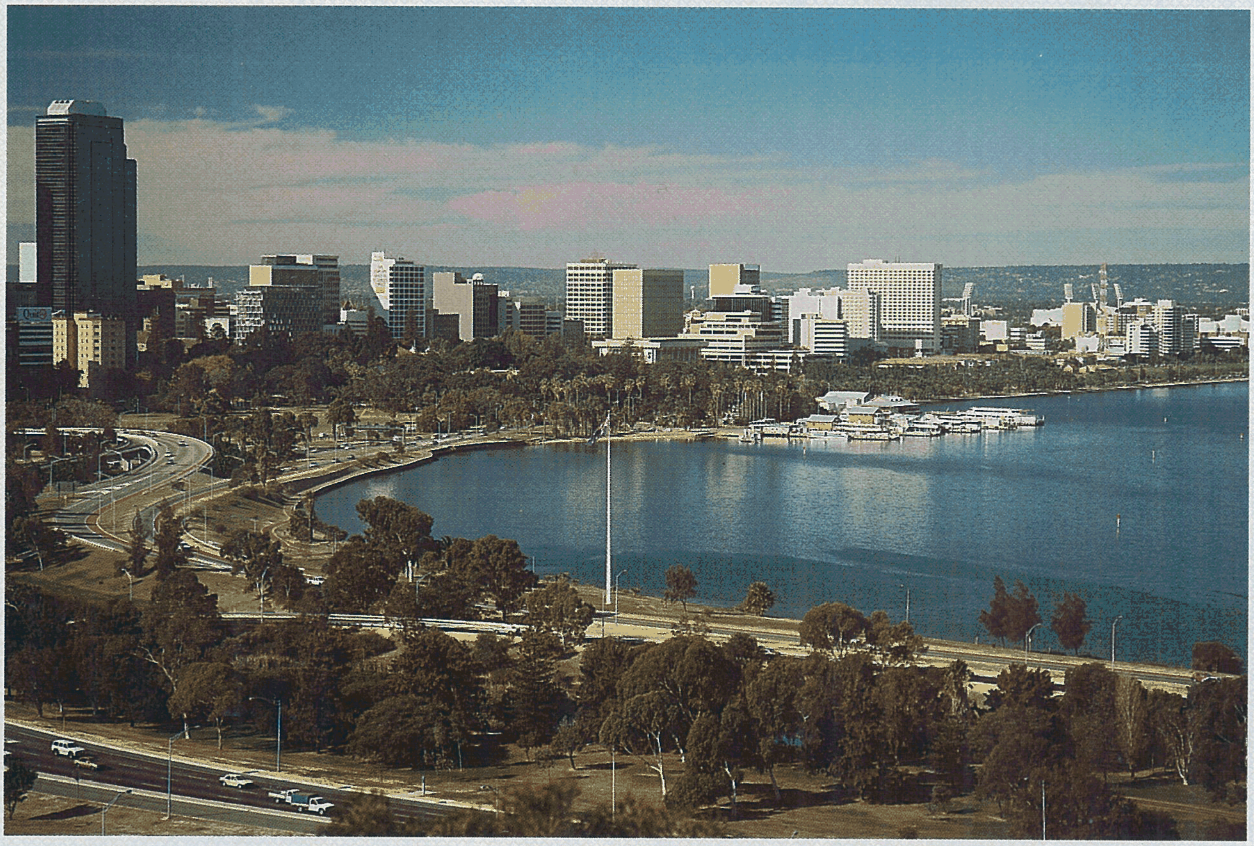
BULLETIN 142

HYDROGEOLOGY AND GROUNDWATER RESOURCES OF THE PERTH REGION WESTERN AUSTRALIA

by W.A. DAVIDSON



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

HYDROGEOLOGY AND GROUNDWATER RESOURCES OF THE PERTH REGION, WESTERN AUSTRALIA

Cover photograph:
View to the east from Kings Park over the Swan River foreshore to the city of Perth. In the distance (about 15 km) is the Darling Scarp, where the land rises abruptly some 200 m above the coastal plain.

FRONTISPIECE

Drilling Wanneroo production bore W257, June 1988 — deepest water production bore in the Perth Region. Total depth drilled 1108 m, screened interval 978–1082 m, screen diameter 203 mm ID, duty pumping rate 10 000 m^3/d (100 000 imperial gallons per hour) steady-state drawdown 50 m, water salinity 177 mg/L TDS.

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W. A. Davidson

Perth 1995

MINISTER FOR MINES
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Contents

Introduction

Geology

Hydrogeology

Groundwater resources

Groundwater management

Plates

Figures

Tables

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Hydrogeology and groundwater resources of the Perth Region, Western Australia

by

W. A. Davidson

Abstract

The Perth Region covers an area of about 4000 km^2 and is underlain by more than 10 000 m of sedimentary rocks of the Perth Basin. Groundwater in the Cainozoic and Mesozoic succession, to a depth of about 1100 m, is currently being exploited to provide about 40% of the scheme water to the region. The remainder of the scheme water is obtained from surfacewater catchments to the east of the region. As urban development continues to expand and as the surfacewater catchments become fully utilized, Perth will become more dependent on groundwater. Groundwater is, therefore, becoming increasingly important to Perth, and Government policies on sustainable abstraction and quality protection have been implemented to prevent gradual depletion and deterioration of the groundwater resources.

Perth has a variety of naturally occurring environmental ecosystems that are also dependent on groundwater for their healthy maintenance. Many areas of native vegetation and wetlands rely on shallow depth to groundwater for survival and this has placed severe limitations on the location of production bores and on the use of groundwater for urban, industrial, agricultural and recreational purposes.

Important to groundwater resource assessment and management is a thorough understanding of the hydrogeology of the resource region. To this end, the groundwater resources of the Perth Region have been systematically investigated by drilling since 1961. This Bulletin is a synthesis of the data collected during these investigations. It establishes the geological framework, delineates the hydrogeological boundaries and quantifies the groundwater resources of the region. Under present landuse conditions, and from flownet and water-balance analyses, the maximum projected total and sustainable groundwater abstraction from the unconfined and confined aquifers of the Perth Region would be about 500 x 10^6 m^3/year. However, with further urban development and increased groundwater recharge from stormwater catchments, this value may be raised to about 600 x 10^6 m^3/year. Current rates of abstraction (about 300 x 10^6 m^3/year) are therefore well within sustainable limits and the potential exists for significant additional abstraction.

Keywords: Perth Basin, Perth Region, stratigraphy, aquifers, groundwater resources, groundwater quality, groundwater management, water balance

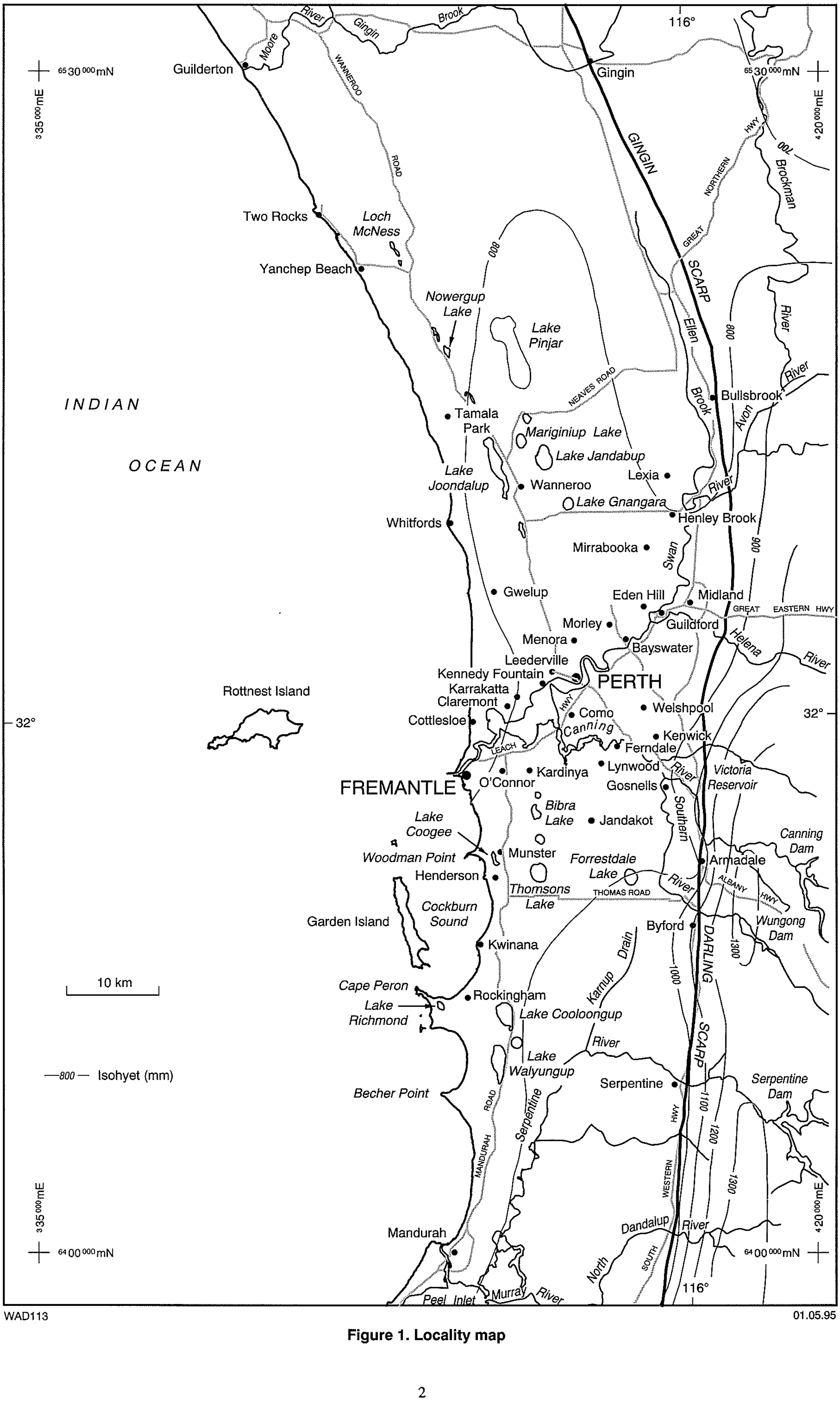

Figure 1. Locality map

Introduction

'Supply of fresh water from springs and lagoons is abundant .... on the whole it may confidently be assumed that water is plentiful all over this territory.'

These words, written by Captain James Stirling in his report of 1827 (Hunt, 1980), describe the initial sanguine expectation of the available water resources for the future settlement of Perth. However, even Captain Stirling could not have appreciated the prophetic accuracy of this statement. Subsequent exploration for groundwater in the Perth Region, from the first day of settlement in 1829 to the present, has confirmed the veracity of Stirling's statement, and has revealed the extent and the enormous renewable volume of the resource. This Bulletin demonstrates that the quantity and quality of the groundwater beneath the Perth Region is sufficient for the developing urban areas and suitable for the environment to well beyond the 21st century.

From the outset, the availability of shallow groundwater has been essential to the growth of the settlement. As the population grew and urban development expanded, this groundwater, with the watertable only a few metres below ground level, became increasingly exploited and many private and public wells were sunk, particularly in low-lying areas. In Perth, natural springs (Spring Street, Mill Street and Kennedy Fountain) provided ready access to groundwater; in Fremantle, galleries were tunnelled into the coastal limestone for water supply. Kennedy Fountain, erected by Governor A. E. Kennedy in 1861, was the first public water-supply fountain established for Perth and is still in operation. Both prior to and since European settlement, water supplies have certainly been abundant and good quality groundwater has always been available and vital for the continuing growth and development of the Perth Region (Fig. 1). However, inadequate knowledge about water-borne diseases and poor groundwater-quality management resulted in contamination of the groundwater from the many cesspits constructed for sewage disposal beneath the settlement. Such was the pollution that typhoid became endemic and deaths peaked at 134 in 1897 (Hunt, 1980).

The notion and reality that all shallow groundwater within the vicinity of the developing settlement was putrid and contaminated beyond safe human consumption led to a desire to obtain deeper artesian groundwater. The first artesian bore was drilled at Gosnells in 1870 (Hunt, 1980); however, this was sunk to search for gold and not evaluated for water supply. At about the same time (1871), a bore was drilled near the upper Canning Bridge to search for coal (Passmore, 1912). This bore intersected an artesian flow but, because the water was saline, it also was never evaluated for water supply and thus soon forgotten. A bore drilled in the Perth railway yards (Pound bore) between 1880 and 1881 was, however, moderately successful and it was used to supplement the reticulation of Perth in 1891. A second bore was completed in 1897 (West Perth Station Yard bore) and also used for public water supply.

These first attempts at securing a permanent and useable groundwater supply did little to satisfy the growing demands for water. So intolerable were the water supply and drainage problems that Victoria Reservoir was constructed and commissioned for use in 1891. The success of Victoria Reservoir led to the misconception that surface-water catchments were the only reliable means of obtaining the required water supplies. This view continued well into the twentieth century with the construction of the major water storages in the hills. However, within a short period of time and around the turn of the century, the Victoria Reservoir became contaminated from cattle grazing within the catchment area and refuse from residents of timber mills. This led to further attempts to develop artesian borewater supplies and numerous successful bores were drilled in the Guildford area and nearer Perth. As a result of this drilling, Perth was mostly supplied with uncontaminated groundwater until the construction of the Canning Dam in 1940.

As the population of the area continued to grow and the urban sprawl extended to the north and south of Perth, the need to develop groundwater for the metropolitan water supply increased. Detailed and comprehensive drilling programs carried out by the Department of Mines (now the Department of Minerals and Energy), under the supervision of the Geological Survey of Western Australia (Geological Survey), to investigate and evaluate the groundwater resources of the deep confined (artesian) aquifers commenced in 1961, and those of the shallow unconfined aquifers commenced in 1962. With the technical advice and hydrogeological expertise of the Geological Survey, these investigations have been continued to the present by the Metropolitan Water Supply, Sewerage and Drainage Board and its successors, Metropolitan Water Authority and the Water Authority of Western Australia (Water Authority). The knowledge of the groundwater systems gained from this drilling has been essential to the development and management of the groundwater resources, particularly with respect to environmental considerations. As a result of these investigation programs, Perth is now supplied with high quality groundwater, free of contamination, unlike the polluted water supplies experienced during early settlement of the city.

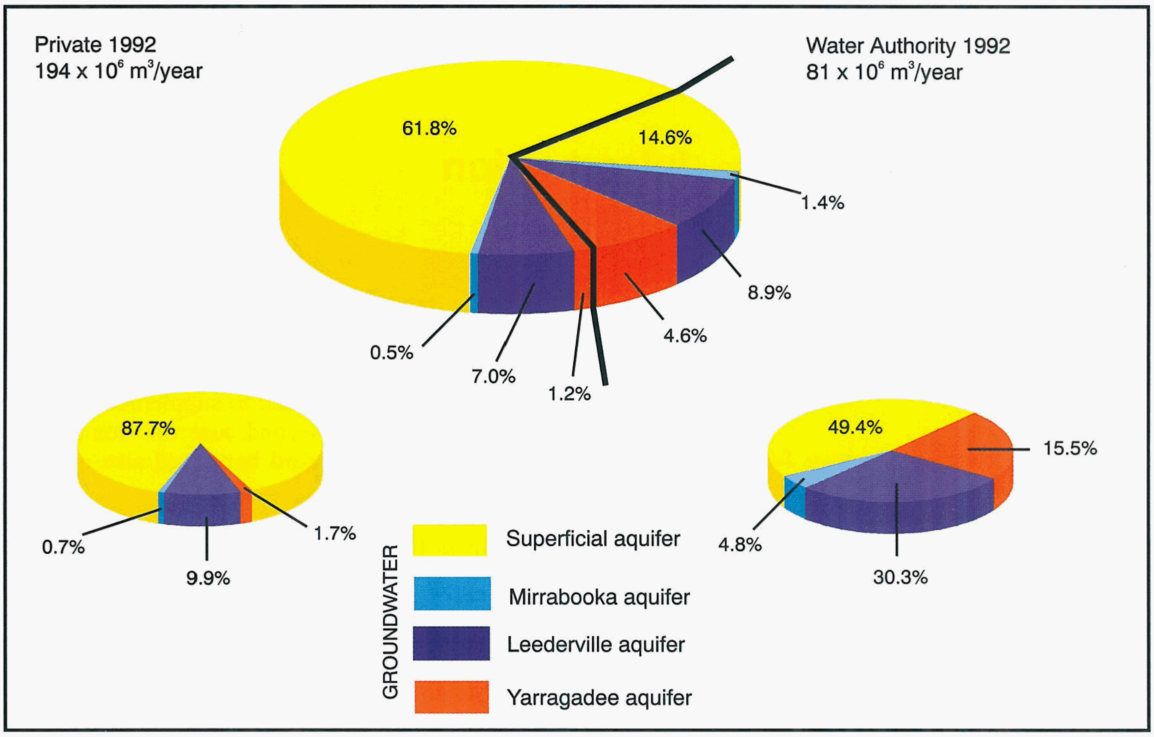

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Figure 2. Groundwater consumption in the Perth Region, 1992

During the 12 month period July 1991 to June 1992, total water usage in the Perth Region was about 406 x 10^6 m^3, of which 68% (275 x 10^6 m^3) was obtained from groundwater. Of the total groundwater usage, 29% (81 x 10^6 m^3) was reticulated by the Water Authority for public water supply and 71% (194 x 10^6 m^3) was privately utilized by Local Government, industry, agriculture and the general public (Fig. 2). Of the groundwater allocated for public water supply, 49% (40 x 10^6 m^3) was obtained from the unconfined superficial aquifer, 5% (4 x 10^6 m^3) from the semi-confined Mirrabooka aquifer, 30% (24 x 10^6 m^3) from the shallow confined Leederville aquifer and 16% (13 x 10^6 m^3) from the deep confined Yarragadee aquifer (Water Authority, 1992a).

Purpose and scope

There is a very large and renewable groundwater resource within the Perth Region and, although groundwater has become increasingly important as a water supply to metropolitan Perth, there has been no consolidated description or analysis of the drilling results. This is needed in order to provide an understanding of the hydrogeological basis for development, management and protection of the groundwater resources, and also for protection of those ecosystems that depend on groundwater. A detailed description of the hydrogeology for future computer modelling is also required.

To assist in the management of groundwater resources in a climate of ever-increasing demand, this Bulletin synthesizes the drilling data, defines the geology and hydrogeology of the Perth Region and, in particular, describes the occurrence of the groundwater resources and gives estimates of groundwater recharge, throughflow, discharge and storage. This work builds on numerous earlier publications and includes many new geological and hydrogeological data. The plates provide a comprehensive dataset showing the distribution and structure of the major geological formations, and the hydrogeological features of each of the major aquifers.

Because groundwater is of vital importance to humanity, industry and the environment, this Bulletin aims to provide the hydrogeological basis for management and protection of the groundwater resources. It will also provide the hydrogeological framework for future computer-aided groundwater modelling. The descriptive information relates to the onshore Perth Basin; however, where relevant, the extension of aquifers offshore and effects of seawater intrusion are described. Management of the groundwater resources is discussed in relation to current responsibilities and management practices.

Location

The Perth Region includes most of the Perth metropolitan area and is bounded approximately by Gingin Brook to the north, the South Dandalup River to the south, the Darling Scarp to the east and the Indian Ocean to the west (Fig. 1). The area lies almost entirely within the Swan Coastal Plain except for the northeastern part which includes a small portion of the Dandaragan Plateau. The region covers an area of about 4000 km^2 (approximately 2600 km^2 lies to the north of Perth City and 1400 km^2 to the south) and extends from Perth some 80 km to Guilderton on the north coast, and 70 km south to Mandurah.

Physiography and landuse

Climate

The climate of the Perth Region is Mediterranean in type with hot, dry summers and mild, wet winters. The hot, dry summers are caused by a belt of anticyclones (zones of high pressure) that passes over the region between October and March. Little rainfall is associated with the anticyclones because the air descending within these high pressure zones becomes warmer and has a greater capacity to retain moisture. Such weather conditions are usually accompanied by clear skies and high levels of ultraviolet radiation. During the cool winter months, rainfall results from subpolar, low-pressure cells that cross the region as cold fronts and are usually accompanied by strong winds and cloudy skies.

The average annual rainfall ranges from about 700 mm in the northern coastal area to about 1300 mm on the Darling Plateau southeast of Perth (Fig. 1). Approximately 90% of the rain falls between April and October and the remaining months are characteristically hot and dry, resulting in large evaporation losses from wetlands. The average annual potential evaporation is about 1800 mm, or equivalent to about twice the average annual rainfall, and is exceeded by rainfall only during the months of May through to, and including, August. The mean maximum temperature ranges between 17 and 30°C with the hottest months being January and February. The mean minimum temperature ranges between 9 and 18°C with the coldest months being July and August (Table 1).

Rainfall records for the Perth Region between 1876 and 1990 show a rising trend to the 1930s and a decline thereafter, with rainfall in the 1970s and 1980s being below average (Fig. 3). Figure 3 also depicts short-term cycles, during which the annual rainfall is mostly above or mostly below the long-term average for several successive years. The decreasing trend in average rainfall currently being experienced is probably, therefore, part of a longer cycle which should show an increasing trend in the future.

Geomorphology

In the Perth Region, the Swan Coastal Plain is about 34 km wide in the north, 23 km in the south, and is bounded to the east by the Gingin and Darling Scarps which rise steeply to more than 200 m above sea level. The scarps represent the eastern boundary of marine erosion, which occurred during the Tertiary and Quaternary periods; at many localities the Darling Scarp is a fault scarp. The Swan Coastal Plain consists of a series of distinct landforms (McArthur and Bettenay, 1960), roughly parallel to the coast (Fig. 4). The most easterly landform comprises the colluvial slopes which form the foothills of the Darling and Dandaragan Plateaus and which represent dissected remnants of a sand-covered, wave-cut platform known as the Ridge Hill Shelf. To the west of the colluvial slopes lies the Pinjarra Plain, a piedmont and valley-flat alluvial plain consisting predominantly of clayey alluvium that has been transported by rivers and streams from the Darling and Dandaragan Plateaus. The plain is generally about 5 km wide west of the colluvial slopes, but along the Serpentine River it is about 15 km wide in an east–west direction.

To the west of the Pinjarra Plain, the Bassendean Dune System forms a gently undulating eolian sand plain about 20 km wide with the dunes to the north of Perth generally having greater topographic relief than those to the south. The dunes probably accumulated as shoreline deposits and

Table 1. Climatic data for Perth area

	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*Annual average*
Mean monthly and annual rainfall (mm) and raindays													
Rainfall	9	13	19	46	123	182	173	135	80	55	22	14	869
Raindays	3	3	4	8	14	17	18	17	14	11	6	4	
Mean daily temperatures (°C)													
Mean temperature	24	24	23	20	17	14	13	14	15	17	20	22	
Mean maximum	30	30	28	25	21	18	17	18	20	21	25	27	
Mean minimum	18	18	17	14	12	10	9	9	10	12	14	16	
Mean monthly relative humidity (%)													
0900 hours	50	52	56	64	72	78	78	74	68	60	54	51	
1500 hours	41	40	42	48	53	60	59	56	53	50	46	44	
Mean daily pan evaporation (mm)													
Mean daily evaporation	8	8	6	4	3	2	2	3	4	5	6	8	1 805
Highest mean daily reading	10	12	9	5	4	3	3	3	4	7	8	9	
Lowest mean daily reading	6	6	5	3	2	1	2	2	3	4	5	6	

Source: Bureau of Meteorology
Station: Perth Regional Office, Wellington Street

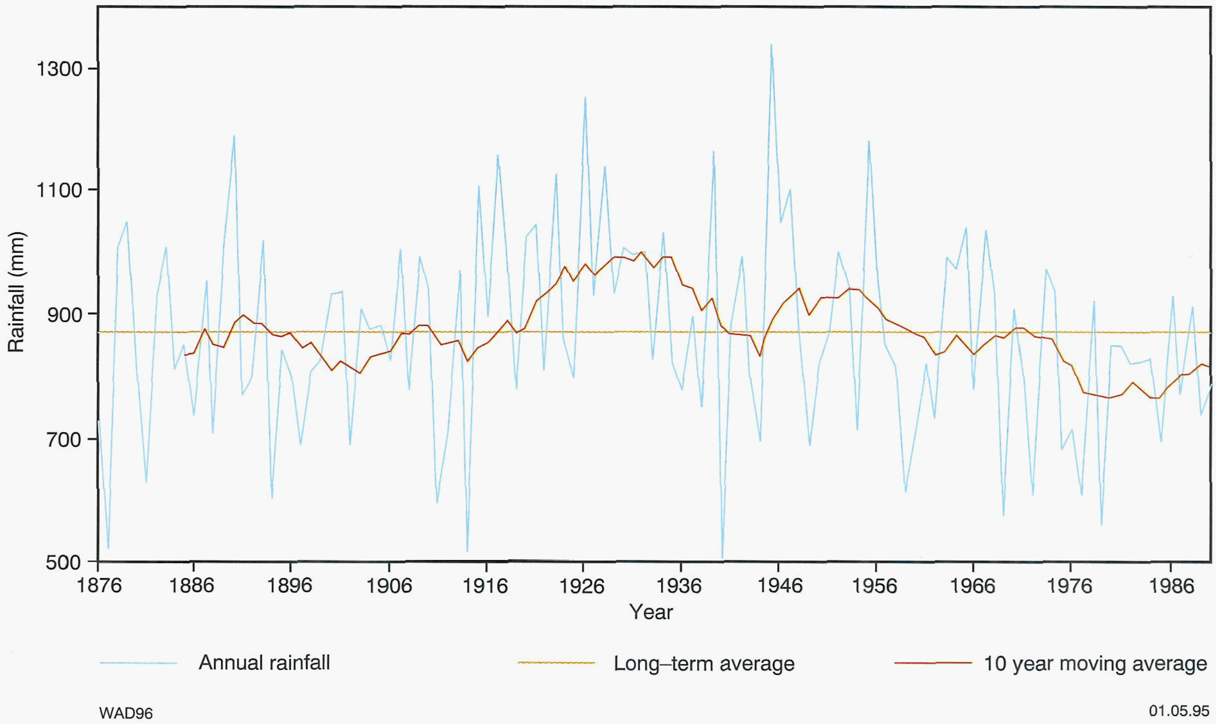

Figure 3. Perth rainfall

coastal dunes during interglacial periods of high sea level and originally consisted of mostly lime sand with quartz sand and minor fine-grained, black, heavy-mineral concentrations. Apart from a small local area to the south of Perth, the carbonate material has been completely leached leaving dunes consisting entirely of quartz sand.

West of the Bassendean Dune System are two systems of dunes which fringe the coastline. The most easterly of these is the Spearwood Dune System, which consists of slightly calcareous eolian sand remnant from leaching of the underlying limestone. The most westerly dune system, which flanks the ocean, is the Quindalup Dune System consisting of wind-blown lime and quartz beach sand forming dunes or ridges which are generally oriented parallel to the present coast, but which may also occupy blowouts within the Spearwood Dune System.

The rivers that cross the coastal plain are flanked by clayey flood plains and river terraces of recent origin. Other wetlands, consisting of swamps and lakes, have formed in the interdunal swales of the Bassendean Dune System, in the interbarrier depressions between the Spearwood Dune and Bassendean Dune Systems, and within the Spearwood Dune System.

South of Perth, the coastal plain has an average elevation of about 25 m Australian Height Datum (AHD), with a maximum of about 75 m. To the north of Perth, the plain rises gradually from the coast to about 100 m AHD (Fig. 5) but is generally more undulating along the coastal strip of the Quindalup Dune and Spearwood Dune Systems than in the central and eastern areas.

Wetlands

Wetlands of the Perth Region have been defined as *'areas of seasonally, intermittently or permanently waterlogged soils or inundated land, whether natural or otherwise, fresh or saline, e.g. waterlogged soils, ponds, billabongs, lakes, swamps, tidal flats, estuaries, rivers and their tributaries'* (Wetlands Advisory Committee, 1977). From this definition, eleven wetland types have been recognized (Table 2).

Drainages

Six major drainages cross the area (Fig. 1). From north to south they are Gingin Brook, Swan River, Canning River, Serpentine River, North Dandalup River and South Dandalup River. Except for Gingin Brook, which rises on the Dandaragan Plateau, each has its headwaters on the Darling Plateau. Runoff resulting from rainfall on the plateaus and areas adjacent to the rivers on the coastal plain, together with groundwater discharge, contributes to flow within the rivers. The major tributaries, Ellen Brook, Helena River and Southern River, also carry runoff from the Darling Plateau although Ellen Brook and Southern River carry mainly groundwater discharge as base flow.

Most of the major drainages are perennial and have greater flows during the rainy winter months than during summer, when the flow is mainly from groundwater discharge. Many of the smaller drainages, most of which are ephemeral and dissipate on the coastal plain, originate on the Dandaragan and Darling Plateaus. Those that have base levels above the watertable contribute to groundwater recharge and are losing streams. Others, such as the major drainages and tributaries which cross the coastal plain,

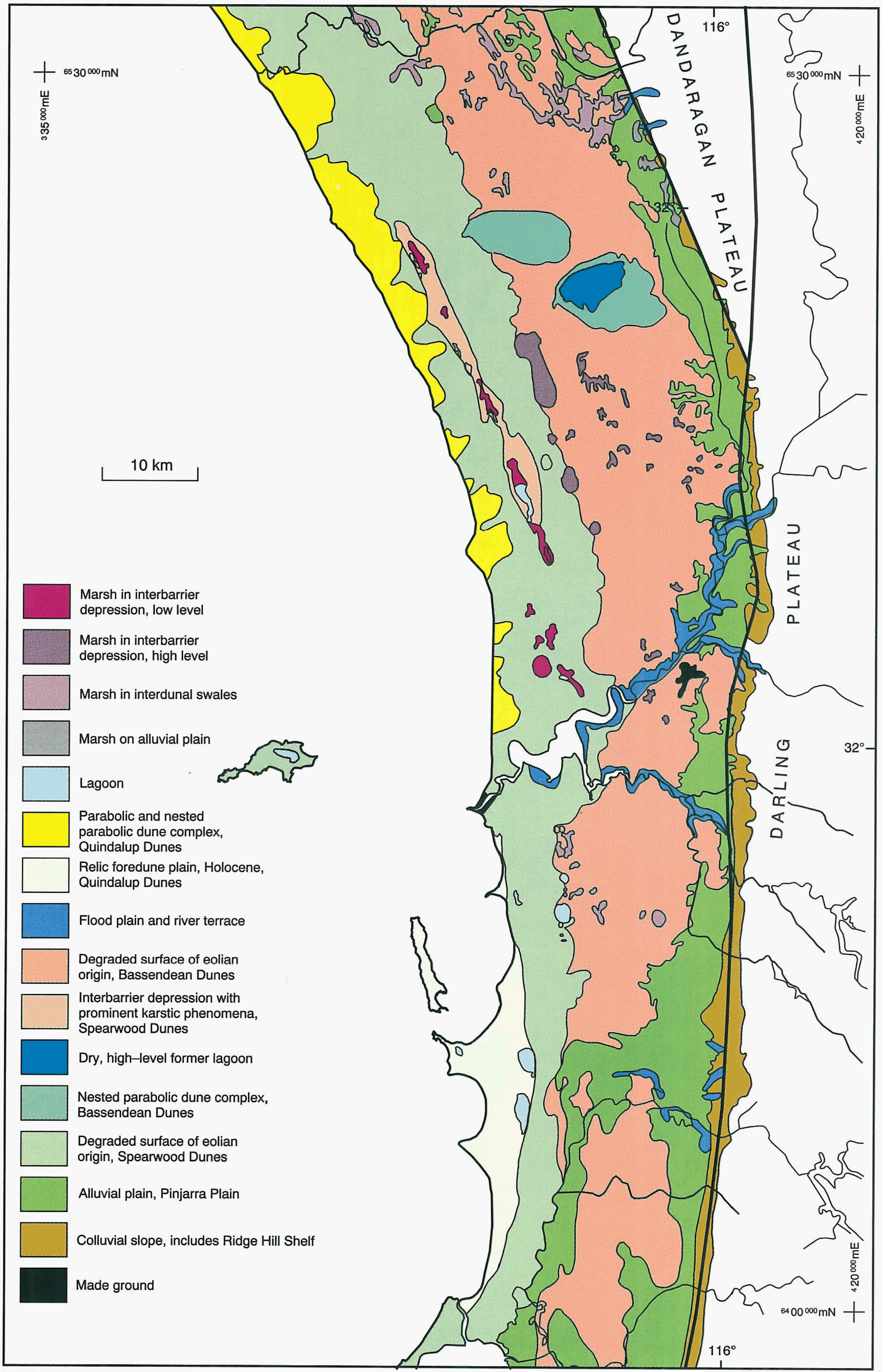

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Figure 4. Generalized geomorphology

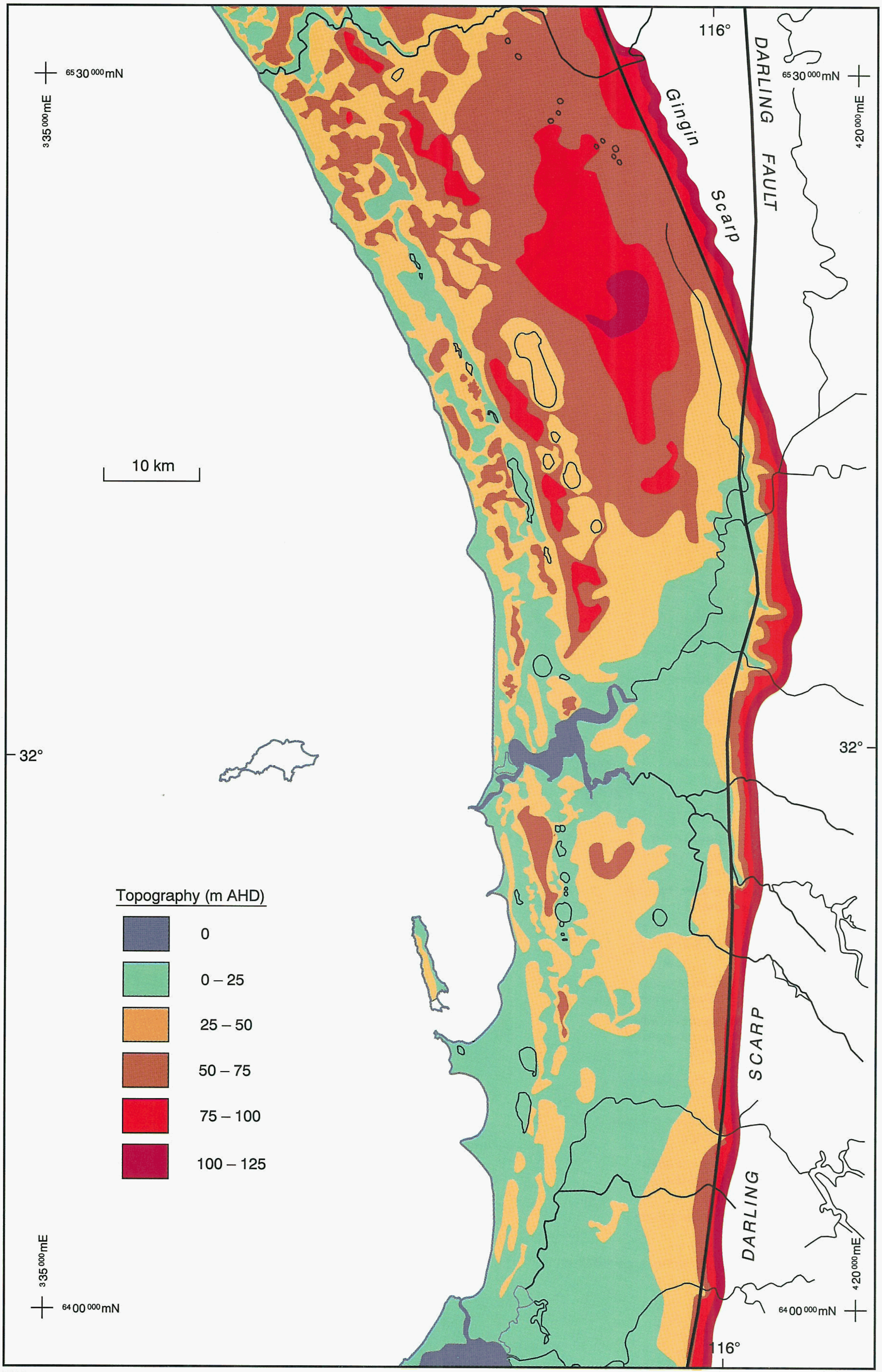


Figure 5. Generalized topography

Table 2. Wetland classification of the Perth Region (from LeProvost et al., 1987)

Wetland type	*Water permanence*	*Cross-sectional shape*	*Example*
River	Permanently inundated	Channel	Swan and Canning Rivers
Creek	Seasonally inundated	Channel	Ellen and Piesse Brooks
Artificial channel	Seasonally inundated	Channel	Water Authority drains
Water body	Permanently inundated	Estuary	Swan River estuary
Peripheral	Permanently inundated	Estuary	Alfred Cove
Lake	Permanently inundated	Basin	Lake Joondalup, Bibra Lake
Sumpland	Seasonally inundated	Basin	Lake Pinjar, swamps
Dampland	Seasonally waterlogged	Basin	Many, but not named
Artificial basin	Permanently inundated	Basin	Freeway interchange lakes
	Seasonally inundated	Basin	Compensating basins or stormwater
Floodplain	Seasonally inundated	Flat	Floodplain of Swan and Canning Rivers
Palusplain	Seasonally waterlogged	Flat	Waterlogged pasture flats

Note: This Bulletin uses the term drainage synonymously with channel

generally have base levels above the watertable in the east and are losing streams in these areas. To the west, the base levels of the major drainages are mostly below the watertable and, in these areas, they become gaining streams and sites of groundwater discharge. Depending on climatic conditions and variations in watertable elevations, different sections of the drainages may be losing streams during some periods of the year and gaining streams during others. Groundwater also discharges into numerous naturally occurring and artificial field drains which are connected to the major drainages and to some of the lakes.

Lakes and swamps

The lakes of the coastal plain can be classified according to their age, origin and topographic location. Six types of lakes have been recognized (Allen, 1981a) with the oldest lying along the eastern margin of the coastal plain, at the contact between the Pinjarra Plain and the Bassendean Dunes, and the youngest along the western margin of the plain within the interdunal depressions of the Quindalup and Spearwood Dunes. This classification is useful when considering the relationship of the lakes to the geomorphological units of the coastal plain. However, the wetland classification of Le Provost et al. (1987), which has been approved by the Western Australian Water Resources Council, is the classification currently being used by the Geological Survey. In this classification, lakes and swamps are defined according to the permanency of water inundation (Fig. 6) and cross-sectional shape (Table 2).

All lakes occupy shallow depressions in the land surface. Along the coastal belt of limestone, some lakes lie in dolines, particularly in areas where the land surface is karstic. Elsewhere, the lakes occur in interdunal and interbarrier depressions. Some lakes and most of the swamps exist in swales in otherwise flat terrain. Many of the lakes are surrounded by vegetation and are often bordered with reeds and sedges. They all contain sediments of biogenic origin consisting of peat, peaty sand, diatomite, calcareous clay (boglime) and freshwater marly limestone. The lacustrine sediments on the up groundwater-flow side of the lakes are generally more sandy than those on the down groundwater-flow side, which are commonly peaty in nature.

Most of the lakes of the Swan Coastal Plain are shallow and range in depth from about 0.5 to 3 m. Exceptions are Lake Richmond in the Rockingham area, which is about 10 m deep, and some of the lakes that occur in dolines of

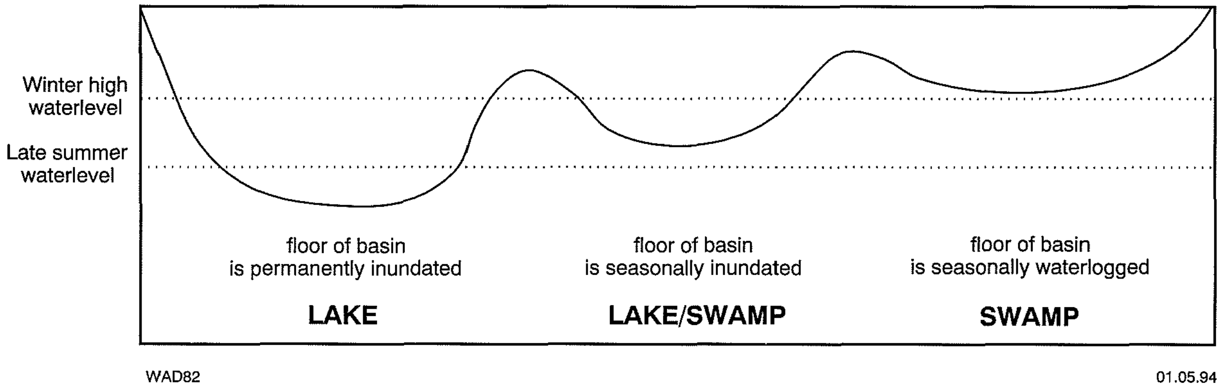
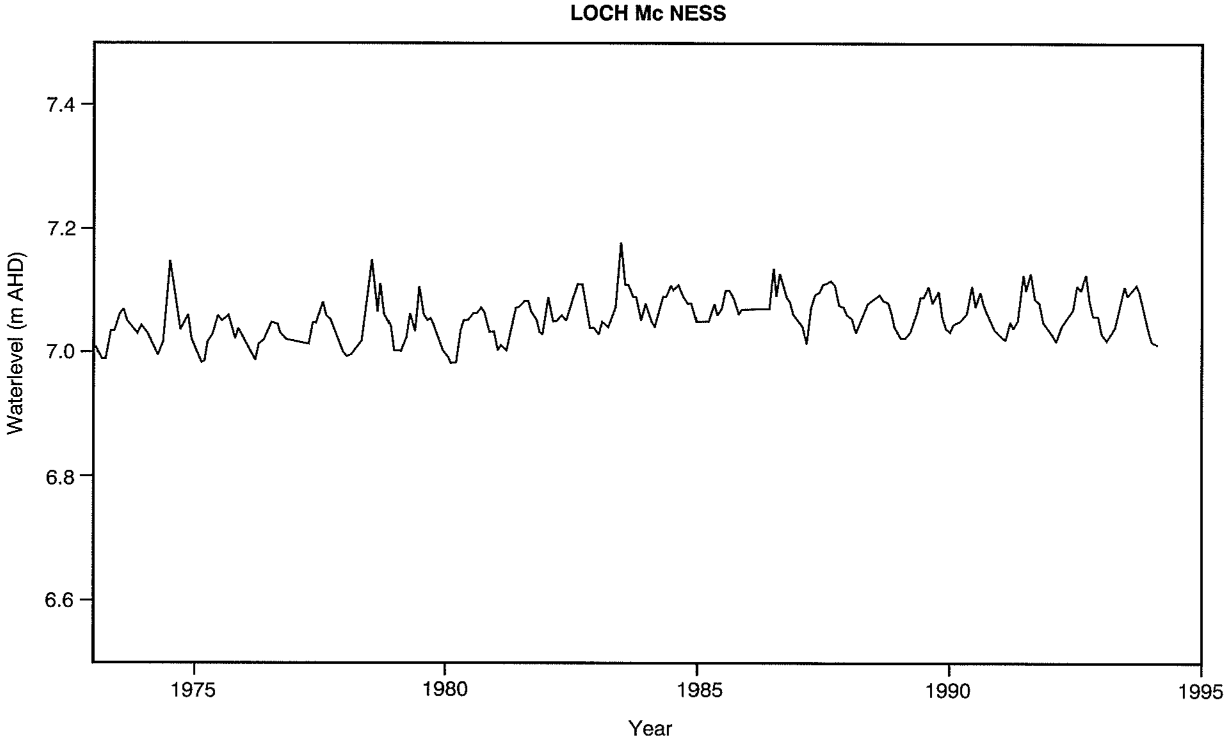


Figure 6. Classification of lakes and swamps (after Semeniuk, 1988)



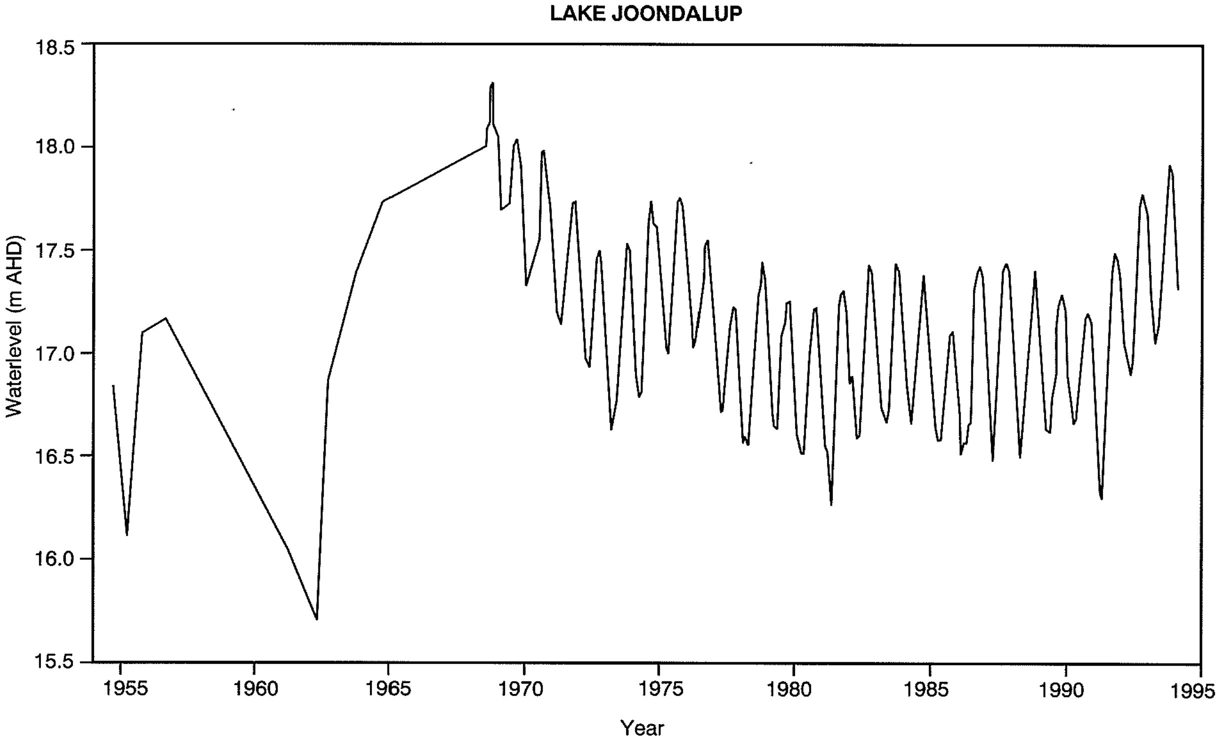


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Figure 7. Hydrographs of Loch McNess and Lake Joondalup

the coastal limestone belt (e.g. Lake Nowergup, which is about 5 m deep).

Water in the lakes is perched above the peaty lacustrine sediments only during periods of exceptionally high rainfall. Following rain, hydraulic connection between lakewater and groundwater is rapidly attained and the lakewater levels represent the isopotential levels of the groundwater flow system connected to the lake (Allen, 1980; Davidson, 1983; Hall, 1985; Townley et al., 1993). During summer, because of declining groundwater levels and lack of rainfall, many of the very shallow lakes become dry. Along the coastal limestone belt, the maximum waterlevel in some of the lakes is believed to be controlled by cavernous limestone that acts as spillways. This phenomenon has been reported as occurring in Loch McNess and Lake Joondalup, but is not evident from the hydrographs of these lakes (Fig. 7).

The swamps of the coastal plain, defined as sumplands and damplands, are seasonally waterlogged or inundated and usually contain water only during the winter months. Many of the swamps are perched above the watertable and downward leakage of water is inhibited by peaty swamp deposits and in some areas, particularly south of Perth, by a ferruginous hardpan colloquially called 'coffee rock'. Those swamps that are not perched are hydraulically connected to the watertable, in much the same way as are the lakes. However, because they are very shallow and mostly occupy swales, they retain water only during heavy rainfall and when the watertable is at its maximum elevation.

Both lakes and swamps are evaporative basins and, as a consequence, the salinity of their water varies greatly depending mainly on the evaporative losses and also the groundwater flow system associated with their existence. The salinity of water in the lakes and swamps also varies seasonally, being freshest at the end of winter and most saline towards the end of summer. After heavy rainfall, this more-saline water is flushed into the groundwater to form a brackish plume down hydraulic gradient from the lakes and swamps. Some lakes and swamps are not associated with groundwater outflow but are sites of groundwater evaporative sinks. Most of these are extremely saline (e.g. Lake Walyungup).

Population and landuse

The population of Perth in 1986 was 1 050 350; in 1991 it had reached 1 184 600, a growth rate of about 2.5% per year. Figure 8 illustrates the population growth of Perth since 1901 and shows that the rate has steadily increased since the end of World War II (1945). Figure 8 also shows that, except for periods of imposed water restrictions, the rate in water demand over this time has coincided with the rate in population growth.

Most of the population of Perth resides in suburban areas adjacent to the Swan River estuary, along the coast from Two Rocks to Mandurah, and within a southeast corridor to Armadale. Smaller urban areas have developed to the north and to the south but most are within rural land cleared for pastoral, horticultural, silvicultural and viticultural purposes. The remaining bushland comprises mostly State Forest and Crown Land in the north or reserves and undeveloped private land adjacent to the coast (Fig. 9). Market gardens (horticulture) are mainly located in depressions within the Spearwood Dunes and within low-lying areas between the Spearwood and Bassendean Dune Systems where the soil is commonly peaty. Pine forests (silviculture) have been developed over large tracts of sandy soil within the Spearwood and Bassendean Dunes to the north of Perth. Vineyards (viticulture) are located on the loamy soils of the Pinjarra Plain, particularly within the Swan River valley.

Major heavy industry has been established in the Kwinana district, adjacent to the coast and about 25 km southwest of Perth. Many other smaller industries and commercial areas are located throughout the Perth Region, but only the more significant centres are shown on Figure 9.

Previous work

Groundwater resource assessment

There are over 300 published reports relating to hydrogeology, groundwater resources and groundwater management within the Perth Region (Smith, 1992, 1993). There is also a large number of unpublished Geological Survey and consultants' reports on aspects of the regional hydrogeology. It is not practical to comment on all of these reports and only those considered to be of historical or major hydrogeological relevance are reviewed. Others are cited throughout the Bulletin where appropriate.

During the early years of settlement, when water supplies were obtained from shallow depths, the Government Geologist, Hardman (1885), failed to recognize the classical features of a large sedimentary artesian basin. He wrote in his report to Parliament that it would be 'hopeless to expect to find artesian water' in sufficient quantity to supply the increasing needs of the growing settlement. Despite this pessimistic report, an artesian bore was drilled to a depth of 152 m at Midland in 1895. The relative success of this bore encouraged further exploratory drilling, and between 1895 and 1905 some 40 artesian bores were drilled (Maitland, 1913). Geological data from this and subsequent drilling were used by Forman (1933), and later by Pudovskis (1962), in an attempt to establish the relationship of the aquifers to the stratigraphy of the Perth Region.

Systematic exploratory drilling commenced in 1961 and 7 lines of deep exploratory bores have been drilled across the Swan Coastal Plain. Berliat (1964) described the results of drilling six exploratory bores, ranging in depth from 180 to 265 m, between Byford and the coast (Byford Line) and concluded that large quantities of groundwater are available but that salinity generally increases towards the west and with increasing depth. During 1964 and 1965, seven exploratory bores (348–658 m deep) were drilled between Bullsbrook and the coast (Pinjar Line) and these helped to define the stratigraphy north of Perth (Whincup, 1966). Also, to the

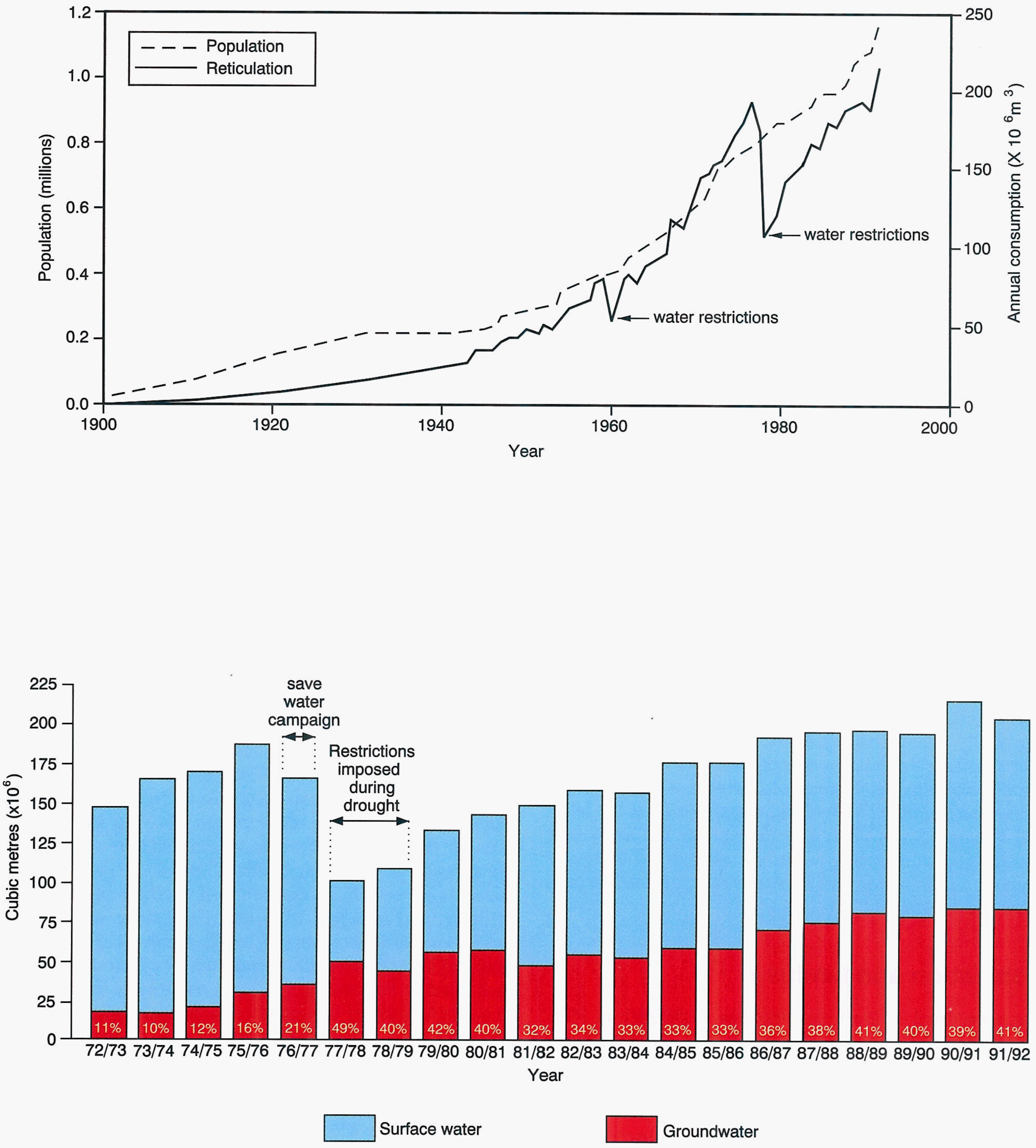

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Figure 8. Population growth and Water Authority reticulation

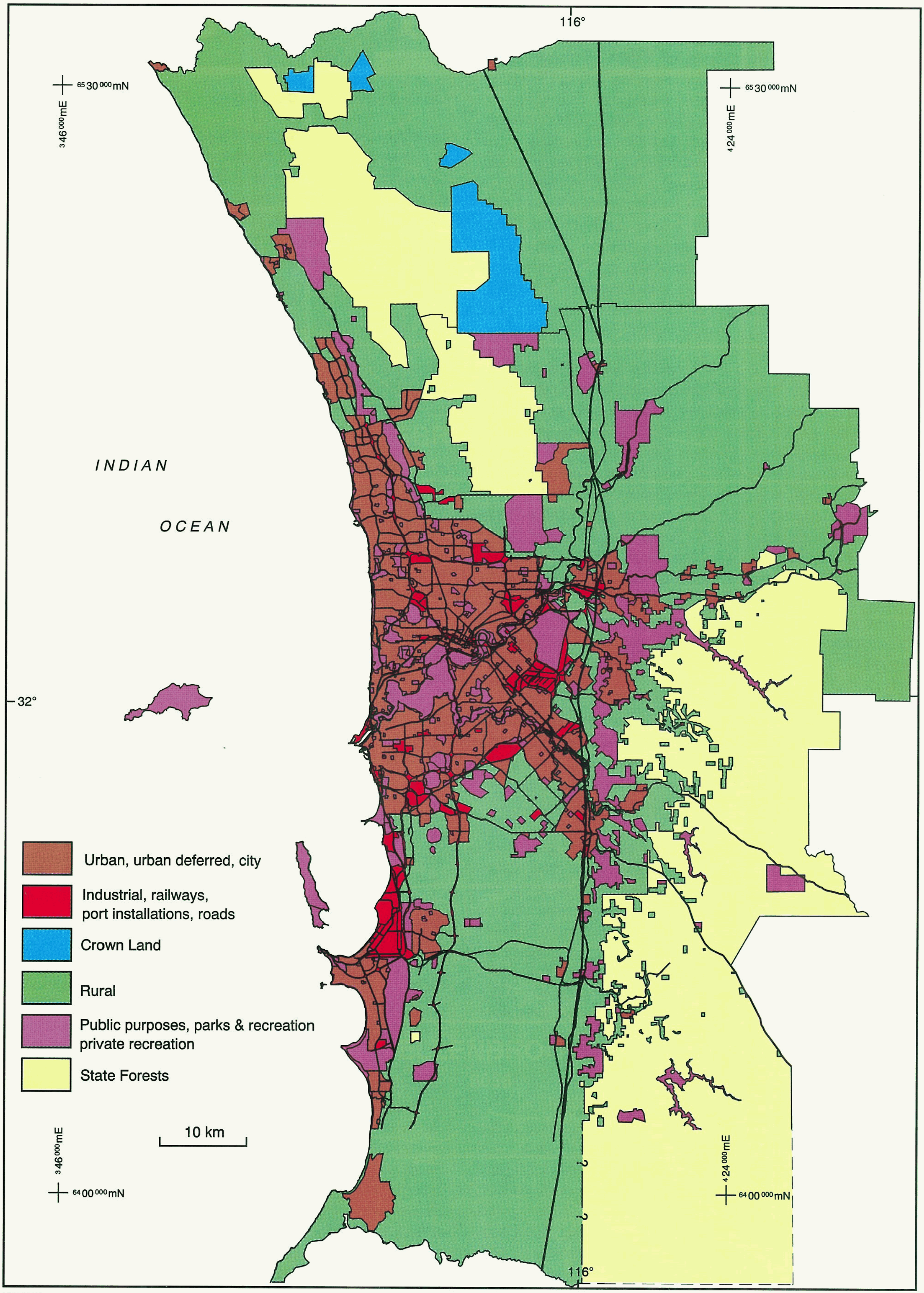

Figure 9. Landuse

north of Perth, Sanders (1967) reported the results of drilling six bores between Gingin and the coast (Gingin Brook Line). To the south of Perth, Emmenegger (1964) outlined the initial results of drilling in the Mandurah area and this was later expanded to include 18 exploratory bores (Commander, 1974). Morgan (1969) briefly described the hydrogeology of the Kwinana–Pinjarra area and Allen (1978) has detailed the results of drilling nine bores (71–810 m deep) in a line between Serpentine and the coast (Becher Point Line) as part of the Metropolitan Water Authority drilling program. The results of exploratory drilling during 1975 and 1976 in the Mirrabooka area, about 17 km northeast of Perth, helped delineate a semi-confined aquifer containing large quantities of low-salinity groundwater (Allen, 1977).

Allen (1979) gave a brief description of the groundwater resources of the confined aquifers beneath the Perth Region that included all drilling data available to 1978 but excluded the work carried out in the Mirrabooka area. This work was expanded to include a brief description of the groundwater resources of the unconfined aquifers (Allen, 1981a). As a regional overview, Commander et al. (1991) described the groundwater resources of the onshore Perth Basin, of which about 10% is occupied by the Perth Region. Also during 1990, Thorpe and Davidson (1991), using hydraulic characteristics of the aquifers together with naturally occurring isotopes, were able to delineate areas of aquifer recharge and make estimates of the rate of groundwater flow within the confined aquifers of the Perth Region.

In conjunction with the deep exploratory drilling, results of shallow drilling to investigate the unconfined aquifers of the Perth Region have been reported since the early 1960s. Morgan (1964a) prepared a progress report on drilling for shallow groundwater in the Gnangara area, north of Perth; since then, many published and unpublished reports have been written. Balleau (1972) determined from pumping tests the hydraulic characteristics of the shallow aquifer in the Gnangara area. Allen (1976a) synthesized the results of drilling in both the northern and southern Perth areas and made estimates of the unconfined groundwater resources. Davidson (1984a, 1987) estimated, by flownet analysis, the quantity of groundwater through-flow within the unconfined aquifers and established a recharge–discharge water balance for the southern Perth area and for a local area to the northeast of Perth.

Recharge investigations

Concomitant with groundwater resource assessments, estimates of groundwater recharge have periodically been made and these have been facilitated by specially designed infiltration studies. Bestow (1971), Sharma et al. (1983, 1991a), Farrington (1984), Anson (1985), Sharma and Hughes (1985), Sharma (1986, 1987), Sharma and Craig (1989), Thorpe (1989), and Farrington and Bartle (1991) used naturally occurring isotopes and tracers to estimate the rainfall recharge to the unconfined aquifers of the Perth Region. These estimates of recharge were made for different landuse and climatic conditions and showed that recharge rates mostly ranged from 5 to 40% of the rainfall depending on location and landuse.

Groundwater contamination

Groundwater contamination inevitably occurs as a result of urbanization and has always been of concern since shortly after settlement in 1829. During the early years of development, the primary sources of groundwater contamination were septic-sewage disposal, household waste and animal excrement from grazing livestock. Groundwater from shallow bores and wells located near septic tanks commonly became contaminated and, for health reasons, were backfilled or sealed off. Many of the wetlands, particularly the swamps, were used as landfill sites for discarded household wastes and, as a consequence, groundwater supply wells and bores down hydraulic gradient from these disposal sites eventually became contaminated.

After World War II, industrial development was encouraged and local groundwater contamination from industrial waste soon became a problem. Remedial action involved identifying and locating the source of contamination and shutting down or sealing off water-supply bores. Since 1970, there has been a growing awareness of the problems associated with groundwater contamination and many investigations have been carried out (Hirschberg, 1989). Recent legislation covered by the Water Authority Act 1984 and the Environmental Protection Act 1986 empowers the Department of Environmental Protection to enforce increased standards of groundwater protection and remedial cleanup work of any groundwater contamination.

Groundwater and the environment

The groundwater resources of the Perth Region support extensive wetland and vegetation ecosystems. Environmental considerations are, therefore, closely associated with groundwater resources assessment and groundwater quality control. For many years the wetlands were used for landfill waste disposal and it was not until about 1970 that they were recognized as having environmental importance. Allen (1976b) selected four of the many wetlands and proposed a detailed hydrogeological study for each of them. Since 1976, six lakes have been investigated by drilling and many others have been environmentally assessed for water quality and biota.

During more recent years, vegetation has been recognized as having significant environmental importance, particularly in preventing soil erosion by stabilizing the land surface in providing habitats for many species of animals. Random tree deaths have occurred throughout the Perth Region and have been investigated by a multidisciplinary group comprising the Water Authority, Department of Agriculture, Department of Conservation and Land Management, and the Commonwealth Scientific and Industrial Research Organisation (Water Authority of Western Australia, 1992b). It is apparent from these investigations that most tree deaths result from low soil-moisture content due to periodic and unfavourable climatic conditions.

Groundwater resource management

The importance of groundwater management to the developing settlement became increasingly apparent with the successful construction of about 40 artesian bores between 1895 and 1905. It was clear that legislation was required to protect the users of the groundwater from haphazard and excessive exploitation of the resources. For this reason, groundwater became the property of the Crown and, under the established Rights in Water and Irrigation Act 1914, artesian water became available to private users by licence from the managing authorities. This legislation only applied to the users of artesian water resources and, as a consequence, the availability of shallow non-artesian groundwater was taken for granted by the people of Perth until the early 1970s when the Rights in Water and Irrigation Act 1914 was amended to include non-artesian groundwater. Also, between 1970 and 1972 the Metropolitan Water Supply, Sewerage and Drainage Act 1909 was amended to allow proclamation of Underground Water Pollution Control Areas (UWPCA) and Public Water Supply Areas (PWSA) in the Perth Region. This legislation marked the commencement of modern groundwater-management practices.

During the low-rainfall period of the late 1970s, the watertable declined to very low levels and many normally inundated wetlands became dry. These conditions were exacerbated by increased groundwater abstraction for irrigation and it was soon recognized that a detailed water-balance study was required. Hence, between 1982 and 1987, a comprehensive water-balance study of the unconfined aquifers beneath the Perth Region was carried out by the Water Authority in collaboration with the Centre for Water Research at the University of Western Australia, Department of Conservation and Land Management, and the Geological Survey (Cargeeg et al., 1987). The study used a computer-based model to determine the effect on the watertable of variations in landuse and climate and concluded that active management of the groundwater resources of the Perth Region was essential to meet increasing public and private demands on groundwater and to maintain the sustainability of the the environment. The study lead to the licensing of non-domestic groundwater use being extended across those parts of the Perth Region not previously proclaimed.

Drilling and testing data

Exploratory drilling

Unconfined aquifer

Systematic exploratory drilling to assess the groundwater resources of the unconfined aquifer of the Perth Region commenced in the northern area in 1962 and in the southern area in 1972 (Allen, 1976a). To date, more than 2000 investigation bores have been drilled (Table 3). Initially, bores spaced on a 3–5 km grid across the coastal plain were drilled by the cable-tool percussion method to a depth of about 3 m below the base of the unconfined aquifer. Subsequently, investigation bores of similar depth were drilled at each of the proposed production-bore sites and used to help design production-bore depths and screened intervals. These bores were also used for waterlevel monitoring during pumping tests of the production bores.

At some localities of specific environmental importance, or for proposed future public water-supply groundwater abstraction, a deep bore (base of aquifer) and a shallow bore to a depth of about 6 m below the watertable have been drilled by cable-tool or reverse-air circulation methods. In addition to these bores, a broad network of shallow, watertable-monitoring bores has been drilled in the northern area and in the Jandakot Mound area to the south.

An investigation-drilling program to determine the hydrogeological environment of lakes likely to be affected by groundwater abstraction was proposed by Allen (1976b). As a consequence, Lake Jandabup was investigated during 1977; Lake Mariginiup during 1978–79; Bibra Lake during 1983; Thomsons Lake during 1984, and Lake Nowergup during 1989.

As part of the groundwater assessment of the unconfined aquifer, pumping tests have been carried out using both specially constructed bores at many of the exploratory boresites and those drilled for production. The usual procedure has been to carry out a step-drawdown test, followed by an eight-hour constant-rate test. The test bores are mostly screened in the bottom third of the superficial aquifer. Because of the partial penetration of the screens, which leads to early vertical leakage, and because nearby observation bores are mostly fully screened, the results of the tests cannot be used unequivocally for calculation of aquifer parameters. Particularly rapid and small responses were obtained from pumping tests in the Tamala Limestone. At ten sites, multiple observation bores were monitored during the tests and drawdown analyses from these gave reliable transmissivity values (Hirschberg, 1981; Wharton, 1981a,b; Smith, 1982a,b,c; Deeney, 1984a,b; Smith and Davidson, 1984, 1985; Martin and Baddock, 1989). Drawdown data from these tests are contained on file at the Geological Survey.

Lithological samples from the deep (base of aquifer) investigation bores have been geologically logged; most of the samples have been retained in the Geological Survey core library. Descriptions of the logs are contained on file and within the Geological Survey database. To help define geological boundaries and the subcropping formations, gamma-ray logs have been run on each of the bores and, where practicable, lithological samples have been palynologically examined.

Each investigation bore has been surveyed to the Australian Map Grid (AMG) co-ordinates and levelled to the Australian Height Datum. Water samples have been collected from each bore and comprehensive chemical analyses have been carried out on them by the Water Authority Scientific Services Branch and the Chemistry Centre (W.A.).

A summary of the drilling projects designed to investigate and monitor the groundwater characteristics of the unconfined aquifer is given in Table 3 and

Table 3. Superficial (unconfined) aquifer investigation projects and bores

Project bores	*Commenced*	*Total*	*Remarks*
Applecross dewatering	1982	16	GF series of bores
Applecross investigation	1982	3	Multi-port bores
Artificial recharge	1981	10	Discontinued in 1986
Barragoon investigation	1992	12	B series north coastal
Bateman sewerage	–	6	Monitoring ceased 1986
Beenyup monitoring	1974	2	Sewerage installation
Bibra Lake main sewer	1981	6	Sewer dewatering
Bibra Lake monitoring	1983	21	8 sites; limnological study
Bond bores	1974	12	Yanchep–Two Rocks area
Cockburn Sound study	1976	5	6 bores drilled, 1 abandoned
Continuous monitoring	1973	12	1 recorder removed
Coogee dewatering	1986	15	Installation pump station
Coogee Spring study	1990	10	Requested by DEP
CSIRO landfill study	–	27	–
Dewatering Rockingham	–	20	Cape Peron pipeline
Gingin monitoring	1973	21	GSWA project
Gnangara liquid waste	1981	26	Groundwater contamination study
Gnangara mound monitoring	1962	145	GN, GA, GB, GC, GD, GE series
Gwelup monitoring	1974	36	Scheme area
Hertha Road	1974	26	Waste disposal–landfill
Hooker bores	1973	7	Residential development
Jandabup monitoring	1977	34	Limnological study
Jandakot aquifer evaluation	1980	28	Pumping tests
Jandakot monitoring	–	44	Jandakot Mound
Jandakot observation	1975	36	Scheme area
Jones Street pollution	1976	13	Waste disposal–landfill
Joondalup monitoring	1974	38	Western Gnangara mound
Kwinana effluent monitoring	1984	10	Wastewater treatment
Kwinana treatment	1984	10	Wastewater treatment
Lake Banganup	–	14	Limnological study
Lake Nowergup	1989	39	Limnological study
Lake Thompson investigation	1972	133	Regional investigation
Lake Thompson drainage	–	29	Drainage investigation
Lexia observation	1983	42	Two bores at most sites
Mariginiup monitoring	1978	24	18 sites
Mayor Road monitoring	1981	11	Munster sewerage station
Mirrabooka monitoring	1973	61	Scheme area
Mirrabooka observation	1960	136	Scheme area
Muchea rutile plant	–	2	Monitor effects of abstraction
Mussell Pool	1976	10	Environmental
Nedlands water quality	1991	12	Water quality in urban area
Net recharge	1981	23	Gnangara Mound
Northeast corridor	1992	159	Watertable monitoring
Pacminex exploratory bores	1973	6	Proposed alumina refinery
Perth coastal interface	1990	7	Saltwater interface
Perth coastal scheme	1989	39	Proposed scheme area
Pinjar observation	1975	28	Proposed scheme area
Pinjar monitoring	1976	34	Gnangara Mound
Pinjar aquifer evaluation	1982	5	2 clusters
Pinjar vegetation study	1989	3	Effects of abstraction
Port Kennedy monitoring	1983	9	Wastewater treatment
Queens Park contamination	1983	1	Foundry sand
Quinns TWS	1978	4	Town water supply
Saltwater interface	1985	15	Perth metropolitan
Swan Groundwater Area	1975	8	8 sites
Thompsons Lake	1984	20	Limnological study
Two Rocks	1978	12	6 private bores
Wanneroo observation	1974	26	Scheme area
Wanneroo aquifer evaluation	1982	14	6 sites
Wanneroo monitoring	1975	34	Scheme area
Warton Road pollution	1981	7	Septic tank waste
Whitfords	1971	6	Future scheme area
Whitfords investigation	1992	13	Proposed scheme area
Woodman Point wastewater	1983	9	Wastewater treatment
Yanchep Beach–Sun City	1978	7	4 saltwater interface bores
Yanchep investigation	1973	24	Gnangara Mound
Yanchep National Park	–	8	Environmental

Table 3. (*continued*)

Project bores	*Commenced*	*Total*	*Remarks*
Yeal observation	1978	24	Future production sites
Cape Peron monitoring	–	3	Cathodic protection
Lake Coogee	1981	50	Private bores
Canning Vale recharge	1979	32	6 bores retained for monitoring
Ellen Brook–Swan Avon	1982	15	Salinity investigation
Forestry watering points and sumps	1947	49	46 surface water, 3 bores
Jane Brook–Swan Avon	1982	16	Salinity investigation
Liquid waste disposal — Orange Grove	1981	4	Industrial liquid waste
Lakes and wetlands	1945	175	G series other than specific projects
Shenton Park	–	2	Sewage treatment
	TOTAL	2 055	

Source: SWRIS (State Water Resources Information System)
Note: dashes imply unavailability of data

the locations of the bores are shown on Figure 10. The waterlevel and water-quality data are stored in the State Water Resources Information System (SWRIS) at the Water Authority; generally, waterlevels are monitored monthly and groundwater quality about once per five-year interval.

Confined aquifers

Exploratory drilling to assess the groundwater resources of the confined aquifers within the Perth Region was commenced in 1961 by the Department of Minerals and Energy, under the supervision of the Geological Survey. To 1969, four lines (Gingin Brook, Pinjar, Woodman Point and Byford Lines) of deep exploratory bores had been drilled (Allen, 1979). Since 1969, the Water Authority and its predecessors have further investigated the resources by drilling three lines of deep exploratory bores (Wreck Point, Whitfords and Becher Point Lines) together with a network of artesian monitoring (AM) bores.

At most of the artesian monitoring sites two bores were drilled by mud-rotary method and electrically logged. One of these bores was constructed with a short perforated interval in the middle of the Leederville aquifer and the other bore with a perforated interval approximately 100 m beneath the upper contact margin of the Yarragadee aquifer. These intervals were selected to permit monitoring of comparable hydraulic heads within the aquifers. Drilling of the artesian monitoring network of bores was completed in 1985 and a summary of the bore data is given in Table 4. Most of the shallower bores are equipped with 80 mm diameter galvanized pipe and the deeper bores with 114 mm diameter steel casing.

During the Mirrabooka investigation-drilling project, the Mirrabooka aquifer was identified as constituting an elongate, north–south strip through the eastern area. The aquifer was subsequently investigated during 1975 and 1976 (Allen, 1977) and the investigation extended northwards into the Lexia area between 1983 and 1986 (Davidson, 1987). A summary of the bore data obtained from drilling into the Mirrabooka aquifer is given in Table 5.

All investigation bores into the confined aquifers (Fig. 11) have been surveyed to AMG coordinates and levelled to AHD. Waterlevels have been monitored and samples collected and analysed for chemical constituents. These data are contained in SWRIS.

Production drilling

Since 1977, groundwater has accounted for about 40% of the Water Authority supply (Fig. 8) but, as the surface water catchments become fully utilized, groundwater will become increasingly more important for future water supplies, and additional production bores will be required.

All existing production bores have been drilled by mud-rotary method and each electrically logged. The 91 production bores in the unconfined (superficial) aquifer are usually designated with a number ending in zero. They are mostly about 230 mm in casing diameter and screened over a 10–15 m interval against the bottom third to a half of the aquifer. At most localities, a preliminary investigation bore had been drilled. The production bores in the Mirrabooka aquifer are designated with a number ending in two, are about 220 mm in casing diameter, and usually contain about 30 m of screens. Production bores in the Leederville aquifer are designated with a number ending in five and are mostly constructed with about 300 mm diameter casing and 50–100 m of screens. The production bores in the Yarragadee aquifer are sometimes designated with a number ending in seven but other numbers are common; for example, Bold Park No. 1 and Leederville No. 5 bores (BP1 and L5). These bores are mostly constructed with about 270 mm diameter casing and have a screened length of about 100 m.

Currently, there are 133 Water Authority production bores in operation (Table 6, Figs 12 and 13) and the water obtained from all, except that from the Yarragadee aquifer, requires treatment before being supplied for human

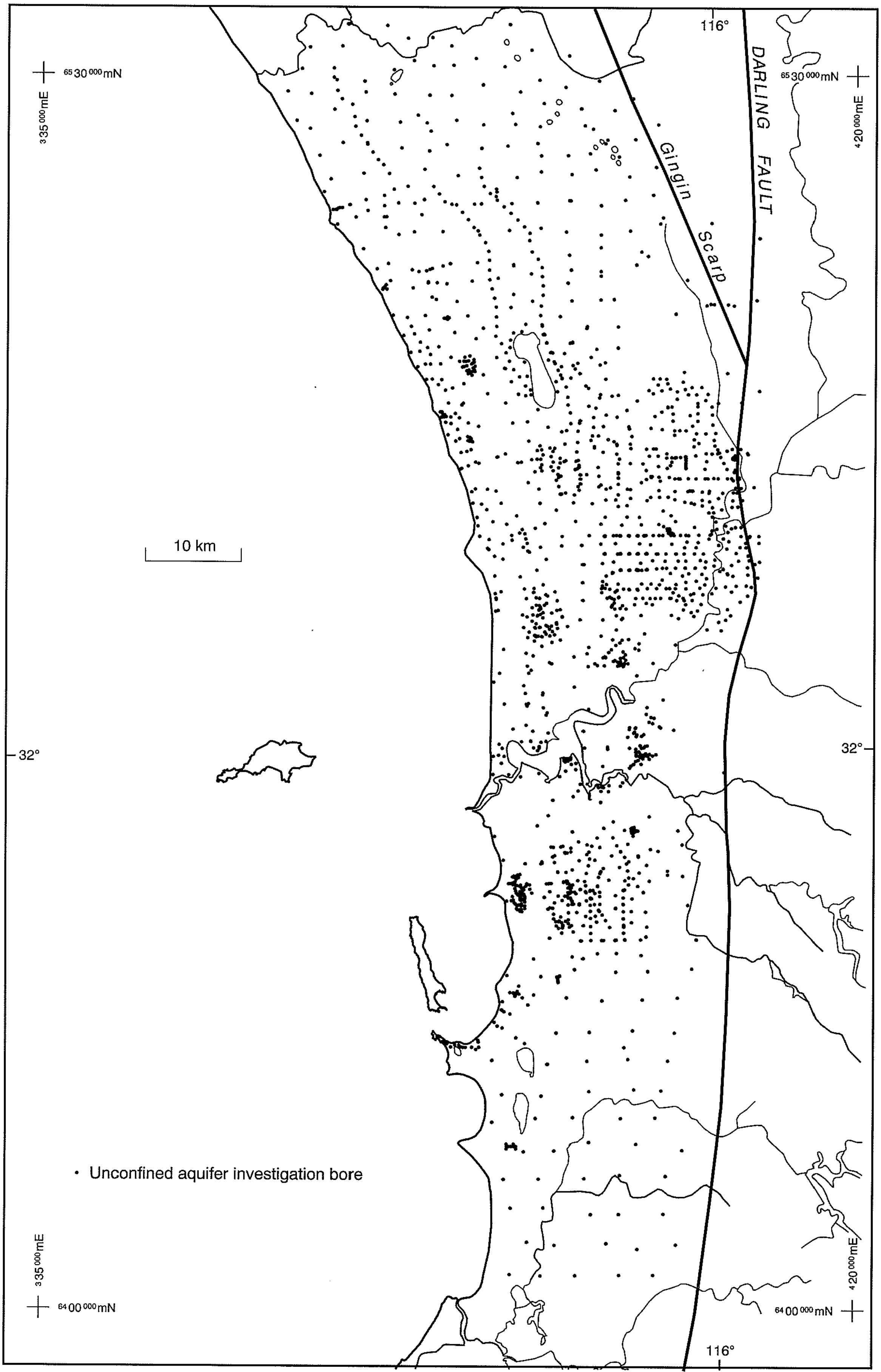

Figure 10. Unconfined aquifer investigation bores

Table 4. Artesian monitoring (AM) bore data

AM Bore	*Ground level (GL) (m AHD)*	*Top casing (m AHD)*	*Depth below GL (m)*	*Casing*		*Perforations below GL (m)*	*Waterlevel Sep–Oct 92 (m AHD)*	*Salinity (mg/LTDS)*	*Aquifer*	*Comments*
				Diameter (mm)	*Depth GL (m)*					
1	52.92	53.65	794	114	–	465–475	–	–	Leederville	
2	35.65	36.18	907	245	907	819–825	27.01	1 050	Yarragadee	Barragoon No 1
2A	35.61	36.56	540	114	–	495–501	24.84	–	Leederville	
3	26.66	27.60	729	114	431	400–408	23.53	652	Leederville	
4	50.26	51.00	304	80	304	248–252	49.47	760	Yarragadee	
4A	50.20	50.40	549	114	550	434–440	48.71	780	Yarragadee	
5	51.64	52.40	302	80	296	284–289	42.33	1160	Yarragadee	
5A	51.54	51.98	166	114	162	138–144	36.94	343	Leederville	
6	64.21	65.03	300	50	186	154–159	48.22	630	Yarragadee	
6A	64.20	64.69	75	114	73	48–54	48.58	420	Leederville	
7	102.28	102.83	721	114	331	177–183	76.71	280	Leederville	
8	52.32	53.20	810	114	652	636–642	22.55	880	Leederville	
9	58.80	59.44	303	80	224	207–212	43.20	318	Leederville	
9A	58.45	59.21	128	114	128	96–102	47.33	253	Leederville	
10	69.25	69.86	298	80	298	286–291	–	1 620	Yarragadee	
10A	69.26	70.02	115	80	114	103–108	–	230	Leederville	
11	190.30	191.02	810	114	630	603–609	–	–	Leederville	
12	16.05	16.96	838	80	572	548–553	–	456	Leederville	Wreck Pt No 1
13	53.58	54.62	798	80	416	392–397	–	1 030	Yarragadee	Wreck Pt No 2
13A	53.73	54.58	189	114	189	156–162	–	300	Leederville	
14	75.45	76.42	810	80	745	721–726	–	166	Yarragadee	Wreck Pt No 3
14A	75.26	76.51	–	80	322	298–302	–	190	Yarragadee	Wreck Pt No 3A
14B	75.07	75.86	–	80	163	139–144	50.03	220	Leederville	Wreck Pt No 3B
15	69.33	69.69	784	80	359	334–340	59.16	750	Leederville	Wreck Pt No 4
6	–	–	–	–	–	–	–	–	–	Not drilled
17	72.30	73.03	301	80	283	259–264	37–76	198	Yarragadee	
17A	72.44	72.10	175	114	175	146–152	35.04	229	Leederville	
18	77.19	77.99	300	80	228	210–215	48.51	460	Leederville	
18A	59.89	60.34	676	114	–	–	–	–		Abandoned
19	68.67	69.32	802	114	330	316–323	45.28	706	Leederville	
20	29.32	30.19	467	80	459	375–380	29.80	1 090	Yarragadee	
20A	29.36	30.02	183	80	175	156–161	14.18	194	Leederville	
21	58.87	59.20	464	80	455	322–328	35.28	120	Yarragadee	
21A	59.12	59.62	144	80	136	123–132	30.72	260	Leederville	
22	80.98	81.64	610	80	592	540–549	33.46	396	Yarragadee	
22A	80.50	80.86	263	114	264	236–242	33.80	178	Leederville	
23	29.46	30.09	470	80	442	403–412	35.28	682	Yarragadee	
23A	29.68	30.25	182	114	175	144–152	11.58	293	Leederville	
24	49.58	49.98	908	140	908	882–890	30.25	202	Yarragadee	
24A	49.76	50.73	333	114	335	321–327	16.50	200	Leederville	
25	72.59	73.18	605	80	568	316–322	26.68	860	Leederville	
25A	72.85	73.40	474	–	–	436–445	25.85	530	Yarragadee	
26	36.92	37.72	674	114	626	588–596	25.74	–	Yarragadee	
26A	37.98	38.31	370	–	–	–	33.18	470	Leederville	RAAF No 3
26B	37.40	37.65	373	–	–	–	30.35	1 200	Leederville	RAAF No 4
26C	37.37	37.90	243	–	–	–	–	640	Leederville	RAAF No 5
27	34.06	34.34	762	80	531	522–528	21.73	199	Yarragadee	Whitfords No 1
27A	34.02	34.29	220	80	203	197–200	5.24	790	Leederville	Whitfords No 1A
27B	33.90	34.20	140	80	125	119–122	4.65	285	Leederville	Whitfords No 1B
28	52.63	53.36	625	80	607	381–390	12.37	590	Leederville	
29	48.44	48.96	753	114	751	729–735	21.71	3 850	Yarragadee	
29A	48.57	49.48	379	114	370	327–333	22.99	–	Leederville	
30	49.80	50.01	747	80	668	665–668	20.90	3 450	Yarragadee	Whitfords No 4
30A	49.79	50.02	350	80	326	320–323	13.18	1 060	Leederville	Whitfords No 4A
30B	49.86	50.19	220	80	206	200–203	17.60	280	Leederville	Whitfords No 4B
30C	49.75	50.44	135	114	135	110–116	35.92	–	Mirrabooka	
30Z	39.04	39.48	565	114	500	333–410	11.65	1 300	Leederville	
31	5.59	6.30	800	80	728	722–725	18.69	3 160	Yarragadee	Whitfords No 5
31A	5.68	6.43	220	80	210	200–203	14.06	572	Leederville	Whitfords No 5A
32	12.98	13.14	404	80	391	374–379	19.25	410	Yarragadee	Triggs No 1
33	7.17	7.40	283	80	212	195–200	5.15	1 290	Leederville	Hamersley No 1
33A	7.19	7.19	533	114	535	495–505	20.76	422	Yarragadee	
34	40.03	41.13	519	80	500	380–388	10.18	2 560	Leederville	
34A	40.91	41.56	735	114	716	702–708	20.67	–	Yarragadee	
35	16.16	17.17	460	80	440	310–318	12.49	940	Leederville	
35A	16.86	17.76	649	114	650	619–630	19.33	4 650	Yarragadee	
36	16.31	16.72	616	114	610	526–532	17.94	–	Yarragadee	
36A	16.55	16.74	173	80	164	155–163	6.74	680	Leederville	King Edward St No 1
36B	15.12	15.97	200	80	195	162–170	–5.56	440	Leederville	Roberts St No 1
36C	15.07	15.44	232	80	226	218–226	7.94	570	Leederville	Hector St No 1
37	21.21	22.03	499	80	379	359–369	5.97	610	Leederville	
37A	21.44	22.55	804	114	803	765–775	20.39	–	Yarragadee	
38	11.23	–	247	100	–	–	–	–		Helena No 1
38A	11.22	12.05	550	114	550	500–507	–	968	Yarragadee	
39Z	8.19	8.26	595	80	431	406–414	15.01	1 230	Kings Park	Claremont No 2

Table 4. (*continued*)

AM Bore	*Ground level (GL) (m AHD)*	*Top casing (m AHD)*	*Depth below GL (m)*	*Casing Diameter (mm)*	*Casing Depth GL (m)*	*Perforations below GL (m)*	*Waterlevel Sep–Oct 92 (m AHD)*	*Salinity (mg/LTDS)*	*Aquifer*	*Comments*
40	22.68	22.96	741	80	730	687–696	15.11	1 230	Yarragadee	
40A	21.61	21.94	459	114	459	442–447	6.56	1 380	Leederville	
40B	22.41	22.70	220	114	99	75–81	6.48	270	Kings Park	
41	20.78	21.28	505	80	500	457–463	16.63	3 260	Yarragadee	
41A	20.87	21.39	221	80	219	197–203	17.93	1 270	Leederville	
41B	20.99	21.63	115	114	–	73–79	21.83	510	Leederville	
42	8.99	9.76	600	80	589	569.5–576	12.45	1 080	Yarragadee	
42A	8.56	9.28	323	114	325	288–295	3.73	1 120	Leederville	
43	28.77	29.50	607	80	300	274–282	3.97	560	Leederville	
43A	28.76	29.22	794	114	794	753–760	–6.02	–	Yarragadee	
44	6.37	6.93	333	80	320	135–145	17.44	3 870	Leederville	
45	38.71	38.97	409	80	403	223–231	2.75	820	Leederville	
46	28.30	28.64	801	80	620	597–602	12.98	1 530	Yarragadee	Woodman Pt No 1
46A	28.25	28.52	253	80	246	223–228	3.97	700	Leederville	Woodman Pt No 1A
46B	28.12	28.69	120	80	118	95–100	4.98	580	Leederville	Woodman Pt No 1B
47	27.32	27.50	742	80	564	541–546	12.46	2 500	Yarragadee	Woodman Pt No 2
47A	27.57	27.83	427	80	174	151–156	4.49	1 020	Leederville	Woodman Pt No 2A
47B	27.27	27.45	67	80	66	60–63	7.33	582	Leederville	Woodman Pt No 2B
48	23.95	24.48	618	80	444	421–426	22.03	3 090	Yarragadee	Woodman Pt No 3
48A	23.99	24.56	168	80	168	145–150	22.54	254	Leederville	Woodman Pt No 3A
49	36.49	36.83	554	114	554	526–533	11.67	2 710	Yarragadee	
49A	36.68	37.13	229	114	229	196–202	3.16	992	Leederville	
50	15.57	15.82	354	114	343	314–319	11.73	–	Yarragadee	
50A	15.69	16.43	155	114	153	131–137	5.02	–	Leederville	
50X	30.66	31.37	90	114	87	48–54	29.72	–	Leederville	
50Y	30.81	31.21	301	114	306	271–277	30.37	1 810	Yarragadee	
50Z	20.69	20.91	183	–	–	–	26.26	641	Leederville	Byford No 2
51	27.19	27.71	421	80	420	335–345	26.61	509	Yarragadee	
51A	27.25	27.71	105	114	103	75–81	25.73	470	Leederville	
52	3.99	4.81	481	80	475	457–462	11.30	1 410	Yarragadee	
52A	4.06	4.34	124	80	124	99–105	2.57	1 650	Leederville	
52Y	6.02	7.00	435	80	436	381–396	14.15	1 860	Yarragadee	Garden Island Nth
52Z	4.09	4.85	387	80	386	362–367	13.17	1 440	Yarragadee	Garden Island Sth
53	21.60	22.36	244	150	–	150–157	3.28	337	Leederville	Byford No 5
53A	21.89	22.32	551	114	551	474–486	11.44	2 470	Yarragadee	
54	5.30	5.88	448	80	448	405–412	10.35	2 760	Yarragadee	
55	7.44	8.20	401	114	368	360–366	11.28	880	Yarragadee	
55A	7.52	8.27	137	144	137	110–116	4.07	1 820	Leederville	
56	34.24	34.70	353	80	344	246–255	26.32	840	Yarragadee	
56A	34.42	35.18	84	114	84	33–44	33.65	682	Leederville	
57	2.26	2.86	801	80	500	483–488	9.46	2 510	Yarragadee	Becher Pt No 1
57A	2.57	3.22	197	114	197	170–176	4.32	815	Leederville	
58	9.15	9.85	746	80	402	379–384	9.75	1 760	Yarragadee	Becher Pt No 2
58A	9.74	10.48	187	80	176	153–158	5.43	878	Leederville	
59	8.08	9.08	796	80	392	375–380	10.49	1 800	Yarragadee	Becher Pt No 3
59A	8.02	8.25	130	80	117	107–112	5.32	340	Leederville	Becher Pt No 3A
60	16.33	17.01	810	80	571	483–495	10.69	1 940	Yarragadee	Becher Pt No 4
60A	16.60	17.12	303	80	299	282–287	10.70	1 440	Yarragadee	Becher Pt No 4A
60B	16.58	16.96	74	80	70	54–59	15.70	890	Leederville	Becher Pt No 4B
61	37.02	37.40	802	80	626	603–608	24.53	1 030	Yarragadee	Becher Pt No 5
61A	36.54	36.83	129	80	121	112–117	30.90	290	Yarragadee	Becher Pt No 5A
61B	37.55	38.07	80	114	80	55–61	32.37	–	Leederville	
61Y	28.39	29.24	264	114	–	187–256	>29.06	–	Yarragadee	
61Z	27.88	28.69	157	114	–	70–115	29.93	–	Leed. & Yarra.	
62	7.66	8.34	386	80	375	333–339	9.03	1 830	Yarragadee	
62A	7.64	8.15	161	80	159	135–141	4.98	619	Leederville	
63	21.82	22.27	349	80	350	312–320	10.71	1 880	Yarragadee	
63A	21.93	22.52	132	114	126	103–109	15.00	717	Leederville	
64	54.72	55.16	357	80	340	307–318	36.45	240	Yarragadee	
64A	55.57	56.43	66	114	–	36–42	51.76	160	Yarragadee	
65	2.07	3.02	363	80	363	114–123	7.97	2 450	Leederville	
65A	2.09	2.83	119	80	118	105–110	4.68	774	Leederville	
65B	2.15	2.90	340	114	340	312–318	8.08	2 230	Yarragadee	
66	20.87	21.43	384	114	350	341–347	10.40	603	Yarragadee	
66A	20.90	21.51	105	114	103	75–81	7.66	705	Leederville	
67	11.19	11.61	375	80	376	342–347	7.08	5 130	Yarragadee	
67A	11.45	12.09	125	114	125	99–105	3.82	910	Leederville	
68	9.38	10.12	327	80	327	296–304	8.85	–	Yarragadee	
68A	9.43	10.08	130	114	130	100–107	5.71	631	Leederville	
69	41.44	42.31	417	114	–	192–198	–	364	Yarragadee	
70	21.38	22.15	505	114	502	457–465	–	229	Yarragadee	
70A	21.36	22.11	110	114	106	80–86	–	508	Leederville	

Note: dashes imply unavailability of data

Table 5. Mirrabooka aquifer investigation bore data

Bore	*Ground level (GL) (m AHD)*	*Top casing (m AHD)*	*Depth below GL (m)*	*Perforated interval GL (m AHD)*	*Water-level Sept–Oct 92 (m AHD)*	*Salinity TDS (mg/L)*	*Top of Mirrabooka aquifer (m AHD)*
L20A	55.29	55.97	83	66–72	47.26	208	-3.5
L30A	52.67	53.23	72	63–66	46.94	195	-5.3
L50A	52.16	52.64	64	59–62	40.67	305	–4.0
L60A	54.43	54.98	70	61–64	39.41	169	-3.1
L120A	68.55	69.18	85	75–78	48.83	137	–1.9
L130A	52.47	53.05	80	72–76	45.01	188	–4.6
L140A	51.63	52.04	82	68–74	44.80	149	-3.4
L160A	38.10	38.66	46	39–43	32.02	294	-1.1
L210A	57.10	57.61	70	62–64	54.48	276	-8.4
L230A	54.23	54.58	79	72–76	47.26	204	–4.8
L240A	49.65	50.19	82	64–70	44.61	350	-3.3
L250A	42.96	43.43	68	52–60	43.63	226	-1.5
L260A	36.23	36.68	46	38–43	34.80	298	+2.2
L320A	47.85	48.44	64	60–63	44.03	152	–0.1
L330A	40.07	40.62	58	52–54	39.79	252	-1.9
L52 (a)	44.29	44.63	245	85–95	–	–	–4.0
L132 (a)	57.42	58.19	160	105–135	–	138	–4.6
L142 (a)	51.68	52.09	229	110–120	–	–	-3.4
M70	20.38	21.47	80	40–80	20.58	170	-11.1
M190	24.02	24.48	60	32–60	20.79	250	–4.4
M370	43.83	44.25	60	48–60	34.67	160	–6.2

Note: L Lexia
M Mirrabooka
(a) Proposed production bores

consumption. Before commissioning for production, each of the production bores was subjected to controlled pumping tests for periods ranging between 24 and 120 hours to determine depth of pump setting and duty pumping rates. All waterlevel and water-quality data are contained in SWRIS.

