the groundwater levels have remained relatively stable.

Similarly, at the Pittong monitoring site, the area of land affected by salinity has increased 8 % over the period from 1996 to 2000, while the groundwater levels had dropped slightly over the same period. This phenomenon has been verified by the landholders in the area who have witnessed new salinity discharge sites emerge in the past five years.

In the period from October to December 2005 approximately 1150 potential saline sites in the designated urban growth areas of four municipalities in the Corangamite region were examined by the Department of Primary Industries (DPI 2006). Of these, 558 sites totalling 3920.5 ha were accurately mapped by 16 individual assessors, each using handheld GPS. The mapping was based solely on vegetation indicators, using one of the standard salinity mapping methods developed by PIRVic (Clark and Allan 2005). Parameters recorded were the severity rating (i.e. the percentage of the site affected by low, medium, high or severe salinity) and the type of salinity (natural, induced or a combination of both). Additional mapping was completed using traditional stereo photogrammetry of recent aerial photos.

In total, 4823.9 ha were mapped as salt affected within the 22 urban growth areas. This represented 585 sites of which 350 were new or previously unmapped sites and a 40 % increase from the previous assessment. The 2005 mapping categorised 12 % of the area as secondary salinity, 21 % as of primary salinity and 67 % as combined primary and secondary salinity. Only 5 % of the areas were highly saline, with 25 % moderate and 70 % slightly saline (DPI 2006).

3.7.2 Current trends in stream salinity

Trend analysis on all rivers and streams with a record of salinity measurement was completed in 2003 for the development of the Corangamite Salinity Action Plan (Dahlhaus et al. 2005). A semi-parametric statistical method (Morton 1997) based on the Generalised Additive Model (GAM) approach (Hastie and Tibshirani 1990) was used to obtain stream salinity trends that are independent of fluctuations in flow and season, and hence are indicative of the impacts of saline groundwater inflows caused by catchment salinisation. Although the method corrects for flow and seasonal effects, the analyses do not account for longer term climate variations, such as a run of wet years or a run of dry years.

Electrical Conductivity (EC), used as a surrogate measure for water salinity, has been regularly measured at some stream gauging stations in the Corangamite region for about 30 years. The length of record varies and several stations no longer monitor EC, nevertheless all available EC data were used to determine the trends. The results (Table 3, Figure 6) show a wide variation in water salinity trends over the gauging period. Considering those stations with a longer-term record (greater than 10 years) and trends with statistical significance, the Moorabool River shows the greatest increase, with the end-of-valley salinity having almost doubled over the past 30 years. The linear trend of the mean monthly EC measured at the Batesford gauge for the 1976 to 2005 period is 23.7 ± 6.0 µS/cm/yr (Table 3.3). Extrapolating the non-linear trend (Figure 3.7), the EC will continue to rise to a projected mean EC of between 2320 µS/cm and 2404 µS/cm by 2012.

By contrast, the EC trends in the Barwon River show that the end-of-valley salinity has decreased over the past 30 years. Extrapolating the non-linear trend indicates that the mean EC will continue to decline (Figure 3.7). The causes for these trends are difficult to ascertain, as they are influenced by the regulation of the rivers, the diversion of surface water and groundwater from the streams and the harvesting of surface water in farm dams.

Table 3.3 EC trends in the Corangamite region waterways.

The linear trends are shown with their standard errors (95% confidence level) which are adjusted for the degree of autocorrelation in the GAM analysis (Morton 1997). Locations are shown in Figure 3.6

Gauge Number	Station name	EC Records		Salt load	Mean EC	Linear EC trend
		Start	End	tonnes/day	µS/cm	µS/cm/yr
232202	Moorabool Rvr @ Batesford	Nov-76	Feb-05	81	1521	23.7 ± 6..0
232204	Moorabool Rvr @ Morrisons	Nov-76	Jun-01	44	643	-0.8 ± 2.6
232210	Moorabool Rvr West Branch @ Lal Lal	Dec-76	Feb-05	5	421	1.9 ± 1.0
232211	Moorabool Rvr West Branch @ Mount Doran	Nov-76	Jul-90	21	473	10.9 ± 2.7
233200	Barwon Rvr @ Pollocksford	Nov-76	Feb-05	495	1991	-31.8 ± 8.3
233211	Birregurra Crk @ Ricketts Marsh	Oct-76	Dec-04	294	10429	-175.1 ± 112.2
233214	Barwon Rvr East Branch @ Forrest	Mar-78	Aug-01	3	150	-0.1 ± 0.3
233215	Leigh Rvr @ Mount Mercer	Nov-76	Sep-01	82	1146	-1.4 ± 3.8
233218	Barwon Rvr @ Inverleigh	Oct-76	Jun-01	330	2196	-21.7 ± 13.9

233223	Warrambine Crk @ Warrambine	Nov-76	Jan-84	10	4287	104.2 ± 236.4
233224	Barwon Rvr @ Ricketts Marsh	Oct-76	Jul-01	99	897	-2.2 ± 5.5
233228	Boundary Crk @ Yeodene	Jun-85	Aug-01	4	597	12.8 ± 5.4
234200	Woady Yaloak Rvr @ Pitfield	Nov-76	Jul-90	49	2138	-35.4 ± 35.1
234201	Woady Yaloak Rvr @ Cressy (Yarima)	Nov-76	Feb-05	242	5265	3.4 ± 23.7
234203	Pirron Yallock Crk @ Pirron Yallock	Jan-77	Feb-05	35	1221	10.3 ± 7.4
235202	Gellibrand Rvr @ Upper Gellibrand	Dec-76	Jul-89	8	139	0.4 ± 0.7
235203	Curdies Rvr @ Curdie	Jan-77	Oct-93	183	1194	5.9 ± 7.6
235204	Little Aire Crk @ Beech Forest	Jan-77	Aug-01	2	98	-0.3 ± 0.2
235205	Arkins Crk West Branch @ Wyelangta	May-78	Aug-01	1	100	-0.1 ± 0.3
235208	Gellibrand Rvr @ Carlisle	Dec-76	Feb-88	62	200	0.0 ± 1.3
235209	Aire Rvr @ Beech Forest	Mar-91	Aug-01	3	117	0.0 ± 0.6
235210	Lardner Crk @ Gellibrand	Dec-76	Jun-01	6	154	0.2 ± 0.9
235212	Chapple Crk @ Chapple Vale	Dec-76	Jun-88	4	199	0.4 ± 1.3
235216	Cumberland Rvr @ Lorne	Oct-76	Jun-01	1	18	-0.1 ± 0.2
235219	Aire Rvr @ Wyelangta	Nov-76	Jun-88	16	125	-0.5 ± 0.7
235222	Anglesea Rvr (Salt Crk) @ Anglesea	Aug-76	Nov-82	2	800	160.8 ± 90.0
235223	Scotts Crk @ Scotts Crk	Jan-77	May-87	18	1927	-0.8 ± 36.5
235224	Gellibrand Rvr @ Burrupa	Dec-76	Jul-01	109	273	-0.4 ± 0.7
235226	St George Rvr @ Allenvale	Nov-76	Jun-88	2	186	0.3 ± 1.4
235227	Gellibrand Rvr @ Bunkers Hill	Dec-76	Aug-01	37	221	-0.6 ± 0.6
235229	Ford Rvr @ Glenaire	Nov-76	May-87	8	169	-1.0 ± 1.0
235232	Painkalac Crk @ Painkalac Crk Dam	Oct-76	Apr-87	2	403	-19.6 ± 8.3
235233	Barham Rvr East Branch @ Apollo Bay	Nov-77	Jul-90	9	201	0.6 ± 0.9
235234	Love Crk @ Gellibrand	May-79	Jun-01	5	445	-0.8 ± 3.0
235237	Scotts Crk @ Curdie (Digneys Bridge)	Jul-88	Jan-01	162	1468	21.7 ± 21.8
235239	Ten Mile Crk @ Kawarren	May-85	Jan-94	1	429	-12.2 ± 6.8
235240	Yahoo Crk @ Kawarren	May-85	Jan-94	1	439	-6.8 ± 5.3
235241	Porcupine Crk @ Kawarren	May-86	Jan-94	3	334	-8.5 ± 6.4

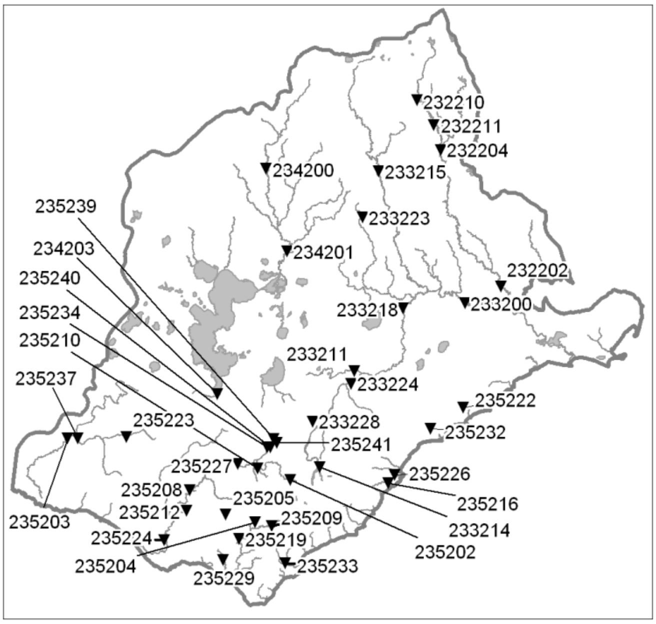


Figure 3.6 Locations of the gauging stations listed in Table 3.3

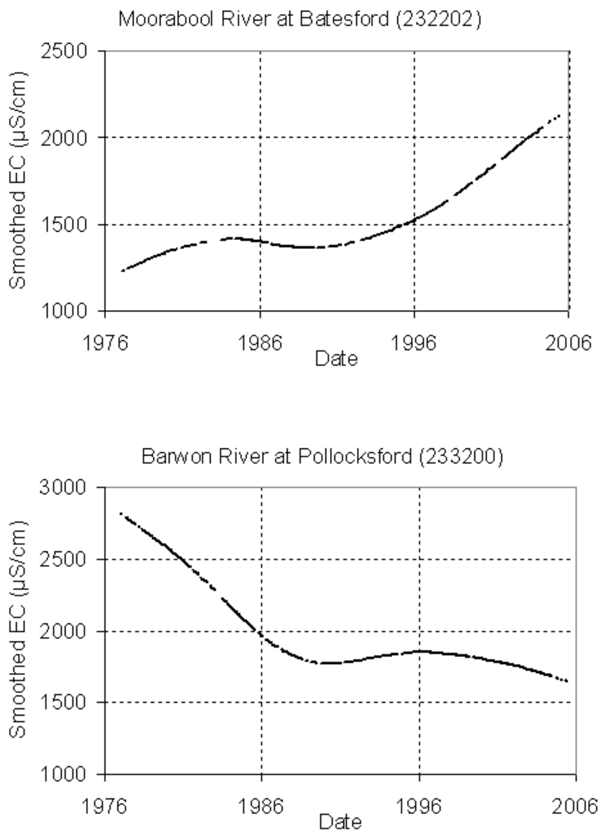


Figure 3.7 End of valley trends in stream salinity for the Moorabool River and Barwon River.