Analyses of drawdowns from uncontrolled, single-bore tests for confined aquifer coefficients are equivocal owing to partial screen penetration and leakage effects (Commander, 1971; Smith, 1979). Attempts have been made to monitor drawdown in bores at distances of several kilometres from the pumping bore, but these have generally been unsuccessful (Moncrieff, 1981). However, a test carried out on Wanneroo W255, screened against the Leederville aquifer, was successful (Commander, 1975).

Private and contamination-investigation drilling

Groundwater from shallow depths, suitable for irrigation and industry, is readily available over most of the Perth Region and has been extensively used by Local Government authorities, industry and the general public. Consequently, some 80 000 shallow bores have been drilled, mainly for household garden irrigation, and it has been estimated that one in four households use private groundwater supplies (Cargeeg et al., 1987). In those areas where the shallow groundwater is in small supply or too brackish for irrigation, deeper bores (approximately 200 m) have been drilled into the confined aquifers for industrial use and public open space, market garden and viticulture irrigation.

Because of the importance of groundwater to irrigation, industry, public water supply and the environment, there have been increasing efforts made to prevent it from becoming contaminated and many hundreds of bores have been drilled to investigate risk areas such as waste-disposal and landfill sites.

The Geological Survey has always been recognized as the State custodian of drilling and bore data. Consequently, numerous data comprising geological logs, drillers' logs, wireline logs, waterlevels, pumping results and water quality have been obtained. These are contained in many files, numerous hydrogeology reports, a comprehensive card index system and, more recently, in a computerized database (AQWABASE) at the Geological Survey. A large volume of hydraulic and water-quality data is also contained in SWRIS at the Water Authority.

Wireline logging

Geophysical wireline logs were run by the Geological Survey or, on occasion, by contractors. Gamma-ray logs were run in all the deep, unconfined aquifer bores and gamma-ray logs and long- and short-normal resistivity logs were run in each of the deep government bores and many private bores into the confined aquifers. Gamma–gamma, neutron, spontaneous potential, point resistance, conductivity, temperature, flow meter, downhole video and calliper logs have been run in a few of the deep bores. A

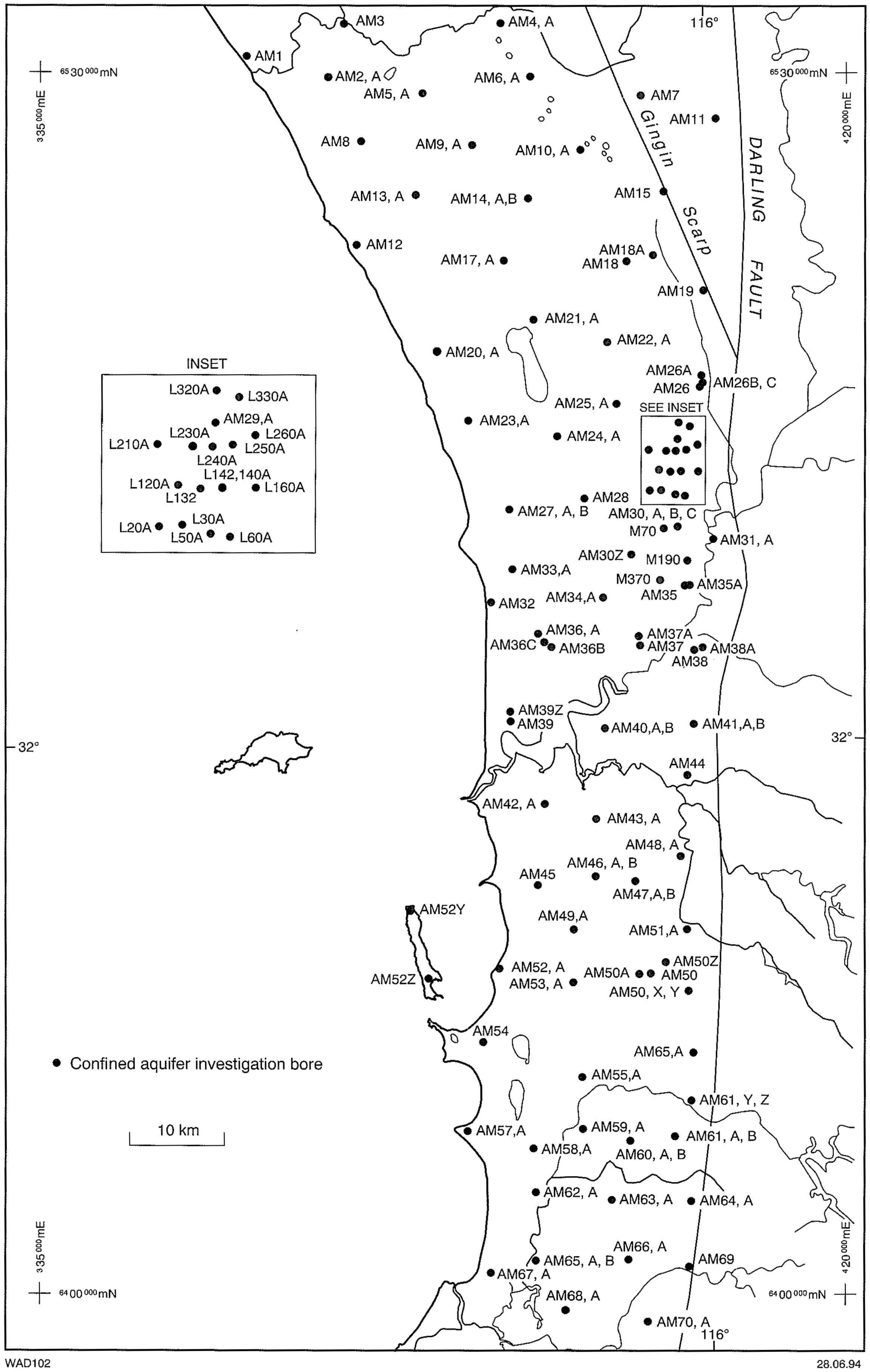

Figure 11. Confined aquifer investigtion bores

Table 6. Water Authority groundwater abstraction data

Scheme		*Total*	*Aquifer*	*Abstraction 1991/92*	
			bores	*m^3/d*	*$m^3/year \times 10^6$*
Mirrabooka		27	Superficial	37 662	13.747
		6	Mirrabooka	5 283	1.928
		5	Leederville	13 245	4.835
		1	Yarragadee	5 785	2.111
	Total	**39**		**61 975**	**22.621**
Gwelup		10	Superficial	16 992	6.202
		3	Mirrabooka	5 167	1.886
		5	Leederville	14 636	5.342
	Total	**18**		**36 795**	**13.430**
Wanneroo		24	Superficial	36 088	13.172
		6	Leederville	27 919	10.191
		1	Yarragadee	4 192	1.530
	Total	**31**		**68 199**	**24.893**
Jandakot		13	Superficial	10 965	4.002
		2	Leederville	3 196	1.167
	Total	**15**		**14 161**	**5.169**
Pinjar		9	Superficial	5 334	1.947
		1	Leederville	3 099	1.131
		1	Yarragadee	2 814	1.027
	Total	**11**		**11 247**	**4.105**
Yanchep/		4	Superficial	935	0.341
Two Rocks		4	Superficial	896	0.327
	Total	**8**		**1 831**	**0.668**
Independent		2	Leederville	5 003	1.826
Artesian		9	Yarragadee	21 484	7.842
	Total	**11**		**26 487**	**9.668**
TOTALS		91	Superficial	108 872	39.738
		9	Mirrabooka	10 450	3.814
		21	Leederville	67 098	24.492
		12	Yarragadee	34 275	12.510
		133		**220 695**	**80.554**

total of about 2500 wireline logs have been used to help correlate stratigraphic sequences over wide areas, to estimate groundwater salinity at varying depths and to detect various problems, such as corrosion, within the bores.

Groundwater salinities, within the confined aquifers, have been determined from the 64-inch long-normal resistivity logs using the relationship developed by Archie (1942): resistivity is measured in ohm metres (Ω m).

$$R_0 = FR_w \quad \text{...} \quad (1)$$

where R_0 = formation resistivity from 64-inch log (Ω m)
F = formation resistivity factor
R_w = formation-water resistivity (Ω m)

The formation resistivity factor (F) has been obtained empirically by measuring the resistivity of the formation water (R_w) sampled from the bore and using the formation resistivity from the 64-inch log (R_0) which corresponded to the interval sampled. This value of F was then used with the R_0 reading to determine the R_w of other sand beds within the aquifer. The total dissolved solids (TDS) was obtained from the empirical chart (Fig. 14) developed by D. L. Rowston of the Geological Survey (Kevi, 1988) relating TDS to R_w. The resistivity probes of the Geological Survey are periodically calibrated by logging a specially designed bore (Keysbrook calibration bore) for this purpose. An index of well logs is maintained by the Geological Survey and the original logs have been archived.

Temperature corrections and, where necessary, bed-thickness corrections were applied to the value of R_0 using published charts (Keys and McCary, 1971). An instrumental correction factor of 1.25 was also applied to logs obtained from the Geological Survey Gearhart Owen well-logging equipment.

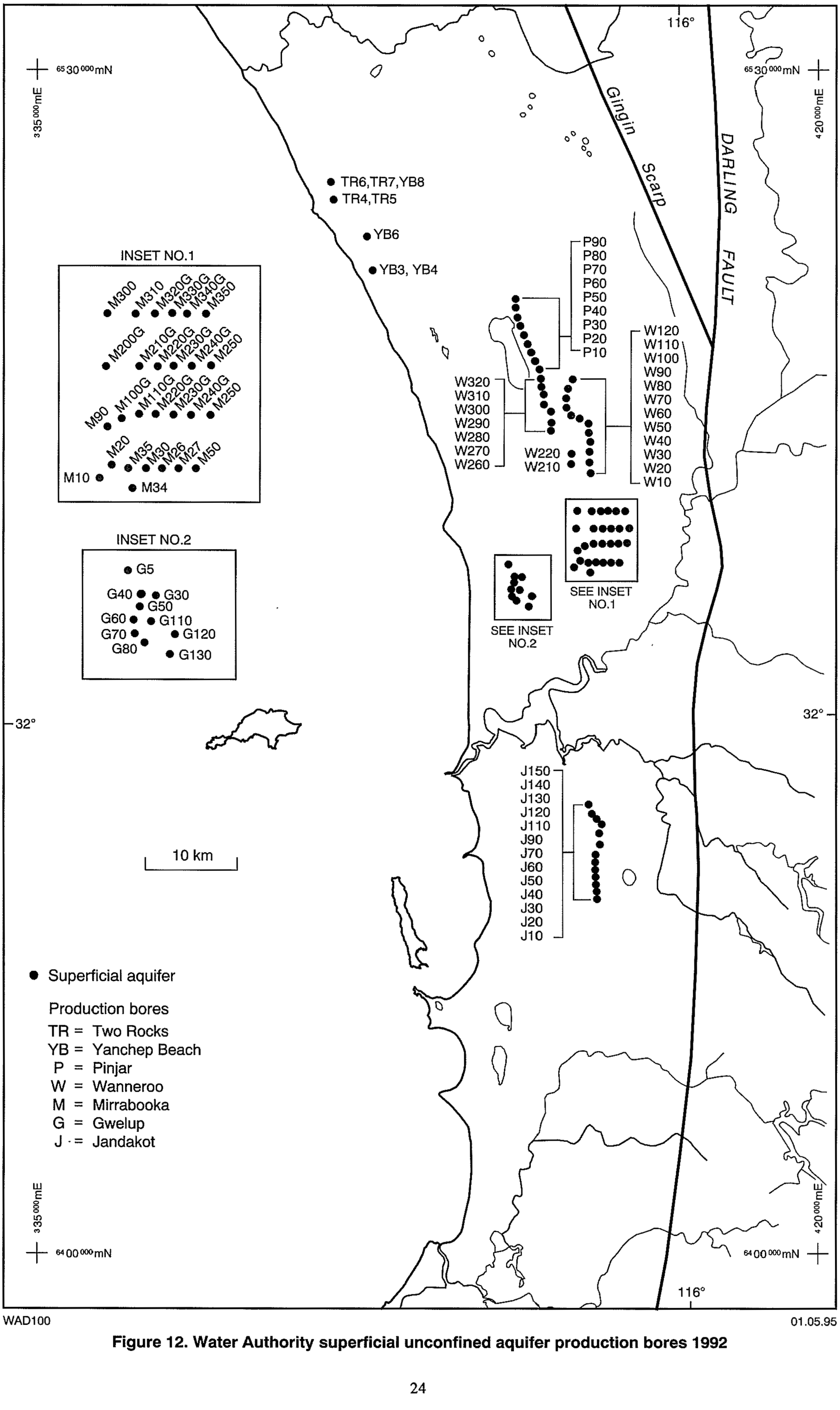

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Figure 12. Water Authority superficial unconfined aquifer production bores 1992

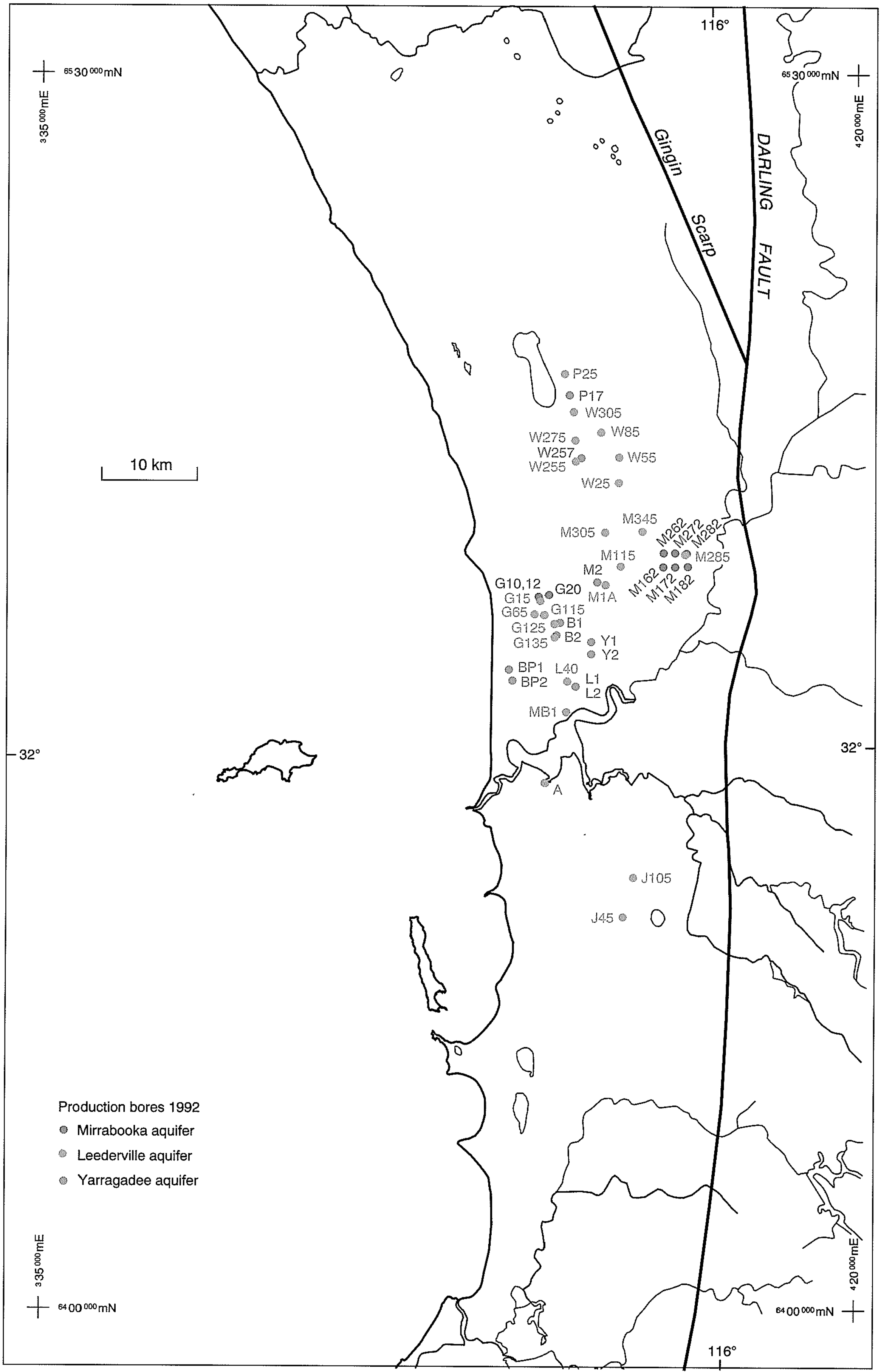

Figure 13. Water Authority confined aquifer production bores 1992

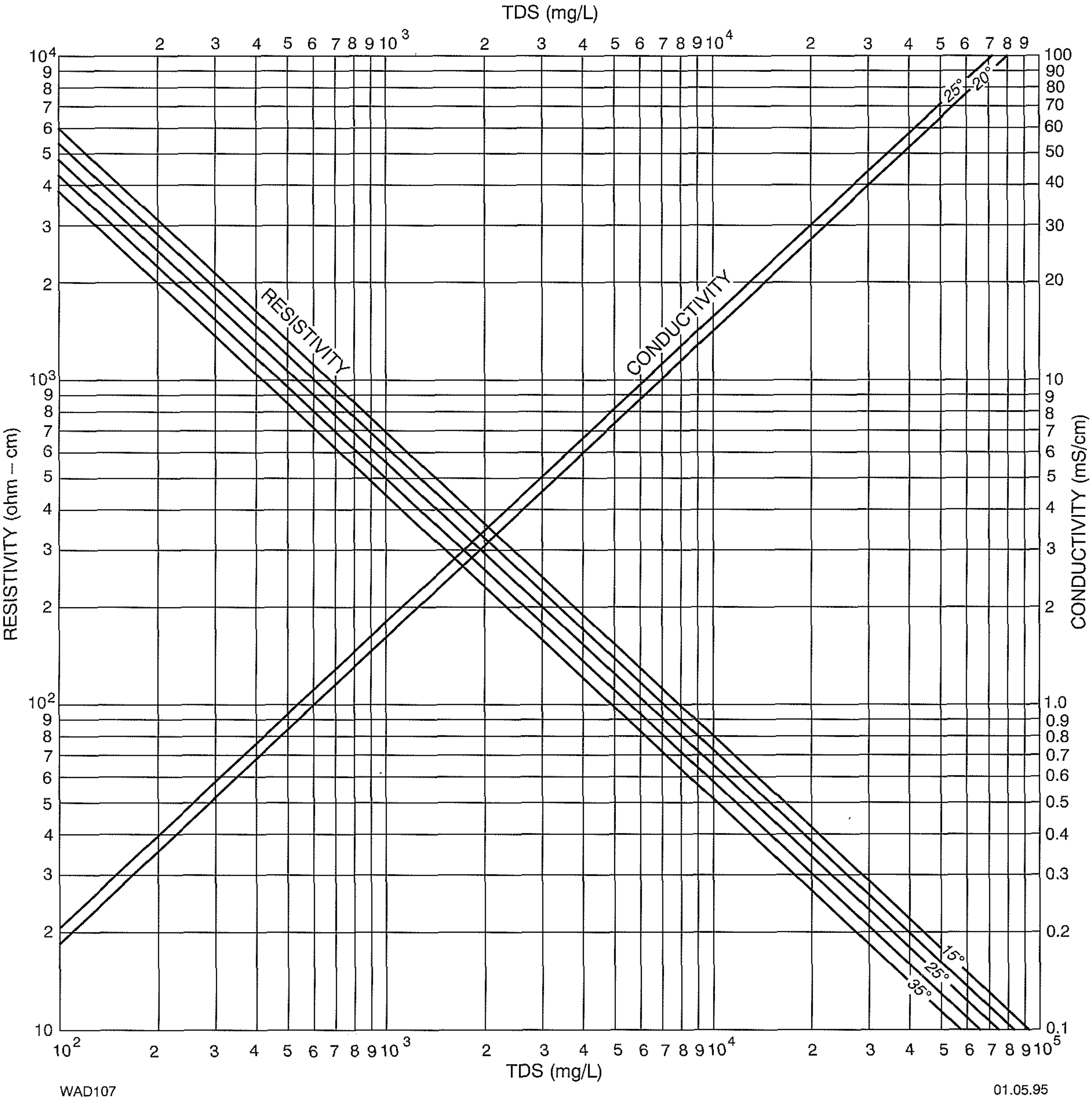

Figure 14. Relationships of groundwater salinity, resistivity, and conductivity at various temperatures

Palynology

Sidewall cores were obtained at about 30 m intervals from each of the artesian monitoring (AM) bores. Sampling was concentrated mainly in shales and siltstones adjacent to the upper and lower possible contacts of geological formations, with core locations having been selected from gamma-ray logs. The cores were processed and examined for indicator spores and pollens and, where possible, assigned an age. Sludge samples were obtained from most of the investigation bores during drilling and many of the samples from the base of the unconfined aquifer were palynologically examined to determine the underlying geological formations. Cores and sludge samples are stored in the Geological Survey core library. About 3000 of these samples have been examined and more than 600 unpublished reports have been prepared by the Geological Survey.

Palynology, geophysical wireline logs and lithology have been collated in this Bulletin to identify and map the various geological formations to a depth of some 1000 m beneath the Perth Region.

Geology

Setting

The Perth Region covers the central portion of the eastern onshore margin of the Perth Basin and overlies the southern end of the Dandaragan Trough, a major structural subdivision within the basin. Seismic data indicate that the sedimentary succession in this part of the Perth Basin is about 12 000 m thick (Playford et al., 1976) and separated from the crystalline rocks of the Yilgarn Craton by the Darling Fault. The strata have been gently folded in the northern area to form the Yanchep Syncline (in the west), Pinjar Anticline (central) and Swan Syncline (in the east).

The Perth Basin was formed during periods of rifting and sagging along the continental margin of southwestern Australia that culminated in separation from the rest of Gondwana during the Early Cretaceous. These events resulted in a faulted sedimentary sequence, which is bounded to the east by the Darling Fault and overlain by comparatively undeformed, mid-Neocomian and younger sediments deposited during the tectonically quiet period following separation. Prior to breakup, continental sedimentation (predominantly fluvial) prevailed through to the Late Jurassic and into the Cretaceous. During the Neocomian and following breakup, marine incursion resulted in periods of continental, paralic and marine sedimentation. By the Albian Stage of the Cretaceous, marine sedimentation dominated and thick sequences of glauconitic shale and greensand were deposited.

Over most of the Perth Region the Cretaceous sediments are concealed below a veneer of late Tertiary–Quaternary sediments. However, on the Dandaragan Plateau, between the Gingin Scarp and the Darling Fault, Cretaceous units outcrop in some of the valleys and deeply incised drainages. The Cainozoic sediments range from Tertiary marine carbonate deposits, occupying deeply eroded channels, to relatively flat-lying Quaternary shoreline and coastal-dune deposits with more recent alluvial and colluvial deposits associated with the present drainages and escarpment.

Stratigraphy

The stratigraphic units to a depth of about 2000 m are described in order of deposition and summarized in Table 7. Units that are defined in this Bulletin are described formally under discrete headings (e.g. Mariginiup Member). Detailed stratigraphic data from the artesian network of bores (AM bores) and other selected bores are given in Table 8 and a revised stratigraphic column is shown in Figures 15 and 16.

Jurassic

Cattamarra Coal Measures

The Cattamarra Coal Measures, previously referred to as the Cattamarra Coal Measures Member of the Cockleshell Gully Formation (Playford and Low, 1972), has been given formation status (Mory, 1994) and, in the Perth Region, replaces the stratigraphic unit previously referred to as the Cockleshell Gully Formation. The reference type section is in Eneabba No. 1 well (AMG Zone 50, 338446m E, 6727627m N) between 1554 and 2302 m depth.

The Cattamarra Coal Measures, which may be more than 1500 m thick, consists of interbedded non-marine, probably fluvial sandstones, siltstones and shales with minor coal seams. In the Perth Region, the sandstones are pale grey in colour, often clayey, mostly medium to coarse grained and are present in beds up to 50 m thick. The siltstones and shales are dark grey, sometimes carbonaceous, often laminated, and occur in beds up to 30 m thick. The upper section of the formation is commonly weathered to a yellow, reddish-brown colour; the lower sections are locally cemented and hard.

The formation extends beneath all of the coastal plain between Gingin Brook and the South Dandalup River, but it lies at a relatively shallow depth only in the southern area where the Yarragadee Formation is absent and where the Cattamarra Coal Measures has been block faulted upwards into juxtaposition with the Yarragadee Formation to the west. The formation is conformably overlain by the Yarragadee Formation beneath most of the Perth Region except in the southern area, where it is present at depths ranging from 13 to 405 m and is unconformably overlain by the Gage Formation, South Perth Shale, Leederville Formation (Mariginiup Member) or the superficial formations (Plate 1). The Cattamarra Coal Measures is of Pliensbachian to Aalenian age (Cockbain, 1990).

Yarragadee Formation

The Yarragadee Formation, defined by McWhae et al. (1958), consists of laterally discontinuous interbedded sandstones, siltstones and shales and is more than 2000 m thick. The type locality is 2.4 km south-southeast of Yarragadee homestead, some 300 km north of Perth (AMG Zone 50, 345646 m E, 6780254 m N) but, because this section is thin, a subsurface reference section has been nominated for Gingin No. 1 well from 356 to 3315 m by Playford et al. (1976) and Backhouse (1984).

Table 7. Stratigraphic sequence

	Age	*(10^6 years)*		*Stratigraphy*	*Symbol*	*Maximum thickness (m)*	*Lithology*	*Groundwater*
CAINOZOIC	Quaternary–Late Tertiary			Safety Bay Sand	Qs	24	Sand and shelly fragments	Superficial aquifer
				~~				
			Superficial formations	Becher Sand	Qc	20	Sand, silt, clay and shell fragments	
				~~				
				Tamala Limestone	Qt	110	Sand, limestone, minor clay	
				~~				
				Bassendean Sand	Qd	80	Sand and subordinate silt and clay	
				Gnangara Sand	Qn	30	Sand, gravel and subordinate silt and clay	
				Guildford Clay	Qg	35	Clay with subordinate sand and gravel	Local confining bed
				~~				
		2		Yoganup Formation	Ty	10	Sand, silt, clay and pebbles	Superficial aquifer
		2		Ascot Formation	Ta	25	Limestone, sand, shells and clay	
			~~	~~~~				
		2		Rockingham Sand	Tr	110	Sand, silt and subordinate clay	Rockingham aquifer
			~~	~~~~				
	Early Tertiary	54		Kings Park Formation	Tk	530	Shale, calcareous and glauconitic siltstone, minor sand	Confining bed
				Mullaloo Sandstone Member	Tkm	200	Sand, clayey and glauconitic	Minor aquifers
				Como Sandstone Member	Tkc	57	Sand, minor clay	
~~	~~~~	~~~~	~~~~	~~~~				
MESOZOIC	Cretaceous	80	Coolyena Group	Lancelin Formation	Kcl	120	Mudstone (marl), silty, clayey and glauconitic	Confining bed
				Poison Hill Greensand	Kcp	90	Sand, silty, clayey and glauconitic	Mirrabooka aquifer
		88		Gingin Chalk	Kcg	40	Chalk, sandy and glauconitic	Local confining bed
		98		Molecap Greensand	Kcm	80	Sand, clayey and glauconitic	Mirrabooka aquifer
				~~				
		114		Osborne Formation	Kco	180	Sandstone, siltstone and shale	
				Mirrabooka Member	Kcom	160	Sandstone, siltstone and shale	
				Kardinya Shale Member	Kcok	140	Shale, siltstone, minor sandstone	Confining bed
				Henley Sandstone Member	Kcoh	100	Sand, silty, clayey and glauconitic	Leederville aquifer
			~~	~~~~				
		118	Warnbro Group	Leederville Formation	Kwl	600	Sandstone, siltstone and shale	
				Pinjar Member	Kwlp	150	Sandstone, siltstone and shale	
				Wanneroo Member	Kwlw	450	Sandstone, siltstone and shale	
				Mariginiup Member	Kwlm	250	Sandstone, siltstone and shale	
				South Perth Shale	Kws	300	Shale, siltstone, minor sandstone	Confining bed
				Gage Formation	Kwg	350	Sandstone, siltstone and shale	Yarragadee aquifer
			~~	~~~~				
	Cretaceous–Jurassic	140		Parmelia Formation	Kp	>287	Sandstone, siltstone and shale	
				Carnac Member	Kpc		Shale and siltstone	Local confining beds
				Otorowiri Member	Kpo		Shale and siltstone	
	Jurassic	146		Yarragadee Formation	Jy	>2 000	Sandstone, siltstone and shale	Yarragadee aquifer
				Cattamarra Coal Measures	Jc	>500	Sandstone, siltstone and shale	

~~~~ unconformity
~~~~

Table 8. Stratigraphic data from artesian monitoring (AM) and selected bores

Bore	Ground level (m AHD)	Base of formation below ground level (m)																						
				Tk							Kco			Kwl					Kp					
		TQ	Tr	Tkm		Tkc	Kcl	Kcp	Kcg	Kcm	Kcom	Kcok	Kcoh	Kwlp	Kwlw	Kwlm	Kws	Kwg		Kpc		Kpo	Jy	Jc
Artesian monitoring bores																								
1	53	99	–	–	–	–	157	–	167	218	–	–	–	222	499	505	517	–	680	794	–	–	–	–
2	36	61	–	–	–	–	96	–	120	123	–	210	–	220	605	775	803	829	–	–	–	–	881	–
3	27	39	–	–	–	–	44	–	60	70	–	164	–	167	606	729	–	–	–	–	–	–	–	–
4A	50	41	–	–	–	–	–	–	–	–	–	–	–	92	143	200	204	332	–	–	–	–	549	–
5	52	54	–	–	–	–	–	–	–	–	–	–	–	–	242	277	–	–	–	–	–	–	302	–
6	64	28	–	–	–	–	–	–	–	–	–	–	–	–	80	–	–	–	–	–	–	–	300	–
7	102	3	–	–	–	–	–	–	–	–	–	20	–	168	306	–	–	–	–	721	–	–	–	–
8	52	75	–	–	162	–	183	–	226	–	–	340	–	371	810	–	–	–	–	–	–	–	–	–
9	59	58	–	–	–	–	–	–	–	–	–	–	–	203	303	–	–	–	–	–	–	–	–	–
10	69	51	–	–	–	–	–	–	–	–	–	–	–	93	111	135	–	–	298	–	–	–	–	–
11	190	3	–	–	–	–	–	76	93	113	–	229	270	342	684	714	–	–	782	810	–	–	–	–
12	16	45	–	–	191	–	208	–	247	256	–	373	–	419	750	838	–	–	–	–	–	–	–	–
13	54	65	–	–	–	–	–	–	–	–	–	–	–	108	259	323	–	–	–	–	–	–	798	–
14	75	69	–	–	–	–	–	–	–	–	–	–	–	–	161	170	–	–	–	–	–	–	810	–
15	69	20	–	–	–	–	–	63	71	81	–	97	–	180	480	497	–	–	–	784	–	–	–	–
16	Not drilled		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
17	72	80	–	–	–	–	–	–	–	–	–	–	–	–	108	199	–	–	–	–	–	–	301	–
18	77	69	–	–	–	–	–	–	–	–	–	–	–	102	300	–	–	–	–	–	–	–	–	–
18A	60	37	–	–	–	–	–	51	59	102	–	–	143	365	490	–	–	–	676	–	–	–	–	–
19	69	27	–	–	–	–	–	–	–	–	–	137	148	194	480	500	–	–	698	802	–	–	–	–
20	29	56	–	–	–	–	–	–	–	–	–	–	–	68	192	269	312	–	–	–	–	–	467	–
21	59	60	–	–	–	–	–	–	–	–	–	–	–	–	132	192	218	–	–	–	–	–	464	–
22	82	64	–	–	–	–	–	–	–	–	–	–	–	153	414	–	–	–	610	–	–	–	–	–
23	29	57	–	–	–	–	–	–	–	–	–	–	–	84	190	240	304	335	–	–	–	–	470	–
24	50	55	–	–	–	–	–	66	80	103	–	142	157	223	423	507	798	908	–	–	–	–	–	–
25	73	63	–	–	–	–	–	78	87	122	–	144	–	150	348	382	430	474	605	–	–	–	–	–
26	37	24	–	–	–	–	–	57	63	82	–	94	103	–	426	481	527	–	662	674	–	–	–	–
27	34	67	–	–	–	–	–	–	–	80	–	–	97	118	273	325	389	434	–	–	–	–	762	–
28	53	58	–	–	–	–	–	144	165	192	–	218	225	292	503	554	625	–	–	–	–	–	–	–
29	48	54	–	–	–	–	–	122	137	149	–	163	184	300	516	578	636	–	–	–	–	–	753	–
30	50	53	–	–	–	–	–	122	129	148	–	168	206	225	500	527	626	–	–	–	–	–	747	–
30Z	39	34	–	–	–	–	–	–	–	–	199	217	226	330	508	523	565	–	–	–	–	–	–	–
31	6	15	–	–	–	–	–	–	–	–	–	91	98	103	326	406	441	–	–	–	–	–	800	–
32	13	54	–	–	209	232	–	–	–	–	–	–	–	–	–	–	294	363	–	–	–	–	404	–
33A	7	34	–	52	–	–	–	–	–	–	105	109	117	126	264	309	376	437	–	–	–	–	533	–
34A	41	46	–	–	–	–	–	–	–	–	–	116	214	270	495	540	638	735	–	–	–	–	–	–
35A	17	20	–	–	–	–	–	–	–	–	48	134	144	198	450	495	561	–	–	–	–	–	649	–
36	16	36	–	–	–	–	–	–	–	55	–	88	114	144	276	297	398	465	–	–	–	–	616	–
37A	21	29	–	–	–	–	–	–	–	–	142	174	205	336	540	601	681	732	–	–	–	–	804	–
38A	11	18	–	–	–	–	–	–	–	–	–	30	62	137	335	381	420	550	–	–	–	–	–	–
39Z	8	32	–	122	558	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	595	–
40	23	33	–	166	326	383	–	–	–	–	–	–	–	–	493	517	610	705	–	–	–	–	741	–
41	21	23	–	–	62	–	–	–	–	–	–	69	94	–	312	355	399	419	–	–	–	–	505	–
42	29	28	–	–	–	–	–	–	–	–	–	167	177	186	333	399	499	600	–	–	–	–	–	–
43A	29	48	–	–	–	–	–	–	–	–	–	180	–	275	369	506	558	647	–	–	–	–	794	–
44	6	12	–	–	–	–	–	–	–	–	–	28	35	132	186	280	333	–	–	–	–	–	–	–

Table 8. *(continued)*

Bore	*Ground level (m AHD)*	*Base of formation below ground level (m)*																						
				Tk							*Kco*			*Kwl*					*Kp*					
		TQ	*Tr*	*Tkm*		*Tkc*	*Kcl*	*Kcp*	*Kcg*	*Kcm*	*Kcom*	*Kcok*	*Kcoh*	*Kwlp*	*Kwlw*	*Kwlm*	*Kws*	*Kwg*		*Kpc*		*Kpo*	*Jy*	*Jc*
45	39	63	–	–	–	–	–	–	–	–	–	181	–	222	338	396	409	–	–	–	–	–	–	–
46	28	49	–	–	–	–	–	–	–	–	–	88	116	216	360	420	475	581	–	–	–	–	801	–
47	27	48	–	–	–	–	–	–	–	–	–	55	66	145	235	302	340	405	–	–	–	–	742	–
48	24	27	–	–	–	–	–	–	–	–	–	–	–	–	197	320	–	357	–	–	–	–	618	–
49	36	54	–	–	–	–	–	–	–	–	–	104	117	192	300	375	432	449	–	–	–	–	554	–
50	16	28	–	–	–	–	–	–	–	–	–	–	–	37	123	209	241	–	–	–	–	–	354	–
50Y	31	27	–	–	–	–	–	–	–	–	–	–	–	100	–	–	–	–	–	–	–	–	–	301
50Z	21	13	–	–	–	–	–	–	–	–	–	–	–	91	–	–	–	–	–	–	–	–	–	183
51	27	15	–	–	–	–	–	–	–	–	–	–	–	44	57	128	–	–	–	–	–	–	–	421
52	4	28	–	–	–	–	–	–	–	–	–	–	–	95	204	243	378	481	–	–	–	–	–	–
52Y	6	34	–	–	–	–	–	–	–	–	–	164	174	238	252	288	331	435	–	–	–	–	–	–
52Z	4	34	94	–	186	–	–	–	–	–	–	223	238	–	–	302	361	–	–	–	–	–	–	387
53A	22	42	–	–	–	–	–	–	–	–	–	63	–	141	264	355	393	523	–	–	–	–	551	–
54	5	28	138	–	–	–	–	–	–	–	–	–	–	–	194	243	331	392	–	–	–	–	–	448
55	7	18	–	–	–	–	–	–	–	–	–	–	–	75	120	245	305	339	–	–	–	–	401	–
56	34	15	–	–	–	–	–	–	–	–	–	–	–	–	47	119	–	–	–	–	–	–	–	353
57	2	37	136	–	–	–	–	–	–	–	–	–	–	–	157	283	326	405	–	–	–	–	–	801
58	9	24	101	–	–	–	–	–	–	–	–	–	–	–	140	246	288	345	–	–	–	–	746	–
59	8	14	–	–	–	–	–	–	–	–	–	–	–	28	128	229	263	333	–	–	–	–	796	–
60	16	12	–	–	–	–	–	–	–	–	–	–	–	–	78	160	185	213	–	–	–	–	810	–
61	37	16	–	–	–	–	–	–	–	–	–	–	–	–	39	105	–	–	–	–	–	–	–	802
62	8	17	51	–	–	–	–	–	–	–	–	–	–	–	70	195	237	276	–	–	–	–	–	386
63	22	15	–	–	–	–	–	–	–	–	–	–	–	25	99	216	240	–	–	–	–	–	349	–
64	55	13	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		357
65	2	9	57	–	–	–	–	–	–	–	–	–	–	–	69	188	208	–	–	–	–	–		363
66	21	10	–	–	–	–	–	–	–	–	–	–	–	–	36	142	149	188	–	–	–	–	384	–
67	11	21	44	–	–	–	–	–	–	–	–	–	–	–	96	186	246	–	–	–	–	–	–	375
68	9	8	58	–	–	–	–	–	–	–	–	–	–	–	80	176	203	287	–	–	–	–	–	327
69	41	2	–	–	–	–	–	–	–	–	–	–	–	–	–	60	–	–	–	–	–	–	–	417
70	21	4	–	–	–	–	–	–	–	–	–	–	–	–	–	103	–	–	–	–	–	–	–	505
Miscellaneous bores (onshore)																								
P3	62	58	–	–	–	–	–	–	–	–	–	–	–	–	271	308	360	450	–	–	–	–	542	–
P4	71	84	–	–	–	–	–	–	–	–	–	–	–	–	256	297	377	–	–	–	–	–	519	–
P6	6	39	–	–	–	–	–	–	–	–	–	–	–	–	194	258	341	–	–	–	–	–	604	–
P7	67	6	–	–	–	–	–	–	–	–	–	9	26	–	256	277	350	–	555	–	–	–	–	–
W1	91	113	–	–	–	–	–	128	144	174	–	204	234	299	526	612	854	906	–	–	–	–	–	–
W257	55	63	–	–	–	–	–	115	124	128	–	140	171	247	435	580	815	915	–	–	–	–	1 108	–
M1	42	52	–	–	–	–	–	–	–	58	–	122	197	238	451	514	579	716	–	–	–	–	–	–
M55	32	35	–	–	–	–	–	–	–	–	183	200	208	283	450	500	–	–	–	–	–	–	–	–
M285	35	39	–	–	–	–	–	71	–	90	118	143	183	219	458	516	526	–	–	–	–	–	–	–
M305	45	49	–	–	–	–	–	–	–	–	100	174	201	263	463	488	–	–	–	–	–	–	–	–
M345	46	47	–	–	–	–	–	–	–	–	188	206	–	238	516	–	–	–	–	–	–	–	–	–
BP1	13	49	–	–	108	–	–	–	–	–	–	116	122	174	201	253	293	436	–	–	–	–	615	–
YSC1	26	55	–	–	–	–	75	–	83	–	–	158	–	210	345	362	448	504	–	–	–	–	–	–
Y2	14	34	–	–	–	–	–	–	–	–	56	171	201	256	439	488	552	732	–	–	–	–	–	–
J45	31	52	–	–	–	–	–	–	–	–	–	91	129	207	285	396	434	–	–	–	–	–	–	–

Table 8. (*continued*)

Bore	*Ground level (m AHD)*	*Base of formation below ground level (m)*																						
				Tk							*Kco*			*Kwl*					*Kp*					
		TQ	*Tr*	*Tkm*		*Tkc*	*Kcl*	*Kcp*	*Kcg*	*Kcm*	*Kcom*	*Kcok*	*Kcoh*	*Kwlp*	*Kwlw*	*Kwlm*	*Kws*	*Kwg*		*Kpc*		*Kpo*	*Jy*	*Jc*
J105	28	42	–	–	–	–	–	–	–	–	–	60	88	176	268	367	400	–	–	–	–	–	–	–
JWS1	22	45	–	–	–	–	–	–	–	–	–	159	–	236	342	429	484	555	–	–	–	–	822	–
WP	4	30	–	–	–	–	–	–	–	–	–	50	–	–	67	207	324	399	–	–	–	–	449	–
GB1	117	14	–	–	–	–	–	18	23	–	–	100	–	184	316	–	–	–	–	–	–	–	–	–
GB2	58	46	–	–	–	–	–	–	–	–	–	–	–	97	152	168	–	–	–	–	–	–	509	–
GB3	31	34	–	–	–	–	–	–	–	–	–	–	–	40	253	360	376	405	–	–	–	–	719	–
GB4	9	45	–	–	–	–	53	–	66	86	–	165	–	175	535	–	–	–	–	–	–	–	–	–
GB5	103	2	–	–	–	–	–	–	–	–	–	–	–	18	82	–	–	–	–	127	451	516	–	–
Petroleum wells (offshore)																								
QR1	0	355	Undifferentiated Cainozoic sequence			–	–	–	–	–	–	–		———	611	———	760	775	1 590	–	–	1 670	2 210	–
C1	0	410				–	–	–	–	–	–	–	–		870		1 485	1 590	2 160	2 435	–	–	–	–
Mu1	0	442				–	–	–	–	–	–	–	–		867		1 505	1 625	2 000	–	–	–	–	–
GR1	0	620				–	–	–	–	–	–	–	–		1 045		1 585	1 800	2 535	–	–	2 615	3 000	–
GR2	0	575				–	–	–	–	–	–	–	–		1 085		1 350	1 365	1 580	1 790	2 850	2 930	2 985	–
Wa1	0	1 080				–	–	–	–	–	–	–	–		1 490		1 945	2 070	2 930	–	–	2 965	3 300	–
Pe1	0	865				–	–	–	–	–	–	–	–		1 280		1 620	1 730	–	3 060	3 500	3 550	4 000	–

Notes:

TQ	Superficial formations
Tr	Rockingham Sand
Tk	Kings Park Formation
Tkm	Mullaloo Sandstone Member
Tkc	Como Sandstone Member
Kcl	Lancelin Formation
Kcp	Poison Hill Greensand
Kcg	Gingin Chalk
Kcm	Molecap Greensand
Kco	Osborne Formation
Kcom	Mirrabooka Member
Kcok	Kardinya Shale Member
Kcoh	Henley Sandstone Member
Kwl	Leederville Formation
Kwlp	Pinjar Member
Kwlw	Wanneroo Member
Kwlm	Marinjiniup Member
Kws	South Perth Shale
Kwg	Gage Formation
Kp	Parmelia Formation
Kpc	Carnac Member
Kpo	Otorowiri Member
Jy	Yarragadee Formation
Jc	Cattamarra Coal Measures
P	Pinjar
W	Wanneroo
M	Mirrabooka
BP	Bold Park
YSC	Yanchep Sailing Club
Y	Mt Yokine
J	Jandakot
JWS	Jandakot Water Supply
WP	Woodman Point
GB	Gingin Brook
QR	Quinns Rock
C	Charlotte
Mu	Mullaloo
GR	Gage Roads
W	Warnbro
Pe	Peel

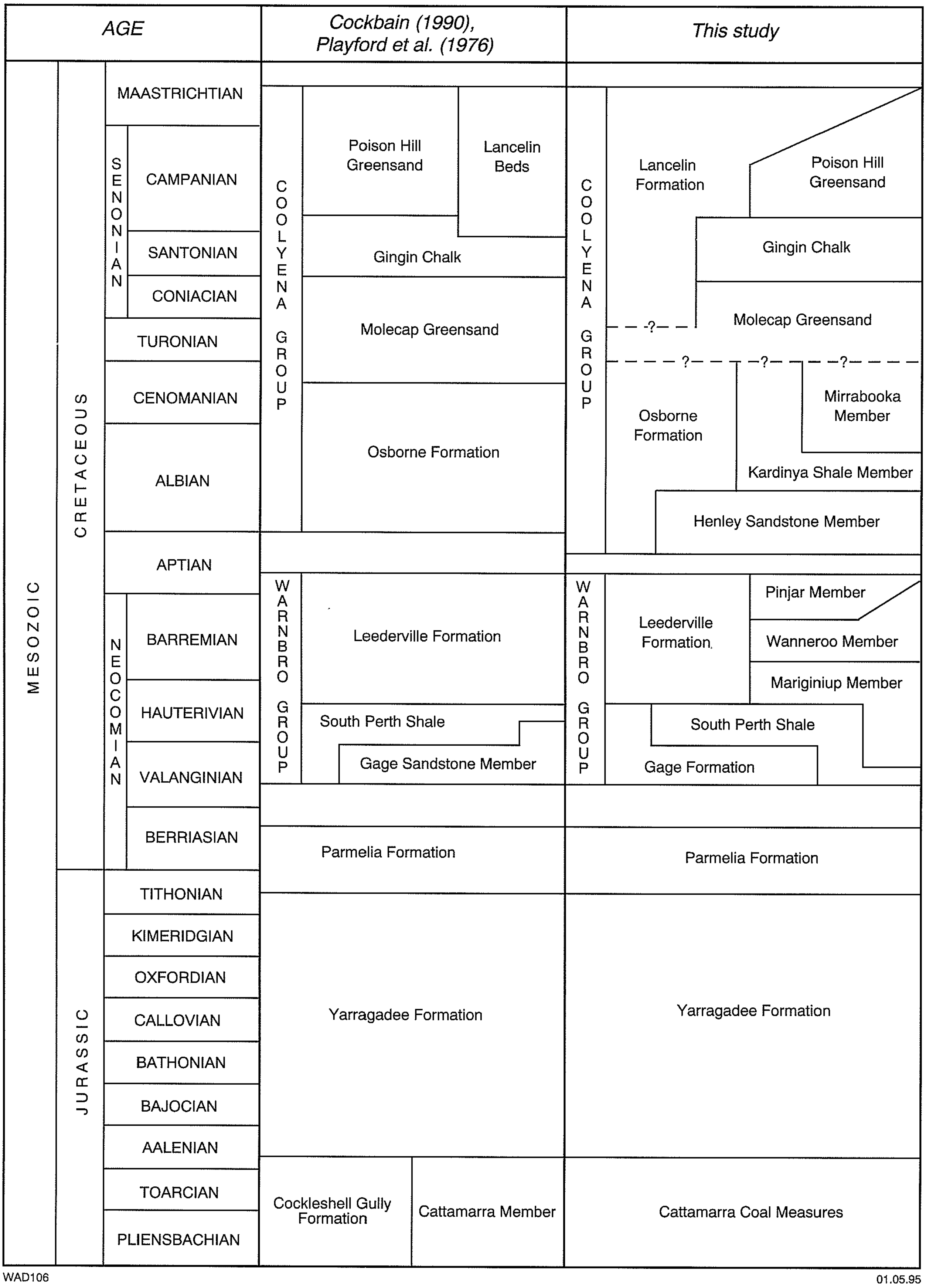

Figure 15. Mesozoic stratigraphic column, Perth Basin, Perth Region

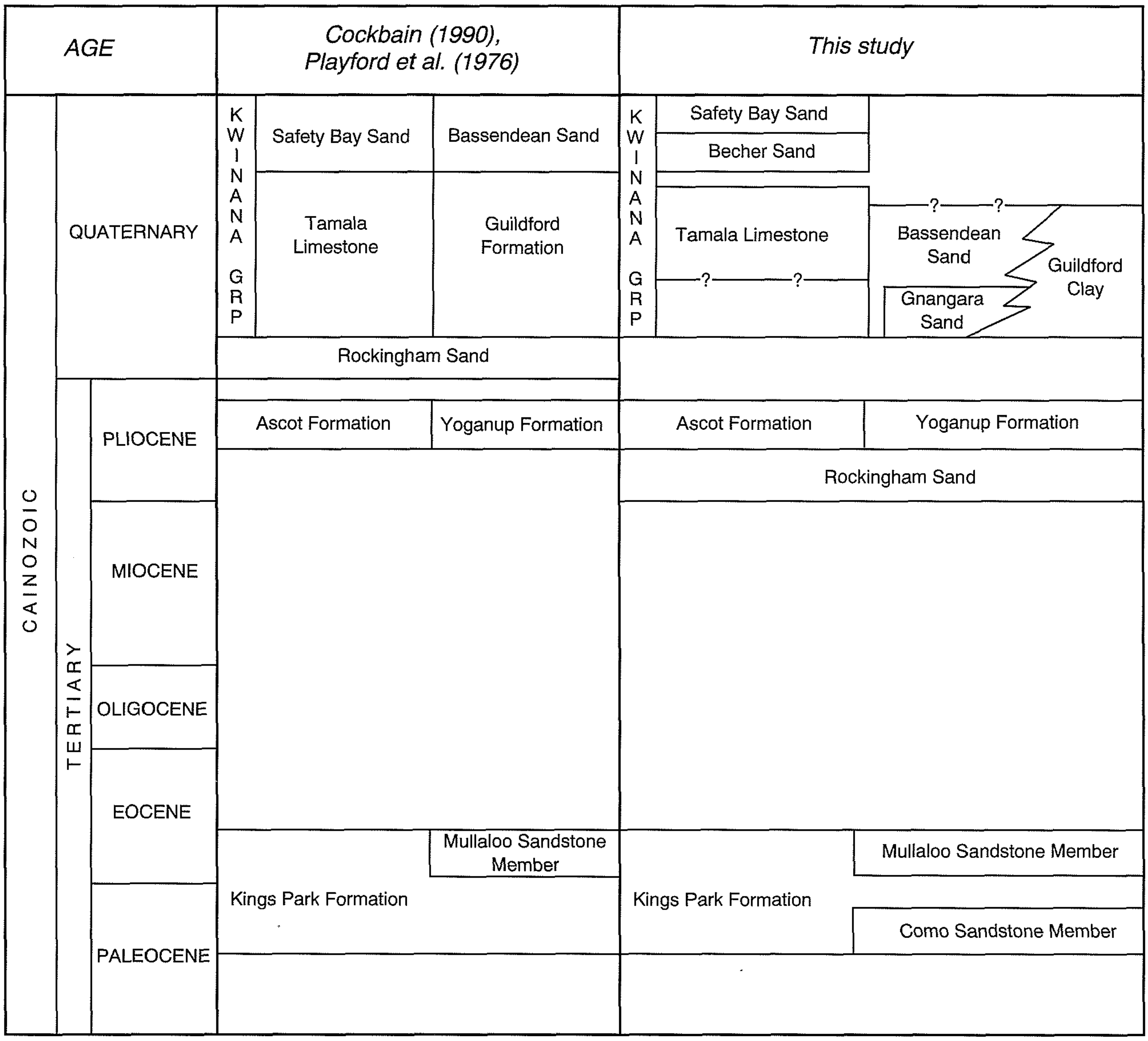

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Figure 16. Cainozoic stratigraphic column, Perth Basin, Perth Region

Within the Yanchep and Swan Synclines, the formation is non-marine, probably fluvial, with individual sandstone beds up to 30 m thick. These consist of pale grey, medium- to very coarse-grained, poorly sorted, slightly felspathic and weakly cemented sand. The siltstones and shales are of similar thickness to the sandstone beds and are commonly pyritic and micaceous (Allen, 1981a). Within the area of the Pinjar Anticline, and particularly beneath the Wanneroo area, the Yarragadee Formation was probably laid down in a shallow-marine or paralic environment. Here the sandstones are of similar thickness to those elsewhere but are generally finer grained and better sorted. Thinly interbedded sandstone, siltstone and shale also occur throughout the entire thickness of the Yarragadee Formation.

The Yarragadee Formation extends beneath the coastal plain except in the south and southeast margin of the Perth Region where it has been faulted and eroded out prior to the deposition of the Gage Formation, South Perth Shale and the Leederville Formation. In the northeastern area, the Yarragadee Formation is conformably overlain by the Parmelia Formation (Backhouse, 1984); elsewhere it is unconformably overlain by the Gage Formation, South Perth Shale or Leederville Formation (Mariginiup Member and Wanneroo Member). Near Perth, the upper section of the Yarragadee Formation and overlying Cretaceous units have been eroded prior to the deposition of the Kings Park Formation. Structure contours on the top of the Yarragadee Formation (Plate 2), taken together with surface topographic contours (Fig. 5), show that the formation lies at depths greater than 800 m in the Yanchep Syncline and at about 860 m in the Wanneroo area. The surface of the Yarragadee Formation rises gradually in a southerly direction from a depth of about 800 m in the Perth area to about 130 m in the southern part of the Perth Region. The Yarragadee Formation is of Aalenian to Tithonian age (Cockbain, 1990).

Jurassic–Cretaceous

Parmelia Formation

The Parmelia Formation, defined by Backhouse (1984), consists of interbedded sandstones, siltstones and shales with the type section in Peel No. 1 well (AMG Zone 50, 353561 m E, 6429303 m N) between 1625 and 3551 m depth.

In the Perth Region, the individual sandstone beds are variable in thickness but are generally only about 5 m thick. The sandstone beds, which are lithologically similar to those of the upper part of the Yarragadee Formation, consist of pale-grey, fine to very coarse (predominantly medium), subangular grains in a weak kaolinitic or siliceous cement. The shale and siltstone beds are together about the same thickness as the sandstone beds and are pale to dark grey, micaceous, carbonaceous and subfissile. Siltstone also occurs as thin laminae within the shale and sandstone beds (Backhouse, 1984).

Separate from the interbedded siltstones and shales, two thick siltstone–shale members are contained within the Parmelia Formation. The Otorowiri Member occurs at the base of the formation but was intersected only in the northeastern area in borehole GB5. The Carnac Member, which is present in the middle of the formation, is a thick, dark-grey siltstone–shale sequence. In AM15, the member is at least 287 m thick (its base was not intersected).

The Parmelia Formation is identified in the northeastern area where it conformably overlies the Yarragadee Formation, and is unconformably overlain by the Gage Formation, South Perth Shale or Leederville Formation (Mariginiup Member and Wanneroo Member). Structure contours on the top of the Parmelia Formation are shown in Plate 3 and, together with surface topographic contours (Fig. 5), indicate that the formation lies at depths ranging from about 60 to 700 m. However, without palynological data and from geophysical logs alone, it is difficult to distinguish from the Yarragadee Formation and thus may be of broader extent. The Parmelia Formation is of Tithonian to Berriasian age (Backhouse, 1984).

Cretaceous (Warnbro Group)

During the Early Cretaceous, there was continental to shallow-marine sedimentation within the Perth Region of the Perth Basin. These sediments, collectively referred to as the Warnbro Group (Cockbain and Playford, 1973), comprise the Gage Formation, South Perth Shale and Leederville Formation. The Warnbro Group unconformably overlies the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formation on an erosional surface developed during the Neocomian (Plate 4).

Gage Formation

The Gage Formation was formerly referred to as the Gage Sandstone Member of the South Perth Shale (Bozanic, 1969). In this Bulletin it has been upgraded to the Gage Formation because it consists of interbedded sandstones, siltstones and shales, and can be mapped at the base of the Warnbro Group over a large area of the central onshore margin of the Perth Basin. The type section is between 1588 and 1801 m in Gage Roads No. 1 well, approximately 35 km offshore, west of Perth, and in the Vlaming Sub-basin (AMG Zone 50, 346768 m E, 6463299 m N).

The sandstone beds are of variable thickness (3 to 30 m) which typically fluctuates directly with that of the formation. They consist of pale-grey, fine- to coarse-grained sand similar to that of the Yarragadee Formation, from which they probably originated by erosion. The interbedded siltstones and shales are pale grey to grey brown in colour, slightly micaceous and commonly in beds less than 6 m thick. However, cumulatively, with the interbedded sandstones, they may form thick sections of mainly sandstone or mainly siltstone.

The Gage Formation was probably deposited in a paralic environment infilling structurally low areas on the intra-Neocomian erosional unconformity (Plate 4). The formation unconformably overlies the Yarragadee Formation except in the southwest where it unconformably overlies the Cattamarra Coal Measures. It is overlain, with a conformable and abrupt contact, by the South Perth Shale or the Leederville Formation (Mariginiup Member) and, near Perth, unconformably by the Kings Park Formation. Structure contours on the top of the Gage Formation (Plate 5), together with surface topographic contours (Fig. 5), show that the formation lies at depths ranging from 150 to 900 m. A maximum onshore thickness of about 350 m (Plate 6) has been estimated for the Gage Formation from geophysical log interpretation. However, with further drilling and palynological examination, the Gage Formation in some areas may be reinterpreted as Yarragadee Formation. The Gage Formation is of Valanginian to Hauterivian age (Cockbain, 1990).

South Perth Shale

The South Perth Shale, defined by Playford et al. (1976), with its type section in South Perth No. 1 bore (AMG Zone 50, 391353 m E, 6460822 m N) between 498 and 567 m, is predominantly of shallow-marine origin and consists mainly of thinly interbedded, grey to black siltstone and shale with minor thin, sandy beds and local thin, calcareous beds.

In the southern Perth Region, the South Perth Shale is commonly cemented, hard, and is pyritic and glauconitic. In the northern area this unit may be weakly cemented, though mostly it is uncemented and has a tendency to be squeezed by overburden pressure into uncased boreholes.

The South Perth Shale unconformably overlies the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formation, and conformably overlies the Gage Formation (Plate 7). The South Perth Shale is overlain, with a conformable and transitional contact, by the Leederville Formation (Mariginiup Member and Wanneroo Member) and, near Perth, is unconformably overlain by the Kings Park Formation. Structure contours on the top of the South Perth Shale (Plate 8), together with surface topographic contours (Fig. 5), show that the formation is present at depths ranging from 140 to 900 m. The formation has an estimated maximum thickness of about 300 m (Plate 9) and, like the Gage Formation, it is best developed in the tectonically downthrown parts of the Perth Basin. The South Perth Shale is of Valanginian to Hauterivian age (Cockbain, 1990).

Leederville Formation

The Leederville Formation, defined by Cockbain and Playford (1973), with its type section in the Leederville Valley (Redan Street) bore between 198 and 433 m (AMG Zone 50, 389905 m E, 6466073 m N), consists predominantly of discontinuous, interbedded sandstones, siltstones and shales with some conglomerate to the east, near the Darling Scarp (Allen, 1979).

The sandstone beds of the Leederville Formation are of variable thickness and are similar to those of the Yarragadee Formation, although they are generally individually thinner. The sand is fine to coarse grained, angular to subangular, and mainly poorly sorted. Pyrite and carbonaceous material are common in the non-marine facies of the formation and glauconite is common in the marine facies, particularly south of Perth. Thin calcareous- and pyritic-cemented beds of sand occur in the marine facies over most the of the southern half of the Perth Region.

Individual sandstone beds are commonly between 6 and 20 m thick, although locally, beds may reach 60 m in thickness, particularly south of Perth. However, the areas with the thickest sandstone beds do not necessarily coincide with the areas of greatest formation thickness.

The Leederville Formation unconformably overlies the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formation, and conformably overlies the Gage Formation or the South Perth Shale with a transitional contact (Plate 10). The formation is unconformably overlain by the Osborne Formation (Henley Sandstone Member and Kardinya Shale Member), Molecap Greensand, Gingin Chalk or the superficial formations. In the Perth area, much of the Leederville Formation has been eroded prior to the deposition of the Kings Park Formation. In the Rockingham area it has been deeply eroded and is overlain by the Rockingham Sand. Structural contours on the top of the Leederville Formation (Plate 11), together with surface topographic contours (Fig. 5), show that the formation lies at depths ranging from 10 to 360 m.

The thickest sections of the Leederville Formation occur within the synclinal structures (Plate 12), and the maximum thickness onshore is about 600 m within the axis of the Yanchep Syncline to the east of Guilderton. North of Perth, in the axis of the Swan Syncline, the maximum thickness of the Leederville Formation is about 450 m, whereas over the Pinjar Anticline the minimum thickness is about 50 m. To the east, the formation overlaps the Darling Fault, which forms the approximate boundary between the sedimentary rocks of the Perth Basin and the crystalline rocks of the Yilgarn Craton.

Beneath the onshore area between Guilderton and Mandurah, the Leederville Formation comprises three distinct and mappable units which are described, for the first time, as members of the formation. In order of deposition they are the Mariginiup Member, Wanneroo Member and Pinjar Member and range in age from Valanginian to Aptian (Fig. 15).

Mariginiup Member

Derivation of name: Lake Mariginiup, Wanneroo

Type section: Artesian monitoring bore AM 24, 423–507 m depth. Location; AMG Zone 50, 389624 m E, 6491151 m N.

Lithology: The Mariginiup Member consists of thinly interbedded and discontinuous grey to black siltstones and shales with minor, very thin (≤1 m) beds of mostly fine-grained sandstone. The member is predominantly of marine origin, commonly glauconitic, micaceous, in places fossiliferous, and variably cemented with a pyritic or calcareous cement. In the northern area, the Mariginiup Member is slightly more sandy and coarser grained than it is in the south.

Stratigraphic relationships: The Mariginiup Member is the basal member of the Leederville Formation and represents the conformable transitional period of sedimentation between the South Perth Shale (below) and the Wanneroo Member. It unconformably overlies the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formation and conformably overlies the Gage Formation or the South Perth Shale (Plate 10). The member is conformably overlain by the Wanneroo Member or the Pinjar Member and in places is unconformably overlain by the superficial formations. The structural contours on the top of the Mariginiup Member (Plate 13), together with surface topographic contours (Fig. 5), show that the member is present at depths ranging from 20 to 800 m. Palynological data (Backhouse, 1980a) indicate that the Mariginiup Member is of Valanginian to early Barremian age.

Discussion: Because the sediments of the Mariginiup Member are transitional between those of the South Perth Shale and the Wanneroo Member, they have been included previously in either the South Perth Shale or the Leederville Formation. This has caused problems in correlation. The Mariginiup Member extends beneath most of the Perth Region and the coastal strip to near Cataby, and also beneath the Dandaragan Plateau to the Watheroo area, nearly 200 km north of Perth. Onshore, the member has a maximum thickness of about 250 m within the Yanchep Syncline (Plate 14) and is easily recognizable in geophysical logs by the progressive increase in gamma radiation with depth and, in sections of cementation, by the characteristic spiky, high resistivities (Figs 17 and 18).

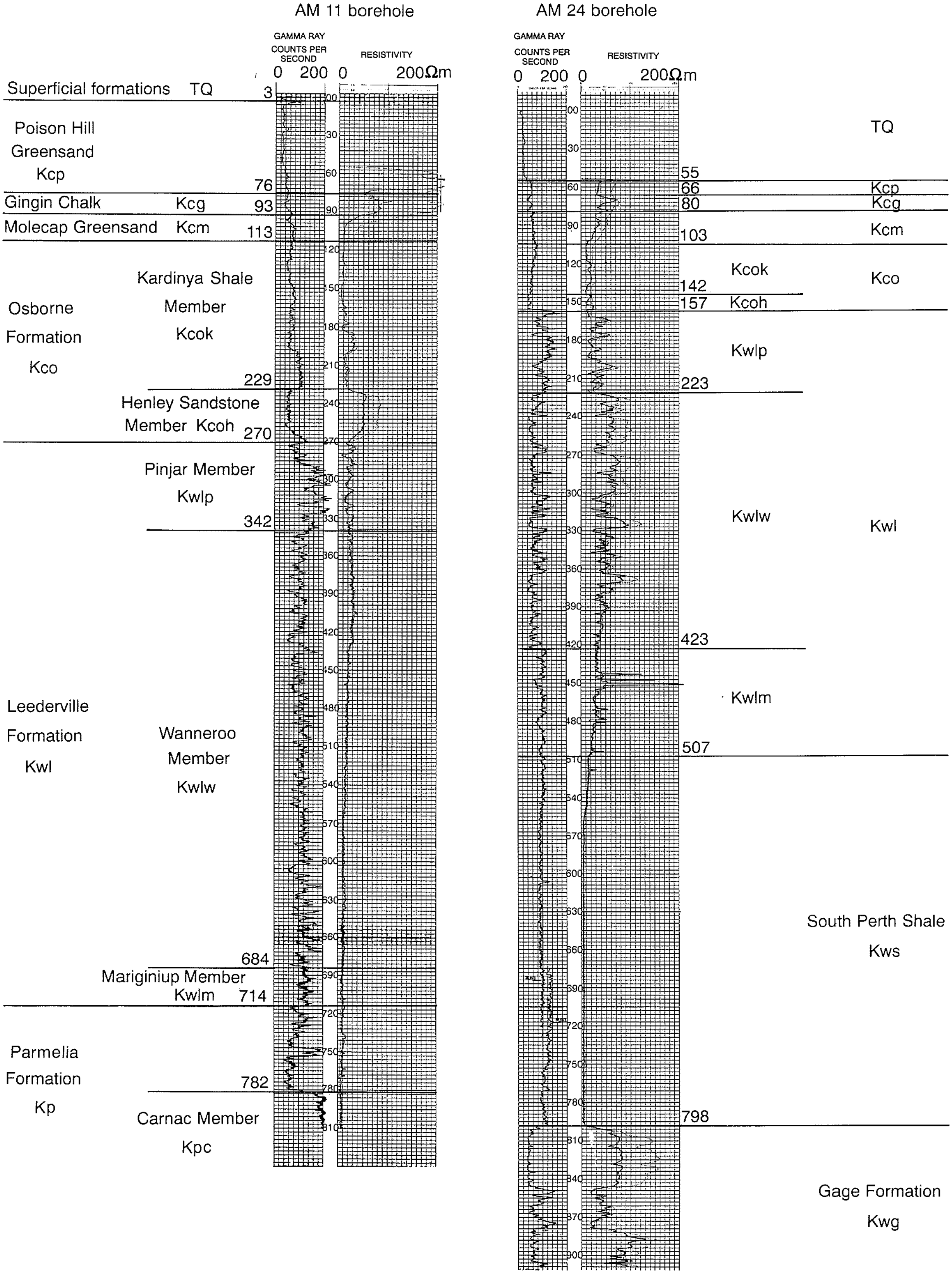

Figure 17. Geophysical wireline logs from AM11 and AM24 boreholes

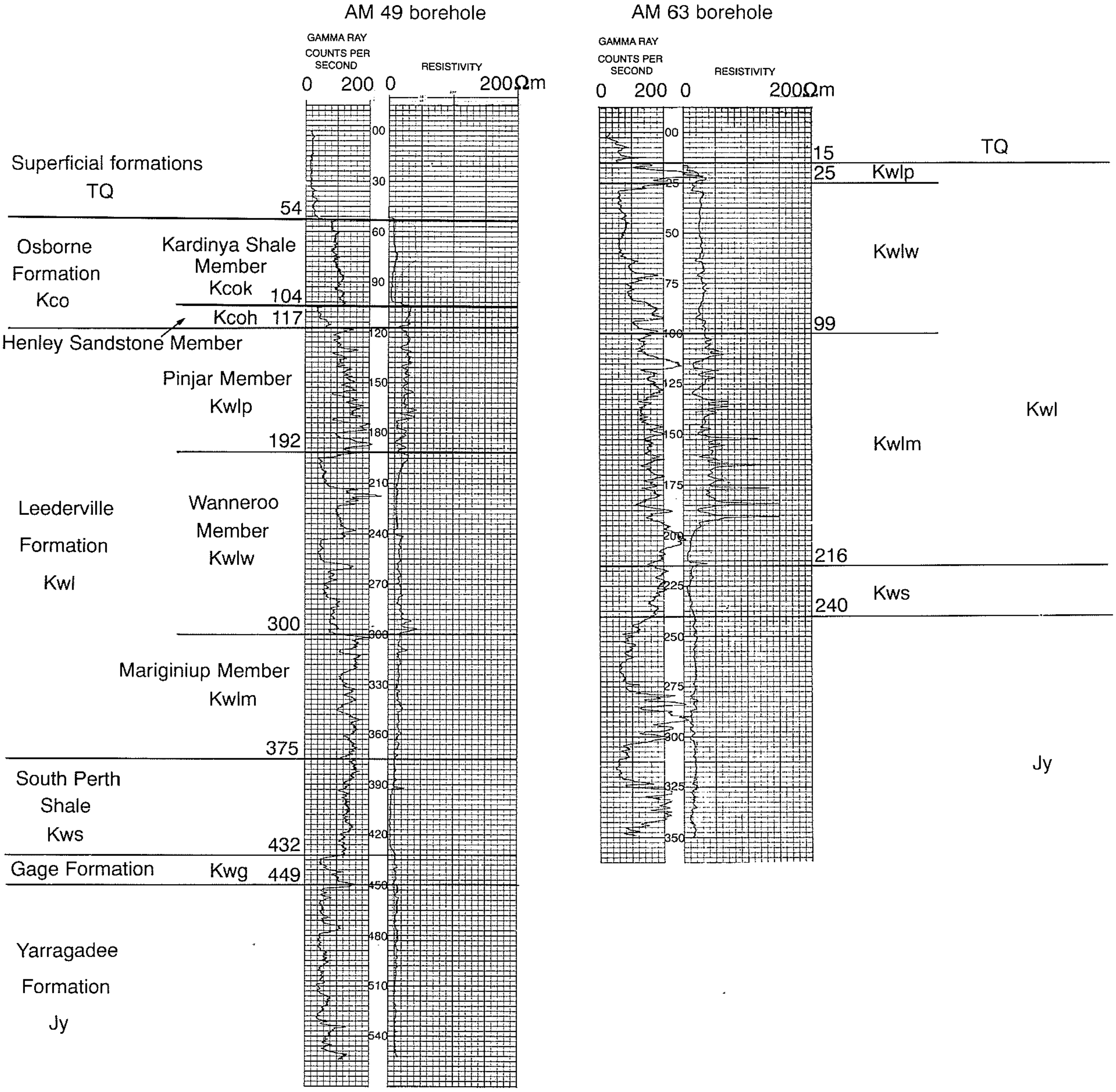

Figure 18. Geophysical wireline logs from AM49 and AM63 boreholes

Wanneroo Member

Derivation of name: Wanneroo townsite, north of Perth.

Type section: Artesian monitoring bore AM 24, 223–423 m depth. Location; AMG Zone 50, 389624 m E, 6491151 m N.

Lithology: The Wanneroo Member consists of discontinuous interbedded sandstones, siltstones and shales of marine and non-marine origin. Individual sand beds range in thickness from less than 10 m to more than 20 m, but are generally between 12 and 15 m. The sandstone interbeds are weakly consolidated, pale grey, fine to very coarse grained (predominantly coarse), poorly sorted, angular to subangular, and slightly silty. The siltstones and shales are grey, somewhat micaceous, and exist as beds of thickness similar to that of the sandstones. Along the southeastern margin of the Perth Region, and in many areas adjacent to the Darling Fault, granitic scree boulders from the Darling Scarp are commonly found within the Wanneroo Member.

Stratigraphic relationships: The Wanneroo Member of the Leederville Formation conformably overlies the South Perth Shale or the transitional Mariginiup Member, and in places unconformably overlies the Yarragadee Formation or Parmelia Formation (Plate 15). It is overlain conformably by the Pinjar Member and unconformably by the Osborne Formation (Henley Sandstone Member and Kardinya Shale Member), Molecap Greensand, Kings Park Formation, Rockingham Sand or superficial formations. The structure contours on the top of the Wanneroo

Member (Plate 16), together with surface topographic contours (Fig. 5), show that the member lies at depths ranging from 20 to 450 m. Based on palynological data (Backhouse, 1980a), the Wanneroo Member is of late Neocomian to Aptian age.

Discussion: The Wanneroo Member lies beneath most of the Perth Region (Plate 16) where it is easily recognizable in geophysical logs by the characteristic blocky and relatively low gamma-radiation trace of the sandstone beds (Figs 17 and 18). It has an onshore maximum thickness of about 450 m within the Yanchep Syncline (Plate 17). In the Jandakot area, south of Perth, the uppermost sandstone bed of the Wanneroo Member is generally thicker than the sandstone beds at greater depth and elsewhere within the Perth Region.

Pinjar Member

Derivation of name: Lake Pinjar, Wanneroo

Type section: Artesian monitoring bore AM 24, 157–223 m depth. Location; AMG Zone 50 389624 m E, 6491151 m N.

Lithology: The Pinjar Member consists of discontinuous, interbedded sandstones, siltstones and shales of marine and non-marine origin, with individual sandstone beds about 3 to 6 m thick. The sandstones are weakly consolidated, grey, fine to very coarse grained, poorly sorted, subangular to subrounded, and commonly silty. The siltstones and shales are dark grey to black, typically micaceous, thinly laminated with fine-grained sandstone, and with minor lignitic fragments to the north.

Stratigraphic relationships: The Pinjar Member is the uppermost member of the Leederville Formation. It is conformable on the Wanneroo Member (Plate 18) and is unconformably overlain by the Osborne Formation (Henley Sandstone Member and Kardinya Shale Member), Molecap Greensand, Gingin Chalk or the superficial formations. Over the Pinjar Anticline the Pinjar Member has been completely eroded prior to the deposition of the superficial formations. Structure contours on the top of the Pinjar Member are shown in Plate 19 and, together with surface topographic contours (Fig. 5), indicate that the member is present at depths ranging from 10 to 360 m. Palynological data (Backhouse, 1980a) suggest that the Pinjar Member is of late Neocomian to Aptian age.

Discussion: The Pinjar Member underlies most of the Perth Region and extends beneath the coastal strip some 50 km north of the region to near Lancelin. It has a maximum onshore thickness of about 150 m within the Yanchep and Swan Synclines (Plate 20) and it is recognizable in geophysical wireline logs by the thin (<6 m), low-gamma radiation sandstones interbedded with higher gamma-radiation siltstones and shales (Figs 17 and 18).

Cretaceous (Coolyena Group)

The Coolyena Group, defined by Cockbain and Playford (1973), comprises in order of deposition the Osborne Formation, Molecap Greensand, Gingin Chalk and Poison Hill Greensand. It has been extended to include the contiguous Lancelin Formation. The Coolyena Group of sediments unconformably overlies the Warnbro Group and was deposited under shallow-marine conditions during a period of tectonic stability. Structure contours on the base of the Coolyena Group are shown in Plate 21.

Osborne Formation

The Osborne Formation, defined by McWhae et al. (1958), with its type section in the King Edward Street bore (AMG Zone 50, 388103 m E, 6470027m N) between 37 and 133 m, has been redefined to include a basal sandstone sequence (Henley Sandstone Member), a middle shale unit (Kardinya Shale Member) and an upper, interbedded sandstone and shale sequence (Mirrabooka Member). The upper predominantly sandy sequence of the Osborne Formation (Mirrabooka Member) may be conformable with the sandstone beds of the overlying Molecap Greensand (Playford et al., 1976), although at some localities there is evidence for a hiatus. Without comprehensive palynological data, the contact boundary between these formations is often difficult to map from borehole lithologies and geophysical logs, and the contact boundary will be subject to further modifications when more data become available.

Over the Pinjar Anticline, the Osborne Formation has been completely eroded prior to the deposition of the superficial formations. Elsewhere, the formation unconformably overlies the Wanneroo Member or the Pinjar Member of the Leederville Formation (Plate 22). It is both conformably and unconformably overlain by the Molecap Greensand, and unconformably overlain by the Gingin Chalk or the superficial formations on an erosional surface. Structure contours on top of the Osborne Formation (Plate 23), together with surface topographic contours (Fig. 5), show that the formation lies at depths ranging from 10 to 250 m.

The Osborne Formation is of shallow-marine origin and, as redefined, consists of a basal, weakly consolidated, comparatively thick sandstone section (Henley Sandstone Member), a middle siltstone–shale sequence (Kardinya Shale Member), and an upper sandstone–shale sequence (Mirrabooka Member). Beneath the Perth Region and within the Swan Syncline, it has a maximum thickness of about 180 m (Plate 24) and ranges in age from Aptian to possibly Turonian (Fig. 15).

Henley Sandstone Member

Derivation of name: Henley Brook, northeast of Perth

Type section: Artesian monitoring bore AM 11, 229–270 m depth. Location; AMG Zone 50, 406475 m E, 6524957 m N.

Lithology: The Henley Sandstone Member consists of sandstone and minor siltstone. The sandstone is weakly consolidated to friable, fine to coarse grained, very poorly sorted and characteristically dark greenish brown and glauconitic. Very coarse to gravel-sized, well-rounded grains with high sphericity are common.

Stratigraphic relationships: The Henley Sandstone Member is a predominantly sandstone unit at the base of the Osborne Formation. It unconformably overlies the Wanneroo Member or the Pinjar Member of the Leederville Formation (Plate 25). Its upper contact with the Kardinya Shale Member of the Osborne Formation (Plate 26) is usually abrupt but may be gradational or may interfinger with the shale sequence. Based on palynological data (Backhouse, 1981), the Henley Sandstone Member is of late Aptian to early Albian age.

Discussion: The Henley Sandstone Member occurs mainly within the Swan Syncline and in the Perth area where it is easily recognizable in geophysical logs as a sandy unit with low gamma radiation and relatively high resistivity (Figs 17 and 18). It has an onshore maximum thickness of about 100 m (Plate 27).

Kardinya Shale Member

Derivation of name: Kardinya suburb, south of Perth

Type section: Artesian monitoring bore AM 42, 28–167 m depth. Location; AMG Zone 50, 387984 m E, 6452223 m N.

Lithology: The Kardinya Shale Member consists of moderately to tightly consolidated, interbedded siltstones and shales. These are dark green to black, often puggy, glauconitic, and contain thin interbeds of mostly fine-grained sandstone. Scattered coarse grains of high sphericity are common throughout the siltstones and shales.

Stratigraphic relationships: The Kardinya Shale Member is a relatively thick siltstone–shale unit within the Osborne Formation. It conformably overlies the Henley Sandstone Member, but in the south where the Henley Sandstone Member is absent, it unconformably overlies the Wanneroo Member or the Pinjar Member of the Leederville Formation (Plate 28). In the northern Perth area it is overlain conformably by the interbedded sandstone–shale sequence of the Mirrabooka Member, and unconformably by the Molecap Greensand or the Gingin Chalk. In the southern area it is unconformably overlain, on an erosional surface, by the superficial formations (Plate 29). Palynological data (Backhouse, 1979) indicate that the Kardinya Shale Member is of Albian to Cenomanian age.

Discussion: The Kardinya Shale Member is encountered mainly beneath the central Perth Region where it is recognizable in geophysical logs by its relatively high gamma radiation and low resistivity (Fig. 19). It has an onshore maximum thickness of about 140 m (Plate 30).

Mirrabooka Member

Derivation of name: Mirrabooka suburb, north of Perth

Type section: Artesian monitoring bore AM 30Z, 34–199 m depth. Location; AMG Zone 50, 397560 m E, 6478832 m N.