These non-linear smoothed trends are derived from the GAM analysis of the EC data for the periods listed in Table 3.3

3.8 Discussion

This review of the geomorphological and historical evidence supports the premise that shallow groundwater and salinity have been present in the Corangamite region landscapes for centuries. In some areas (e.g. the volcanic landscapes of the Western Uplands and the Western Plains) the depth of the groundwater below the surface has remained relatively unchanged over the past 200 years, despite the widespread land-use change.

With the onset of pastoral settlement on the Western Plains in the late 1830’s, the change in land-use was a transition from native grasslands to pastures and crops. The extent of natural salting in the landscape is impossible to accurately quantify because in many situations the naturally occurring salinity has been modified by the post-settlement changes to the environment. However there is sufficient geomorphic, historical and field mapping evidence that both saline wetlands and land salinity were present before European settlement, and that these saline areas were diverse and extensive throughout the region.

If the integrity of this natural salting is intact, these areas need to be viewed as environmental assets. Most of the larger saline wetlands are already classed as international environmental assets, and many of the smaller ones are protected under municipal planning overlays. The biodiversity value of the primary land salinity has only recently been recognised and some sites have rare halophytic plants present. In the areas mapped as primary salinity, 12 % has an ecological vegetation community with bioregional conservation status classified as endangered, and 6.1 % classified as vulnerable. By contrast, in the areas mapped as secondary salinity, only 0.4 % of the vegetation is classed as endangered and 0.3 % as vulnerable. The saline wetlands have 8.9 % of their ecological vegetation community classified as endangered bioregional conservation status.

Nearly all of the permanent wetlands are believed to receive groundwater discharge, such that they vary in their salinity range from brackish to hypersaline. The geomorphic evidence, archaeological research and earliest historical records indicate that climate is the dominant control on lake levels. This conclusion was also reached by Jones (1995) who used a water balance approach to show that the falling lake levels in two closed lakes (in volcanic craters) in the region was due to the changed precipitation to evaporation ratio over the past century. Salinity management of these assets relies on maintaining groundwater levels and in at least one case, groundwater extraction has been linked to the drying of saline lakes in the region (Adler and Lawrence 2004).

Nearly 77 % of the mapped primary salinity and 74 % of the secondary salinity occurs in areas mapped as local groundwater flow systems. The high percentage of primary salinity in local systems is counterintuitive to the argument that local systems are the most responsive to land-use change. This implies that 1) saline groundwater discharge was present in these areas before widespread land-use change, or 2) the saline discharge emanates from underlying regional groundwater systems, or 3) a substantial proportion of the salinity and/or groundwater flow systems are incorrectly mapped.

A closer examination of the data reveals that nearly all of the primary salinity in local groundwater flow systems occurs in areas where unconsolidated Quaternary sediments overlie regional groundwater flow systems of the Western Plains. While the relatively thin veneer of Quaternary sediments is hydrologically responsive to land-use, the major influence on salinity is the underlying regional groundwater discharge, which has remained relatively unchanged with the change in land use from the native grasslands to pastures and crops.

In the Western Uplands, the land-use change was more dramatic, particularly during the three decades following the discovery of gold. Yet historical records show that earliest recorded groundwater levels were within the range of the present day levels. One explanation for this observation is that the groundwater systems in these areas are regulated by the rate of discharge, with average annual recharge in excess of discharge. These discharge-driven groundwater systems may have been relatively ‘full’ for centuries.

Although land salinity has been present in the Corangamite region since the beginnings of pastoral settlement, it was not documented as an issue until over a century later. This may be due in part to the increased economic impacts of salinity as the size of land holdings decreased, particularly with the Soldier

Settlement and Closer Settlement schemes following the 1914-1918 war (Nathan 2000). However, it is likely that the widespread clearing of the native vegetation has induced a hydrological response in some groundwater systems in the region, causing secondary salinity to develop. The region-wide trends in watertables measured in the salinity monitoring bores suggest that in most locations equilibrium may have been reached. This argument is supported by the observation that many discharge areas have remained static or reduced in size.

Nevertheless the data from the most recent monitoring and mapping indicate that land salinity in some locations has expanded during the past decade. In these areas the falling trend in groundwater levels suggests that other factors such as changes to soil waterlogging and regolith hydrology are implicated in the spread of salinity (Dahlhaus and MacEwan 1997).

3.9 Conclusions

Salinity has been an episodic feature of the Corangamite region throughout the Quaternary. The salinity of the lakes on the volcanic plains has varied with climate change and is recorded in the geomorphology, especially the lunettes. The Aboriginal archaeological evidence supports variations in salinity during the aboriginal occupation of the Corangamite landscapes during the Pleistocene and Holocene.

The earliest historical accounts of the landscape record shallow water tables and saline lakes and drainage lines as existing features of the landscape. There is no recorded evidence found which supports significant rises in groundwater following widespread land-use change. From the earliest recorded history, observed changes to the landscape hydrology were linked to anthropogenic causes, but they are contrary to the current axiom.

This review adds to the growing body of evidence that rising water tables are not the single cause of salinity in many of Australia's landscapes (Dahlhaus et al. 2000; Fawcett 2004; Wagner 2005; Bann and Field 2006). The increasing salinity which threatens the Corangamite region's assets cannot be universally equated to rising groundwater following European settlement. Land-use change was not a single 'event' but is a continuum, with many landscapes undergoing constant but relatively minor change (native grasslands replaced with exotic grasslands or crops; or native forests replaced with regrowth or plantation forests).

In ignorance of the context provided by researching beyond the hydrogeologic evidence, the traditional salinity management has focussed on using trees to lower the shallow watertables. However, this review has shown that in many areas salinity is an inherent component of the region's landscapes, and sustains world class environmental assets (Ramsar wetlands). Maintaining appropriate salinity levels is vital for their ecological health. Managing salinity by lowering the groundwater levels is contradictory to the geomorphic and historical evidence, and may threaten environmental assets. Determining the most appropriate salinity management in the Corangamite region requires assessing the risk to each individual asset.

3.10 Acknowledgements:

The Corangamite Catchment Management Authority provided the funding for this research. The work contributes towards PD's PhD studies partly funded through an Australian Postgraduate Award. Thanks to Dr Erica Nathan who provided some of the historical references.

4 Increasing land salinisation and falling watertables: assessing 20 years of salinity management in the Pittong region, western Victoria.

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4.1 Abstract

An investigation of the impacts of salinity management in the Pittong area in south west Victoria reveals an apparent contradiction to the current salinity paradigm in Australia. In this landscape the area of salinised land has continued to expand and new saline discharge areas have emerged, despite over 20 years of active salinity management, a decade of below average rainfall, and a general trend of falling watertables. This investigation integrates the regional geological, geophysical and hydrogeological data; collates the previous salinity mapping and landholder observations; analyses data from a land salinity monitoring site; interprets an extensive geophysical survey (EM38DD); and analyses groundwater monitoring data in relation to rainfall using a time-trend method. A revised model is proposed that implicates deep regional saline groundwater flow, controlled by geological structures, as the point-sources of saline discharge. Implications for salinity management are that the eradication of saline land is not possible at the local scale, but efforts should focus on reducing the spread of salt.

Keywords: Dryland salinity, groundwater flow systems, electromagnetic survey, Pittong, Corangamite, Woady Yaloak River.

4.2 Introduction

Land and water salinisation in dryland agricultural regions of Australia is a well documented problem (Ghassemi et al. 1995), which has been a focus of government investment for decades. Despite this considerable investment, the problem continues to expand in some areas. In the State of Victoria the Auditor General concluded that although the State government had invested $257 million in salinity management during the period from 1990 to 2000, dryland salinity had worsened over the same period (Auditor General 2001). Since then, the State and Federal governments have committed $504 million to salinity management in Victoria for the 2001–2008 period (CoAG 2000) and a recent report by a committee of the Australian Senate concluded that following this, a further 10 years of commensurate funding would be required (Australian Senate 2006).

In both the Federal and State salinity management frameworks rising groundwater following the clearing of native vegetation is seen as the single cause of salinity and therefore reducing the groundwater recharge is regarded as the solution (DNRE 2000; Coram et al. 2001). Recharge reduction may be achieved through tree plantations or farming systems which incorporate higher water-use pastures and crops (Peck 1993; Ghassemi et al. 1995; Williams et al. 2002). The hydrologic response to recharge management is dependent on the scale of the groundwater flow system implicated in the salinity process, *viz:* local, intermediate or regional systems (Coram et al. 2000). A local groundwater system is one in which the distance from recharge to discharge is typically less than 5 km, and the response may be observed in less than a decade. By comparison, the groundwater flows in a regional system are generally greater than 50 km and the response may be more than a century.

This paper investigates the impacts of 20 years of recharge management in a landscape categorised as a local groundwater system (Kevin 1993; Dahlhaus et al. 2002a). The result is an apparent contradiction to the current axiom in salinity management. In this landscape the area of salinised land has continued to expand and new saline discharge areas have emerged, despite over 20 years of active salinity management, a decade of below average rainfall and a trend of falling watertables.

4.3 Landscape description

This study investigates the salinity processes in a landscape of 6,300 ha at Pittong, 35 km WSW of Ballarat in western Victoria. The area comprises the upper catchment of the Naringhil Creek, a tributary to the Woady Yaloak River. The northern boundary forms part of the watershed between the Naringhil Creek (south) and the Mount Emu Creek (north), which is also the divide between the Lake Corangamite Basin and the Hopkins River Basin in the South East Coast Drainage Division. The study area forms a broad amphitheatre bisected by a central low ridge with elevations from 253 to 470 m AHD (Figure 4.1).

Climate is temperate, with the majority of rainfall in winter and spring. The interpolated long-term (1889-2008) average annual rainfall is 648 mm and annual pan evaporation is 1215 mm (BoM 2009b). Highest annual rainfall recorded for Skipton is 885 mm (1964) and for Linton is 1104 mm (1952). Annual rainfall in excess of 800 mm has been recorded on 7 years at Skipton (109 year record) and on 25 years at Linton (94 year record) (BoM 2009d). The variation in rainfall partially reflects the difference in elevation between the two stations, with Skipton at 295 m and Linton 420 m AHD.