Lithology: The Mirrabooka Member consists of sandstone with thin interbeds of siltstone and shale. The sandstone is weakly consolidated, dark greenish brown, fine to very coarse grained, very poorly sorted, silty and richly glauconitic. The siltstones and shales are moderately consolidated, dark green to black, glauconitic, and contain common spherical, coarse to gravel-sized quartz grains.

Stratigraphic relationships: The Mirrabooka Member is a predominantly sandstone unit contained in the uppermost section of the Osborne Formation. It conformably overlies the Kardinya Shale Member (Plate 31) and is conformably overlain by the Molecap Greensand. However, based on scanty biostratigraphic data, a hiatus may separate the Mirrabooka Member and the Molecap Greensand. Elsewhere, the Mirrabooka Member is unconformably overlain, on an erosional surface, by the superficial formations (Plate 32). Palynological data (Backhouse, 1980b) suggest that the Mirrabooka Member is of Albian to Cenomanian age.

Discussion: The Mirrabooka Member is present in the northern Perth area where it is difficult to distinguish from the overlying Molecap Greensand without palynological evidence (Fig. 20). It has an onshore maximum thickness of about 160 m (Plate 33).

The Mirrabooka Member (Osborne Formation) of the Perth Basin, Western Australia, is totally unrelated to the Silurian Mirrabooka Formation in New South Wales. The name Mirrabooka Member is used because it is established by informal usage in discussions of the hydrogeology of the Perth Region, and there is no significant potential for confusion with the Mirrabooka Formation in New South Wales.

Molecap Greensand

The Molecap Greensand, defined by Fairbridge (1953), has its type section in the greensand quarry on Molecap Hill (AMG Zone 50, 347832 m E, 6528643 m N) 2 km south of Gingin.

In the Perth Region, the Molecap Greensand occurs in the Swan Syncline and the Wanneroo area, where it consists of fine- to medium-grained, yellowish-brown to greenish-grey, glauconitic, silty, and locally clayey sandstone. Phosphatic nodules are common in the upper part of the formation. In the Yanchep Syncline in the Guilderton area, the Molecap Greensand consists of poorly sorted, glauconitic, very sandy, greenish grey-brown mudstone.

The Molecap Greensand overlies the Mirrabooka Member of the Osborne Formation, mostly with a transitional and conformable contact (Plate 34), but in some areas a hiatus is suggested between the Molecap Greensand and the Osborne Formation. The Molecap Greensand is overlain conformably by the Gingin Chalk or, where this is absent, unconformably by the Poison Hill Greensand or the superficial formations (Plate 35).

The Molecap Greensand is of shallow-marine origin and the contours on the top of the formation (Plate 35), together with surface topographic contours (Fig. 5), show

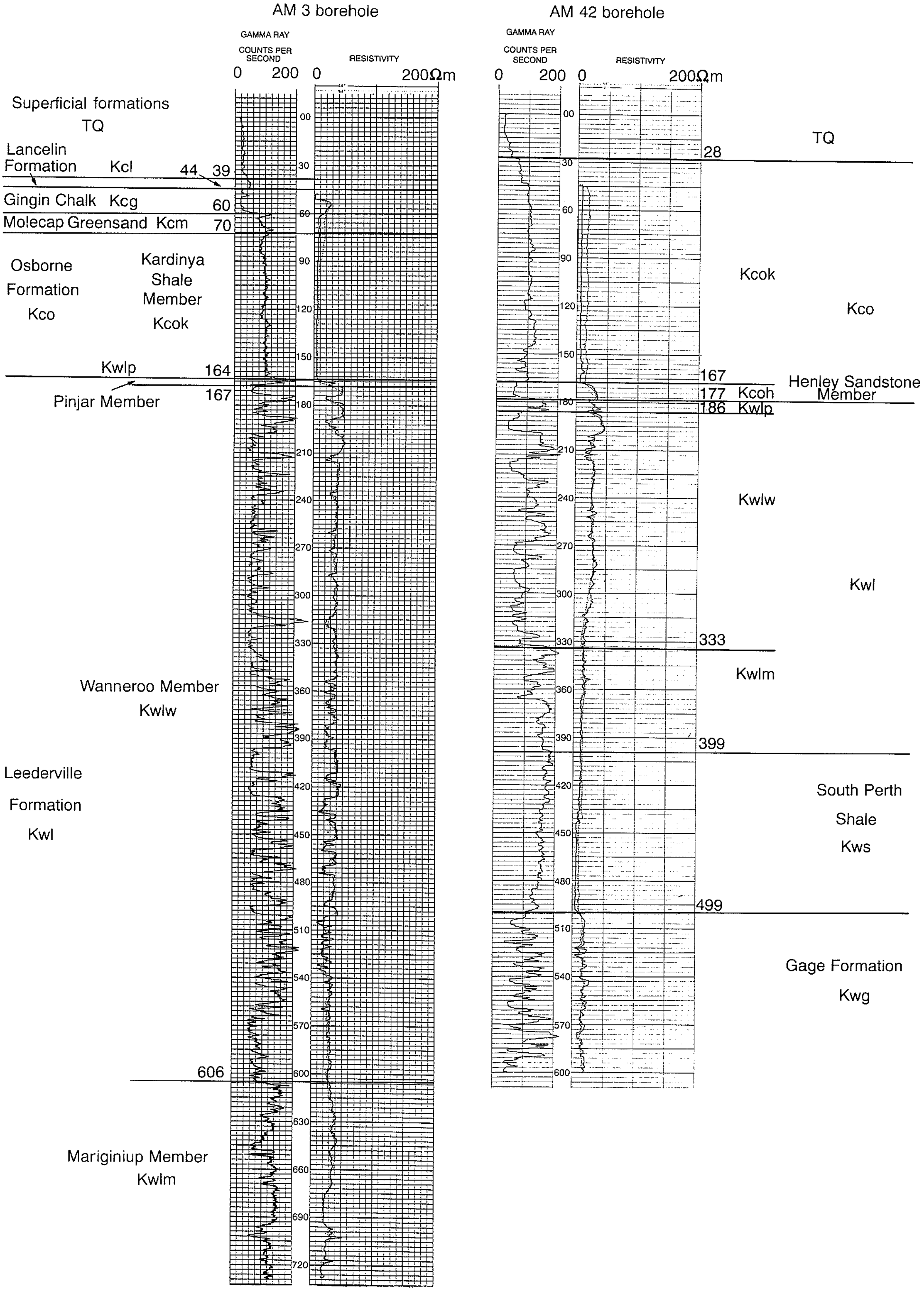

Figure 19. Geophysical wireline logs from AM3 and AM42 boreholes

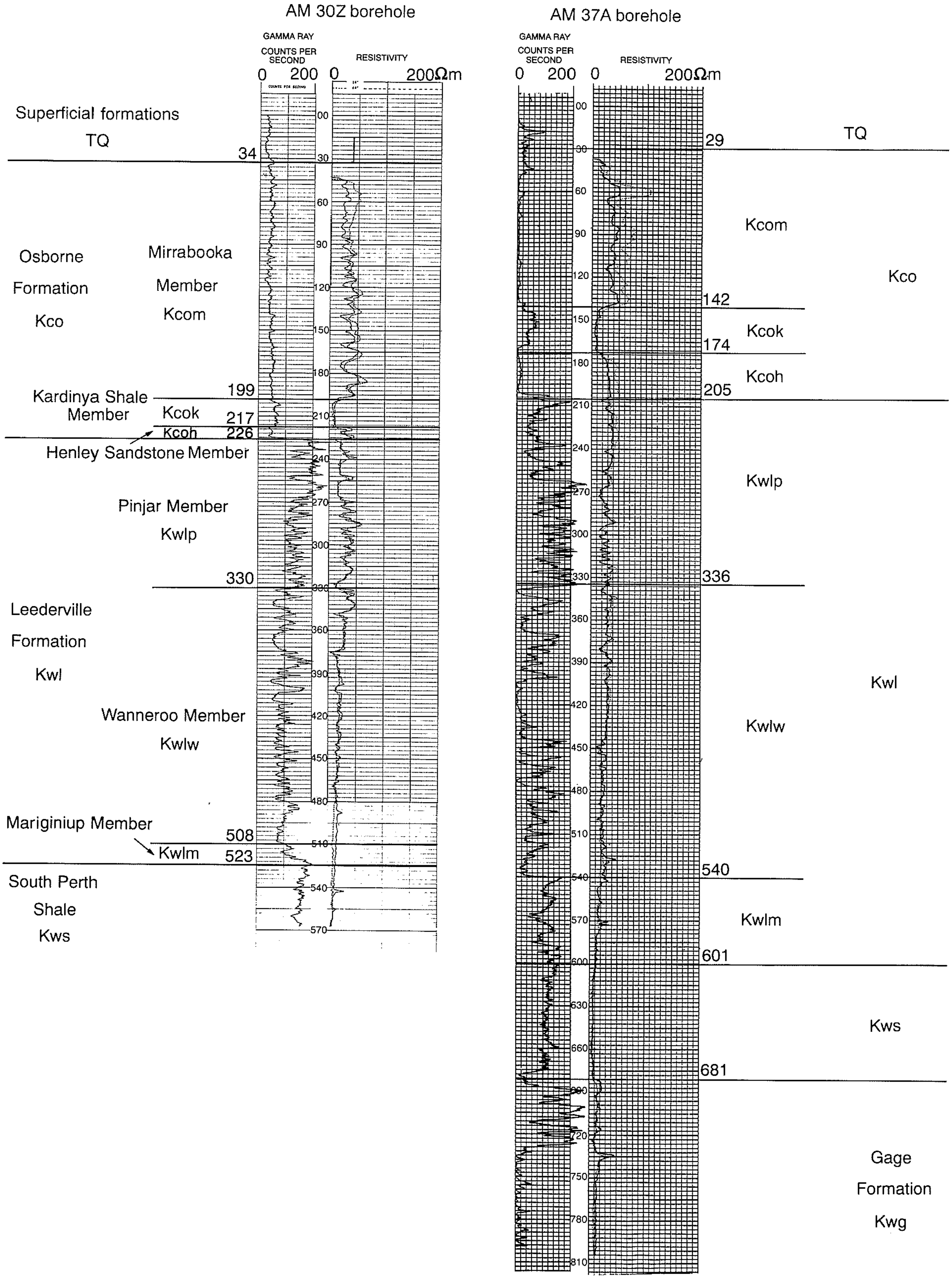

Figure 20. Geophysical wireline logs from AM30Z and AM37A boreholes

that it ranges in depth from about 40 to 230 m. However, with further drilling and palynological evidence the extent of the Molecap Greensand, and that of the Mirrabooka Member of the Osborne Formation, may be modified. The Molecap Greensand is mostly unconsolidated, has a maximum thickness of about 80 m (Plate 36) and is of Turonian to Santonian age (Fig. 15).

Gingin Chalk

The Gingin Chalk, defined by Glauert (1910), has its type section in MacIntyre Gully (AMG Zone 50, 395333 m E, 6534769 m N), about 1.6 km north of Gingin.

The Gingin Chalk is of shallow-marine origin and consists of weakly to moderately consolidated, pale-grey to whitish-green, slightly glauconitic chalk containing very thin beds of green sand in the Yanchep Syncline and thicker, more abundant sandy beds in the Swan Syncline. In the northern Perth area the chalk facies is very minor or absent and the sand facies difficult to distinguish from the sandy beds of the underlying Molecap Greensand. Correlation across this area has been interpreted from geophysical logs and, without palynological data, is subject to modification.

The Gingin Chalk unconformably overlies the Leederville Formation (Pinjar Member) and the Osborne Formation (Kardinya Shale Member) and conformably (or with a hiatus) overlies the Molecap Greensand (Plate 37). This unit is conformably overlain by the Poison Hill Greensand and may interfinger with the Lancelin Formation in the Guilderton area. Structure contours on the top of the Gingin Chalk (Plate 38), together with surface topographic contours (Fig. 5), locate the formation at depths ranging from near groundlevel to 210 m.

The Gingin Chalk is identified only in the northern area where it has a maximum onshore thickness of about 40 m (Plate 39). It is of Santonian to Campanian age (Cockbain, 1990).

Poison Hill Greensand

The Poison Hill Greensand, defined by Fairbridge (1953), has its type section at Poison Hill (AMG Zone 50, 393728 m E, 6536000 m N), about 6.5 km north-northwest of Gingin.

Within the Perth Region, the Poison Hill Greensand consists of unconsolidated pale yellow to dark green, fine- to very coarse-grained, richly glauconitic, silty and locally clayey sand. Individual sand grains are commonly rounded and spherical. The sand is similar in lithology and characteristics to the sand of the Henley Sandstone Member (Osborne Formation) from where it probably originated by erosion of the Pinjar Anticline. However, it is typically less silty and less clayey than the Henley Sandstone Member, with better rounded and more spherical sand grains. In the Mirrabooka area, the upper 50 m of the Poison Hill Greensand consists of fine- to medium-grained, moderately sorted, slightly clayey, pale-green sand. This sand, now referred to as the Poison Hill Greensand, was originally thought to be a channel infill deposit of Quaternary age (Morgan, 1964b; Barnes, 1977; Allen, 1977). However, extensive lithological sampling for palynological examination has not been able to confirm this. Further sampling within the Mirrabooka area may confirm this sandy unit as being Tertiary in age and possibly belonging to the Como Sandstone Member of the Kings Park Formation.

The Poison Hill Greensand conformably overlies the Molecap Greensand or the Gingin Chalk (Plate 40) and it is unconformably overlain by the superficial formations. Structure contours on the top of the Poison Hill Greensand are shown on Plate 41.

The Poison Hill Greensand is identified in the Swan Syncline and in the Wanneroo area and has a maximum onshore thickness of about 90 m (Plate 42).

Lancelin Formation

The Lancelin Formation, formerly the Lancelin Beds (Edgell, 1964), has its type section in Lancelin No. 2B bore between 32 and 46 m (AMG Zone 50, 339929 m E, 6561788 m N) near the township of Lancelin, approximately 100 km north of Perth.

In the Perth Region, the Lancelin Formation is encountered only in the Guilderton area, where it consists of a white to greenish-brown, glauconitic marl above the Gingin chalk. Beneath the Gingin Chalk there is a noncalcareous mudstone unit, atypical of the marl of the Lancelin Formation, which probably represents a fine-grained facies variation of the Molecap Greensand. Until more palynological work is carried out on this fine-grained unit, it has been assigned to the Molecap Greensand rather than the Lancelin Formation.

Generally, the Lancelin Formation conformably overlies the Gingin Chalk (Plate 43). However, it may pass laterally into the Poison Hill Greensand, Gingin Chalk or Molecap Greensand (Cockbain, 1990), and in the Guilderton area the Gingin Chalk may interfinger within the Lancelin Formation. The top of the Lancelin Formation is an erosional surface, unconformably overlain by the Tertiary Kings Park Formation or the younger superficial formations (Plate 44). Palynological and microfossil data (Backhouse, 1986; Rexilius, 1984) suggest the formation is of Coniacian to late Maastrichtian age. However, with further drilling, sampling and palynological examination, its age may be extended into the Turonian.

The Lancelin Formation is of marine origin and, within the Perth Region, has a maximum onshore thickness of about 120 m (Plate 45).

Early Tertiary

Kings Park Formation

The Kings Park Formation, which was redefined by Quilty (1974), occupies a deep channel incised through the Cretaceous sedimentary sequence into the Jurassic (Plate 46). The type section is in Kings Park No. 2 bore between 23 and 492 m (AMG Zone 50, 390556 m E, 6461738 m N). The formation consists predominantly of grey, calcareous, glauconitic siltstone and shale of shallow-marine to estuarine origin. The valley occupied by the Kings Park Formation may once have connected with the Perth Canyon, which now cuts the continental slope west of Rottnest Island (Playford et al., 1976).

There are two sandstone sequences, the Como Sandstone Member (described for the first time) and the Mullaloo Sandstone Member, within the formation and these may occupy secondary channels eroded into the shaly sequence at the base and near the top of the formation, respectively.

The Kings Park Formation unconformably overlies the Jurassic and Cretaceous sediments (Plate 46) and is unconformably overlain by the superficial formations. It has a maximum onshore thickness of about 530 m in the Claremont area west of Perth and is of Paleocene to Eocene age (Playford et al., 1976).

Como Sandstone Member

Derivation of name: Como, suburb south of Perth.

Type section: Artesian monitoring bore AM40, 326–383 m depth. Location AMG Zone 50, 394605 m E, 6460132 m N.

Lithology: The Como Sandstone Member consists of fine- to coarse-grained (predominantly medium), moderately sorted, subangular to subrounded, pale grey to pale-greenish-grey, slightly clayey sand and probably occupies a marine channel of limited extent.

Stratigraphic relationship: The Como Sandstone Member constitutes the lowermost part of the Kings Park Formation.

Discussion: The Como Sandstone Member was intersected in only two of the artesian monitoring bores (AM32 and AM40, Table 8). Onshore, this unit has a maximum known thickness of 57 m (recorded from AM40) and is identified in geophysical logs (Fig. 21) by the monotonously low gamma radiation and the relatively high resistivity compared with the log of the calcareous shales of the Kings Park Formation. Further palynological investigations of samples from the Mirrabooka area may lead to local reassignment of the Poison Hill Greensand to the Como Sandstone Member.

Mullaloo Sandstone Member

The Mullaloo Sandstone Member, defined by Quilty (1974), with its type section between 68 and 365 m in offshore Quinns Rock No. 1 well (AMG Zone 50, 359480 m E, 6480360 m N) about 20 km west of Whitfords, is identified at or near the top of the Kings Park Formation. It consists of poorly sorted, fine to very coarse-grained, pale brownish-green, slightly glauconitic and clayey sand. The member has an onshore maximum thickness of about 200 m and occupies deep marine channels incised into the siltstones and shales of the Kings Park Formation (Plate 47). Some thin overflow sedimentation of the Mullaloo Sandstone Member may have occurred adjacent to and overlapping these channels, but this is not shown on Plate 47. For example, a bore approximately 500 m southwest of the southern boundary of the Mullaloo Sandstone Member and adjacent to the northwestern bank of the Swan River in the Nedlands area, intersected about 5 m of clayey sand, possibly belonging to the Mullaloo Sandstone Member.

Late Tertiary–Quaternary

The geology of the late Tertiary–Quaternary sediments of the Perth Basin has been described by Playford et al. (1976) and only those formations of hydrogeological significance to the Perth Region are described in this Bulletin. They are the Rockingham Sand, Ascot Formation and the Kwinana Group. In order of deposition, the Kwinana Group comprises the Yoganup Formation, Guildford Clay, Gnangara Sand, Bassendean Sand, Tamala Limestone, Becher Sand and the Safety Bay Sand. For ease of description, Allen (1976a) referred to the Ascot Formation and Kwinana Group, collectively, as the 'superficial formations', an informal name which has been widely recognized and accepted within Western Australia. To maintain consistency with various publications on the hydrogeology of the Perth area, the term superficial formations, without quotation marks, is used in this Bulletin.

Rockingham Sand

The Rockingham Sand, defined by Passmore (1967, 1970) with the type section in Bore R1 (AMG Zone 50, 380100 m E, 6526850 m N), consists of brown to pale-grey, somewhat silty, slightly felspathic, medium- to coarse-grained subangular sand. It is of shallow-marine origin and is only known to occur onshore in the Rockingham area, where it has a maximum thickness of about 110 m. Offshore, this unit lies beneath the southern end of Garden Island and possibly beneath Rottnest Island. It occupies an eroded channel incised into the Wanneroo Member of the Leederville Formation (Plate 48) and is unconformably overlain by the superficial formations (Plate 49). The age of the Rockingham Sand is uncertain, but is probably Pliocene (Fig. 16).

Superficial formations (collective term)

The superficial formations are late Tertiary (Pliocene) to Quaternary in age and comprise in order of deposition; Ascot Formation, Yoganup Formation, Guildford Clay, Gnangara Sand, Bassendean Sand, Tamala Limestone, Becher Sand and Safety Bay Sand. They collectively range in thickness to a maximum of about 110 m, and unconformably overlie a gentle, westward-sloping erosional surface of older sediments (Fig. 22, Plate 49).

The superficial formations consist mainly of sand, silt, clay and limestone in varying proportions. Along the eastern margin of the coastal plain the sediments are more clayey than those in the central area, which are predominantly sandy. To the west, the sandy sediments pass laterally into limestone, which borders the coastal strip (Fig. 23, Plate 50).

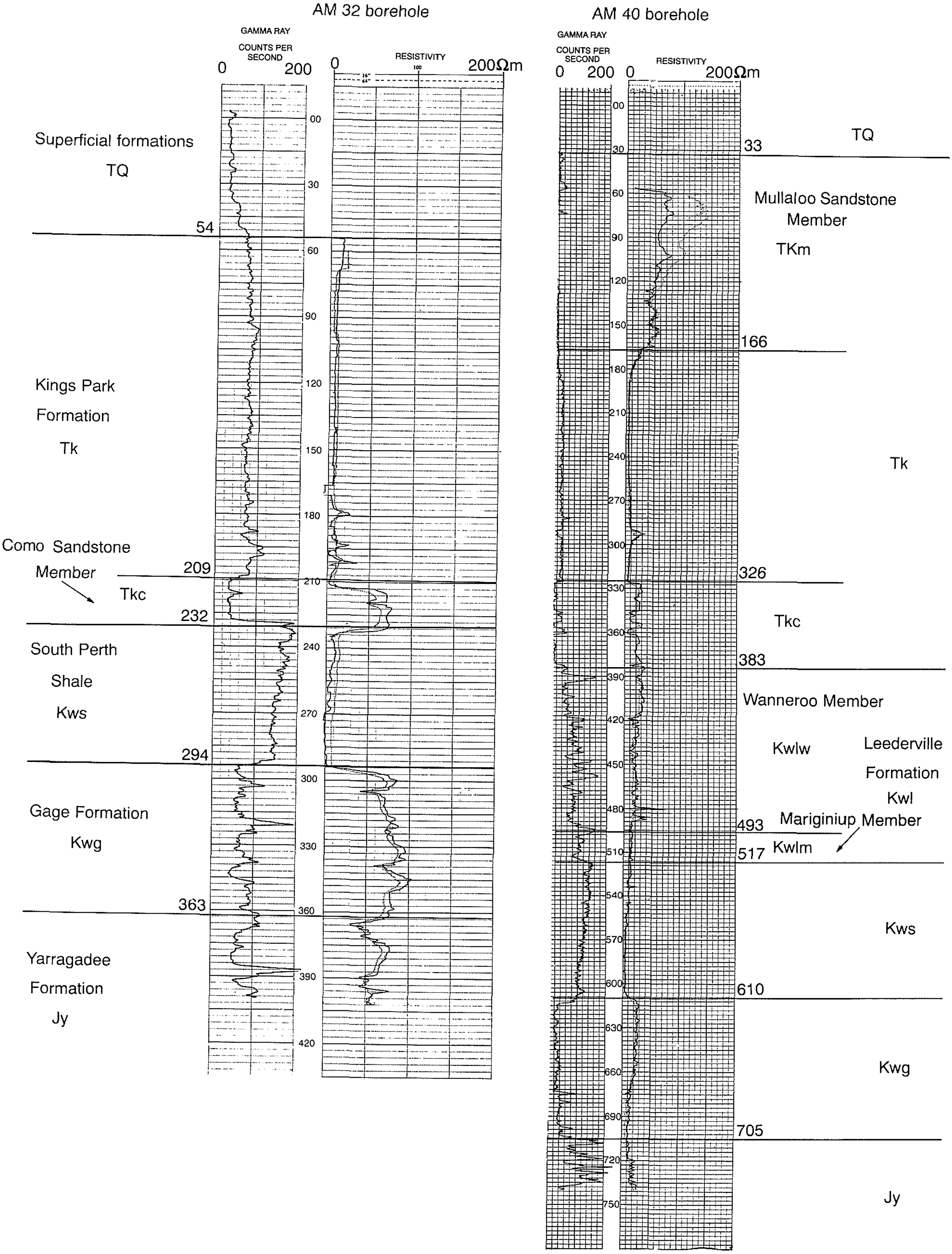

Figure 21. Geophysical wireline logs from AM32 and AM40 boreholes

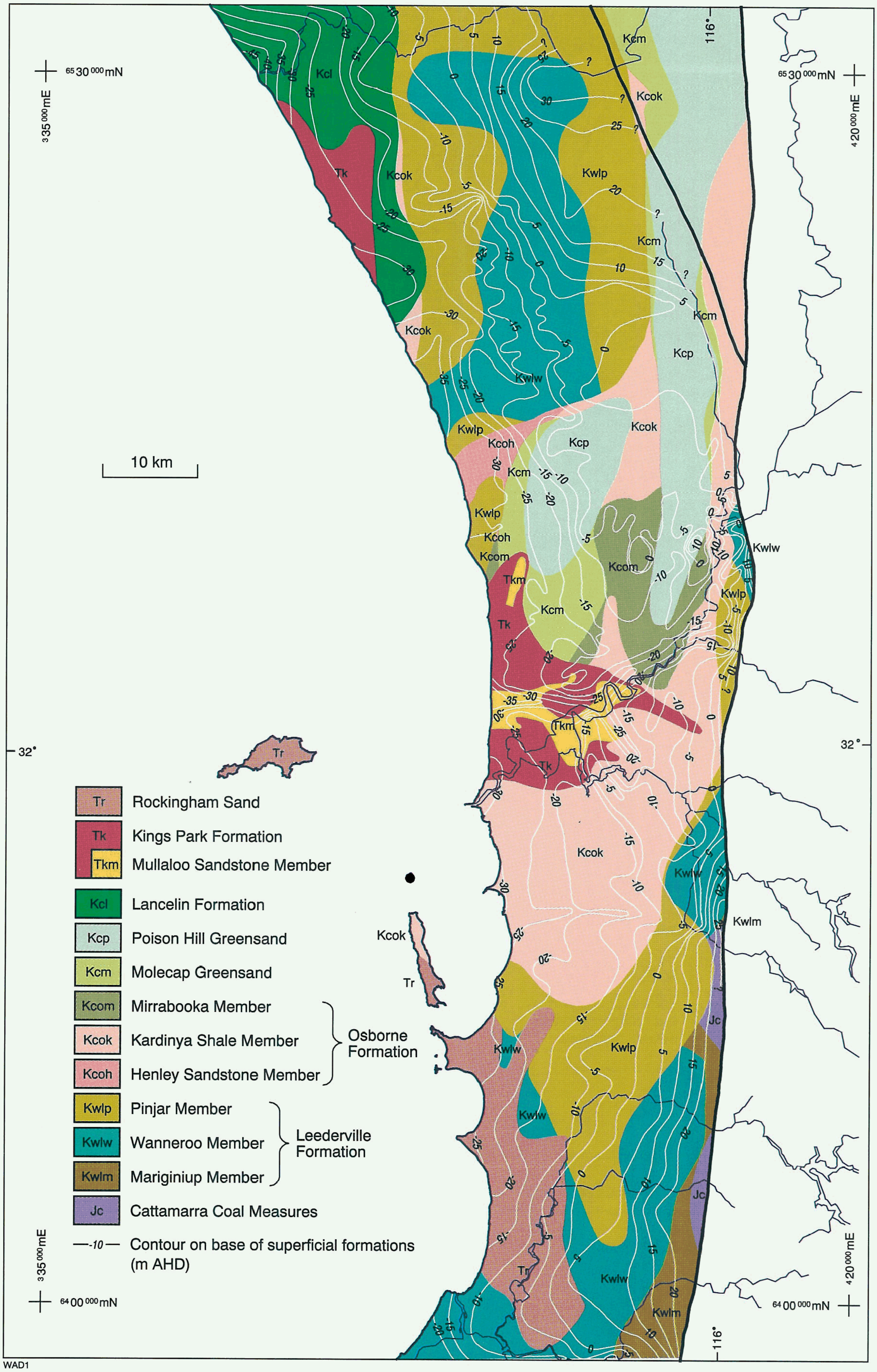

Figure 22. Superficial formations: contours on base of unit; with strata subcrop

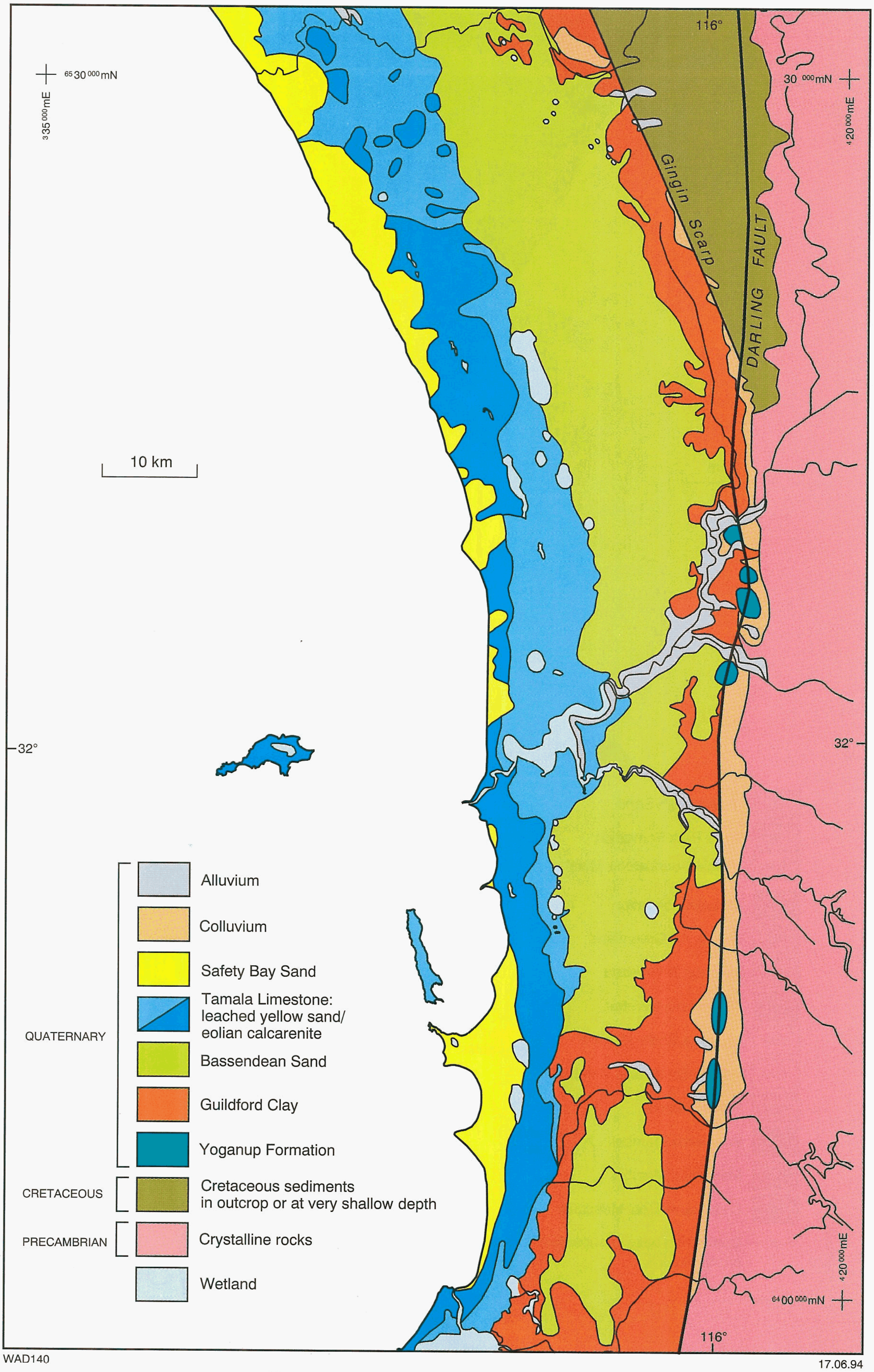

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Figure 23. Surface geology; generalized

Ascot Formation

The Ascot Beds, as defined by Playford et al. (1976), was redefined by Cockbain and Hocking (1989) to Ascot Formation. Apparently continuous sediments of similar lithology but slightly younger age, found in the Jandakot area south of Perth and informally referred to as the Jandakot Beds, were incorporated into the Ascot Formation by Kendrick et al. (1991).

The Ascot Formation consists of hard to friable, grey to fawn calcarenite with thinly interbedded sand commonly containing shell fragments, glauconite and phosphatic nodules near the base of the formation. The fine to coarse sand is very poorly sorted, angular to rounded, and contains a rich assemblage of bivalves and gastropods. To the south of Perth, thick beds of shelly, silty clay are found locally with thinly bedded glauconitic clay near the base of the formation.

Where present, the Ascot Formation lies unconformably on the Leederville Formation, Osborne Formation, Molecap Greensand or Poison Hill Greensand. The formation represents a sequence of depositional events along the neritic margins of a progressively prograding shoreline (Kendrick et al., 1991). It has a maximum thickness of about 20 and 30 m in the southern and northern Perth areas respectively and is widespread at the base of the superficial formations (Fig. 24).

Yoganup Formation

The Yoganup Formation was defined by Low (1971), with the type section in an opencut for mineral-sands mining near Yoganup, approximately 200 km south of Perth (AMG Zone 50, 370433 m E, 6276070 m N). It extends sporadically along the eastern margin of the Perth Region (Fig. 23) and westwards (as subcrop) about 5 km from the foothills of the Darling Scarp. The formation consists of white to yellowish-brown, unconsolidated, poorly sorted sand, gravel and pebbles with local subordinate clay, ferruginized grains and heavy minerals. It may interfinger with the Ascot Formation (Fig. 24) at the base of the superficial formations.

The Yoganup Formation unconformably overlies the Osborne Formation or the Leederville Formation and is unconformably overlain by the Guildford Clay. In the Perth Region, it has a maximum known thickness of about 10 m and has been extensively eroded prior to deposition of the Guildford Clay. The Yoganup Formation is a shoreline deposit representing a buried prograding coastline of dunes, beach ridges and deltaic deposits (Baxter, 1982).

Guildford Clay

The Guildford Clay was originally defined by Aurousseau and Budge (1921) as the 'Guildford Clays' and revised by Low (1971) to Guildford Formation. The name 'Guildford Clay' has persisted and remains in common use, particularly for areas where this unit outcrops (Fig. 23). For this reason, the name Guildford Clay has been reinstated and refers to the clayey sediments originally described by Aurousseau and Budge (1921) for the type area in the Swan River valley around Guildford.

The Guildford Clay consists of pale-grey, blue, but predominantly brown silty and slightly sandy clay, and interfingers to the west with the Gnangara Sand and Bassendean Sand (Fig. 24, Table 9). The unit is up to 35 m thick and commonly contains lenses of fine- to coarse-grained, very poorly sorted, conglomeratic and (in places) shelly sand at its base, particularly in the Swan Valley area. These basal lenses, which occur sporadically along the eastern margin of the coastal plain (Fig. 23), are probably remnant deposits of the Ascot Formation or the Yoganup Formation (thought to be a lateral equivalent of the Ascot Formation (Baxter and Hamilton, 1981)).

The Guildford Clay is predominantly of fluvial origin and restricted mainly to the areas of its outcrop; however, it is also found locally in areas removed from present drainages, such as at Menora (north of Perth) and Fremantle to the southwest of Perth. To the south of Perth, in the Ferndale–Lynwood area, a widespread, thick, black, silty clay, possibly of lacustrine or fluvial origin, is probably a lateral equivalent of the Guildford Clay. The Guildford Clay, which outcrops over much of the eastern Perth Region (Fig. 23), unconformably overlies the Jurassic and Cretaceous rocks, Kings Park Formation, Ascot Formation or Yoganup Formation.

Gnangara Sand

Derivation of name: Lake Gnangara, north of Perth. The name was informally used by Morgan (1964b).

Type section: Mirrabooka observation bore M270, 21.5–46.5 m depth; AMG Zone 50, 401222 m E, 6479624 m N.

The type section is 22.5 m thick and has been geologically logged as occurring between 21.5 to 41.0 m, and 43.5 to 46.5 m (Table 9).

Lithology: The Gnangara Sand consists of pale-grey, fine- to very coarse-grained, very poorly sorted, subrounded to rounded quartz sand and abundant feldspar. At some localities it is apparently of bimodal origin being both fine grained and very coarse grained. The unit is predominantly of fluvial origin, but in those areas containing bimodal sediments is probably estuarine in derivation.

Stratigraphic relationships: The Gnangara Sand is a basal sand which interfingers with the Guildford Clay to the east (Fig. 24). It rests unconformably on the Jurassic and Cretaceous sediments, the Kings Park Formation and Ascot Formation and is conformably overlain by the Bassendean Sand. To the west it is unconformably overlain by the Tamala Limestone.

Discussion: The Gnangara Sand extends over most of the central Perth Region and is readily identifiable from drillhole cuttings by the common occurrence of well-rounded very coarse grains, subangular fine to medium grains, and feldspar. The unit has a maximum known thickness of about 30 m.

Bassendean Sand

The Bassendean Sand was originally defined by Playford and Low (1972) from the type area in the suburb of

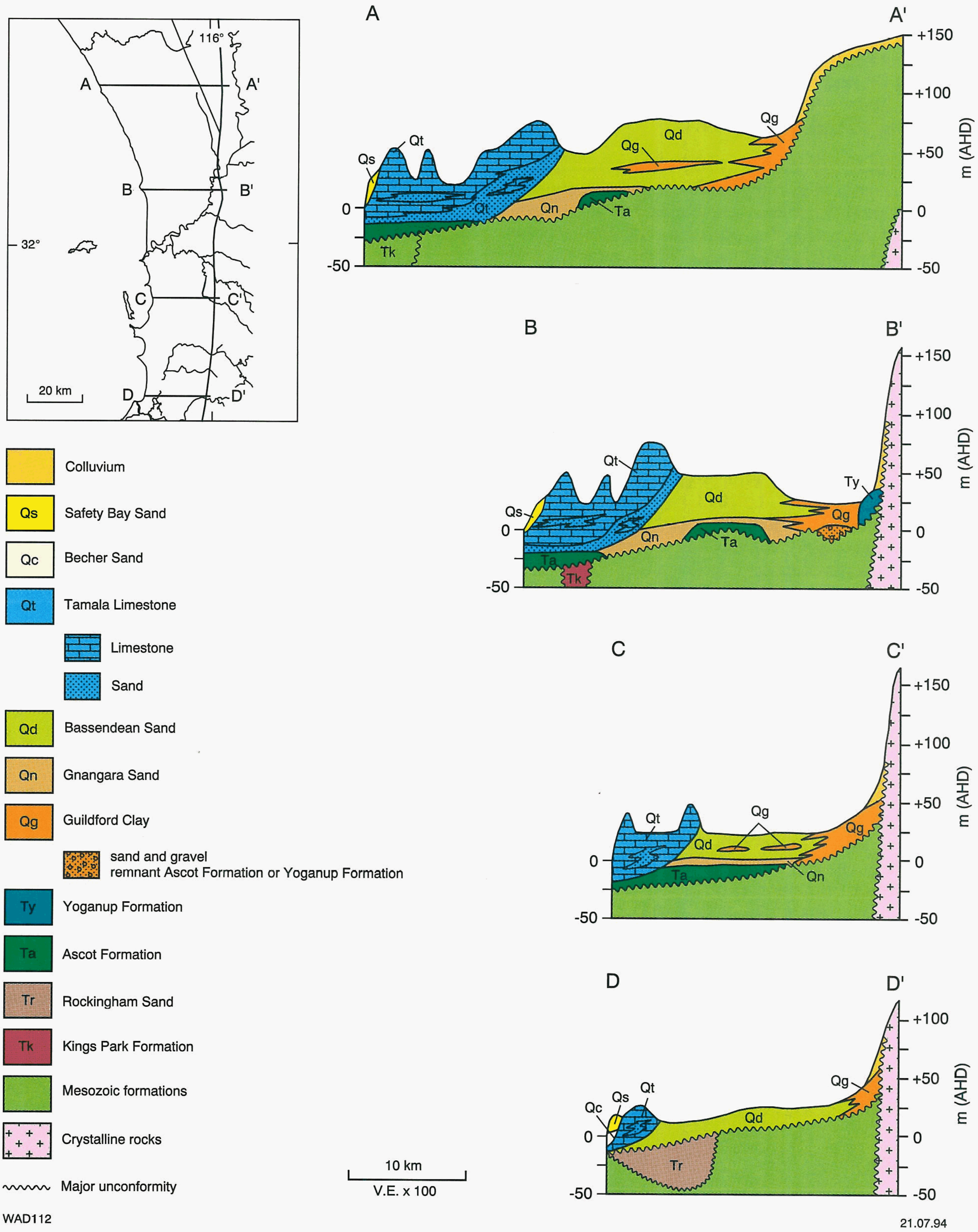


Figure 24. Geological sections showing stratigraphic relationships of superficial formations

Table 9. Superficial formations stratigraphic relationships in bore M270

Depth	*Formation*	*Lithology*
0 – 18.0	Bassendean Sand	Sand; grey brown to whitish grey, fine to coarse, poorly sorted, weakly iron-oxide cemented ('coffee rock') from 2–3.5 m and common black heavy minerals from 17–18 m
18.0 – 20.0	Guildford Clay	Clay; brownish grey, slightly sandy
20.0 – 21.5	Bassendean Sand	Sand; whitish grey, fine to coarse, poorly sorted, common black heavy minerals
21.5 – 41.0	Gnangara Sand	Sand; grey, slightly clayey, fine to very coarse, common gravel, very poorly sorted (?bimodal), fine subangular grains, coarse well-rounded grains
41.0 – 43.5	Guildford Clay	Clay; grey brown, slightly sandy and containing weathered glauconite
43.5 – 46.5	Gnangara Sand	Sand; light greenish grey, medium to coarse quartz, scattered pebbles and rare feldspar, black heavy minerals
~~	~~~~~~UNCONFORMITY~~~~~~	~~~~~~~~~~
46.5+	?Poison Hill Greensand	Sand; light greenish-grey

Bassendean. It is present over most of the central Perth Region and, lithologically, it is readily identifiable from drillhole cuttings. The unit varies in known thickness to a maximum of about 80 m, depending mainly on the topography.

The Bassendean Sand is pale grey to white and fine to coarse, but predominantly medium grained. It consists of moderately sorted, subrounded to rounded quartz sand, and commonly has an upward fining progression in grain size. Fine-grained, black, heavy minerals are commonly scattered throughout the formation but in places are more concentrated in thin layers, probably indicating a shallow-marine origin. A layer of friable, limonite-cemented sand, colloquially called 'coffee rock', occurs throughout most of the area near the watertable.

The Bassendean Sand unconformably overlies the Cretaceous and Tertiary strata, interfingers to the east with the Guildford Clay, and conformably overlies the Gnangara Sand. To the west, it is unconformably overlain by the Tamala Limestone (Fig. 24). The exposed surface of the Bassendean Sand is coincident with the eolian Bassendean Dune System of McArthur and Bettenay (1960). The stratigraphic relationships of the Bassendean Sand with the Guildford Clay and Gnangara Sand indicate that the formation was deposited under changing and conceivably alternating fluvial, estuarine, and shallow-marine environments.

Tamala Limestone

The Tamala Limestone, defined by Playford et al. (1976) from the type section at Womerangee Hill in the Carnarvon Basin (Playford et al., 1975), extends along the coastal strip of the Perth Region and is a creamy white to yellow, or light-grey, calcareous eolianite (Nidagal and Davidson, 1991). The Tamala Limestone contains various proportions of quartz sand, fine- to medium-grained shell fragments, and minor clayey lenses. The quartz sand varies from fine to coarse grained, but is predominantly medium grained, moderately sorted, subangular to rounded, frosted, and commonly stained with limonite. At the base of the Tamala Limestone, glauconite and phosphatic nodules derived from the Molecap Greensand are sometimes present. The limestone contains numerous solution channels and cavities, particularly in the zone where the watertable fluctuates, and in some areas exhibits karst structures.

Along the coastal strip the Tamala Limestone varies in thickness depending mainly on topography, but is known to have a maximum thickness of 110 m. Depending on location, this unit unconformably overlies the Leederville Formation, Osborne Formation, Lancelin Formation or the Bassendean Sand. Along the coastal margin it is unconformably overlain by the Becher Sand or the Safety Bay Sand (Fig. 24). Its exposed and leached upper surface is coincident with the eolian Spearwood Dune System of McArthur and Bettenay (1960).

Becher Sand

The Becher Sand is defined by Semeniuk and Searle (1985) from the type section at Woodman Point, adjacent to the coast and approximately 19 km southwest of Perth. This unit, which extends along the coastal margin of the Perth Region, consists of fine- to medium-grained quartz and skeletal sand that is mostly structureless and bioturbated. Lenses of silty calcareous clay, rich in shell fragments, are also present.

The Becher Sand was previously referred to as part of the Safety Bay Sand but, because it is of near-shore marine origin and not eolian, it is generically different from the Safety Bay Sand. Although it has not been extensively investigated, the Becher Sand is typically 10–15 m thick (Semeniuk and Searle, 1985) with a maximum known thickness of 20 m in the Rockingham area. This unit unconformably overlies the Tamala Limestone and is unconformably overlain by the Safety Bay Sand (Fig. 24).

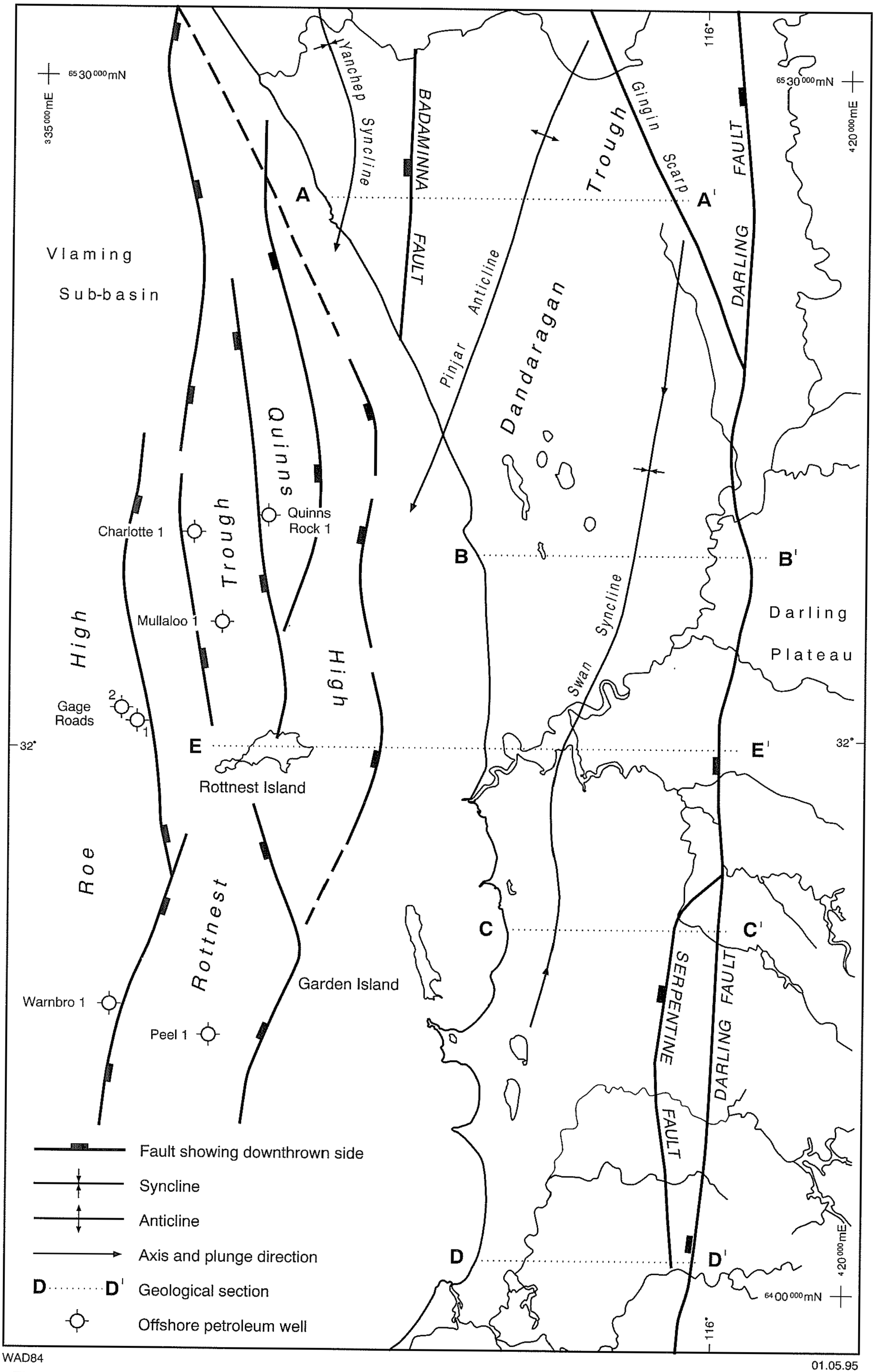


Figure 25. Structural map of the Perth Region showing lines of the geological sections in Figures 24, 26, and 39

Safety Bay Sand

The Safety Bay Sand of Passmore (1967, 1970) and of Playford and Low (1972), with its type section in Rockingham bore R3 (AMG Zone 50, 378077 m E, 6427627 m N) between 0 and 24 m, consists of white, unlithified, calcareous fine- to medium-grained quartz sand and shell fragments with traces of fine-grained, black, heavy minerals. It occurs along the coastal margin as eolian stable and mobile dunes (Quindalup Dune System of McArthur and Bettenay, 1960) and unconformably overlies the Tamala Limestone and the Becher Sand (Fig. 24).

Structure

A major structural event in the Perth Basin took place in the Neocomian Stage when rifting was terminated by the breakup of the Indian and Australian plates and the onset of sea-floor spreading. During breakup, a period of widespread uplift and erosion produced the intra-Neocomian breakup unconformity (Plate 4). By the end of the Neocomian, the present form of the Dandaragan Trough was established, whereas subsidence in the Vlaming Sub-basin continued in response to cooling of the oceanic crust adjacent to the newly developed continental margin.

Onshore, the structure illustrated by the structure contour maps of each of the geological formations has been inferred from borehole evidence. Extensive seismic data are available for areas offshore and to the north and south of Perth. In the Perth Region, folding and faulting in the Dandaragan Trough resulted in low dips to the northeast in the Cattamarra Coal Measures, Yarragadee Formation and Parmelia Formation. Offshore from Perth, the effects of breakup in the Vlaming Sub-basin are much greater, with the development of a number of synclines and faulted anticlines (Davidson and Mory, 1990; Fig. 25). The Darling Fault is the most significant structural feature within the Perth Basin. It is a high-angle fault, dipping to the west, at least 1000 km long and with a vertical displacement of some 12 000 m near Perth. Major movement of the fault ended prior to the intra-Neocomian breakup unconformity; however, some minor movement probably continued into part of the Cainozoic (Playford et al., 1976). The Badaminna Fault in the northwest and the Serpentine Fault in the southeast are also high angle, normal faults, predating the breakup unconformity (Fig. 25). Uplift and erosion has been greatest in the Harvey Ridge to the south of the Perth Region (Playford et al., 1976); the Late Jurassic Yarragadee Formation has been uplifted and eroded out in the Mandurah area. The Dandaragan Trough deepens to the north, with the Parmelia Formation being preserved in the northeast and northwest of the region.

The succeeding Cretaceous strata, which unconformably overlie the Neocomian unconformity surface, are gently folded as a result of penecontemporaneous subsidence, differential compaction of the pre-existing sediments, and draping over fault blocks. As a consequence, the Swan and Yanchep Synclines have developed and there has been local non-deposition of the Gage Formation and the South Perth Shale over the Pinjar Anticline and in the southeastern area. This has resulted in substantial variations in thickness of the post-breakup units (Fig. 26). Evidence of faulting, post-Neocomian unconformity, is inconclusive, although Allen (1980) recognized possible faults in the Swan Valley which cut the Leederville and Osborne Formations.

The Kings Park Formation is a flat-lying, shallow-marine to estuarine deposit laid down in a drowned river valley (Playford et al., 1976) which had been eroded earlier to a depth of about 550 m below sea level and into the Jurassic Yarragadee Formation. The Rockingham Sand occupies a channel eroded into the Cretaceous Leederville Formation to a depth of about 120 m below sea level and which is probably a near-shore erosional feature. The superficial formations are flat lying and rest unconformably on the eroded surface of pre-existing formations. They were deposited during eustatic changes in sea level during the late Tertiary–Quaternary (Allen, 1981a).

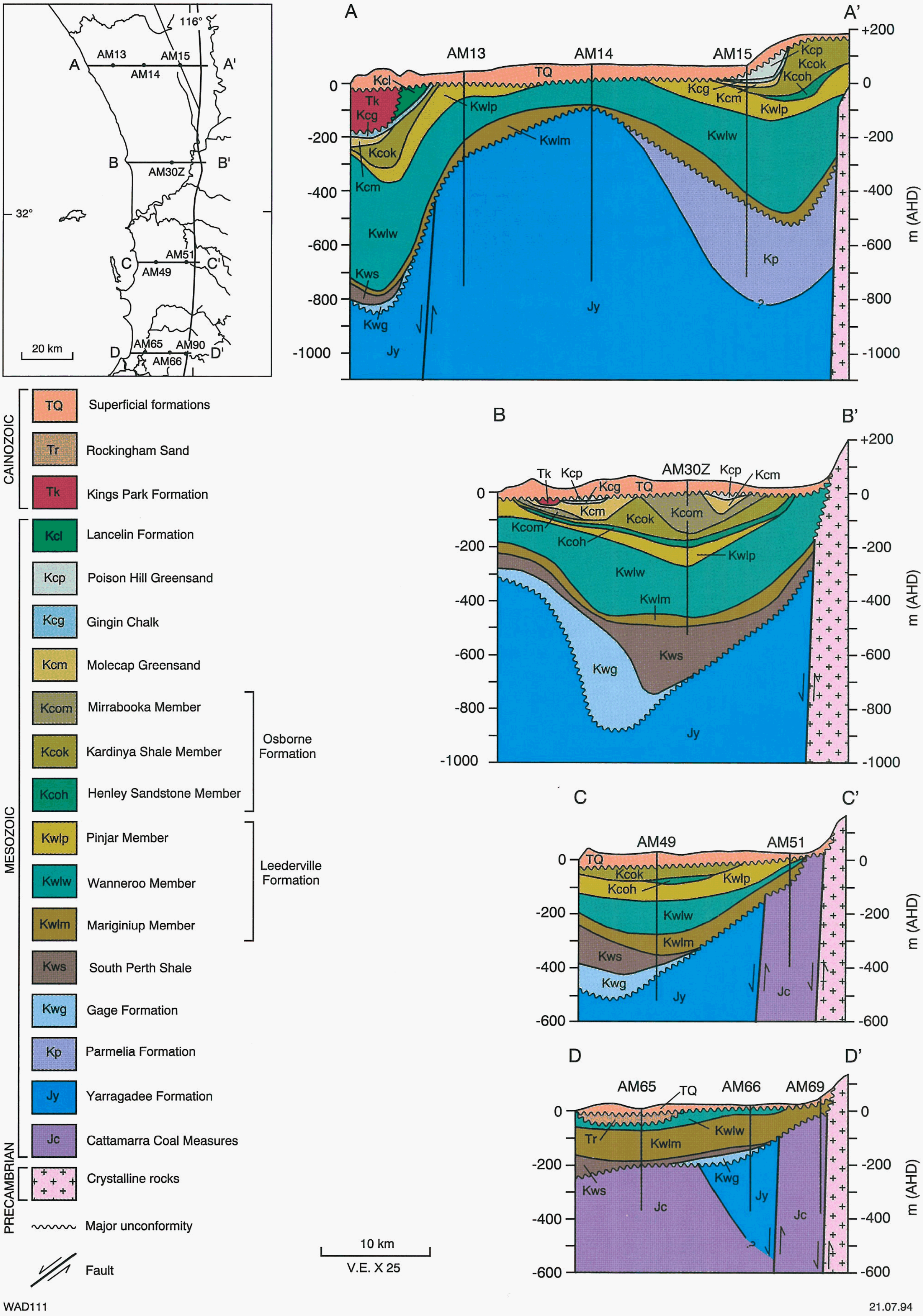


Figure 26. Geological sections showing stratigraphic relationships of Cainozoic and Mesozoic formations

Hydrogeology

Groundwater occurrence

Groundwater pervades the superficial formations beneath the Swan Coastal Plain and the underlying geological formations of the Perth Basin. At some localities, this water is fresh to a depth of at least 1000 m. It originates mainly from direct rainfall recharge on the coastal plain with a small component being derived from local runoff from the Darling and Dandaragan Plateaus. Groundwater in the deeper, confined aquifers also flows into the area from the north.

Groundwater in the Quaternary superficial formations is contained in a regional, unconfined aquifer system (Allen, 1976a, 1981a; Cargeeg et al., 1987) and is locally in hydraulic connection with the underlying Tertiary and Mesozoic formations, which form the confined aquifer systems. In the Perth Region, the unconfined aquifer system is bounded to the east by the Gingin and Darling Scarps, to the west by the Indian Ocean, and arbitrarily to the north by Gingin Brook and to the south by the Murray River.

The confined aquifer systems are assumed to be bounded to the east by the Darling Fault and to extend several kilometres offshore to the west. They form the central part of the confined aquifer systems of the regional Perth Basin (Commander et al., 1991) and, in the Perth Region, they have been investigated to a depth of about 1100 m. The extent of the fresh groundwater beneath the ocean is not known, but it may extend as far offshore as Rottnest Island.

The geological formations have been grouped into six distinct aquifers, each being assigned the name of the major geological unit contributing to the aquifer. These aquifers are locally hydraulically connected; elsewhere, they are separated by major confining beds or by the distribution of the geological formations. The stratigraphic sequence and the relationship of the aquifers are summarized in Table 7. In descending order they are

- **Superficial aquifer:** a major unconfined aquifer comprising the Quaternary–Tertiary sediments of the coastal plain; Safety Bay Sand, Becher Sand, Tamala Limestone, Bassendean Sand, Gnangara Sand, Guildford Clay, Yoganup Formation, and Ascot Formation. The groundwater in the superficial aquifer ranges in age from the present, at the watertable, to about 2000 years at the base of the aquifer (Thorpe and Davidson, 1991).
- **Rockingham aquifer:** a minor semi-unconfined aquifer consisting of the late Tertiary–?Quaternary Rockingham Sand. The age of the groundwater in the Rockingham aquifer is not known but is probably similar to that at the base of the superficial aquifer (2000 years).
- **Kings Park aquifers:** these two minor confined aquifers are the early Tertiary Mullaloo Sandstone Member and Como Sandstone Member of the Kings Park Formation. The age of the groundwater in the Kings Park aquifers is not known.
- **Mirrabooka aquifer:** a locally important semi-confined to confined aquifer comprising the Cretaceous Poison Hill Greensand, Gingin Chalk, Molecap Greensand and the Mirrabooka Member of the Osborne Formation. The age of the groundwater in the Mirrabooka aquifer is not known, but is probably between 2000 and 10 000 years.
- **Leederville aquifer:** a major confined aquifer comprising the Cretaceous Osborne Formation (Henley Sandstone Member) and Leederville Formation (Pinjar Member, Wanneroo Member, and Mariginiup Member). Groundwater in the Leederville aquifer ranges in age from about 1900 years to more than 36 800 years, but is generally less than 36 000 years (Thorpe and Davidson, 1991).
- **Yarragadee aquifer:** a major confined aquifer comprising the Cretaceous Gage Formation and Parmelia Formation, and the Jurassic Yarragadee Formation and Cattamarra Coal Measures. Groundwater contained in the Yarragadee aquifer ranges in age from about 600 years (in the intake area to the south of Perth) to more than 37 700 years elsewhere, but is generally older than 36 000 years (Thorpe and Davidson, 1991).

Superficial aquifer

The superficial aquifer is a complex, unconfined, multilayered aquifer. It was originally referred to as the 'Superficial Formations' aquifer by Allen (1976a) and incorporated the various formations of the Kwinana Group and underlying late Tertiary formations, excluding the Rockingham Sand. It has also been colloquially referred to as the 'Bassendean aquifer', 'unconfined aquifer' and 'shallow aquifer'. However, in this Bulletin it is referred to as the superficial aquifer.

The superficial aquifer is a major unconfined aquifer extending throughout the coastal plain, west of the Gingin and Darling Scarps. The sediments which constitute the superficial aquifer range from predominantly clayey

(Guildford Clay) in the east adjacent to the Darling Fault, through a sandy succession (Bassendean Sand and Gnangara Sand) in the central coastal plain area, to sand and limestone (Safety Bay Sand, Becher Sand and Tamala Limestone) within the coastal belt. Over most of the area the aquifer directly overlies sedimentary rocks of Cretaceous age. In the Swan River estuary area, it rests on the early Tertiary Kings Park Formation and, in the Rockingham area, on the late Tertiary–?Quaternary Rockingham Sand (Plate 49). The superficial aquifer has a maximum thickness of about 70 m, but average thicknesses of 45 and 20 m in the northern and southern Perth Region respectively (Plate 51).

The upper surface of the unconfined aquifer is the watertable, whose variations in depth (Plate 52) depend mainly on topography (Fig. 5) but also on the hydraulic conductivity (permeability) of the sediments and location within the groundwater flow system. Over much of the central area of the Bassendean Dunes and beneath the low lying areas of the Spearwood Dunes, the many lakes and swamps and the large areas of groundwater inundation during winter indicate that the aquifer has reached its upper limit of storage. As a consequence of the varying hydraulic conductivities and depths to water, the watertable fluctuates seasonally by about three metres in areas of clay adjacent to the Darling Fault, by about one metre in the central sandy area, and less than 0.5 m in limestone along the coast. The watertable elevation is highest during September–October and lowest during April–May.

The watertable configuration (Fig. 27; Plate 53) is dominated by the presence of two major groundwater mounds in the central coastal plain area, the Gnangara (North and South) and Jandakot Mounds. The presence of these mounds is determined mainly by the regional topography, partially by the drainage pattern (with drainage developed parallel to, and at the base of, the Gingin and Darling Scarps) and partially by the hydraulic characteristics of the sediments. The superficial aquifer of the Perth Region has been divided into ten discrete hydrogeological areas (Fig. 27) on the basis of topography, geology, and the discharge boundaries formed by the rivers and the ocean.

Groundwater recharge

The groundwater mounds — Gnangara Mound (South), Jandakot Mound, Stakehill Mound and Safety Bay Mound — are recharged directly by rainfall infiltration and, apart from discharge boundaries and a few drains, are characterized by the absence of surface flow. The mounds have developed because the rate of vertical rainfall infiltration is greater than the rate of horizontal groundwater flow through the aquifer. They will continue to develop until the horizontal hydraulic gradient is sufficiently steep to enable all of the recharge water to be transmitted as groundwater flow. At this stage, the watertable will be at its maximum elevation. During periods of little or no recharge, the rate of horizontal groundwater flow exceeds that of vertical infiltration and the mounds begin to subside as the watertable lowers and the hydraulic gradients flatten. This cycle is repeated seasonally and, depending on the amount and intensity of the rainfall, results in the seasonal fluctuations in watertable levels.

Direct rainfall recharge also occurs over the Gnangara Mound (North), Swan Helena, Cloverdale, Armadale, Byford and Serpentine areas and, in these areas, some recharge may result from minor ephemeral streams debouching from the Darling and Dandaragan Plateaus and discharging onto the coastal plain. Rainfall over each of these hydrogeological areas readily percolates to the watertable but recharge rates may vary considerably, depending on landuse and geology. There is a general reduction in rainfall infiltration towards the east where the sediments have greater clay content.

Rainfall recharge estimates have been made in a number of studies since 1970. Bestow (1971) estimated that about 7.3% of the mean annual rainfall over the Gnangara area contributes to rainfall recharge and that the remainder is lost to evaporation and transpiration. Allen (1976a) calculated that about 8.5% of the rainfall recharges the aquifer in the northern area and 5.5% in the southern area. Sharma and Pionke (1984) estimated that about 12% of the rainfall over native bushland recharges the superficial aquifer, and that beneath a mature pine plantation there may be no groundwater recharge. Davidson (1984a, 1987) estimated, by flownet analysis, that about 14% of rainfall recharges the aquifer in the southern Perth area and 13% in the northern Perth area.

From a local investigation on land used for pasture, Sharma et al. (1988) estimated that between 50 and 60% of the direct rainfall recharges the aquifer, but that on a more regional scale these estimates may not apply. Thorpe (1989), using naturally occurring tritium as an indicator of groundwater recharge, found that about 21% of rainfall recharges the aquifer near the crest of the Gnangara Mound (South). For the same banksia woodland area, Farrington and Bartle (1989) determined recharge rates of between 20 and 22% by chloride balance techniques. Sharma et al. (1991b) showed that approximately 40% of the rainfall over a market garden area, to the north of Perth, recharges the aquifer.

In the urban areas of Perth, rainfall recharge is enhanced by roof and road catchments which channel rainwater into soak wells and stormwater basins. It has been estimated (Cargeeg et al., 1987) that about 21% of the rainfall recharges the aquifer beneath urban Perth. Within the urban areas, there is additional recharge to the superficial aquifer as a result of garden and parkland irrigation of imported (scheme) water or water obtained from the deeper aquifers.

Some recharge to the superficial aquifer also results from upward leakage and discharge of groundwater from the underlying aquifers (Plate 54). This occurs in areas where there are increasing hydraulic heads with depth and where there are no confining beds between the underlying aquifers and the superficial aquifer.

In this Bulletin, rainfall recharge has been estimated on a regional scale by both groundwater flownet and water-balance analyses. The determined percentages of

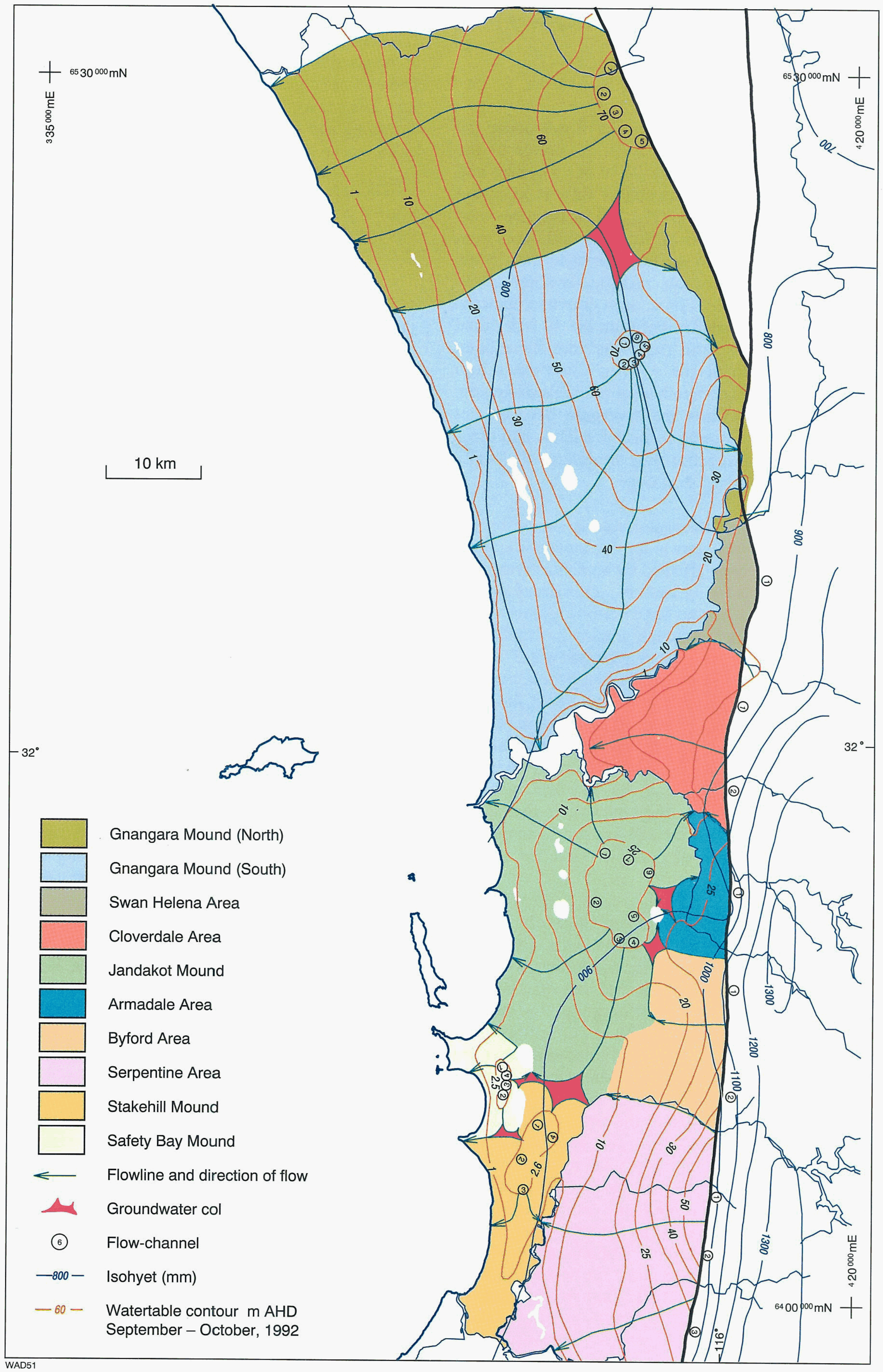


Figure 27. Superficial aquifer groundwater flownet

rainfall recharge, by this approach, are considered to be representative average annual values covering many years.

Groundwater flow

Groundwater in the superficial aquifer flows under the influence of gravity and away from the crests of the groundwater mounds and foothills of the Darling and Dandaragan Plateaus. The direction of flow is indicated on the watertable contour map (Fig. 27) by the arrows on the flowlines drawn normal to the watertable contours. Flow terminates at the discharge boundaries formed by the major drainages and the ocean, and locally some of the lakes. Some of the flowlines have been drawn to coincide with the hydraulic boundaries between the 10 individual hydrogeological areas, and the remainder have been arbitrarily selected to divide each of these areas into roughly equal segments. Beneath most of the Perth Region, the groundwater flowlines are divergent because net recharge is occurring. However, near wetlands and areas of high groundwater abstraction they are commonly locally convergent, thus indicating discharge.

The configuration of the watertable is shown by the watertable contour map, drawn for September–October, 1992 (Fig. 27). It has been affected by human activity such as clearing of bushland for agriculture, urban development, drainage, and groundwater abstraction. Clearing the bushland for pasture and livestock grazing has facilitated rainfall recharge and caused rising groundwater levels. Large areas adjacent to and west of Ellen Brook, north of Perth, and many areas to the south of Perth, become inundated during winter and require drainage. Urban development has similarly induced additional rainfall recharge and some of the naturally occurring seasonal lakes are now permanently inundated. In other areas, the watertable has been lowered by groundwater abstraction and some of the naturally occurring lakes and swamps have become permanently dry, or contain water for shorter periods of the year.

The hydraulic gradients, depicted by the horizontal separation of the watertable contours, vary across the coastal plain mainly because of the variations in aquifer thickness and hydraulic conductivities, but also because of the areal variations in rainfall recharge and the location of groundwater discharge boundaries. In the eastern area of clayey sediments, the hydraulic conductivities are generally less than 10 metres per day (m/d) and the hydraulic gradients are relatively steep in comparison with those in the central sandy area of the coastal plain. In the eastern area the hydraulic gradients also generally steepen towards the discharge boundaries formed by the drainages which subparallel the Gingin and Darling Scarps. In the central sandy area, where the hydraulic conductivities vary with bedding and range from 10 m/d to more than 50 m/d (average ~15 m/d), the hydraulic gradients are relatively uniform. In the western area, at about the contact between the Bassendean Sand and the Tamala Limestone (Plate 50) and roughly coinciding with the north–south linear chain of lakes, the hydraulic gradients are relatively steep. This is due largely to the marginally lower hydraulic conductivities of the finer grained sand at the eastern margin of the Tamala Limestone and also in part to the high hydraulic conductivities (100–1000 m/d) of the Tamala Limestone to the west, resulting in a draining effect of the groundwater from the east and the steeper gradients. The hydraulic gradients within the Tamala Limestone are very low owing to the high hydraulic conductivity of the limestone and the eustatic control of the watertable level by the ocean level.

The rate of groundwater flow through the superficial aquifer can be estimated using the Darcy equation as expressed by Domenico and Schwartz (1990).

$$v = \frac{ki}{\theta} \quad \text{or} \quad v = \frac{Ti}{b\theta} \qquad \text{.......................................}(2)$$

where v = linear velocity (m/d)
$k = \frac{T}{b}$ = horizontal hydraulic conductivity (m/d)
i = hydraulic gradient (Plate 53, dimensionless)
θ = effective porosity (interconnected pore space, dimensionless)
T = transmissivity (Plate 55, m^2/d)
b = saturated thickness (Plate 51, m).

The rate of groundwater flow depends on the hydraulic conductivity and hydraulic gradient of the aquifer. However, because of the large lateral and vertical variations in hydraulic conductivity (Table 10), the average hydraulic conductivity of the aquifer has been obtained by dividing the transmissivity value by the saturated thickness of the aquifer. From equation (2) and assuming an effective porosity of 0.2, equivalent to the average specific yield of the aquifer, the rate of groundwater flow through the sandy sediments of the superficial aquifer ranges from about 50 to 150 m/year, depending on location. This is supported by studies at a local scale where, using bromide as a tracer, Salama et al. (1989) and Thierrin et al. (1993) determined groundwater flow rates of 40–100 m/year beneath a landfill site in Morley, and 100–150 m/year beneath a petrol service station in Eden Hill. Along the coastal margin, the rate of groundwater flow through the Tamala Limestone is highly variable, ranging from about 200 to 2000 m/year, depending mainly on the degree of interconnecting solution channels within the limestone. However, by injection of bromide tracer, Barber et al. (1990b) determined groundwater flow rates of 85 and 335 m/year within the Tamala Limestone beneath Tamala Park, approximately 30 km northwest of Perth. At some localities, the Tamala Limestone may have comparatively low hydraulic conductivities.

Lakes

Lakes are important habitats for many species of plants and animals and, because of their environmental significance and land value, they have been extensively investigated from a hydrogeological perspective by the Geological Survey, Water Authority, and the CSIRO Division of Water Resources. With respect to groundwater flow, there are four major types of lake (Fig. 28) within the Perth Region.

1. **Perched lakes:** Water in these lakes is perched above the watertable by clayey sediments, peaty lacustrine

Table 10. Superficial aquifer adopted hydraulic conductivity values (modified from Hazel, 1973; Martin and Baddock, 1989)

Lithology	*Hydraulic conductivity (m/d)*
Sand	
very coarse to gravel	246
very coarse	204
coarse	73
medium to very coarse (moderately sorted)	50
fine to gravel (poorly sorted)	10
medium	16.5
fine to medium	8.2
fine	4.1
fine to very fine	1.7
very fine	0.8
silty	4
clayey	1
Clay	0.4
Sand and Limestone: Ascot Formation	8
Limestone and calcarenite: Tamala Limestone	100–1 000

deposits or, particularly in the southern Perth Region, by 'coffee-rock' (iron-oxide cemented sand). Most of these lakes are only temporarily perched and become dry during the summer owing to evaporation and some downward leakage to the watertable. Others, that are hydraulically connected to the watertable during winter, may temporarily hold perched water during summer when the watertable declines to a depth beneath the base of the lakes. On the coastal plain, temporary perching most commonly occurs where the watertable is less than 3 m below groundlevel and 'coffee rock' is shallower or is exposed at the surface. On the Dandaragan Plateau, lakes are perched on a lateritic hardpan more than 50 m above the watertable.

2. **Groundwater recharge lakes:** These lakes generally exist high in the landscape where depth to watertable exceeds 2 m. When the watertable rises into the bed of the lake, the lake may become a groundwater discharge lake or a groundwater throughflow lake. Many are within the sandy sediments of the Bassendean Sand and, since rainfall runoff within the Bassendean Dune System is negligible, the groundwater recharge catchment area of these lakes is limited mostly to the surface area and immediate surrounds of the lakes. Stormwater and compensating basins, which receive stormwater runoff, may be classified as groundwater recharge lakes.

3. **Groundwater discharge lakes:** These lakes are not common and are found low in the landscape where they form groundwater discharge sinks within the surrounding watertable (e.g. Lakes Cooloongup and Walyungup). Because they are groundwater sinks and are not seasonally flushed by rainfall or groundwater throughflow, the lake water is commonly hypersaline due to evaporative concentration of the dissolved salts. Those lakes that periodically become groundwater throughflow lakes (e.g. Lake Coogee) are seasonally flushed and contain brackish to saline water.

4. **Groundwater throughflow lakes:** These lakes extend throughout the coastal plain of the Perth Region and are by far the most common type of lake. The relationship between some of these lakes and the groundwater flow system has been investigated by Allen (1980), Davidson (1983), Hall (1985) and Townley et al. (1993). These investigations have shown that the elevation of the watertable on the up-hydraulic gradient side of groundwater throughflow lakes is marginally higher than that of the lake surface, resulting in discharge of groundwater into the lake. The water in these lakes is maintained by this groundwater flow together with rain falling on the lake surface. On the down-hydraulic gradient side of these lakes, the elevation of the watertable is lower than the lake waterlevel, resulting in some outflow from the lake to groundwater (e.g. Lake Jandabup). The seasonal fluctuations in lake waterlevels are in phase with variations in watertable levels but the response in the lake is usually greater for periods of heavy rainfall or higher evapotranspiration. The depth of the groundwater capture zone of these lakes depends mostly on the width of the lake in the direction of groundwater flow and also on the anisotropy of the aquifer. The width of the groundwater capture zone, normal to the groundwater flow direction, is commonly about twice the length of the lake in the same direction as groundwater flow (Townley et al., 1993). These investigations have shown that most of the aquifer thickness, within the groundwater capture zone, contributes groundwater discharge to the lakes. Also, of the accumulated groundwater outflow and rainfall to the lakes, about 90% is lost to evapotranspiration (evaporation from the free-standing water plus transpiration from the vegetation). Consequently, the salinity of the lake water is higher than that of the discharging groundwater and a plume of more saline groundwater results at the outflow side of the lake.

Groundwater discharge

Groundwater moves very slowly through the superficial aquifer and is eventually discharged at the hydraulic boundaries formed by the rivers, ocean, and some of the lakes. During movement, the groundwater is recharged by rainfall infiltration and discharge occurs by evaporation from wetlands; transpiration from vegetation where roots are able to reach the capillary fringe associated with the watertable, leakage into underlying aquifers where downward hydraulic gradients occur and confining beds are absent, and by abstraction of groundwater from boreholes. Groundwater in the superficial aquifer also discharges into natural and constructed drainages (particularly in the southern area), into wetlands, and at springs. Springs seep mainly adjacent to the major drainages where the watertable intersects the levee banks. This mostly results in at least a generally wetted area at the land surface; at some localities, flow may occur. Similarly, along the coastline, groundwater discharges

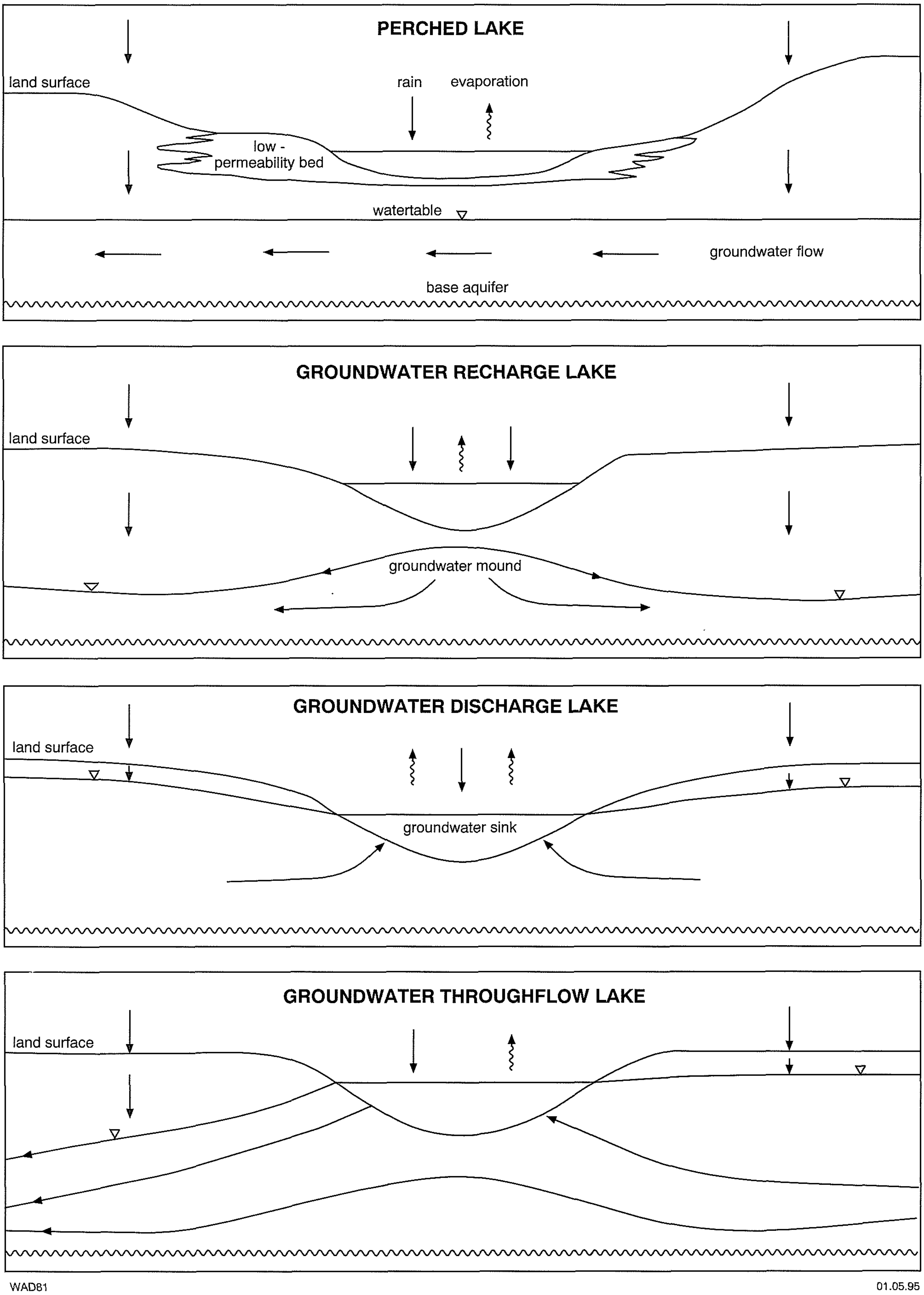


Figure 28. Groundwater flow associated with lakes

through a general seepage face on the beach or under the ocean, or forms small springs along rocky parts of the coast (Allen, 1981a). Some discharge is believed to take place offshore from springs connected to solution channels within the Tamala Limestone.

At the end of its flow path, groundwater discharges into the ocean, Peel Inlet and the Swan River estuary over a saltwater wedge that forms the interface between land- and ocean-derived groundwater. Because groundwater discharges to the ocean, the elevation of the watertable near the coast is controlled by the ocean level and the prevailing climatic conditions over the recharge area to the east.

Groundwater storage

The volume of groundwater in storage in the superficial aquifer, represented by the amount of water in pore spaces available to bores if the sediments were dewatered, has been calculated using the contour map of the aquifer saturated thickness (Plate 51) together with estimated specific yields of 0.30 for the coastal belt of Tamala Limestone, 0.20 for the central area of Bassendean Sand and Gnangara Sand and 0.05 for the area of the Guildford Clay. The volumes of groundwater held in storage within the superficial aquifer for the ten discrete hydrogeological areas have been calculated by multiplying the saturated aquifer volume by the estimated values of specific yield. These are given in Table 11. The total available groundwater held in storage within the superficial aquifer is about 25 800 x 10^6 m^3, which compares closely with the estimate of 24 500 x 10^6 m^3 by Allen (1981a).

Groundwater balance

Method of analysis

A simplified groundwater balance for the region, which did not include the effects of changing groundwater storage, urban drainage or infiltration of recycled groundwater, was attempted by Allen (1981a). He showed that large errors or imbalances between groundwater inputs and outputs may arise, mainly due to the inaccuracies of estimating evapotranspiration. Davidson (1984a) calculated detailed groundwater balances for the superficial aquifer in the southern Perth area, using a groundwater flownet. This methodology has been extended to the entire Perth Region, with detailed flownet analysis for each hydrogeological area.

Table 11. Superficial aquifer groundwater storage (x$10^6$$m^3$)

Hydrogeological area	*Eastern clay*	*Central sand*	*Coastal limestone*	*Total*
Gnangara Mound (North)	300	3 500	3 100	6 900
Gnangara Mound (South)	100	6 300	5 400	11 800
Swan Helena	100	-	-	100
Cloverdale	100	700	-	800
Jandakot Mound	-	2 300	1 500	3 800
Armadale	50	200	-	250
Byford	100	50	-	150
Serpentine	150	600	-	750
Stakehill Mound	-	-	900	900
Safety Bay Mound	-	-	300	300
TOTAL	**900**	**13 650**	**11 200**	**25 750**

The groundwater balance equates all groundwater entering the groundwater flow system to all that which leaves the system, as expressed by equation (3).

$$R + H + I + L_U = d + d_O + L_D + a + R'' + a' + E + E' \ldots. (3)$$

where R = rainfall over the hydrogeological area
H = recharge from hills run-off (Collins and Rosair, 1978)
I = imported water e.g. scheme water used for irrigation and septic systems
L_U = leakage upwards from underlying aquifer
d = groundwater discharge to major lakes, drains and river
d_O = groundwater discharge to ocean
L_D = leakage downwards into underlying aquifer
a = abstraction pumped out of the area
R'' = loss due to recycling groundwater abstracted within the area for irrigation
a' = unaccounted abstraction
E = apparent evapotranspiration (mostly from wetlands not depicted by d)
E' = unaccounted evapotranspiration due to inherent inaccuracies of the flownet analysis method, and
E_t = $E + E'$ = total evapotranspiration

The components of the water balance of the superficial aquifer have been determined by analysis of the groundwater flownet (Plate 53). In each of the hydrogeological areas groundwater flowlines have been positioned to coincide, where possible, with the cadastral boundaries of the Water Authority groundwater management areas. The groundwater flowlines have been drawn to represent the direction of groundwater flow, i.e. perpendicular to the synoptic watertable contours (September–October, 1992). Areas between flowlines are referred to as flow-channels, and the areas between each 5 m watertable contour and the bounding flowlines are termed flownet cells. The components of the groundwater balance equation are calcuated for each flownet cell (Tables 12–21).

The net recharge contributing to groundwater flow in the flownet can be expressed as the sum of six components from equation (3), as shown in equation (4).

$$\text{Net recharge} = R + H + I + L_U - E_t$$
$$= d + d_O + L_D + a + R'' + a' \ldots\ldots\ldots\ldots (4)$$

The amount of groundwater flow through each flownet cell, bounded by associated watertable contours and flowlines, has been calculated by two methods. Comparisons of the results are given in Tables 12–21. The first method makes use of groundwater hydraulics to estimate groundwater throughflow in the aquifer. The second method is a chloride mass balance approach, which is based on the relative concentrations of chloride in rainwater and in the groundwater.

Throughflow determined by groundwater hydraulics:

The volume of groundwater outflow (Q_{Do}) from each flownet cell is calculated by using the Darcy equation.

$$Q_{Do} = T\,i\,L = kbiL \qquad (5)$$

where Q_{Do} = volume of groundwater passing through section (m^3/d)
T = transmissivity of aquifer, Plate 55 (m^2/d)
i = hydraulic gradient, Plate 53 (dimensionless)
L = section width of flownet cell, Plate 53 (m)
k = horizontal hydraulic conductivity, Plates 51 and 55 (m/d)
b = saturated aquifer thickness, Plate 51 (m).

The limiting conditions set out by Darcy (1856) are assumed: that flow in the porous medium is laminar, that flow velocities are very low, and that the Reynolds number of turbulence — which expresses the dimensionless ratio of inertial to viscous (or resistive) forces — is less than one. Within the Tamala Limestone, where solution cavities and steep hydraulic gradients exist, groundwater flow may not be laminar and the limiting conditions may not be satisfied. This may occur locally, immediately west of the geological contact between the Bassendean Sand and the Tamala Limestone, but is not significant on a regional scale.

The transmissivity of each flownet cell was obtained from the transmissivity isoline map (Plate 55). This was constructed using transmissivities obtained from aquifer pumping tests and from hydraulic conductivities estimated from lithological logs (Table 10) and related to the aquifer thickness.

The hydraulic gradients were obtained by dividing the particular watertable contour interval by the mean distance between contours. This method has the merit of simplicity and involves little error compared with the more precise calculation of the tangent at the down-gradient contour. The section width of each flownet cell was measured directly from the flownet.

Throughflow determined by chloride mass balance:

The amount of groundwater flow through each flownet cell has also been calculated by using the chloride mass balance equation:

$$Q_{Clo} = \frac{(Cl_r \times R/365 \times A) + (Q_{Di} \times Cl_i)}{Cl_o} \qquad (6)$$

where Q_{Clo} = groundwater outflow from each flownet cell (m^3/d)
Cl_r = chloride concentration in rainfall (mg/L)
R = average annual rainfall (m/year)
A = area of each flownet cell (m^2)
Q_{Di} = groundwater inflow into each flownet cell which is equivalent to outflow of previous cell by the Darcy equation (m^3/d)
Cl_i = chloride concentration in groundwater inflow (mg/L)
Cl_o = chloride concentration in groundwater outflow (mg/L)

Because the aquifer consists predominantly of leached siliceous sand, it is assumed that all chloride in the groundwater originates from rainfall. The chloride concentration in rainfall (including dryfall) over the Perth Region, ranges from about 14 mg/L along the coast to about 10 mg/L along the Gingin and Darling Scarps (Hingston and Gailitis, 1977). The chloride concentration in the groundwater inflow and outflow can be estimated from the isochlor map (Plate 55) which shows the average chloride concentration within the superficial aquifer. The groundwater flow (Q_{Clo}) is calculated from equation (6). Groundwater inflow (Q_{Di}) is obtained from the flownet and is equivalent to the outflow of the previous cell, calculated by using equation (5).

Flownet analysis

Reliability of methods

The analysis of vertical groundwater fluxes within the flownet is made by comparison of the flow calculated by the hydraulic method (Q_{Do}) with the flow calculated by the chloride mass balance method (Q_{Clo}). It is based on the assumption that the volume of groundwater flow through each flownet cell (Q_{Do}), obtained by using equation (5), is correct. The discrepancies in flow, shown by the chloride balance (Q_{Clo}) obtained by using equation (6), indicate gains to and losses from the flow system that are not identified by using equation (5) alone. The chloride mass balance method is applicable if the climatic conditions have remained fairly constant for many years. The relatively small cyclic variations in rainfall (Fig. 3) have an insignificant effect on the chloride concentration in the groundwater, because of the slow rates of groundwater flow and the long residency time of the groundwater in the aquifer. From estimates made of the oxygen-18 and deuterium composition of groundwater from the deeper confined aquifers, dated at over 10 000 years by ^{14}C methods (Thorpe and Davidson, 1991), the present climatic conditions are similar to those of many years ago.

A reduction in chloride concentration of the groundwater across a flownet cell and a gain to throughflow by chloride balance ($Q_{Clo} > Q_{Di}$) suggests recharge has occurred from rainfall (R'). An increase in chloride concentration and reduction in flow ($Q_{Clo} > Q_{Di}$) suggests there has been a net loss due to evapotranspiration (E).

When the throughflow by chloride balance (Q_{Clo}) is less than that for Q_{Do} ($Q_{Clo} < Q_{Do}$), calculated by using equations (5 and 6), a gain to groundwater flow has occurred without changing the chloride concentration of the groundwater. This can result from upward leakage of groundwater from a lower aquifer (L_U), importation of irrigation water (I), or from rainfall recharge carrying accumulated salts (R") from swampy areas. Moreover, as is mostly the case, it can result from the loss due to evapotranspiration of recycled groundwater used for irrigation.

When the throughflow (Q_{Clo}) is greater than that for Q_{Do} ($Q_{Clo} > Q_{Do}$), groundwater has been lost from the flow system without any change in the chloride concentration. This can occur by downward leakage of groundwater into an underlying aquifer (L_D), discharge into drainages (d), or by abstraction and piping of groundwater out of the area (a).

The two methods, aquifer hydraulics (Q_{Do}) and chloride balance (Q_{Clo}), used to calculate the amount of groundwater flow through each flownet cell have basic and unavoidable inaccuracies. These are due to inaccuracies of estimating each of the elements in equations (5) and (6) and, in particular, the processes of estimating aquifer transmissivities and chloride concentrations of rainfall and groundwater. For these reasons, an error function (e), of unknown magnitude, could be applied to each of the throughflow calculations. However, because the two methods often produce large calculated differences in throughflow, the error function, although present, is considered to be insignificant.

With respect to Q_{Do} and Q_{Clo} flow, 13 different combinations are possible (Fig. 29). These are grouped into three main classes: gains equal to losses, gains greater than losses, and gains less than losses. Each combination illustrated is numbered (top right corner) so that the individual flownet cell depicted in Tables 12–21 can be readily categorized. The tables show the nature of the gains or losses, which have been individually selected to best fit the hydrogeology and the environment in each area. Where more than one process is involved and the individual quantities are not known, the total gains or the total losses are assumed to be equally proportioned.

Gnangara Mound (North)

The Gnangara groundwater mound was originally defined by Allen (1976a) to be the area bounded by Gingin Brook to the north, the Swan River to the south, Gingin Scarp and Ellen Brook to the east, and the ocean to the west. The configuration of the watertable contours (Plate 53) shows that the original Gnangara groundwater mound can be divided into a northern and a southern area, each with separate rainfall catchments, individual origins of groundwater flow, and unique bounding flowlines.

The Gnangara Mound (North) covers an area of about 927 km^2 and extends across the coastal plain from the Gingin Scarp in the east to the ocean in the west. The northern boundary is arbitrarily taken as Gingin Brook, although the brook does not represent a continuous bounding flowline. The southern boundary is taken as the bounding flowline between the Gnangara Mound (North) and the Gnangara Mound (South) areas and its position may vary slightly depending on seasonal conditions.

Along the eastern margin, the sediments are more clayey (Guildford Clay) than in the central part of the coastal plain, where they are predominantly sandy (Bassendean Sand). To the west, the sandy formations pass laterally into limestone (Tamala Limestone), which borders the coastal strip (Plate 50). The aquifer has a maximum saturated thickness of about 50 m (Plate 51) in the central coastal plain area of the Bassendean Dunes. Aquifer transmissivities generally increase in a westerly direction from about 100 m^2/d adjacent to the Gingin Scarp to about 600 m^2/d in the central area, and to more than 10 000 m^2/d in the cavernous limestone belt (Plate 55). The high transmissivity in the west results in a flattening of the hydraulic gradient towards the coast (Plate 53).

The Gnangara Mound (North) has been divided into five separate groundwater flow-channels each originating at the base of the Gingin Scarp. Each of flow-channels 2, 3 and 4 carries groundwater across the coastal plain to discharge westward into the ocean over a saltwater wedge formed between ocean water and land-derived groundwater. Most of the groundwater within flow-channel 1 discharges into Gingin Brook, but some remains as base flow to the brook. The groundwater in flow-channel 5 discharges into Ellen Brook.

Groundwater recharge ensues mainly from rainfall infiltration at rates ranging up to 18% of the rainfall (Table 12) but some unknown quantity also originates from surface runoff from the Dandaragan Plateau (Fig. 1). Of the total rainfall recharge to the superficial aquifer, about 29 750 m^3/d are lost to the underlying Leederville aquifer by downward leakage. This downward leakage is equivalent to about 3% of the rainfall over the recharge area to the Leederville aquifer. Also, approximately 1950 m^3/d discharge into Gingin Brook and about 8350 m^3/d into Ellen Brook.

Towards the coast, in an area of upward hydraulic gradients (Plate 54), approximately 2800 m^3/d of groundwater recharge the superficial aquifer by upward leakage from the Leederville aquifer (flow-channels 2, 3 and 4).

In the urbanized area of Yanchep Beach – Two Rocks, recycling of groundwater abstracted for irrigation will cause the salinity of the groundwater to steadily increase. Evaporation concentrates the dissolved salts of the irrigated water and these will eventually be leached to the groundwater.

Along the western margin of the area, a total of about 155 350 m^3/d of groundwater discharges to the ocean from flow-channels 2, 3 and 4.

Substituting values from Table 12 into equation (4):

$$\begin{aligned}\text{Net recharge} &= R + H + I + L_U - E_t \\ &= 695.71 + 0 + 0.18 + 1.02 - 620.47 \\ &= d + d_O + L_D + a + R'' + a' \\ &= 3.76 + 56.70 + 10.86 + 0.33 + 4.45 + 0.34 \\ &= 76.44 \times 10^6 \text{ m}^3\text{/year}\end{aligned}$$

This net recharge represents 10.99% of the annual rainfall of 695.71 x 10^6 m^3 over the Gnangara Mound (North). Total evapotranspiration is about 620.47 x 10^6 m^3/year.

Over the entire area of the Gnangara Mound (North) the average recharge is about 11% of the rainfall or equivalent to 80 mm of rain per year. In the eastern area adjacent to the Gingin Scarp the watertable is shallow (at a depth generally less than 3 m) and recharge contributing to groundwater flow is equivalent to about 3% of the rainfall. The depth to the watertable increases in a westerly direction and the recharge rate also increases to about 10% of rainfall. Beneath the relatively high limestone area fringing the coast the watertable is generally beneath the

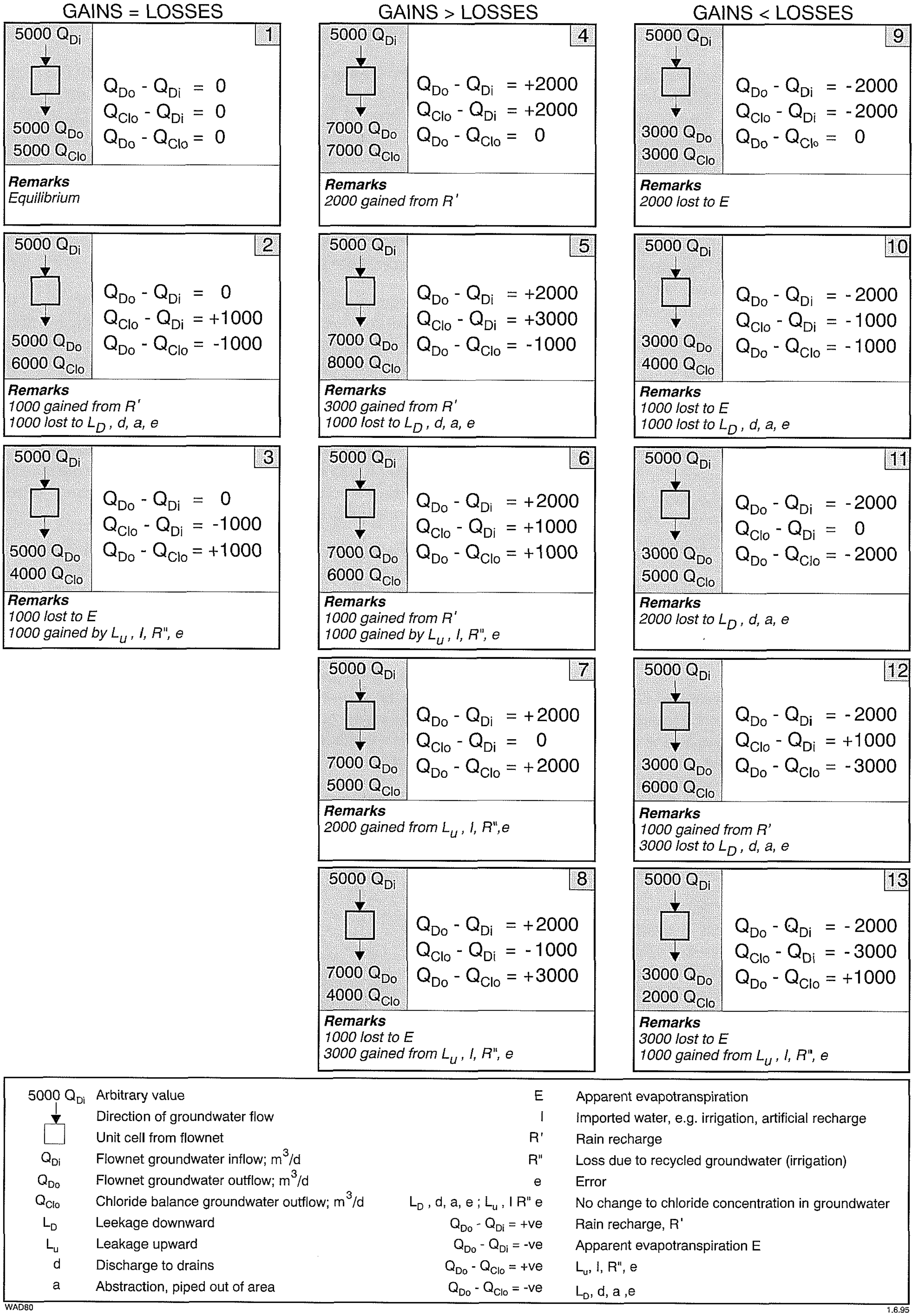


Figure 29. Flow combinations using aquifer hydraulics and chloride balance

Table 12. Gnangara Mound (North) — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channels*					*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Area between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % rain recharge per unit area (rounded to whole %)*		
		1	*2*	*3*	*4*	*5*					*T_R*	*L_{DR}*	*N_R*
70	Q_{Do}	(5) 250	(5) 100	(5) 200	(5) 150	(5) 150	850		31	63 700	3	2	1
	Q_{Clo}	600	200	450	350	350	1 950						
	G_N	250	100	200	150	150	850	–850					
	R'	600	200	450	350	350	1 950	+1 950					
	L_D	350	100	250	200	200	1 100	–1 100					
	T_R L_{DR} N_R (%)	4 2 2	2 1 1	2 1 1	4 2 2	6 3 3		0					
60	Q_{Do}	(5) 1 000	(5) 1 100	(5) 2 550	(5) 4 250	(5) 750	9 650		170	317 100	6	3	3
	Q_{Clo}	1 500	1 650	7 150	8 300	1 300	19 900						
	G_N	750	1 000	2 350	4 100	600	8 800	–8 800					
	R'	1 250	1 550	6 950	8 150	1 150	19 050	+19 050					
	L_D	750	550	4 600	4 050	300	10 250	–10 250					
	d	–	–	–	–	250	250	–250					
	R''	250	–	–	–	–	250	+250					
	T_R L_{DR} N_R (%)	4 2 2	6 2 4	12 8 4	8 4 4	1 0 1		0					
50	Q_{Do}	(5) 1 600	(5) 3 950	(5) 9 100	(5) 12 000	(12) 250	26 900		186	387 650	10	3	7
	Q_{Clo}	2 600	4 500	10 450	14 250	15 200	47 050						
	G_N	600	2 850	6 550	7 750	–	17 750	–17 750					
	L_N	–	–	–	–	500	500	+500					
	R'	1 600	3 450	7 900	10 000	14 450	37 400	+37 400					
	L_D	1 000	600	1 350	2 250	7 500	12 700	–12 700					
	d	–	–	–	–	7 450	7 450	–7 450					
	T_R L_{DR} N_R (%)	2 1 1	6 1 5	10 2 8	12 3 9	16 8 8		0					
40	Q_{Do}	(12)1 500	(5) 8 000	(5) 13 350	(5) 21 500	(5) 900	(5) 45 250		96	199 800	11	2	9
	Q_{Clo}	3 150	8 500	13 850	21 900	950	48 350						
	G_N	–	4 050	4 250	9 500	650	18 450	–18 450					
	L_N	100	–	–	–	–	100	+100					
	R'	1 550	4 550	4 750	9 900	700	21 450	+21 450					
	L_D	1 350	500	500	400	50	2 800	–2 800					
	d	300	–	–	–	–	300	–300					
	T_R L_{DR} N_R (%)	4 3 1	11 1 10	11 1 10	18 1 17	4 0 4		0					

Table 12. (*continued*)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channels*					*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Area between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % rain recharge per unit area (rounded to whole %)*		
		1	*2*	*3*	*4*	*5*					*TR*	*LDR*	*NR*
30	Q_{Do}	(5) 1 650	(5) 14 200	(7) 21 200	(5) 24 550	(12) 650	62 250		93	206 450	9	1	8
	Q_{Clo}	1 700	15 150	21 200	25 550	1 450	65 050						
	GN	150	6 200	7 850	3 050	–	17 250	–17 250					
	LN	–	–	–	–	250	250	+250					
	R'	200	7 150	7 850	4 050	550	19 800	+19 800					
	LD	50	1 050	–	1 000	800	2 900	–2 900					
	LU	–	100	–	–	–	100	+100					
	TR LDR NR (%)	1 0 1	11 2 9	13 0 13	8 2 6	5 7 0		0					
20	Q_{Do}	GINGIN BROOK	(6) 20 550	(6) 27 550	(6) 28 150	ELLEN BROOK	76 250		76	158 750	9	0	9
	Q_{Clo}		19 750	27 050	27 750		74 550						
	GN		6 350	6 350	3 600		16 300	–16 300					
	R'		5 550	5 850	3 200		14 600	+14 600					
	LU		800	500	400		1 700	+1 700					
	TR LDR NR (%)		9 0 9	12 0 12	6 0 6			0					
10	Q_{Do}		(4) 27 500	(6) 31 250	(8) 32 000		90 750		56	116 750	12	0	12
	Q_{Clo}		27 500	30 750	23 800		82 050						
	GN		6 950	3 700	3 850		14 500	–14 500					
	R'		6 950	3 200	–		10 150	+10 150					
	E		–	–	4 350		4 350	–4 350					
	LU		–	500	500		1 000	+1 000					
	R''		–	–	7 700		7 700	+7 700					
	TR LDR NR (%)		15 0 15	11 0 11	8 0 8			0					
1	Q_{Do}		(4) 47 900	(6) 45 550	(6) 45 800		139 250		155	323 300	15	0	15
	Q_{Clo}		47 900	45 350	44 350		137 600						
	GN		20 400	14 300	13 800		48 500	–48 500					
	R'		20 400	14 100	12 350		46 850	+46 850					
	a		–	200	700		900	–900					
	I		–	50	200		250	+250					
	R''		–	350	1 950		2 300	+2 300					
	TR LDR NR (%)		15 0 15	15 0 15	16 0 16			0					

Table 12. (*continued*)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channels*					*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Area between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % rain recharge per unit area (rounded to whole %)*		
		1	*2*	*3*	*4*	*5*					*T_R*	*L_{DR}*	*N_R*
Coast	Q_{Do}		$^{(4)}$ 54 900	$^{(6)}$ 52 400	$^{(6)}$ 48 050		155 350		64	132 550	12	0	1
	Q_{Clo}		54 900	51 150	47 100		153 150						
	G_N		7 000	6 850	2 250		16 100	–16 100					
	R'		7 000	5 600	1 300		13 900	+13 900					
	I		–	150	100			+250					
	R"		–	1 100	850			+1 950					
	T_R L_{DR} N_R (%)		10 0 10	15 0 15	13 0 13			0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet
Q_{Clo} = Groundwater flow by chloride (Cl) balance
G_N = Net gain to groundwater flow
L_N = Net loss from groundwater flow
R' = Apparent rain recharge
E = Apparent evapotranspiration
L_D, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)
L_U, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R = Total rainfall

$T_R = \frac{R' + R'' + L_N - E}{R} \times 100$ (total recharge as percentage of rainfall)
$L_{DR} = \frac{L_D}{R} \times 100$ (leakage down as percentage of rainfall)
$N_R = \frac{G_N + a + d - L_U - I}{R} \times 100$ (net throughflow as percentage of rainfall)
Superscript (e.g. $^{(5)}$) denotes flow combination shown on Figure 27

root zone of vegetation, and in this area the recharge rate is about 15% of the rainfall. From the average specific yields of the aquifer (Tamala Limestone 0.30, Bassendean Sand 0.20, and Guildford Clay 0.05), these recharge percentages represent an average annual fluctuation in watertable level of about 0.38 m in the Tamala Limestone, 0.38 m in the central area of the Bassendean Sand, and 0.46 m in the Guildford Clay to the east and adjacent to Ellen Brook and nearby lakes and swamps. These theoretical average values of watertable fluctuations commonly differ slightly from locally recorded values because, in many areas, the watertable is close to or above groundlevel (Plate 52), thereby preventing further rises. In other areas the watertable is at a much greater depth, allowing maximum recharge to take place. Lithology of the sediments also influences the magnitude of the seasonal variations in watertable level. Larger variations (≤3 m) are common in clayey areas of low permeability, and smaller variations occur in areas of highly permeable sand (≤2 m) and limestone (≤1 m).

Gnangara Mound (South)

The Gnangara Mound (South) covers an area of about 1212 km^2 and extends from Ellen Brook in the east to the ocean in the west and southward to the Swan River. It occupies the southern part of the original Gnangara groundwater mound and has a maximum saturated thickness of about 70 m, coinciding with the crest of the mound (Plate 51). The sediments adjacent to Ellen Brook are clayey (Guildford Clay) and interfinger to the west with sandy sediments of the Bassendean Sand which, in turn, pass laterally into the Tamala Limestone along the coastal strip. Adjacent to the Swan River and its estuary, steep hydraulic gradients are common where clayey sediments of the Guildford Clay retard groundwater flow and generate numerous springs and naturally occurring drains. The transmissivity of the aquifer ranges from about 100 m^2/d for the clayey eastern sediments, to about 1000 m^2/d for the sandy sediments, near the crest of the mound. Transmissivity exceeds 6000 m^2/d for the cavernous limestone along the coast (Plate 55). A steepening of the hydraulic gradient in the Wanneroo area may imply a zone of relatively low transmissivity between the 40 and 20 m watertable contours.

The Gnangara Mound (South) has been divided into six separate groundwater flow-channels that carry groundwater flow radially from the crest of the groundwater mound to the discharge boundaries formed by the ocean (flow-channels 1, 2 and 3), the Swan River (flow-channel 4), and Ellen Brook (flow-channels 5 and 6).

Groundwater recharge to the superficial aquifer results from rainfall infiltration at rates ranging up to 36% of the rainfall (Table 13). Of the total rainfall recharge to the superficial aquifer, about 28 000 m^3/d leak downward into the underlying aquifers (approximately 16 500 m^3/d into the Mirrabooka aquifer and 11 500 m^3/d into the Leederville aquifer). This total downward leakage is equivalent to about 2% of the rainfall over the combined recharge areas of the Mirrabooka and Leederville aquifers.

Towards the discharge boundaries formed by the ocean, Ellen Brook and the Swan River, and in areas of upward hydraulic gradients where confining beds are absent, approximately 13 600 m^3/d (10 400 m^3/d from the Mirrabooka aquifer and 3200 m^3/d from the Leederville aquifer) recharge the superficial aquifer by upward leakage.

Urbanization and market gardening are responsible for the loss of about 31 450 m^3/d by evapotranspiration of recycled groundwater used for irrigation, and about 94 100 m^2/d have been abstracted for public water supply.

At the hydraulic boundaries, approximately 196 550 m^3/d of groundwater discharge into the ocean from flow-channels 1, 2 and 3, and about 32 550 m^3/d discharge into Ellen Brook and the Swan River estuary from flow-channels 3, 4, 5 and 6.

Substituting values from Table 13 into equation (4):

$$
\begin{aligned}
\text{Net recharge} &= R + H + I + L_U - E_t \\
&= 935.26 + 0 + 1.46 + 4.96 - 798.71 \\
&= d + d_O + L_D + a + R'' + a' \\
&= 15.18 + 71.74 + 10.22 + 34.35 + 11.48 + 0 \\
&= 142.97 \times 10^6 \text{ m}^3\text{/year}
\end{aligned}
$$

This net recharge represents 15.28% of the annual rainfall of 935.26 x 10^6 m^3 over the Gnangara Mound (South). Total evapotranspiration is about 798.71 x 10^6 m^3/year.

The higher rates of recharge (15–36% of rainfall) are noted in areas where the depth to the watertable is greater than about 6 m, where there is downward leakage to the underlying aquifer or where groundwater abstraction has lowered the watertable and provided space for additional recharge. The maximum recharge rate of 36% occurs within the market gardening area of Wanneroo, where tillage of the land has facilitated recharge. This high value compares favourably with the 40% recharge rate obtained independently by Sharma et al. (1991b).

The average recharge of about 15% of the rainfall is equivalent to about 118 mm of rain per year. In the eastern and southern clayey areas adjacent to Ellen Brook and the Swan River, the average recharge is about 5% of rainfall. In the central sandy area and coastal limestone area it is about 16% of the rainfall. From the average specific yields of the aquifer, these recharge percentages represent an average annual fluctuation in watertable levels of about 0.40 m in the Tamala Limestone, 0.65 m in the central area of the Bassendean Sand and 0.83 m in the Guildford Clay adjacent to Ellen Brook and the Swan River. As for the Gnangara Mound (North), these theoretical average values of watertable fluctuations commonly differ slightly from locally recorded values.

Swan Helena Area

The Swan Helena Area is approximately 58 km^2 and is bounded to the east by the Darling Scarp and elsewhere by the Swan and Helena Rivers. Apart from the colluvial

Table 13. Gnangara Mound (South) — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m³/d)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m³/d) in specific channels*						*Total flow (m³/d)*	*Flow balance (m³/d)*	*Area between contours (km²)*	*Total rain (R) (m³/d)*	*Average % rain recharge per unit area (rounded to whole %)*		
		1	*2*	*3*	*4*	*5*	*6*					*TR*	*LDR*	*NR*
70	Q_{Do}	(5) 1 650	(5) 450	(4) 150	(5) 350	(5) 1 000	(5) 1 050	4 650		14	30 700	16	1	15
	Q_{Clo}	1 800	500	150	400	1 100	1 150	5 100						
	GN	1 650	450	150	350	1 000	1 050	4 650	–4 650					
	R'	1 800	500	150	400	1 100	1 150	5 100	+5 100					
	LD	150	50	–	50	100	100	450	–450					
	TR LDR NR (%)	17 | 1 | 16	18 | 2 | 16	16 | 0 | 16	18 | 2 | 16	17 | 2 | 15	16 | 1 | 15		0					
60	Q_{Do}	(5) 19 350	(5) 8 400	(5) 4 250	(5) 6 250	(5) 9 350	(5) 8 100	55 700		153	335 350	16	1	15
	Q_{Clo}	20 400	9 400	5 100	6 350	9 600	8 200	59 050						
	GN	17 700	7 950	4 100	5 900	8 350	7 050	51 050	–51 050					
	R'	18 750	8 950	4 950	6 000	8 600	7 150	54 400	+54 400					
	LD	1 050	1 000	850	100	250	100	3 350	–3 350					
	TR LDR NR (%)	19 | 1 | 18	21 | 2 | 19	17 | 3 | 14	15 | 0 | 15	14 | 1 | 13	12 | 0 | 2		0					
50	Q_{Do}	(5) 31 900	(5) 14 650	(5) 7 050	(5) 11 650	(6) 14 850	(12) 4 400	84 500		164	359 450	17	2	15
	Q_{Clo}	40 600	21 950	13 700	14 500	12 300	9 350	112 400						
	GN	12 550	6 250	2 800	5 400	5 500	–	32 500	–32 500					
	LN	–	–	–	–	–	3 700	3 700	+3 700					
	R'	21 250	13 550	9 450	8 250	2 950	1 250	56 700	+56 700					
	LD	3 600	500	150	50	–	2 450	6 750	–6 750					
	d	–	–	–	–	–	2 500	2 500	–2 500					
	a	5 100	6 800	6 500	2 800	–	–	21 200	–21 200					
	LU	–	–	–	–	2 550	–	2 550	+2 550					
	TR LDR NR (%)	19 | 3 | 16	31 | 1 | 30	24 | 0 | 24	14 | 0 | 14	6 | 0 | 6	8 | 4 | 4		0					
40	Q_{Do}	(5) 36 000	(5) 14 800	(5) 8 500	(5) 12 850	(5) 16 900	ELLEN	89 050		187	409 650	12	2	10
	Q_{Clo}	42 950	26 700	22 850	23 400	13 900	BROOK	129 800						
	GN	4 100	150	1 450	1 200	2 050		8 950	–8 950					
	R'	11 050	12 050	15 800	11 750	–		50 650	+50 650					
	E	–	–	–	–	950		950	–950					
	LD	1 150	800	1 600	3 500	–		7 050	–7 050					
	a	5 800	11 100	12 750	7 050	–		36 700	–36 700					
	LU	–	–	–	–	3 000		3 000	+3 000					
	TR LDR NR (%)	12 1 11	13 1 12	21 2 19	14 4 10	0 0 0			0					

Table 13. (*continued*)

Watertable contour (m AHD)	Legend (see notes)	Flow (m^3/d) in specific channels						Total flow (m^3/d)	Flow balance (m^3/d)	Area between contours (km^2)	Total rain (R) (m^3/d)	Average % rain recharge per unit area (rounded to whole %)		
		1	2	3	4	5	6					TR	LDR	NR
30	Q_{Do}	(5) 40 150	(6) 31 500	(5) 12 650	(5) 13 950	(10) 6 300		104 550		152	333 150	18	2	16
	Q_{Clo}	42 850	18 900	22 500	28 550	12 850		125 650						
	GN	4 150	16 700	4 150	1 100	–		26 100	–26 100					
	LN	–	–	–	–	10 600		10 600	+10 600					
	R'	6 850	4 100	14 000	15 700	–		40 650	+40 650					
	E	–	–	–	–	4 050		4 050	–4 050					
	LD	2 700	500	50	4 000	–		7 250	–7 250					
	d	–	–	–	–	6 550		6 550	–6 550					
	a	–	–	9 800	10 600			20 400	–20 400					
	R"	–	13 100	–	–			13 100	+13 100					
	TR LDR NR (%)	10 4 6	36 1 35	16 0 16	17 4 13	21 0 21			0					
20	Q_{Do}	(5) 46 050	(6) 37 950	(6) 29 100	(5) 16 750	ELLEN		129 850		149	326 600	11	1	10
	Q_{Clo}	46 400	37 800	25 550	19 500	BROOK		129 250						
	GN	5 900	6 450	16 450	2 800			31 600	–31 600					
	R'	6 250	6 300	12 900	5 550			31 000	+31 000					
	LD	350	500	–	2 000			2 850	–2 850					
	a	–	–	600	750			1 350	–1 350					
	I	–	50	400	–			450	+450					
	R"	–	600	3 750	–			4 350	+4 350					
	TR LDR NR (%)	9 1 8	23 2 21	18 0 18	5 2 3				0					
10	Q_{Do}	(8) 49 750	(6) 46 400	(5) 31 000	(8) 17 000			144 150		140	308 350	8	0	8
	Q_{Clo}	45 100	41 150	42 350	16 200			144 800						
	GN	3 700	8 450	1 900	250			14 300	–14 300					
	R'	–	3 200	13 250	–			16 450	+16 450					
	E	950	–	–	550			1 500	–1 500					
	LD	–	300	–	–			300	–300					
	a	–	–	14 450	–			14 450	–14 450					
	LU	450	–	1 550	400			2 400	+2 400					
	I	–	2 800	150	50			3 000	+3 000					
	R"	4 200	2 750	1 400	350			8 700	+8 700					
	TR LDR NR (%)	5 0 5	13 1 12	15 0 15	0 0 0				0					

Table 13. (*continued*)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channels* 1	2	3	4	5	6	*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Area between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % rain recharge per unit area (rounded to whole %)* *TR*	*LDR*	*NR*
1	Q_{Do}	(6) 64 650	(6) 61 050	(6) 58 550	(8) 21 850			206 100		169	368 000	15	0	15
	Q_{Clo}	64 400	60 200	58 200	14 350			197 150						
	GN	14 900	14 650	27 550	4 850			61 950	–61 950					
	R'	14 650	13 800	27 200	–			55 650	+55 650					
	E	–	–	–	2 650			2 650	–2 650					
	LU	250	850	350	3 350			4 800	+4 800					
	I	–	–	–	400			400	+400					
	R"	–	–	–	3 750			3 750	+3 750					
	TR LDR NR (%)	16 0 16	15 0 15	15 0 15	0 0 0				0					
Coast	Q_{Do}	(6) 67 100	(6) 64 950	(6) 64 500	SWAN RIVER AND ELLEN BROOK			196 550		84	91 100	12	0	12
	Q_{Clo}	66 600	64 600	62 850				194 050						
	GN	2 450	3 900	5 950				12 300	–12 300					
	R'	1 950	3 550	4 300				9 800	+9 800					
	LU	500	350	–				850	+850					
	I	–	–	150				150	+150					
	R"	–	–	1 550				1 550	+1 550					
	TR LDR NR (%)	15 0 15	15 0 15	11 0 11					0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet

Q_{Clo} = Groundwater flow by chloride (Cl) balance

GN = Net gain to groundwater flow

LN = Net loss from groundwater flow

R' = Apparent rain recharge

E = Apparent evapotranspiration

LD, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)

LU, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))

R = Total rainfall

TR = $\frac{R' + R'' + L_N - E}{R}$ x 100 (total recharge as percentage of rainfall)

LDR = $\frac{L_D}{R}$ x 100 (leakage down as percentage of rainfall)

NR = $\frac{G_N + a + d - L_U - I}{R}$ x 100 (net throughflow as percentage of rainfall)

Superscript (e.g. (5)) denotes flow combination shown on Figure 27

Table 14. Swan Helena Area — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in channel 1*	*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Areas between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % rain recharge per unit area (rounded to whole %)* T_R	L_{DR}	N_R
20	Q_{Do}	$^{(5)}$ 3 050	3 050		26	60 550	6	1	5
	Q_{Clo}	3 400	3 400						
	G_N	3 050	3 050	−3 050					
	R'	3 400	3 400	+3 400					
	L_D	350	350	−350					
	T_R L_{DR} N_R (%)	6 1 5	–	0					
	Q_{Do}	$^{(6)}$ 6 200	6 200		28	65 200	5	0	5
	Q_{Clo}	5 150	5 150						
	G_N	3 150	3 150	−3 150					
	R'	2 100	2 100	+2 100					
	L_U	50	50	+50					
	R"	1 000	1 000	+1 000					
	T_R L_{DR} N_R (%)	5 0 5	–	0					
River	Q_{Do}	$^{(6)}$ 6 650	6 550		4	9 300	5	0	5
	Q_{Clo}	6 500	6 500						
	G_N	450	450	−450					
	R'	300	300	+300					
	R"	150	150	+150					
	T_R L_{DR} N_R (%)	5 0 5	–	0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet
Q_{Clo} = Groundwater flow by chloride (Cl) balance
G_N = Net gain to groundwater flow
L_N = Net loss from groundwater flow
R' = Apparent rain recharge
E = Apparent evapotranspiration
L_D, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)
L_U, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R = Total rainfall

$T_R = \frac{R' + R'' + L_N - E}{R} \times 100$ (total recharge as percentage of rainfall)
$L_{DR} = \frac{L_D}{R} \times 100$ (leakage down as percentage of rainfall)
$N_R = \frac{G_N + a + d - L_U - I}{R} \times 100$ (net throughflow as percentage of rainfall)
Superscript (e.g. $^{(5)}$) denotes flow combination shown on Figure 27

slopes of the Darling Scarp, the area is underlain by clayey sediments of the Guildford Clay with a saturated thickness of some 30 m with an aquifer transmissivity of about 100 m^2/d.

Recharge results mainly from rainfall infiltration and, to a lesser extent, from surface runoff from the Darling Scarp. Total annual recharge has been estimated to be equivalent to about 6% of the rainfall over the area (Table 14) and of this, approximately 350 m^3/d (equivalent to about 1% of the rainfall) leak downwards into the Leederville aquifer. This occurs where the confining bed of the Osborne Formation (Kardinya Shale Member) is absent between the superficial aquifer and the Leederville aquifer and where there are downward hydraulic gradients (Plate 54). Towards the Swan River, in an area of increasing hydraulic heads with depth and absence of shale, approximately 50 m^3/d leak upwards from the Leederville aquifer to recharge the superficial aquifer.

Substituting values from Table 14 into equation (4):

$$
\begin{aligned}
\text{Net recharge} &= R + H + I + L_U - E_t \\
&= 49.29 + 0 + 0 + 0.02 - 46.41 \\
&= d + d_O + L_D + a + R'' + a' \\
&= 2.43 + 0 + 0.1 + 0 + 0.37 + 0 \\
&= 2.90 \times 10^6 \text{ m}^3\text{/year}
\end{aligned}
$$

This net recharge represents 5.88% of the annual rainfall of 49.29 x 10^6 m^3 over the Swan Helena Area. Total evapotranspiration is about 46.41 x 10^6 m^3/year.

The low percentage of rainfall recharge is an indication of the low hydraulic conductivities of the aquifer and shallow watertable. The average recharge of nearly 6% of the rainfall is equivalent to about 50 mm of rain per year and, by applying the average specific yield of the Guildford Clay, represents a theoretical average annual fluctuation in the watertable level of about 1.00 m. This calculated average value of watertable fluctuation is less than locally recorded values in areas where the depth to the watertable is sufficient to permit greater rises.

Table 15. Cloverdale Area — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channel*		*Total flow*	*Flow balance*	*Area between contours*	*Total rain (R)*	*Average % recharge per unit area (rounded to whole %)*		
		1	*2*	*(m^3/d)*	*m^3/d*	*(km^2)*	*(m^3/d)*	*T_R*	*L_{DR}*	*N_R*
20	Q_{Do}	(4) 500	(5) 1 000	1 500		24	59 150	3	0	3
	Q_{Clo}	500	1 050	1 550						
	G_N	500	1 000	1 500	–1 500					
	R'	500	1 050	1 550	+1 550					
	L_D	–	50	50	–50					
	T_R L_{DR} N_R (%)	3 0 3	3 0 3		0					
10	Q_{Do}	(5) 7 300	(6) 4 000	11 300		83	197 850	5	0	5
	Q_{Clo}	7 400	3 950	11 350						
	G_N	6 800	3 000	9 800	–9 800					
	R'	6 900	2 950	9 850	+9 850					
	L_D	100	–	100	–100					
	L_U	–	50	50	+50					
	T_R L_{DR} N_R (%)	5 0 5	5 0 5		0					
River	Q_{Do}	(13) 6 000	(6) 7 500	13 500		64	154 300	2	0	2
	Q_{Clo}	4 650	7 000	11 650						
	G_N	–	3 500	3 500	–3 500					
	L_N	1 300	–	1 300	+1 300					
	R'	–	3 000	3 000	+3 000					
	E	2 650	–	2 650	–2 650					
	L_U	50	–	50	+50					
	I	150	50	200	+200					
	R"	1 150	450	1 600	+1 600					
	T_R L_{DR} N_R (%)	0 0 0	5 0 5		0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet
Q_{Clo} = Groundwater flow by chloride (Cl) balance
G_N = Net gain to groundwater flow
L_N = Net loss from groundwater flow
R' = Apparent rain recharge
E = Apparent evapotranspiration
L_D, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)
L_U, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R = Total rainfall

$T_R = \frac{R' + R'' + L_N - E}{R} \times 100$ (total recharge as percentage of rainfall)
$L_{DR} = \frac{L_D}{R} \times 100$ (leakage down as percentage of rainfall)
$N_R = \frac{G_N + a + d - L_U - I}{R} \times 100$ (net throughflow as percentage of rainfall)
Superscript (e.g. (5)) denotes flow combination shown on Figure 27

Cloverdale Area

The Cloverdale Area is approximately 171 km^2 and is bounded to the east by the Darling Scarp and elsewhere by the Helena, Swan and Canning Rivers. The area is underlain by clayey sediments of the Guildford Clay that interfinger to the west with sandy sediments of the Bassendean Sand. The aquifer has a maximum saturated thickness of about 30 m (Plate 51) and transmissivities range from about 100 m^2/d in the east to more than 200 m^2/d in the west. The area has been divided into two groundwater flow-channels, each carrying rainfall recharge to the discharge boundaries formed by the rivers.

Total annual recharge has been estimated to be equivalent to about 4% of the rainfall over the area (Table 15) and of this about 150 m^3/d leak downward into the Leederville aquifer. Near the Swan River in flow-channel 1 and adjacent to the Canning River in flow-channel 2, approximately 100 m^3/d of groundwater leak upwards from the Leederville aquifer to recharge the superficial aquifer (Plate 54).

Substituting values from Table 15 into equation (4):

$$
\begin{aligned}
\text{Net recharge} &= R + H + I + L_U - E_t \\
&= 150.12 + 0 + 0 + 0.07 + 0.04 - 144.67 \\
&= d + d_O + L_D + a + R'' + a' \\
&= 4.93 + 0 + 0.05 + 0 + 0.58 + 0 \\
&= 5.56 \times 10^6 \ m^3/\text{year}
\end{aligned}
$$

This net recharge represents 3.70% of the annual rainfall of 150.12 x 10^6 m^3 over the Cloverdale Area. Total evapotranspiration is about 144.67 x 10^6 m^3/year.

Table 16. Jandakot Mound — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channels*							*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Area between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % rain recharge per unit area (rounded to whole %)*		
		1	*2*	*3*	*4*	*5*	*6*	*7*					*TR*	*LDR*	*NR*
25	Q_{Do}	(5) 1 050	(5) 5 950	(5) 1 950	(5) 1 450	(5) 4 550	(5) 1 800	(4) 3 750	20 500		59	140 650	22	0	22
	Q_{Clo}	1 600	9 100	3 000	2 200	6 950	2 750	5 750	31 350						
	GN	1 050	5 950	1 950	1 450	4 550	1 800	3 750	20 500	–20 500					
	R'	1 600	9 100	3 000	2 200	6 950	2 750	5 750	31 350	+31 350					
	a	550	3 150	1 050	750	2 400	950	2 000	10 850	–10 850					
	TR LDR NR (%)	0 23 23	23 0 23	23 0 23	23 0 23	23 0 23	22· 0 22	23 0 23		0					
20	Q_{Do}	(6) 4 050	(8) 15 600	(6) 4 350	(5) 2 600	(4) 6 200	(5) 2 800	(5) 7 500	43 100		105	254 550	12	1	11
	Q_{Clo}	2 650	5 650	7 100	5 650	6 200	3 500	10 400	41 150						
	GN	3 000	9 650	2 400	1 150	1 650	1 000	3 750	22 600	–22 600					
	R'	1 600	–	5 150	4 200	1 650	1 700	6 650	20 950	+20 950					
	E	–	300	–	–	–	–	–	300	–300					
	LD	–	–	50	1 000	–	700	–	1 750	–1 750					
	d	–	–	2 700	2 050	–	–	2 900	7 650	–7 650					
	I	150	1 000	–	–	–	–	–	1 150	+1 150					
	R"	1 250	8 950	–	–	–	–	–	10 200	+10 200					
	TR LDR NR (%)	21 0 21	19 0 19	12 0 12	13 3 10	11 0 11	4 2 2	11 0 11		0					
10	Q_{Do}	(8) 12 800	(8) 34 550	(8) 7 750	(5) 3 100	LAKE FORREST-DALE	(6) 3 000	(5) 7 700	68 900		123	294 800	11	1	10
	Q_{Clo}	2 700	14 350	3 750	4 050		2 950	8 900	36 700						
	GN	8 750	18 950	3 400	500		200	200	32 000	–32 000					
	R'	–	–	–	1 450		150	1 400	3 000	+3 000					
	E	1 350	1 250	600	–		–	–	3 200	–3 200					
	LD	–	–	500	450		–	–	950	–950					
	d	–	–	–	500		–	1 200	1 700	–1 700					
	LU	–	–	–	–		50	–	50	+50					
	I	1 000	2 000	–	–		–	–	3 000	+3 000					
	R"	9 100	18 200	4 500	–		–	–	31 800	+31 800					
	TR LDR NR (%)	24 0 24	19 0 19	7 1 6	3 1 2		6 0 6	2 0 2		0					

Table 16. (*continued*)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m³/d) in specific channels*							*Total flow (m³/d)*	*Flow balance (m³/d)*	*Area between contours (km²)*	*Total rain (R) (m³/d)*	*Average % rain recharge per unit area (rounded to whole %)*		
		1	*2*	*3*	*4*	*5*	*6*	*7*					T_R	L_{DR}	N_R
1	Q_{Do}	$^{(8)}$13 950	$^{(6)}$54 900	$^{(6)}$11 000	$^{(13)}$1 700	SOUTHERN		$^{(12)}$7 000	88 550		176	419 750	6	0	6
	Q_{Clo}	11 400	39 300	12 300	1 150	RIVER		7 950	72 100						
	G_N	1 150	20 350	3 250	–			–	24 750	–24 750					
	L_N	–	–	–	1 400			700	2 100	+2 100					
	R'	–	4 750	4 550	–			250	9 550	+9 550					
	E	1 400	–	–	1 950			–	3 350	–3 350					
	L_D	–	–	1 300	–			–	1 300	–1 300					
	d	–	–	–	–			950	950	–950					
	L_U	–	–	–	550			–	550	+550					
	I	250	1 550	–	–			–	1 800	+1 800					
	R"	2 300	14 050	–	–			–	16 350	+16 350					
	T_R L_{DR} N_R (%)	2 | 0 | 2	18 | 0 | 18	3 | 1 | 2	0 | 0 | 0			3 | 0 | 3		0					
River/Coast	Q_{Do}	$^{(7)}$15 150	$^{(12)}$51 450	$^{(6)}$15 000	KARNUP			CANNING	81 600		59	133 700	8	0	8
	Q_{Clo}	13 950	57 700	12 150	DRAIN			RIVER	83 800						
	G_N	1 200	–	4 000					5 200	–5 200					
	L_N	–	3 450	–					3 450	+3 450					
	R'	0	2 800	1 150					3 950	+3 950					
	a	–	6 250	–					6 250	–6 250					
	I	100	–	300					400	+400					
	R"	1 100	–	2 550					3 650	+3 6150					
	T_R L_{DR} N_R (%)	3 | 0 | 3	10 | 0 | 10	11 | 0 | 11						0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet
Q_{Clo} = Groundwater flow by chloride (Cl) balance
G_N = Net gain to groundwater flow
L_N = Net loss from groundwater flow
R' = Apparent rain recharge
E = Apparent evapotranspiration
L_D, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)
L_U, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R = Total rainfall

$T_R = \frac{R' + R'' + L_N - E}{R} \times 100$ (total recharge as percentage of rainfall)

$L_{DR} = \frac{L_D}{R} \times 100$ (leakage down as percentage of rainfall)

$N_R = \frac{G_N + a + d - L_U - I}{R} \times 100$ (net throughflow as percentage of rainfall)

Superscript (e.g. $^{(5)}$) denotes flow combination shown on Figure 27

The low percentage of rainfall recharge is an indication of low aquifer hydraulic conductivities and shallow watertable. The average recharge of about 4% of the rainfall is equivalent to 32 mm of rain per year. Applying the average specific yield of the Guildford Clay, this figure represents a theoretical average annual fluctuation in the watertable level of about 0.64 m. This theoretical average value of watertable fluctuation is less than locally recorded values in areas where the depth to the watertable is sufficient to permit greater rises in waterlevel.

Jandakot Mound

The crest of the Jandakot Mound, which covers an area of about 522 km^2, is situated just south of Jandakot aerodrome. The central area, within the 25 m watertable contour, has a maximum saturated thickness of about 40 m. Most of the Jandakot Mound area is underlain by the Bassendean Sand, which has aquifer transmissivities ranging between 200 and 1000 m^2/d. A strip of the aquifer with relatively low transmissivities, associated with the western chain of lakes, lies within an area of steeper hydraulic gradients between the 20 and 10 m watertable contours (Plate 53). West of the chain of lakes and within the Tamala Limestone to the coast, the hydraulic gradients flatten and the aquifer transmissivity values increase to more than 4000 m^2/d.

The Jandakot groundwater mound has been divided into 7 separate groundwater flow-channels, each originating at the crest of the mound and carrying groundwater radially to the discharge boundaries formed by Lake Forrestdale, Karnup Drain, Southern River, Canning River, Swan River, and the Ocean (Plate 53).

Groundwater recharge to the superficial aquifer results from rainfall infiltration at rates ranging up to 24% of the rainfall (Table 16). Of the total rainfall recharge to the superficial aquifer, about 4000 m^3/d leak downwards into the underlying aquifers (Rockingham aquifer 500 m^3/d; Leederville aquifer 3500 m^3/d) at a rate of about 2% of the rainfall over the leakage area (Plate 54). Within a small area of flow-channel 4, approximately 550 m^3/d of groundwater discharge upwards from the Leederville aquifer into the superficial aquifer.

Urbanization and market gardening within flow-channels 1, 2 and 3 are responsible for the loss of about 62 000 m^3/d by evapotranspiration of recycled groundwater used for irrigation. Also, about 6350 m^3/d of imported scheme water have been lost to evapotranspiration.

At the hydraulic boundaries, about 15 150 m^3/d of groundwater discharge into the Swan River, 66 450 m^3/d into the ocean, 1700 m^3/d into Karnup Drain, 6200 m^3/d into Lake Forrestdale, 3000 m^3/d into Southern River, and about 7000 m^3/d into the Canning River.

Substituting values from Table 16 into equation (4):

$$\begin{aligned}\text{Net recharge} &= R + H + I + L_U - E_t \\ &= 453.86 + 0 + 2.32 + 0.20 - 389.74 \\ &= d + d_O + L_D + a + R'' + a' \\ &= 12.06 + 24.25 + 1.46 + 6.24 + 22.63 + 0 \\ &= 66.64 \times 10^6 \text{ m}^3/\text{year}\end{aligned}$$

This net recharge represents 14.68% of the annual rainfall of 453.86 x 10^6 m^3 over the Jandakot Mound. Total evapotranspiration is about 389.74 x 10^6 m^3/year.

The wide range in recharge rates (0–24% of rainfall) given in Table 16 relates to the varying depths to the watertable. The higher recharge rates commonly prevail where the depth to the watertable is greater. The average recharge of about 15% of the rainfall is equivalent to 128 mm of rain per year. In the clayey areas adjacent to the Swan, Canning and Southern Rivers, and the Karnup Drain, the average recharge rate is about 5% of the rainfall. In the central sandy and coastal limestone areas the recharge is equivalent to about 15% of the rainfall. From the average specific yields of the aquifer (Tamala Limestone 0.30, Bassendean Sand 0.20 and Guildford Clay 0.05), these recharge percentages represent an average annual fluctuation in watertable levels of about 0.43 m in the Tamala Limestone, 0.64 m in the central area of the Bassendean Sand and 0.95 m in the Guildford Clay adjacent to the Southern River and Karnup Drain. These calculated average values of watertable fluctuation are commonly less than locally recorded values, particularly for those areas where the watertable is deeper than about 2 m.

Armadale Area

The Armadale Area is about 68 km^2 and is bounded to the north by the Canning River, to the east by the Darling Scarp, to the south by the northern edge of the Byford Area, and to the west by bounding flowlines terminating in Lake Forrestdale and Southern River. The saturated thickness of the superficial aquifer is not accurately known, but is mostly less than 25 m (Plate 51) and consists of clayey, sandy sediments with an average transmissivity of about 100 m^2 /d (Plate 55).

Groundwater recharge ensues mainly from rainfall infiltration through the clayey sediments of the Guildford Clay and sandy sediments of the Bassendean Sand, with some minor recharge from rainwater runoff from the Darling Scarp. The total annual recharge has been estimated to be equivalent to some 5% of the rainfall over the area (Table 17) and of this, about 1700 m^3/d, equivalent to 1% of the rainfall, leak downwards into the Leederville aquifer.

Adjacent to the Canning River and in an area of increasing hydraulic heads with depth, approximately 200 m^3/d of groundwater leak upwards into the superficial aquifer from the Leederville aquifer.

At the end of its flow-path, groundwater discharges into Lake Forrestdale at a rate of about 1000 m^3/d and into the Southern River at a rate of about 4900 m^3/d.

Substituting values from Table 17 into equation (4):

$$\begin{aligned}\text{Net recharge} &= R + H + I + L_U - E_t \\ &= 61.56 + 0 + 0 + 0.07 - 58.86 \\ &= d + d_O + L_D + a + R'' + a' \\ &= 2.15 + 0 + 0.62 + 0 + 0 + 0 \\ &= 2.77 \times 10^6 \text{ m}^3/\text{year}\end{aligned}$$

Table 17. Armadale Area — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Watertable contour	*Legend (see notes)*	*Flow (m^3/d) in channel*	*Total flow*	*Flow balance*	*Areas between contours*	*Total rain (R)*	*Average % rain recharge per unit area (rounded to whole %)*		
(m AHD)		*1*	*(m^3/d)*	*(m^3/d)*	*(km^2)*	*(m^3/d)*	*TR*	*LDR*	*NR*
25	Q_{Do}	$^{(5)}$ 3 900	3 900		35	88 200	5	1	4
	Q_{Clo}	4 400	4 400						
	GN	3 900	3 900	–3 900					
	R'	4 400	4 400	+4 400					
	E	–	–	–					
	LD	700	700	–700					
	LU	200	200	+200					
	TR LDR NR (%)	5 1 4		0					
Lake/River	Q_{Do}	$^{(5)}$ 5 900	5 900		33	80 450	4	1	3
	Q_{Clo}	6 900	6 900						
	GN	2 000	2 000	–2 000					
	R'	3 000	3 000	+3 000					
	LD	1 000	1 000	–1 000					
	TR LDR NR (%)	5 1 4		0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet
Q_{Clo} = Groundwater flow by chloride (Cl) balance
GN = Net gain to groundwater flow
LN = Net loss from groundwater flow
R' = Apparent rain recharge
E = Apparent evapotranspiration
LD, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)
LU, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R = Total rainfall

TR = $\frac{R' + R'' + L_N - E}{R}$ x 100 (total recharge as percentage of rainfall)
LDR = $\frac{L_D}{R}$ x 100 (leakage down as percentage of rainfall)
NR = $\frac{G_N + a + d - L_U - I}{R}$ x 100 (net throughflow as percentage of rainfall)
Superscript (e.g. $^{(5)}$) denotes flow combination shown on Figure 27

This net recharge represents 4.50% of the annual rainfall of 61.56 x 10^6 m^3 over the Armadale Area. Total evapotranspiration is about 58.86 x 10^6 m^3/year.

The low percentage of rainfall recharge is due to the low aquifer hydraulic conductivities and the generally shallow watertable. The average recharge of about 5% of the rainfall is equivalent to 41 mm of rain per year. By applying the average specific yield of the aquifer (predominantly Guildford Clay), this represents an average annual fluctuation in the watertable level of about 0.80 m. This theoretical average value of watertable fluctuation is commonly less than values recorded in areas where the depth to the watertable is normally greater than about 2 m.

Byford Area

The Byford Area is about 166 km^2 and extends across the eastern part of the coastal plain from the Darling Scarp to Karnup Drain. The superficial aquifer has a maximum saturated thickness of about 20 m and consists of clayey sediments of the Guildford Clay with an average transmissivity of about 100 m^2/d. Recharge is mainly from rainfall infiltration, but some is from stream flow draining the Darling Range and dissipating on the coastal plain. The high clay content of the sediments ensures poor drainage, and numerous field drains have been constructed in an attempt to make the low-lying and waterlogged areas arable.

The Byford Area has been divided into two flow-channels (Table 18), each carrying rainfall recharge to the discharge boundary formed by Karnup Drain. Total annual recharge has been estimated to be equivalent to about 4% of the rainfall over the area and of this some 4100 m^3/d leak downward into the Leederville aquifer. Towards the discharge boundary, approximately 1900 m^3/d of groundwater leak upwards from the Leederville aquifer and into the superficial aquifer (Plate 54).

Substituting values from Table 18 into equation (4):

$$\begin{aligned}\text{Net recharge} &= R + H + I + L_U - E_t \\ &= 160.47 + 7.70 + 0 + 0.69 - 163.22 \\ &= d + d_0 + L_D + a + R'' + a' \\ &= 4.14 + 0 + 1.50 + 0 + 0 + 0 \\ &= 5.64 \text{ x } 10^6 \text{ m}^3\text{/year}\end{aligned}$$

This net recharge represents 3.51% of the annual rainfall of 160.47 x 10^6 m^3 over the Byford Area. Total evapotranspiration is about 163.22 x 10^6 m^3/year.

The low percentage of rainfall recharge is due to the low aquifer hydraulic conductivities and the generally shallow watertable. The average recharge of about 4% of the rainfall is equivalent to 34 mm of rain per year and,

Table 18. Byford Area — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Watertable contour (*m AHD*)	*Legend* (*see notes*)	*Flow* (m^3/d) *in specific channnel* 1	2	*Total flow* (m^3/d)	*Flow balance* (m^3/d)	*Area between contours* (km^2)	*Total rain* (*R*) (m^3/d)	*Average % recharge per unit area (rounded to whole %)* TR	LDR	NR
40	Q_{Do}		$^{(5)}$ 50	50		1	2 700	4	2	2
	Q_{Clo}		100	100						
	GN		50	50	−50					
	R'		100	100	+100					
	LD		50	50	−50					
	TR LDR NR (%)		4 2 2		0					
30	Q_{Do}		$^{(5)}$ 350	350		6	16 250	4	2	2
	Q_{Clo}		600	600						
	GN		300	300	−300					
	R'		550	550	+550					
	LD		250	250	−250					
	TR LDR NR (%)		4 2 2		0					
25	Q_{Do}	$^{(5)}$1 400	$^{(5)}$ 1 550	2 950		48	128850	3	1	2
	Q_{Clo}	1 850	2 250	4 100						
	GN	1 400	1 200	2 600	−2 600					
	R'	1 850	1 900	3 750	+3 750					
	LD	450	700	1 150	−1 150					
	TR LDR NR (%)	3 1 2	3 1 2		0					
20	Q_{Do}	$^{(5)}$250	$^{(6)}$ 3 250	5 500		38	101500	4	2	2
	Q_{Clo}	4 250	2 650	6 900						
	GN	850	1 700	2 550	−2 550					
	R'	2 850	1 100	3 950	+3 950					
	LD	2 400	–	2 400	−2 400					
	LU	400	600	1 000	+1 000					
	TR LDR NR (%)	6 5 1	2 0 2		0					
10	Q_{Do}	$^{(5)}$ 4 850	$^{(5)}$ 4 350	9 200		68	178850	3	0	3
	Q_{Clo}	5 200	5 350	10 550						
	GN	2 600	1 100	3 700	−3 700					
	R'	2 950	2 100	5 050	+5 050					
	LD	250	–	250	−250					
	d	300	1 500	1 800	−1 800					
	LU	200	500	700	+700					
	TR LDR NR (%)	4 0 4	2 0 2		0					
Drain	Q_{Do}	KARNUP	$^{(4)}$4500	4 500		5	11 500	1	0	1
	Q_{Clo}	DRAIN	4500	4 500						
	GN		150	150	−150					
	R'		150	150	+150					
	d		200	200	−200					
	LU		200	200	+200					
	TR LDR NR (%)		1 0 1		0					

Notes:

Q_{Do}	=	*Groundwater flow by aquifer hydraulics from flownet*
Q_{Clo}	=	Groundwater flow by chloride (Cl) balance
GN	=	Net gain to groundwater flow
LN	=	Net loss from groundwater flow
R'	=	Apparent rain recharge
E	=	Apparent evapotranspiration
LD, d, a	=	Losses (leakage downward and out, discharge to drainage, abstraction)
LU, I, R''	=	Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R	=	Total rainfall

$\mathrm{TR} = \frac{R' + R'' + L_N - E}{R} \times 100$ (total recharge as percentage of rainfall)

$\mathrm{LDR} = \frac{L_D}{R} \times 100$ (leakage down as percentage of rainfall)

$\mathrm{NR} = \frac{G_N + a + d - L_U - I}{R} \times 100$ (net throughflow as percentage of rainfall)

Superscript (e.g. $^{(5)}$) denotes flow combination shown on Figure 27

applying the average specific yield of the Guildford Clay, represents an average annual fluctuation in the watertable level of about 0.68 m. This theoretical average value of watertable fluctuation is less than locally recorded values, particularly for those areas where the watertable is normally at a depth greater than about 2 m.

Serpentine Area

The Serpentine Area is about 441 km^2 and is bounded to the east by the Darling Scarp, to the north and west by the Serpentine River, and to the south by the Dandalup–Murray Rivers system. The superficial aquifer has an average saturated thickness of about 10 m (Plate 51) and consists mainly of sandy sediments of the Bassendean Sand with an average transmissivity of about 100 m^2/d (Plate 55). Recharge is mainly by infiltration of rainfall, but some may come from stream flow draining the Darling Plateau and dissipating over the area. The watertable is generally very shallow and numerous field drains have been constructed throughout the area.

The Serpentine Area has been divided into three flow-channels (Table 19), each carrying rainfall recharge to the discharge boundaries formed by the rivers. Total annual recharge has been estimated to be equivalent to about 6% of the rainfall over the area and of this about 23 500 m^3/d leak downward into the underlying aquifers (3950 m^3/d to the Rockingham aquifer, 15 300 m^3/d to the Leederville aquifer and 4250 m^3/d to the Yarragadee aquifer). Towards the Serpentine River, approximately 4000 m^3/d of groundwater leak upwards from the Leederville aquifer to recharge the superficial aquifer (Plate 54). Numerous field drains cross the area and approximately 21 550 m^3/d of groundwater discharge into them.

Substituting values from Table 19 into equation (4):

$$\begin{aligned}\text{Net recharge} &= R + H + I + L_U - E_t\\ &= 418.58 + 11.30 + 0 + 1.46 - 408.02\\ &= d + d_O + L_D + a + R'' + a'\\ &= 13.74 + 0 + 8.58 + 0 + 1.0 + 0\\ &= 23.32 \times 10^6 \text{ m}^3\text{/year}\end{aligned}$$

This net recharge represents 5.57% of the annual rainfall of 418.58 x 10^6 m^3 over the Armadale Area. Total evapotranspiration is about 408.02 x 10^6 m^3/year.

Recharge rates range between 2 and 12% of the rainfall and the higher recharge rates are typically associated with areas of greater depth to the watertable. Over the entire Serpentine Area, the average recharge of about 6% of the rainfall is equivalent to 53 mm of rain per year and, applying the average specific yield of the Bassendean Sand, represents an average annual fluctuation in the watertable level of about 1.06 m. This theoretical average value of watertable fluctuation is slightly less than locally recorded values and is biased by the shallowness of the watertable in many areas.

Stakehill Mound

The Stakehill Mound covers an area of about 153 km^2 and occupies a strip of country between the Serpentine River and the coast. The superficial aquifer consists of sand and eolian calcarenite; the latter has been variably lithified to form soft to hard limestone (Tamala Limestone). The aquifer has an average saturated thickness of about 20 m (Plate. 51) and a maximum aquifer transmissivity of around 1000 m^2/d (Plate 55) that roughly coincides with the crest of the subdued groundwater mound.

The Stakehill Mound has been divided into four groundwater flow-channels (Table 20), each carrying rainfall recharge from the crest of the groundwater mound to the discharge boundaries formed by Lake Walyungup, the ocean, and the Serpentine River. Total annual recharge has been estimated to be equivalent to about 8% of the rainfall over the area and of this some 8050 m^3/d leak downward into the Rockingham aquifer. Market garden irrigation in the area causes approximately 8150 m^3/d of groundwater to be lost to the atmosphere by evapotranspiration.

Substituting values from Table 20 into equation (4):

$$\begin{aligned}\text{Net recharge} &= R + H + I + L_U - E_t\\ &= 136.35 + 0 + 0 + 0 - 124.86\\ &= d + d_O + L_D + a + R'' + a'\\ &= 2.79 + 2.48 + 2.94 + 0.31 + 2.97 + 0\\ &= 11.49 \times 10^6 \text{ m}^3\text{/year}\end{aligned}$$

This net recharge represents 8.43% of the annual rainfall of 136.35 x 10^6 m^3 over the Stakehill Mound. Total evapotranspiration is about 124.86 x 10^6 m^3/year.

The low percentage of rainfall recharge is probably partially due to the dense vegetation over much of the area, resulting in high interception rates of rainfall and high losses due to evapotranspiration. Over the entire area of the Stakehill Mound, the average recharge of about 8% of the rainfall is equivalent to some 75 mm of rain per year and, applying an average specific yield of 0.2 for the aquifer, represents an average annual fluctuation in watertable level of about 0.38 m.

Safety Bay Mound

The Safety Bay Mound covers an area of some 49 km^2 with its crest midway between the coast and Lakes Cooloongup and Walyungup. The superficial aquifer consists predominantly of medium-grained, slightly silty sand with some limestone (Safety Bay Sand, Becher Sand and Tamala Limestone). It has an average saturated thickness of about 20 m (Plate 51) and an aquifer transmissivity of about 600 m^2/d (Plate 55).

The Safety Bay Mound has been divided into four groundwater flow-channels (Table 21), each carrying rainfall recharge from the crest of the groundwater mound to the discharge boundaries formed by the ocean and Lakes Cooloongup and Walyungup. Total annual recharge has been estimated to be equivalent to about 12% of the rainfall over the area and of this around 1800 m^3/d leak downward into the Rockingham aquifer. Owing to urbanization, approximately 4100 m^3/d of groundwater are being lost via evapotranspiration from irrigation water.

Table 19. Serpentine Area — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Water-table contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channel* 1	2	3	*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Area between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % recharge per unit area (rounded to whole %)* TR	LDR	NR
50	Q_{Do}	(5) 1 050	(5) 450		1 500		25	67 800	7	5	2
	Q_{Clo}	3 650	1 000		4 650						
	GN	1 050	450		1 500	–1 500					
	R'	3 650	1 000		4 650	+4 650					
	LD	2 600	550		3 150	–3 150					
	TR LDR NR (%)	7 | 5 | 2	6 | 3 | 3			0					
40	Q_{Do}	(5) 4050	(5) 1 700		5 750		26	69 800	11	3	8
	Q_{Clo}	6700	2 150		8 850						
	GN	3000	1 250		4 250	–4 250					
	R'	5650	1 700		7 350	+7 350					
	LD	1700	350		2 050	–2 050					
	d	950	100		1 050	–1 050					
	TR LDR NR (%)	12 | 4 | 8	8 | 2 | 6			0					
30	Q_{Do}	(5) 6650	(5) 2 600	(5) 100	9 350		37	98 350	8	3	5
	Q_{Clo}	9300	3 750	150	13 200						
	GN	2600	900	100	3 600	–3 600					
	R'	5250	2 050	150	7 450	+7 450					
	LD	1650	950	50	2 650	–2 650					
	d	1000	200	–	1 200	–1 200					
	TR LDR NR (%)	9 | 3 | 6	6 | 3 | 3	6 | 2 | 4		0					
25	Q_{Do}	(12) 6000	(12) 1000	(5) 700	7 700		56	149 300	4	2	2
	Q_{Clo}	7100	4250	1 750	13 100						
	GN	–	–	600	600	–600					
	LN	650	1600	–	2 250	+2 250					
	R'	450	1650	1 650	3 750	+3 750					
	LD	600	2000	1 050	3 650	–3 650					
	d	600	1250	–	1 850	–1 850					
	LU	100	–	–	100	+100					
	TR LDR NR (%)	2 | 1 | 1	6 | 4 | 2	3 | 2 | 1		0					
20	Q_{Do}	(12) 4750	(2) 1000	(12) 250	6000		78	203 800	5	3	2
	Q_{Clo}	7100	4400	3900	5400						
	GN	0	0	0	0	0					
	LN	1250	0	450	1700	+1 700					
	R'	1100	3400	3200	7700	+7 700					
	LD	1500	2000	1850	5350	–5 350					
	d	1050	1400	1800	4250	–4 250					
	LU	200	–	–	200	+200					
	TR LDR NR (%)	4 | 2 | 2	4 | 2 | 2	6 | 3 | 3		0					

Table 19. *(continued)*

Water-table contour (m AHD)	*Legend (see notes)*	*Flow (m³/d) in specific channel* 1	2	3	*Total flow (m³/d)*	*Flow balance (m³/d)*	*Area between contours (km²)*	*Total rain (R) (m³/d)*	*Average % recharge per unit area (rounded to whole %)* T_R	L_{DR}	N_R
10	Q_{Do}	⁽⁵⁾5400	⁽⁵⁾1500	⁽⁵⁾400	7 300		129	332 200	5	1	4
	Q_{Clo}	12350	8200	1850	22 400						
	G_N	650	500	150	1 300	–1 300					
	R'	7600	7200	1600	16 400	+16 400					
	L_D	2000	1600	900	4 500	–4 500					
	d	5350	5100	550	11 000	–11 000					
	L_U	400	–	–	400	+400					
	T_R L_{DR} N_R (%)	5 | 1 | 4	5 | 1 | 4	5 | 3 | 2		0					
1	Q_{Do}	⁽⁶⁾11950	⁽⁶⁾7000	⁽⁴⁾550	19 500		52	130 700	7	0	7
	Q_{Clo}	10500	2400	550	13 450						
	G_N	6550	5500	500	12 550	–12 550					
	R'	5100	900	500	6 500	+6 500					
	L_U	1000	2300	–	3 300	+3 300					
	I	–	–	–	–	–					
	R"	450	2300	–	2 750	+2 750					
	T_R L_{DR} N_R (%)	7 | 0 | 7	7 | 0 | 7	5 | 0 | 5		0					
River	Q_{Do}	SERPENTINE	⁽¹²⁾4000	⁽¹¹⁾150	4 150		38	94 850	4	2	2
	Q_{Clo}	RIVER	7950	550	8 500						
	L_N		3000	400	3 400	+3 400					
	R'		950	0	950	+950					
	L_D		1950	200	2 150	–2 150					
	d		2000	200	2 200	–2 200					
	T_R L_{DR} N_R (%)		4 | 2 | 2	8 | 4		0					

Notes:

Q_{Do}	=	Groundwater flow by aquifer hydraulics from flownet
Q_{Clo}	=	Groundwater flow by chloride (Cl) balance
G_N	=	Net gain to groundwater flow
L_N	=	Net loss from groundwater flow
R'	=	Apparent rain recharge
E	=	Apparent evapotranspiration
L_D, d, a	=	Losses (leakage downward and out, discharge to drainage, abstraction)
L_U, I, R"	=	Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R	=	Total rainfall

$T_R = \frac{R' + R'' + L_N - E}{R} \times 100$ (total recharge as percentage of rainfall)

$L_{DR} = \frac{L_D}{R} \times 100$ (leakage down as percentage of rainfall)

$N_R = \frac{G_N + a + d - L_U - I}{R} \times 100$ (net throughflow as percentage of rainfall)

Superscript (e.g. ⁽⁵⁾) denotes flow combination shown on Figure 27

Substituting values from Table 21 into equation (4):

$$
\begin{aligned}
\text{Net recharge} &= R + H + I + L_U - E_t \\
&= 42.78 + 0 + 0 + 0 - 37.85 \\
&= d + d_0 + L_D + a + R'' + a' \\
&= 1.20 + 1.57 + 0.66 + 0 + 1.50 + 0 \\
&= 4.93 \times 10^6 \text{ m}^3\text{/year}
\end{aligned}
$$

This net recharge represents 11.52% of the annual rainfall of 42.78 x 10^6 m³ over the Safety Bay Mound. Total evapotranspiration is about 37.85 x 10^6 m³/year.

Over the entire area of the Safety Bay Mound, the average recharge of about 12% of the rainfall is equivalent to 101 mm of rain per year. Applying an average specific yield of 0.2 for the aquifer, this represents an average annual fluctuation in the watertable level of about 0.51 m.

Groundwater–oceanwater interface

Groundwater within the superficial aquifer of the Perth Region discharges into the ocean, Swan River estuary, and

Table 20. Stakehill Mound — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m^3/d)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m^3/d) in specific channels*				*Total flow (m^3/d)*	*Flow balance (m^3/d)*	*Area between contours (km^2)*	*Total rain (R) (m^3/d)*	*Average % rain recharge per unit area (rounded to whole %)*		
		1	*2*	*3*	*4*					*TR*	*LDR*	*NR*
2.6	Q_{Do}	(5) 550	(5) 750	(5) 100	(5) 1 150	2 550		23	56 100	7	2	5
	Q_{Clo}	800	1 100	150	1 700	3 750						
	GN	550	750	100	1 150	2 550	–2 550					
	R'	800	1 100	150	1 700	3 750	+3 750					
	LD	250	350	50	550	1 200	–1 200					
	TR LDR NR (%)	7 | 2 | 5	7 | 2 | 5	7 | 2 | 5	7 | 2 | 5		0					
1	Q_{Do}	(6) 1 600	(6) 3 750	(6) 2 350	(6) 4 000	11 700		76	186 700	7	2	5
	Q_{Clo}	1 550	3 100	1 750	3 500	9 900						
	GN	1 050	3 000	2 250	2 850	9 150	–9 150					
	R'	1 000	2 350	1 650	2 350	7 350	+7 350					
	LD	550	800	800	1 650	3 800	–3 800					
	R"	600	1 450	1 400	2 150	5 600	+5 600					
	TR LDR NR (%)	6 | 2 | 4	10 | 2 | 8	8 | 2 | 6	5 | 2 | 3		0					
Coast/River	Q_{Do}	LAKE	(5) 4 000	(6) 5 600	(12) 1 850	11 450		54	130 750	7	2	5
	Q_{Clo}	WALYUNGUP	5 650	5 100	3 450	14 200						
	GN		250	3 250	–	3 500	–3 500					
	LN		–	–	2 150	2 150	+2 150					
	R'		1 900	2 750	–	4 650	+4 650					
	E		–	–	550	550	–550					
	LD		800	2 050	200	3 050	–3 050					
	d		–	–	1 400	1 400	–1 400					
	a		850	–	–	850	–850					
	R"		–	2 550	–	2 550	+2 550					
	TR LDR NR (%)		9 | 4 | 5	5 | 2 | 3	16 | 2 | 14		0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet
Q_{Clo} = Groundwater flow by chloride (Cl) balance
GN = Net gain to groundwater flow
LN = Net loss from groundwater flow
R' = Apparent rain recharge
E = Apparent evapotranspiration
LD, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)
LU, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R = Total rainfall

TR = $\frac{R' + R'' + LN - E}{R}$ x 100 (total recharge as percentage of rainfall)
LDR = $\frac{LD}{R}$ x 100 (leakage down as percentage of rainfall)
NR = $\frac{GN + a + d - Lu - I}{R}$ x 100 (net throughflow as percentage of rainfall)
Superscript (e.g. (5)) denotes flow combination shown on Figure 27

Table 21. Safety Bay Mound — estimates of groundwater flow in superficial aquifer (rounded to nearest 50 m³/d)

Watertable contour (m AHD)	*Legend (see notes)*	*Flow (m³/d) in specific channels* 1	2	3	4	*Total flow (m³/d)*	*Flow balance (m³/d)*	*Area between contours (km²)*	*Total rain (R) (m³/d)*	*Average % rain recharge per unit area (rounded to whole %)* T_R	L_{DR}	N_R
2.5	Q_{Do}	$^{(5)}$ 150	$^{(5)}$ 350	$^{(5)}$ 250	$^{(5)}$ 200	950		6	14 450	9	2	7
	Q_{Clo}	200	450	300	250	1 200						
	G_N	150	350	250	200	950	–950					
	R'	200	450	300	250	1 200	+1 200					
	L_D	50	100	50	50	250	–250					
	T_R L_{DR} N_R (%)	10 2 8	9 2 7	8 1 7	9 2 7		0					
1	Q_{Do}	$^{(5)}$ 1 400	$^{(6)}$ 2 900	$^{(6)}$ 1 650	$^{(6)}$ 1 400	7 350		27	64 900	12	2	10
	Q_{Clo}	1 950	1 850	900	550	5 150						
	G_N	1 250	2 550	1 400	1 200	6 400	–6 400					
	R'	1 800	1 500	650	350	4 300	+4 300					
	L_D	300	350	150	150	950	–950					
	d	250	–	–	–	250	–250					
	R"	–	1 400	900	1 000	3 300	+3 300					
	T_R L_{DR} N_R (%)	7 1 6	14 2 12	16 2 14	14 2 12		0					
Coast	Q_{Do}	$^{(5)}$ 1 950	$^{(6)}$ 4 100	LAKE WALYUNGUP	LAKE COOLOONGUP	6 050		16	37 850	7	2	5
	Q_{Clo}	2 450	3 500			5 950						
	G_N	550	1 200			1 750	–1 750					
	R'	1 050	600			1 650	+1 650					
	L_D	400	200			600	–600					
	d	100	–			100	–100					
	R"	–	800			800	+800					
	T_R L_{DR} N_R (%)	4 2 2	12 2 10				0					

Notes:

Q_{Do} = Groundwater flow by aquifer hydraulics from flownet
Q_{Clo} = Groundwater flow by chloride (Cl) balance
G_N = Net gain to groundwater flow
L_N = Net loss from groundwater flow
R' = Apparent rain recharge
E = Apparent evapotranspiration
L_D, d, a = Losses (leakage downward and out, discharge to drainage, abstraction)
L_U, I, R" = Gains (leakage upward and in, imported water, loss due to recycled groundwater (irrigation))
R = Total rainfall

$T_R = \frac{R' + R'' + L_N - E}{R} \times 100$ (total recharge as percentage of rainfall)
$L_{DR} = \frac{L_D}{R} \times 100$ (leakage down as percentage of rainfall)
$N_R = \frac{G_N + a + d - L_U - I}{R} \times 100$ (net throughflow as percentage of rainfall)
Superscript (e.g. $^{(5)}$) denotes flow combination shown on Figure 27

Peel Inlet. Because the groundwater underlying the ocean and estuaries is saline, a wedge-shaped boundary or interface is formed between this saline groundwater and the lower density fresh groundwater below the land. The shape and movement of this interface depends on the hydrodynamics at the interface.

The relationship between ocean- and land-derived groundwater is approximated by the Ghyben–Herzberg relationship, whereby the fresh water extends below sea level by about forty times the height of the watertable above sea level. However, the saltwater interface is usually at a greater depth than would be predicted by the Ghyben–Herzberg relationship. This is because the Ghyben–Herzberg relationship applies only to the situation where there is no groundwater flow and where the position of the interface remains stationary under conditions of hydrostatic equilibrium. In the Perth Region, groundwater discharge from the superficial aquifer to the ocean results in an interface deeper and closer to the ocean than that determined by the Ghyben–Herzberg relationship (Fig. 30). The interface is a narrow mixing zone a few metres thick (usually less than 10 m) resulting mainly from tidal and watertable fluctuations and dispersion. However, the upper surface of the interface is considered to be a groundwater flowline which means that no groundwater flow takes place across the interface. Also, discharge at the coast is generally through a seepage-face, and the groundwater flowlines are curvelinear and become almost vertical at the point of discharge (Fig. 30). In areas along the coast where the gradient on the watertable is almost flat, the Ghyben–Herzberg relationship between ocean- and land-derived groundwater may apply.

Along the coast of the Perth Region, the shape of the saltwater interface is difficult to determine because of the cavernous nature of the Tamala Limestone and the variable hydraulic conductivities which range between 100 and 1000 m/d, depending on location and depth. Some of the variations in salinity profile, associated with the saltwater interface and identified during the Perth Urban Water Balance Study (Cargeeg et al., 1987), are given in Figure 31. In some instances, solution channels within the limestone or low-permeability clay lenses influence the varying depths of the saltwater interface within the superficial aquifer.

It is not possible, therefore, to predict the slope of the saltwater interface within the Tamala Limestone, but in areas where the aquifer is predominantly sandy, the slope of the interface and that of the watertable can be approximated by forms of the Darcy equation (see equations 7 and 8 on Fig. 30; Todd, 1959). Predicting the slope of the saltwater interface is particularly valid for the developing urban areas south of Perth, where the coastal superficial aquifer consists mainly of sand (Safety Bay Sand and Becher Sand). In these areas it is important to estimate the depth to the saltwater interface so that preliminary planning can be made on bore construction details and estimates of possible groundwater abstraction. Following this preliminary phase of planning, some investigation drilling may be required to confirm the predicted position of the saltwater interface.

Many suburbs of the Perth Region fringe the coast and Swan River estuary and, because groundwater is extensively abstracted for irrigation and reticulation, the distance inland to which the saltwater interface extends is perhaps more important than its shape and is given by the following forms of the Darcy equation (Todd, 1959).

$$Q = {}^{1}\!/\!_{2}\,\frac{(\rho_o-\rho_f)}{\rho_f}\,\frac{Tb}{L} \quad \text{or} \quad L = {}^{1}\!/\!_{2}\,\frac{(\rho_o-\rho_f)}{\rho_f}\,\frac{Tb}{Q} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

where Q = groundwater flow to the ocean per metre of ocean front from flownet ($m^3/d/m$)
b = saturated thickness of aquifer (m)
L = distance inland of saltwater interface (m)
T = transmissivity of aquifer (m^2/d)
ρ_f = density of fresh groundwater (kg/m^3)
ρ_o = density of oceanwater (kg/m^3)

The salinity of oceanwater is about 36 000 mg/L (density 1.036 kg/m^3) and that of the groundwater along the coastal strip, around 500 mg/L (density 1.0005 kg/m^3).

The inland extent of the saltwater interface (Plate 55) is known at a few localities from investigation drilling: elsewhere it has been determined using equation (9). Estimates of groundwater flow to the ocean and estuary (Tables 12, 13, 16, 20 and 21) and estimates of aquifer transmissivities and saturated thickness have been determined from Plates 55 and 51 respectively. The maximum known inland distance of the saltwater interface is about 1000 m from the coast. Along the Swan River estuary it is known to extend inland locally a maximum of about 500 m except beneath the Cottesloe peninsula where it extends from the estuary to the coast.

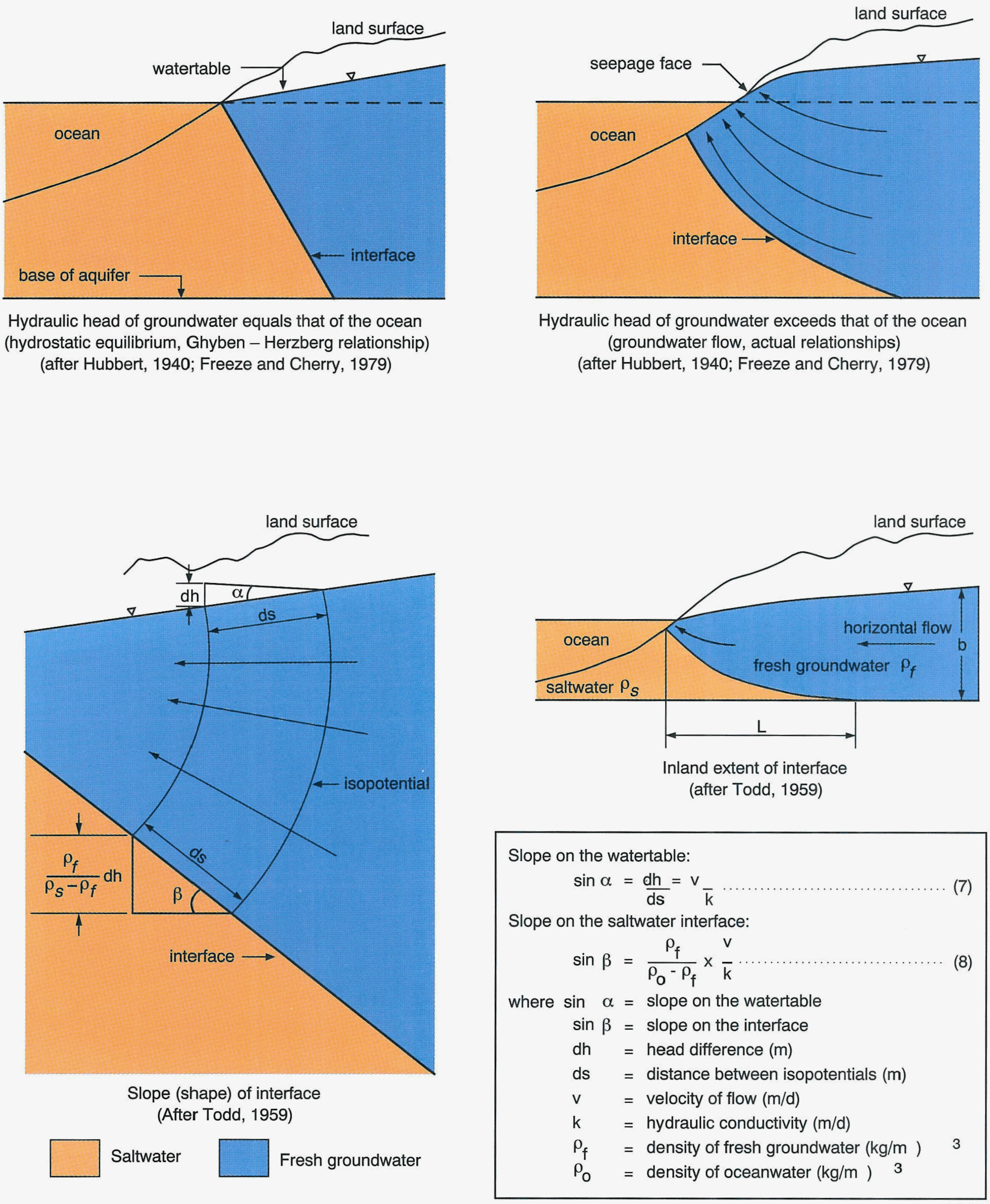
Groundwater abstraction close to the coast will cause a reduction in groundwater flow and discharge to the ocean. This will result in movement inland of the saltwater interface by a distance directly proportional to the reduction in groundwater discharge. Local instances partially explain the discrepancy between the calculated distance inland of the saltwater interface and the actual recorded distance. However, the location of the saltwater interface along most of the coastal strip is relatively stable, as has been observed at Yanchep (Davidson, 1981a), Kwinana (Haselgrove, 1981), and inland of Lake Coogee (Western Australia Water Resources Council, 1983).

Groundwater quality

The physical and chemical properties of groundwater from the superficial aquifer vary mainly with geological location and position within the groundwater flow system relative to recharge and discharge. Representative water analyses from production bores are shown in Table 22. Analyses from hundreds of investigation bores have also been used to prepare the various water-quality maps.