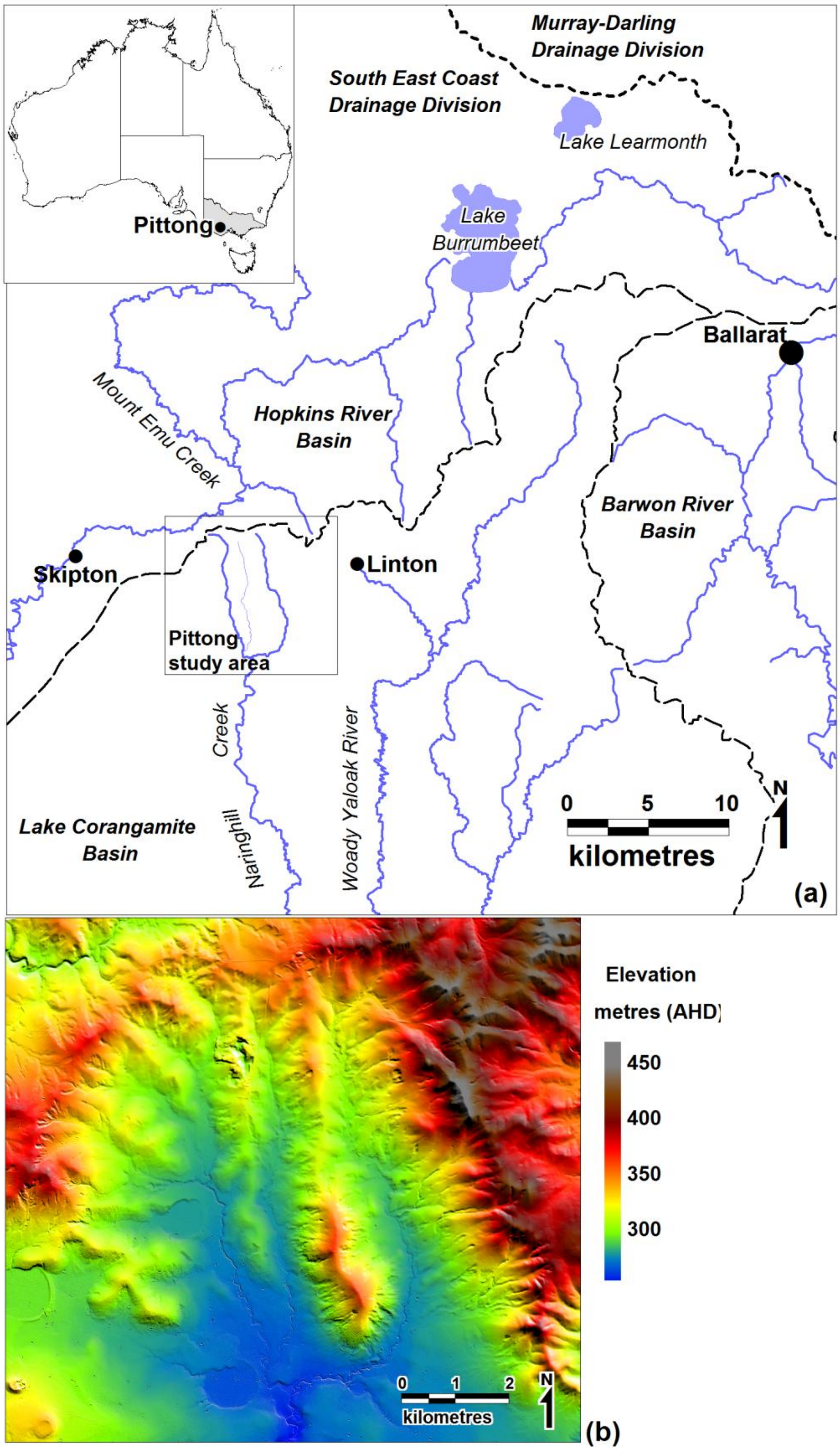

Figure 4.1 (a) Location map; and (b) elevation of the Pittong area.

In the late 18th century the Pittong area supported an small number of Aboriginal people (Clark 1990), who occupied the grassy woodlands of Eucalyptus species, estimated at 15 trees per hectare (DSE 2004a). Pastoral settlement by European people commenced around 1840, and land clearing accelerated from the early 1850's when gold was discovered around Linton. The supply of timber to the mines had denuded most of the native forests around the goldfields by 1870 (Langtree 1887). In the current day landscape, remnant native vegetation covers around 4 % of the area. In the centre of the area an open-pit mining operation covers 65 ha (1 %) and extracts approximately 44,000 T/annum of kaolin clay. The remaining 95 % of the area is used for agricultural production, largely mixed farming, comprising wool growing, cereal and oilseed cropping, meat production and timber plantations.

Soil salinisation has been recognised as a limitation to agricultural production in the Pittong area from the early 1950's (Cope 1958). The area was identified as a target area for salinity management in both the first regional salinity strategy (Nicholson et al. 1992b) and the second generation salinity strategy 14 years later (Nicholson et al. 2006). These strategies also recognise that the export of salt from the area threatens the ecological health of the waterways and a large wetland of international importance at the end of valley. Over the past 20 years, the landholders in the region have been at the forefront of land rehabilitation and catchment management, and have been awarded National acclaim for their land management practices aimed at controlling the groundwater fluxes in an effort to reduce salinity.

4.3.1 *Geological setting*

The basement rocks of the Pittong area are the Cambrian age sedimentary rocks of the St Arnaud Group, a thick turbidite sequence of quartz-rich sandstones (arenites) and shales (Taylor et al. 1996). Tectonic activity from the Late Ordovician to Early Silurian periods folded and faulted the rocks, metamorphosing the shales into phyllite and quartz-mica schists, and injecting quartz veins (some of which are mineralised).

Three granite bodies were emplaced during the Late Devonian (GSV 2003), *viz:* the Tiac Granite, a coarse-grained equigranular biotite granite, in the north west of the study area; the Mount Bute Granite, a coarse-grained to medium-grained hornblende biotite granite (adamellite), which underlies the northern part of the Pittong study area; and the Illoura Granodiorite, a coarse-grained hornblende biotite granodiorite and porphyritic biotite granite, which underlies the southern portion of the area. The emplacement of the igneous rocks caused contact metamorphism of the surrounding St Arnaud Group rocks, resulting in an aureole of hornfels, approximately 1 km wide around the rim of the granites.

Erosion during the late Palaeozoic and Mesozoic resulted in the removal of at least 2 km of crustal rocks to expose the granites at the surface (Taylor et al. 1996). At the commencement of the Cainozoic Era, uplift rejuvenated erosion resulting in the widespread deposition of the White Hills Gravels. A remnant of these ferruginous quartz sandstones and conglomerates is distributed in a wide arc across the northern portion of the Pittong study area.

Deep weathering of the granites occurred during the late Palaeogene and early Neogene periods, resulting in a very thick (20-40 m) regolith of sandy kaolin clay that is now commercially exploited. Higher in the landscape the regolith developed on the granites is largely made up of grus, which had been exploited for road-making sand by the local municipality. On the eastern and northern boundaries of the study area, the erosion-resistant hornfels now forms the watershed of the Naringhil Creek catchment.

Volcanism during the late Neogene and Quaternary Periods emplaced basalts in the southern portion of the area, which form the northern fringe of the Victorian Volcanic Plains. Quaternary colluvium, alluvium and paludal deposits form the most recent sediments. The geology of the target area is illustrated in Figure 4.2.

Duplex soil profiles are widespread across the area, typically comprising sandy loam A horizons (20 - 40 cm thick), which include well developed A_2 (E) horizons, over pedal clay B horizons. On the upper slopes the soil profiles are thinner and generally coarser grained with gravel and sand (decomposed granite) in the top metre. In the lower parts of the landscape the gley soils are present in the lower profile (MacEwan and Dahlhaus 1996).

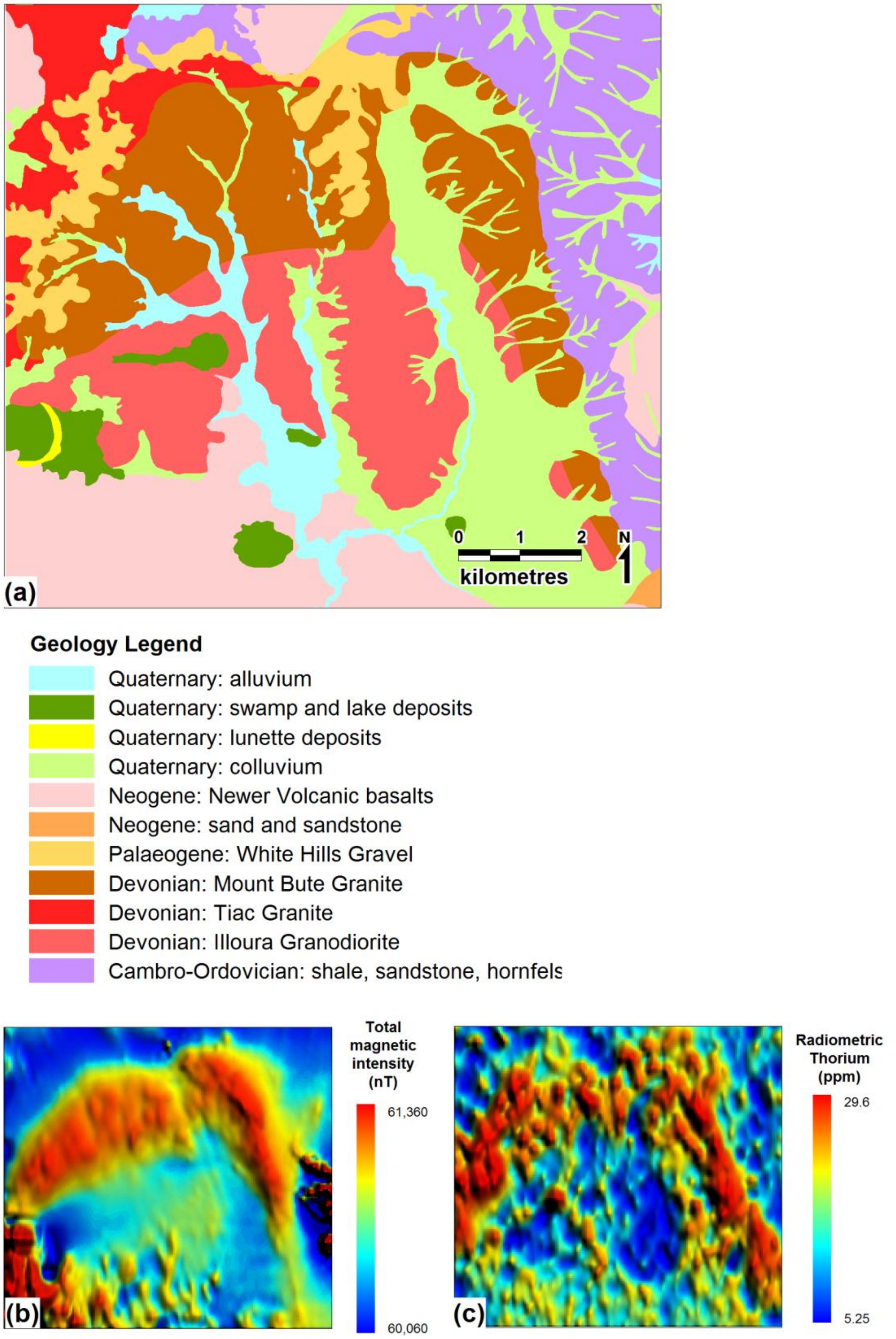

Figure 4.2 (a) Geology, (b) total magnetic intensity and (c) radiometric thorium of the Pittong study area.