Salinity

The salinity of the groundwater in the superficial aquifer ranges from about 130 to 12 000 mg/L total dissolved solids (TDS) (Allen, 1981a) but rarely exceeds 1000 mg/L TDS (Fig. 32; Plate 56). The lowest salinity water is found



Hydraulic head of groundwater equals that of the ocean (hydrostatic equilibrium, Ghyben – Herzberg relationship) (after Hubbert, 1940; Freeze and Cherry, 1979)

Hydraulic head of groundwater exceeds that of the ocean (groundwater flow, actual relationships) (after Hubbert, 1940; Freeze and Cherry, 1979)

Slope (shape) of interface (After Todd, 1959)

Inland extent of interface (after Todd, 1959)

Slope on the watertable:

$$\sin\alpha = \frac{dh}{ds} = \frac{v}{k} \quad \text{.................................... (7)}$$

Slope on the saltwater interface:

$$\sin\beta = \frac{\rho_f}{\rho_o - \rho_f} \times \frac{v}{k} \quad \text{.................................... (8)}$$

where $\sin\alpha$ = slope on the watertable
$\sin\beta$ = slope on the interface
dh = head difference (m)
ds = distance between isopotentials (m)
v = velocity of flow (m/d)
k = hydraulic conductivity (m/d)
ρ_f = density of fresh groundwater (kg/m^3)
ρ_o = density of oceanwater (kg/m^3)

Figure 30. Superficial aquifer: schematic sections of groundwater–oceanwater interface

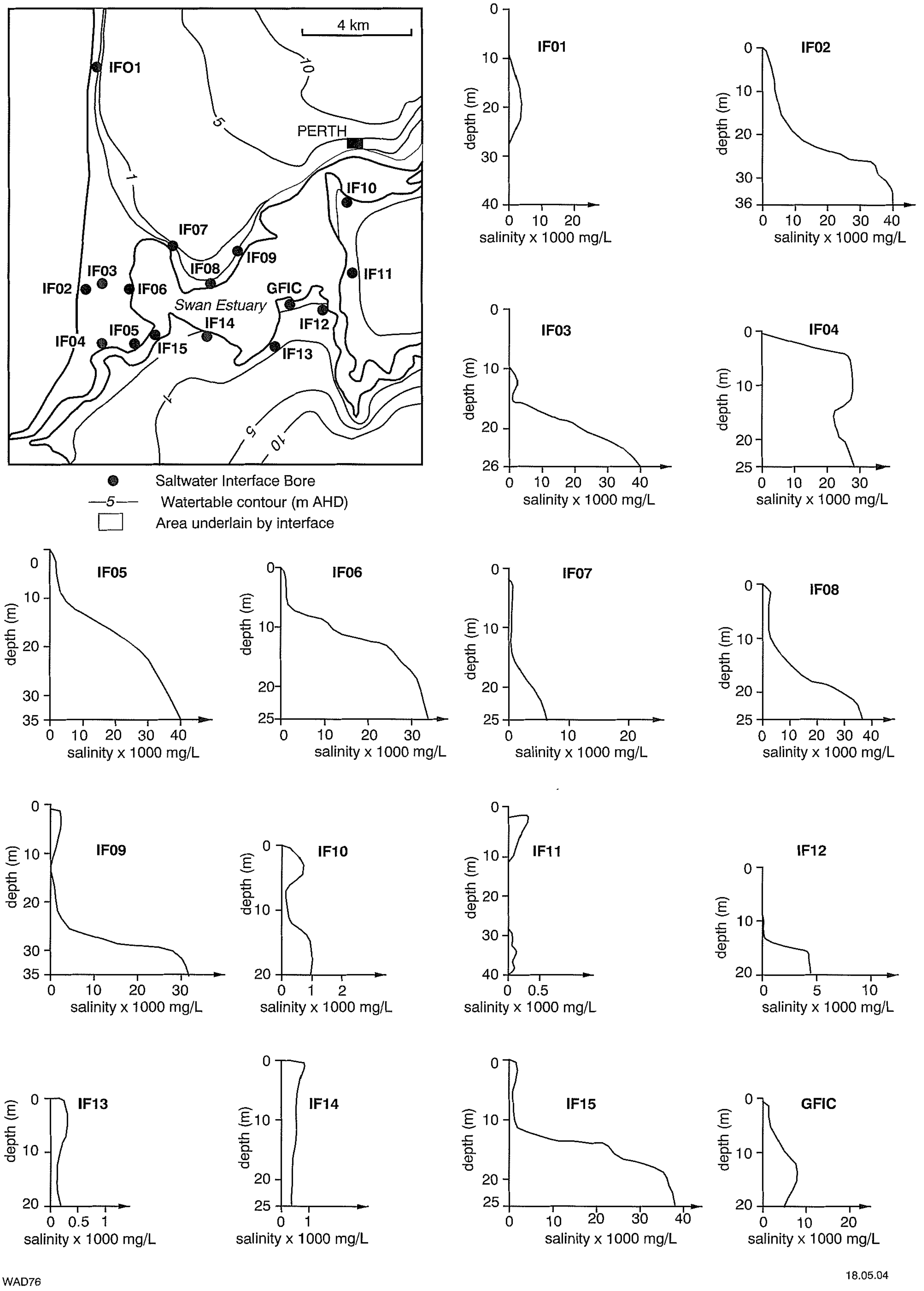


Figure 31. Saltwater interface salinity profiles (modified from Cargeeg et al., 1987)

Table 22. Superficial aquifer — chemical analyses of groundwater from production bores, 1992

Bore	*pH*	*EC mS/m @25°C mg/L*	*Temp. °C*	*TDS -CO_2*	*TH*	*TA*	*Ca*	*Mg*	*Na*	*K*	*CO_3*	*HCO_3*	*Cl*	*SO_4*	*NO_3*	*Fe*	*Remarks*
					mg/L												
J150	6.8	45	20	267	122	98	42	4	41	3	<0.6	120	83	2	0.02	1.68	Jandakot
J140	6.3	99	20	541	204	108	56	16	104	5	<0.6	131	254	2	<0.02	3.36	“
J130	6.0	44	20	261	73	43	17	7	52	3	<0.6	53	48	67	<0.02	0.40	“
J120	6.4	45	19	267	94	67	24	8	49	2	<0.6	81	98	5	<0.02	0.31	“
J110	6.9	37	19	202	106	92	35	5	30	3	<0.6	112	57	4	<0.02	0.18	“
J90	6.3	56	20	342	115	79	29	11	65	3	<0.6	96	116	26	<0.02	0.40	“
J70	6.0	28	20	178	50	42	13	4	35	2	<0.6	52	57	6	<0.02	0.23	“
J60	7.0	65	20	394	163	131	50	9	64	3	<0.6	160	132	11	<0.02	0.39	“
J50	7.4	74	20	463	224	178	74	10	72	3	<0.6	217	145	10	<0.02	0.20	“
J40	7.4	92	20	560	233	198	67	16	97	4	<0.6	241	189	6	<0.02	0.22	“
J30	7.2	120	19	713	273	217	78	19	132	4	<0.6	264	260	18	<0.02	5.67	“
J20	7.0	110	19	692	280	211	86	16	121	3	<0.6	257	247	16	<0.02	0.58	“
J10	7.0	98	20	587	247	195	79	12	98	3	<0.6	237	201	8	<0.02	0.52	“
G120	6.6	60	21	332	148	92	45	9	52	5	<0.6	113	91	29	5.19	1.18	Gwelup
G110	6.5	69	21	384	162	96	52	8	63	4	<0.6	117	117	38	3.74	5.71	“
G80	7.0	105	21	684	392	153	130	16	60	8	<0.6	186	110	225	<0.02	12.80	“
G70	6.5	89	21	538	287	109	94	13	65	5	<0.6	133	108	148	0.92	11.30	“
G 50	6.4	50	21	281	102	67	27	8	47	4	<0.6	81	81	31	0.86	8.35	“
G40	6.3	56	21	310	112	75	32	8	55	4	<0.6	91	101	26	0.54	6.82	“
G30	6.2	60	21	345	128	73	37	9	62	4	<0.6	89	115	33	0.91	7.83	“
G 10	7.0	64	21	366	169	139	54	8	57	3	<0.6	169	107	9	<0.02	4.20	“
G130	6.1	64	21	354	117	72	33	8	60	6	<0.6	88	110	38	6.77	2.98	“
G120	6.3	68	21	376	141	107	45	7	61	4	<0.6	131	105	50	1.54	2.43	“
G60	6.3	68	21	381	151	80	45	9	66	6	<0.6	98	118	37	6.34	3.76	“
M10	5.5	40	20	264	58	26	12	7	52	3	<0.6	32	92	32	0.02	0.45	Mirrabooka
M20	5.6	36	20	221	56	32	11	7	41	3	<0.6	39	79	17	<0.02	0.26	“
M30	6.4	63	20	366	156	134	51	7	54	5	<0.6	163	114	7	<0.02	1.73	“
M26	5.8	44	20	267	83	51	20	8	44	3	<0.6	62	84	24	0.68	0.49	“
M34	5.5	29	20	208	54	37	12	6	33	3	<0.6	45	62	19	<0.02	1.06	“
M27	5.9	41	20	257	82	58	22	7	40	2	<0.6	71	75	20	<0.02	1.76	“
M50	5.7	42	20	278	73	22	13	10	41	2	<0.6	27	105	13	<0.02	8.86	“
M350	4.7	38	20	206	50	<1	5	9	36	2	<0.6	<1.2	100	12	<0.02	7.38	“
M250	4.4	43	19	282	87	<1	9	16	38	2	<0.6	<1.2	132	23	<0.02	14.95	“
M130	5.7	52	19	318	88	53	22	8	59	3	<0.6	65	119	4	<0.02	1.16	“
M120	6.4	76	20	514	217	153	69	11	72	4	<0.6	187	151	9	<0.02	3.65	“
M110	5.4	63	19	446	100	44	18	13	75	3	<0.6	53	166	13	<0.02	3.18	“
M140	5.4	66	19	424	108	2	12	19	76	3	<0.6	2	95	154	<0.02	12.05	“
M150	6.5	53	19	337	113	69	29	10	61	2	<0.6	84	100	37	<0.02	1.09	“
M90	5.7	43	20	265	65	15	8	11	54	3	<0.6	19	98	36	<0.02	0.39	“
M100	5.7	40	20	244	61	18	11	8	49	3	<0.6	23	90	27	1.01	0.39	“
M200	5.7	48	19	324	63	23	7	11	65	2	<0.6	28	108	36	<0.02	0.26	“
M210	6.3	57	20	367	153	80	41	12	50	3	<0.6	97	77	68	<0.02	4.30	“
M220	6.1	50	20	332	123	55	31	11	48	4	<0.6	67	69	75	<0.02	0.08	“
M230	6.8	42	20	316	157	97	47	10	36	3	<0.6	118	62	52	<0.02	4.54	“
M240	5.4	37	20	235	76	12	10	12	42	2	<0.6	15	60	71	0.05	2.72	“
M310	6.1	51	20	371	140	57	38	11	56	6	<0.6	70	96	70	0.05	4.00	“
M320	6.2	52	20	325	126	67	34	10	49	4	<0.6	81	80	54	<0.02	4.90	“
M330	6.1	40	19	240	91	57	26	6	40	3	<0.6	70	72	22	<0.02	1.14	“
M340	5.4	40	19	270	68	12	12	9	54	3	<0.6	14	95	53	<0.02	4.00	“
W310	5.4	30	19	225	31	14	4	5	45	2	<0.6	17	76	5	<0.02	0.41	Wanneroo
P50	5.0	26	19	192	20	5	1	4	37	3	<0.6	6	66	1	<0.02	0.33	“
P40	5.1	33	20	280	27	3	1	6	51	3	<0.6	4	83	9	<0.02	0.36	“
P30	5.0	30	20	248	25	3	2	5	48	3	<0.6	4	80	10	<0.02	0.51	“
P20	5.1	47	20	339	57	9	5	10	63	4	<0.6	11	111	32	<0.02	0.75	“
P10	5.6	43	19	325	56	24	10	8	67	4	<0.6	30	122	4	<0.02	0.46	“
W320	5.3	30	19	211	31	15	5	5	42	3	<0.6	18	76	2	<0.02	0.33	“
W300	5.3	26	19	215	33	12	4	6	44	2	<0.6	14	74	11	<0.02	0.31	“
W290	5.7	36	19	263	69	36	18	6	46	3	<0.6	44	77	25	<0.02	1.06	“
W280	5.7	36	19	250	69	40	17	7	45	3	<0.6	49	71	27	<0.02	0.85	“
W260	5.9	32	20	195	53	39	13	5	32	2	<0.6	48	60	13	<0.02	0.58	“
W220	5.8	43	19	274	62	34	12	8	57	3	<0.6	41	100	8	<0.02	0.38	“
W210	5.7	39	19	267	62	25	12	8	54	3	<0.6	31	98	12	<0.02	0.31	Wanneroo
W10	6.3	36	19	255	96	76	30	5	44	3	<0.6	93	81	3	<0.02	0.63	“
W20	6.3	21	19	137	26	10	3	5	31	2	<0.6	12	55	11	0.07	0.28	“
W30	6.4	54	19	1 330	56	111	52	6	45	4	<0.6	135	75	33	<0.02	2.90	“
W40	6.0	35	19	1 266	02	71	30	7	44	4	<0.6	87	74	22	<0.02	0.90	“
W50	6.1	39	19	236	94	67	28	6	38	3	<0.6	82	62	17	<0.02	0.99	“
W60	5.2	18	19	156	23	14	3	4	31	3	<0.6	18	57	1	<0.02	0.24	“
W70	5.6	28	19	240	48	35	13	4	43	3	<0.6	43	78	3	<0.02	0.51	“
W80	5.3	30	20	322	37	21	7	5	42	2	<0.6	25	71	7	<0.02	0.22	“
W90	5.3	34	20	294	43	19	8	5	46	3	<0.6	24	80	8	<0.02	0.30	“
W100	5.4	32	20	269	43	22	8	5	47	2	<0.6	26	82	10	<0.02	0.30	“
W110	6.5	47	20	1 432	25	97	42	5	44	3	<0.6	118	85	4	<0.02	0.94	“
W120	5.9	35	20	388	61	38	16	5	52	3	<0.6	47	87	8	<0.02	0.44	“

Table 22. (*continued*)

Bore	*pH*	*EC mS/m @25°C*	*Temp. °C*	*TDS -CO_2*	*TH*	*TA*	*Ca*	*Mg*	*Na*	*K*	*CO_3*	*HCO_3*	*Cl*	*SO_4*	*NO_3*	*Fe*	*Remarks*
		mg/L								*mg/L*							
TR4	7.4	74	20	417	228	181	78	8	64	2	<0.6	220	118	13	1.23	0.03	Two Rocks
TR7	7.3	73	20	432	244	190	3	9	63	2	<0.6	231	120	19	0.38	0.03	"
TR5	7.5	74	20	436	237	182	80	9	68	2	<0.6	222	117	13	1.32	0.02	"
YB7	7.3	83	20	501	275	252	93	11	73	3	<0.6	307	132	8	1.03	0.02	Yanchep
YB3	7.5	65	20	362	200	153	67	8	54	3	<0.6	185	102	11	1.30	0.04	"
YB4	7.6	63	20	360	188	146	63	8	54	3	<0.6	178	102	11	1.25	0.01	"
YB6	7.3	85	20	488	269	216	91	10	73	3	<0.6	263	136	10	0.67	0.02	"
GDWQA	6.5–8.5			1 000	500				300				400	400	10.00	0.30	

Notes: GDWQA Guidelines for drinking water quality in Australia, 1987
EC Electrical conductivity
TDS Total dissolved solids by calculation at 180°C
TH Total hardness as calcium carbonate
TA Total alkalinity as calcium carbonate

in the recharge areas at the origin of the groundwater flow systems and, in particular, near the crests of the Gnangara (South) and Jandakot Mounds, where it is less than 250 mg/L TDS and derived entirely from direct rainfall infiltration. The salinity generally increases in the direction of groundwater flow and with depth but, in some areas, the groundwater may be marginally more saline at the watertable owing to concentration of salts by evaporation. In the eastern clayey areas, particularly the Byford Area, the groundwater is relatively more saline. Here, the clayey sediments inhibit rainfall infiltration, resulting in high evaporation rates and concentration of salts. Groundwater salinity is highest at the discharge boundaries formed by the rivers, and in plumes down-hydraulic gradient from many of the lakes, where evaporation has concentrated dissolved salts (Fig. 33). Groundwater recharge down-hydraulic gradient from the lakes controls the tendency of the plumes to extend to the base of the aquifer and gradually dissipate in the direction of groundwater flow.

The upward discharge of brackish groundwater from the Leederville aquifer into the superficial aquifer causes the salinity of the groundwater in the superficial aquifer locally to exceed 2000 mg/L TDS adjacent to the Canning River in the southeast (Fig. 32). Along the coast and adjacent to the Swan–Canning River estuary, where groundwater from the superficial aquifer discharges over a saltwater interface, there is a transition zone(≤10 m thick) where groundwater salinity increases with depth and ranges up to 36 000 mg/L.

pH

pH is a measure of hydrogen ion concentration on a scale of 0 to 14 where 7 is neutral, less than 7 is acidic and greater than 7 is alkaline. The pH values of the groundwater range from 4.0 to 8.0. Groundwater at the watertable within the Bassendean Sand is generally acidic, with a pH range of 4.0 to 6.5. The low pH values are due to organic acids resulting from decomposition of vegetation in swampy environments. Groundwater from the base of the Bassendean Sand and the Gnangara Sand has a pH range of 6.5 to 7.5, whereas in the calcareous sediments of the Ascot Formation and Tamala Limestone, pH ranges from 7.0 to 8.0.

The pH value may change during storage of the groundwater, most commonly because carbon dioxide released from solution changes the carbon dioxide–bicarbonate–carbonate equilibrium, often with resulting precipitation of calcium carbonate. For this reason, the pH of the groundwater in situ may be lower than that of the same groundwater at the reticulation end of the water-supply system.

Colour and turbidity

The physical properties of colour (Hazen units) and turbidity are highly variable. Groundwater from near the watertable commonly has higher colour intensity but lower turbidity than groundwater from near the base of the superficial aquifer. The increased colour intensity is due to the presence of organic compounds, which are concentrated near the watertable and swamps and give the water a characteristic brown colour. The turbidity results from colloidal material derived from clay minerals in the sediments and is extremely variable because of the thin beds of clay present throughout the area. Groundwater from sand beds within the Guildford Clay, from clayey sections of the Ascot Formation and from clayey lenses within the Tamala Limestone is generally more turbid than groundwater from the Bassendean Sand. Plate 57 is a generalized map showing variations in groundwater turbidity that can be expected from bores screened against the entire aquifer thickness.

Hardness

Hardness is expressed in terms of an equivalent quantity of calcium carbonate. Groundwater hardness is commonly related to the lathering properties of the water. Water is often described as being hard if soap fails to lather, if boiler scale is present in kettles or if calcium carbonate precipitates in cooling systems and around shower roses. The qualitative degree or scale of hardness is subjective. For example, in areas where the water supply is obtained

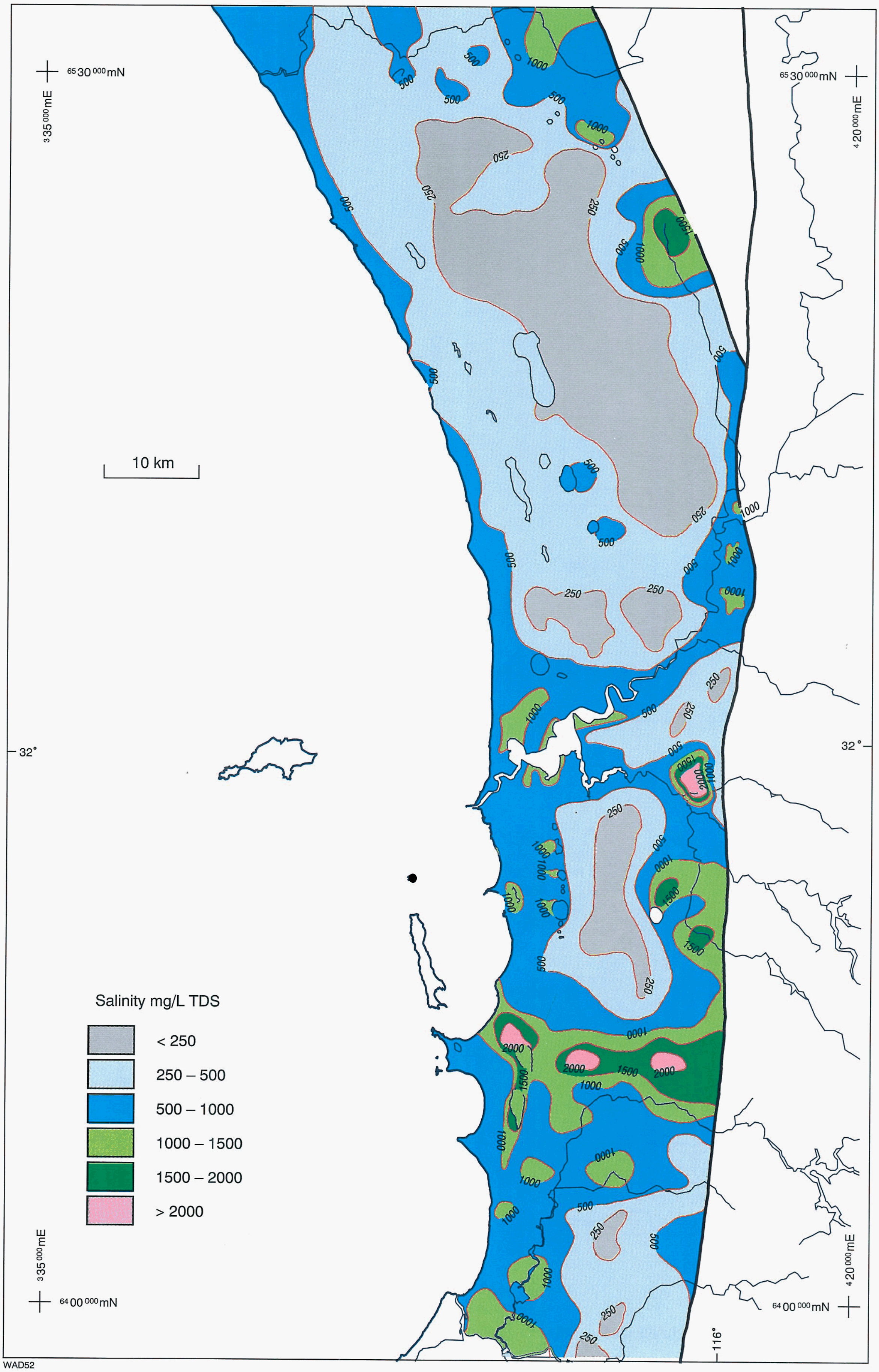
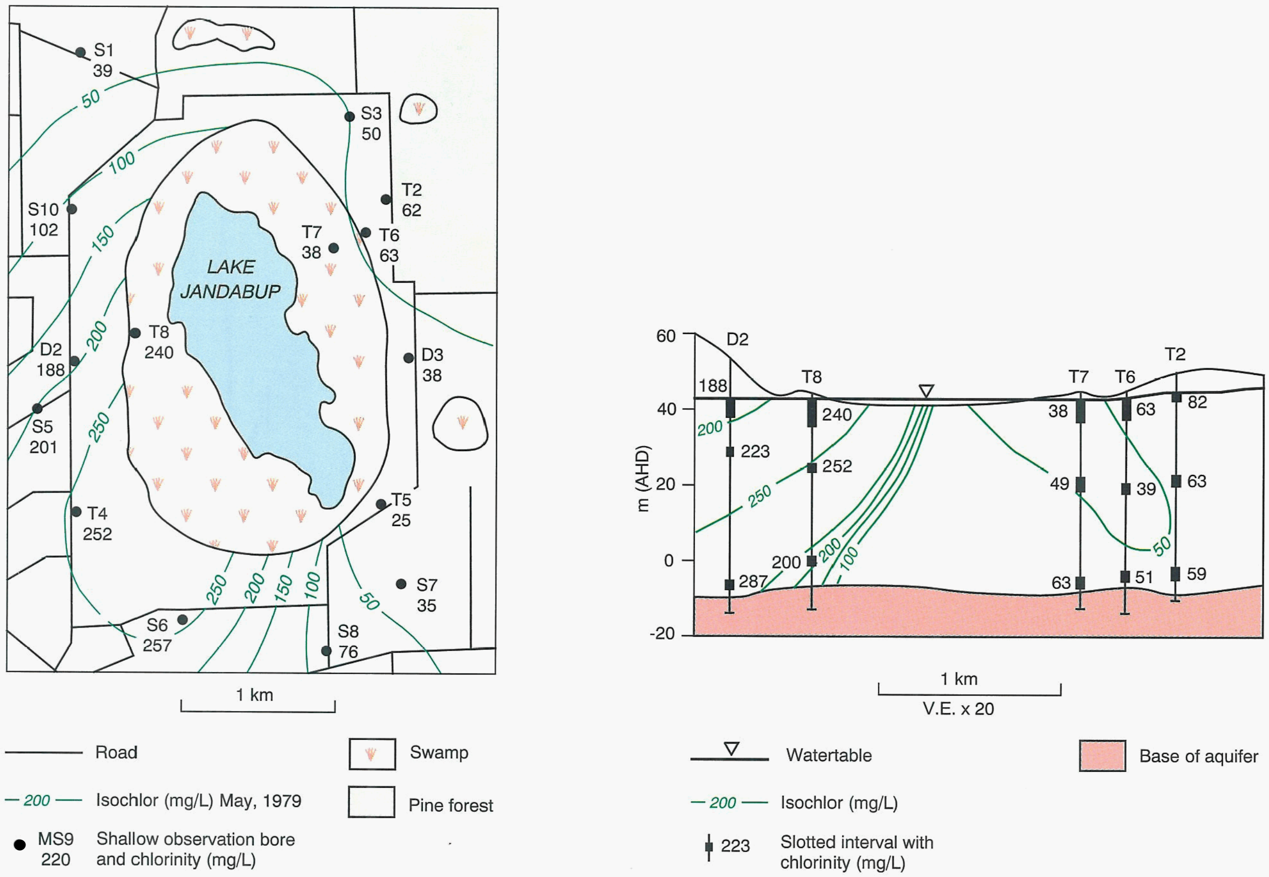
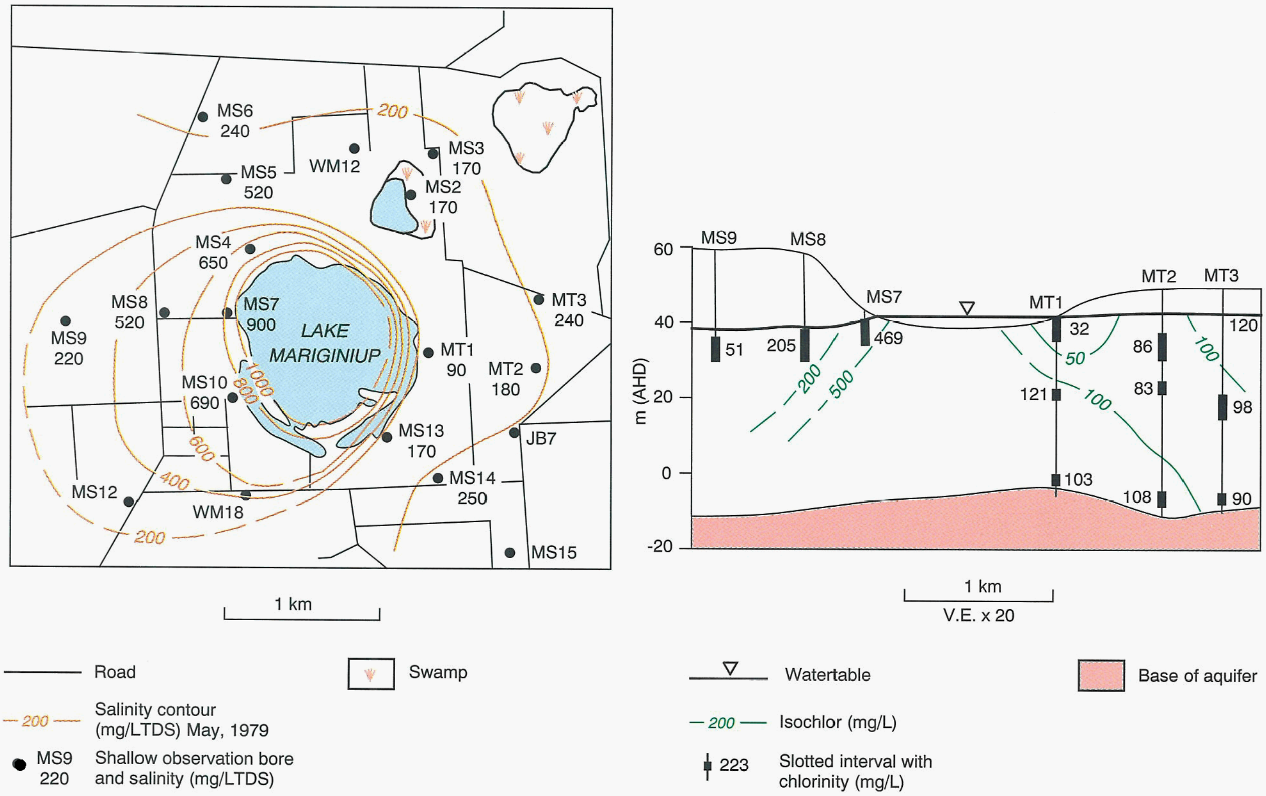


Figure 32. Superficial aquifer groundwater salinity



LAKE JANDABUP CHLORINITY (from Allen, 1980)



LAKE MARIGINIUP SALINITY AND CHLORINITY (from Hall, 1985)

WAD108

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Figure 33. Salinity plumes associated with lakes

directly from rainfall, the water may be considered hard if the hardness is 100 mg/L, while in a coastal limestone area, groundwater of hardness 100 mg/L may be regarded as being soft. For this reason the Chemistry Centre of Western Australia established the following groundwater hardness scale suitable for practical use within the Perth Region.

Hardness scale (mg/L as $CaCO_3$):

<50	very soft
50–100	moderately soft
100–150	slightly hard
150–200	moderately hard
200–300	hard
>300	very hard

The hardness of groundwater in the superficial aquifer commonly increases in the direction of groundwater flow and ranges from less than 50 mg/L within the Bassendean Sand to about 500 mg/L in the Tamala Limestone (Plate 58). Within the transition zone of the saltwater interface adjacent to the coast, hardness increases to more than 1000 mg/L.

Iron

Groundwater contains dissolved iron (mainly in reducing conditions) as ferrous iron which is unstable in the presence of oxygen and is oxidized to ferric iron when the groundwater is exposed to air. This process commonly occurs during irrigation with groundwater, resulting in the staining of walls and pavings by iron oxides and hydroxides. The solubility of ferrous iron, in the presence of carbon dioxide, is controlled by the solubility of ferrous carbonate, and varies from 1 to 10 mg/L in the pH range 7–8 when 25 mg/L of bicarbonate is present. Between pH 6 and 7, the solubility of ferrous iron may be greater than 10 mg/L even in the presence of more than 100 mg/L of bicarbonate (Hem, 1959). Within the Perth Region, dissolved iron in the groundwater of the superficial aquifer ranges from less than 1 mg/L to more than 50 mg/L. Concentrations commonly increase towards the base of the superficial aquifer (Plate 59). The iron probably originates from a chemical reaction between acidic groundwater and ilmenite grains (Baxter, 1977), which are contained mainly within the Bassendean Sand. It may also result from solution of the yellow goethite coatings on the sand grains (Glassford and Kelligrew, 1976) or from solution of pyrite (iron sulfide) associated with palaeolake deposits. In areas of increasing hydraulic heads with depth, where the superficial aquifer rests directly on the Leederville aquifer, groundwater of high dissolved-iron concentration discharges upwards from the Leederville aquifer into the superficial aquifer. This is evident in local areas of the Tamala Limestone (Nidagal and Davidson, 1991) and in the central southern area (Plate 59), where the concentration of dissolved iron in the groundwater exceeds 50 mg/L at the base of the superficial aquifer.

Nitrate

Within the Perth Region, high nitrate levels are present in the superficial aquifer groundwater in the urbanized and intensive horticulture areas. They result from direct leaching of nitrate from fertilizers and reduced nitrogen compounds such as ammonia and proteins, which undergo oxidation by soil microbes to form nitrite and nitrate. Almost all of the ammonia from septic tanks is oxidized to nitrate. From the analyses of more than 300 non-synoptic water samples, Davidson and Jack (1983) showed that beneath native bushland, rural and forested areas the nitrate concentration is generally less than 1 mg/L (Plate 60). In the rural grazing areas, low nitrate concentrations of the groundwater reflect the low nitrate input to the groundwater from animal faeces. Along the coast, in the limestone belt where *Acacia* vegetation is abundant, nitrate concentrations tend to be slightly higher (1–7 mg/L) reflecting rapid passage of enriched water derived from the nitrogen-fixing vegetation. Locally, very high nitrate concentrations result from intensive poultry and pig farming and the disposal of industrial and liquid wastes. In the urbanized area (Fig. 34), which includes some market gardening, nitrate concentrations vary greatly and frequently exceed 20 mg/L. Although the sources of the nitrate concentrations cannot individually be identified, three generalizations can be made.

- Septic sewage and garden fertilizers may generate nitrate concentrations up to 20 mg/L.
- Nitrate concentrations between 20 and 60 mg/L are likely to be associated with septic sewage and intense fertilization of horticultural areas and recreation and sporting grounds.
- Industrial and liquid waste are most likely to be responsible for nitrate concentrations greater than 60 mg/L.

Current concentration levels may not be indicative of equilibrium conditions and may continue to rise. However, nitrate may be removed by two processes.

Nitrate can be biologically reduced to form nitrous oxide and nitrogen. This process requires an anaerobic, organic-rich environment to be effective. Denitrification may occur within the peaty sediments of wetlands, but where the sediments are predominantly sandy, nitrate may be leached to the groundwater without reduction in concentration (Whelan and Parker, 1981).

Denitrification may also be effected by oxidation of ferrous iron to ferric iron. This results in the precipitation of iron oxide on the sand grains of the aquifer and a reduction in dissolved iron within the groundwater. This process has been observed to occur down-hydraulic gradient from a poultry feed lot near Wanneroo, and at Karrakatta Cemetery west of Perth, where high nitrate concentrations of the groundwater would normally be expected.

Contamination of groundwater by nitrate has occurred within the Gwelup borefield (Plate 60), where nitrate concentrations are as high as 30 mg/L. The nitrate concentrations have steadily increased beneath the higher, more sandy, areas to the west, and are linked to horticulture fertilization and septic disposal (Barber et al., 1993). Beneath the low-lying, more clayey areas of the Gwelup

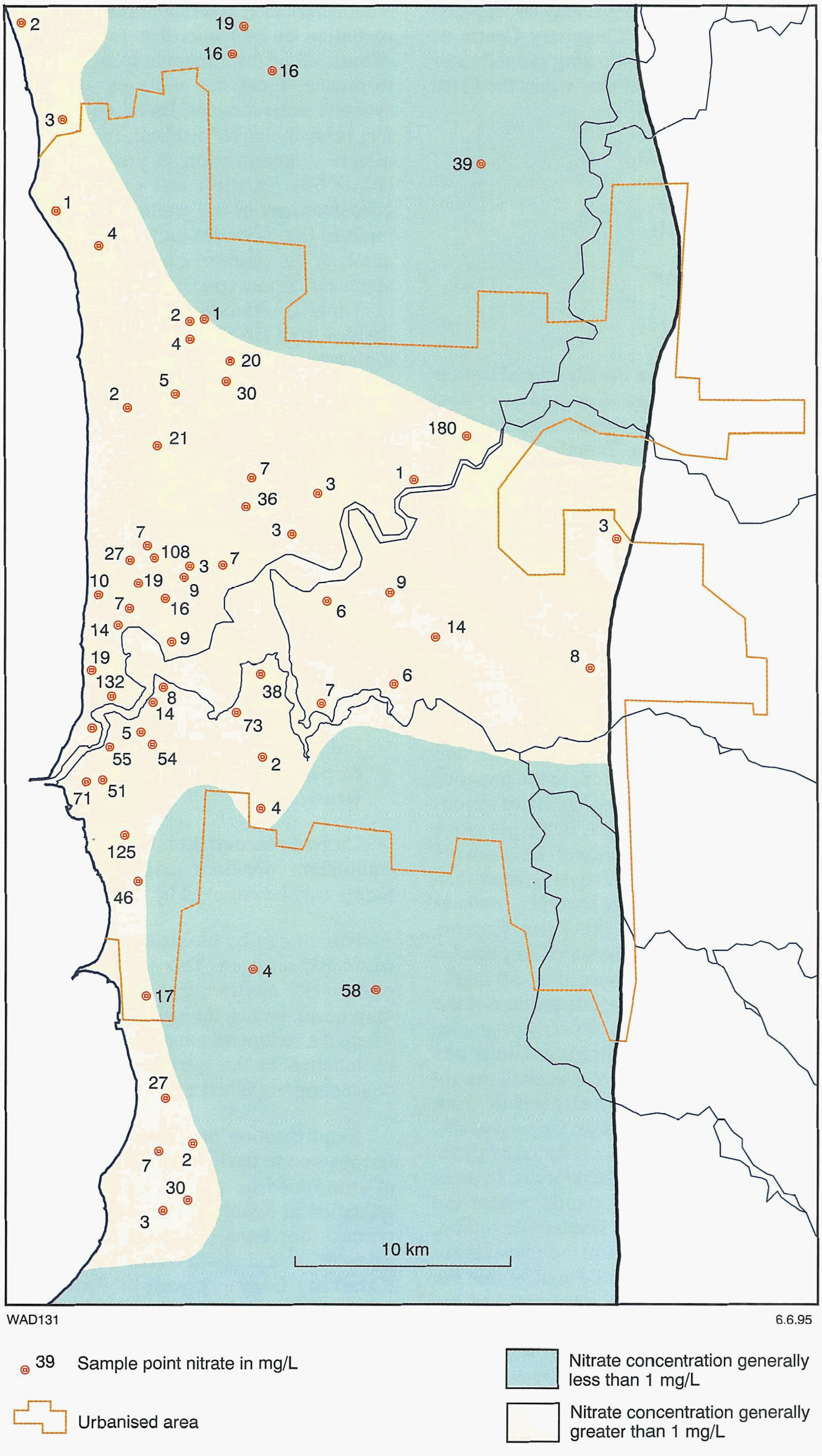


Figure 34. Superficial aquifer groundwater nitrate concentrations, Perth urban area (from Davidson and Jack, 1983)

scheme, denitrification has removed leached nitrate from the groundwater. Unlike the Gwelup borefield, which is within the urban area, the Pinjar, Wanneroo, Mirrabooka and Jandakot schemes are unaffected by urban nitrate sources, although the Pinjar and Jandakot schemes may be subject to some contamination from rural activities.

Phosphorus

Phosphorus concentrations (Plate 61) are generally less than 0.1 mg/L but in some localities they exceed 0.2 mg/L. Elevated phosphorus concentrations are most likely due to application of fertilizer, but natural phosphorus may result from phosphatic nodules commonly occurring at the base of the superficial aquifer and in the underlying Cretaceous sediments (Allen, 1981a).

The very low concentration of phosphorus in the groundwater, even in unsewered areas of Perth, indicates that most of the phosphorus known to be present in sewage is adsorbed by the sediments above the watertable. Phosphorus concentrations can be expected to increase in the future once the adsorption capacity of the sediments is exceeded. Removal of tree loppings and garden prunings also helps to prevent phosphorus build-up within the urban areas.

Sulfate and sulfide

Sulfate ion concentrations in the groundwater are mostly naturally occurring and less than 100 mg/L. Higher concentrations (Plate 62) can result from oxidation of sulfides associated with peaty wetland deposits, evaporative concentration from a shallow watertable, saltwater intrusion, industrial areas using sulfur products, and from application of fertilizers.

The sulfate/chloride ratio (SO_4/Cl) in rainfall reflects the ratio in ocean water (Gerritse et al., 1990) and is similar to the ratio in the groundwater of the superficial aquifer over most of the Perth Region. However, in areas of intense horticulture and industrial activity, the ratio may be greater due to the application of fertilizers and the dumping of industrial wastes. Pionke et al. (1990) list the following SO_4/Cl ratios.

- rainfall: ~0.05–0.1 (Cargeeg et al., 1987),
- natural groundwater: ~0.03–0.05 (Hirschberg, 1984),
- seawater impacted groundwater: ~0.05 (Gerritse et al., 1988),
- groundwater impacted by irrigated horticulture: 0.13–0.24 (Pionke et al., 1990) and exceeding 0.15 (Hirschberg, 1984), and
- industrial impacted groundwater: 0.5 to >0.35 (Gerritse et al., 1988; Cargeeg et al., 1987).

The oxidation of sulfides in the soil and application of fertilizers (Appleyard, 1994a) may lead to eventual increase in the sulfate/chloride ratio of the groundwater.

Sulfide is present in groundwater as hydrogen sulfide throughout most of the Perth Region, but less commonly within the coastal limestone belt. The gas is generated by bacterial and chemical processes associated with peaty and clayey deposits that often contain pyrite. In irrigation water, very low concentrations of hydrogen sulfide are readily detected by smell (bad-egg odour). When exposed to the atmosphere, it is rapidly oxidized and dissipated.

Major ions

The major ions of the water analyses given in Table 22 were converted to percentage equivalents per million for the respective anions and cations and are presented as a trilinear diagram in Figure 35. This figure shows that the groundwater can be classified into three broad chemical types.

- Sodium chloride-rich groundwater in the Bassendean Sand
- Calcium- and bicarbonate-rich groundwater in the Tamala Limestone and at the base of the superficial formations in the Ascot Formation
- A mixture of sodium chloride, and calcium and bicarbonate groundwater at the base of the superficial aquifer, where the Tamala Limestone and Ascot Formation are absent, and in the underlying Mirrabooka and Leederville aquifers.

Radon–222

Radon–222 (radon) is a radioactive gas derived from the decay of radium–226 (radium) which originates from uranium–238 (uranium). Both radium and uranium are found in trace quantities in minerals and, as a consequence, radon has been detected within the groundwater of the superficial aquifer (Thorpe, 1994).

In Australia the National Health and Medical Research Council has set an upper limit of 100 Becquerels per litre as the guideline for radon in drinking water. All groundwater samples tested for radon within the Perth Region were below the limit. However, most groundwater from the granitic rocks of the Yilgarn Craton, and from the superficial aquifer containing heavy minerals or uranium-bearing phosphatic nodules, had higher levels of radon than the groundwater elsewhere.

Temperature

The temperature of the groundwater at the watertable ranges from 19 to 24°C depending on location, depth to watertable, and the season. Greatest seasonal variation (19–24°C) is recorded where the watertable is at a depth of less than 2 m. Elsewhere, the temperature of the groundwater at the watertable is relatively constant at about 21°C.

Rockingham aquifer

The Rockingham aquifer is a local semi-unconfined aquifer which exists only in the Rockingham area where it is

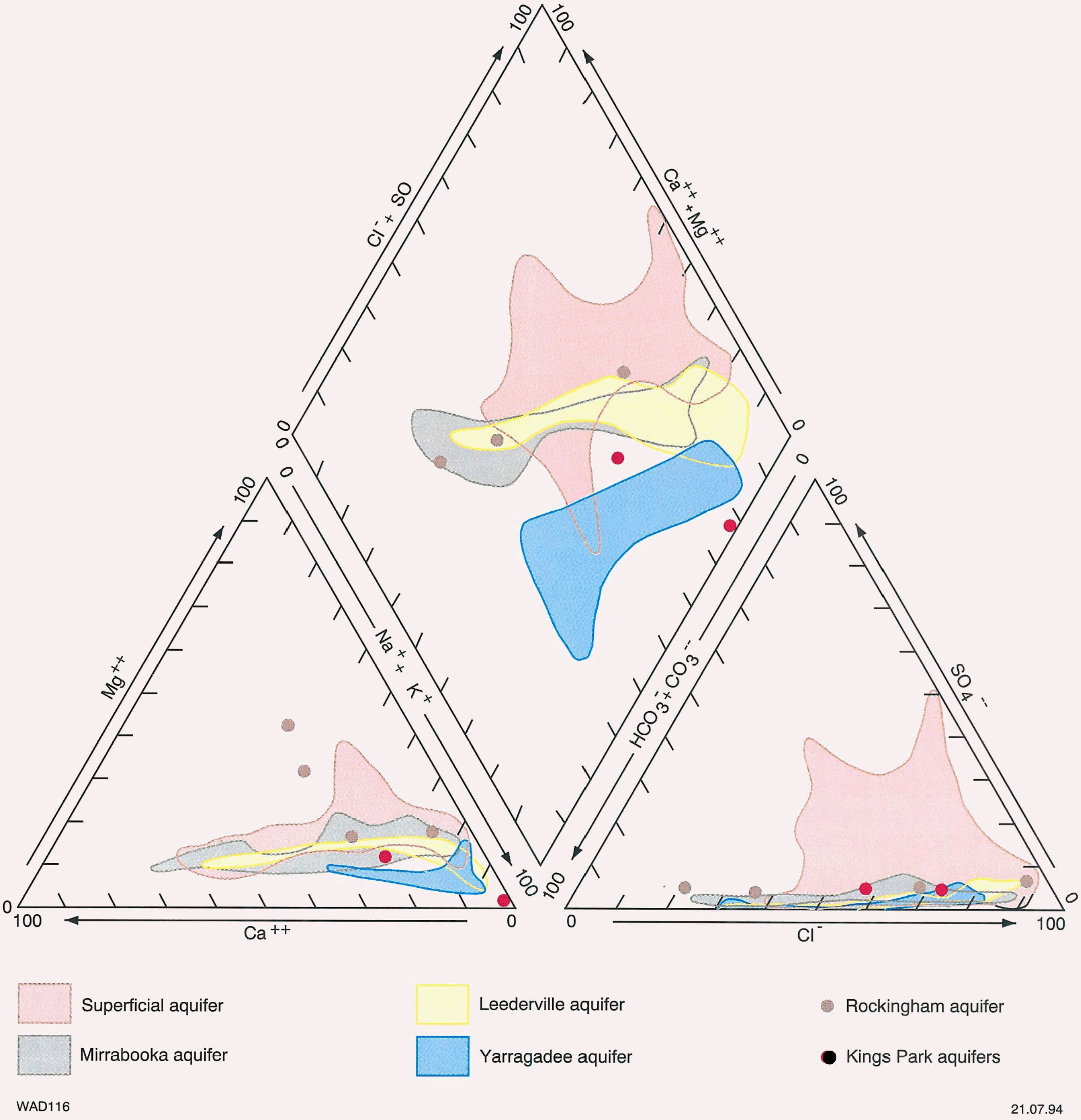


Figure 35. Groundwater quality, hydrochemical trilinear diagram

extensively used for irrigation of parklands and sporting areas. It consists predominantly of medium- to coarse-grained, slightly silty sand. The aquifer covers an area of about 280 km^2 and occupies a channel eroded into the Leederville aquifer. It has a maximum onshore thickness of about 110 m with up to 70 m from the base containing oceanwater beneath the upper part containing fresh (<1000 mg/L TDS) groundwater. Discontinuous clay lenses at the base of the superficial formations locally confine the Rockingham aquifer from the overlying superficial aquifer. Regionally, however, the two aquifer systems are hydraulically connected and commonly have similar horizontal hydraulic conductivities, resulting in the semi-unconfinement of the Rockingham aquifer.

Groundwater recharge

Groundwater in the Rockingham aquifer is in hydraulic continuity with that in the overlying superficial aquifer and is recharged by downward groundwater leakage. Annual recharge is dependent mainly on climatic factors, of which rainfall is the most important. As the head difference between the watertable in the superficial aquifer and the potentiometric level of the Rockingham aquifer changes, so will the recharge rate to the Rockingham aquifer. Abstraction of groundwater from the Rockingham aquifer will increase the head difference and induce additional recharge. Groundwater also enters the Rockingham aquifer (along its eastern margin) as groundwater discharge from the Leederville aquifer. This takes place above a saltwater interface, at about -64 m AHD.

The quantity of groundwater recharge to the Rockingham aquifer, by downward leakage from the superficial aquifer, can be expressed mathematically by the following form of the Darcy equation:

$$\frac{Q_{oa}}{A} = \frac{k'}{b'}\Delta h \quad \text{or} \quad Q_{oa} = A\frac{k'}{b'}\Delta h \ldots\ldots\ldots\ldots\ldots (10)$$

where $\frac{Q_{oa}}{A}$ = recharge rate (m/d)

Q_{oa} = vertical leakage through overlying aquifer (m^3/d)

A = recharge area within which vertical leakage is occurring (m^2)

$\frac{k'}{b'}$ = leakage coefficient

k' = vertical hydraulic conductivity of overlying aquifer (1×10^{-3} m/d)

b' = saturated thickness of overlying aquifer (m)

Δh = average difference between the potentiometric head at the top of the Rockingham aquifer and the watertable in the superficial aquifer (m)

Equation (10) includes the assumption that the recharge (leakage) balances groundwater throughflow in the Rockingham aquifer and that no water is taken from storage. The hydraulic-head difference between the watertable and the potentiometric level at the top of the Rockingham aquifer is not known but is probably less than one metre. For this reason, the area of recharge to the Rockingham aquifer is also not known but is assumed to be equivalent to the area of its onshore subcrop (280 km^2). By assuming an average saturated thickness of 20 m for the superficial aquifer, and an average head difference of one metre between the watertable and the potentiometric level of the Rockingham aquifer, the recharge to the Rockingham aquifer is:

$$Q_{oa} = 280 \times 10^6 \times \frac{1 \times 10^{-3}}{20} \times 1\ m^3/d = 14\,000\ m^3/d$$

From the flownet analysis of the superficial aquifer, recharge to the Rockingham aquifer, by leakage from the superficial aquifer, is about 14 300 m^3/d (Jandakot Mound 500 m^3/d, Serpentine Area 3950 m^3/d, Stakehill Mound 8050 m^3/d and Safety Bay Mound 1800 m^3/d). The discrepancy between the two methods of recharge estimation is about 2% and well within the order of accuracy expected for each method. For this reason, the estimate based on flownet analysis of 14 300 m^3/d (5.22 x 10^6 m^3/year) is accepted as being more accurate. It is equivalent to about 2.17% of rainfall over the recharge area.

Groundwater discharges from the Leederville aquifer into the Rockingham aquifer above the saltwater interface (-64 m AHD) along the eastern margin of the Rockingham Sand. This recharge to the Rockingham aquifer is about 3300 m^3/d based on groundwater flow calculations for the Leederville aquifer.

Groundwater abstraction from the Rockingham aquifer will cause an increase in the hydraulic-head difference between the Rockingham aquifer and the superficial and Leederville aquifers. This will cause a slight lowering of the watertable which, depending on its depth below groundlevel, may result in additional recharge to the superficial aquifer by reducing evaporative losses. It will also induce additional downward leakage into the Rockingham aquifer and increased groundwater discharge from the Leederville aquifer into the Rockingham Sand along the eastern margin of the Rockingham aquifer.

Groundwater flow and discharge

The groundwater flow system of the Rockingham aquifer has not been fully investigated and only estimates of throughflow and storage can be made. Because the groundwater in the Rockingham aquifer originates from the superficial aquifer by downward flow (14 300 m^3/d) and from the Leederville aquifer by lateral groundwater flow (3300 m^3/d) the total groundwater flow within the Rockingham aquifer is about 17 600 m^3/d or 6.42 x 10^6 m^3/year.

Groundwater flows westward in the Rockingham aquifer, over a saltwater interface (related to the ocean), and then discharges along the coast and possibly offshore via the superficial aquifer. The depth to the saltwater interface in the Rockingham aquifer has not been delineated by drilling except at AM 54, AM 57 and AM 58 (Fig. 11) where it is about 70 m, <66 m and 75 m below groundlevel, respectively.

Groundwater storage

The top 40 m of the Rockingham aquifer contains groundwater of salinity less than 1000 mg/L TDS, which overlies saline water. The volume of fresh groundwater (<1000 mg/L) above the saltwater interface, which has been estimated by multiplying the saturated thickness by the average specific yield of 0.2, is about 2200 x 10^6 m^3. This volume will vary according to the position of the saltwater interface which, in turn, will be affected by groundwater abstraction from the aquifer.

Groundwater–oceanwater interface

The saltwater interface within the Rockingham aquifer remains at about -64 m AHD (AM54 -64.7 m, AM57 < -63.7m and AM58 -65.9 m), which indicates a relatively horizontal surface within the aquifer above which groundwater flow occurs and below which groundwater flow is negligible. For this reason, the quantity of groundwater discharge from the Leederville aquifer into the Rockingham aquifer below -64 m AHD, is probably also negligible. Because the watertable in the superficial aquifer (above the Rockingham aquifer) is relatively flat

Table 23. Rockingham aquifer — chemical analyses of groundwater from investigation bores

Bore	pH	EC mS/m @25°C	TDS $-CO_2$	TH	TA	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	SiO_2	NO_3	Fe	Remarks
			mg/L														
T281	7.3	82	440	230	236	41	31	79	3	0	287	107	19	11	0.02	<0.05	Lake Thompson investigation
T441	7.5	123	690	228	145	55	22	158	9	0	177	289	30	30	0.02	<0.05	
T481	7.3	59	300	200	213	29	31	41	10	0	259	49	19	13	0.02	<0.05	
T581	6.3	577	3 270	685	112	98	107	934	23	0	137	1 700	228	13	0.02	<0.05	
GDWQA			1 000	500				300				400	400		10.00	0.30	

Notes: GDWQA Guidelines for drinking water quality in Australia, 1987
EC Electrical conductivity
TDS Total dissolved solids (excluding CO_2) by claculation at 180°C
TH Total hardness as calcium carbonate
TA Total alkalinity as calcium carbonate

and on average at an elevation of about 1.5 m AHD, the depth to the saltwater interface closely approximates the Ghyben–Herzberg relationship. Under these conditions, rising of the saltwater interface will readily occur as a result of groundwater abstraction from high-yielding shallow bores.

Groundwater quality

The salinity of the groundwater in the Rockingham aquifer is highly variable, ranging from about 300 mg/L TDS to more than 3000 mg/L TDS (Table 23) in the mixing zone between low-salinity groundwater and underlying saline groundwater.

Most of the recharge to the Rockingham aquifer is by downward leakage from the superficial aquifer through the Tamala Limestone and some is by lateral discharge from the Leederville aquifer. Consequently, as seen from Figure 35, the groundwater is predominantly of the sodium chloride/calcium and bicarbonate type.

Above the saltwater interface the groundwater has a hardness (as $CaCo_3$) of about 200 mg/L but in the mixing zone of the interface the hardness increases to more than 600 mg/L. Sulfate ion concentration also increases within the mixing zone, from less than 20 mg/L above the interface to more than 200 mg/L within the mixing zone. Rising of the interface due to excessive groundwater abstraction will cause a deterioration in the groundwater quality by increasing the salinity, and would eventually render the water unsuitable for production.

Kings Park aquifers

The Kings Park Formation contains two aquifers. In the upper part of the formation, the Mullaloo Sandstone Member is a locally important semi-unconfined to confined aquifer consisting of poorly sorted, silty, commonly glauconitic sand. It has a maximum thickness of about 200 m and probably occupies a deep meandering channel within the calcareous siltstones of the formation. Towards the base of the formation, the Como Sandstone Member, consisting of moderately sorted sand, may also be an important local confined aquifer, but drilling has identified it only at two localities (AM 32 and AM 40 borehole sites, Fig. 11) with a maximum thickness of 57 m. This unit may also occupy a narrow meandering channel within the Kings Park Formation. The hydrogeology of the Kings Park aquifers has not been previously described.

Groundwater recharge

Recharge to both the Mullaloo Sandstone Member and the Como Sandstone Member takes place where they extend to the boundary of the Kings Park Formation, and where they are in hydraulic contact with the Mirrabooka, Leederville and Yarragadee aquifers. In these areas recharge occurs by lateral groundwater movement and discharge from these older aquifers.

As the recharge areas to the Kings Park aquifers have not been delineated, the quantity of recharge cannot be calculated with any certainty. It is suggested that the upper aquifer (Mullaloo Sandstone Member) is recharged by lateral flow and groundwater discharge from flow-channels 2 and 3 (Plate 63) of the Mirrabooka aquifer at a rate of about 6100 m^3/d. The lower aquifer (Como Sandstone Member) is probably recharged by groundwater discharge from flow-channels 3, 4 and 5 (Plate 64) of the Leederville aquifer (2000 m^3/d) and flow-channel 3 (Plate 77) of the Yarragadee aquifer (1000 m^3/d). Assuming that these estimates of recharge are correct, the total recharge to the Kings Park aquifers is some 9100 m^3/d or 3.32×10^6 m^3/year.

Groundwater flow, storage and discharge

More detailed drilling and testing are required to define flow directions and permit more-accurate estimates of groundwater flow and storage in the Kings Park aquifers. By assuming that the total groundwater flow within the aquifers is derived from groundwater discharge from the geological formations incised by erosion and adjacent to

Table 24. Kings Park aquifers — chemical analyses of groundwater from artesian monitoring (AM) bores

Bore	*pH*	*EC mS/m @25°C*	*TDS -CO_2*	*TH*	*TA*	*Ca*	*Mg*	*Na*	*K*	*CO_3*	*HCO_3*	*Cl*	*SO_4*	*SiO_2*	*NO_3*	*Fe*
			mg/L													
AM39	9.7	211	1 170	21	221	5	2	418	10	79	109	475	41	89	0.04	<0.05
AM40B	6.5	49	265	67	81	17	6	64	7	<2	95	97	9	16	<1.0	1.7
GDWQA		1 000	500					300				400	400		10	0.3

Notes:				
	AM	Artesian monitoring	TDS	Total dissolved solids by calculation at 180°C
	GDWQA	Guidelines for drinking water quality in Australia, 1987	TH	Total hardness as calcium carbonate
	EC	Electrical conductivity	TA	Total alkalinity as calcium carbonate

the Kings Park Formation, the total groundwater throughflow is about 9100 m^3/d or 3.32 x 10^6 m^3/year.

Groundwater within the Kings Park aquifers eventually discharges westward over a saltwater interface and into the ocean. Groundwater in the Mullaloo Sandstone Member probably discharges into the superficial aquifer offshore but near the coast, whereas that from the Como Sandstone Member probably discharges some distance offshore.

Groundwater quality

The salinity of the groundwater in the Kings Park Formation is highly variable with the lowest salinity water occurring where the Mirrabooka aquifer discharges into the Mullaloo Sandstone Member. The groundwater salinity probably increases in the direction of groundwater flow, to the west. At AM40 borehole, the salinity of the groundwater in the Mullaloo Sandstone Member is about 265 mg/L (Table 24). Estimated salinities in the Como Sandstone Member from resistivity wireline logs are about 1200 mg/L in AM40 borehole and 500 mg/L in AM32 borehole. These estimated salinities are consistent with the salinities of the groundwater in the adjacent sections of the Leederville aquifer.

Thin, local beds of sand and silt within the less permeable calcareous siltstone section of the Kings Park Formation may contain saline connate groundwater or oceanwater entrapped during earlier high ocean levels.

Mirrabooka aquifer

The Mirrabooka aquifer is present along the eastern margin of the coastal plain in the Swan Syncline, and across the metropolitan area (Fig. 36; Plate 63). It is a predominantly sandy, major semi-confined aquifer and comprises the Poison Hill Greensand, Gingin Chalk, Molecap Greensand, and Mirrabooka Member.

The Mirrabooka aquifer consists of white, pale-green and greenish-brown glauconitic sandstone and silty sandstone with subordinate dark, greenish-grey interbedded shale. The sediments of the Poison Hill Greensand and Molecap Greensand in the East Mirrabooka area were originally called the 'Channel Sand' (Allen, 1977): this name was later changed to 'Marine Sand'. Allen (1981b) and Davidson (1987) attributed these sediments to the Osborne Formation and, together with the sandy beds in the upper part of the Osborne Formation, informally named them the 'Mirrabooka Sand Member'. The extent of the Mirrabooka aquifer is, therefore, more widespread than previously recognized and represents a locally significant aquifer in the northern Perth area, where it is in hydraulic continuity with the superficial aquifer.

Beneath the Dandaragan Plateau, the Mirrabooka aquifer is mostly above the watertable and unsaturated. Where it does contain groundwater it is generally of low permeability and is recharged by rain infiltration. There are insufficient data to calculate the percentage of rainfall recharge over the Dandaragan Plateau but it is considered to be insignificant.

Groundwater recharge

The Mirrabooka aquifer is a semi-confined and locally confined aquifer which exists only in the northern Perth area, where it is confined below by shales of the Osborne Formation (Kardinya Shale Member) and locally by interbedded shale lenses. Beneath the coastal plain, the groundwater in the Mirrabooka aquifer is in hydraulic continuity with the groundwater in the overlying superficial aquifer; the downward component of groundwater flow in the superficial aquifer recharges the Mirrabooka aquifer. The rate of recharge, which can be expressed mathematically by equation (10), varies with the vertical hydraulic-head gradient associated with leakage of water through the superficial aquifer. The recharge rate per unit area is valid for only one average vertical downward-head difference, but because the seasonal variations in head difference are small, the calculated daily recharge rate for the Mirrabooka aquifer is considered to represent 1/365 of the annual recharge. Locally, this head difference will be significantly increased by abstraction of groundwater from the Mirrabooka aquifer.

Areal differences in recharge rates are attributed not only to differences in hydraulic head, but also to variations

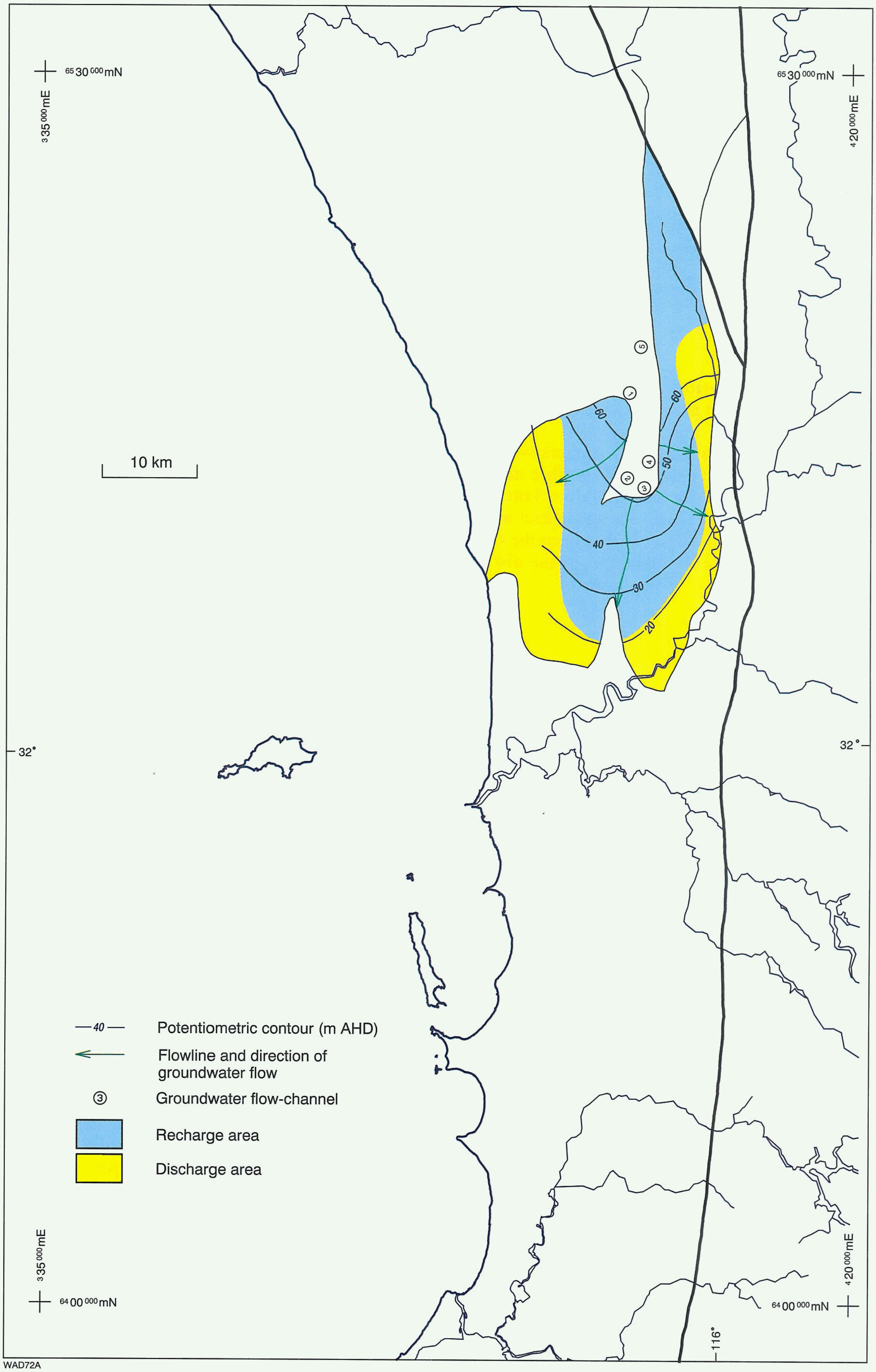


Figure 36. Mirrabooka aquifer groundwater flownet September–October 1992

of vertical hydraulic conductivity and saturated thickness of the superficial aquifer. The vertifical hydraulic conductivity (k') has been determined from ^{14}C dating (Thorpe and Davidson, 1991) and aquifer pumping tests (Davidson, 1979, 1987; Hall and Davidson, 1983) and an average value of 8 x 10^{-4} m/d has been used for the entire recharge area of the Mirrabooka aquifer. The saturated thickness (b') of the superficial aquifer has been obtained from Plate 51, and the head difference between the superficial and Mirrabooka aquifers by superimposing and subtracting the potentiometric levels of the Mirrabooka aquifer from the watertable levels of the superficial aquifer. The local, increased head differences around production bores have not been included in this regional assessment of recharge. Negative values indicate hydraulic heads decreasing with depth, and positive values indicate those increasing.

In the area of downward hydraulic gradients (heads decreasing with depth) the vertical leakage through the superficial aquifer into the Mirrabooka aquifer has been calculated using equation (10) for the five flow-channels of the Mirrabooka aquifer flownet (Fig. 36). Recharge to the Mirrabooka aquifer by this method is 17 350 m^3/d (Table 25), which is approximately equal to the 16 500 m^3/d determined by flownet analysis for the Gnangara Mound (South). The discrepancy between the two methods of regional recharge estimation is about 5% and within the order of accuracy expected from these methods. However, the estimate of 16 500 m^3/d (6.02 x 10^6 m^3/year) based on the flownet analysis is accepted as being more accurate. It is equivalent to about 2.06% or 17 mm of rainfall over the recharge area. From the flownet analysis of the superficial aquifer, recharge ranges up to about 4% or 34 mm of the rainfall in some areas (Table 13). Total recharge to the Mirrabooka aquifer is 11.09 x 10^6 m^3/year and equivalent to the regional recharge of 6.02 x 10^6 m^3/year plus the induced local recharge of 5.07 x 10^6 m^3/year due to abstraction from the aquifer. The amount of recharge will vary from year to year depending on climatic factors, of which rainfall is the most important, and also on abstraction rates. As the head difference between the watertable in the superficial aquifer and the potentiometric level of the Mirrabooka aquifer changes, the recharge rate to the Mirrabooka aquifer will also change. The average head difference varies seasonally by about 0.5 m (Davidson, 1987).

Groundwater flow and discharge

The groundwater-flow system of the Mirrabooka aquifer is hydraulically connected to that of the superficial aquifer. The direction of groundwater flow in the Mirrabooka aquifer is imprecisely known but it is believed that, in the northeastern area, flow is eastward in the upper part of the aquifer and southward in the lower (Davidson, 1992). In the Swan Valley area the resultant groundwater flow in the Mirrabooka aquifer is southeastward, and across the remainder of the metropolitan area it is assumed to be subparallel to the groundwater-flow direction in the superficial aquifer (Fig. 36). Across the metropolitan area, the configuration of the potentiometric surface of the Mirrabooka aquifer is poorly defined. The potentiometric contours shown in Figure 36 are based on sparse data from the Mirrabooka aquifer, and scattered hydraulic-head data from the base of the superficial aquifer.

Table 25. Mirrabooka aquifer — estimates of groundwater flow (rounded to nearest 50 m^3/d and reduced by 5%)

Method of determination	*Flow-channel*					
	1	*2*	*3*	*4*	*5*	*Total*
By recharge estimates	950	2 650	6 300	2 050	5 400	17 350
Reduced 5% (a)	900	2 500	6 100	1 950	5 150	16 500

Note: (a) The throughflow values determined by recharge estimates have been reduced by 5% to coincide with the total estimates of throughflow determined by flownet analysis of the superficial aquifer

Hydraulic-head data are insufficient to permit construction of a detailed flownet. However, based on the data available, the Mirrabooka aquifer groundwater-flow system has been divided into five separate flow-channels (Fig. 36), each receiving recharge by downward leakage from the superficial aquifer. Groundwater flow within the aquifer is, therefore, equal to the amount of groundwater recharge minus the discharge. The total maximum groundwater throughflow, based on recharge estimates using a vertical hydraulic conductivity of 8 x 10^{-4} m/d, is 17 350 m^3/d or about 6.33 x 10^6 m^3/year. This estimate of total throughflow exceeds that obtained by the flownet analysis of the superficial aquifer by about 5% and has consequently been adjusted to 16 500 m^3/d or 6.02 x 10^6 m^3/year (Table 25). This estimate of throughflow will increase when abstraction is increased, causing greater downward hydraulic-head differentials and additional recharge.

Towards the end of the groundwater-flow path, much of the groundwater throughflow in the Mirrabooka aquifer eventually discharges by upward leakage into the superficial aquifer because of increasing hydraulic heads with depth (Fig. 36). The remainder, about 6100 m^3/d, flows laterally to discharge into the Mullaloo Sandstone Member or other unidentified sandy beds of the Kings Park Formation, particularly from flow-channels 2 and 3. In low-lying areas, upward-hydraulic heads may influence bores screened against the Mirrabooka aquifer to discharge naturally as artesian flows.

The Mirrabooka aquifer directly overlies the Kardinya Shale Member of the Osborne Formation, which inhibits downward groundwater leakage into the Henley Sandstone Member of the Leederville aquifer. Minor downward leakage into the Leederville aquifer may occur, but it cannot be quantified and is considered to be insignificant.

Based on estimates of groundwater flow, measured hydraulic gradients from Plate 63, aquifer thicknesses determined by summing the isopachs from Plates 33, 36, 39 and 42, and using equation (5), the average horizontal hydraulic conductivity of the Mirrabooka aquifer is determined to be about 1 m/d (0.87 m/d flow-channel 1; 1.25 m/d flow-channel 2; 1.20 m/d flow-channel 3; and

0.98 m/d flow-channel 4). From equation (2) and assuming an average effective porosity of 0.2, the average rate of groundwater flow is about 5 m/year (4.4 m/year flow-channel 1; 3.8 m/year flow-channel 2; 5.5 m/year flow-channel 3; and 6.0 m/year flow-channel 4). In all cases, the rates of groundwater flow have been influenced by abstraction and are marginally greater than would be expected under natural conditions.

Groundwater storage

Based on the isopach maps for the Poison Hill Greensand (Plate 33), Gingin Chalk (Plate 36), Molecap Greensand (Plate 39) and the Mirrabooka Member (Plate 42), the volume of unconfined groundwater in storage within the Mirrabooka aquifer has been estimated by multiplying an assumed specific yield of 0.2 by the saturated thickness of the aquifer. Because the Mirrabooka aquifer is semi-confined the volume of groundwater held in elastic storage can be estimated using a storage coefficient of 1×10^{-3}. Elastic storage is defined by Fetter (1988) as being the amount of water per unit volume of a saturated formation that is stored, or expelled from storage, owing to compressibility of the formation per unit change in head. The total volume of groundwater in storage within the Mirrabooka aquifer is about $11\,200 \times 10^6$ m^3 (elastic or confined storage is about 30×10^6 m^3).

Groundwater quality

Groundwater from the Mirrabooka aquifer ranges in salinity from 130 to 350 mg/L TDS (Table 26). The lowest salinity water is generally found in the recharge area and at the top of the aquifer, where it is in direct hydraulic contact with the groundwater in the superficial aquifer.

The pH values of the groundwater vary between 5.0 and 7.7, with the higher pH water beneath the Ascot Formation. This is probably as a result of downward leakage through the calcareous sediments of the formation. The groundwater is predominantly a mixture of the sodium chloride, and calcium and bicarbonate types (Fig. 35).

Leederville aquifer

The Leederville aquifer is a major confined aquifer spanning the Perth Region. It overlaps the Darling Fault south of the Dandaragan Plateau and extends both north and south of the area. This aquifer is present beneath the entire coastal plain except near the Swan Estuary, where it has been eroded out prior to deposition of the Kings Park Formation (Plate 11), and in the southeast corner where the superficial formations rest directly on the Cattamarra Coal Measures (Plate 49). The Leederville aquifer is a multilayer groundwater-flow system consisting of discontinuous interbedded sandstones, siltstones and shales of the Henley Sandstone Member (Osborne Formation) and the Pinjar, Wanneroo, and Mariginiup Members (Leederville Formation).

Parts of the Leederville aquifer were originally referred to as 'Leederville horizon' and 'City horizon' (Forman, 1933); 'Leederville Sandstone' (Whincup, 1966); 'South Perth Formation' (Berliat, 1964; Sanders, 1967); 'Yarragadee Formation' (Sanders, 1967), and 'South Perth Shale' (Commander, 1974). The Leederville aquifer was first defined in the Perth Region by Allen (1979).

From Plates 12 and 27, the Leederville aquifer has a maximum thickness of more than 550 m in the Yanchep Syncline. In the northern part of the Swan Syncline and in the Wanneroo area it is about 500 and 400 m thick respectively. Across the Pinjar Anticline the aquifer has a minimum thickness of about 50 m. South of Perth, the Leederville aquifer ranges in thickness from about 50 m in the southeast to about 300 m in the Jandakot area.

The aquifer is unconfined at the intake areas where it directly underlies the superficial aquifer, but over short distances it becomes confined by discontinuous interbedding of siltstone and shale. Elsewhere, it is confined above by the Kardinya Shale Member of the Osborne Formation (Plate 28) and below by the South Perth Shale (Plate 10). Artesian groundwater flows can be expected from bores drilled into the Leederville aquifer in low-lying areas along the valleys of the Swan, Canning, Southern and Serpentine Rivers and in low areas along the coastal strip.

Groundwater recharge

Over about half of the coastal plain in the Perth Region, where the Osborne Formation shale has been removed by erosion (Plate 49), the Leederville aquifer subcrops beneath the superficial formations. In these areas it is in direct contact and hydraulic connection with the superficial aquifer and, where there is a downward hydraulic gradient, recharge occurs (Fig. 37; Plate 64). In the northern area, recharge takes place mainly over the Pinjar Anticline. Beneath the area of the Dandaragan Plateau the Leederville aquifer is overlain by the Coolyena Group of sediments and recharge to the aquifer occurs only where deep valleys have been incised to expose the aquifer in the many creek beds, enabling infiltration of stream flow to occur. To the south of Perth, recharge to the Leederville aquifer occurs mainly along the eastern margin of the coastal plain. However, because of declining hydraulic heads within the aquifer, the area of downward heads is getting larger and the recharge area is gradually extending westward.

The rate of recharge, which can be expressed mathematically by equation (10), varies with the vertical hydraulic-head loss associated with leakage of water through the superficial aquifer. The recharge rate per unit area is valid for only one average vertical downward-head difference at any one time, but because the seasonal variations in head difference are small (commonly less than 5 m) the calculated daily recharge rate for the Leederville aquifer is considered to be in steady state and to represent 1/365 of the annual recharge. The hydraulic-head differences (Dh) between the head in the Leederville aquifer measured from the artesian monitoring (AM) bores perforated in the middle of the Leederville Formation, and the superficial aquifer measured at the watertable, are shown in Plate 64. The saturated thickness (b') through

Table 26. Mirrabooka aquifer — chemical analyses of groundwater from investigation and production bores

Bore	*pH*	*EC mS/m @25°C*	*Temp. °C*	*TDS*	*TH*	*TA*	*Ca*	*Mg*	*Na*	*K*	CO_3	HCO_3	*Cl*	SO_4	SiO_2	NO_3	*Fe*
										mg/L							
M70	5.8			270	75	25	7						64				0.05
M190	6.8			250	170	103	22						53				0.05
M370	5.0		20	160	39	12	4	7	46	4			82		11	0.03	0.91
MP282	5.2	27	21	150	31	33	6	4	39	3	0	40	63	4	14	<0.02	3.00
MP172	5.8	28	21	152	31	25	4	5	38	3	<2	31	68	2	16	<0.02	0.97
MP182	6.9	37	21	197	95	105	30	5	29	5	<2	128	47	<2	17	<0.05	3.00
MP262	5.0	27	20	130	23	8	3	4	34	3	0	10	65	4	11	0.02	0.98
MP162	6.6	38	21	200	105	105	32	6	29	4	0	128	50	2	16	0.04	4.3
MP272	5.1	23	20	130	17	20	2	3	32	3	0	24	55	4	14	0.03	0.80
L20A	7.7	38		130	208	112	44	4	23	4	<2	137	40	2	20	0.20	1.0
L30A	7.2	36		100	195	98	34	4	28	4	<2	119	48	4	13	0.04	
L50A	6.4	55		305	95	75	25	8	71	9	<2	92	121	6	19	0.07	
L60A	6.3	31		169	41	25	5	7	41	8	<2	31	73	4	15	0.20	
L120A	6.4	22		137	23	34	10	2	27	6	<2	41	45	8	18	0.16	
L130A	7.4	34		188	100	105	35	4	24	3	<2	128	40	2	15	<0.02	1.3
L132	6.3	25		138	51	43	14	4	25	4	<2	52	46	3	16		0.68
L140A	6.3	25		149	52	53	11	6	26	5	<2	65	45	4	18	<0.02	8.30
L160A	7.3	48		294	130	149	42	5	57	6	<2	182	66	8	18	0.02	6.0
L210A	7.5	43		276	140	156	41	8	27	9	<2	190	39	5	51	<0.02	0.58
L230A	6.4	36		204	66	48	20	4	43	8	<2	58	77	6	17	<0.02	
L240A	6.2	58		350	66	47	10	10	81	22	<2	57	151	7	17	<0.02	
L250A	6.3	41		226	75	71	22	5	44	6	<2	87	80	4	20	<0.02	1.2
L260A	7.3	53		298	170	160	56	7	40	5	<2	195	71	2	19	0.03	0.34
L320A	6.0	27		152	35	30	9	3	32	5	<2	36	56	9	20	0.02	
L330A	7.4	48		252	180	155	63	5	23	4	<2	189	46	4	12	<0.02	0.34
GDWQA	6.5–8.5			1 000	500				300				400	400		10.00	0.3

Notes:

GDWQA	Guidelines for drinking water in Australia, 1987	TA	Total alkalinity as calcium carbonate
EC	Electrical conductivity	M	Mirrabooka investigation
TDS	Total dissolved solids by calculation at 180°C	MP	Mirrabooka Production
TH	Total hardness as calcium carbonate	L	Lexia investigation

which leakage is occurring is equivalent to half the thickness of the Leederville Formation plus the thickness of the Henley Sandstone Member and the saturated thickness of the superficial aquifer. The average vertical hydraulic conductivity (k') for this thickness has been determined from the ^{14}C dating of Thorpe and Davidson (1991): a value of 5 x 10^{-4} m/d has been used for the entire recharge and discharge areas of the Leederville aquifer. The calculated recharge by downward leakage from the superficial aquifer and through the upper half of the Leederville aquifer, gives an average value for recharge to the whole of the Leederville aquifer. The shale of the Osborne Formation (Kardinya Shale Member) is assumed to have a vertical hydraulic conductivity of about 1 x 10^{-6}; consequently, groundwater leakage through the shale is considered insignificant.

The area of the Leederville aquifer has been divided into eight individual groundwater flow-channels, roughly coinciding with the groundwater management areas delineated by the Water Authority. Flow-channels 1 to 4 are north of the Swan River and channels 5 to 8 are south of the river. From hydraulic data and using equation (10) the total recharge to the Leederville aquifer is 85 650 m^3/d or 31.26 x 10^6 m^3/year. Of this about 63 350 m^3/d recharge the Leederville aquifer north of the Swan River and the balance recharges to the south. If recharge beneath the Dandaragan Plateau is excluded (14 300 m^3/d), the total recharge beneath the coastal plain is about 71 350 m^3/d. Recharge to the Leederville aquifer calculated from flownet analysis of the superficial aquifer (Tables 12–21) is about 66 350 m^3/d. The discrepancy of about 7% compared with the 71 350 m^3/d calculated using equation (10) is well within the order of accuracy expected from these determinations. Beneath the coastal plain, recharge to the Leederville aquifer is equivalent to 2–3% of the total rainfall over the recharge area.

Recharge to the Leederville aquifer also takes place through upward discharge from the Yarragadee aquifer in areas where the South Perth Shale confining bed between the aquifers is absent, and where there are increasing heads with depth and upward hydraulic gradients. Total recharge to the Leederville aquifer by upward discharge from the Yarragadee aquifer (Table 27) and within the Leederville aquifer flownet area is about 2350 m^3/d (0.86 x 10^6 m^3/year) with approximately 2000 m^3/d recharging the aquifer north of the Swan River, and 350 m^3/d recharging south.

Groundwater flow

Over about half of the Perth Region, the groundwater flow system of the Leederville aquifer is hydraulically connected to the flow system within the superficial aquifer. In areas of downward hydraulic gradients (decreasing heads with depth) recharge occurs; where upward gradients exist, discharge occurs. Elsewhere, the Leederville aquifer flow system is separated from the superficial aquifer flow

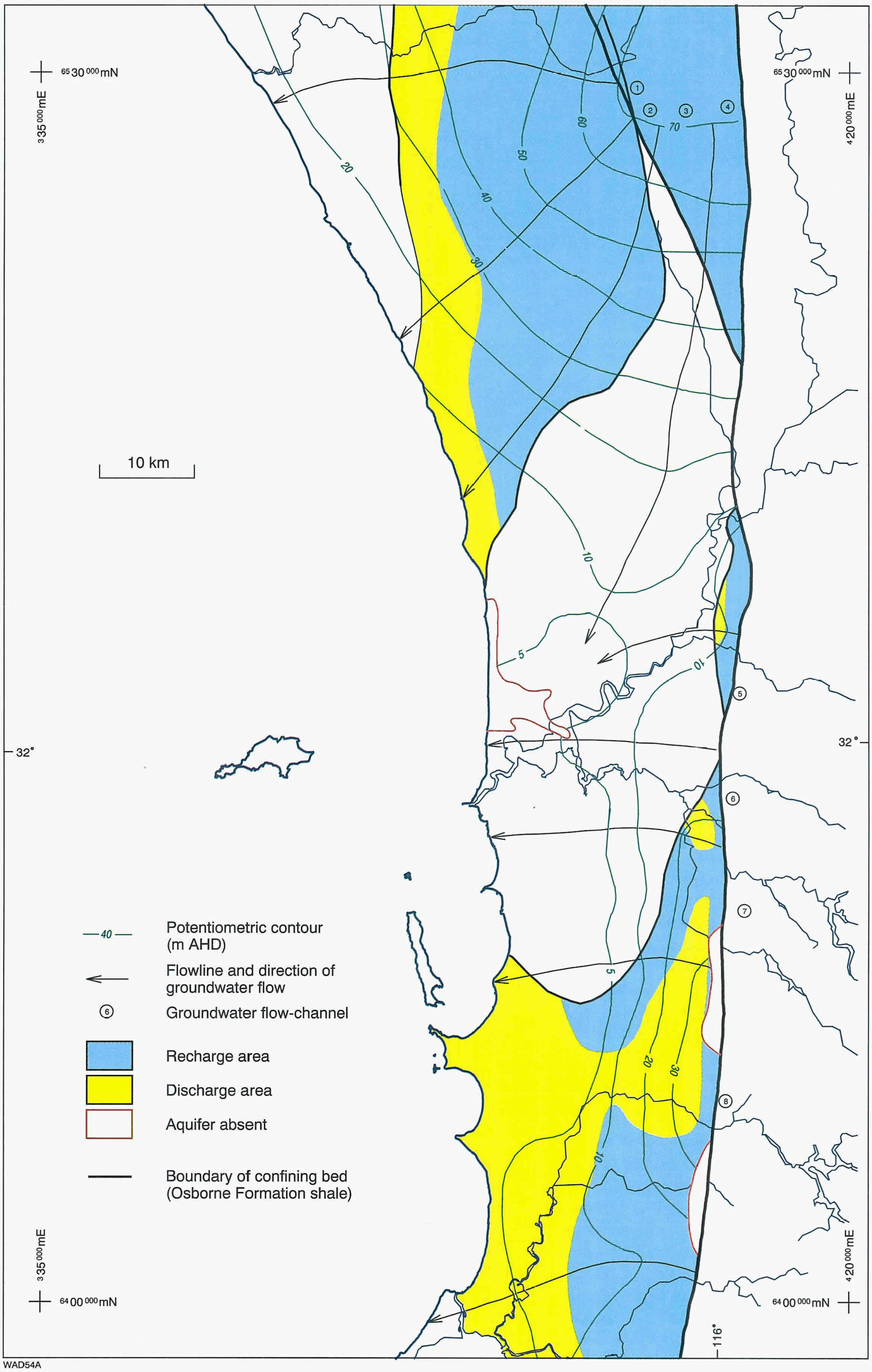


Figure 37. Leederville aquifer groundwater flownet September–October 1992

Table 27. Leederville aquifer — estimates of recharge and discharge (rounded to nearest 50 m^3/d)

Potentiometric contours		*Flow-channels*								*Total*
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	
(m AHD)		*North of Swan River*					*South of Swan River*			*(m^3/d)*
70	L_D	1 000	800	1 500	1 200					4 500
	L_U	–	–	–	–					–
	D_U	–	–	–	–					–
	D_D	50	50	50	50	N/A	N/A	N/A	N/A	200
	N_{RD}	+950	+750	+1 450	+1 150					+4 300
	a	–	–	–	–					–
	Q	950	750	1 450	1 150					4 300
60	L_D	2 450	1 500	2 500	2 100					8 550
	L_U	–	–	–	–					–
	D_U	–	–	–	–					–
	D_D	1 350	900	50	50	N/A	N/A	N/A	N/A	2 350
	N_{RD}	+1 100	+600	+2 450	+2 050					+6 200
	a	–	–	–	–					–
	Q	2 050	1 350	3 900	3 200					10 500
50	L_D	8 000	4 150	700	1 700					14 550
	L_U	–	–	–	–					–
	D_U	–	–	–	–					–
	D_D	3 100	2 500	600	50	N/A	N/A	N/A	N/A	6 250
	N_{RD}	+4 900	+1 650	+100	+1 650					+8 300
	a	–	–	–	–					–
	Q	6 950	3 000	4 000	4 850					18 800
40	L_D	5 050	4 000	2 650	2 400					14 100
	L_U	250	–	–	–					250
	D_U	50	–	–	–					50
	D_D	1 650	2 000	1 150	50	N/A	N/A	N/A	N/A	4 850
	N_{RD}	+3 600	+2 000	+1 500	+2 350					+9 450
	a	–	–	–	–					–
	Q	10 550	5 000	5 500	7 200					28 250
30	L_D	700	6 200	3 150	750			150	2 400	13 350
	L_U	450	250	50	–			–	–	750
	D_U	800	–	–	–			–	650	1 450
	D_D	–	600	650	–	N/A	N/A	50	1 200	2 500
	N_{RD}	+350	+5 850	+2 550	+750			+100	+550	+10 150
	a	–	6 100	–	–			–	–	6 100
	Q	10 900	4 750	8 050	7 950			100	550	32 300
20	L_D	–	3 600	2 100	500		150	2 550	3 450	12 350
	L_U	900	50	50	–		–	50	–	1 050
	D_U	1 400	250	–	–		50	400	1 700	3 800
	D_D	–	–	50	–	N/A	50	950	1 350	2 400
	N_{RD}	-500	+3 400	+2 100	+500		+50	+1 250	+400	+7 200
	a	–	–	500	–		–	–	–	500
	Q	10 400	8 150	9 650	8 450		50	1 350	950	39 000
10	L_D	–	1 750	1 100	1 500	200	200	2 250	6 100	13 100
	L_U	–	–	–	–	–	50	150	50	250
	D_U	150	950	–	50	–	100	–	700	1 950
	D_D	–	–	–	–	–	–	–	1 750	1 750
	N_{RD}	+150	+800	+1 100	+1 450	+200	+150	+2 400	+3 700	+9 650
	a	–	2 450	1 950	800	–	–	350	–	5 550
	Q	10 250	6 500	8 800	9 100	200	200	3 400	4 650	43 100
5	L_D		50	250	–	–	–	100	3 100	3 500
	L_U		–	–	–	–	–	50	–	50
	D_U		550	650	–	–	–	–	1 250	2 450
	D_D	N/A	–	–	–	–	–	–	50	50
	N_{RD}		-500	-400	–	–	–	+150	+1 800	+1 050
	a		–	6 550	7 800	–	–	800	–	15 150
	Q		6 000	1 850	1 300	200	200	2 750	6 450	18 750

Table 27. (*continued*)

Potentiometric contours (m AHD)		*Flow-channels*								*Total*
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*(m³/d)*
			North of Swan River				*South of Swan River*			
Coast	Lᴅ	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1 650	1 650
	Lᴜ								–	–
	Dᴜ								1 500	1 500
	D_D								–	–
	N_{RD}								+150	+150
	a								–	–
	Q								6 600	6 600

Notes: Lᴅ = Recharge by downward leakage from superficial aquifer, m³/d
Lᴜ = Recharge by upward leakage from Yarragadee aquifer, m³/d
Dᴜ = Discharge by upward leakage to superficial aquifer, m³/d
D_D = Discharge by downward leakage to Yarragadee aquifer, m³/d
N_{RD} = Net recharge, discharge, m³/d
a = Apparent abstraction, m³/d
Q = Net groundwater throughflow, m³/d

system by confining shales (Kardinya Shale Member) of the Osborne Formation (Fig. 37).

Based on hydraulic-head measurements obtained from the artesian monitoring (AM) bores perforated approximately in the middle of the aquifer, the potentiometric surface of the Leederville aquifer fluctuates seasonally by 1 to 15 m. Over most of the area, the seasonal variation is less than 5 m, but in areas of high groundwater abstraction from the Leederville aquifer, the variations are commonly more than 10 m. The configuration of the potentiometric surface for September–October 1992, is shown in Plate 64. In the northern area, the potentiometric surface slopes predominantly southwestward from beneath the Dandaragan Plateau. In the south it slopes westward from the eastern margin of the coastal plain. In the central Perth area, the shape of the potentiometric surface has been affected by groundwater abstraction, as shown by the near closures of the 5 and 10 m potentiometric contours.

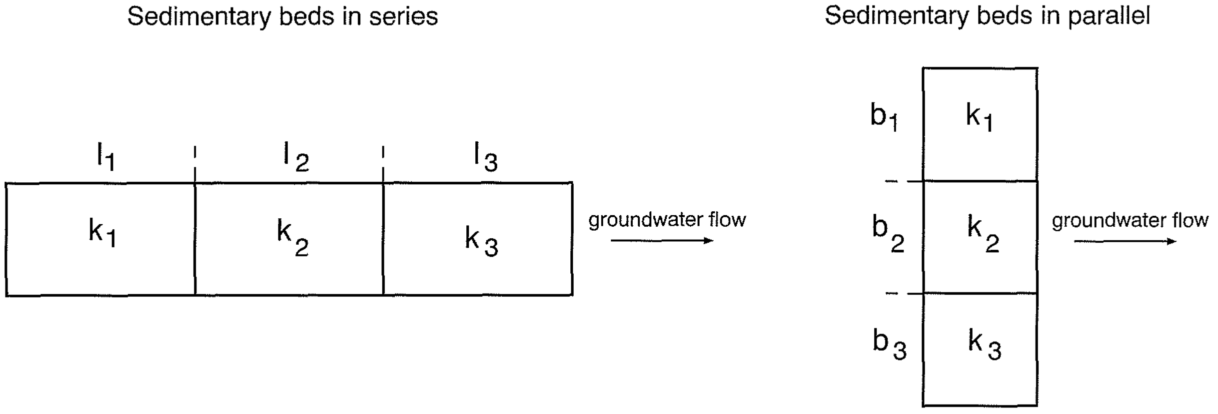
The Leederville aquifer has been divided into eight separate groundwater flow-channels. In the northern area, flow-channels 1 to 3 originate beneath the Dandaragan Plateau where recharge occurs from deeply incised streams. Flow-channel 4 also originates beneath the Dandaragan Plateau and along the eastern margin of the coastal plain which, at small scale, approximately coincides with the Darling Fault. South of the Swan River, flow-channels 5 to 8 all originate along the eastern margin of the coastal plain where recharge occurs by downward leakage from the superficial aquifer. The direction of groundwater flow, north of the Swan River, is generally to the southwest, except beneath the Swan Valley where some flow is to the southeast; south of the Swan River groundwater flow is westward. The quantity of groundwater throughflow (Q), for the areas unaffected by abstraction, is considered to be equal to the amount of inflowing groundwater plus groundwater recharge minus the discharge (Table 27).

The Leederville aquifer is a multilayered aquifer consisting of discontinuous interbedded sandstones, siltstones and shales in the general proportion of 50% sandstone to 50% siltstone plus shale. As a consequence, the average horizontal hydraulic conductivity of the aquifer will be substantially less than the local hydraulic conductivity of individual sandstone beds, depending on the degree of interconnection of the beds. If the sandstone beds are laterally extensive and continuous, the average hydraulic conductivity of the aquifer will be about half the hydraulic conductivity of the sandstone, which constitutes 50% of the aquifer. However, if the sandstone beds are laterally discontinuous, the regional hydraulic conductivity could approach the hydraulic conductivity of the siltstone and shale beds (Marsily, 1986; Fig. 38, equations 11 and 12).

The horizontal hydraulic conductivity of sandstone beds in the Leederville aquifer, derived from pumping tests (Smith, 1979), is about 10 m/d, and that of the siltstone and shale beds is assumed to be about 1×10^{-6} m/d. If the interbedded sandstones, siltstones and shales are laterally extensive, the average horizontal hydraulic conductivity of the aquifer will approach 5 m/d (as the sandstones constitute approximately half the aquifer thickness). However, if the interbedded lenses are laterally discontinuous over short distances, the average hydraulic conductivity of the aquifer will approach 1×10^{-6} m/d (the local hydraulic conductivity of the siltstones and shales).

Average horizontal hydraulic conductivities of the aquifer have been calculated for each flownet cell, in areas unaffected by abstraction, by dividing the transmissivity values, which are determined using the throughflow values from Table 27 and equation (5), by the aquifer thickness. North of the Swan River the average hydraulic conductivity values vary between 1 and 9 m/d (average 1.5 m/d) and south of the Swan River they vary between 0.2 and 0.6 m/d (average 0.5 m/d). As these values approach the hydraulic conductivity of individual sandstone beds, it is inferred that the sandstones are reasonably extensive.

The resultant transmissivities of the Leederville aquifer are shown on Plate 65. In areas of groundwater abstraction from the Leederville aquifer the throughflow has been determined using equation (5) and the average hydraulic conductivities for north and south of the Swan River. For each of these areas, the difference



Harmonic mean if the sedimentary beds are in series:

$$\frac{\Sigma l_1}{k \text{ mean}} = \Sigma \frac{l_1}{k_1} \quad \text{(11)}$$

Arithmetic mean if the sedimentary beds are in parallel:

$$k \text{ mean } \Sigma b_1 = \Sigma b_1 k_1 \quad \text{(12)}$$

where k = horizontal hydraulic conductiviity (m/d)
l = length of sedimentary bed in flow direciton (m)
b = thickness of sedimentary bed (m)

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Figure 38. Horizontal hydraulic conductivities of multilayered aquifers

between incoming and outgoing groundwater is attributed to apparent abstraction (a), given in Table 27. The total net groundwater outflow, based on recharge estimates using a vertical hydraulic conductivity of 5 x 10^{-4} m/d and estimated transmissivities from Plate 65, is 29 150 m^3/d or 10.64 x 10^6 m^3/year (19 400 m^3/d north of the Swan River and 9750 m^3/d south of the river). Under present conditions of abstraction, this is equivalent to an average groundwater outflow of about 250 m^3/d per kilometre width of flow-channel.

The rate of groundwater flow through the Leederville aquifer has been determined by using equation (2) and assuming an average effective porosity of 0.2 (Table 28). North of the Swan River the average flow rate is about 4 m/year and south of the river it is about 1 m/year. That the flow rates in the north are slightly greater than the 1 m/year determined by ^{14}C dating of the groundwater (Thorpe and Davidson, 1991) is due to the effects of abstraction inducing steeper hydraulic gradients within the aquifer. For areas in the south where there is no abstraction, the flow rates of about 1 m/year are consistent with those determined by ^{14}C dating.

Groundwater discharge

Groundwater in the Leederville aquifer flows westward and eventually discharges offshore into the ocean via the superficial formations. Onshore, some groundwater in the Leederville aquifer discharges into the superficial aquifer where the Kardinya Shale Member is absent and where there are increasing heads with depth and upward hydraulic gradients (Plate 64). A total of about 11 250 m^3/d (4.11 x 10^6 m^3/year) of groundwater discharges into the superficial aquifer with approximately 4850 m^3/d discharging from the aquifer north of the Swan River and 6400 m^3/d discharging south of the river (Table 27).

Beneath the Perth area where the Cretaceous sediments have been eroded prior to the deposition of the Kings Park Formation, approximately 2000 m^3/d of groundwater discharge, by lateral flow, into the sandstone beds of the Kings Park Formation (Mullaloo Sandstone and Como Sandstone Members). Groundwater discharge to the Kings Park Formation depends on the level of groundwater abstraction from the Leederville aquifer adjacent to the discharge area. This is because the effects of abstraction will induce groundwater flow to the abstraction area and away from the discharge area. Beneath the Rockingham area where the Leederville Formation has been eroded to a depth of about 100 m prior to the deposition of the Rockingham Sand, approximately half of the groundwater throughflow in flow-channel 8 (3300 m^3/d) discharges into the Rockingham aquifer over a saltwater interface. The remaining 3300 m^3/d of the groundwater throughflow flow westward beneath the Rockingham Sand to discharge eventually offshore.

Table 28. Leederville aquifer — estimates of groundwater flow velocity (m/year)

Potentiometric contours (m AHD)	*Flow-channels*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
	North of Swan River					*South of Swan River*		
60	4.24	1.47	2.46	3.65				
50	9.44	2.43	2.12	6.31				
40	5.21	3.29	2.58	7.30				
30	3.65	2.45	3.13	6.57				
20	2.43	4.75	3.60	6.30			0.76	0.51
10							2.28	0.91
Average flow rate not weighted to area size		4.17						1.12

In areas where the South Perth Shale is absent and there are decreasing heads with depth (downward-hydraulic gradients), about 20 350 m^3/d or 7.43 x 10^6 $m^3/year$ (Table 27) of groundwater leak downwards into the Yarragadee aquifer (14 950 m^3/d north of the Swan River and 5400 m^3/d south of the river).

Groundwater storage

Groundwater in the Leederville aquifer is contained in the interbedded sandstones, siltstones and shales but only that which is stored in the sandstone beds is considered readily available for abstraction. The average ratio of sandstone to siltstone plus shale, calculated from gamma-ray logs of the artesian monitoring (AM) boreholes for the Leederville aquifer, is about 0.5. The highest ratio prevails where the Wanneroo Member is thickest and the lowest ratio where the Mariginiup Member is thickest. On average, the Henley Sandstone Member has a ratio of about 0.7, the Pinjar Member about 0.5, the Wanneroo Member about 0.6 and the Marginiup Member a ratio of about 0.3.

Using an average sandstone to siltstone plus shale ratio of 0.5 and multiplying by an assumed specific yield of 0.2 for the sandstone beds, the volume of unconfined groundwater held in storage within the sandstone beds of the Leederville aquifer has been estimated from the isopach maps of the Henley Sandstone Member (Plate 27) and the Leederville Formation (Plate 12). Since the Leederville aquifer is confined, the elastic storage of the sandstone beds can be estimated using an average storage coefficient of 1 x 10^{-4}. The total volume of groundwater in storage beneath the Perth Region is about 120 000 x 10^6 m^3 (elastic or confined storage is about 20 x 10^6 m^3).

Groundwater balance

The steady-state groundwater balance of the Leederville aquifer equates water entering the flow system to that leaving the system and is expressed by equation (13), with values obtained from Table 27.

$$L_D + L_U = D_U + D_D + a + Q \qquad (13)$$

where L_D = recharge by downward leakage from superficial aquifer (m^3/d)
L_U = recharge by upward leakage from Yarragadee aquifer (m^3/d)
D_U = discharge by upward leakage to superficial aquifer (m^3/d)
D_D = discharge by downward leakage to Yarragadee aquifer, (m^3/d)
a = apparent abstraction (m^3/d)
Q = net groundwater throughflow (m^3/d). Includes lateral groundwater discharge into the Rockingham and Kings Park aquifers.

For the entire Perth Region, the apparent steady-state water balance is given by

$$85\,650 + 2\,350 = 11\,200 + 20\,350 + 27\,300 + 29\,150$$

$$88\,000 = 88\,000 \text{ m}^3/\text{d (or } 32.12 \times 10^6 \text{ m}^3/\text{year).}$$

The amount of groundwater abstraction from the Leederville aquifer is about 119 700 m^3/d (Water Authority Schemes 67 100 m^3/d and other abstraction 52 600 m^3/d). This exceeds the apparent abstraction of 27 300 m^3/d by 92 400 m^3/d which will be accounted for by a changing water balance (non-steady state) resulting in lowering of potentiometric levels, particularly at abstraction areas, and induced additional leakage from the superficial aquifer in the recharge areas. Together with these changes, leakage downwards into the Yarragadee aquifer will be reduced, as will leakage upwards into the superficial aquifer, groundwater outflow from the area and discharge to the Rockingham and Kings Park aquifers. Recharge by upward leakage from the Yarragadee aquifer will be increased.

North of the Swan River the apparent steady-state water balance is given by

$$63\,350 + 2000 = 4850 + 14\,950 + 26\,150 + 19\,400$$

$$65\,350 = 65\,350 \text{ m}^3/\text{d (or } 23.85 \times 10^6 \text{ m}^3/\text{year).}$$

Total groundwater abstraction from the Leederville aquifer north of the Swan River is 101 500 m^3/d (Water Authority 63 900 m^3/d, Swan Valley irrigation and other abstraction 37 600 m^3/d). This exceeds the apparent abstraction of 26 150 m^3/d by 75 350 m^3/d and potentiometric levels will decline until a new balance is reached and steady state occurs.

South of the Swan River the apparent steady-state water balance is given by

$$22\,300 + 350 = 6350 + 5400 + 1150 + 9750$$

$$22\,650 = 22\,650 \text{ m}^3/\text{d (or } 8.27 \times 10^6 \text{ m}^3/\text{year)}.$$

Total groundwater abstraction from the Leederville aquifer south of the Swan River is 18 200 m^3/d (Water Authority 3200 m^3/d and other abstraction 15 000 m^3/d). This exceeds the apparent abstraction of 1150 m^3/d by 17 050 m^3/d and potentiometric levels will decline until a new balance is reached and steady state occurs.

Groundwater–oceanwater interface

A series of saltwater interfaces exist between ocean- and land-derived groundwater. These are mostly offshore (Fig. 39) within the Leederville aquifer, except in the Rockingham area where the groundwater discharges into the Rockingham aquifer, possibly also over a series of saltwater wedges. Assuming the onshore potentiometric gradient of the Leederville aquifer extends uniformly offshore, the saltwater interface will be about 15 km out to sea in the Guilderton area and probably less than 10 km in the Woodman Point area.

Wireline logs of offshore petroleum exploration well Quinns No. 1 (Table 29) show that the salinity of the groundwater in the Leederville aquifer increases with depth and varies between 800 and 10 000 mg/L TDS. This indicates that the saltwater interface west of Whitfords may be at least 20 km offshore.

Groundwater quality

Salinity

Groundwater from Water Authority production bores in the Leederville aquifer ranges in salinity from 176 to 2511 mg/L TDS (Table 30). In other bores, the salinity may increase to more than 10 000 mg/L (Allen, 1981a). Based on downhole resistivity logs, the groundwater salinity is generally lowest at the intake areas and increases with depth and distance from these areas. The lowest salinity groundwater (Fig. 40) is contained in the Wanneroo Member on the crest of the Pinjar Anticline. However, the salinity also varies between different beds of sand, possibly as a result of connate water being trapped within the siltstones and shales during periods of marine deposition. Oceanwater may also have been entrapped within the shales during periods of marine inundation that followed deposition of the Leederville Formation. Sludge samples and sidewall cores of the shales, when tested for siltiness between the teeth, often tasted saline, indicating that salt has been locked up within the shales. Some of this salt is gradually being released to the groundwater within the adjacent sandstone beds, causing the groundwater in the thin sandstone beds to be commonly more saline than the groundwater in the thicker sandstone beds. For these reasons, the groundwater in the Henley Sandstone, Pinjar, and Mariginiup Members is commonly more saline than that in the Wanneroo Member.

The Leederville aquifer can be divided into an upper and a lower zone according to groundwater salinity distribution. In each zone, the salinity increases with depth; for convenience, divisions of <500 mg/L, 500–1000 mg/L, 1000– 2000 mg/L, 2000–3000 mg/L, and >3000 mg/L have been mapped for each zone.

Although not entirely controlled by geology, the upper zone substantially coincides with the Henley Sandstone Member and Pinjar Member, and the lower zone with the Wanneroo and Maringiniup Members. However, these salinity divisions are not ubiquitous and, although the lower zone is pervasive, the upper zone is restricted to about 60% of the area (Plate 66). The salinity maps (Plates 67–76) show the distribution of groundwater in each salinity division, the contours on the surface of each salinity division, spot thicknesses of the salinity division, and the underlying salinity division.

The lowest salinity groundwater (<500 mg/L TDS) is found mainly in the central northern area (Plates 67 and 72), where the Wanneroo Member of the Leederville Formation lies directly beneath the superficial formations (Plate 49). Over most of this area, recharge to the Leederville aquifer occurs by downward leakage from the superficial aquifer (Plate 64). South of Perth, groundwater in the Leederville aquifer is generally more saline than it is to the north of Perth. This is because the hydraulic conductivities of the sediments of the Pinjar, Wanneroo, and Mariginiup Members in the recharge areas to the south are lower than those to the north, resulting in lower rates of recharge to the aquifer and increased salinities.

The highest salinity groundwater in the Leederville aquifer lies beneath the Rockingham Sand (Plate 11) in a saltwater interface, or mixing zone, between ocean-derived saline groundwater in the Rockingham aquifer and land-derived groundwater in the Leederville aquifer. High-salinity groundwater also occurs in areas where saline groundwater in the Yarragadee aquifer discharges upwards into the Leederville aquifer. For example, in the Kenwick area, approximately 10 km southeast of Perth, the salinity of the groundwater exceeds 3000 mg/L TDS throughout the entire thickness of the Leederville aquifer (Plates 75 and 76).

Major ions

The major ions of the analyses given in Table 30, expressed as percentage equivalents per million, are plotted on the trilinear diagram (Fig. 35). Groundwater from the Henley Sandstone, Pinjar and Wanneroo Members is generally of sodium chloride type and that from the calcareous beds of the Mariginiup Member (Plate 14) is commonly a mixture of sodium chloride, and calcium and bicarbonate types.

Bicarbonate concentrations of groundwater from the production bores range from 62 to 200 mg/L, with the highest concentration occurring in groundwater from

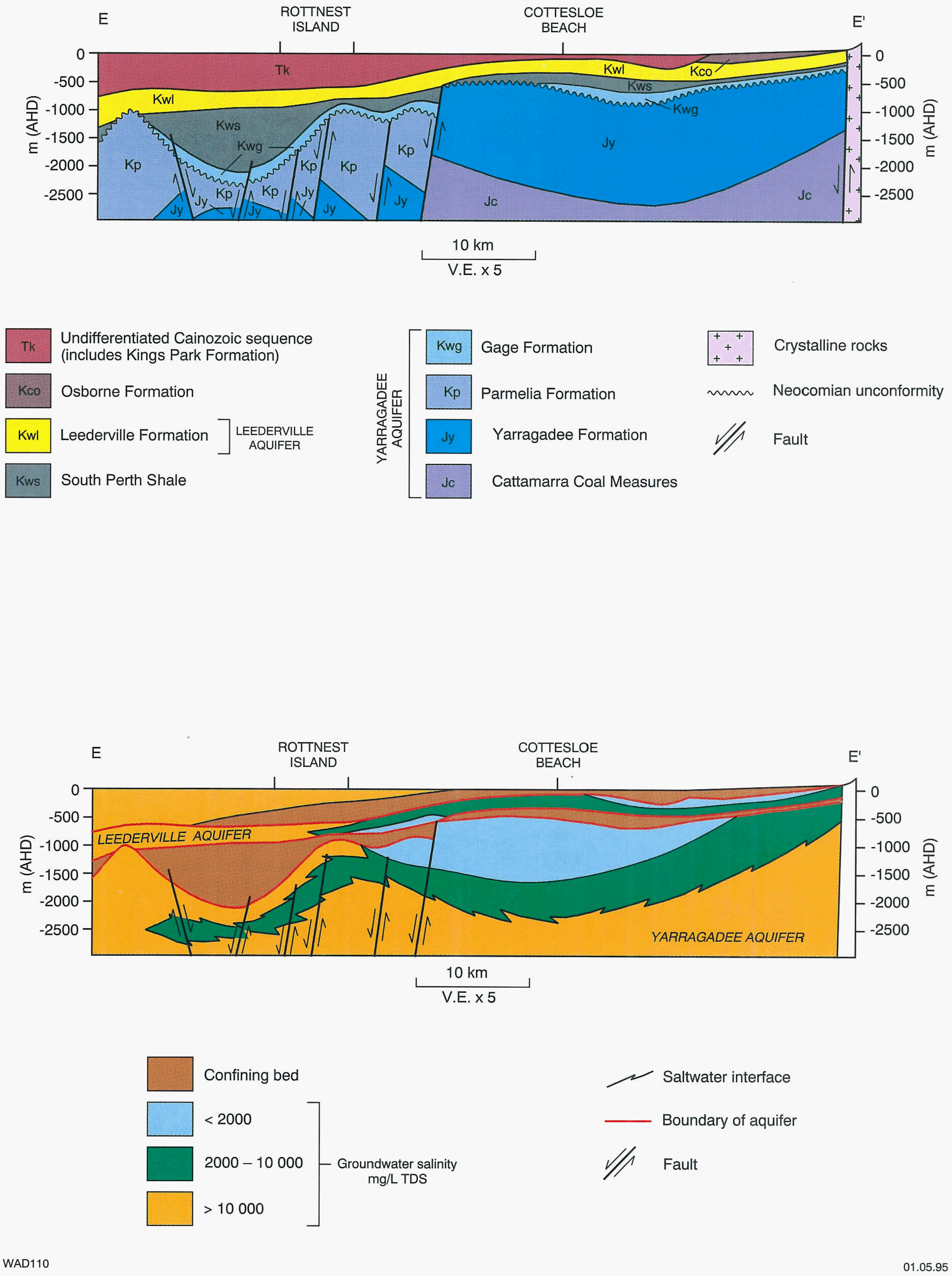

Figure 39. Confined aquifers; schematic section of groundwater–oceanwater interface

Table 29. Range of groundwater salinities (TDS) determined from offshore petroleum exploration wells (from Davidson and Mory, 1990)

Unit	*Charlotte 1*	*Gage Roads 1*	*Gage Roads 2*	*Mullaloo 1*	*Peel 1*	*Quinns Rock 1*	*Warnbro*
Leederville Formation	4 000– 28 000	25 000– 50 000	13 000– 42 000	8 500– 8 800	48 000– >50 000	800– 10 000	
Gage Formation		23 000– 36 000	28 000– 31 000	30 000– 31 000	42 000– >50 000		25 000– 29 000
Parmelia Formation		25 000– 45 000	22 000– 47 000	28 000– 38 000	15 000– >50 000	11 000– 31 000	11 000– 31 000
Yarragadee Formation	31 000– >50 000	6 000– 15 000	11 000	np	tight	28 000– 44 000	5 000– 7 500

Notes: np = not penetrated

production bore J105 in the Jandakot area, approximately 18 km south of Perth (Fig. 12). Hardness, measured as calcium carbonate concentration, ranges from 78 to 327 mg/L and, on the scale set by the Chemistry Centre, the groundwater from the production bores ranges from moderately soft to very hard, but rarely exceeds slightly hard.

The sulfate concentrations in the groundwater are naturally occurring and commonly less than 50 mg/L. The higher concentrations, 90 mg/L from bore M345 and 133 mg/L from bore J105, may be due to remnant oceanwater locked within the interbedded shales of the aquifer during periods of marine inundation.

Iron

Dissolved-iron concentrations in groundwater from the production bores range from 0.42 to 18.47 mg/L, and probably result from the presence of pyrite in the shale interbeds within the aquifer. For this reason, iron concentrations will vary greatly both laterally and with depth. However, over the Pinjar Anticline, where the Wanneroo Member directly underlies

Table 30. Leederville aquifer — chemical analyses of groundwater from production bores, 1992

Bore	*pH*	*EC mS/m @25°C*	*Temp. °C*	*TDS $-CO_2$*	*TH*	*TA*	*Ca*	*Mg*	*Na*	*K*	*CO_3*	*HCO_3*	*Cl*	*SO_4*	*NO_2*	*Fe*	*Remarks*
										mg/L							
J45	6.6	175	25	968	203	144	40	25	256	9	<0.6	175	481	20	<0.02	5.74	Jandakot
J105	7.3	456	228	511	327	165	54	47	773	28	<0.6	200	1 346	133	<0.02	0.93	"
G15	6.9	63	26	335	123	83	34	9	64	8	<0.6	101	135	5	<0.02	5.00	Gwelup
G65	6.8	85	27	442	120	73	28	12	101	9	<0.6	89	204	12	<0.02	7.40	"
G115	6.8	84	26	446	116	75	26	13	104	11	<0.6	91	205	10	<0.02	6.80	"
G135	6.4	102	29	638	121	51	18	18	166	14	<0.6	62	319	26	<0.02	18.47	"
M345	6.5	180	127	311	139	57	11	27	403	19	<0.6	70	685	90	<0.02	16.74	Mirrabooka
M285	7.0	66	25	373	78	83	16	9	93	9	<0.6	102	146	13	0.03	3.25	"
M1A	7.0	59	23	327	127	123	39	7	53	6	<0.6	150	103	3	<0.02	2.23	"
M305	7.4	49	–	260	85	–	16	11	55	8	–	–	63	3	<0.02	6.00	"
M55	6.5	154	–	785	120	65	12	21	236	16	<0.6	79	387	49	0.02	13.00	"
W85	6.5	30	23	222	87	84	28	4	26	5	<0.6	103	47	0	<0.02	2.99	Wanneroo
W25	6.5	75	23	381	90	55	18	11	96	9	<0.6	67	164	19	<0.02	11.44	"
W255	6.7	45	23	239	87	73	25	6	45	6	<0.6	89	82	3	<0.02	5.64	"
W275	6.7	28	23	176	83	80	27	4	25	5	<0.6	98	43	0	<0.02	3.15	"
W305	6.8	41	21	–	137	126	48	5	26	5	<0.6	153	46	1	<0.02	2.40	"
P25	6.6	36	21	217	81	75	24	5	34	5	<0.6	91	61	0	<0.02	4.00	"
W55	6.5	72	23	375	88	55	18	10	92	8	<0.6	67	163	18	<0.02	9.06	"
P65	6.9	46	–	300	110	–	32	7	48	6	–	–	85	1	<0.02	1.60	"
L4	7.5	190	138	192	98	146	20	12	389	17	<0.6	178	600	34	<0.02	0.42	Independent
GDWQA	6.5–8.5			1 000	500				300				400	400	10	0.3	

Notes:
GDWQA Guidelines for drinking water quality in Australia, 1987
EC Electrical conductivity
TDS Total dissolved solids by calculation at 180°C
TH Total hardness as calcium carbonate
TA Total alkalinity as calcium carbonate

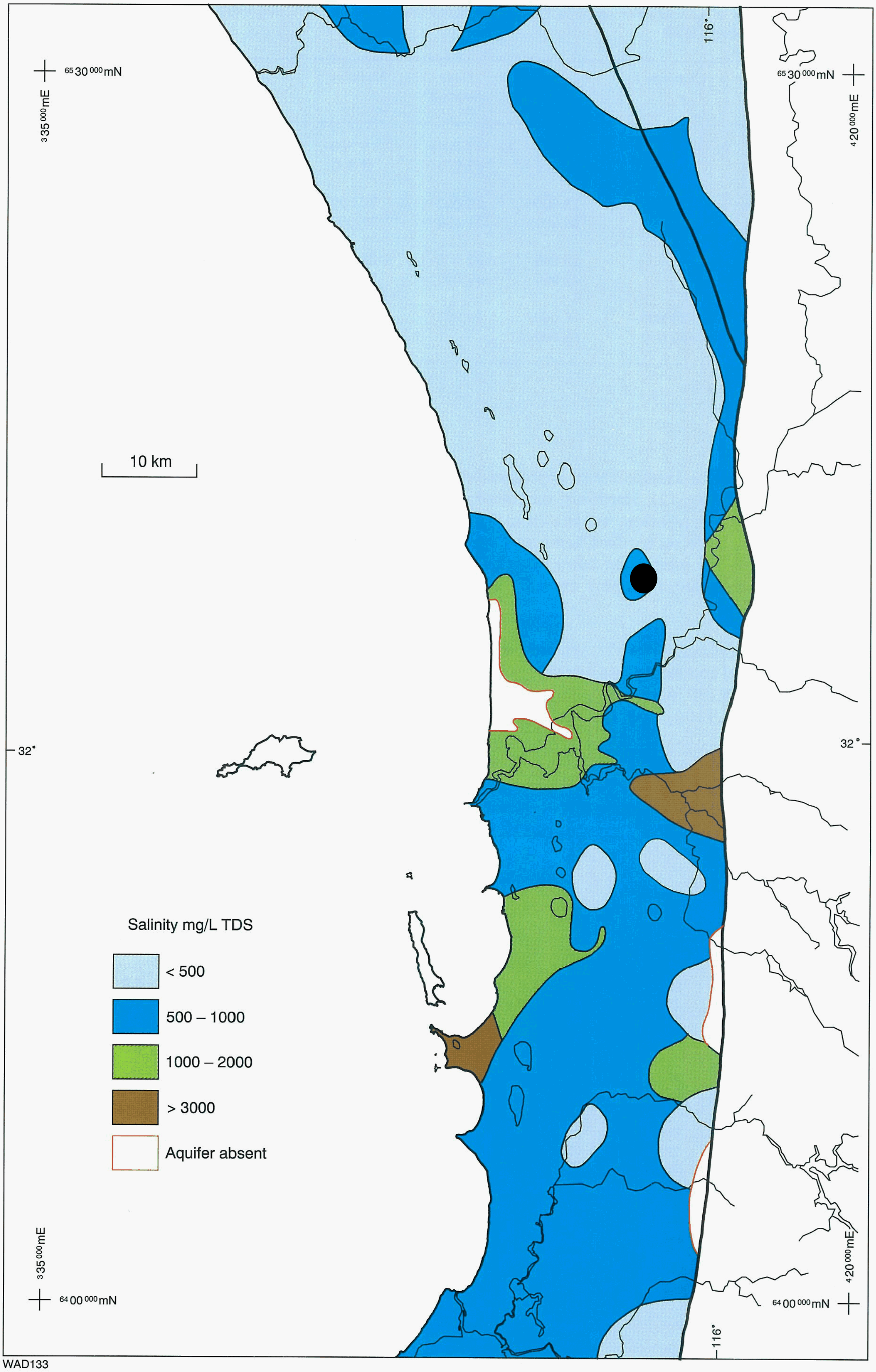

Figure 40. Leederville aquifer lowest salinity groundwater

the superficial formations, the dissolved-iron concentrations are commonly lower than elsewhere (<1 mg/L).

Groundwater from the artesian monitoring (perforated at about the middle of the aquifer) and production bores mostly contains dissolved iron at concentrations exceeding the Australian guidelines for drinking water. Treatment is therefore required before this water may be used for public water supply.

Temperature

The temperature of the groundwater in the Leederville aquifer ranges from 20 to 39°C (Table 30) but it is mostly below 30°C. However, beneath the Kings Park Formation in Water Authority production bore Leederville L4, a temperature of 38°C has been recorded. On average, the geothermal gradient is about 2.5°C per 100 m depth.

Yarragadee aquifer

The Yarragadee aquifer is a major confined aquifer underlying the entire Perth Region and extending to the north and south within the Perth Basin. It is a multi-layer aquifer, more than 2000 m thick, consisting of interbedded sandstones, siltstones and shales of the Gage Formation, Parmelia Formation, Yarragadee Formation and Cattamarra Coal Measures. Over most of the area, the Yarragadee Formation (Plate 2) is the major component of the aquifer, but in the northeastern and southern areas, the Parmelia Formation (Plate 3) and the Cattamarra Coal Measures (Plate 1) are, respectively, the major components. Only about the upper 500 m of the aquifer have been investigated by drilling.

The Yarragadee aquifer was originally referred to as the 'Claremont–South Perth horizon' (Forman, 1933) and 'Claremont Sandstone aquifer' (Berliat, 1964; Whincup, 1966). The 'City horizon' of Forman (1933) also included groundwater from the aquifer. Allen (1979) referred to it as the 'Yarragadee aquifer system', and included in it the Gage Sandstone. Allen (1979) described the Cockleshell Gully Formation as a separate aquifer, but recognized that it is juxtaposed with the Yarragadee Formation by faulting and believed the two formations to be in hydraulic continuity.

The Yarragadee aquifer is confined above by the South Perth Shale (Plate 2), where present, or by shale beds (particularly the Mariginiup Member) within the Leederville Formation. In two small areas to the southeast, where the Cattamarra Coal Measures is directly overlain by the superficial formations (Plate 1), groundwater in the Yarragadee aquifer is in hydraulic continuity with that in the superficial aquifer. Groundwater within the Yarragadee aquifer is also in hydraulic continuity with groundwater in the Leederville aquifer where the South Perth Shale is absent on the crest of the Pinjar Anticline north of Perth, and adjacent to the Darling Fault south of Perth (Fig. 41; Plate 77). The aquifer contains groundwater with downward hydraulic heads in the recharge areas (Plate 77); elsewhere, the groundwater is under pressure and has a potentiometric surface higher than the watertable in the superficial aquifer. Artesian flows can be expected from bores drilled in topographically low areas away from the intake areas.

Groundwater recharge

Groundwater recharge to the Yarragadee aquifer is by downward leakage of groundwater from the Leederville aquifer where the South Perth Shale is absent and a downward hydraulic head prevails (Plate 77). Recharge also takes place from the superficial aquifer in the southeast where the superficial formation rests directly on the Cattamarra Coal Measures (Plate 49). Unverified recharge may also occur from local streams discharging runoff from the Darling Plateau and dissipating over the southeastern margin of the coastal plain (Allen, 1979).

The rate of recharge, which can be expressed mathematically by equation (10), varies with the vertical hydraulic-head loss associated with leakage of water through the superficial aquifer and the Leederville aquifer. The recharge rate per unit area is valid for only one vertical downward-head difference at any one time, but because the seasonal variations in head difference are small, the calculated daily recharge rate for the Yarragadee aquifer is considered to be in steady state and to represent 1/365 of the annual recharge. The hydraulic-head difference (Dh) between the head in the Yarragadee aquifer (measured about 100 m below its upper surface), and that in the Leederville aquifer (measured about midway through the Leederville Formation) is shown in Plate 77. Ideally, hydraulic data from the top of the Yarragadee aquifer should be used, but this is not available. The saturated thickness (b') through which leakage is occurring is equivalent to half the thickness of the Leederville Formation plus 100 m of the Yarragadee aquifer. The average vertical hydraulic conductivity (k') has been determined from ^{14}C dating (Thorpe and Davidson, 1991) and a value of 5×10^{-4} m/d has been used for the recharge and discharge areas except beneath the Dandaragan Plateau. This value may be less than the actual value because it is based on recharge to the Yarragadee aquifer being vertical in the intake areas. In reality, the age of the groundwater in the intake areas of the Yarragadee aquifer may be a combination of younger vertical recharge groundwater and older throughflow groundwater. However, without suitable pumping tests and until more definitive data are available, the lesser value of vertical hydraulic conductivity is considered satisfactory for the current regional appraisal. Beneath the Dandaragan Plateau, where thick shales occur in the Parmelia Formation, a vertical hydraulic conductivity of 1×10^{-6} m/d is assumed. The shale of the South Perth Shale is also assumed to have a vertical hydraulic conductivity of 1×10^{-6} m/d. Consequently, groundwater leakage through these shales is considered insignificant.

The area of the Yarragadee aquifer has been divided into seven individual groundwater flow-channels (Fig. 41; Plate 77) with flow-channels 1 to 4 mostly occupying the

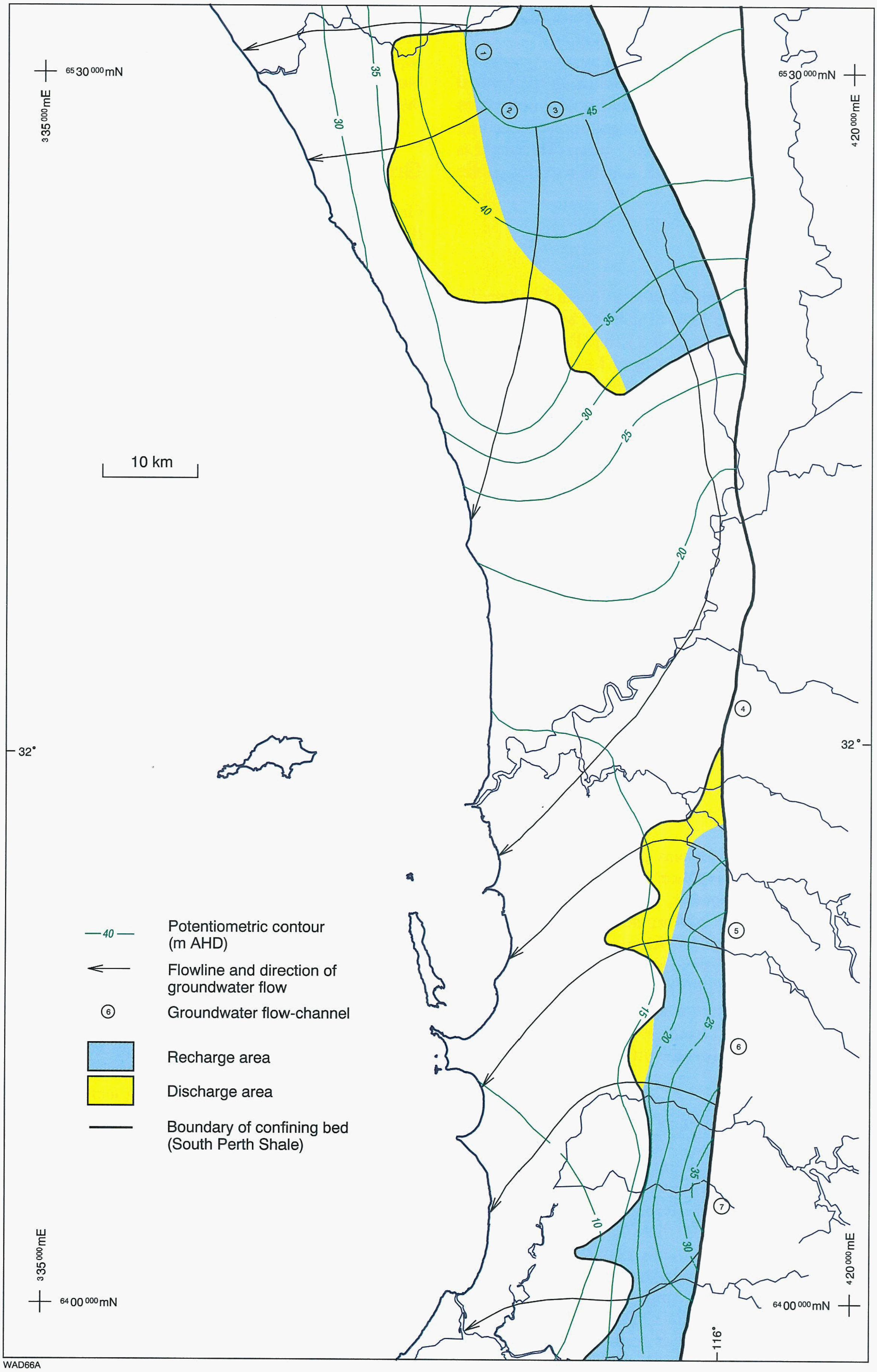

Figure 41. Yarragadee aquifer groundwater flownet: September – October 1992

Table 31. Yarragadee aquifer — estimates of recharge and discharge (rounded to nearest 50 m^3/d)

Potentiometric contours (mAHD)		*Flow-channels*							
		1	*2*	*3*	*4*	*5*	*6*	*7*	*Total*
		Northern area				*Southern area*			
Inflow	L_D	1 000	2 500	2 000	500				6 000
40	L_D	50	500	2 750	2 150				5 450
	D_U	450	200	–	–				650
	Q	600	2 800	4 750	2 650				10 800
35	L_D	–	50	1 450	1 500			1 000	4 000
	D_U	350	1 850	150	–			–	2 350
	Q	250	1 000	6 050	4 150			1 000	12450
30	L_D			400	800			1 900	3 100
	D_U			50	–			–	50
	Q			6 400	4 950			2 900	14 250
25	L_D			150	50	200	1 350	1 850	3 600
	D_U			50	–	–	–	–	50
	Q			6 500	5 000	200	1 350	4 750	17 800
20	L_D				–	200	650	450	1 300
	D_U				–	50	–	–	50
	Q				5 000	350	2 000	5 200	12 550
15	L_D				50	100	100	200	450
	D_U				50	150	50	–	250
	Q				5 000	300	2 050	5400	12 750
10	L_D							50	50
	D_U							–	–
	Q							5 450	5 450
Total	L_D	**15 900**				**8 050**			**23 950**
Total	D_U	**3 150**				**250**			**3 400**

Notes: L_D = Recharge by downward leakage from superficial and Leederville aquifers, m^3/d.
D_U = Discharge by upward leakage into the Leederville aquifer, m^3/d.
Q = Net groundwater throughflow, m^3/d.

area north of Perth and flow-channels 5 to 7 occupying the southern area. From hydraulic data and using equation (10), total recharge to the Yarragadee aquifer, within the flownet area, is about 23 950 m^3/d or 8.74 x 10^6 m^3/year (north of Perth 15 900 m^3/d including 6000 m^3/d inflow from the north, and south of Perth 8050 m^3/d; Table 31). Within the area of the Leederville aquifer flownet (Plate 64) 20 350 m^3/d of groundwater recharge the Yarragadee aquifer by downward leakage.

Groundwater flow

The regional groundwater flow within the Yarragadee aquifer is southwestward (Fig. 41), based on the configuration of the potentiometric surface for September–October 1992 and the delineation of the seven separate groundwater flow-channels. Groundwater flow in flow-channels 1 to 4 originates to the northeast of the Perth Region, beneath the Swan Coastal Plain and the Dandaragan Plateau. Flow-channel 4 also receives some groundwater recharge from the east, adjacent to the Darling Fault. Flow-channels 5 to 7, all originate at the Darling Fault where it is believed that the Yarragadee aquifer does not overlap the fault. The potentiometric surface is generally 10 to 20 m higher north of Perth than it is south of Perth, reflecting the effect of the regional topography and elevations of the watertable within the respective recharge areas.

Throughout, particularly in the southern area, the gradient on the potentiometric surface is relatively flat, indicating that the rate of groundwater movement is very slow. Variation of the potentiometric surface is approximately in phase with rainfall and, seasonally, less than one metre. However, in areas of groundwater abstraction from the Yarragadee aquifer, the seasonal variations in potentiometric levels may reach 7 m. The configuration of the potentiometric surface near Perth is uncertain because of lack of data where the Kings Park Formation occupies a deep channel eroded into the Yarragadee Formation.

It is likely that most of the groundwater flow occurs in the top part of the aquifer, at least in the top 500 m; beneath this depth, the increasing groundwater salinity indicates a lack of flushing, implying limited groundwater flow. Groundwater in the Yarragadee aquifer enters the Perth Region as throughflow from north of Gingin. The volume of this groundwater flow is not known but is probably about twice the recharge occurring northeast of the 45 m potentiometric contour (Fig 41) within the Perth Region, and in the order of 6000 m^3/d. The quantity of groundwater throughflow (Q) is considered to be equal to the amount of groundwater inflow plus groundwater recharge minus the discharge (Table 31). The total net groundwater throughflow, based on recharge and discharge estimates and using a vertical hydraulic conductivity of 5×10^{-4} m/d is 23 950 m^3/d or 8.74×10^6 m^3/year (15 900 m^3/d through flow-channels 1 to 4 and 8050 m^3/d through flow-channels 5 to 7).

The multilayered Yarragadee aquifer consists of discontinuous interbedded sandstones, siltstones and shales in the general proportion of 50% sandstone to 50% siltstone plus shale. As a consequence of the lensing nature of the interbedded sandstones, siltstones and shales, the average horizontal hydraulic conductivity will range between 1×10^{-6} m/d (harmonic mean, equation (11)) and 6 m/d (arithmetic mean, equation (12)). Because no suitable pumping tests have been carried out on the Yarragadee aquifer, the transmissivity values of the aquifer for each flownet cell, unaffected by abstraction, have been determined using the throughflow values from Table 31 and equation (5). These were divided by 500 (assumed effective thickness in metres of the aquifer) to obtain the average horizontal hydraulic conductivities (0.03 and 3.0 m/d) of the aquifer. In areas of groundwater abstraction from the Yarragadee aquifer the throughflow has been determined using equation (5) and an average regional hydraulic conductivity of 0.7 m/d. Future pumping tests may indicate that the horizontal hydraulic conductivity is an order of magnitude greater than the estimated regional value of 0.7 m/d. However, these pumping-test values will represent the hydraulic conductivity values for local sandstone beds or lenses and will be affected by the cumulative and opposing effects of boundary conditions due to the shale beds and leaky artesian conditions provided by the interbedded siltstones. In determining regional groundwater throughflow, the regional estimated value of 0.7 m/d is probably realistic.

The average rate of groundwater flow through the Yarragadee aquifer is about 0.9 m/year (Table 32) and has been determined using equation (2) and by assuming an average effective porosity of 0.2. This value confirms the very slow rate of flow, of less than 1 m/year, predicted by the ^{14}C dating of the groundwater (Thorpe and Davidson, 1991).

Groundwater discharge

Groundwater discharges from the Yarragadee aquifer into the Leederville aquifer in areas where there are upward hydraulic-head differentials and where the confining South Perth Shale is absent (Plate 77). This discharge has been estimated using equation (10), an average vertical hydraulic conductivity of 5×10^{-4} m/d for the sediments between the middle of the Leederville Formation and 100 m below the top of the Yarragadee aquifer, and the head differentials given in Plate 77. The total onshore upward groundwater discharge from the Yarragadee aquifer into the Leederville aquifer and within the Yarragadee aquifer flownet area is 3400 m^3/d or 1.24×10^6 m^3/year (3150 m^3/d north of Perth and 250 m^3/d south of Perth). Within the area bounded by the Leederville aquifer flownet (Plate 64), about 2350 m^3/d of groundwater discharges upwards from the Yarragadee aquifer into the Leederville aquifer. Most of the groundwater throughflow in the Yarragadee aquifer discharges offshore, possibly over a series of saltwater wedges, into the overlying strata.

Near Perth, some of the groundwater in the Yarragadee aquifer discharges into sandy beds of the Como Sandstone Member within the Kings Park Formation, and possibly into the Leederville aquifer (Allen, 1981a) along the contact margin of the Kings Park Formation (Plate 46).

Groundwater storage

There is a very large volume of fresh to saline groundwater in storage within the Yarragadee aquifer beneath the Perth Region. However, the groundwater is fresh only in the intake areas, where salinity is less than 1000 mg/L TDS to depths of about 500 m below the top of the aquifer. In the Wanneroo area, production bore W257 was drilled 293 m into the Yarragadee aquifer and, at a depth of 1108 m (528 m below the base of the Leederville Formation), the bore had not fully penetrated the fresh-groundwater zone. Away from the intake areas, the groundwater becomes increasingly brackish.

Based on a sandstone to siltstone plus shale ratio of 1:1, an assumed specific yield of 0.2 for the sandstone beds, and an average thickness of 500 m for the aquifer, there are about 180 000 x 10^6 m^3 of groundwater in storage. Of this total approximately 76 000 x 10^6 m^3 are fresh and less than 1000 mg/L TDS (north of Perth, 57 000 x 10^6 m^3 and south of Perth, 19 000 x 10^6 m^3). Since the Yarragadee aquifer is confined, the elastic storage of the sandstone beds can be estimated using an average storage coefficient of 1×10^{-4}. Total groundwater held in elastic storage is about 100 x 10^6 m^3 (fresh, 40 x 10^6 m^3 and brackish, 60 x 10^6 m^3).

Groundwater balance

The steady-state groundwater balance of the Yarragadee aquifer equates water entering the flow system to that leaving the flow system and is expressed by equation (14) with values obtained from Table 31.

$$L_D = Q + D_U + a \quad (14)$$

where L_D = recharge by downward leakage from overlying aquifer and within the area bounded by the Yarragadee aquifer flownet, plus inflow from the north (m^3/d)
Q = groundwater flow (m^3/d)
D_U = discharge by upward leakage into overlying aquifer (m^3/d)
a = Water Authority abstraction (m^3/d) (Table 6)

Table 32. Yarragadee aquifer — estimates of groundwater-flow velocity (m/year)

Potentiometric contours (m AHD)	*Flow-channels*						
	1	*2*	*3*	*4*	*5*	*6*	*7*
40	0.15	0.64	1.73	0.69			
35	0.05	0.11	0.90	1.51			
30			0.89	2.13			0.71
25			0.84	3.65			0.82
20					0.13	0.47	0.82
15					0.10	0.48	0.84
Average flow rate not weighted to area size:			0.88/m/year				

From equation (14)

$$23\,950(L_D) = 20\,550(Q) + 3400(D_U) + 34\,300(a).$$

This means that steady-state has not been attained and that abstraction exceeds throughflow by more than 13 750 m^3/d if private abstraction is also considered. Because equilibrium has not been obtained, the potentiometric levels will continue to decline, particularly within the abstraction areas, until additional induced leakage satisfies abstraction. During this adjustment period, it can be expected that leakage upwards from the Yarragadee aquifer into the Leederville aquifer will be reduced and that the groundwater outflow from the area will also be reduced.

Groundwater quality

Salinity

Groundwater in the Yarragadee aquifer ranges in salinity from about 140 to more than 10 000 mg/L TDS. Groundwater of salinity less than 1000 mg/L only occurs in the Yarragadee aquifer in a north–south elongate strip approximately coincident with the crest of the Pinjar Anticline, and in the southeastern area of the Cattamarra Coal Measures adjacent to the Darling Fault (Fig. 42; Plate 78). In the Wanneroo area the salinity of the groundwater in the Yarragadee aquifer is less than 500 mg/L to a depth greater than 1100 m below ground-level (production bore W257). Elsewhere, in areas of greater thickness of Pinjar and Mariginiup Members, the salinity of the groundwater typically increases with increasing depth and in the direction of groundwater flow.

Groundwater of low salinity may extend more than 20 km offshore from the central Perth Region. From electric logs of offshore petroleum exploration wells shown in Figure 25, the salinity of the groundwater in the Yarragadee aquifer may be about 6000 mg/L TDS in the Yarragadee Formation at Gage Roads No. 1 well (Table 29). This suggests that the salinity of the groundwater in the Yarragadee aquifer gradually increases in a westerly direction and that beneath Rottnest Island it could conceivably be less than 1000 mg/L TDS. However, this will depend on the influence of the offshore faults (Figs 25 and 39) on groundwater flow within the Yarragadee aquifer.

Major ions

The major ions of the analyses given in Table 33, expressed as percentage equivalents per million, are plotted on the trilinear diagram (Fig. 35). Groundwater in the Yarragadee aquifer is generally of sodium chloride type, indicating that most recharge to the aquifer occurs in areas where the overlying calcareous cemented units of the Leederville Formation are absent. There is some recharge, however, through these cemented units and, in these areas, the groundwater is a mixture of sodium chloride, and calcium and bicarbonate types.

Based on the hardness standards set by the Chemistry Centre, the groundwater in the Yarragadee aquifer is considered to be generally very soft to moderately soft.

The sulfate concentrations in the groundwater are all less than 50 mg/L (Table 33) and are naturally occurring.

Iron

Groundwater from the Gage, Parmelia and Yarragadee Formations of the Yarragadee aquifer typically contains very low concentrations of dissolved iron and thus rarely requires treatment before being used for public water supplies. However, groundwater from the Cattamarra Coal Measures contains dissolved iron at concentrations exceeding the guidelines for drinking-water quality in Australia and therefore requires treatment.

The variations in dissolved-iron concentration within the groundwater of the Yarragadee aquifer are mostly due to variations in lithology of the overlying geological units.Where pyrite commonly occurs in the shale interbeds of the Leederville Formation, and in areas of downward hydraulic heads, groundwater in the Yarragadee aquifer may contain relatively high concentrations of dissolved iron. Since pyrite may occur at any level within the Leederville Formation, it cannot be satisfactorily mapped but, as a generalization, it exists mostly within the cemented zones of the Mariginiup Member (Plate 14).

Temperature

The temperature of the groundwater in the Yarragadee aquifer ranges from 28 to 45°C (Table 33) and averages

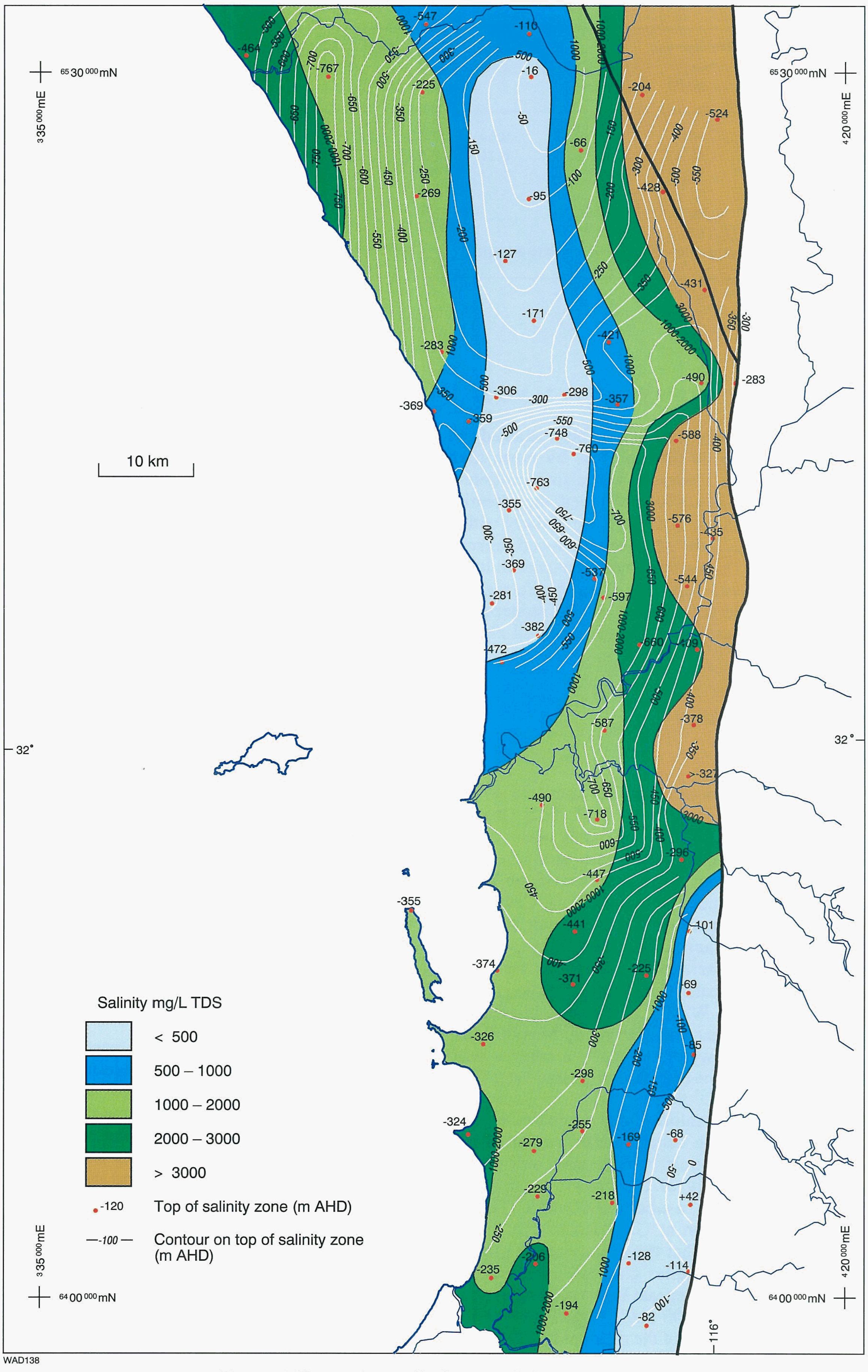

Figure 42. Yarragadee aquifer lowest salinity groundwater

about 39°C. The thermal gradient is about 2.5°C per 100 m depth but temperatures are unlikely to exceed 100°C (Bestow, 1982) because the maximum depth to the base of the aquifer, within the Perth Region, is about 3000 m. This results in a temperature of about 95°C (20°C at the watertable plus 75°C due to 3000 m depth of aquifer). The highest temperature groundwater lies beneath the Kings Park Formation in the central Perth Region.

Table 33. Yarragadee aquifer — chemical analyses of groundwater from production bores, 1992

Bore	*pH*	*EC mS/m @25°C*	*Temp. °C*	*TDS $-CO_2$*	*TH*	*TA*	*Ca*	*Mg*	*Na*	*K*	*CO_3*	*HCO_3*	*Cl*	*SO_4*	*NO_3*	*Fe*	*Remarks*
										mg/L							
P17	7.5	23	28	143	45	65	14	2	27	4	<0.6	79	27	3	<0.02	0.02	Wanneroo
W257	8.0	29	40	177	19	90	6	1	53	3	<0.6	109	32	0	<0.02	0.04	"
M2	7.8	120	36	662	57	116	13	6	217	8	<0.6	140	304	18	<0.02	0.04	"
Y1	7.7	184	39	1 014	65	141	14	7	344	12	<0.6	171	499	27	<0.02	0.08	"
Y2	7.8	135	37	740	42	134	8	5	256	9	<0.6	163	326	26	<0.02	0.07	"
B2	7.6	134	40	730	53	147	12	6	248	10	<0.6	178	322	18	<0.02	0.07	"
A	7.5	163	38	1 225	82	152	17	10	415	13	<0.6	185	614	38	<0.02	0.17	"
MB2	7.6	237	39	1 309	114	162	25	13	435	14	<0.6	197	662	39	<0.02	0.19	"
B1	7.7		42	681	50	143	11	5	234	11	<0.6	173	291	15	<0.02	0.06	"
BP1	7.4	128	43	714	67	172	10	10	231	18	<0.6	209	302	13	<0.02	0.34	"
BP2	7.4	104	45	760	60	187	8	9	253	18	<0.6	228	316	11	<0.02	0.25	"
L1	7.7	121	40	832	61	138	13	7	301	14	<0.6	167	360	24	<0.02	0.04	"
L2	7.7	245	41	1 363	121	151	27	13	441	17	<0.6	183	703	39	<0.02	0.1	"
L5	7.6	160	42	840	55		11	7	290	11			390	28	<0.02	0.09	"
CG2	6.7	104		547	89	72	6	18	158	17	<2	88	249	32	<0.02	6.6	"
GDWQA				1 000	500				300				400	400	10	0.3	

Notes:	GDWQA	Guidelines for drinking water quality in Australia, 1987	
	EC	Electrical conductivity	
	TDS	Total dissolved solids by calculation at 180°C	

TH	Total hardness as calcium carbonate
TA	Total alkalinity as calcium carbonate

Groundwater resources

The most significant and extensively exploited groundwater resources of the Perth Region are contained within the superficial, Mirrabooka, Leederville, and Yarragadee aquifers. Useful local supplies of groundwater are also obtained for private use from the Rockingham and Kings Park aquifers.

The potential groundwater abstraction within the Perth Region can be considered relative to the four major water-balance components of recharge, throughflow, discharge, and storage. Estimates of the magnitude of these can be used to establish principles for groundwater management. However, it is not possible to exploit one of these components without affecting the others. For example, abstraction of groundwater will cause local lowering of waterlevels around pumping bores and steepening of hydraulic gradients towards the areas of abstraction. These changes in hydraulic gradient will propagate to the recharge areas, inducing additional recharge and causing increased groundwater flow to the pumping bores. Irrespective of the depth of the aquifer being utilized, abstraction will eventually cause some lowering of the watertable. Abstraction of groundwater from shallow bores in the unconfined superficial aquifer will cause a greater but more localized lowering of the watertable than abstraction from deeper bores in the confined aquifers. The deeper the abstraction interval the more widespread will be the effect of the abstraction, and for confined aquifers the effect may extend several kilometres from the location of abstraction.

The effects of groundwater abstraction on waterlevels depend on the abstraction rate of individual bores and on the number, location and spacing of those bores. Abstraction of groundwater from a single bore causes waterlevel drawdowns which radially diminish with increasing distance from the bore, resulting in a waterlevel cone of depression around the bore (Fig. 43). When two or more bores are situated within the radius of influence of the individual cones of depression produced by each bore, the resultant mutual drawdown from the combined effects of abstraction is equivalent to the sum of the individual drawdowns at that location (Fig. 43). The radius of the cone of depression caused by abstraction depends mainly on the type of aquifer. For unconfined aquifers, the radii of the cones of depression on the watertable are generally small (mostly less than 1 km) and localized around the point of abstraction. For confined or pressure-water aquifers, the radii of the cones of depression on the potentiometric surface are greater and, after prolonged abstraction, they eventually extend to the source of recharge, to hydraulic boundaries or to areas of groundwater discharge. Initially, the groundwater from the confined aquifer will be removed from elastic storage. However, when the potentiometric surface of a confined aquifer is lowered by abstraction to beneath the confining layer, the developing cone of depression will assume the shape of that formed within an unconfined aquifer and, thereafter, groundwater will be released by gravity drainage (dewatering).

The effects of groundwater abstraction on watertable and potentiometric levels are monitored monthly in the many hundreds of investigation bores located throughout the Perth Region (Figs 10 and 11). At some localities these data from the Leederville and Yarragadee aquifers are suspect (Wharton, 1991) and, owing to the gradual accumulation of silt within the monitoring bores, commonly show greater apparent drawdowns than might be expected. The validity of all monitoring data will, therefore, be dependent on the periodic maintenance of all investigation monitoring boreholes.

The sustainable groundwater abstraction potential may be best assessed by quantifying the additional groundwater recharge induced by reducing losses due to evapotranspiration. Depending on environmental constraints, significant gains can be achieved by clearing or altering the vegetation or by lowering the watertable a small amount. Paved areas and roof catchments also increase groundwater recharge within urban areas by channelling stormwater directly into the ground.

Superficial aquifer

Abstraction potential

The superficial aquifer of the Perth Region provides the most readily available source of groundwater to the region. Because the groundwater is of low salinity and at shallow depth, it is extensively exploited for public water supply, industry, agriculture and domestic irrigation. In areas where the watertable is less than 3 m below groundlevel (Plate 52), the superficial aquifer supports phreatophytic vegetation and wetland ecosystems.

Of the ten hydrogeological areas of the superficial aquifer (Plate 53), the most important shallow-groundwater resources are within the Gnangara Mound (North and South) and the Jandakot Mound. In the other areas, the shallow groundwater is not used for public water supply, but it is an important resource to the environment and for private use.

Recharge

Groundwater recharge to the superficial aquifer of the Perth Region is mostly from direct rainfall infiltration.

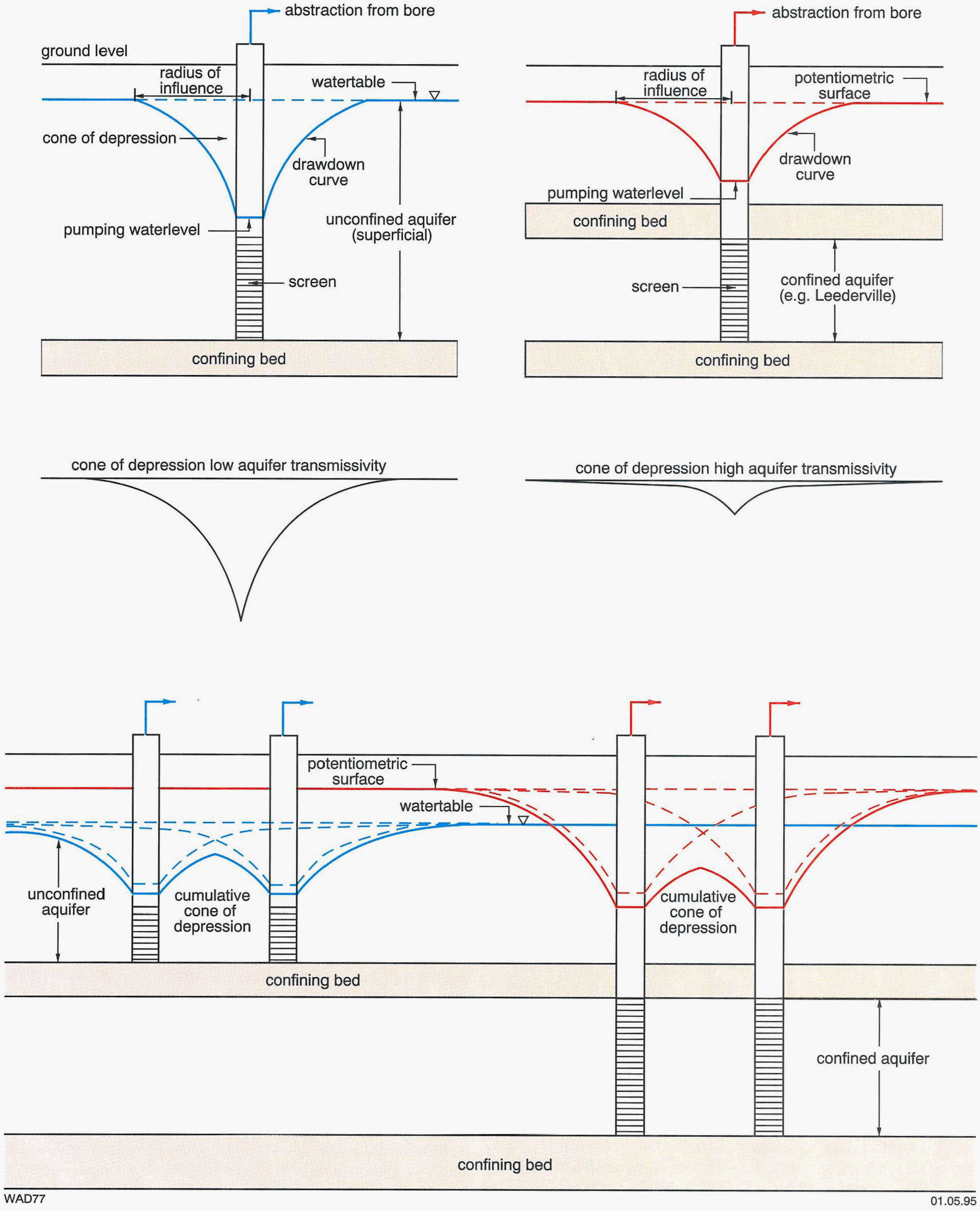

Figure 43. Effects of groundwater abstraction from bores on waterlevels

Rainfall recharge rates vary across the coastal plain (Plate 79; Tables 12–21) and are influenced mainly by rainfall intensity (Fig. 3) and distribution (Fig. 2), geology (Plate 50), depth to the watertable (Plate 52) and landuse (Fig. 9). In general, recharge rates expressed as a percentage of rainfall are

- 0–10% eastern clay area; watertable less than 6 m below groundlevel
- 5–40% central sand area; watertable generally greater than 6 m below groundlevel
- 10–25% western limestone area; watertable generally greater than 12 m below groundlevel.

The above estimates of recharge are based on the relationship of chloride concentration in rainwater to that in the groundwater, and represent the average recharge over many years. They do not represent the annual variation in recharge resulting from short-term changes in climatic conditions, of which seasonal rainfall is the dominant factor.

Seasonal variations in rainfall recharge are best illustrated by hydrographs of waterlevels from selected bores (Figs 44 and 45). The hydrographs from bores outside the State Forests and Crown Land typically show normal recharge events with the seasonal amplitude of the hydrographs varying with location and the geological environment. In the eastern clayey areas, the seasonal variations in waterlevels are generally less than 3 m, in the central sandy area less than 2 m, and in the western limestone area less than 1 m. Under present climatic conditions, the superficial aquifer in these areas appears to be in equilibrium with rainfall recharge, groundwater flow and groundwater discharge. This is evident from the hydrographs, which show no long-term trends in waterlevel decline or incline. In areas where the watertable is less than 6 m below groundlevel, it should be possible to increase rainfall recharge by slightly lowering the watertable and reducing the losses due to evapotranspiration. Figure 46 (Bestow, 1976) illustrates an empirical relationship showing that a lowering of the watertable by 1 m may result in a reduction in transpiration of about 400 mm. Considering Plate 52 and Figure 46, and by lowering the watertable a few centimetres, it should be possible to increase rainfall recharge rates to about 10% of the rainfall in the eastern area, to about 25% in the central area (but not within the State Forests and Crown Land where it appears there is currently no recharge), and to about 20% along the coast (Table 34).

Within the State Forests and Crown Land on the Gnangara Mound (North and South), the watertable hydrographs from bores (Fig. 44) show uncharacteristic declining waterlevel trends with occasional erratic seasonal variations. These declining trends are mostly due to the many years of below-average rainfall (Fig. 3). However, some of the hydrographs in Figure 44 (bores PM1, GC19, GA13 and GG4) show steady declines in waterlevels without any seasonal variations, indicating both an absence of rainfall recharge to the watertable within the area, and that the field-capacity moisture content of the surface soils has not been exceeded. Within the Perth Region and under most landuse conditions (farmland, bushland and urban), the field capacity of the soils should be exceeded each winter, particularly during the wettest months (July and August). Why the field capacity of the soils has not been exceeded over large areas of the State Forests is unclear but probably related to a combination of vegetation density, soil condition and below-average rainfall.

The percentage of rainfall recharge to the superficial aquifer is significantly influenced by vegetation density and soil condition. In some areas of extremely dense vegetation (native bushland and pine forests) most of the rainfall is intercepted above groundlevel and evaporates. That which reaches the soil surface may infiltrate into the root zone and eventually be transpired by the vegetation. Under these conditions, there may be negligible recharge to the watertable, resulting in hydrographs similar to those shown in Figure 44. Within many parts of the Perth Region, soils are water repellent, particularly in areas of sandy soils. Nonwetting, or water repellence, is a soil condition that reduces infiltration of water into the soil and is caused mainly by the hydrophobic properties of plant residue coatings on the sand grains. Water repellence is generally most severe in areas of dicotyledon (mainly flowering trees and shrubs) plant growth and less severe in areas of monocotyledon (mainly cereal and other grasses) plant growth (Upson, 1992). However, there are exceptions to this generality (Bond, 1964; McGhie, 1980; McGhie and Posner, 1981) and water repellence can develop gradually in areas of monocotyledons during prolonged hot climatic periods without rainfall. Although unverified, it is likely that water-repellent soils prevail within the State Forests and thus significantly contribute to a reduction in rainfall recharge, resulting in hydrographs similar to those shown in Figure 44.

Because of the uncertainty surrounding the lack of rainfall recharge within the State Forests and Crown Land, a long-term average of 10% of rainfall has been adopted as the groundwater recharge rate for these areas.

The groundwater resources of the unconfined and confined aquifers of the Perth Region are ultimately limited by rainfall recharge rates to the superficial aquifer. These rates have been shown to be influenced by climate, geology, landuse and soil condition. Under present conditions the total annual rainfall recharge to the superficial aquifer is about 343 x 10^6 m^3 but, by careful utilization of the groundwater, this value could be increased to about 557 x 10^6 m^3 (Table 34). Within the urban areas, rainfall recharge to the groundwater is enhanced by channelling stormwater into the ground via roadworks, compensation basins, stormwater sumps and roof catchments. However, in some areas, a volume of local groundwater roughly equivalent to this additional recharge is used for garden irrigation during the summer months. In other areas, a significant quantity of rainfall runoff discharges to drains and flows to rivers and the ocean. Some of this discharge could be induced to recharge the aquifer by locally lowering the watertable to provide space for additional recharge.

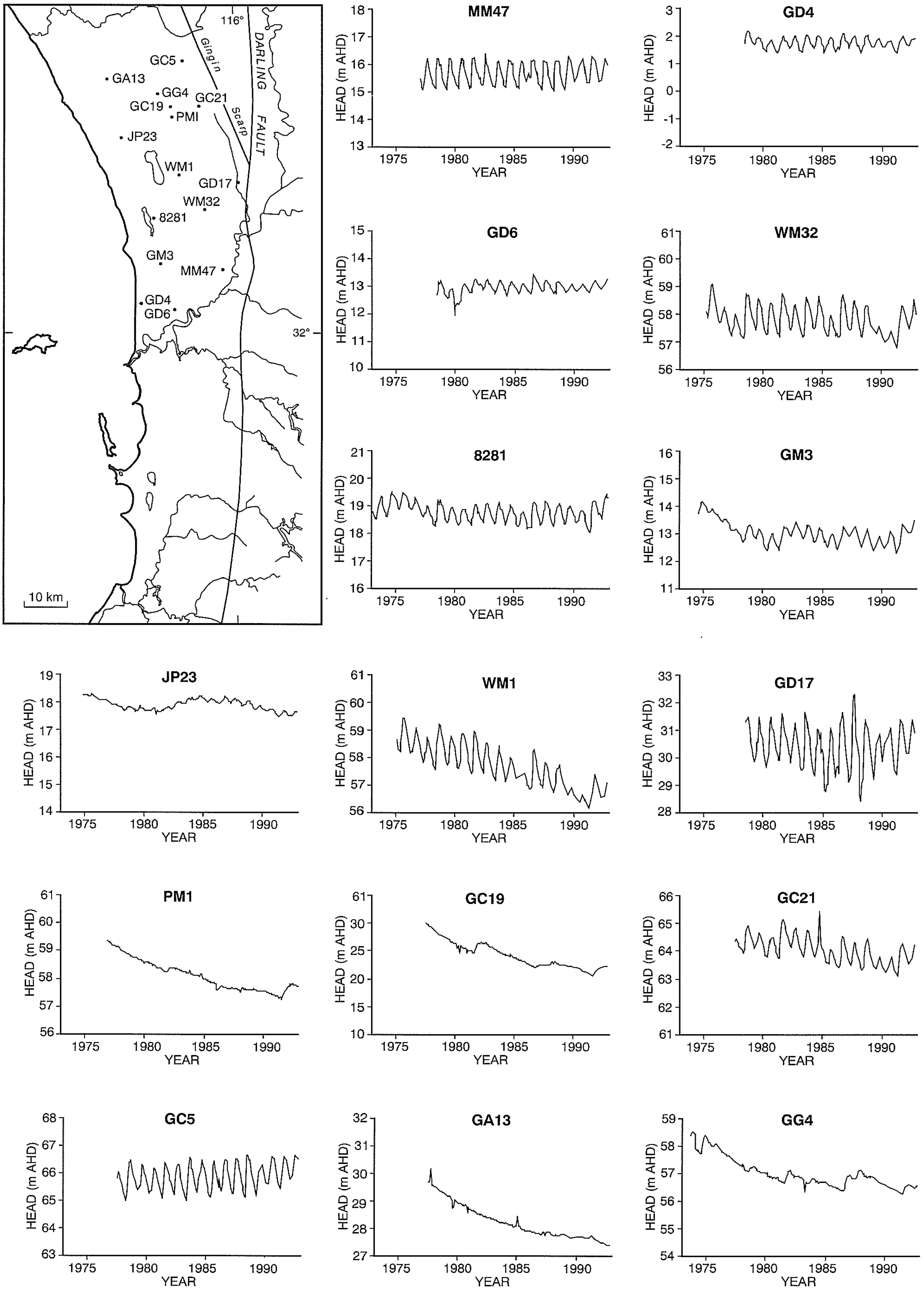

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Figure 44. Superficial aquifer watertable hydrographs from selected bores north of Perth

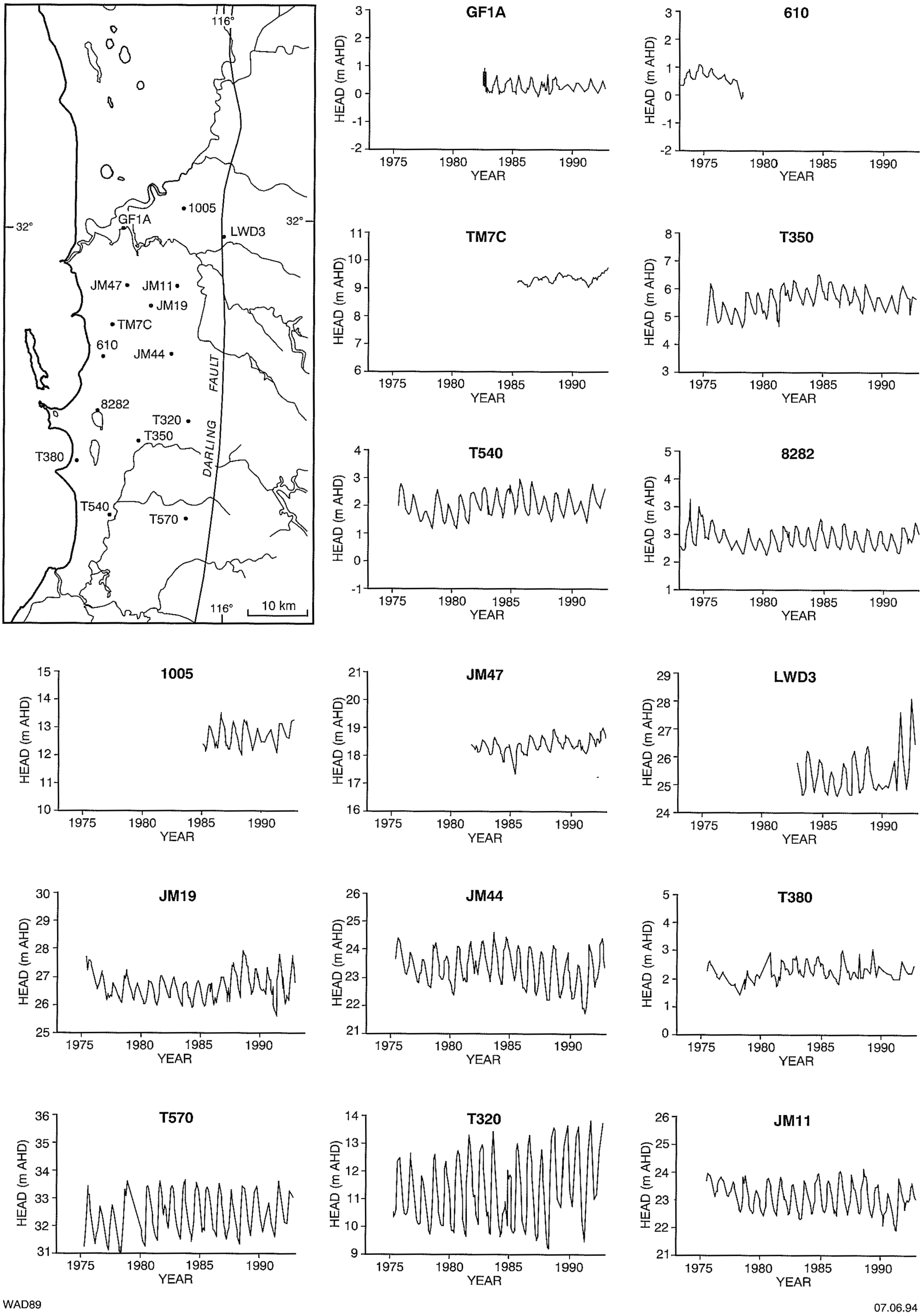

Figure 45. Superficial aquifer watertable hydrographs from selected bores south of Perth

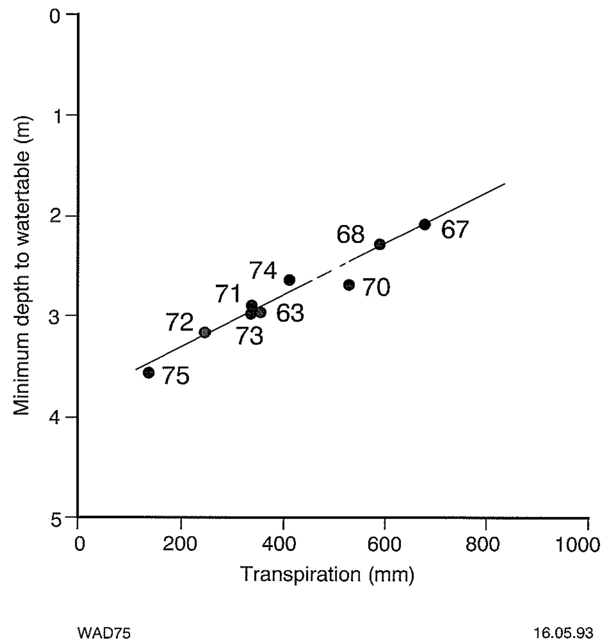

Figure 46. Superficial aquifer relationships between transpiration and minimum depth to watertable at Gnangara No 5 borehole (from Bestow, 1976)

Throughflow and discharge

Groundwater flow within the superficial aquifer is down hydraulic gradient towards the discharge boundaries at the ocean and rivers. The quantity of groundwater flow depends on the hydraulic gradient and the transmissivity of the aquifer and varies significantly from place to place and between the individual hydrogeological areas (Tables 12–21). Because the hydraulic gradient and transmissivity values are both fairly constant with respect to time, the resultant seasonal variations in groundwater flow are considered insignificant. However, in areas of groundwater abstraction, the hydraulic gradients are locally steepened and groundwater is induced to flow towards these areas. Cones of depression will develop in the watertable around groundwater abstraction bores and, in areas of shallow depth to the watertable, a small decline in waterlevel will reduce evapotranspiration losses and induce additional groundwater recharge and more throughflow. Because of this and areal variations in groundwater throughflow over the Perth Region, it is not possible to quantify the groundwater resources in terms of a single throughflow value. However, the groundwater resources can be quantified in terms of groundwater discharge at the hydraulic boundaries, excluding lakes (Table 35). It has been estimated by flownet analysis that 158.40 x $10^6 m^3$/year discharge from the superficial aquifer into the ocean and 60.54 x $10^6 m^3$/year discharge into the major water courses and associated field drains (approximately 10.26 x $10^6 m^3$/year discharge into Ellen Brook, 20.97 x $10^6 m^3$/year into the Serpentine River, 0.13 x $10^6 m^3$/year into the Murray River system, and 28.47 x $10^6 m^3$/year into the Swan/Canning River system).

The estimates of groundwater discharge are an indication of the magnitude of only one aspect of the groundwater resource of the superficial aquifer. Although in reality it would be impossible to abstract all of the discharge, it would also be unwise; particularly in areas where the groundwater discharges over a saltwater interface. To prevent the deleterious inland migration of the saltwater interface, it is advisable to maintain at least 20% of the groundwater discharge (Bestow, 1976). However, because the land adjacent to the rivers and the ocean is generally prime urban real estate requiring groundwater for irrigation, or is environmentally sensitive to changing waterlevels, about 30% of the groundwater discharge should be maintained to prevent excessive inland movement of the saltwater interface and subsequent

Table 34. Superficial aquifer — estimates of rainfall recharge (x $10^6 m^3$/year)

Hydrogeological areas	*Current recharge (Tables 12–21 and water balance)*			*Maximum potential recharge*
	Total recharge	*Recharge to underlying aquifer*	*Net recharge*	
Gnangara Mound (North)	76.44	10.86	65.58	89.86
Gnangara Mound (South)	142.97	10.22	132.75	202.32
Swan Helena	2.90	0.10	2.80	4.93
Cloverdale	5.56	0.05	5.51	15.01
Jandakot Mound	66.64	1.46	65.18	97.98
Armadale	2.77	0.62	2.15	6.16
Byford	5.64	1.50	4.14	16.04
Serpentine	23.32	8.58	14.74	88.57
Stakehill Mound	11.49	2.94	8.55	27.27
Safety Bay Mound	4.93	0.66	4.27	8.55
Total	**342.66**	**36.99**	**305.67**	**556.69**
Potential additional recharge		**214.03**		

Table 35. Superficial aquifer — estimates of groundwater outflow from flow system (x 10^6 m^3/year)

Hydrogeological area	*Ocean*	*Rivers and associated drains*					*Total*
		Gingin Brook	*Ellen Brook*	*Swan/ Canning*	*Serpentine River*	*Murray River*	
Gnangara Mound (North)	56.70	0.71	3.05	–	–	–	60.46
Gnangara Mound (South)	71.14	–	7.21	7.98	–	–	86.93
Swan Helena	–	–	–	2.39	–	–	2.39
Cloverdale	–	–	–	4.93	–	–	4.93
Jandakot Mound	24.25	–	–	11.02	2.54	–	37.81
Armadale	–	–	–	2.15	–	–	2.15
Byford	–	–	–	–	4.14	–	4.14
Serpentine	–	–	–	–	13.61	0.13	13.74
Stakehill Mound	3.50	–	–	–	0.68	–	4.18
Safety Bay Mound	2.21	–	–	–	–	–	2.21
Total	**158.40**	**0.71**	**10.26**	**28.47**	**20.97**	**0.13**	**218.94**

deterioration in quality of the groundwater used for irrigation, and to sustain the natural environment adajcent to the discharge boundaries. Based on these considerations, the total groundwater-discharge resource of the superficial aquifer is about 153 x 10^6 m^3/year.

Storage

Beneath most of the Perth Region, groundwater storage in the superficial aquifer is in steady state, with recharge balancing groundwater throughflow and discharge. In some areas of the State Forests on the Gnangara Mound (North and South), waterlevels are declining; consequently, the quantity of groundwater held in storage beneath these areas is diminishing. However, it is believed that this is a temporary trend induced by below-average rainfall and a change in soil infiltration conditions. With a return to average or above-average rainfall, waterlevels are expected to recover.

Under present climatic conditions the total quantity of groundwater held in storage within the superficial aquifer is about 25 800 x 10^6 m^3 (Table 11). This is equivalent to about 650 times the current annual abstraction from the superficial aquifer for public water supply.

Effects of abstraction

The groundwater resources of the superficial aquifer are extensively exploited by more than 80 000 shallow production bores and annually about 170 x 10^6 m^3 of groundwater are abstracted for private use. The groundwater is used for irrigation of household gardens, agricultural crops, and parks, gardens, golf courses and playing fields. During 1992, about 170 x 10^6 m^3 of groundwater were licensed for abstraction by the Water Authority. Of this, about 157 x 10^6 m^3/year were for industry and agriculture, and 13 x 10^6 m^3/year for household garden irrigation. Approximately 67 x 10^6 m^3 of unlicensed groundwater abstraction were also used for garden irrigation. The total private allocation of groundwater is therefore about 237 x 10^6 m^3/year. Of this total, 24 x 10^6 m^3/year are obtained from the confined aquifers and 213 x 10^6 m^3/year have been allocated from the superficial aquifer. However, only about 80%, or 170 x 10^6 m^3/year, of the allocation from the superficial aquifer has been utilized. The total private groundwater abstraction for 1992 was therefore 194 x 10^6 m^3 (170 x 10^6 m^3 + 24 x 10^6 m^3). From five groundwater schemes (Figs 12 and 13), the Water Authority also had 91 bores in production during 1992 and about 40 x 10^6 m^3 of groundwater from the superficial aquifer were used for public water supply (Table 36). Total groundwater abstraction from the superficial aquifer is, therefore, about 210 x 10^6 m^3/year. Depending on bore construction, individual bore yields range from less than 100 m^3/d in the clayey areas of the Guildford Clay, to 500–2000 m^3/d in the central Bassendean Sand area, to more than 10 000 m^3/d in some cavernous areas of the Tamala Limestone adjacent to the coast.