4.4 Methods

4.4.1 *Geological data compilation*

Over the past fifty years, more than 1,300 mineral exploration bores have been drilled in the region, with approximately 900 located in the study area. The lithological logs of these bores were collated with the additional information from 34 groundwater observation bores and 2 groundwater supply bores (stock water) to gain an understanding of the spatial distribution of the thickness and properties of the regolith and underlying rocks. These data were further enhanced by the processing and interpretation of the available regional geophysical datasets, including ground-based gravity, airborne magnetics and airborne radiometrics data which were particularly useful in defining the boundaries of the granite plutons (Figure 4.2). Observations and data contained in previous unpublished research and investigation projects were checked by field mapping and observations, and the combined data has been used to refine the mapped boundaries of the geological units and establish conceptual hydrogeological and salinity models.

4.4.2 *Salinity mapping*

Several salinity mapping surveys have been previously undertaken in the Pittong area for different purposes. Cope (1955; 1958) identified land salinisation occurring in the Pittong region during the first state-wide survey, however it was Duff (1983) who first examined the salinity in detail. On the basis of vegetation, aerial photograph interpretation and soil salinity testing, Duff (1983) mapped 19 saltland areas in the Pittong region as part of a much greater survey of the Corangamite region. He concluded that the granite landscapes recorded the highest incidence of salting, with 1.8 % of the land salinised.

Following the release of the initial salinity management plan (Nicholson et al. 1992b) the Pittong region became the focus of a number of research and investigation projects mostly undertaken by the University of Ballarat and the Department of Primary Industries (and their precursors). The sporadic salinity mapping undertaken in these projects was captured from the unpublished reports and rationalised with the previous mapping to create a single dataset of salinity distribution. In all the previous surveys, the extent of salinity was mapped using standard vegetation indicators (Bozon and Matters 1989). In places where numerous surveys overlapped, the boundaries of the salinised land were taken to enclose the maximum area, since the surveys were carried out at different times (i.e. years and seasons).

To provide more rigour in determining the trends in the aerial extent of salinity, the Department of Primary Industries established a long-term monitoring site in the area in September 1996. The 13 ha site in the north west of the Pittong study area is part of the Victorian Dryland Salinity Monitoring Network (VDSMN site no. 9197) (Clark and Hekmeijer 2004). The topography, vegetation, soil salinity, apparent electrical conductivity, and groundwater levels at the site were initially recorded and reassessed in September 2000 and November 2007 (Hekmeijer and Clark 2008). On each occasion, the aerial extent of the salinity was monitored at the site using a standard method documented by Clark and Allan (2005).

4.4.3 *Topographic surveys and orthoimagery*

A digital elevation model (DEM) of the Pittong region has been derived from two main sources of data: 1) that collected using airborne Light Detection and Ranging (LIDAR) technology and supplied as interpolated x,y,z points quality assured by comparison to ground survey points (DSE 2008a); and 2) elevation data collected using a Trimble dual-frequency real-time kinetic Global Positioning System (GPS) mounted on a four-wheeled motorbike, and a fixed GPS base station which was calibrated to the national map grid and geoid using the AUSPOS online GPS processing service. All data were provided in Map Grid of Australia (MGA) Zone 54 projection on the Geodetic Datum of Australia 1994 (GDA94), with elevation corrected to the Australian Height Datum (AHD; AusGeoid98). In all, over 4.5 million data points collected between 2003 and 2007 were used to construct the DEM using a minimum curvature algorithm with a grid cell size of 5 m. The elevation is accurate to ±0.5 m in areas where LIDAR data was used and ±0.1 m where the GPS data was used. The DEM has been used to calculate the relative elevation of the watertables and compare them to the mapped salinised areas.

The topographic data is supported by a series of digital aerial images which have been georectified to the same geographic projection. The most current orthoimagery has a pixel resolution of 0.35 m and was captured in December 2007 (DSE 2010). The aerial imagery was supplemented by various historic aerial photographs dating from 1946 and georectified digital images captured in 2002 and 2004. Aerial infrared photography captured in February 2004 was also available for the western half part of the Pittong region. All images were used to assist in ascertaining the presence or absence of salinity at a particular location and time, as well as the aerial extents of the salinisation.

4.4.4 Electromagnetic surveys

Electromagnetic (EM) surveys are a recognised tool to map salinity (Spies and Woodgate 2005) and have been utilised in the Pittong region. The VDSMN site (Figure 4.3) has been surveyed on the three occasions previously mentioned using a Geonics EM38 instrument, with approximately 200 readings taken at 15 m intervals along traverses 50 m apart. The electrical conductivity (EC) readings were converted to apparent conductivity (EC_a) using an algorithm developed by Slavich (1990) and then the class of salinity (very high, high, medium, low) determined using a factor for the soil texture as described by Clark & Hekmeijer (2008). Numerical surfaces of the data from these surveys have been modelled using a minimum curvature interpolation algorithm with a 2 m grid spacing.

A more extensive regional survey was undertaken between March 2005 and October 2007, using a sled-mounted Geonics EM38DD instrument trailing behind a four-wheeled motorbike (Figure 4.3). Both horizontal and vertical dipole data was simultaneously collected along the traverse lines at intervals varying from 2 to 7 m. The traverse spacing varied from 10 to 100 m, with the vast majority being around 30 m apart. The EM38 data represented the average conductivity of the soil over two depths – from the surface of the ground to a depth of approximately 0.5 m, and from the ground surface to approximately 1.2 m depth. The survey was undertaken in three stages: the north western portion was surveyed in March 2005; the south western portion in September 2005; and the eastern portion in October 2007. The surveys were timed to ensure that there was sufficient moisture in the soil profile (to 1 m depth) to accurately represent the soil salinity.

For each survey the instrument readings were calibrated against a representative number of soil EC analyses from the upper and lower profiles. In total, the soil profile at 58 representative sites was recorded using a trailer-mounted push-tube sampler. At each site composite soil samples were taken as representative of two depths: surface to 0.5 m depth; and 0.8 m to 1.1 m depth. The soil samples were prepared and tested for moisture content, particle size analysis, the EC and pH of a 1:5 soil water paste ($EC_{1:5}$, $pH_{1:5\ (H_20)}$ & $pH_{1:5\ (CaCl)}$), all of which were undertaken using standard test methods and calibrated laboratory equipment.

The soil test results were used to generate predictions for each data point using a spatial regression model, ESAP (Lesch et al. 2000). In particular, the EC of a saturated soil paste extract (EC_e) was predicted from log-transformed EM38DD conductivity readings using the regression model. The result was 70,120 accurately located data points, each with a prediction of the EC_e in the upper and lower parts of the soil profile. Numerical surfaces of the EC_e data were generated for each depth range using a minimum curvature interpolation algorithm and a grid cell size of 10 m.

4.4.5 Hydrogeological investigations

The regional groundwater flow directions were analysed over a surrounding region of approximately 5000 km^2 using the reduced water levels derived from the data available on the government groundwater databases. Based on the assumption of previous regional hydrogeological mapping (Bradley et al. 1994) that the groundwater in the unconfined surface aquifers of different lithologies is connected, a coarse regional flow field was modelled using 715 bores and a grid cell size of 250 m.

In addition to reviewing the regional scale hydrogeology, data from 34 monitoring bores within the Pittong area were collated from previous hydrogeological investigations. The majority of the bores were constructed as standpipe piezometers by government drillers between 1989 and 1997. Although the monitoring record from these bores is fragmented the data is reliable as they were specifically constructed for the purposes of monitoring standing groundwater levels related to land salinity.

The waterlevel trends in 27 bores (Figure 4.3) have been analysed using HARTT-XLS (v5.0) a tool developed by Ferdowsian et al. (2001) for differentiating between the effect of rainfall fluctuations and underlying groundwater trends in a bore hydrograph. The method uses multiple regression analyses to provide a time trend of groundwater level rise or fall and the lag between rainfall and groundwater level response. For the analysis, monthly rainfall data was extracted from the Bureau of Meteorology Data Drill facility (BoM 2009b) for the period from 1900 to 2009. The bores were selected on the basis of their data integrity, and those bores that had been damaged or had periods during which they were dry were excluded. The majority of the bores have over 15 years of monitoring, mostly sampled regularly at 1 to 3 month intervals. Twenty six bores have gaps of 12 months without monitoring, and 12 bores have gaps of 24 months or more. Average EC was also calculated for each bore with the majority of readings being taken over the past 4 years since regular monitoring has recommenced.

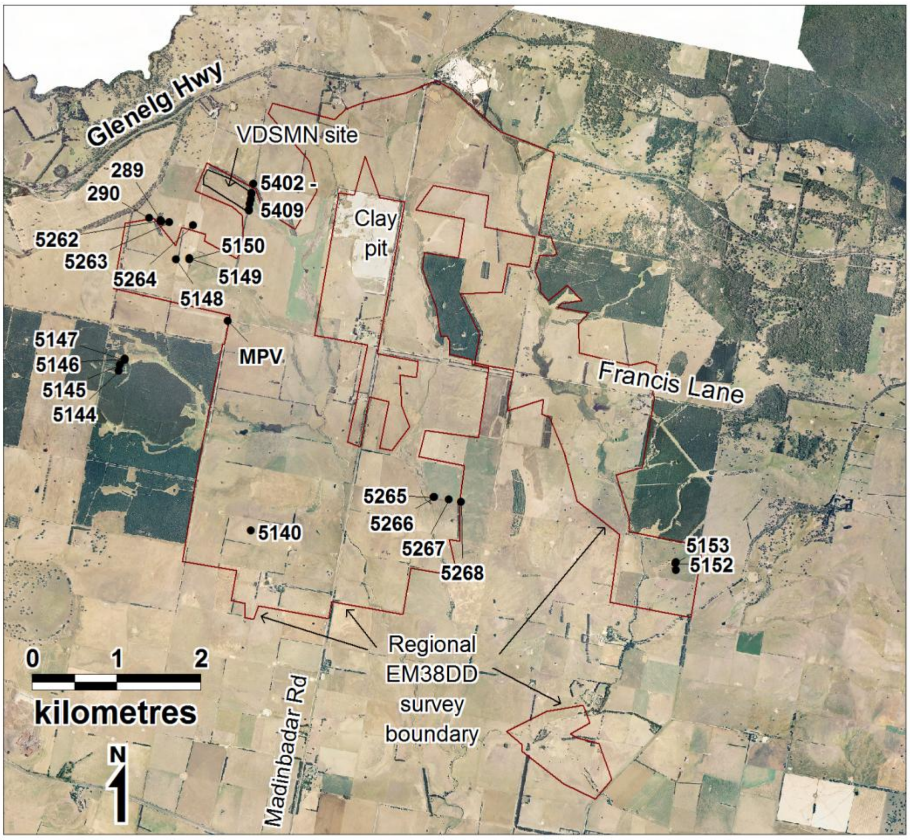

Figure 4.3 Locations of bores and EM surveys on aerial image.