Within the urban area (Fig. 9) the total groundwater abstraction from the superficial aquifer is equivalent to about 20% of the rainfall over the area. However, by flownet analysis (Tables 12 to 21), the equivalent of about 5% of the rainfall is recycled during irrigation to become part of the groundwater throughflow. Also by flownet

Table 36. Superficial aquifer — Water Authority groundwater abstraction, 1992

Water Authority scheme	*Bores*	*Abstraction (m^3/d)*	*(m^3/year x 10^6)*
Northern area:			
Yanchep/Two Rocks	8	1 831	0.67
Pinjar	9	5 334	1.95
Wanneroo	24	36 088	13.17
Mirrabooka	27	37 662	13.75
Gwelup	10	16 992	6.20
Southern Area:			
Jandakot	13	10 965	4.00
Total	**91**	**108 872**	**39.74**

analysis, the average groundwater throughflow is equivalent to about 15% of the rainfall (Plate 80). Therefore, the total groundwater recharge within the urban areas is equivalent to about 30% (i.e. 20% – 5% + 15%) of the rainfall over the area. This apparent increase in rainfall recharge is due to the effects of urbanization. The hydrographs of bores MM47, GD4, GD6, GF1A and 1005 (Figs 44 and 45) indicate that the aquifer, within the urban areas, is in steady state with respect to rainfall recharge, groundwater flow and abstraction.

The effect of abstraction from individual bores on waterlevels, and consequently the watertable, depends on the abstraction rate and the hydraulic properties of the aquifer, of which aquifer transmissivity (Plate 55) is the most important. At an arbitrary abstraction rate of 500 m^3/d the likely drawdown of the waterlevel in a bore will be about 20 m in the eastern clayey area, less than 10 m in the sandy central area, and less than one metre in the limestone area adjacent to the coast.

The cumulative effect of groundwater abstraction on the watertable depends on the abstraction rate of individual bores and on the number, location and spacing of the bores. By using the watertable contour map (Plate 53), the transmissivity map (Plate 55) and specific yields of 0.30 (Tamala Limestone), 0.20 (Bassendean Sand and Gnangara Sand) and 0.05 (Guildford Clay), the effects of abstraction on the watertable could be computed for any combination of bore locations and abstraction rates. The computer model would need to be adjusted to compensate for a reduction in watertable drawdowns resulting from water being gained for abstraction by a reduction in drainage and evapotranspiration.

The Water Authority, with assistance from the Centre for Water Research (University of Western Australia) and the Geological Survey, developed a vertical flux (vertical flow in and out of aquifer) with aquifer flow (horizontal groundwater flow) computer-aided model as part of the Perth Urban Water Balance Study (Cargeeg et al., 1987). The main function of the model is to determine and predict the effect on the watertable of variations in climate, landuse and groundwater abstraction. This model is currently being upgraded by the Water Authority.

The effects of abstraction on the salinity of the groundwater in the superficial aquifer also depends on the location and the quantity of abstraction. Locally, some bores have shown a temporary summer increase in salinity but these mostly recover to normal salinity during winter. These bores are generally in areas of variable groundwater salinity (Plate 56), commonly in clayey areas of the Guildford Clay, and the increase in salinity is due to abstraction drawing nearby more-saline groundwater to the pumping bore. This phenomenon will inevitably be repeated each summer. Adjacent to the ocean, Swan River estuary and Peel Inlet, where groundwater discharges over a saltwater wedge, abstraction from bores may cause an inland migration or upward coning of the saltwater interface. This occurs at many localities during summer and is due mainly to the high rates of groundwater abstraction required to irrigate expansive areas of grassed parklands. Adjacent to the Swan River estuary and the lower reaches of the Canning River, abstraction from private bores for household garden irrigation has, at many localities, induced the inland movement of saline river water. During the wet winter months of the year (May to September) there is generally no irrigation in these areas and the saltwater interface recedes to almost its original position. In some areas of excessive groundwater abstraction the saltwater interface does not return to its previous winter position and thus moves farther inland each year. At some localities, the groundwater has become too saline for irrigation and bores have been temporarily abandoned. With time, and without further groundwater abstraction, the salinity of the groundwater will decrease to that of the naturally occurring groundwater.

Rockingham aquifer

Abstraction potential

The groundwater resource of the Rockingham aquifer has not been fully evaluated. Based on the flownet analyses, the annual recharge to the aquifer is about $6.42 \times 10^6 m^3$, consisting of about $5.22 \times 10^6 m^3$ downward leakage from the superficial aquifer plus $1.20 \times 10^6 m^3$ lateral discharge from the Leederville aquifer.

Groundwater flow in the Rockingham aquifer is westward over a saltwater interface and, since there are no apparent natural, onshore groundwater losses from the aquifer, the quantity of groundwater throughflow is equal to the total recharge of $6.42 \times 10^6 m^3$/year. If 30% of this throughflow is required to prevent a deleterious ingression of the saltwater interface, the groundwater resource of the Rockingham aquifer is limited to about $4.49 \times 10^6 m^3$/year. However, this value may be increased slightly if abstraction causes additional leakage from the superficial and Leederville aquifers.

Approximately $2200 \times 10^6 m^3$ of groundwater of salinity less than 1000 mg/L TDS are stored within the Rockingham aquifer.

Effects of abstraction

The groundwater resource of the Rockingham aquifer is being moderately exploited for local private use and for parkland and golf course irrigation; individual bore yields range between 1000 and 2000 m^3/d. Monitoring data from the aquifer have not indicated any decline in waterlevels at current rates of abstraction.

Fresh groundwater of salinity less than 1000 mg/L TDS overlies a saltwater interface at a depth (depending on the land elevation) of between 60 and 80 m. Excessive local abstraction may cause this saltwater interface to upcone into the base of production bores causing an increase in water salinity and rendering the bores unserviceable.

Kings Park aquifers

Abstraction potential

The groundwater resources of the Kings Park aquifers have not been evaluated and are considered to be of only local importance. The resource within the Mullaloo Sandstone Member is known to be extensively utilized for irrigation of a golf course and parklands within a 2 km radius of Perth City.

Based on current estimates of groundwater recharge to the Kings Park aquifers, a total renewable resource of about 3 x 10^6 m^3/year is available from the aquifers, though this estimate should be used with caution, as there are very few drilling data.

Effects of abstraction

A pumping test conducted on a production bore adjacent to the southern bank of the Swan River (approximately 1 km south of Perth) and screened against the Mullaloo Sandstone Member has shown that the aquifer is confined, low yielding (less than 1000 m^3/d) and of limited extent (Davidson, 1981b). During the test, the drawdown response due to pumping indicated that barrier boundary conditions are present, suggesting that the aquifer occupies a channel of limited extent. The test also showed that induced leakage into the aquifer, caused by abstraction of groundwater from the aquifer, was slow and that if abstraction is excessive, the aquifer would eventually be temporarily dewatered.

Mirrabooka aquifer

Abstraction potential

The Mirrabooka aquifer lies to the north of Perth and contains groundwater of salinity less than 500 mg/L TDS. The aquifer is recharged by groundwater leakage from the superficial aquifer. The average recharge rate is equivalent to about 2% of the rainfall over the recharge area (Plate 80), resulting in a renewable regional groundwater resource of about 6.02 x 10^6 m^3/year. Together with the induced local recharge of 5.07 x 10^6 m^3/year, equivalent to present abstraction, the total current recharge to the Mirrabooka aquifer is about 11.09 x10^6 m^3/year.

Groundwater in the Mirrabooka aquifer flows in a southeasterly to southwesterly direction; 3.80 x 10^6 m^3/year eventually discharge upwards into the superficial aquifer and 2.22 x 10^6 m^3/year discharge laterally into sand beds of the Mullaloo Sandstone Member within the Kings Park Formation.

The Mirrabooka aquifer, an important local source of groundwater for public water supply and irrigation, contains approximately 11 200 x 10^6 m^3 of groundwater in storage.

Effects of abstraction

The Water Authority has nine production bores screened against the Mirrabooka aquifer; six in the Mirrabooka Public Water Supply Area, and three in the Gwelup Area. There are three bores yet to be commissioned for production as part of the proposed Lexia groundwater scheme in the Swan Groundwater Area (Fig. 12). Under present conditions of abstraction the regional aquifer appears to be in steady state with respect to recharge, throughflow and abstraction, as indicated by the hydrographs of bores some distance from the abstraction (Fig. 47). However, even though the duration of records is very short and inadequate, the hydrograph for borehole M172 indicates a small downward trend in waterlevels near the pumping bores. This decline suggests that abstraction currently slightly exceeds groundwater throughflow within the abstraction area.

Approximately 1.93 x 10^6 m^3 (5300 m^3/d) of groundwater was abstracted from the six Mirrabooka production bores during 1992 and it is not planned to increase this rate of production. Once in production, the three additional Lexia scheme production bores will increase the abstraction from the Mirrabooka aquifer by about 2.74 x 10^6 m^3/year (7500 m^3/d) or about 2500 m^3/d per bore. Total Water Authority abstraction from the Mirrabooka aquifer in the eastern area, when all bores are operating at peak capacity, will therefore be about 4.67 x 10^6 m^3/year or 12 800 m^3/d. During 1992, there was also some 1.25 x 10^6 m^3/year (3400 m^3/d) of groundwater licensed for private abstraction in the Swan Groundwater Area.

Since the groundwater throughflow in the Mirrabooka aquifer, beneath the Mirrabooka Public Water Supply and Swan Groundwater Areas, is about 8050 m^3/d (flow-channels 3 and 4, Plate 63) and the total current abstraction is about 8700 m^3/d, the increased abstraction will see at least an extra 8150 m^3/d (8700 – 8050 + 7500) drawn from the superficial aquifer by induced downward leakage. If the saturated thickness of the superficial aquifer remains the same and the hydraulic-head difference between the superficial aquifer and the Mirrabooka aquifer is unaltered, the area (A) providing leakage required to meet the increased abstraction to each of the production bores is given by a reorganization of equation (11).

$$A = \frac{Qoa}{K'/b' \, \Delta h}$$

where A = recharge area within which vertical leakage is occurring (m^2)
Qoa = vertical leakage through overlying aquifer due to increased abstraction per production bore (2500 m^3/d)
k' = vertical hydraulic conductivity of overlying aquifer (8 x 10^{-4} m/d)
b' = saturated thickness of overlying aquifer from Plate 51 (average 40 m)
k'/b' = leakage coefficient (2 x 10^{-5}/d)
Δh = average difference between the head in the upper part of the Mirrabooka aquifer and the watertable in the superficial aquifer, September/October 1992 (3 m)

$$A = \frac{2500}{2 \times 10^{-5} \times 3} \ m^2$$

$$\approx 41.7 \ km^2$$

Assuming that flow to the pumping bores is radial and equal in all directions, the radius of influence will be about 3600 m. Since the individual bore spacings are between

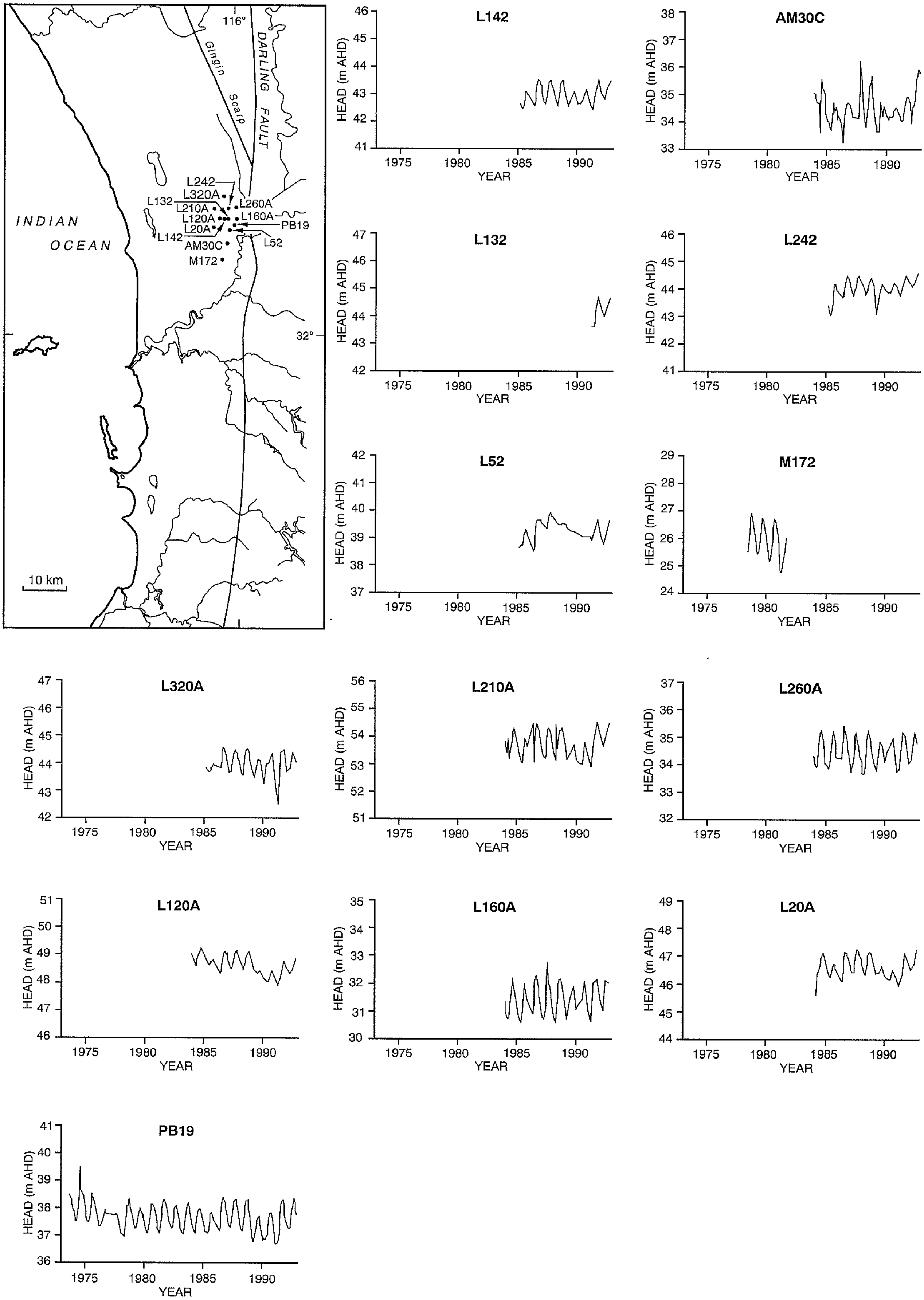

Figure 47. Mirrabooka aquifer hydrographs of potentiometric levels from bores

1000 and 3000 m there will be some overlap of areas contributing recharge by leakage. However, by assuming that the required additional leakage of 8150 m^3/d is centred around a locus, the area required to provide the leakage is 135.8 km^2 (8150/2 x 10^{-5} x 3). Over this area, most of the required additional leakage will be obtained from groundwater throughflow within flow-channels 4 and 5 (Plate 53) of the superficial aquifer. Some will come from induced rainfall recharge caused by a slight lowering of the watertable and a reduction in evapotranspiration losses. If all the required additional leakage came from induced rainfall recharge it would be equal to 3% of the rainfall (or 24 mm) over the area. However, since only about 10% of the area has a depth to the watertable of less than 4 m and because a 1 m drop in the watertable will reduce evapotranspiration by about 400 mm (Bestow, 1976; Fig. 46), a drawdown of about 0.6 m (24 x 10 x 1000/400 mm) would be required to obtain all of the required leakage from rainfall recharge. Because most of the required additional leakage will come from increased groundwater throughflow in the superficial aquifer, the resultant overall drawdown of the watertable in the eastern area will probably be less than 0.2 m. However, around pumping bores, a drawdown in the watertable of about 0.5 m may occur (Davidson, 1984b).

In the Gwelup Public Water Supply Area, three production bores in the Mirrabooka aquifer are currently operating at an annual abstraction rate of about 1.89 x 10^6 m^3/year. Because of the lack of waterlevel data, it is not possible to evaluate the effects of this abstraction on potentiometric levels in the aquifer. However, watertable levels in the superficial aquifer are reasonably stable. It is therefore believed that for the Mirrabooka aquifer the current rate of abstraction is in equilibrium with groundwater recharge due to induced leakage from the superficial aquifer, and that the rate of groundwater throughflow has remained relatively constant.

The salinity of the groundwater within the Mirrabooka aquifer is generally less than 500 mg/L TDS as is that in the superficial aquifer, from which leakage to the Mirrabooka aquifer occurs. For this reason, there has been no noticeable increase in salinities of groundwater from the Mirrabooka aquifer resulting from the effects of abstraction.

Leederville aquifer

Abstraction potential

Recharge

The Leederville aquifer is recharged by downward leakage of groundwater from the superficial aquifer in areas where the two aquifers are in direct hydraulic connection and where there are downward hydraulic heads. Under present conditions of abstraction and groundwater throughflow, the recharge to the Leederville aquifer north of the Swan River is about 23.12 x 10^6 m^3/year, and to the south of the river about 8.14 x 10^6 m^3/year, resulting in a total aquifer recharge of 31.26 x 10^6 m^3/year. These recharge estimates are equivalent to 0–10% of the rainfall over the recharge areas (Plate 81). Increased groundwater abstraction will steepen the hydraulic gradient between the superficial and Leederville aquifers and induce additional groundwater recharge to the Leederville aquifer.

Throughflow and discharge

Groundwater flow in the Leederville aquifer is mostly in a westerly direction. About 7.43 x 10^6 m^3/year leak downward into the Yarragadee aquifer, 4.11 x 10^6 m^3/year leak upward into the superficial aquifer, 1.20 x 10^6 m^3/year discharge laterally into the Rockingham aquifer and about 0.73 x 10^6 m^3/year discharge laterally into the sandy beds of the Kings Park Formation. The remainder of the groundwater flow discharges offshore into the superficial aquifer.

Storage

The Leederville aquifer is a very important source of groundwater for public water supply, irrigation and industry. A total of some 120 000 x 10^6 m^3 of groundwater is in storage within the aquifer. Of this total, about 30 000 x 10^6 m^3 are of salinity less than 1000 mg/L TDS and suitable for public water supply, 30 000 x 10^6 m^3 of salinity 1000–2000 mg/L TDS and suitable for parkland irrigation, and 60 000 x 10^6 m^3 exceed 2000 mg/L TDS and are suitable for some industrial uses or desalination. These estimates are based on an assumed specific yield of 0.2 and may be compared with a more conservative estimate of total storage (33 000 x 10^6 m^3) made by Allen (1981a), who assumed a specific yield of 0.1 and a reduced thickness for the aquifer. Regardless of the variations in these estimates, a very large volume of groundwater is held in storage within the Leederville aquifer. For comparison, the design volume of water for Lake Argyle (Ord River Dam) is about 6000 x 10^6 m^3, and that for Sydney Harbour about 1000 x 10^6 m^3.

Effects of abstraction

The Leederville aquifer is a confined aquifer of variable leakage depending on the vertical hydraulic conductivity and thickness of both the overlying and underlying confining beds, and of the interbedded siltstones and shales. Because the vertical hydraulic conductivity of the overlying Kardinya Shale Member is probably less than 1 x 10^{-6}m/d, the aquifer is almost entirely confined in areas of greatest thickness of the shale and becomes progressively more leaky towards the margins of the shale. In areas where the Leederville Formation subcrops beneath the superficial formations (Plate 49), the Leederville aquifer is leaky confined. Owing to the many interbeds of siltstone and shale within the aquifer, it becomes progressively more confined with depth.

Beneath the central Perth Region where the Leederville aquifer is confined by the Kardinya Shale Member, the drawdown effects of groundwater abstraction from the aquifer will propagate to the areas of recharge and greatest leakage. For this reason, the effects of prolonged abstraction from bores within the vicinity of Perth will result in potentiometric-level drawdowns many kilometres from the location of abstraction. The greatest drawdowns will occur at the pumping bore and will diminish with distance from the bore (Fig. 43). There are many production bores within the central Perth area and the cumulative effects of these have extended to the recharge area (Plate 54). Since steady state has not been obtained over the entire area of the Leederville aquifer, because abstraction is currently exceeding groundwater through-flow and recharge, the potentiometric heads within the aquifer are gradually declining (Figs 48 and 49; Wharton, 1991). They will continue to decline until the downward hydraulic-head difference between the superficial aquifer and the Leederville aquifer is sufficient to maintain groundwater throughflow, abstraction and steady-state conditions. However, because the watertable in the superficial aquifer is declining (Fig. 44) over much of the recharge area to the Leederville aquifer, steady-state conditions may not be attained for many years.

Total groundwater abstraction from the Leederville aquifer during 1992 was about 43.69 x 10^6 m^3, equivalent to a daily rate of about 119 700 m^3. Of this total, approximately 37.04 x 10^6 m^3 (101 500 m^3/d) were abstracted from the northern area and 6.65 x 10^6 m^3 (18 200 m^3/d) from the southern area (Table 37). Individual bore yields of more than 5000 m^3/d are common from the Leederville aquifer.

The effect of abstraction from the Leederville aquifer on the groundwater resources have been assessed for current abstraction rates and the following water-balance conditions modified from Table 27.

- Recharge by downward leakage from superficial aquifer (L_D) will increase.
- Recharge by upward leakage from Yarragadee aquifer (L_U) will reduce to zero as a result of abstraction from the Yarragadee aquifer.
- Discharge by upward leakage to the superficial aquifer (D_U) will reduce to zero as a result of abstraction from the Leederville aquifer: the present area of discharge will become a recharge area.
- Discharge by downward leakage to the Yarragadee aquifer (D_D) will increase due to abstraction from the Yarragadee aquifer.
- Groundwater storage of the Leederville aquifer will remain unaltered.

Groundwater abstracted from the Yarragadee aquifer is ultimately obtained from the Leederville aquifer by downward leakage. Thus, total recharge to the Leederville aquifer required to satisfy the current abstraction from the Leederville aquifer plus the Yarragadee aquifer in the northern area is 48.797 x 10^6 m^3/year (37.043 x 10^6 + 11.754 x 10^6; Tables 37 and 38) or about 152 350 m^3/d. Since this total abstraction is about twice the estimated 1992 recharge rate of 63 350 m^3/d (Table 27), the potentiometric surface of the Leederville aquifer will continue to decline in the recharge area until the downward hydraulic-head difference between the superficial aquifer and the Leederville aquifer is sufficient to induce the additional recharge required to satisfy the total abstraction. In the central area where most of the abstraction takes place, the rate of decline in the potentiometric surface of the Leederville aquifer is decreasing (Figs 48 and 49), indicating that groundwater abstraction and throughflow are approaching steady-state conditions. Without further increases in groundwater abstraction from the Leederville and Yarragadee aquifers, these steady-state conditions will eventually extend into the recharge area of the Leederville aquifer.

The predicted configuration of the potentiometric surface of the Leederville aquifer (Plate 82), when steady state is achieved at present abstraction rates, has been obtained by superimposing the predicted hydraulic-head difference map of the superficial aquifer and Leederville aquifer (Plate 82) on the 1992 watertable contour map (Plate 53). Over much of the northern recharge area to the Leederville aquifer, the potentiometric surface will drop, on average, about 10 m and, at the current rates of decline (Figs 48 and 49), steady-state conditions will be achieved in about 50 years.

In the southern area, the total abstraction of 10.738 x 10^6 m^3/year (Leederville aquifer 6.646 x 10^6 + Yarragadee aquifer 4.092 x 10^6; Tables 37 and 38), or about 29 400 m^3/d, is some 1.3 times the recharge rate of 22 300 m^3/d (Table 27). Consequently, the potentiometric surface of the Leederville aquifer is declining. For steady state to be obtained the potentiometric surface of the Leederville aquifer will need to drop, on average, about 10 m. At the present rates of decline, steady state should be achieved in about 50 years (as for the northern area) providing that the elevation of the watertable remains seasonally constant.

The additional recharge of 89 000 m^3/d (32.485 x 10^6 m^3/year) to the Leederville aquifer in the northern area, required to satisfy abstraction, is equivalent to about 4% of the rainfall (30 mm) over the area where the Leederville aquifer is directly overlain by the superficial aquifer. Since the depth to the watertable is less than 4 m below groundlevel over more than 10% of this area, the resultant drawdown in the watertable, due to the abstraction from the Leederville aquifer, will be less than 0.75 m (Fig. 46; i.e. 30 x 10 x 1000/400 mm). Because steady state will not occur for about 50 years, the annual drawdown in the watertable will be about 15 mm. This is less than the present rate of decline in the watertable (Fig. 44) beneath the State Forests, suggesting that the decline is mainly due to causes other than abstraction of groundwater from the Leederville and Yarragadee aquifers. By comparing the hydraulic-head differences between the superficial aquifer and the Leederville aquifer for 1977 (Plate 83) with those of 1992 (Plate 64), a map of the resultant change in head-difference was constructed (Plate 84). It shows that, in the State Forests, the head difference between the watertable in the superficial aquifer and the potentiometric surface of the Leederville aquifer has decreased over the15-year period even though during this time groundwater abstraction from the Leederville aquifer has increased. This indicates that the watertable is declining at a faster rate than the potentiometric surface because of reduced rainfall recharge to the superficial aquifer

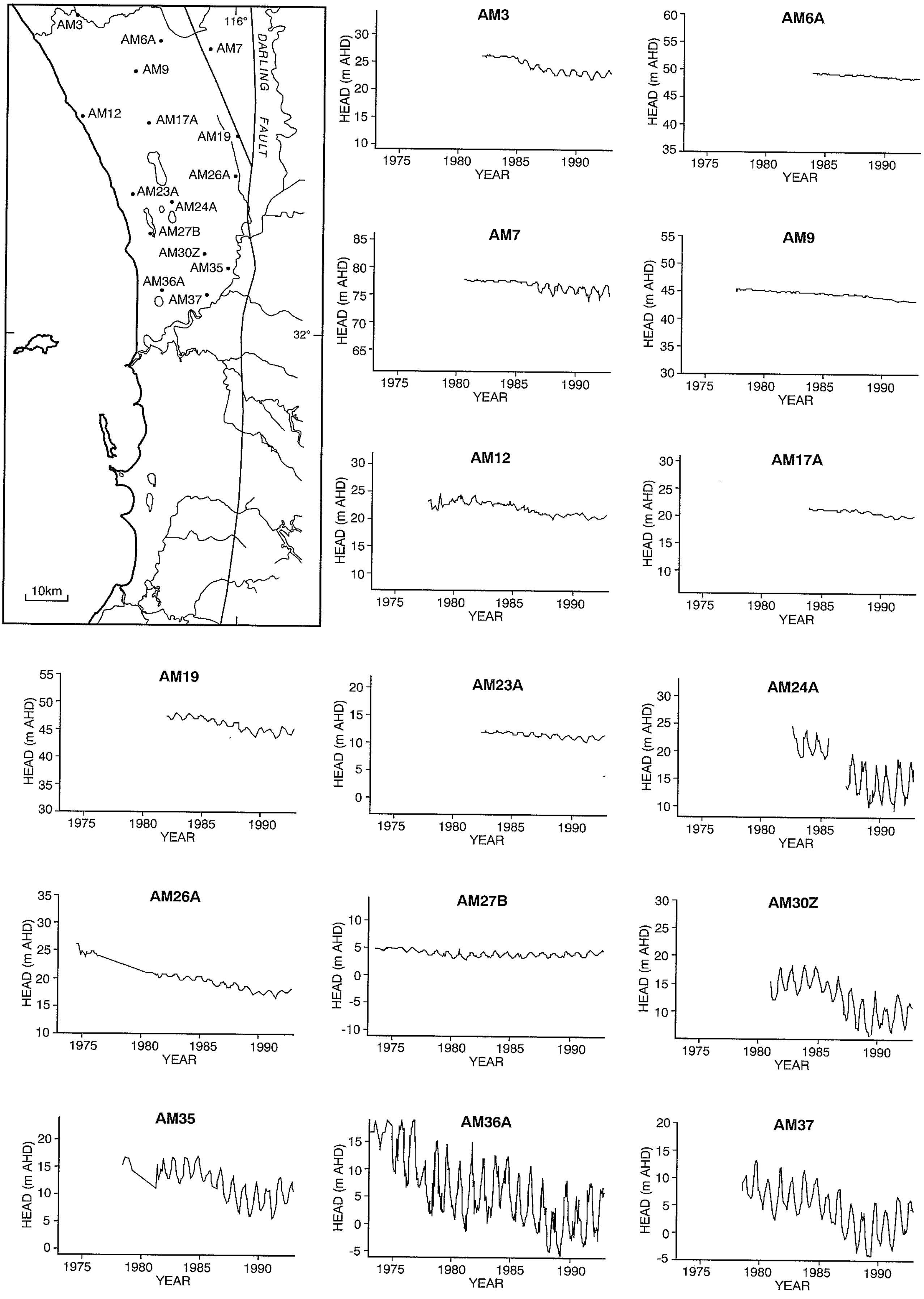

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Figure 48. Leederville aquifer hydrographs of potentiometric levels from bores north of Perth

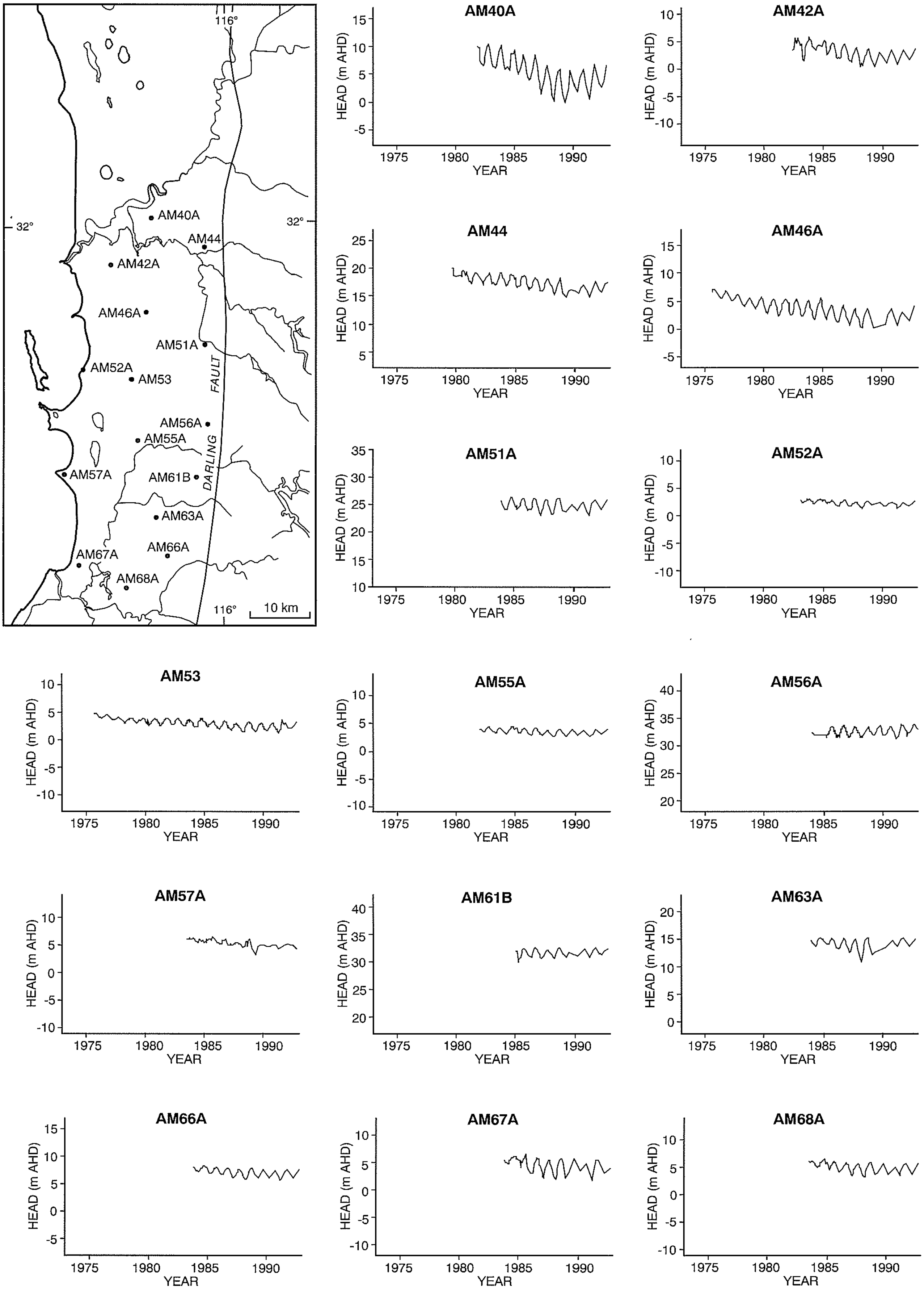

Figure 49. Leederville aquifer hydrographs of potentiometric levels from bores south of Perth

Table 37. Leederville aquifer — estimates of groundwater abstraction, 1992 (x10^6 m^3)

Management	*Water Authority*		*Private licences*		*Total*
area	*bores*	*abstraction*	*bores*	*abstraction*	*abstraction*
North					
Gingin GWA	0	0	55	10.895	10.895
Yanchep GWA	0	0	1	0.328	0.328
Wanneroo GWA	0	0	12	1.515	1.515
Wanneroo PWSA	6	10.191	0	0	10.191
Bullsbrook GWA	0	0	9	0.715	0.715
Swan GWA	0	0	224	5.337	5.337
Mirrabooka PWSA	5	4.835	0	0	4.834
Perth GWA–North	2	1.826	27	1.789	3.615
Gnangara UWPCA	1	1.131	0	0	1.131
Gwelup PWSA	5	5.342	0	0	5.342
Sub total	**19**	**23.325**	**328**	**20.579**	**43.903**
South					
Perth GWA–South	0	0	92	5.502	5.502
Cockburn GWA	0	0	1	0.500	0.500
Jandakot PWSA	2	1.167	4	0.025	1.192
Serpentine GWA	0	0	31	1.806	1.806
Stakehill GWA	0	0	8	0.386	0.386
Sub total	**2**	**1.167**	**136**	**8.219**	**9.386**
Total	**21**	**24.492**	**464**	**28.798**	**53.289**

Assuming that 2/3 of the licensed bores have been drilled and are in operation:

Northern recharge area	19	23.325	~218	~13.719	~37.043
Southern recharge area	2	1.167	~91	~5.479	~6.646
Total	**21**	**24.492**	**309**	**19.198**	**43.689**

resulting from lower than average rainfall and, possibly, a reduction in the infiltration properties of the soil.

In the southern area, the required additional recharge to the Leederville aquifer of 7100 m^3/d or 2.592 x 10^6 m^3/year is equivalent to about 0.5% (5 mm) of the rainfall over the area where the Leederville aquifer directly underlies the superficial aquifer. Because the depth to the watertable is less than 4 m below groundlevel over much of this area, the additional recharge will not cause a measurable drawdown in the watertable. The information on Plate 84 shows that field drains are stabilizing the elevation of the watertable in the area of increasing head difference between the superficial aquifer and the Leederville aquifer.

The salinity of the groundwater in the Leederville aquifer varies laterally and also with depth (Plates 67–76). Abstraction will cause groundwater to move laterally and also vertically towards the screened intervals of bores. In areas of widely varying salinities, the salinity of pumped groundwater will vary with time depending mainly on the rate of groundwater abstraction. In some areas, the salinity may temporarily increase. However, with prolonged abstraction, groundwater from the recharge areas will be induced to flow towards the abstraction areas and the salinity of the pumped groundwater may decrease. This has occurred at production bore M305 where the salinity of the groundwater from the Leederville aquifer has decreased from about 900 to 260 mg/L TDS since the bore was drilled in 1979. Providing the potentiometric surface of the Leederville aquifer remains mostly above sea level adjacent to the coast, seawater intrusion into the aquifer should not be of major concern.

Yarragadee aquifer

Abstraction potential

Recharge

The Yarragadee aquifer is recharged by downward leakage of groundwater from the Leederville aquifer in areas where the confining bed between the two aquifers is absent (Plate 77). Some local recharge also occurs in the southeast where the superficial aquifer rests directly on the Yarragadee aquifer (Cattamarra Coal Measures) adjacent to the Darling Fault. The current estimated total recharge to the Yarragadee aquifer is 8.74 x 10^6 m^3/year (north of Perth 5.80 x 10^6 m^3/year and south of Perth 2.94 x 10^6 m^3/year). Increased groundwater abstraction from the Yarragadee aquifer will induce additional leakage and recharge into the aquifer.

Table 38. Yarragadee aquifer — estimates of groundwater abstraction, 1992 (x10^6 m^3)

Management area	*Water Authority bores*	*Water Authority abstraction*	*Private licences bores*	*Private licences abstraction*	*Total abstraction*
Wanneroo GWA	2	9.372			9.372
Mirrabooka PWSA	1	2.111			2.111
Perth GWA–North	8	7.006	1	0.080	7.086
Northern recharge area	**11**	**18.489**	**1**	**0.080**	**18.569**
Perth GWA–South	1	0.836	1	0.005	0.841
Cockburn GWA			2	2.400	2.400
Serpentine			9	0.851	0.851
Southern recharge area	**1**	**0.836**	**12**	**3.256**	**4.092**
Total	**12**	**19.325**	**13**	**3.336**	**22.661**

Throughflow and discharge

Groundwater in the Yarragadee aquifer flows mostly in a westerly direction and discharges offshore by upward leakage into the overlying aquifers. During groundwater flow there is some upward leakage (about 1.26 x 10^6 m^3/year) into the Leederville aquifer.

Storage

A very large volume of groundwater is stored within the Yarragadee aquifer, which has an average thickness of about 2000 m. Within the top 500 m of the aquifer, the groundwater is fresh to brackish: in the basal 1500 m it is inferred to be mostly saline. Of the approximately 180 000 x 10^6 m^3 of groundwater stored in the top 500 m of the aquifer, about 76 000 x 10^6 m^3 have a salinity of less than 1000 mg/L TDS, and 104 000 x 10^6 m^3 a salinity of 1000–3000 mg/L. The volume (270 000 x 10^6 m^3) of saline groundwater (>3000 mg/TDS) stored in the basal 1500 m of the aquifer has been estimated by assuming an average specific yield of 0.1 for the sandstone beds and a sandstone to siltstone plus shale ratio of 1:1. The aquifer contains an important water resource for public water supply and large industries but, because of its depth, is generally too expensive to develop for small supplies.

Effects of abstraction

The Yarragadee aquifer is confined above by the South Perth Shale over most of the Perth Region and elsewhere by the interbedded shales within it, and within the Leederville Formation where the South Perth Shale is absent. In a small area to the southeast of the region and adjacent to the Darling Fault, the Yarragadee aquifer is in direct hydraulic contact with the overlying superficial aquifer. Individual bore yields are commonly about 10 000 m^3/d and, because the Yarragadee aquifer is confined, the effects of groundwater abstraction from the aquifer will extend several kilometres to the recharge areas (Plate 77) where recharge is by downward groundwater leakage from the superficial and Leederville aquifers.

In the northern area (flow-channels 1–4, Plate 77), the groundwater abstraction from the Yarragadee aquifer of 11.754 x 10^6 m^3/year (32 200 m^3/d) is about twice the estimated annual recharge to the aquifer of about 5.804 x 10^6 m^3 or 15 900 m^3/d (Table 31). Consequently, the potentiometric surface of the Yarragadee aquifer is declining at rates ranging up to 0.63 m/year (Plate 77, Fig. 50; Wharton, 1991), but averaging about 0.3 m/year. In the central Perth area where most of the abstraction takes place, the rate in decline of the potentiometric surface is decreasing as the aquifer, in this area, approaches steady state with respect to groundwater flow and abstraction.

To the south, the Yarragadee aquifer lies directly beneath the superficial aquifer in part of the Serpentine Groundwater Area and most of the groundwater abstraction is compensated for by induced local recharge. As a consequence, the hydrographs from bores in this area (Fig. 51) are stable and show no declining waterlevel trends. However, a pumping test carried out on Summerfield Road production bore CG2, screened against the Yarragadee aquifer in the Cattamarra Coal Measures, showed that the aquifer in this area is hydraulically connected to the superficial aquifer through the Leederville aquifer. After pumping for nine days at an abstraction rate of 7700 m^3/d, the watertable in nearby shallow bores and dams drew down a maximum of about 0.8 m (Rockwater, 1987). The test was carried out during January 1987 and it is believed that, should the bores be operated only during the groundwater recharge period of the winter months, the resultant drawdowns of the watertable would be much reduced and probably not detectable.

Over the entire southern area (flow-channels 5–7, Plate 77), the groundwater abstraction from the Yarragadee aquifer, which affects the configuration of the potentiometric surface, is about 3.241 x 10^6 m^3/year (4.092 x 10^6 – 0.851 x 10^6; Table 38) or 8900 m^3/d. This is about equivalent to the present rate of recharge (8050 m^3/d; Table 31) which means that the hydraulic-head difference between the Leederville and Yarragadee aquifers should not change, providing abstraction from both is unaltered.

The additional recharge of 16 300 m^3/d required to satisfy the current abstraction from the Yarragadee aquifer in the northern area can be obtained by doubling the current hydraulic-head difference between the Leederville and Yarragadee aquifers in the recharge area, excluding

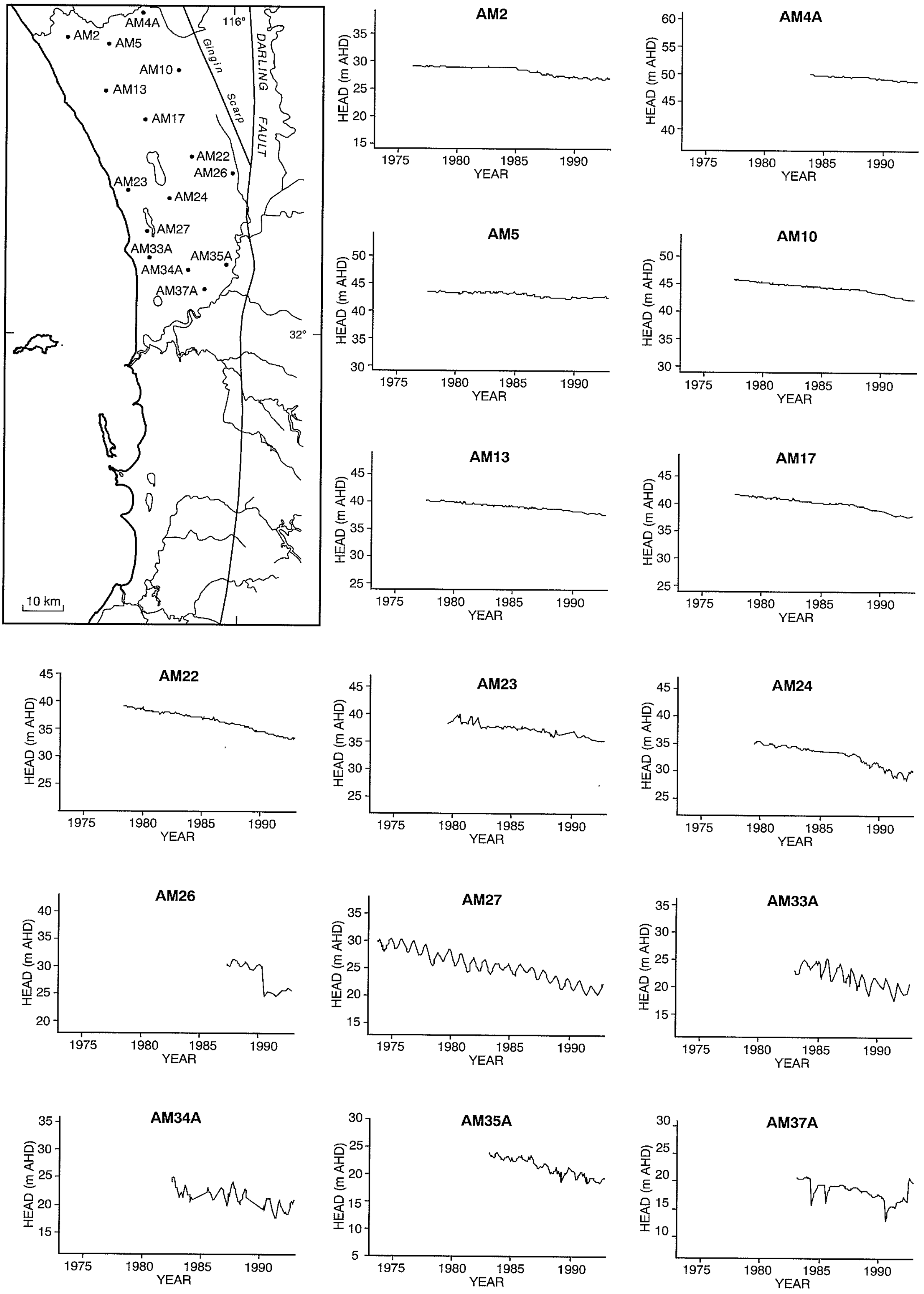

Figure 50. Yarragadee aquifer hydrographs of potentiometric levels from bores north of Perth

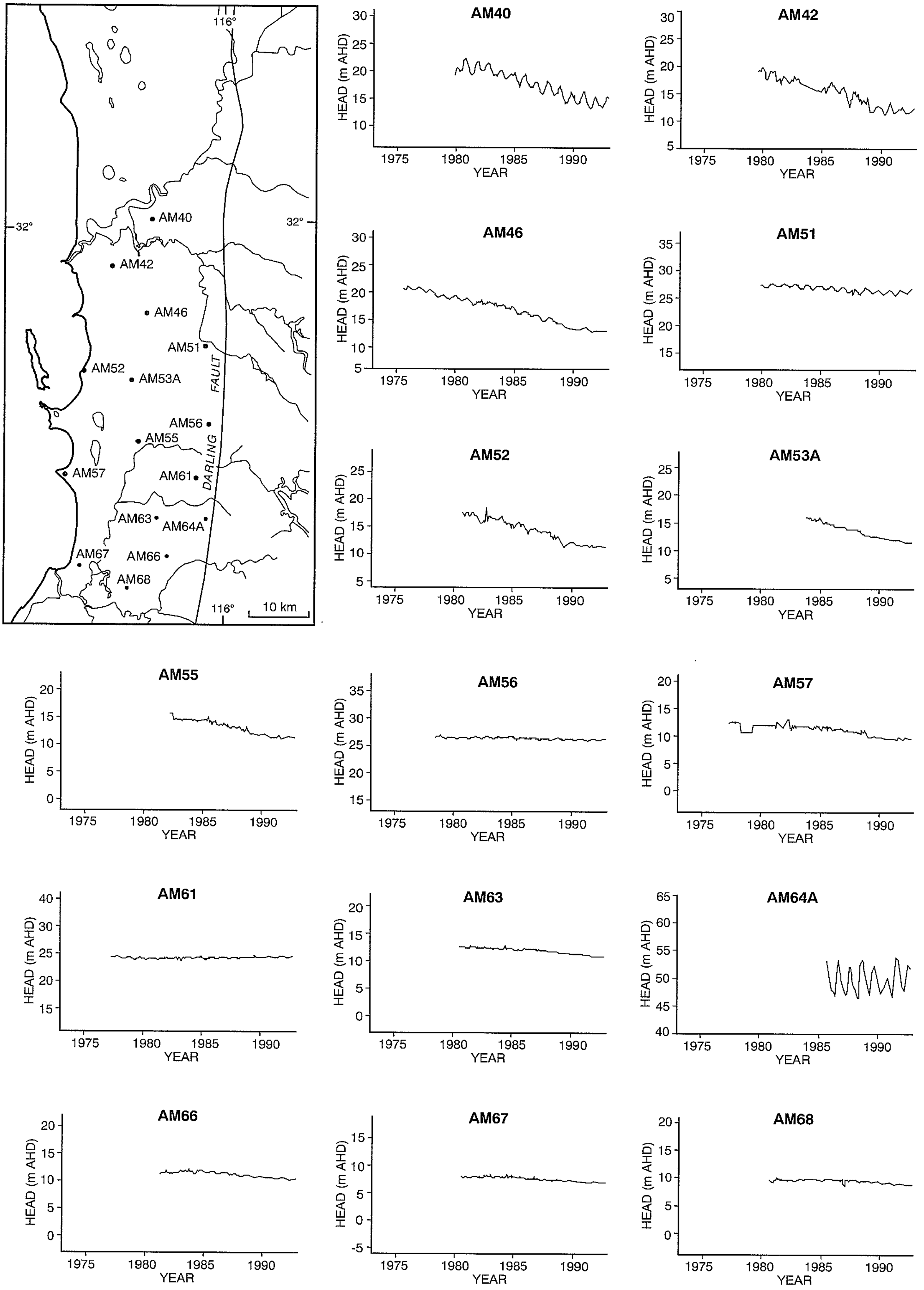

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Figure 51. Yarragadee aquifer hydrographs of potentiometric levels from bores south of Perth

the area beneath the Dandaragan Plateau. This will eventually cause a cessation of upward leakage of groundwater from the Yarragadee aquifer into the Leederville aquifer. By applying the required head difference to the predicted steady-state potentiometric surface of the Leederville aquifer (Plate 82) the resultant steady-state potentiometric surface of the Yarragadee aquifer can also be predicted, as shown in Plate 85. At the present average rate of waterlevel decline (0.3 m/year), steady-state conditions within the Yarragadee aquifer will be achieved in about 100 years, providing abstraction from the Leederville and the Yarragadee aquifers remains unaltered. These predictions are highly speculative but they do indicate that additional abstraction can be achieved without causing the onshore potentiometric levels to decline below ocean level.

The effects of abstraction from the Yarragadee aquifer on groundwater salinity will depend on the location and quantity of the abstraction. In areas close to brackish or saline groundwater (Plate 78), the salinity may increase due to abstraction inducing flow of the more saline groundwater towards the abstraction area. In areas of brackish groundwater, adjacent to fresh groundwater, the salinity of the abstracted groundwater should gradually decrease as the less saline groundwater is induced to flow to the abstraction area. With prolonged abstraction, recharge to the aquifer will be induced and the salinity of the groundwater should gradually decrease. At present rates of groundwater abstraction, and because the potentiometric surface of the Yarragadee aquifer is above sea level adjacent to the coast, seawater intrusion into the onshore part of the aquifer should not occur.

Groundwater management

The need for groundwater management

Groundwater is a major source of water, and of great importance to the continuing development of the Perth Region. It supplies public schemes and industry, and irrigation water for public open space, recreation grounds, horticulture and privately owned household gardens. Groundwater is also essential to the maintenance of the aquatic ecosystems of the wetlands and phreatophytic vegetation on the Swan Coastal Plain. Because groundwater exists at shallow depth beneath much of the area it is readily exploited.

As the surface water catchments of the Darling Plateau become fully utilized and as the population of Perth and surrounding areas grows, groundwater resources will become relatively more important and the competition between users of groundwater, including the environment, will increase. With growth of urban and industrial centres there will be increasing risk of groundwater contamination. There is, therefore, an obvious need for effective groundwater management. However, management of groundwater is a complex issue because of the variety of factors to be considered.

By the year 2000, total groundwater abstraction within the Perth Region may rise to 350 x 10^6 m^3/year (Webster, 1989) from the 1992 total of 281 x 10^6 m^3. To satisfy this predicted growth in demand, it is important that the groundwater resources of the Perth Region are managed in accordance with the concept of sustainable yield as defined under the State Conservation Strategy (Department of Conservation and Environment, 1987). While adopting the strategy of conservation and sustainable yield, it is also important that the groundwater resources are shared equitably between the major users, one of which is the natural environment whose water requirements must be taken into account (Webster, 1989).

The quality of the groundwater required varies considerably. High-quality, low-salinity groundwater is required for public water supplies; marginal quality groundwater can be used for most irrigation requirements and poor quality, brackish to saline groundwater can be utilized in most industries. Environmental needs vary from very fresh to hypersaline, depending on the location.

The Government of Western Australia, through the State Conservation Strategy, recognizes that the environment is a primary consideration in the process of managing groundwater quality and abstraction. Moreover, the principles of sustainable yield and conservation are important in the equitable administration of the groundwater resources. To these ends, legislation has been enacted so that the groundwater resources can be managed with respect to quantity, quality and the environment (Ventriss, 1989).

Legislation and institutional responsibilities

The legislative basis for management and allocation of groundwater in Western Australia is constituted in two amended statutes; the Rights in Water and Irrigation Act 1914 and the Metropolitan Water Authority Act 1982. Both of these Acts were formed on the basis that all groundwater resources are vested in the Crown (Ventriss and Green, 1987). These Acts are now administered by the Water Authority of Western Australia in the newly established Water Authority Act 1984.

Other government agencies have major roles influencing groundwater management (Table 39) and their integration is effected through the Water Resources Council of Western Australia and by the Integrated Catchment Management Policy Group of the Department of Premier and Cabinet. Both of these organizations have responsibility to advise Cabinet on policy for integration of land and water planning.

To provide the State with improved water resources management, Cabinet has decided to merge the Hydrogeology Branch of the Department of Minerals and Energy and the Waterways Commission with the Water Resources Division of the Water Authority. This merger will form the Water Resources Commission, to be effective from January 1996.

The **Department of Minerals and Energy**, through its Geological Survey Division, is responsible for exploration and assessment of the State's groundwater resources. Through this division, the Department ensures that the community is provided with information about groundwater resources and has access to independent advice relevant to groundwater management.

In fulfilling these roles the Geological Survey systematically records and interprets the geology of the State and provides this information to Government, industry and the general public in order to assist the exploration, development and conservation of the State's groundwater resources. This knowledge is used as a basis for decision making by Government in urban planning, landuse matters and engineering developments, and

Table 39. Principal agencies involved in groundwater management

Function	*Authority*	*Investigation*		*Advice*	*Review*	*Legislation*
1. Resource assessment						
Local	WAWA	WAWA	DME	WAWA	WAWA	Water Authority Act 1984
Regional	DME	DME	WAWA	DME	DME	Mining Act
2. Resource allocation						
Private	WAWA	WAWA	DME	WAWA	WAWA	Water Authority Act 1984
Scheme	WAWA	WAWA	DME	WAWA	WAWA	Water Authority Act 1984
Equitability	WAWA	WAWA	WAWRC	WAWRC	WAWA	Rights in Water & Irrigation Act 1984
Quality	HDWA	WAWA	WAWA	HDWA	HDWA	Health Act
3. Resource protection						
Sustainability	WAWA	DME	DME	DME	WAWA	Water Authority Act 1984
Development	WAWA	WAWA	DME	WAWA	DEP	Water Authority Act 1984
4. Resource management						
Drilling data	DME	WAWA	WAWA	DME	WAWA	Rights in Water & Irrigation Act 1914
Monitoring	WAWA	WAWA	DME	WAWA	WAWA	Water Authority Act 1984
Licensing	WAWA	WAWA	DME	WAWA	WAWA	Rights in Water & Irrigation Act 1914
5. Management areas						
GWA	WAWA	WAWA	DME	WAWRC	WAWA	Rights in Water & Irrigation Act 1914
UWPCA	WAWA	WAWA	DME	WAWRC	WAWA	Metropolitan Water Authority Act 1982
PWSA	WAWA	WAWA	DME	WAWRC	WAWA	Metropolitan Water Authority Act 1982
WR	WAWA	WAWA	CALM	WAWRC	DEP	Water Authority Act 1984
6. Pollution control						
Landfill	DLG	DLG	DME	WAWA	HDWA	Local Government Act 1960–1992
Rubbish	DLG	DME	WAWA	HDWA	HDWA	Local Government Act 1960–1992
Industrial	DPUD	WAWA	DME	DEP	DEP	Town Planning and Development Act 1928
Septage/sewage	WAWA	WAWA	HDWA	HDWA	HDWA	Health Act
7. Environmental protection						
Land planning	DPUD	DPUD	CALM	DEP	DPUD	Metropolitan Region Town Planning Scheme Act 1982
Forests	CALM	CALM	WAWA	DEP	CALM	Conservation and Land Management Act 1984
Reserves	CALM	CALM	WAWA	DEP	CALM	Conservation and Land Management Act 1984
Lakes	DEP	WAWA	DME	DEP	DEP	Environmental Protection Act 1986
Rivers	WC/SRT	WC/SRT	CALM	DEP	DEP	Waterways Conservation Act 1976
Drainage	WAWA/DLG	WAWA	DME	WAWA	WAWA	Water Authority Act 1984
Roads	MRD/DLG	MRD	WAWA	WAWA	MRD	Main Roads Act 1930–1984

Notes:	WAWA	Water Authority of Western Australia	GWA	Groundwater Area
	DME	Department of Minerals and Energy	UWPCA	Underground Water Pollution Control Area
	DPUD	Department of Planning and Urban Development	PWSA	Public Water Supply Area
	CALM	Department of Conservation and Land Management	WR	Water Reserve
	WC	Waterways Commission	DLG	Department of Local Government
	SWT	Swan River Trust	WAWRC	Western Australia Water Resources Council
	MRD	Main Roads Department of Western Australia	DEP	Department of Environmental Protection
	HDWA	Health Department of Western Australia		

problems associated with groundwater contamination (Department of Minerals and Energy, 1993).

The **Water Authority of Western Australia** was established under the provisions of the Water Authority Act 1984 to provide water resources of an appropriate quality and to manage these in the best interest of the community and the environment (Water Authority, 1992a). The Water Authority is assisted by several Advisory Committees, established under the Act, to provide it with advice on groundwater, surface water, irrigation allocation and water resources management issues.

In managing the groundwater resources, the Water Authority has four major functions.

- Measure and assess the groundwater resources in collaboration with the Geological Survey Division of the Department of Minerals and Energy. This work includes regional groundwater exploration carried out by the Geological Survey as well as specific local investigations such as around wetlands.
- Manage groundwater abstraction to ensure that the groundwater resources are sustainably and equitably allocated for the environmental, economic and social benefits of the community.
- Protect groundwater quality to ensure that the areas used for public water supply are free from contamination and, under the provisions of the Environmental Protection Act, carry out Pollution Control Licensing of activities which have potential to affect water resources. The Water Authority collaborates with other agencies including the Department of Environmental Protection, Department of Conservation and Land Management, Department of Minerals and Energy, Waterways Commission and the Department of Planning and Urban Development

in preparing strategies and policies for protection of groundwater quality.

- Drain areas of groundwater inundation in collaboration with Local Government.

The **Department of Planning and Urban Development** provides planning advice to the State Planning Commission. Conserving natural resources, particularly water and native vegetation, is considered of primary importance and, to this end, the Department critically reviews planning proposals for industrial and urban developments (Department of Planning and Urban Development, 1991).

The **Department of Conservation and Land Management** is responsible for the management of national parks, nature reserves, marine parks, marine nature reserves, State forests and timber reserves (Department of Conservation and Land Management, 1991). Groundwater management often influences the Department's land management practices and close liaison is required with the Water Authority of Western Australia on matters relating to wetland ecosystems and the competition for groundwater resources between forestry and public water supply.

The **Waterways Commission** and **Swan River Trust** are responsible for preserving, restoring and managing waterways declared as Management Areas under Waterways Conservation Act 1976 (Waterways Commission, 1992; Swan River Trust, 1992). Pollution control powers for the Management Areas are delegated from the Department of Environmental Protection and involve licensing and monitoring industrial effluent discharge, detecting and dealing with specific pollution problems such as the discharge of polluted groundwater, and clearing up of accidental chemical or oil spills which threaten to pollute waterways. Some of these waterways provide a source for groundwater recharge and others are sites for groundwater discharge.

The **Main Roads Department** liaises closely with the Water Authority of Western Australia on matters of road alignment and construction. This cooperative approach helps minimize the hazards associated with groundwater pollution, in areas of significant and important groundwater resources, from accidental spillage along the roadways (Main Roads Department Western Australia, 1991).

The **Health Department of Western Australia** is responsible for ensuring that disposal of sewage and municipal waste does not cause a problem to health through groundwater contamination (Health Department of Western Australia, 1992). Currently, the functions of solid-waste management have been transferred to the Office of Waste Management in the Department of Environmental Protection, pending a review of the relevant sections of the Health Act. The Department has developed waste-management standards, particularly for landfill and waste-disposal sites, to minimize the occurrence and problems associated with groundwater contamination.

The **Department of Local Government**, through its Councils, is required to manage waste-disposal sites in accordance with the Acts administered by the Health Department, Water Authority, Department of Conservation and Land Management, Waterways Commission and the Department of Environmental Protection (Department of Local Government, 1992). Management is aimed at minimizing groundwater contamination and preventing pollution of waterways. Local authorities are also responsible for constructing drains to discharge stormwater, surfacewater and groundwater into the ocean, river or compensating basin.

The **Western Australian Water Resources Council** is a statutory organization whose functions are to advise the Minister for Water Resources in relation to

- the assessment, development, conservation, management and protection of the water resources of the State; and
- the formulation of policies in relation to water resources and water services (Western Australian Water Resources Council, 1992).

The Water Resources Council, in collaboration with other government authorities, initiates, conducts or arranges studies, investigations and research relating to the water resources of the State, and the availability and use of such water resources. The Council publishes guidelines for the formulation of by-laws for the conservation, management and protection of water resources, and encourages local authorities to pass by-laws in accordance with the guidelines. In carrying out its functions, the Council considers the quality of groundwater, equitable use of groundwater, loss or wastage of groundwater and the preservation and conservation of groundwater.

The **Department of Environmental Protection** has broad powers under the Environmental Protection Act 1986 to control groundwater pollution. Both the Water Authority and the Waterways Commission manage water-pollution control within specified areas and under delegated powers of the Act. The Department advises the Government on environmental issues such as environmental impact assessment, environmental investigation, and pollution control (Environmental Protection Authority, 1991).

The Department is also responsible for establishing environmental protection policies to safeguard the wetlands of the Swan Coastal Plain and to protect the major groundwater resources of the Perth Region from contamination and over exploitation. Under these policies, the need to maintain groundwater and lake levels within limits necessary to support environmental requirements, for example, is requiring the Water Authority to review its use of groundwater as a wetland protection strategy during droughts. Some lake levels may need to be artificially maintained by groundwater from bores. In other areas, Water Authority production bores into the superficial aquifer, may need to be closed down.

Groundwater allocation management

Ownership of groundwater in Western Australia is vested in the Crown and allocation is subject to State Legislation. In the Perth Region, all bores are required to be licensed except in certain areas where bores used for domestic and stock purposes are exempted (Ventriss, 1990).

Current practice is to allocate the groundwater resources according to four principles (Banyard and Davidson, 1991):

- water use and salinity,
- groundwater throughflow,
- groundwater storage depletion, and
- water balance.

Water use and salinity

Where possible, the Water Authority allocates groundwater resources according to beneficial use so that the fresh groundwater, of salinity less than 1000 mg/L TDS, is used for public water supply and selected agriculture; the brackish groundwater of salinity 1000–2000 mg/L TDS is used for parkland irrigation, and the more saline groundwater of salinity greater than 2000 mg/L TDS is used in industry. This management strategy can be applied in those areas where the salinity of the groundwater varies with depth and between aquifers. However, in some areas it may not be practical or economic because of excessive depths to groundwater of the various salinities. For example, groundwater of salinity less than 500 mg/L TDS occurs to a depth of more than 1100 m below groundlevel in the Wanneroo Public Water Supply Area at production bore W257; therefore in this area it is not practical to require groundwater of a higher salinity to be used.

Groundwater throughflow

The groundwater resources of the various aquifers can be managed by limiting abstraction to a proportion of the estimated groundwater throughflow. This is an imprecise method of resource allocation because, in the early stages, abstraction causes waterlevel drawdowns, steeper hydraulic gradients towards the abstraction areas, and induces increased groundwater throughflow. However, used as an iterative process of resource availability, abstraction can be gradually increased to safe capacity. The safe capacity of abstraction is determined from the effects of abstraction on waterlevels and water quality. In the Perth Region, where there are many wetland areas environmentally sensitive to changing groundwater levels and deterioration of groundwater quality, the safe capacity of abstraction is limited by environmental constraints. This limitation is particularly relevant when abstraction is from the shallow unconfined superficial aquifer, and it becomes less of a limiting factor with increasing depth of abstraction and where the degree of hydraulic connection with the watertable decreases.

For environmental reasons, the proportion of groundwater throughflow within the superficial aquifer that can be safely abstracted is best determined at the discharge boundaries formed by the rivers and the ocean. To avoid the deleterious inland movement of the saltwater interface, it has further been estimated that about 30% of the throughflow in the superficial aquifer should continue to discharge at the coast and estuaries. Allowing for some groundwater discharge, about 153 x 10^6 m^3/year (70% of 218.94 x 10^6 m^3/year, Table 35) of groundwater could be safely abstracted. Since the superficial aquifer is in equilibrium with current abstraction (210 x 10^6 m^3/year), recharge, throughflow and discharge (steady-state conditions), and there are no downward trends in watertable levels adjacent to the discharge boundaries, the total environmentally permissible abstraction from the superficial aquifer is about 363 x 10^6 m^3/year. For the Gnangara Mound (North and South) and Jandakot Mound, this total safe abstraction is equivalent to an increase in present abstraction of about 100 x 10^6 m^3/year from the Gnangara Mound (North and South) and 30 x 10^6 m^3/year from the Jandakot Mound. However, to satisfy the management strategy requiring 30% of the throughflow to discharge at the ocean and estuaries, a large number of regularly spaced production bores would be required adjacent to the entire length of the discharge boundaries.

Some of the groundwater in the Mirrabooka aquifer has been shown to discharge upwards into the superficial aquifer, and the remainder discharges laterally into the sandy beds of the Kings Park Formation. All of the groundwater flow, equivalent to the total recharge of about 6 x 10^6 m^3/year is available for abstraction. At present rates of abstraction (about 5 x 10^6 m^3/year) the aquifer is in steady state with recharge, throughflow, abstraction and discharge. An increase in abstraction will induce additional recharge by increasing downward leakage of groundwater from the superficial aquifer, and as a consequence more water will become available for abstraction. Because the Mirrabooka aquifer is a semi-confined to semi-unconfined aquifer, some local drawdown (<0.5 m) of the watertable will occur around the production bores (Davidson, 1984b). This small drawdown should not cause environmental problems if the bores are correctly located and abstraction carefully managed.

The total groundwater outflow from the Leederville aquifer (10.6 x 10^6 m^3/year; Table 27) and Yarragadee aquifer (7.5 x 10^6 m^3/year; Table 31) is about 18.1 x 10^6 m^3/year and is theoretically available for groundwater abstraction. However, as present abstraction from both aquifers (59.5 x 10^6 m^3/year; Tables 37 and 38) exceeds the groundwater outflow, the potentiometric head is declining, inducing additional throughflow. It is estimated that, at current abstraction rates, steady state will be achieved in about 50 years for the Leederville aquifer and 100 years for the Yarragadee aquifer. The annual groundwater throughflow in the Leederville and Yarragadee aquifers beneath a production area may be considerably less than the required abstraction. To permit the required abstraction, the Water Authority allows local draw in excess of groundwater throughflow but determines the area of influence of the abstraction and limits any additional abstraction from that area. For these reasons, management of the groundwater resources of the Leederville and Yarragadee aquifers should not be based on groundwater throughflow estimations, because additional throughflow will be induced as abstraction is increased. More importantly, management should be directed at preventing inland movement of the saltwater interface by maintaining the zero potentiometric level near the coast. To achieve this and to permit additional groundwater abstraction from the Leederville and Yarragadee aquifers, future production bores would need to be located within and adjacent to the recharge areas, and away from the coast.

Groundwater storage depletion

Groundwater resources may also be allocated as a percentage of total groundwater storage. A non-renewable portion of storage will be released where the watertable or potentiometric surface is permanently reduced. Theoretically, the aquifers would have a limited life and, in due time, alternative future sources of water would need to be exploited. Under the management principle of sustainable yield, a progressive depletion of storage would not be permitted. However, a small lowering of the watertable (<1 m) may be acceptable in some areas where the watertable is less than 4 m below groundlevel. This small reduction in storage would reduce evapotranspiration losses from the superficial aquifer and provide extra space for induced additional recharge. In areas of environmental significance, where wetlands are important to the natural ecosystem, this management option is unacceptable for allocating the groundwater resources of the unconfined superficial aquifer unless environmental mitigation programs are put into effect (e.g. artificial maintenance of wetlands). It may be acceptable practice for the confined aquifers, because a small lowering of the hydraulic head will extend the area of intake and increase recharge by salvage of groundwater that would otherwise be lost by evapotranspiration. This would only be significant in the Mirrabooka and Leederville aquifers where they are in hydraulic connection with the unconfined superficial aquifer. It would be far less effective in the deep confined Yarragadee aquifer which is recharged mostly from the overlying Leederville aquifer. Extreme lowering of potentiometric levels will, however, induce inland movement of the saltwater interface and possibly cause land subsidence.

Progressive long-term storage depletion is not a preferred management option. However, where the throughflow and groundwater resources are small, as in some areas of the Guildford Clay along the eastern margin of the Perth Region, some storage depletion is justified if the groundwater is indeed to be used. Under these circumstances groundwater allocations could be made in terms of total estimated storage.

Controlled depletion of storage may be permitted until steady state is reached within the unconfined and confined aquifers. It may be acceptable to mine the large storage of fresh groundwater in the confined aquifers beneath the ocean, west of the coastline. Otherwise this groundwater will eventually discharge to the ocean.

Water balance

The water balance approach for groundwater management is the preferred option for management of the groundwater resources so that abstraction can be sustained in perpetuity. Regardless of the aquifer from which groundwater is being abstracted, the effects of abstraction will propagate to the recharge areas and eventually to the watertable. For example, groundwater abstraction from the Yarragadee aquifer will induce downward leakage from the Leederville aquifer which, in turn, will induce downward leakage from the superficial aquifer, resulting in a slight lowering of the watertable. The net result will be that additional rainfall recharge will occur because of a reduction in those groundwater losses due to drainage from a shallow watertable, evaporation from some wetlands, and transpiration from some vegetation.

From throughflow calculations alone, about 363 x 10^6 m^3/year of groundwater could be abstracted from the superficial aquifer without causing detrimental environmental effect. However, by abstracting this quantity of groundwater from the superficial aquifer, additional rainfall recharge would certainly be induced. Based on interpretation of the flownet analyses, the maximum recharge that can be induced is about 214 x 10^6 m^3/year (Table 34). This excludes additional recharge from the urban and State Forest areas. The total groundwater resources available for abstraction, without causing deleterious environmental impacts, is determined from equation (15) and shown diagrammatically in Figure 52.

$$Am = Qi + Rc + R_I - kQo \qquad (15)$$

where Am = maximum sustainable abstraction
Qi = groundwater inflow from the northeast (7 x 10^6 m^3/year comprising Leederville aquifer 5 x 10^6 m^3/year — Table 27, plus Yarragadee aquifer 2 x 10^6 m^3/year — Table 31)
Rc = current recharge to superficial aquifer (343 x 10^6 m^3/year — Table 34)
R_I = induced additional recharge to superficial aquifer (214 x 10^6 m^3/year — Table 34)
Qo = current groundwater outflow from superficial aquifer (219 x 10^6 m^3/year — Table 35)
k = sustainable outflow factor (0.3 *see* **Groundwater resources**: throughflow and discharge in the superficial aquifer)

$$\text{thus } Am = (7 \times 10^6) + (343 \times 10^6) + (214 \times 10^6) - 0.3\,(219 \times 10^6)$$
$$= 498 \times 10^6 \text{ m}^3\text{/year}$$

To minimize watertable drawdown and to spread the effects of abstraction over wide areas, groundwater from the Rockingham, Mirrabooka, Leederville and Yarragadee aquifers should be utilized in preference to that contained in the superficial aquifer, particularly in those areas of direct vertical hydraulic connection with the superficial aquifer. Computer modelling could be carried out to assess the maximum abstraction sustainable from the deeper aquifers without causing unacceptable drawdown of the watertable in the recharge areas. If about half of the

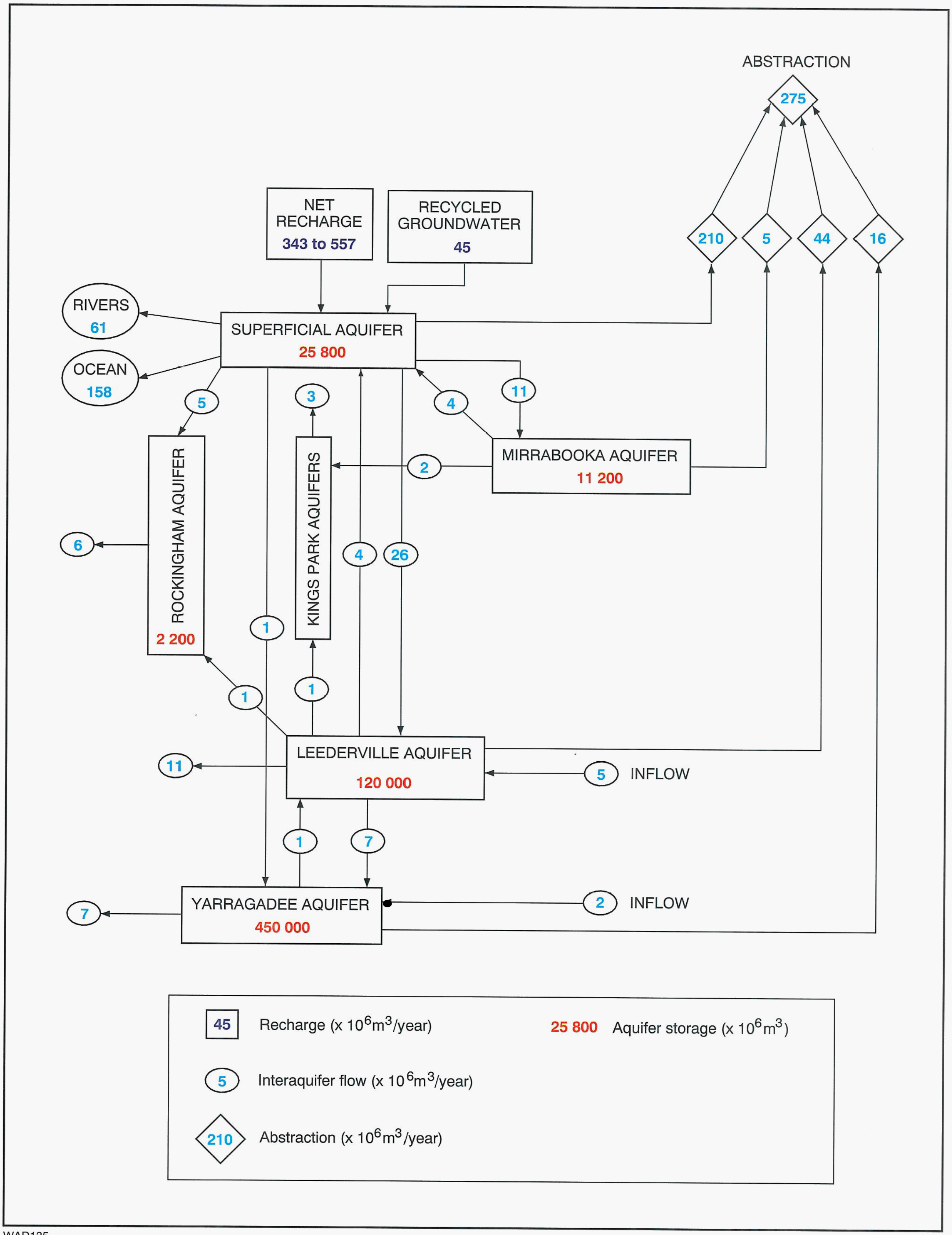

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Figure 52. Summary of groundwater resources

Table 40. Current and potential sustainable abstraction ($x10^6 m^3$/year)

Aquifer	*Northern area*		*Southern area*		*Total*	
	current	*potential*	*current*	*potential*	*current*	*potential*
Superficial	121	179	89	140	210	319
Rockingham	–	–	–	9	–	9
Mirrabooka	5	10	–	–	5	10
Leederville	37	80	7	20	44	100
Yarragadee	12	50	4	10	16	60
Total	**175**	**319**	**100**	**179**	**275**	**498**

potential additional recharge of 214 x 10^6 m^3/year to the superficial aquifer is apportioned to the deeper aquifers, the total sustainable abstraction of 498 x 10^6 m^3/year could be obtained from the various aquifers as set out in Table 40. With the expansion of urban development into the rural areas, additional rainfall recharge will be induced to a maximum, equivalent to about 30% of the rainfall. Therefore, the estimates of sustainable groundwater abstraction (given in Table 40) may be conservative but will depend on future urban development and the correct location of production bores. Also, a considerable volume of drainage water currently discharges from existing urban areas. Additional abstraction, which is possible in these areas, would reduce the amount of water required to be drained and increase the total sustainable abstraction to about 600 x 10^6 m^3/year or about twice the current groundwater abstraction.

Groundwater quality management

Over most of the Perth Region, groundwater lies at a shallow depth in the unconfined superficial aquifer. In these areas it is particularly vulnerable to contamination because the overlying sandy sediments are mostly incapable of filtering out chemical pollutants. Once in the groundwater, pollutants that are not naturally degraded can persist for many years and may be eventually discharged into wetlands (lakes, rivers and drains) and into the ocean.

Vulnerability of groundwater to contamination

Groundwater contamination may occur from decomposition of vegetation and bushfires but, on a regional scale, this form of contamination is insignificant. The major causes of groundwater contamination are human activities such as urbanization, industrialization and agriculture, which result in chemical substances and microorganisms entering the groundwater in local areas (point sources) or over regionally wide areas (non-point sources). Point sources are generally the most severe causes of groundwater contamination and usually result from deliberate or accidental disposal of solid or liquid wastes in small areas. Less severe are non-point sources, such as leaching of chemicals applied as agricultural fertilizers. The leaching of nutrients from septic tanks in unsewered areas is also considered as a non-point source of contamination.

The vulnerability of the groundwater to all sources of contamination depends on the chemical composition of the contaminants, the lithology of the sediments, the depth below groundlevel to the watertable, and the climate (Appleyard, 1993a). The mobility of contaminants within the unsaturated zone and within the groundwater depends on the viscosity and solubility of the contaminants and on the degree to which these contaminants are adsorbed by organic matter or minerals. Clay minerals and organic matter have a high capacity to adsorb contaminants but quartz sand, unless coated with iron oxide, has a low capacity. Porosity, permeability and degree of anistropy of the sediments affect both the rate of contaminant flow within the aquifer and the required residency time for adsorption to occur. Karst features and solution channels within limestone, non-stratified, well-sorted, coarse-grained quartz sand, and shallow depth below groundlevel to the watertable all greatly increase the vulnerability of the groundwater to contamination.

The map of vulnerability of groundwater to contamination (Fig. 53) is based on all these factors and shows that areas of high vulnerability to contamination exist on the coastal plain (usually associated with shallow depth to the watertable) and in sandy sediments or karstic limestone. Groundwater in these areas is highly susceptible to contamination from agricultural, industrial and urban activities. Areas of low vulnerability to groundwater contamination occur on the Dandaragan and Darling Plateaus where the watertable is deep and where the permeability of the strata is low. Low vulnerability also occurs in some areas of Guildford Clay because of the low permeability and high adsorptive properties of the clayey sediments.

Investigations of groundwater contamination

Groundwater contamination resulting from human activities has been a problem since settlement in 1829. However, since about 1970, there has been an increased awareness of the problems associated with groundwater contamination, such as the possible adverse effects of pollution on wetlands, public water supplies, private

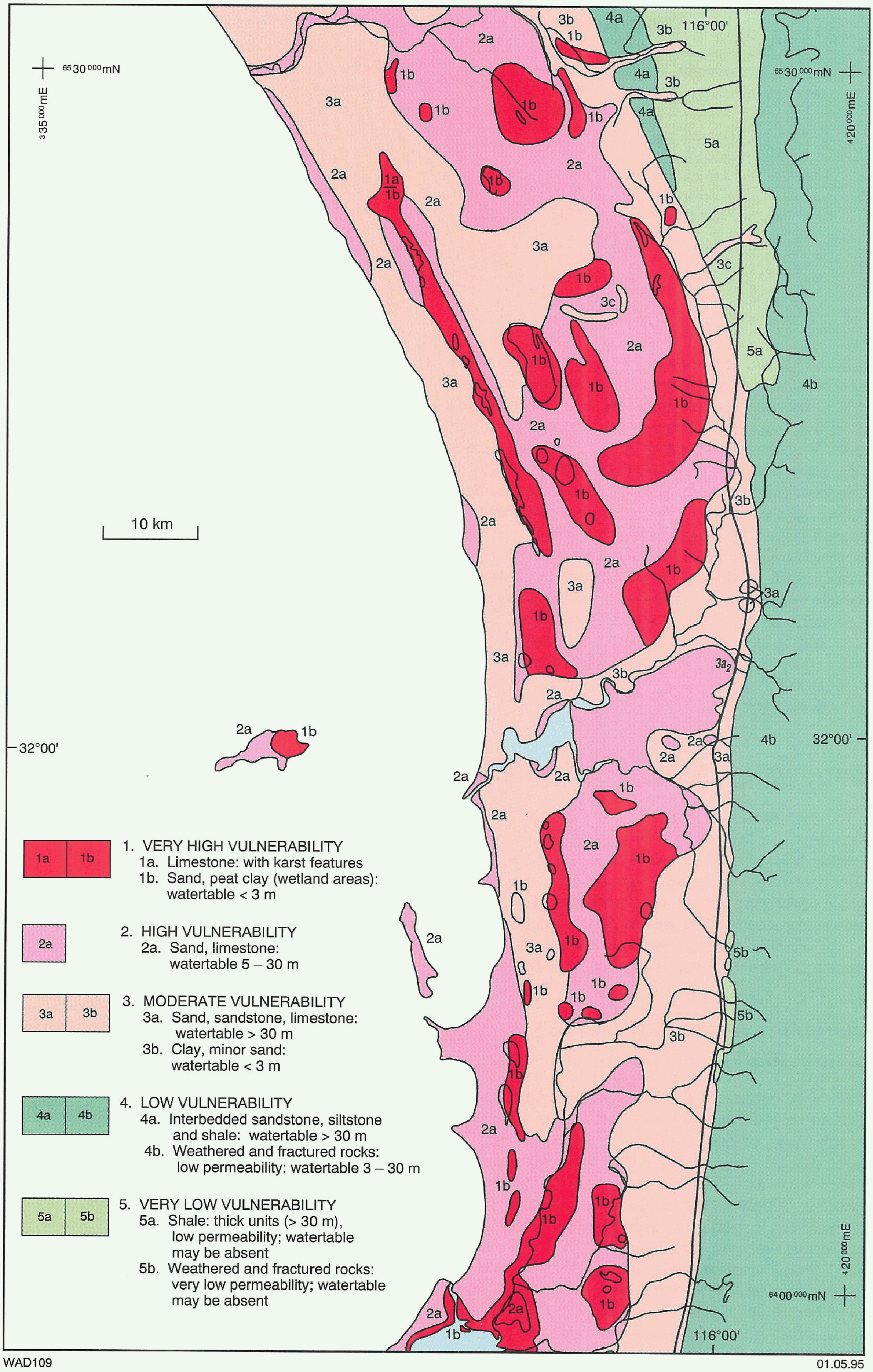

Figure 53. Vulnerability of groundwater to contamination (from Appleyard, 1993a)

reticulation, and Cockburn Sound. To combat the increasing problems associated with groundwater contamination and to help prevent further contamination, an Effluent Licensing Advisory Panel was formed in 1977. This became a statutory, multi-departmental body in 1980, chaired by an executive officer of the former Public Works Department, charged with enforcing the effluent-disposal provisions of the Rights in Water and Irrigation Act 1914. Following promulgation in 1987 of the Environmental Protection Act 1986, responsibility for water-pollution control was delegated to the Water Authority of Western Australia. During the 10-year period from 1977 to 1987, those industrial sites at which liquid effluent was disposed were investigated for groundwater contamination; the more significant of these are briefly described.

- In the coastal Kwinana area, 33 km south-southwest of Perth, disposal of agricultural chemicals into soakage pits between 1960 and 1984 has created a groundwater contamination plume within the Safety Bay Sand. Computer-aided groundwater modelling and control drilling by the Geological Survey has shown that the plume may reach Cockburn Sound in about 30 years (year 2020). Bores have been drilled to monitor the migration of the plume.
- In the Welshpool area, 8 km southeast of Perth, disposal of plating liquors from a metal-finishing company has resulted in a large groundwater contamination plume containing cyanide and heavy metals. Plating liquors are now treated onsite.
- In the Henderson area, 23 km south-southwest of Perth, injection into the superficial aquifer of high BOD effluent from starch and gluten production has led to methane being emitted from the ground, causing a local fire and explosion hazard in the area.
- In the Munster area, 22 km south-southwest of Perth, cement production from sea sand has resulted in a large, brackish groundwater plume within the superficial aquifer. The plume is being monitored to determine a possible water and salt balance for the area.
- In the Baldivis area, 38 km south of Perth, effluent rich in ammonium sulfate from a nickel refinery has leaked into the groundwater from a disposal pond. The pond has since been decommissioned and recovery of the effluent is underway.
- In the Jandakot area 19 km south of Perth, and in the O'Connor area 14 km southwest of Perth, effluent rich in BOD, surfactants and arsenic from woolscouring plants has contaminated nearby groundwater. It is expected that the contamination will gradually dissipate because one of the plants has since closed down and the other is carrying out remedial recovery and treatment of the effluent.

Miscellaneous investigations

The movement and attenuation of contaminants in the soils and superficial aquifer on the Swan Coastal Plain have been the subject of a number of investigations (Hirschberg, 1989).

- Bestow (1977) studied groundwater contamination of the Hertha Road landfill site, and concluded that the contamination was less severe than expected, owing to the low permeability and adsorptive properties of the peaty sediments.
- During 1979, Whelan et al. (1981) studied the input to the groundwater flow system of phosphate and nitrate from septic tanks and found that the input was considerable due to the poor attenuation properties of the sandy sediments.
- Layton Groundwater Consultants (1979) investigated the type and extent of the contamination in the industrial Kwinana–Owen anchorage areas. They concluded that the groundwater throughout the entire area was commonly polluted with nutrients, chemicals, hydrocarbons, heavy metals and saltwater, mostly originating from spillage or disposal within industrial sites. Some of the hydrocarbons were fixed in the sand above the watertable by bacterial degradation, but most percolated to, and rested on, a thin immiscible film on the watertable.
- Parker et al. (1981) investigated the migration of coliform bacteria through sandy soils and concluded that, although coliform numbers decreased rapidly with depth below septic tanks, these bacteria may reach the groundwater where the watertable is shallow.
- Newman and Marks (1981) reported on the effective removal of heavy metals by sand and concluded, from laboratory experiments, that removal is most favourable in the Safety Bay Sand, less so in the Tamala Limestone sand and least in the Bassendean Sand. The main processes involved in removal of heavy metals were considered to be high specific adsorption in the Safety Bay Sand because of its high pH, moderate cation exchange in the Tamala Limestone sand due to its moderate clay content, and low specific adsorption in the Bassendean Sand because of its low pH.
- Market gardens and local government authorities also contribute to bacterial and nutrient pollution of the groundwater by use of fertilizers and septic tanks. La Brooy (1981) reviewed the attenuation capacity of the different soil types of the Swan Coastal Plain for contamination originating from agricultural, industrial, domestic and urban sources. He concluded that, although contamination appeared to be localized, there was the potential for more serious contamination if problems were allowed to accumulate.
- Whelan and Parker (1981) reported on continued investigations into bacterial and chemical transmission through sand of the Perth area. They concluded that faecal coliforms, nitrogen and phosphorus readily enter the groundwater-flow system beneath septic tanks in areas where the watertable is shallow and the aquifer comprises predominantly coarse sand with minimal clay.