4.5 Results

4.5.1 Land salinisation

The collation and rationalisation of all the previous salinity mapping up to 2006, identified 286.5 ha of land salinity in the Pittong region (Figure 4.4), or 4.5 % of the salinity management target area (6305.5 ha). This compares with 117 ha identified in the first survey in same area in the late 1970's (Duff 1983). Since all previous surveys used similar methods (vegetation indicators and aerial photo interpretation), the majority of the 169.5 ha increase over the past 30 years is considered to represent a genuine expansion of salinised land.

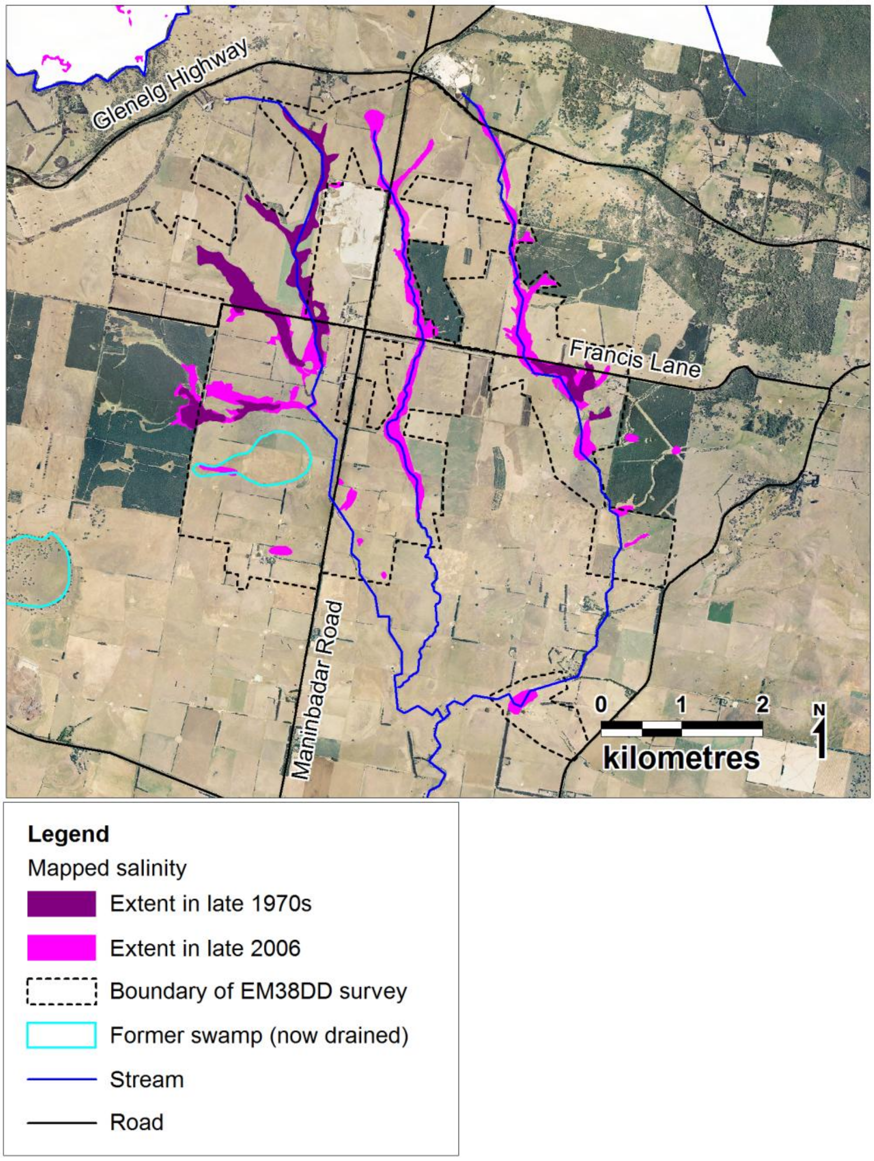

Figure 4.4 Extent of salinity mapped using vegetation indicators and interpretation of aerial photographs.

A more rigorous measurement of trend is that provided by the three surveys at the VDSMN site (Hekmeijer and Clark 2008). When the site was established, the vegetation assessment of the site indicated that 0.515 ha was salinised, with 0.473 ha assessed as Class 1 (low level salinity) and 0.042 ha as Class 2 (moderate salinity) using the method described by Allan (1996). The EM38 surveys of the site show that area of salinity (measured as EC_a > 1 dS/m in 0-60 cm soil depth) increased from 0.79 ha in September 1996 to 1.69 ha in September 2000, then reduced slightly to 1.48 ha in November 2007. In addition, the severity of the salinity has increased over the decade of measurement (Table 4.1; Figure 4.5).

Table 4.1 Summary of the salinity monitoring at the VDSMN site

Salinity (as ECa 0-60 cm)	1996 area (ha)	2000 area (ha)	2007 area (ha)
Medium salinity (ECa 1 - 1.5 dS/m)	0.52	0.97	0.87
High salinity (ECa 1.5 - 2.5 dS/m)	0.27	0.68	0.55
Very high salinity (ECa >2.5 dS/cm)	0	0.04	0.06
Total saline area (ECa >1.0 dS/m)	0.79	1.69	1.48
Total survey area (ha)	12.92	12.90	12.88

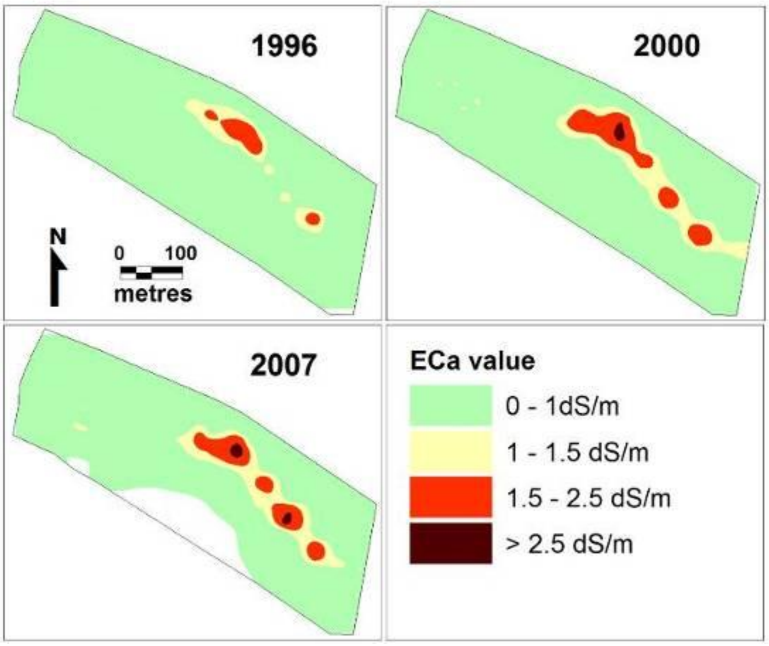

Figure 4.5 Salinity distribution (measured as apparent electrical conductivity ECa) at the VDSMN site.

The regional geophysical survey covered 1890 ha and the predicted EC_e surfaces for each soil depth range are shown in Figure 4.6. Data values ranged from 0 to 50.4 dS/m for the upper soil profile (0 - 0.5 m) and 0 to 38.8 dS/m in the lower soil profile (0.8 - 1.1 m). The mean EC_e in the lower part of the profile (3.8 dS/m) is higher than the upper part of the profile (2.2 dS/m). The area of salinised land with an EC_e classed as moderate or higher in the upper profile is 242.5 ha (Table 4.2), which compares to the 262.0 ha derived from the combined previous salinity mapping in the same area using vegetation indicator species and aerial photograph interpretation. Considering the variations in the salt indicator species over the seasons and years in which the surveys were undertaken and the fact that a few areas were inaccessible to the four-wheeled motorbike, the two methods for assessing the salinised area compare quite well (92.5 %).

Table 4.2 Summary of the salinity mapped by the EM38DD regional survey

ECe	upper profile area (ha)	lower profile area (ha)
Slightly saline (ECe 2 - 4 dS/m)	338.4	597.9
Moderately saline (ECe 4 - 8 dS/m)	170.3	367.0
Very saline (ECe 8 - 16 dS/m)	63.3	137.0
Highly saline (ECe >16 dS/cm)	8.9	42.3
Total saline area (ECe >4 dS/m)	242.5	546.3
Total survey area (ha)	1890	

The areas of highest soil salinity (measured as EC_e) are generally clustered in and adjacent to the main drainage lines. The largest saline area is that associated with a former swamp in the south west sector (Figure 4.4; Figure 4.6), north of Bore 5140 (Figure 4.3), which has been drained. Although the EM38DD survey records high conductivity in these soils of paludal origin, there is very little salinity mapped at the ground surface. The highest EC_e values occur in the broad flat drainage line south of Francis Lane and west of Madinbadar Road (Figure 4.3; Figure 4.6). These alluvial soils have been mapped as highly saline showing salt-encrusted surface soils with patches of halophytic vegetation (i.e. class 4 salinity).

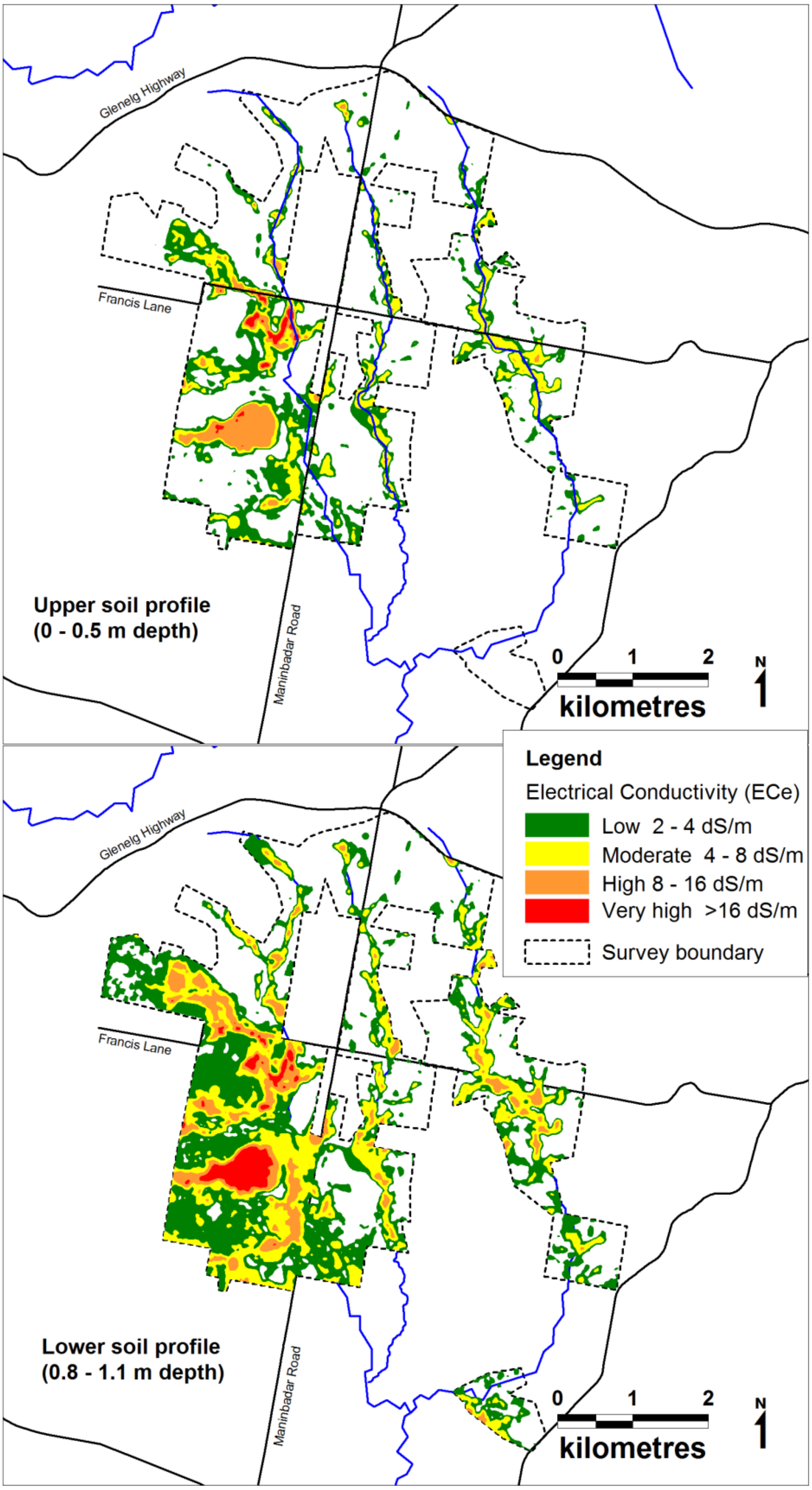

Figure 4.6 Salinity distribution (measured as electrical conductivity ECe) of the upper and lower soil profiles.

4.5.2 Hydrogeology

The analysis of the regional groundwater flow (based on the relative water levels in the 715 bores selected from the government databases) indicates that the overall trend in the regional gradient generally follows the topographic gradient (Figure 4.7a). Groundwater gradients south of the divide between the Murray Darling Drainage Division (north) and the South East Coast Drainage Division (south), trend towards the south west (Figure 4.7b), as do the flows across the Pittong region. This result generally concurs with the Ballarat 1:250,000 scale Murray Darling Basin hydrogeological map sheet (Bradley et al. 1994).

Within the Pittong study area, previous hydrogeological models have been largely based on observations or site investigations at the local scale. Based on research in comparative landscapes in Western Australian by Nulsen (1978), Duff (1983) attributed the salinity at Pittong to local groundwater flows. His model assumed that water entered the regolith higher in the landscape and then moved downslope through a semi-confined aquifer and emerged via preferred pathways to discharge at the surface. Duff noted that the salinity occurred between 290 and 320 m elevation which corresponded to the change in slope where groundwater was assumed closest to the surface. Since the soil salinity values were greatest in the surface soils he concluded that the majority of the salt has accumulated at the surface due to evaporation over the summer period of local saline discharge.

Influenced by the observations of Duff (1983) and the prevailing theories of the time (Dyson 1993), the work by Kevin (1993) for the initial salinity management plan proposed local groundwater flow systems in which the ridges and slopes in the highest elevations were believed to be areas of higher recharge, due to the assumed thin soil cover. Based on their investigations of soil profiles, MacEwan and Dahlhaus (1996) argued that soil hydrology was more influential in soil salinisation than groundwater recharge. They concluded that point discharge of saline groundwater was spread to a much greater area by seasonal interflow through the A_2 (E) soil horizon (Dahlhaus and MacEwan 1997). By contrast, Heislers and Pillai (2000) concluded that saline discharge emanated from several groundwater systems including temporal perched flows, deeper flow cells in the fractured granite, and flow along the weathering zone at the base of the regolith.

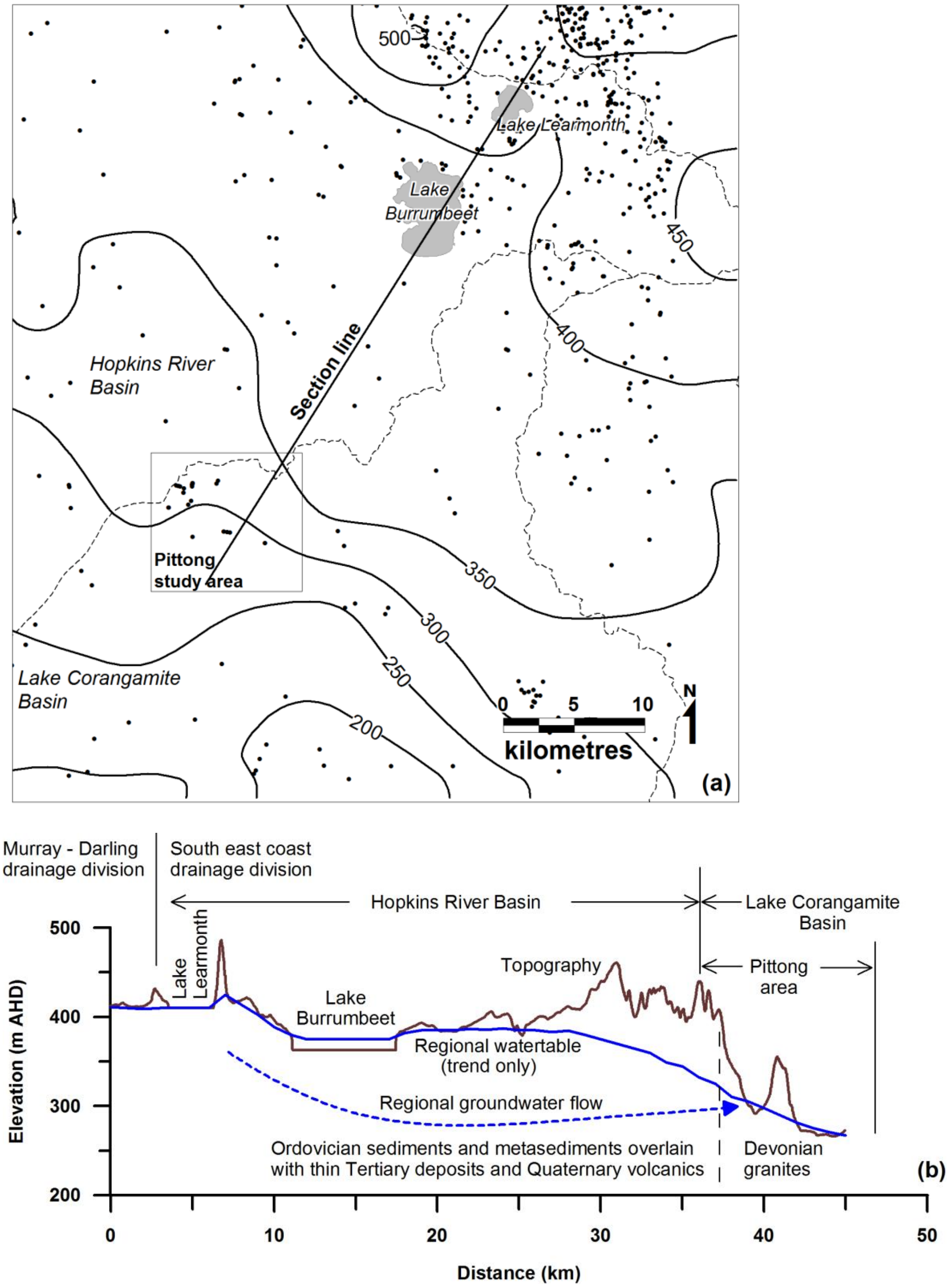

Figure 4.7 Schematic representation of the regional groundwater flow system driving the saline discharge in the Pittong area: (a) regional groundwater contours; and (b) cross section along the line shown in (a), illustrating the regional groundwater flow.

The groundwater bores on which the contours are based are shown by the black dots. Refer to Figure 4.1(a) for detail on the drainage basin boundaries.

Observations by the landholders record that the saline groundwater discharge at springs and seeps has been continuous over the past 30 years. The discharge volumes are variable with no apparent seasonal cycle, and at least two have been observed (by PD) to be flowing (<1 L/min) even during the periods when the rainfall has been very much below average (2003-2008). The majority of discharge appears in the base of drainage lines or on the slopes of the valleys as discrete areas of permanently saturated soil, rather than flowing springs (Figure 4.8). The landholders report that the number of saline discharge seeps has been slowly increasing, with at least five having emerged since 2000 (Figure 4.9).

Figure 4.8 Typical saline seep (from Bore MPV looking SE)

Figure 4.9 Emerging saline seep (about 500m NW of Bore 5140)

The salinity of the spring discharge has been measured at various locations in the landscape and at different times (Conn 1994; Church 2004; Mananis 2006) and is consistently in the range of 10 to 15 dS/m EC. Mananis (2006) measured the salinity of the discharge from a seep in Francis Lane (shown in Figure 4.8) at the end of each month from April to September 2006. Readings averaged 12.4 dS/m with a range from 14.4 dS/m to 8.09 dS/m, the lower reading being attributed to dilution of the discharge with surface water runoff following rainfall.

The permanent saline discharge sites are contrasted with the landholders observations that ephemeral fresh water and brackish water springs appear after periods of prolonged rainfall. These discharge sites appear on the upper slopes of the Pittong landscape and may remain active for up to 3 months, depending on the antecedent rainfall. Their positions are well known by the landholders as they are considered a hazard when moving farm machinery.

By comparison the EC of the groundwater varies considerably (Table 4.3) and does not correlate to elevation or bore depth. The highest EC (16.72 dS/m) is recorded in Bore MPV, a piezometer constructed in 2006 approximately 200 m west of the discharge seep in Francis Lane (Figure 4.8), with the elevation of the screen approximately 6 m lower than the discharge point. The lowest EC (0.54 dS/m) is recorded in Bore 289, a deep piezometer constructed in 1994 higher in the landscape, with the elevation of the screen approximately 2 m higher than the nearest discharge site approximately 700 m downslope to the south east. As a general observation, the EC of groundwater in the bores adjacent to discharge sites is consistently high.

4.5.3 *Groundwater levels*

The HARTT-XLS analysis shows that the majority of waterlevels in the monitoring bores have been falling (Table 4.3), based on the best-fit to the regression models. The overall correlation (measured as R^2) to the fitted regression model is reasonable, with 10 bores >80 % and only 3 bores <60 %. The two deepest bores (289 & 290), located in higher elevations, show steadily declining trends with a high correlation to rainfall trend. The bores in the same transect (5262 - 5264) similarly show a steady decline in watertable (Figure 4.10).

Most of the bores are located in transects associated with a groundwater discharge feature, to monitor the effects of salinity management. Bores 5265 - 5268 monitor the effects of recharge management by way of a tree plantation established on the low central ridge above the site in 1990 (seen on the horizon in Figure 4.8). The two bores in the discharge site (5265 & 5266) show the highest rate of rise and the poorest correlation with rainfall (28 % and 29 %). Bore 5267 situated a little further upslope at the edge of the discharge zone shows similar pattern (Figure 4.11), whereas higher in the landscape bore 5268 shows a slightly declining trend with a stronger correlation to rainfall (80 %). By contrast bores 5144 - 5147 are located in and adjacent to a discharge area which is now surrounded by a Eucalypt plantation established in 2000. These bores show a marked decline in groundwater levels once the plantation became established (Figure 4.12), although this also corresponds to the decline in rainfall.

A tree belt up to 70 m wide and 260 m long was planted on the northern side of the VDSMN site in 1994, and another 20 m wide was established on the southern side in 2007. Despite the measured lowering of watertables at the VDSMN site (bores 5402 - 5409) most bores show an underlying rise in groundwater levels (having taken into account the effect of the decline in rainfall). Two bores show slightly declining trends: one very shallow bore (5405) and one bore approximately 200 m upgradient (north) of the discharge site and on the northern edge of the tree belt. The underlying rising trend accounts for the expansion in the saline area since 1996, although in the past five years there has been a measured decline in watertable of around 1-2 m which may have stabilised the expansion (Table 4.1; Table 4.3).

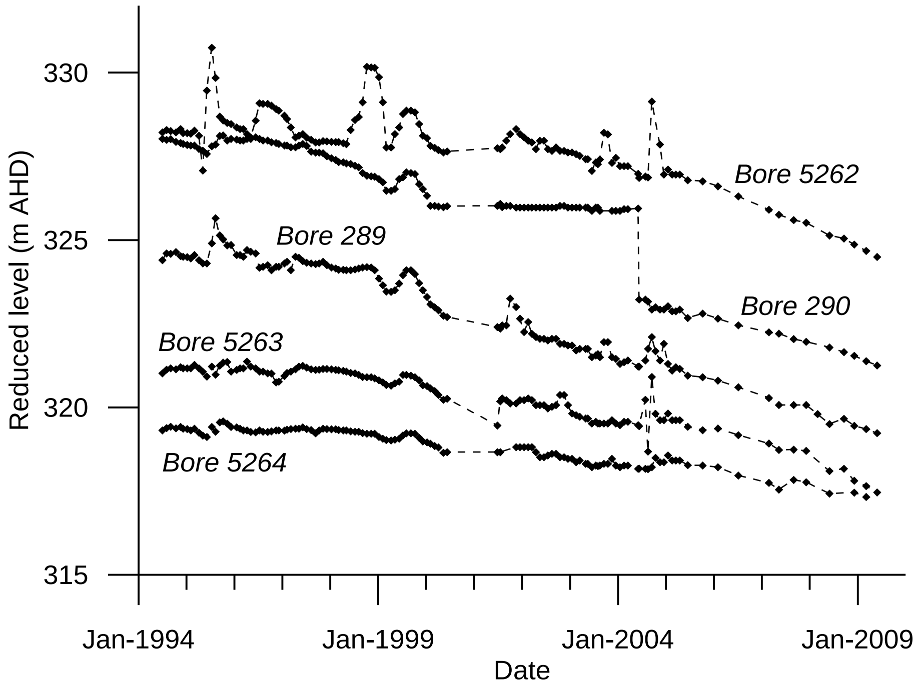

Figure 4.10 Bore hydrographs in the upper catchment area

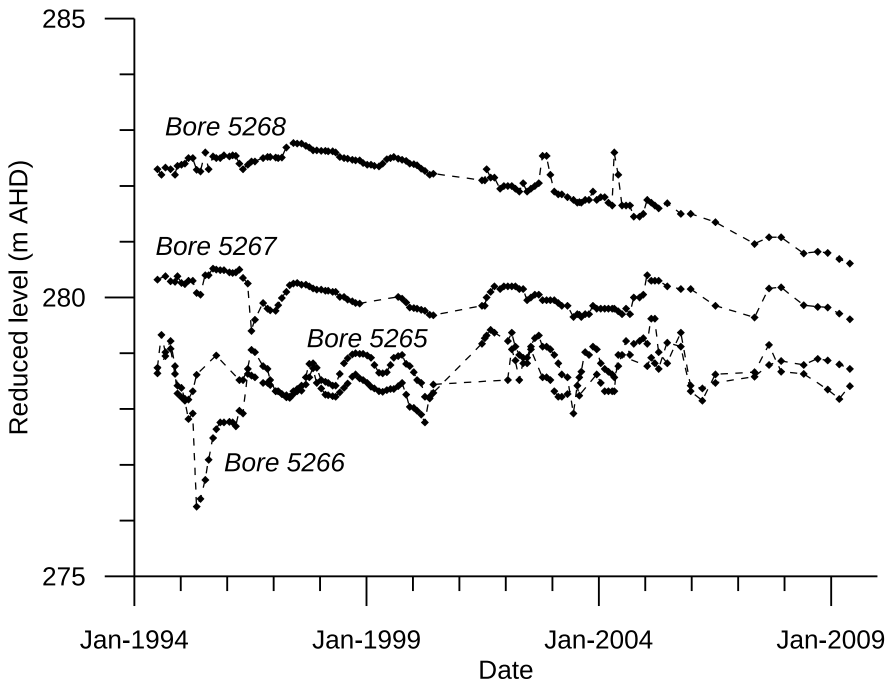

Figure 4.11 Bore hydrographs in the central area

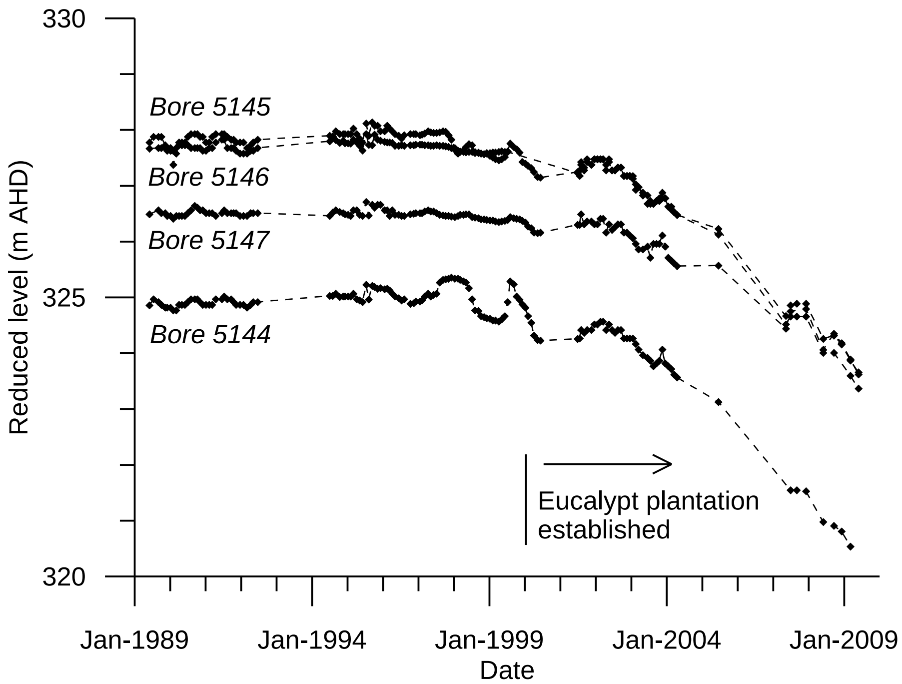

Figure 4.12 Bore hydrographs in the plantation

Table 4.3 Bore details and HARTT-XLS analyses of hydrographs.

Bore identifier	Total depth (m)	Screen elevation (m AHD)	Average EC (dS/m)	Monitoring record				Depth to watertable (m)		HARTT analysis (best fit)		
				from	to	period (years)	readings (no.)	initial	final	Delay (months)	Correlation (R^2)	Rate of rise (m/yr)
289	31.8	309.3	0.54	Jul 1994	May 2009	15	131	-15.65	-20.82	34	0.9737	-0.293
290	34.0	319.1	2.7	Jul 1994	May 2009	15	129	-24.11	-30.88	60	0.8912	-0.418
5140	17.4	284.0	3.21	Jun 1989	May 2009	19	131	-5.38	-6.99	3	0.7706	-0.118
5144	16.3	319.5	6.65	Jun 1989	May 2009	20	149	-9.99	-14.31	17	0.7572	-0.050
5145	16.6	314.6	6.48	Jun 1989	May 2009	20	150	-2.43	-6.84	0	0.8034	-0.017
5146	17.5	309.6	6.57	Jun 1989	May 2009	20	139	-1.6	-2.41	0	0.7984	-0.016
5147	7.5	319.6	6.74	Jun 1989	May 2009	20	149	-0.39	-2.48	0	0.7645	-0.011
5148	17.4	300.9	3.52	Jun 1989	May 2009	20	155	-4.11	-6.34	1	0.8141	-0.015
5149	17.0	295.7	4.74	Jun 1989	May 2009	20	159	-0.34	-2.34	0	0.8101	-0.026
5150	7.3	305.0	10.1	Jun 1989	May 2009	20	148	-0.52	-2.68	0	0.6633	-0.031
5152	16.1	269.5	9.3	Jun 1989	May 2009	20	130	+0.32	-1.95	0	0.7863	-0.053
5153	4.9	280.6	10.2	Jun 1989	May 2009	20	118	+0.22	-2.06	0	0.7919	-0.053
5262	17.7	324.7	3.32	Jul 1994	May 2009	15	130	-13.14	-16.86	30	0.6507	-0.082
5263	17.3	316.9	10.95	Jul 1994	May 2009	15	131	-12.15	-15.71	30	0.8918	-0.148
5264	11.8	310.4	6.72	Jul 1994	May 2009	15	128	1.92	-3.99	1	0.9208	-0.092
5265	11.5	269.0	11.81	Jul 1994	May 2009	15	132	-0.85	-1.08	0	0.2912	+0.252
5266	4.5	276.1	11.84	Jul 1994	May 2009	15	132	-0.81	-0.83	0	0.2785	+0.173
5267	8.6	277.4	11.3	Jul 1994	May 2009	15	122	-4.7	-5.41	1	0.3610	+0.061
5268	19.1	274.9	11.32	Jul 1994	May 2009	15	131	-10.7	-12.39	30	0.8023	-0.052
5402	14.7	294.5	11.26	Apr 1997	May 2009	12	94	-0.30	-1.92	0	0.7643	+0.103
5403	6.8	302.8	13.22	Apr 1997	May 2009	12	94	-0.09	-2.41	0	0.8179	+0.127
5404	10.0	302.5	12.01	Apr 1997	May 2009	12	95	-0.10	-2.82	0	0.7782	+0.039
5405	2.5	310.6	12.3	Apr 1997	Aug 2007	10	73	-0.82	-1.68	0	0.6286	-0.004
5406	6.6	302.7	11.34	Apr 1997	May 2009	12	83	-1.14	-2.8	0	0.7447	+0.141
5407	11.3	299.7	8.47	Apr 1997	May 2009	12	85	-2.79	-5.62	0	0.9157	+0.030
5409	11.5	308.6	-	Nov 2001	Feb 2007	6	34	-3.06	-4.26	0	0.7488	-0.075
MPV	18.3	288.2	16.72	Dec 2006	May 2009	3	7	-6.71	-6.61	1	0.7324	+0.247

4.6 Discussion

Taken in the broad context, the impact of the past 20 years of salinity management in the Pittong area presents an apparent paradox. The declining trend in groundwater levels in most monitoring bores has been consistent for the past 15 to 20 years (Table 4.3). Yet the salinity mapping, observations of the landholders, and the measurements at the VDSMN site during the same period (Table 4.1), indicate that the area of salinised land has been expanding. Additionally, when considered on a site-by-site basis, inconsistencies in the effect of the management emerge.

The expansion of salinity at the VDSMN site is consistent with the underlying rising trend in groundwater levels as indicated by the HARTT analysis of the bores at that site (5402 - 5409 in Table 4.3), which persisted despite a tree-belt established immediately upgradient of the site in 1994 (Figure 4.13). Similarly the plantation established in 1990 on the ridge-top approximately 1 km upslope of Bores 5265 - 5267 has had no discernable effect on waterlevels to date. The HARTT analysis indicates that the measured decline in groundwater (at both sites) correlates to the reduced rainfall but the underlying trend is rising groundwater. Yet areas in which little or no salinity management has been implemented show consistent decline in groundwater levels, even after the effect of rainfall has been taken into account (e.g. Bores 289 & 290; 5140; 5148-5150; 5262-5264 in Table 4.3; and Figure 4.10). The only apparent success has been in the lowering of groundwater levels in the large plantation established in 2000 (Figure 4.12).

Figure 4.13 Tree belt along the northern boundary of the VDSMN site (which is on right side of photo).

These inconsistencies may be partially explained by the observation that the saline discharge may be from the regional groundwater flow system, rather than a local system. All of the mapped salinity is located within the boundaries of the Mount Bute Granite and Illoura Granodiorite plutons. In addition, the northerly extent of the mapped salinity, as determined by the EM38DD survey and the on-ground vegetation mapping, is coincident with the boundary of the Mt Bute granite, as determined by the geological mapping, the kaolin exploration drilling records and the interpretation of the airborne magnetic surveys. This observation suggests that the regional flow through the Palaeozoic sedimentary rocks is obstructed by the granite pluton, forcing some of the groundwater to discharge at the surface.

A closer examination of the EM38DD data shows that the highest EC_e values in both the upper and lower soil profile are clustered into discrete areas, many of which correlate to the landholders' observations of permanent saline seeps. A cross-section taken along the main creek line through the western portion of the area, illustrates this correlation (Figure 4.14). The general; association of the saline groundwater discharge seeps with the geological boundaries and the drainage lines suggests that the discharge is controlled by the underlying geological structures in the granite. This accords with observations in similar deeply weathered landscapes developed on igneous rocks in Western Australia (Engel et al. 1987; Lewis 1991; Salama et al. 1993; Clarke et al. 1998a; 1998b) and Victoria (Fawcett 2004).

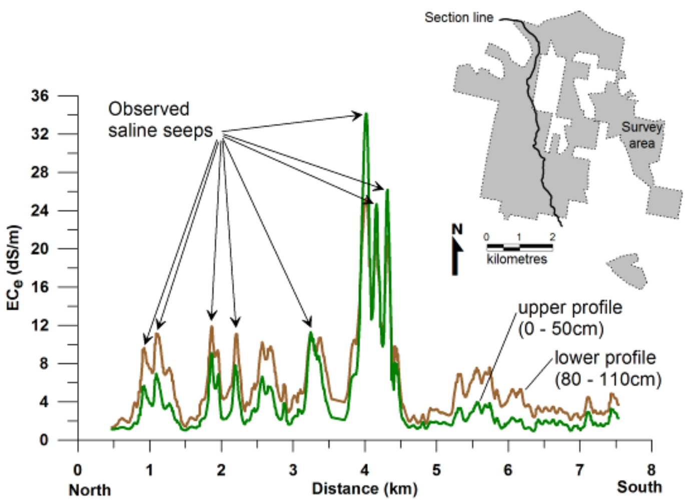

Figure 4.14 ECe profiles along the main creek line through the western portion of the area.

Further evidence implicating regional groundwater is provided by the spatial variation in the EC of the groundwater. The two sites where the underlying trend in groundwater levels is rising (i.e. the VDSMN site: bores 5402 - 5409; and the discharge site in the central area: bores 5265-5267) have high EC values, similar in magnitude to those measured at the discharge seeps. High EC values are also observed in bore MPV adjacent to the discharge seep in Francis Lane, and in bores 5152 and 5153 adjacent to a discharge site on the eastern side of the Pittong area. The anomalous EC of bores 5150 (10.1 dS/m) and 5263 (10.95 dS/m) compared to those around them may be due to the screen intersecting a discontinuity carrying regional flow. By comparison the bores showing an underlying falling trend in groundwater levels generally have lower EC groundwater (Figure 4.15).

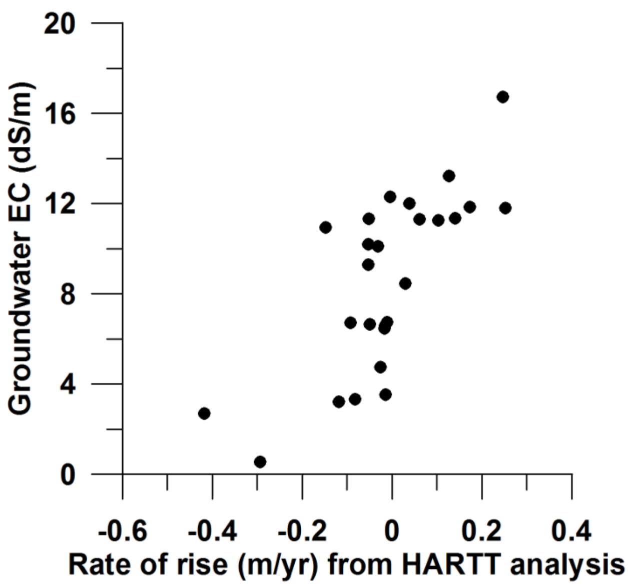

Figure 4.15 Groundwater EC and rate of rise

The cause of the underlying decline in groundwater levels in areas where little or no salinity management has been implemented remains a conundrum. From the general association with lower EC groundwater, it is speculated that these bores monitor the groundwater mainly associated with the local groundwater flow system. The falling trends must be a response to a hydrologic change perhaps associated with the salinity management or changes to agricultural systems, but the exact cause remains obscure.

4.7 Conclusions

At the time of the development of the initial salinity management plan (Nicholson et al. 1992b), the conceptual model of salinity processes was based on rising watertables following the clearing of native vegetation on a local groundwater flow system (Kevin 1993). To mitigate the expansion of salinity, the establishment of tree plantations was recommended at the higher elevations to control recharge and restore hydrogeologic equilibrium, with the salinity mapped by Duff (1983) as the basis for targeting on-ground actions (Nicholson et al. 1992a).

The impact of 20 years of salinity management is contradictory to the initial theory, with an overall increase in land salinity despite generally falling groundwater levels. However a closer examination of all the evidence suggests that point-discharge from the regional groundwater flow system is a more likely influence in the expansion of salinity than the discharge from the local groundwater system. Although this model has yet to be proven, it provides a logical explanation for the expansion of salinity while the local groundwater tables fall.

The implications of this model are that there are no practical means to influence the regional groundwater discharging from the seeps at the local scale. The remaining means to control salinity are to limit its spread and minimise the export of the salt away from the point-discharge seeps. Hence there has been a shift from recharge management to discharge management over the past two years, in an effort to mitigate the spread of soil and water salinisation. Although the early results are encouraging, they are masked by the current drier climate.

This assessment of the past 20 years of salinity management at Pittong adds to the growing evidence that rising groundwater as the single cause of salinity is a simplistic generic model that does not account for all situations (e.g. Dahlhaus et al. 2000; Acworth and Jankowski 2001; Rengasamy 2002; Fawcett 2004; Wagner 2005; Bann and Field 2006; 2007; Dahlhaus et al. 2008a).

4.8 Acknowledgements

Funding for this research has been provided by the Woady Yaloak Catchment Group, the Corangamite Catchment Management Authority, University of Ballarat, and the Department of Primary Industries. The landholders of the Pittong region are thanked for their assistance and access to their properties, in particular Kevin Knight, Alice Knight, and Rod and Victoria Kennedy. Cam Nicholson and Jen Clarke, coordinators of the Woady Yaloak Catchment Group, provided assistance in facilitating the field work. Colin Bullen, Imerys Minerals Australia, provided access to mineral exploration data. Martin and Jo Peters, Farmworks Pty Ltd. undertook the topographical and geophysical surveying.