- Hirschberg (1982, 1986) investigated disposal sites for domestic liquid waste and the hydrogeological aspects of liquid-waste disposal in Perth.
- The health aspects of nitrate in groundwater were studied by Davidson and Jack (1983) and it was concluded that there did not appear to be a health problem in the Perth Region but that more baseline data were required for an adequate assessment.
- The reasons for sulfate increases in the superficial aquifer were investigated by Bawden et al. (1983). They showed that sulfate concentrations were generally greater at the watertable because of oxidation of sulfides, such as pyrite or troilite, that are stored within the reducing environment of the deeper groundwater. Extremely high sulfate concentrations are probably due to fertilizer contamination.
- The nitrate distribution in some urban areas of Perth was studied by Appleyard and Bawden (1987). They concluded that groundwater nitrate concentration beneath urban areas is generally greater than 10 mg/L NO_3–N and due mostly to seepage from septic tanks and leaching of nitrogenous fertilizers.

Barber et al. (1990a) conducted an investigation, commissioned by the Water Authority (Taylor, 1989), to identify groundwater contamination due to leaky petrol-station storage tanks. Forty sites were investigated and eight were found to have soil contaminated with hydrocarbons. A number of these sites also showed contamination of groundwater; one in particular, had a plume several hundred metres long. At each of the contaminated sites the storage tanks were at least 10 years old suggesting that, elsewhere within the Perth Region, contaminated groundwater may exist beneath petrol-storage tanks of this age or older.

Appleyard (1993b) carried out research into the effects of stormwater drains and compensation basins on groundwater quality beneath a light-industrial area, a medium-density residential area, and a major arterial road. Because of runoff recharge at each site, the groundwater adjacent to the basins was found to have lower salinity, and greater dissolved-oxygen concentrations, than the regional groundwater. Concentrations of toxic metals, nutrients, pesticides, and phenolic compounds in the groundwater were found to be low, and within Australian drinking-water guidelines. However, the sediments within the basin draining the major arterial road contained in excess of 3500 ppm (parts per million) of lead.

Municipal-waste disposal

Waste disposal is a major logistic and environmental problem confronting communities worldwide. It is also a major problem in the Perth Region, mainly because the hydrogeological environment is mostly unsuitable for waste disposal. Sandy soils with high permeabilities do little to attenuate leaching from waste-disposal sites, particularly in areas where the watertable is shallow. A proposed site for waste disposal was investigated at Jones Street, about 8 km northwest of Perth, between 1976 and 1979. The results of the investigation (Laws, 1979) indicated that some problems of groundwater contamination may occur because of the shallow depth below groundlevel to the watertable and the presence of upward hydraulic heads within the superficial aquifer.

Hirschberg (1993a) investigated the groundwater quality near 50 municipal landfill sites and found that elevated NH_4–N levels concentrate as a plume as much as 1 km in length at most sites. However, concentrations of heavy metals and pesticides were very low and commonly not detectable. It was concluded that there was minimal health risk to humans from groundwater contaminated with landfill leachate. However, contaminated groundwater rich in nutrients might discharge into, and cause eutrophication of, nearby wetlands.

Inventory of point-source contamination

During 1986, the Geological Survey carried out an investigation of some of the sources of groundwater contamination and produced an inventory of the known and inferred point (local) sources within the Perth Region. Non-point sources, biological contamination and pollution from hydrocarbons (e.g. leakage from petrol-station storage tanks) were excluded from the investigation. Nevertheless, about 700 point sources of contamination were identified (Hirschberg, 1989). These have been placed into seven groups (Table 41) and each activity given a hazard rating defined by the Kwinana Industries Coordinating Committee Report (1987).

Hazard rating 1: High risk to the environment or population due to toxicity, volume of effluent, or location. Requires careful management, regulation and rehabilitation. Contaminants include heavy metals, cyanide, arsenic, pesticides, organochlorides and hydrocarbons.

Hazard rating 2: Moderate risk due to type, volume or location of effluent. Requires regular monitoring and assessment. Contaminants include high concentration of ammonia, nitrate, sulfate, phosphorus and surfactants.

Hazard rating 3: Low risk due to type, volume or location of effluent. Should be recognized and recorded, no monitoring or control required. Contaminants include low to medium concentration of BOD (Biochemical Oxygen Demand), ammonia and nitrate.

The distribution of these point sources of contamination is shown on Figures 54 to 56. Figure 54 shows that the contamination sources from industry and chemical production with a high-risk hazard rating are restricted to relatively small industrial-zoned areas. All are situated in hydrogeologically unfavourable areas and there is a threat of contamination to nearby private bores, wetlands, rivers and the ocean. In densely industrialized areas, groundwater contamination may originate from several sources.

Figure 55 shows potential contamination sources from animal-based industry, food industry and the disposal of bodies. Most are of moderate-risk hazard rating except for the woolscourers and tanneries which have a high-risk

Table 41. Potential point sources of groundwater contamination (from Hirschberg, 1989)

Group	*Activity*	*Total no.*	*Hazard rating/risk category (tentative)*
Industrial-waste sources	metal finishing shops metals production, foundries, casting sand disposal,	44	1
	power stations	48	1–2
	mechanical workshops, battery recycling	65	1–2
	production of cement, bitumen, fibreglass, paper, etc	57	2
	laboratories, photo processing	28	2
	laundries, drycleaners	8	2
Sources of waste from production of chemicals	production of industrial chemicals agrochemicals, petrochemicals, pesticides	42	1
	production of paints, glues, solvents	11	1
	production of fertilizers	7	1–2
Animal-based waste sources	woolscourers	7	1
	tanneries	16	1
	piggeries	106	2
	meat rendering, meat packing, poultry processing	27	2
	abattoirs, feedlots	20	2
Landfill sites	domestic-waste disposal	96	2
Liquid-disposal sites	domestic-liquid disposal, sewage-treatment plants, large septic systems	57	2
Sources of waste from food production and dairies	production of starch/gluten, bakeries	16	2–3
	cheese factories	10	2–3
	fruit/vegetable producers, wineries, breweries, soft-drink production	21	2–3
Sites for disposal of bodies	cemeteries	16	3
	burial sites for animals	4	3

hazard rating. The food industries and the sites for disposal of bodies generally have a low-risk hazard rating.

Figure 56 shows domestic-waste disposal sites, for which local authorities are responsible. Many are located in or near lakes and swamps or adjacent to the rivers because of the lack of suitable sites (Hirschberg, 1993b). Leachates from these sites have caused eutrophication of some of the wetlands and will continue to do so for many years even though most of the environmentally sensitive sites have been closed and rehabilitated into parkland. Bores, monitored for groundwater contamination by the Health Department, have been established at most of the landfill sites according to guidelines published by the Geological Survey (Hirschberg, 1993c).

Collaborative investigations

The Geological Survey, in collaboration with the Water Authority, Health Department, and Department of Environmental Protection, is continuing research and investigations into groundwater contamination from landfill sites, other miscellaneous sites and point sources throughout the Perth Region. Many other investigations, mostly of point sources, are carried out by the Division of Water Resources (CSIRO) and by hydrogeological consultants.

The Geological Survey, in collaboration with the Department of Conservation and Land Management, Department of Agriculture, and the Division of Water Resources (CSIRO), also carries out regional investigations into groundwater contamination by nutrients from non-point sources such as those associated with forestry, horticulture and farming.

These collaborative investigations are necessary for good groundwater-quality management, as can be inferred from the proceedings of three conferences held in Perth between 1979 and 1988.

- 1979 Groundwater pollution conference: Australian Water Resources Council, proceedings 1981
- 1983 Water quality, its significance in Western Australia: Water Research Foundation of Australia, proceedings 1983

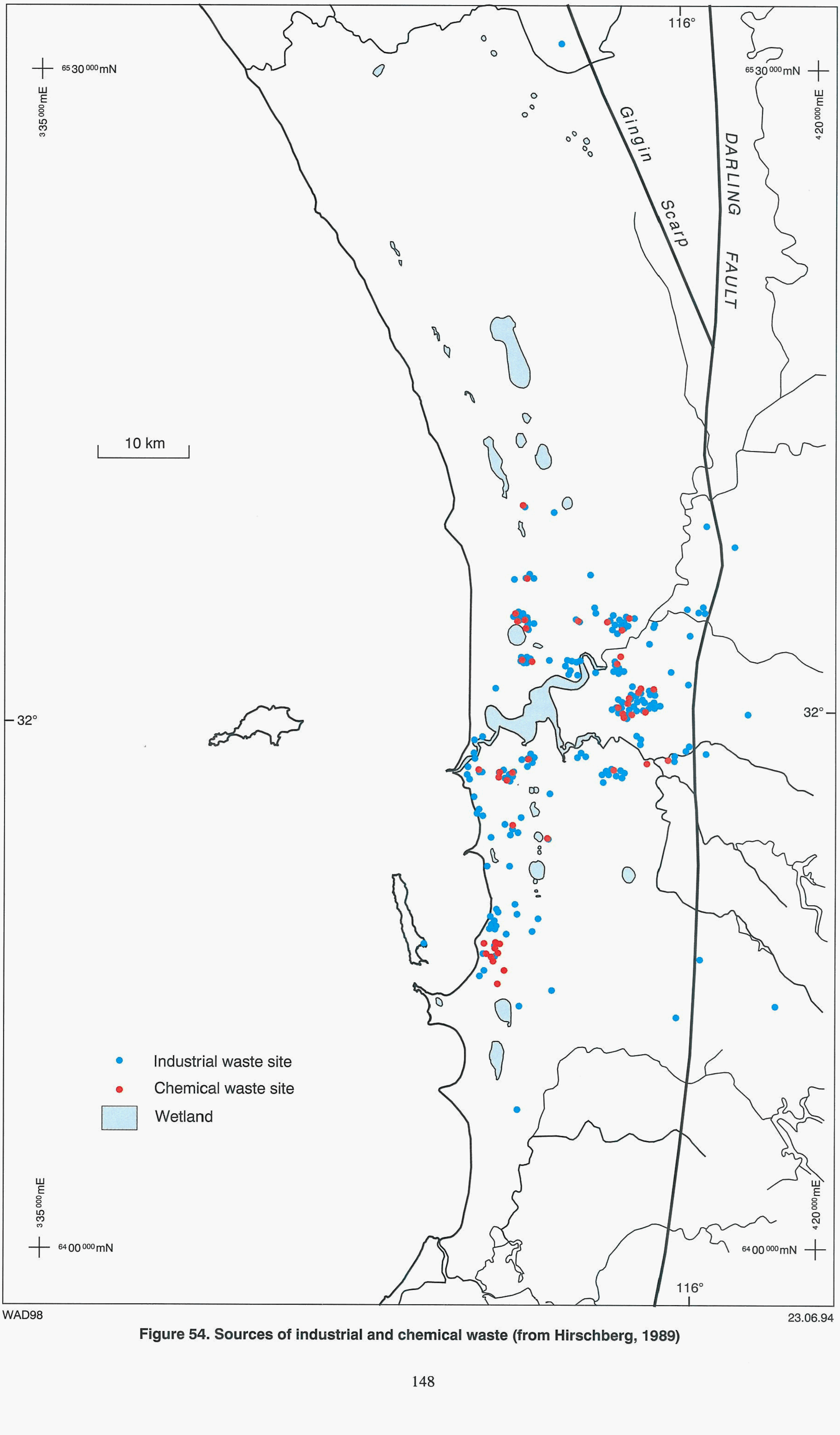

Figure 54. Sources of industrial and chemical waste (from Hirschberg, 1989)

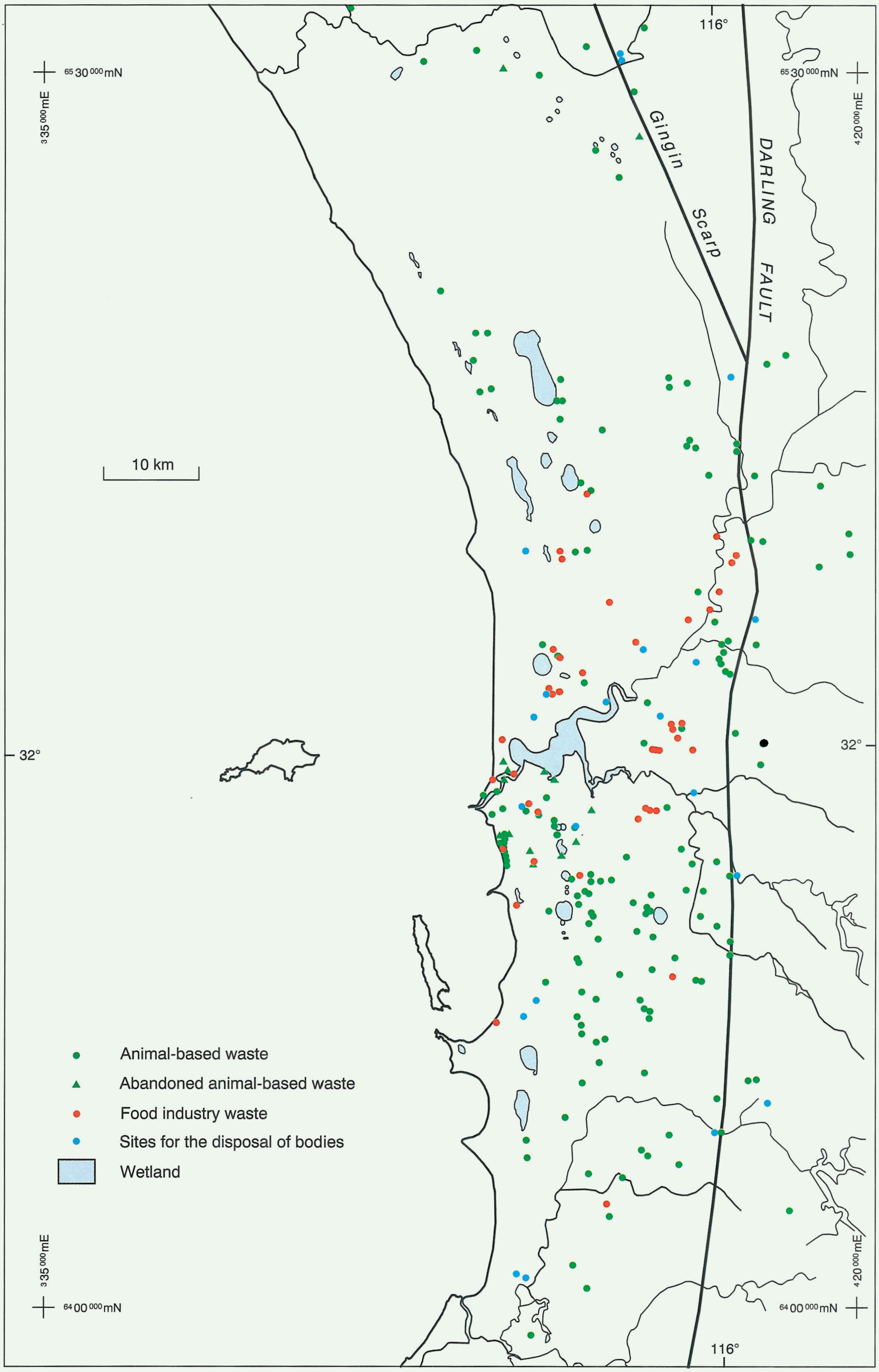

Figure 55. Sources of animal-based, food industry waste, and sites for the disposal of bodies (from Hirschberg, 1989)

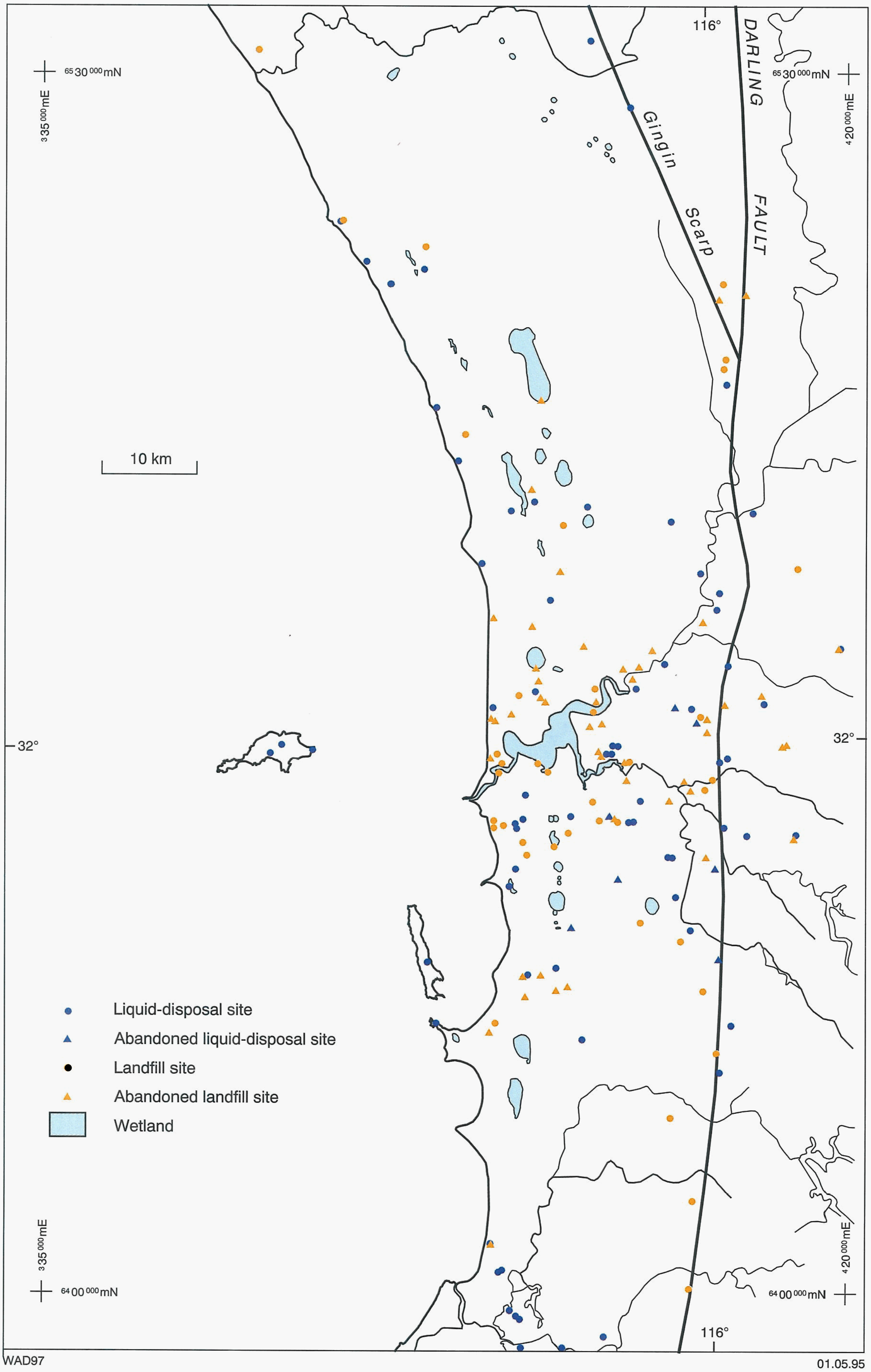

Figure 56. Distribution of sanitary and liquid-disposal sites (from Hirschberg, 1989)

- 1988 Swan Coastal Plain groundwater management conference: Western Australian Water Resources Council, proceedings 1989.

Groundwater-quality protection

The Environmental Protection Act 1986 empowers the Department of Environmental Protection with the overall management of groundwater contamination. In executing the regulations of the Act, the Department has delegated certain responsibilities for domestic-waste disposal to the Health Department, and the licensing of industrial-waste disposal to the Water Authority. Within the Act, the Department of Environmental Protection has the power to enforce remedial cleanup work of accidental and deliberate contamination of groundwater being carried out by those responsible for the contamination.

The Water Authority has provisions under its legislation to make by-laws to manage landuses in declared public water-source areas and has established a policy on catchment protection in order to maintain quality of drinking-water supplies. This policy was adopted by the Board of the Water Authority in April 1991. The Water Authority has identified three priority classifications for its present and future public water supply catchments, namely Priority 1, 2 and 3 source-protection areas. These classifications apply to both surface and groundwater catchments.

The groundwater priority source-protection areas, within the Perth Region, are shown on Figure 57. Irrespective of the protection classification, all water produced from these catchments complies with Health Department requirements, based on the National Health and Medical Research Council and Australian Water Resources Council drinking-water guidelines.

Priority 1 source-protection areas cover public water-supply areas where water-resource protection has the highest priority in land-planning management. These catchments are usually in public ownership and there is either no development or they are subject to well-managed landuse that does not pose any greater risk to the quality of the water than an undeveloped catchment. The protection objective is non-degradation, and is achieved through strict limitations on landuses within the catch-ments. Urban development is an incompatible landuse in Priority 1 source-protection areas. The maintenance of these areas ensures that water sources will continue to be available for the production of the highest possible quality water.

Priority 2 source-protection areas are catchments where water production has a high priority, but is not necessarily the primary consideration for land planning. These catchment areas are usually in private ownership, and limited and managed land development is acceptable. However, Priority 2 source-protection areas recognize existing land zoning and tenure. Developments must comply with a land- and water-management plan for the area. It is accepted that some contamination may exist and there is a risk of further contamination. Management will be primarily effected through restrictions on landuses aimed at ensuring that the level and risk of pollution in these areas is not unduly increased. Where possible, the risk is reduced through the reservation of parks and passive-recreation areas. Urban development is not a preferred landuse.

Priority 3 source-protection areas are catchments where other landuse values predominate over water protection in land planning and management. These areas usually cover existing urban areas or areas planned for urban development. There is a risk of long term contamination of water resources from urbanization and the possible requirement for higher treatment costs in developing future water-supply schemes in these areas. However, planning and management of developments in these areas aim to minimize these risks as far as is practical. The levels of control or restrictions are generally lower than for Priority 2 source-protection areas. The Water Authority endeavours to limit any pollution risks to substances that do not constitute a health hazard, and that are easily and cheaply removed from water.

The minimum level of protection required for Priority 1, 2 and 3 source-protection areas includes

- Exclusion of urbanization, industrial developments and most farming activities; restrictions on forestry (Priority 1).
- Installation of reticulated sewerage in urban areas with appropriate disposal of wastewater effluents, preferably off catchment (Priorities 2 and 3).
- Septic-tank densities and location in non-urban areas to comply with Water Authority recommendations (Priorities 2 and 3).
- Exclusion (Priority 2) and restriction (Priority 3) of industrial and commercial activities handling or processing noxious, toxic or polluting substances.
- Commercial areas designed to prevent catchment contamination through stormwater runoff or discharge of wastes (Priorities 2 and 3).
- Restrictions on intensive agricultural development (Priorities 2 and 3).
- Exclusion (Priority 2) and restriction (Priority 3) of disposal sites for polluting wastes. Sites with appropriate location, construction and management to ensure that no significant pollution can occur, may be acceptable in some Priority 3 areas.

Groundwater and the environment

The environment is an integral part of groundwater management and both quantity of groundwater abstraction and the resultant quality of the groundwater affect the health and sustainability of environmental ecosystems. Good land planning takes into account all aspects of groundwater management and, in the Perth Region, land development projects are particularly sensitive to environmental constraints. As managers of the groundwater resources, the Department of Environmental Protection and the Water Authority seek an effective

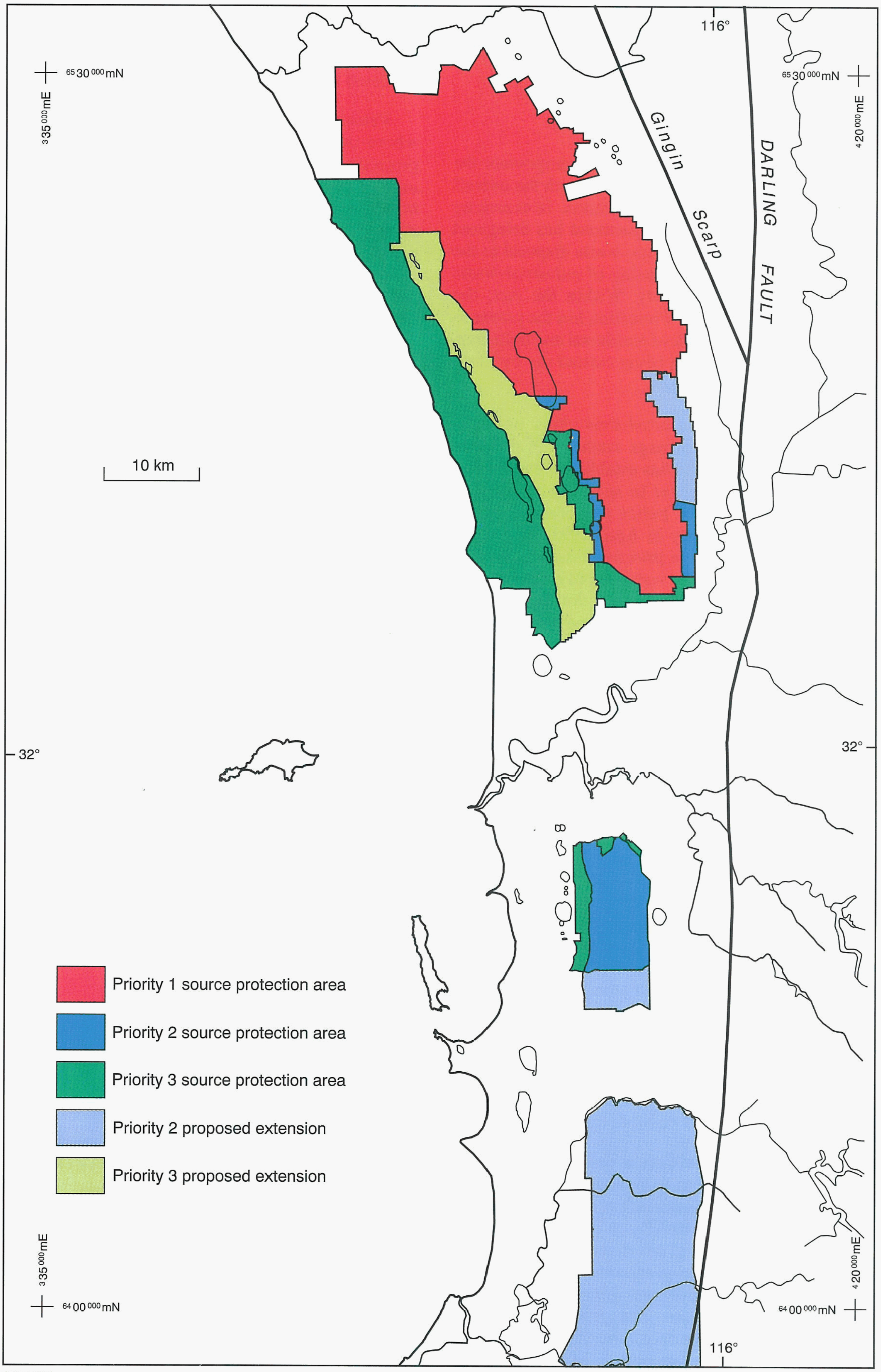

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Figure 57. Water Authority priority source protection areas

interrelationship between landuse and groundwater management through defined priority beneficial uses for the groundwater resources such as environment and recreation, public water supply, and private water supply.

Priority beneficial uses for the groundwater resources must relate to the opportunities for land development. Urbanization provides a potential for groundwater pollution and is, therefore, in conflict with environmental and public water supply beneficial uses. The pollution potential is primarily from industrial areas, waste-disposal sites and unsewered developments.

The Gnangara (North and South) and Jandakot groundwater mounds are major sources of good-quality and secure water supplies, where the pollution potential is large. These areas are primary groundwater source areas for public water supply and maintenance of wetlands. It is therefore essential to protect these groundwater resources from any risk of degradation of quantity or quality. Under the provisions of the Environmental Protection Act 1986, an Environmental Protection Policy (EPP) for the Crown Land of the Gnangara Mound (North and South) was gazetted in 1992. The purpose of this policy is to protect

- *the level and quality of groundwater on or under the policy area (an area consisting of Crown Land and covering a large portion of Gnangara Mound), and*
- *native vegetation and wetlands in the policy area.*

Proposals for landuse changes in these areas are required to be subjected to at least a full public environmental review. This review must include an appropriate management strategy to safeguard the groundwater resources to the maximum extent. The review must also provide an assessment of the benefit of the land-development proposal that can be balanced against the risk of loss of any identified beneficial use of the groundwater resource.

Wetlands management

The healthy maintenance of wetlands is a major objective of groundwater management. Each of the different wetland types on the Swan Coastal Plain, within the Region (Le Provost et al., 1987), supports a diverse flora and fauna ecosystem (Arnold and Wallis, 1987). Since European settlement, the number of naturally occurring wetlands has progressively diminished due to urban and rural land development, and about 50% of the wetlands has been either infilled or drained (Arnold and Sanders, 1981). Clearing of land for agriculture has also caused major changes to about 70% of the wetlands (Halse, 1989).

Most of the lakes of the Swan Coastal Plain are hydraulically connected to the watertable and are particularly sensitive to seasonal variations in watertable elevations. A small decline in the watertable will cause large peripheral areas of the shallow lakes to dry out progressively earlier each summer and only small changes to the surface-water area of the deeper lakes. A permanent decline in the waterlevel may cause death of wetland vegetation and introduction of exotic weeds. In the urbanized areas where watertable levels have risen due to increased groundwater recharge, many of the original swamps have become permanently inundated, causing death to flooded vegetation.

In areas where the invert level of drains, streams, brooks and rivers is below the adjacent watertable, groundwater discharge occurs and contributes to the base flow. Declining watertable levels will cause a reduction in base flow of these drainages and possible water-deficient stresses to the fringing vegetation. A reduction in base flow, due to groundwater abstraction, may be unacceptable in nature reserves such as those of Ellen Brook and Bennett Brook.

Groundwater contaminated with nutrients from septic tanks and fertilizers, together with urban runoff, has caused eutrophication of some of the wetlands (Cargeeg et al., 1987) and contributes to clogging of drains with weeds and algal blooms. Nitrates, once beneath the root zone of vegetation, are not attenuated by the unsaturated sandy soils and so leach down to the watertable. Phosphates are fixed by the sand of the Spearwood and Quindalup Dunes, but once the fixing capacity of this sand has been exceeded, the phosphates will also leach down to the watertable (Whelan et al., 1981).

Appleyard (1990) studied the flux of nitrogen and phosphorous from groundwater to the ocean and concluded that the nitrogen flux ranges from less than 100 kg/year/km of coast, to more than 10 000 kg/year/km of coast. More recent work (Appleyard, 1994b) has shown that, in areas of highly transmissive Tamala Limestone, the nitrogen flux to the ocean may exceed 200 000 kg/year/km of coast. The high nitrogen flux values follow land development, and are found near market gardens, industrial areas, and unsewered residential areas (Fig. 58). The phosphorus flux from groundwater to the ocean is generally less than 100 kg/year/km of coast (as phosphate) and is not directly related to landuse. Low phosphorus concentrations in groundwater probably result from the high adsorption capacity of the coastal sediments and the low solubility of phosphate minerals. A similar study to determine the nutrient discharge to the Swan–Canning Estuary from groundwater (Appleyard, 1992) showed that a maximum of 160 tonnes of nitrogen and 5 tonnes of phosphorus could be discharged from groundwater to the estuary. These values are small compared with loads of nitrogen and phosphorus of 500 and 60 tonnes/year respectively estimated to be received by the estuary from all surface-water sources. The study concluded that there is no evidence of increasing nutrient concentrations in the groundwater adjacent to the estuary.

Contaminants such as nutrients, heavy metals, oil and polycyclic aromatics may enter the groundwater-flow system from urban stormwater runoff (Bliss et al., 1979). Some stormwater drains discharge directly into wetlands causing direct contamination of these wetlands (Bishaw, 1980). Leachates, including ammonia, heavy metals and salts from waste-disposal sites are locally contaminating the groundwater and, in some areas, polluting

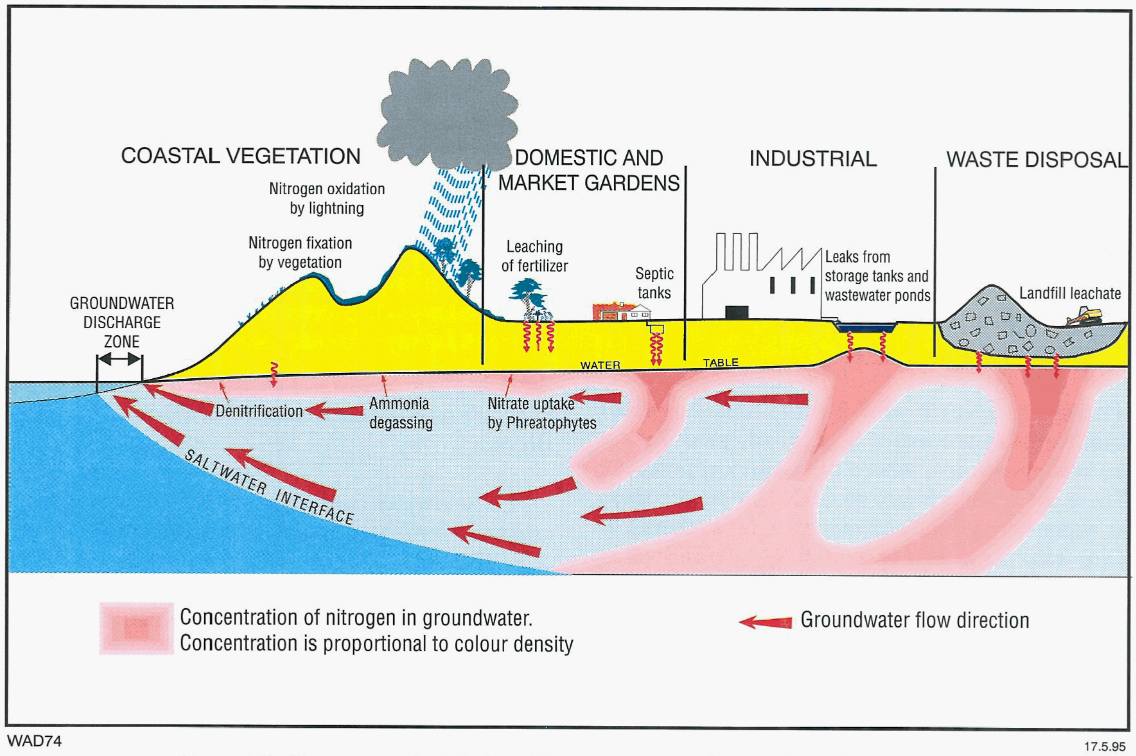


Figure 58. Sources and sinks for nitrogen in groundwater (from Appleyard, 1990)

nearby wetlands (Hedgcock and Moritz, 1989) causing degradation of the wetland ecosystem.

In order to ensure protection from groundwater-borne contaminants, and from stress due to groundwater abstraction, the Water Authority and the Department of Environmental Protection have formulated management policies to preserve and conserve wetlands within the Perth Region. Environmental values have been used to develop management strategies for individual wetlands (Water Authority of Western Australia, 1991). The following wetland-management objectives have been recommended by Balla and Davis (1993).

- Wetlands suitable for the survival of the naturally occurring biota should be identified and preserved. In groundwater abstraction areas, this may require perennial wetlands to be artificially maintained by groundwater (from production bores) of quality similar to that of the wetland. For naturally occurring seasonal wetlands, the drying process is important but should not begin much before December of each year and the rate of waterlevel decline should not exceed about 20 mm/day.

- The vegetation in and around naturally occurring wetlands should be preserved for animals to use as a habitat for feeding, breeding and shelter.

- In order to prevent eutrophication, stormwater rich in nutrients should not discharge into the wetlands selected for preservation.

- The conservation of all types of wetlands within the Perth Region should be encouraged and, where possible, production bores should be located down hydraulic gradient from them.

Vegetation management

The native and introduced vegetation of the Perth Region provide important habitats for the survival of fauna in the region and stability of the environment. Without vegetation the variety of animal life would be greatly reduced and soil erosion by wind and water would cause devastation to the landscape. There are many thousands of species of plants in the Perth Region and these have been described in detail by Marchant et al. (1987). In the urban areas it is the responsibility of the community and local government to ensure that the healthy survival of vegetation is maintained. Within the State Forests, Crown Land and Conservation Reserves, the care of the vegetation is the responsibility of the Department of Conservation and Land Management. Because water reserves are placed over much of the State Forests, the primary landuse is for water production. For this reason, the Department of Conservation and Land Management manages the pine forests, not only for wood production, but also particularly for water production by the Water Authority. Throughout the region, the Conservation Reserves have been selected and located to represent the entire range of ecosystems existing within the region and should be protected and conserved.

In areas where the watertable is shallow, the vegetation may depend on groundwater for transpiration and transport of nutrients from roots to leaves. During the hot, dry summer months when soil moisture and watertable levels are low and plant water demand is great, many species of plants show natural stress signs of water deficiency. Some plants, however, are capable of shutting down the transpiration processes during these periods. Plants that have deep roots to the watertable transpire more than the shallow-rooted plants which rely only on limited, and often seasonal, soil moisture (Colquhoun, 1986). Wetland plants, generally reliant on the watertable for water intake, are more likely to suffer if waterlevels decline rapidly than plants growing higher in the landscape and well above the watertable (Alpin, 1976). In wetland areas, if the decline in the watertable is gradual, the deep-rooted plants that have become reliant on the watertable will adjust to the lower waterlevels. If the decline in watertable is rapid, as can be expected around production bores, mature plants may suffer considerable water-stress deficiencies. Localized, sudden tree deaths have occurred as a result of lower than average rainfall, reduction in soil moisture and a decline in watertable levels exacerbated by groundwater abstraction (Water Authority of Western Australia, 1992b). However, in areas distant from groundwater abstraction, where trees have survived for many years before their roots have reached the watertable, tree deaths must be primarily due to lack of soil moisture rather than gradual decline in the watertable. Over wide areas of native bushland, the soil moisture content within the root zone of the vegetation is probably low due to lower than average rainfall and possibly a reduction in the water infiltration properties, or wettability of the soil. In these areas, tree deaths can be expected during very hot and dry periods. Adjacent to production bores, plants that rely on the watertable for water uptake may be replaced by plants which are not watertable dependent.

In areas of healthy native bushland and pine forests, most of the rainfall returns to the atmosphere by evapotranspiration. The rate of evaporation varies seasonally depending on the air temperature, depth to the watertable, soil moisture content and the density of plant canopies. Evaporation rates are greater from surface water of wetlands and decrease with increasing depth to the watertable, but may be equivalent to about 50% of the evaporation from surface water one metre below ground-level (Pollett et al., 1979). A small lowering of the watertable will, therefore, reduce evaporation losses, resulting in a greater fraction of the rainfall being available for groundwater abstraction. Studies carried out by the Department of Environmental Protection and the Department of Conservation and Land Management have shown that an induced watertable drawdown of at least 0.5 m is within the natural seasonal fluctuations of the watertable and will have insignificant environmental effect (Dames and Moore, 1986). An objective of groundwater resource management is to restrict drawdown with the dual result of decreasing evapotranspiration while maintaining healthy vegetation.

By flownet analysis, the equivalent of about 10% of rainfall recharges the unconfined superficial aquifer beneath the native bushland of the Gnangara Mound (North). Sharma and Pionke (1983) estimated that the recharge beneath native bushland is about 12% of the annual rainfall and that beneath an unthinned mature pine forest the recharge is negligible. Some recharge can be obtained beneath the pine forests by reducing the density of trees. This will decrease interception of rainfall and reduce transpiration of stored soil moisture (Butcher, 1977). As a consequence, the best locations for groundwater abstraction are often within the pine forests and in upland areas where the native vegetation is not dependent on the watertable. In order to spread the effects of groundwater abstraction, groundwater needs to be pumped from the base of the superficial aquifer or, where possible, from the deeper Mirrabooka, Leederville and Yarragadee aquifers. By manipulating rainfall recharge and groundwater abstraction in this way, the groundwater resources of the Perth Region can be managed both for sustainable yield and conservation of the environment.

Groundwater supply and treatment

Bore yield

All the major aquifers are capable of yielding up to 10 000 m^3/d; however, borehole yield depends mostly on bore construction. Various bore constructions are used in the Perth Region. High-capacity production bores commonly utilize steel, fibreglass or varieties of plastic casing, with wirewound stainless steel screens. The majority of lower yielding, shallow, garden-watering bores use small diameter polyvinyl chloride casing with stainless steel mesh screens.

Individual bore yields from the superficial aquifer range from more than 10 000 m^3/d in cavernous Tamala Limestone near the coast, through 500–2000 m^3/d in the central Bassendean Sand area, to less than 100 m^3/d in the clayey areas of the Guildford Clay. The Water Authority production bores, which are generally screened in the bottom third of the superficial aquifer, yield 1000–2000 m^3/d from the Bassendean Sand, and up to 10 000 m^3/d from the Tamala Limestone. Bores constructed for parkland irrigation throughout the region usually achieve yields of 500–1000 m^3/d. Most bores used for garden watering in the urban areas are constructed to yield between 100 and 200 m^3/d. In a few areas, such as adjacent to the Swan River between Perth and Guildford where the superficial formations are mostly clay, borehole yields may be less than 100 m^3/d.

The Rockingham Sand and Kings Park aquifers are used only for parkland irrigation, and bores are generally constructed to yield 1000–2000 m^3/d, and 500–1000 m^3/d respectively.

Bore yields from the Leederville aquifer depend largely on bore construction and water requirements. Water Authority production bores, which commonly use screen lengths of 50–100 m, achieve yields up to 5000 m^3/d. Bores for parkland irrigation yield 200–3000 m^3/d in the northern area and up to 1500 m^3/d in the southern area. In the Swan Valley, private bores generally yield about 500 m^3/d.

The Yarragadee aquifer is used almost exclusively by the Water Authority, and bores are constructed with up to 100 m of screen to yield as much as 10 000 m^3/d.

Problems in obtaining the desired yield from a bore may be due to a variety of physical causes such as

- invasion of the aquifer with drilling fluid;
- mixing of clay and sand of an interbedded sequence due to washouts or caving during drilling or bore development;
- insufficient development;
- mixing of aquifer and gravel-pack material due to over-aggressive development;
- infilling of the bore with aquifer material that has passed through the screens; and
- clogging of screens with fine material from the aquifer or from the gravel pack.

The most common problem associated with production bores is the progressive decline in yield. Yields may decline as pumping equipment becomes less efficient with time. However, the most common problem is the gradual decline in specific capacity (pumping rate divided by drawdown at a particular time) of a bore from commencement of production. This is usually recognized by an unexpected drop in bore yield or uncharacteristic excessive waterlevel drawdown (or a combination of these) and is caused by physical, chemical and microbial processes. The most common physical causes are related to progressive clogging of screens and infilling of the bore with sediment.

Encrustation and corrosion

The screened section of a production bore may become clogged with chemical precipitations and result in reduced yields and/or increased drawdowns. In the Perth Region the most commonly occurring encrustations are those of iron oxyhydroxides and, adjacent to the coast, calcium carbonate. Encrustations of iron oxyhydroxides occur when ferrous-bearing anaerobic groundwater becomes oxygenated at the screens, causing oxidation of the ferrous ion to ferric and precipitation of insoluble ferric oxyhydroxides. This may be more common in bores adjacent to stormwater compensation basins where large quantities of oxygenated water are recharging the aquifer (Appleyard, 1993b).

Calcium carbonate is sometimes precipitated on screens of bores set against the Tamala Limestone, Ascot Formation, and the calcareous beds of the Mariginiup Member of the Leederville Formation. Abstraction causes a reduction in pressure at the screen, inducing dissolved carbon dioxide to be released, thus causing a change in carbonate–bicarbonate equilibrium and precipitation of calcium carbonate.

Local and rapid bore failures occur in many areas and are nearly always due to microbial clogging of the screens by iron-related bacteria which commonly exist in the transition zone where the ferrous ion is chemically oxidized to ferric (McLaughlan and Knight, 1989). The bacteria thrive in the reduced pressure environment of the screens where they multiply rapidly and eventually block the screens with their voluminous, slimy mucilaginous sheaths. Treatment of the screens for iron bacteria is generally only temporary and, because of the explosive growth rate of the bacteria, most infected bores become useless in a very short time.

Corrosion of bores and reticulation pipes is exacerbated by the presence of sulfur bacteria. In bores, the sulfate reducing bacteria are mostly anaerobic, heterotrophic organisms that reduce sulfate to sulfide to produce hydrogen sulfide and sulfuric acid, both of which are corrosive. In irrigation pipes, the aerobic sulfur oxidizing bacteria may thrive, particularly if the water is acidic with a relatively low pH. Under these conditions the bacteria develop into filamentous masses which utilize reduced sulfur compounds to produce sulfuric acid, thus causing corrosion of the pipes. In extreme cases the pipes may become clogged by the gelatinous, filamentous mass of the bacteria. This kind of clogging has occurred in reticulation pipes in the Bayswater and Gwelup suburbs of Perth and is often associated with high sulfate levels from contamination of groundwater by industry in the Bayswater area and by market gardening in the Gwelup area.

Since the problems associated with iron and sulfur bacteria are not ubiquitous, drilling equipment should be sterilized prior to drilling in an unaffected area and all bores should be sterilized after completion of development. These procedures will help retard, although probably not prevent, spreading of the bacteria.

Bore instability

Instability of boreholes is a common occurrence and is due to incorrect bore construction. All the aquifers in the Perth Region locally contain silty, fine-grained material which, if not adequately screened out, will flow with the groundwater and be discharged by the pumping bore. Once discharge of silty material commences, the process gradually increases as the area of silt uptake expands due to subsurface erosion. As material is progressively removed from the borehole, the aquifer will become unstable adjacent to the screened interval. This commonly happens in bores that have inappropriate screens set against the superficial, Mirrabooka, and upper Leederville aquifers. If the screened interval is at shallow depth, subsidence may eventually occur around the pumping bore. To circumvent these problems, the screen aperture size is generally selected so that about 40% of the aquifer material can enter the bore during development of the bore. If a gravel-pack is used in the annulus of the bore, the average size of the pack should not exceed three times the average grain size of the aquifer and the screen aperture should be small enough to retain 90% of the pack material within the annulus of the bore.

Land subsidence and drainage

The potential for land subsidence caused by groundwater abstraction is small if large declines in hydraulic head are avoided. Subsidence is usually due to the compaction of clay, with a small component relating to compressibility of the aquifer. The Mesozoic sediments are moderately consolidated, and there is a very low potential for compaction in the confining beds overlying the major aquifers. Groundwater abstraction from the confined aquifers since 1920 has resulted in a 25 m decline in head in the Leederville aquifer (AM36B), and a 10 m drop in head in the Yarragadee aquifer at Leederville (Wharton, 1991). This head reduction is small, and there has been no subsidence apparent near these bores. However, the land surface should be monitored for subsidence adjacent to production bores in the deep aquifers where decline in hydraulic head will be great.

In the superficial aquifer, highly compressible clays are limited to the Swan River alluvial flats. Compaction of the Guildford Clay is only likely to occur if there is a large decline in the watertable.

Subsidence of a karst type characterizes the coastal belt of Tamala Limestone, where there are well-developed natural karst features at the watertable. Accelerated development of sinkholes could result from changes to the natural hydraulic environment caused by urbanization, and increased recharge and channelling of rainwater into stormwater sumps may be a significant factor. It is not clear to what extent groundwater abstraction could contribute to an increased rate of solution of the limestone, with the consequent collapse of overlying sand. Withdrawal of sand with groundwater from cavities within the limestone may cause collapse of overlying sand into the cavities.

Subsurface erosion has caused small-scale localized sinkholes to develop in the vicinity of springs discharging on the Swan River levees. Such erosion, takes place if fine sand and silt are discharged with the groundwater from drains or from bores. Because of the removal of fine-grained sediment, piping may occur at the discharge point. If groundwater carrying sediment continues to discharge, the pipe or subsurface erosion will extend in the direction of headward removal of the fine material. Piping results because the clayey sediment overlying the aquifer is sufficiently cohesive to form a roof over the developing erosion pipe. The pipe will continue to migrate until it reaches an area where the roof is only partially supported by the clay and a sink hole may then develop at the surface (Fig. 59). There is no way of knowing how far from the discharge point sinkholes will appear and, depending on the depth below ground level to the watertable, they may not appear for many years. Particular care should be taken during landscaping to prevent subsurface erosion which, if unchecked, will eventually result in subsidence. Subsidence of this kind and damage to buildings has occurred adjacent to the Swan River in the wake of uncontrolled landscaping and poor drain construction.

Two kinds of drains have been constructed within the area to remove water from water-logged areas or to lower the watertable and make the land suitable for development; those at the land surface and those below ground level.

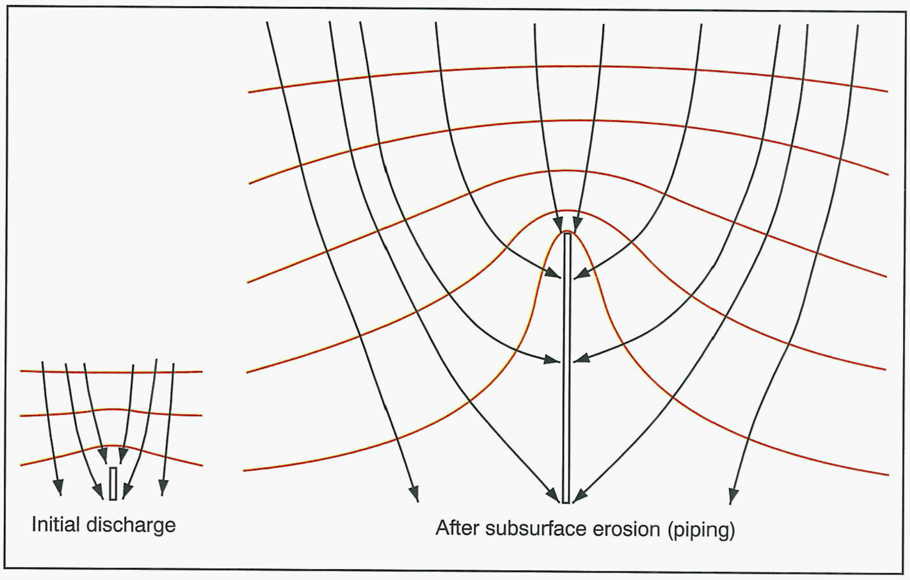
Drains at the land surface are primarily used to remove water from areas of potential agricultural land that are seasonally inundated. This kind of drain is commonly utilized in the southern area. Elsewhere, these land-surface drains are used mostly to transport stormwater from housing and roads to stormwater sumps or compensation basins. Being at the land surface and exposed to the atmosphere, the drains often become clogged by weeds and in some areas, where the groundwater is rich in nutrients, by algal blooms. Because these drains are visible, any problems associated with clogging can be readily rectified. In areas of the Guildford Clay and alluvium (Plate 50), where the land surface is frequently inundated, drains are often not very effective because of the low hydraulic conductivities of the clayey sediments. To be effective in these areas, the drains need to be closely spaced.

Subterranean or below-ground drains are extensively used to lower the watertable in urban Perth. Blocking of these drains is a common occurrence and, similar to blocking of boreholes, is caused by the accumulation of fine silty material within the drains. Where the drains are immediately below the watertable, particularly in unsewered areas, they often become clogged with slimy aerobic iron bacteria and algae. Agricultural drains are relatively inefficient and are notorious for clogging. As for gravel packs in boreholes, incorrect selection of filter packs in drains can lead to silting or blocking of drains. Crushed blue metal (granite and dolerite) is considered unsuitable for filter-packing drains because the resultant pack contains irregular pore spaces of varying sizes which eventually become blocked with fine sand and silt. Graded sand or gravel of grain size approximately 3 to 5 times larger than that of the average grain size of the material in situ should be used to pack the drains. Even this type of pack could eventually become blocked with bacteria and algae. The effect of re-opening drains is to lower the watertable, thus alleviating intermittent flooding in the low-lying areas and possible structural damage to buildings by wetting and drying of the clay sediments at a shallow depth. Adjacent to the Swan and Canning River, structural damage to dwellings has been attributed to swelling clays of the Guildford Clay which expand when wet and shrink when dry. In some areas where the below-ground drains are ineffective, the watertable has risen into the foundation of buildings and roads causing rising damp in buildings and promoting pothole development in roads.

The problems associated with boreholes and drains exist mainly as a consequence of land development. There are, however, many other groundwater-related problems associated with land development. The most common and widespread problem is increasing dampness and, in extreme cases, flooding caused by rising watertable levels resulting from induced additional rainfall recharge to the groundwater from urban roof and road catchments. In many low-lying areas, extensive and elaborate drainage systems need to be installed before development can proceed. These drains usually discharge into lakes, rivers or the ocean. To the north and south of the Perth Region, irrigation has caused rising watertable levels and land salinization in some areas where the groundwater is naturally saline. Such land salinization is not yet prevalent within the Perth Region, but with increased urban development inducing rising watertable levels, this problem may develop in areas of saline groundwater (Plate 56) and shallow depth to the watertable (Plate 52).

Salinity

In areas of widely varying vertical groundwater salinities (Plates 67–77), the salinity of pumped groundwater may vary with time depending mainly on the rate of groundwater abstraction. To prevent intra- and inter-aquifer



Groundwater flownets showing intake area of spring

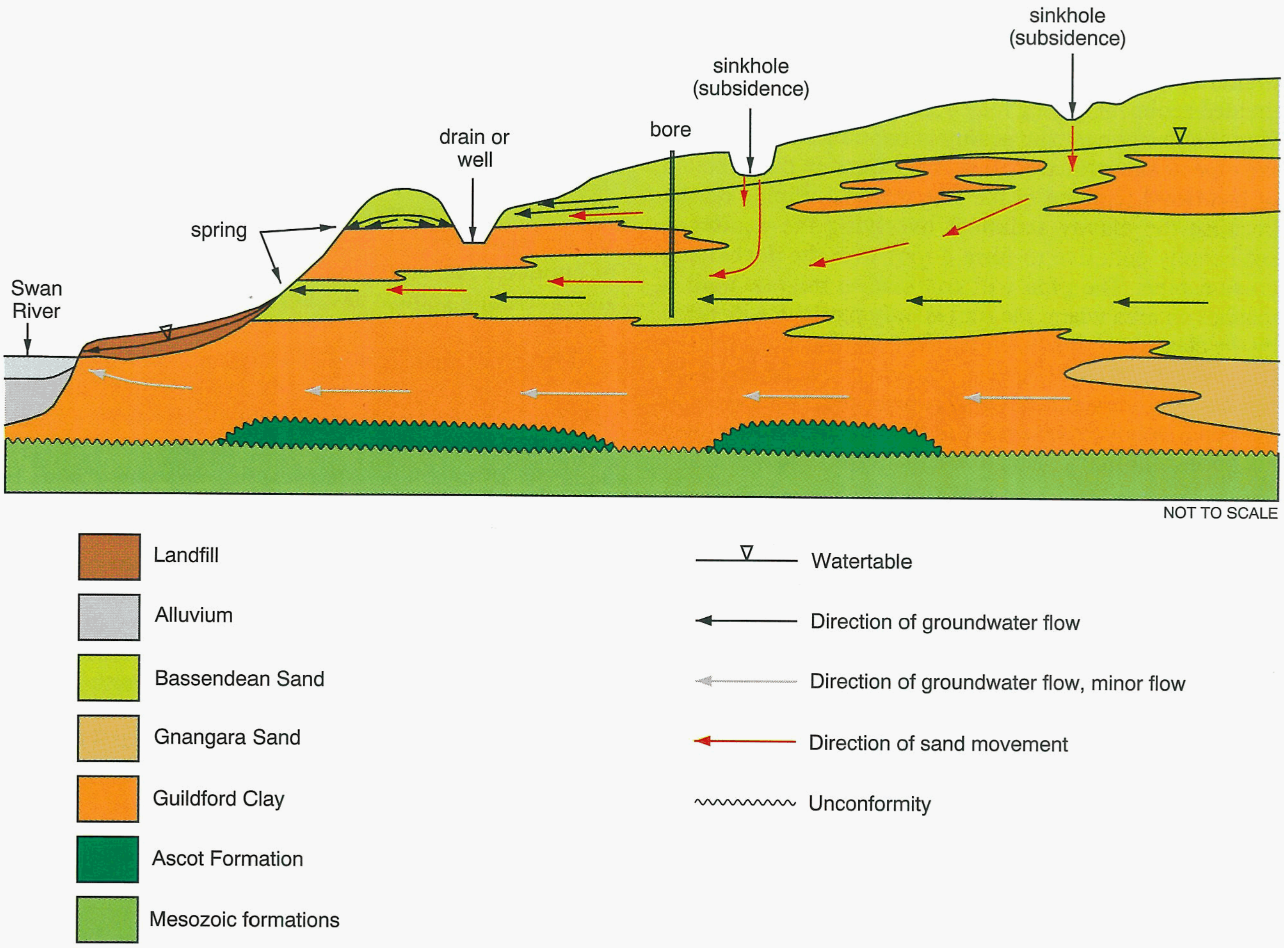


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Figure 59. Schematic diagram; subsurface erosion and subsidence due to discharge of groundwater and sand at spring, drain and bore

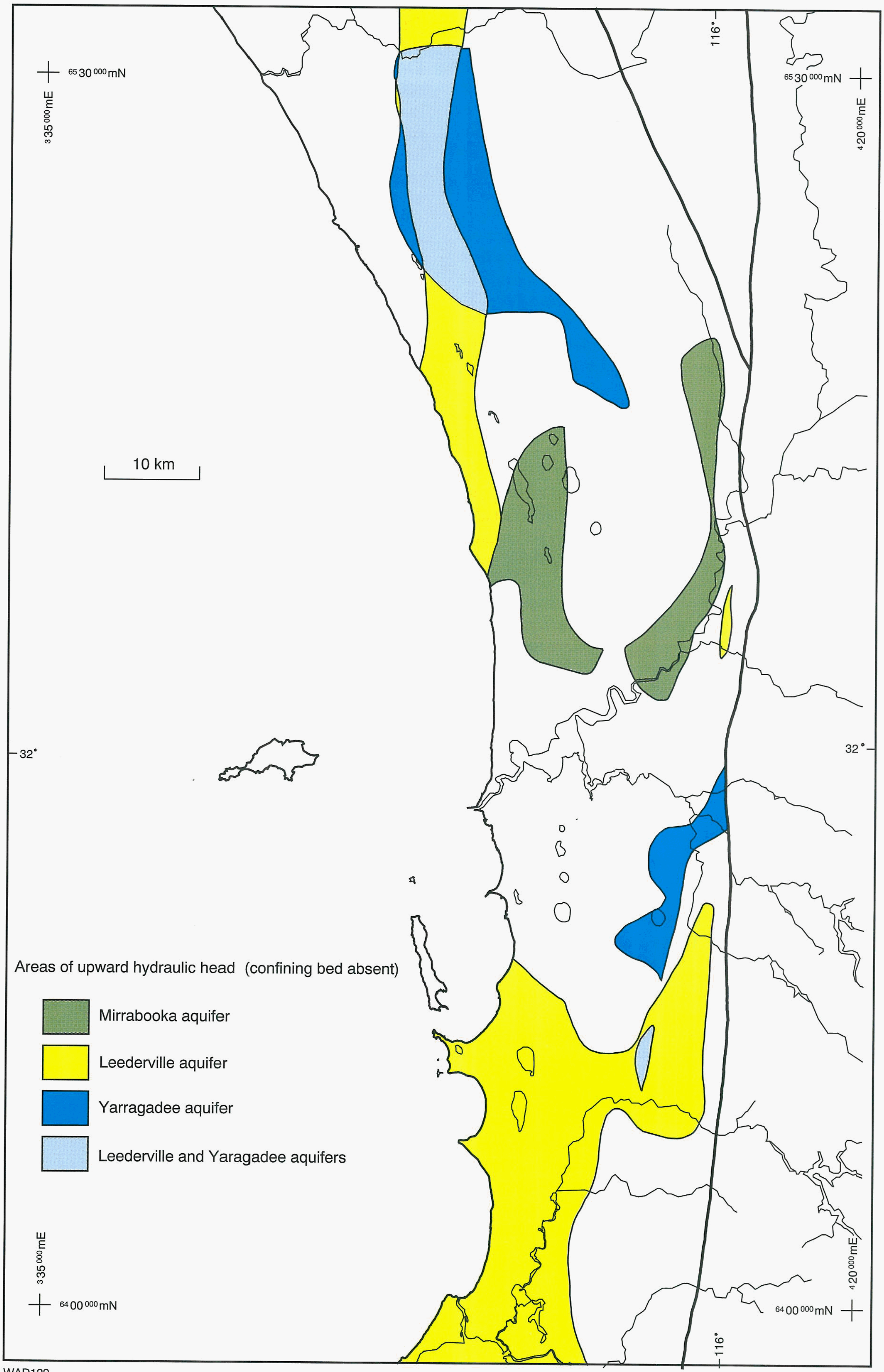

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Figure 60. Areas and aquifers where cement grouting of bores is advantageous

groundwater flow, borehole screens should not straddle sections of the aquifer with greatly varying groundwater salinities. Also, to prevent the downward or upward flow of groundwater within the annulus between the borehole casing and the aquifer, cement grouting of the annulus is required in some areas. This is particularly important for most bores screened against the deeper aquifers, in areas where confining beds are absent, and where hydraulic heads increase with depth (Fig. 60).

Adjacent to the coast and the Swan Estuary, where the fresh groundwater discharges over a saltwater interface (Fig. 30), hydraulic heads increase with depth, raising the potential for upward groundwater flow within bores. To prevent the upward flow of saline water contaminating the upper freshwater section of the aquifer, bores should not be fully penetrating but have short screened intervals.

Treatment for public and private water supply

Groundwater quality in the superficial, Mirrabooka, and Leederville aquifers of the Perth Region is highly variable and, although typically of low salinity, always requires some treatment before it can be used for public water supply. Groundwater from the Cattamarra Coal Measures of the Yarragadee aquifer also requires treatment. The following treatment steps are commonly used to remove dissolved iron and to flocculate and coagulate turbidity:

- chlorine added to facilitate aeration,
- aerated to remove dissolved iron and hydrogen sulfide,
- lime added to adjust pH,
- alum or a polyelectrolite added to coagulate turbidity,
- coagulant removed in inverted cone,
- filtered through sand for final clarification,
- chlorinated,
- fluoridized, and
- stored for at least one hour before reticulation to consumer.

For those properties that are not connected to the Water Authority water-supply schemes and rely on groundwater for domestic supply, some treatment of the groundwater is invariably required. There are several commercially available water purifiers on the market that are used to treat groundwater supplied to the households. Treatment by these methods is relatively expensive and most households that require private supplies also utilize rainwater from roof catchments.

In many areas of the Perth Region, dissolved iron in the groundwater causes severe iron-oxide staining of buildings and pavings when used for garden irrigation. To reduce these deleterious effects of staining, Jack (1978) developed a method by which a solution of sodium silicate within the reticulation system prevents precipitation of the dissolved iron and subsequent staining.

Management: the challenge ahead

The groundwater resources of the Perth Region are essential to the continuing development of the area and to the healthy survival of the natural environment. The sustainability of groundwater-resource development must be a major objective of management in order to assure security of supply for the future. With increasing pressure of urban development, protection of groundwater quality will assume greater importance. Management of the shallow groundwater also has to consider the intricate link with the wetlands of the Swan Coastal Plain, and the vegetation dependent on the watertable. This is essential for environmental conservation and maintenance of ecosystems.

Management of the groundwater resources of the Perth Region involves the cooperation of all responsible state and local government agencies so that maximum community benefit can be achieved. However, as the agency responsible for management of groundwater abstraction, the Water Authority of Western Australia has assumed the primary role in management of the resources (Ventriss, 1988). The Department of Minerals and Energy, through the Hydrogeology Section of the Geological Survey, has a vital role in providing the hydrogeological expertise required by the Water Authority and the other organizations in arriving at various management commitments and decisions.

Astute groundwater management involving correct location, construction and yields of production bores, suitable drainage systems, and controlled landscaping will enable land development of the Perth Region to proceed in a secure and conservational manner to the benefit of the community and the survival of the environment. The knowledge base and hydrogeological expertise of the principal agencies with responsibility for groundwater must form the basis for management. By adhering to the management principles of groundwater-quality protection, sustainability of groundwater yields, and conservation of the environment, the words of Captain James Stirling will resound for many years to come:

> ***'Supply of fresh water from springs and lagoons is abundant .... on the whole it may confidently be assumed that water is plentiful all over this territory'.***

References

ALLEN, A. D. 1976a, Outline of the hydrogeology of the superficial formations of the Swan Coastal Plain: Western Australia Geological Survey, Annual Report 1975, p. 31–42.

ALLEN, A. D., 1976b, Proposed hydrogeological investigation of selected lakes in the metropolitan area: Western Australia Geological Survey, Hydrogeology Report no. 1361 (unpublished).

ALLEN, A. D., 1977, The hydrogeology of the Mirrabooka East area, Perth: Western Australia Geological Survey, Annual Report 1976, p. 14–21.

ALLEN, A. D., 1978, Geology and hydrogeology of the Becher Point line and geological reinterpretation of adjacent borehole lines: Western Australia Geological Survey, Annual Report 1977, p. 19–28.

ALLEN, A. D., 1979, An outline of the confined groundwater resources in the vicinity of Perth, Western Australia: Western Australia Geological Survey, Annual Report 1978, p. 30–40.

ALLEN, A. D., 1980, The hydrogeology of Lake Jandabup, Swan Coastal Plain, Western Australia: Western Australia Geological Survey, Annual Report 1979, p. 32–40.

ALLEN, A. D., 1981a, Groundwater resources of the Swan Coastal Plain, near Perth, Western Australia, *in* Groundwater Resources of the Swan Coastal Plain (1981) *edited by* B. R. WHELAN: Australia, CSIRO, Proceedings of CSIRO and Water Research Foundation of Australia Symposium, p. 29–74.

ALLEN, A. D., 1981b, The hydrogeology of the Swan Valley, Perth Basin, Western Australia: Western Australia Geological Survey, Annual Report 1980, p. 12–26.

ALPIN, T. E. H., 1976, Consequences of variations of water table levels: vegetation and flora, *in* Groundwater Resources of the Swan Coastal Plain *edited by* B. A. CARBON: Australia, CSIRO Division of Land Resources Management, Symposium Proceedings, Perth, 1975, p. 126–137.

ANSON, B., 1985, Investigation of natural groundwater recharge to the unconfined aquifer of the Swan Coastal Plain 1982–1985: Water Authority of Western Australia, Water Resources Directorate, Groundwater Section, Report W 4, (2 volumes).

APPLEYARD, S. J., 1990, The flux of nitrogen and phosphorus from groundwater to the ocean in the Perth Metropolitan Region: Western Australia Geological Survey, Hydrogeology Report no. 1990/64 (unpublished).

APPLEYARD, S. J., 1992, Estimated nutrient loads discharged into the Swan–Canning Estuary from groundwater: Western Australia Geological Survey, Hydrogeology Report no. 1992/20 (unpublished).

APPLEYARD, S. J., 1993a, Explanatory notes for the groundwater vulnerability to contamination maps of the Perth Basin: Western Australia Geological Survey, Record 1993/6.

APPLEYARD, S. J., 1993b, Impact of stormwater infiltration basins on groundwater quality, Perth Metropolitan Region, Western Australia: Environmental Geology, v. 21 no. 4, p. 227–236.

APPLEYARD, S. J., 1994a, The impact of sewered residential development on groundwater quality in the north-west corridor, Perth Metropolitan area: Western Australia Geological Survey, Hydrogeological Report no. 1994/17 (unpublished).

APPLEYARD, S. J., 1994b, The discharge of nitrogen and phosphorus from groundwater into Cockburn Sound, Perth Metropolitan region: Western Australia Geological Survey, Hydrogeological Report no. 1994/39 (unpublished).

APPLEYARD, S. J., and BAWDEN, J., 1987, The effects of urbanisation on nutrient levels in the unconfined aquifer underlying Perth, Western Australia, *in* Proceedings of the International Conference on Groundwater Systems Under Stress: Australian Water Resources Council, Conference Series no. 13, Brisbane, 1986, p. 587–594.

ARCHIE, R. P., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: American Institute of Mining, Metallurgical and Petroleum Engineers, v. 146, p. 54–62.

ARNOLD, J. A., and SANDERS, C. C., 1981, Wetlands of the Swan Coastal Plain, *in* Groundwater Resources of the Swan Coastal Plain (1981) *edited by* B. R. WHELAN: Australia, Commonwealth Scientific and Industrial Research Organisation, Proceedings of Commonwealth Scientific and Industrial Research Organisation, and Water Research Foundation of Australia Symposium, p. 81–95.

ARNOLD, J. M., and WALLIS, R. L., 1987, Wetlands — a consideration in the development of the unconfined groundwater systems underlying Perth, Western Australia, *in* Proceedings of the International Conference on Groundwater Systems Under Stress: Australian Water Resources Council, Conference Series no. 13, Brisbane, 1986, p. 607–618.

AUROUSSEAU, M., and BUDGE, E. A., 1921, The terraces of the Swan and Helena Rivers and their bearing on recent displacement of the strand line: Journal of the Royal Society of Western Australia, v. 7, p. 24–43.

BACKHOUSE, J., 1979, Palynology of artesian monitoring No. 42 borehole: Western Australia Geological Survey, Palaeontology Report no. 19/1979 (unpublished).

BACKHOUSE, J., 1980a, Palynology of artesian monitoring No. 24 borehole: Western Australia Geological Survey, Palaeontology Report no. 4/1980 (unpublished).

BACKHOUSE, J., 1980b, Palynology of artesian monitoring No. 30Z: Western Australia Geological Survey, Palaeontology Report no. 35/1980 (unpublished).

BACKHOUSE, J., 1981, Palynology of artesian monitoring borehole No. 11: Western Australia Geological Survey, Palaeontology Report no. 19/1981 (unpublished).

BACKHOUSE, J., 1984, Revised Late Jurassic and Early Cretaceous stratigraphy in the Perth Basin: Western Australia Geological Survey, Professional Papers, Report 12, p. 1–6.

BACKHOUSE, J., 1986, Palynology of artesian monitoring No. 2A: Western Australia Geological Survey, Palaeontology Report no. 1/1986 (unpublished).

BALLA, S. A., and DAVIS, J. A., 1993, Managing Perth's wetlands to conserve the aquatic fauna: Wetlands of the Swan Coastal Plain, Volume 5, Water Authority of Western Australia.

BALLEAU, W. P., 1972, Summary of aquifer and bore characteristics of the north Gnangara bore field: Western Australia Geological Survey, Annual Report 1971, p. 11–13.

BANYARD, R. E., and DAVIDSON, W. A., 1991, Management of the confined groundwater resource in the Perth metropolitan area, Western Australia, *in* Proceedings of the International Conference on Groundwater in Large Sedimentary Basins, Perth, Western Australia, 1990: Australian Water Resources Council, Conference Series no. 20, p. 256–266.

BARBER, C., BARRON, R., BROWN, J., BATES, L. E., and LOCKSEY, K., 1993, Evaluation of changes in groundwater quality in relation to land-use changes in the Gwelup wellfield, Western Australia: Australia, Commonwealth Scientific and Industrial Research Organization, Division of Water Resources, Water Resources Series no. 12 (unpublished).

BARBER, C., BATES, L., POWER, T., BRIEGEL, D., and LAMBERT, M., 1990a, Groundwater pollution from underground storage of petroleum fuels on the Swan Coastal Plan; preliminary investigation: Australia CSIRO Division of Water Resources, 1990.

BARBER, C., DAVIS, G. B., and BUSELLI, G., 1990b, Development of procedures for more efficient monitoring and assessment of groundwater contamination from point sources of pollution: Final Report to AWRAC, EPA, WAWA, The Mindarie Regional Council and The Atlas Group, p. 130.

BARNES, R. G., 1977, Hydrogeological report on the Pacminex alumina refinery site, Upper Swan: Western Australia Geological Survey, Hydrogeology Report no. 879 (unpublished).

BAWDEN, J., BESTOW, T. T., and HARRIS, P.G., 1983, Increases in the sulphate content of the shallow groundwater of the Perth region, *in* Water quality — its significance in Western Australia: Australia Water Research Foundation, Seminar Papers, Murdoch University, Perth, 1983, p. 143–148.

BAXTER, J. L., 1977, Heavy mineral sand deposits of Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 10.

BAXTER, J. L., 1982, History of mineral sand mining in Western Australia, *in* Reference Papers, Exploitation of Mineral Sands, Western Australia School of Mines, WAIT AID Ltd, Perth.

BAXTER, J. L., and HAMILTON, R., 1981, The Yoganup Formation and Ascot beds as possible facies equivalents: Western Australia Geological Survey, Annual Report 1980, p. 94–95.

BERLIAT, K., 1964, Report on exploratory drilling for underground water in the Perth Basin west of Byford: Western Australia Geological Survey, Annual Report 1963, p. 9–14.

BESTOW, T. T., 1971, The water balance in the north Gnangara area: Western Australia Geological Survey, Annual Report 1970, p. 14–17.

BESTOW, T. T., 1976, Water balance of the coastal plain — present, *in* Groundwater Resources Swan Coastal Plain *edited by* B. A. CARBON: Australia, CSIRO Division of Land Resources Management, Symposium Proceedings, Perth, 1975, p. 77–88.

BESTOW, T. T., 1977, The movement and changes in concentration of contaminants below a sanitary land-fill, Perth, Western Australia, *in* Effects of urbanization and industrialization on the hydrological regime and on water quality: Proceedings of Amsterdam Symposium October 1977, Convened by UNESCO, Organized by UNESCO and the Netherlands National Committee for the I.H.P.in co-operation with I.A.H.S., UNESCO Publication no. 123, p. 370–379.

BESTOW, T. T., 1982, The potential for geothermal energy development in Western Australia: Western Australia Geological Survey, Record 1982/6.

BISHAW, M., 1980, Preliminary observations on nutrient inputs from external sources at Emu Lake: Murdoch University, Perth, BSc honours thesis (unpublished).

BLISS, P. J., BROWN, J. D., and PERRY, R., 1979, Impact of storm run off from urban areas on surface water quality: Symposium on Hydrology and Water Resources, Perth, Western Australia, p. 249–253.

BOND, R. D., 1964, The influence of microflora on physical properties of soil — field studies on water repellent sands: Australian Journal of Soil Research, p. 123–131.

BOZANIC, D., 1969, Quinns Rock No. 1 well completion report: Western Australian Petroleum Pty Ltd, Petroleum Search Subsidy Acts Report (unpublished).

BUTCHER, T. B., 1977, Impact of moisture relationship in the management of *Pinus pinaster* in Western Australia, *in* Forest Ecology and Management, Water Authority of Western Australia, 1986.

CARGEEG, G. C., TOWNLEY, L. R., SMITH, G. R., APPLEYARD, S. J., and SMITH, R. A., 1987, Perth urban water balance study — volumes 1 and 2: Western Australia Water Authority, Reference WP29.

COCKBAIN, A. E., 1990, Perth Basin *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 495–524.

COCKBAIN, A. E., and HOCKING, R. M., 1989, Revised stratigraphic nomenclature in Western Australian Phanerozoic basins: Western Australia Geological Survey, Record 1989/5.

COCKBAIN, A. E., and PLAYFORD, P. E., 1973, Stratigraphic nomenclature of Cretaceous rocks in the Perth Basin: Western Australia Geological Survey, Annual Report 1972, p. 26–31.

COLLINS, P. D. K., and ROSAIR, P. B., 1978, Serpentine coastal plain water resources survey: Western Australia Public Works Department, Water Resources Technical Report no. 76, April, 1978.

COLQUHOUN, I. J., 1986, Eco-physiological studies of two shrub species growing in the Swan Coastal Plain, Perth: University of Western Australia, PhD thesis (unpublished).

COMMANDER, D. P., 1971, Mirrabooka 1A MWB Bore pump test report: Western Australia Geological Survey, Hydrogeology Report no. 852 (unpublished).

COMMANDER, D. P., 1974, Hydrogeology of the Mandurah–Pinjarra area: Western Australia Geological Survey, Annual Report 1973, p. 20–26.

COMMANDER, D. P., 1975, Wanneroo shallow artesian bores — report on pump testing June 1975: Western Australia Geological Survey, Hydrogeological Report no. 1313 (unpublished).

COMMANDER, D. P., ALLEN, A. D., and DAVIDSON, W. A., 1991, The groundwater resources of the Perth Basin, Western Australia, *in* Proceedings of the International Conference on Groundwater in Large Sedimentary Basins, Perth, Western Australia, 1990: Australian Water Resources Council, Conference Series no. 20, p. 35–46.

DAMES and MOORE, 1986, Gnangara mound groundwater resources — environmental review and management programme: Water Authority of Western Australia, Water Resources Management Branch, Report no.. WM 4, 161p.

DARCY, H., 1856, Les Fontaines publiques de la ville de Dijon: Paris, Victor Dalmont, 647p.

DAVIDSON, W. A., 1979, East Mirrabooka 172 pumping test: Western Australia Geological Survey, Hydrogeology Report no. 1975 (unpublished).

DAVIDSON, W. A., 1981a, Yanchep Sun City Pty Ltd shallow groundwater monitoring report, Yanchep Beach– Two Rocks, October 1980: Western Australia Geological Survey, Hydrogeology Report no. 2323 (unpublished).

DAVIDSON, W. A., 1981b, Results of pumping tests at Sir James Mitchell Park and proposals for groundwater development: Western Australia Geological Survey, Hydrogeology Report no. 2377 (unpublished).

DAVIDSON, W. A., 1983, Bibra Lake groundwater appraisal: Western Australia Geological Survey, Hydrogeology Report no. 2528 (unpublished).

DAVIDSON, W. A., 1984a, A flow-net analysis of the unconfined groundwater in the superficial formations of the southern Perth area, Western Australia: Western Australia Geological Survey, Record 1984/9.

DAVIDSON, W. A., 1984b, Investigation of declining water levels in Gratte's bore and dams East Mirrabooka: Western Australia Geological Survey, Hydrogeology Report no. 2552 (unpublished).

DAVIDSON, W. A., 1987, Hydrogeology of the Lexia area Perth, Western Australia: Western Australia Geological Survey, Hydrogeology Report no. 2796 (unpublished).

DAVIDSON, W. A., 1992, Swan Groundwater Area groundwater resources: Western Australia Geological Survey, Hydrogeology Report no. 1992/50 (unpublished).

DAVIDSON, W. A., and JACK, P. N., 1983, Water nitrates — occurrence and health aspects in Western Australia, *in* Water quality — its significance in Western Australia: Australia Water Research Foundation, Seminar Papers, Murdoch University, Perth, 1983, p. 59–63.

DAVIDSON, W. A., and MORY, A. J., 1990, Prospects of obtaining additional groundwater supplies on Rottnest Island: Western Australia Geological Survey, Hydrogeology Report no. 1990/3 (unpublished).

DEENEY, A. C., 1984a, Jandakot aquifer evaluation test pumping of Lake Thompson No. 70 borehole: Western Australia Geological Survey, Hydrogeology Report no. 2555 (unpublished).

DEENEY, A. C., 1984b, Jandakot aquifer evaluation test pumping of Jandakot No. 30 borehole: Western Australia Geological Survey, Hydrogeology Report no. 2556 (unpublished).

DEPARTMENT OF CONSERVATION AND ENVIRONMENT, 1987, A State conservation strategy for Western Australia; a sense of direction: Department of Conservation and Environment, Bulletin 270, Perth, January 1987.

DEPARTMENT OF CONSERVATION AND LAND MANAGEMENT, 1991, Annual Report 1 July 1990 to 30 June 1991: Department of Conservation and Land Management.

DEPARTMENT OF LOCAL GOVERNMENT, 1992, Local Government Act, 1960–82 (consolidated) and amendments.

DEPARTMENT OF MINERALS AND ENERGY, 1993, Annual Report 1992–93: Western Australia Department of Minerals and Energy.

DEPARTMENT OF PLANNING AND URBAN DEVELOPMENT, 1991, Department of Planning and Urban Development, Annual Report 1991.

DOMENICO, P. A., and SCHWARTZ, F. W., 1990, Physical and chemical hydrogeology: New York, John Wiley and Sons, Inc., p. 57.

EDGELL, H. S., 1964, The occurrence of Upper Cretaceous marine strata of Campanian age at Lancelin, Perth Basin: Western Australia Geological Survey, Annual Report 1963, p. 57–60.

EMMENEGGER, C. C., 1964, Report on exploratory drilling for underground water at Mandurah, Perth Basin, Western Australia: Western Australia Geological Survey, Record 1964/15.

ENVIRONMENTAL PROTECTION AUTHORITY, 1991, Environmental Protection Authority, Annual Report 1990/91: Perth, Western Australia.

FAIRBRIDGE, K. R. W., 1953, Australian stratigraphy: Perth, University of Western Australia Text Books Board, p. 516.

FARRINGTON, P., 1984, Recharge processes on the 'Gnangara Mound', *in* Groundwater Research 1984: Commonwealth Scientific and Industrial Research Organisation, Division of Groundwater Research, p. 15–22.

FARRINGTON, P., and BARTLE, G. A., 1989, Water and chloride balances of banksia woodland on coastal deep sands of south western Australia, *in* Groundwater recharge *edited by* M. L. SHARMA: Proceedings of the Symposium on Groundwater Recharge, Mandurah, Western Australia, 1987, Rotterdam, A. A. Balkema, p. 185–196.

FARRINGTON, P., and BARTLE, G. A., 1991, Recharge beneath a Banksia woodland and a *Pinus pinaster* plantation on coastal deep sands in south Western Australia: Forestry Ecology and Management, v. 40, p. 101–118.

FETTER, C. W., 1988, Applied hydrogeology (2nd edition): Philadelphia, Merrill Publishing Company, p. 105–106.

FORMAN, F. G., 1933, Final report on the correlation of the artesian bores in the metropolitan area, Perth: Western Australia Geological Survey, Annual Report 1932, p. 9–10.

FREEZE, R. A., and CHERRY, J. A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., p. 376.

GERRITSE, R. G., BARBER, C., and ADENEY, J. A., 1988, The effect of urbanization on the quality of groundwater in Bassendean sands: Australia, Commonwealth Scientific and Industrial Research Organisation, Division of Water Resources, Report.

GERRITSE, R. G., BARBER, C., and ADENEY, J. A., 1990, The impact of residential urban areas on groundwater quality, Swan Coastal Plain, Western Australia: Australia, Commonwealth Scientific and Industrial Research Organisation, Division of Water Resources, Water Resources Series no. 3, 27p.

GLASSFORD, D. K., and KELLIGREW, L. P., 1976, Evidence for Quaternary westward extension of the Australian desert into southwestern Australia: Search, v. 7, no. 9, p. 394–396.

GLAUERT, L., 1910, The geological age and organic remains of the Gingin 'Chalk': Western Australia Geological Survey, Bulletin 36, p. 115–127.

HALL, J., 1985, The hydrogeology of Lake Mariginiup, Perth, Western Australia: Western Australia Geological Survey, Professional Papers for 1983, Report 14, p. 1–13.

HALL, J., and DAVIDSON, W. A., 1983, East Mirrabooka production bore M262 pumping test: Western Australia Geological Survey, Hydrogeology Report no. 2531 (unpublished).

HALSE, S. A., 1989, Wetlands of the Swan Coastal Plain — past and present, *in* Swan Coastal Plain Groundwater Management Conference — Proceedings *edited by* G. LOWE: Western Australian Water Resources Council, Conference Proceedings, Perth, 1988, Publication no. 1/89, p. 105–112.

HARDMAN, E. T., 1885, Report on the probability of obtaining a water supply for the city of Perth from artesian wells, with remarks on other possible sources, *in* WAYLEN, A. R., MASON, C. T., SHENTON, G., WOOD, B. C., BARNETT, H. C., LEAKE, G. W., SCOTT, E., RANDELL, G., and TRAYLEN, W., Report of the Commission appointed to inquire into and report upon the sanitary condition of the city of Perth and the town of Fremantle, especially with regard to the questions of water supply and the disposal of sewage: Western Australia Parliamentary Paper no. 20 of 1885, p. 10–14.

HASELGROVE, K., 1981, Effect of groundwater use by industry at Kwinana, Western Australia, *in* Groundwater resources of the Swan Coastal Plain (1981) *edited by* B. R. WHELAN: Australia, Commonwealth Scientific and Industrial Research Organisation, Proceedings of Commonwealth Scientific and Industrial Research Organisation, and Water Research Foundation of Australia Symposium, p. 267–278.

HAZEL, C. P., 1973, Lecture notes on groundwater hydraulics: Australian Water Resources Council, Groundwater School, 1973

Adelaide, Underground and Stockwater Supply Branch, Irrigation and Water Supply Commission.

HEALTH DEPARTMENT OF WESTERN AUSTRALIA, 1992, Annual Report of the Health Department of Western Australia for 1991/92.

HEDGCOCK, D., and MORITZ, M., 1989, Water sensitive urban design — a critique of existing planning practice and potential for reform, *in* Swan Coastal Plain Groundwater Management Conference — Proceedings *edited by* G. LOWE: Western Australian Water Resources Council, Conference Proceedings, Perth, 1988, Publication no. 1/89, p. 77–81.

HEM, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: Geological Survey water-supply paper 1473; Washington, United States Government Printing Office.

HINGSTON, F. J., and GAILITIS, V., 1977, Salts in rainfall in Western Australia (1973–1974): Australia, Commonwealth Scientific and Industrial Research Organisation, Technical Memorandum 77/1.

HIRSCHBERG, K-J. B., 1981, Metropolitan Water Board groundwater recharge study at Canning Vale bore completion report: Western Australia Geological Survey, Hydrogeology Report no. 2306 (unpublished).

HIRSCHBERG, K-J. B., 1982, Liquid-waste disposal sites: Western Australia Geological Survey, Hydrogeology Report no. 2390 (unpublished).

HIRSCHBERG, K-J. B., 1984, Lake Coogee — a review of monitoring data for 1982 and 1983: Western Australia Geological Survey, Hydrogeology Report no. 2588 (unpublished).

HIRSCHBERG, K-J. B., 1986, Liquid-waste disposal in Perth. A hydrogeological assessment: Western Australia Geological Survey, Professional Papers for 1984, Report 19, p. 55–61.

HIRSCHBERG, K-J. B., 1989, Groundwater contamination in the Perth metropolitan region, *in* Swan Coastal Plain Groundwater Management Conference — Proceedings *edited by* G. LOWE: Western Australian Water Resources Council, Conference Proceedings, Perth, 1988, Publication no. 1/89, p. 121–134.

HIRSCHBERG, K-J. B., 1993a, Municipal waste disposal in Perth and its impact on groundwater quality: Western Australia Geological Survey, Professional Papers, Report 34, p. 97–109.

HIRSCHBERG, K-J. B., 1993b, Geological and hydrogeological guidelines for landfill site selection: Western Australia Geological Survey.

HIRSCHBERG, K-J. B., 1993c, Guidelines for groundwater monitoring at municipal landfill sites: Western Australia Geological Survey.

HUBBERT, M. K., 1940, The theory of groundwater motion: Journal of Geology, v. 48, p. 785–944.

HUNT, S-J., 1980, Water — the abiding challenge: Metropolitan Water Board Perth, Western Australia.

JACK, P. N., 1978, Do it yourself low cost iron stain prevention: Western Australia Government Chemical Laboratories, information pamphlet (unpublished).

KENDRICK, G. W., WYRWOLL, K-H., and SZABO, B. J., 1991, Pliocene–Pleistocene coastal events and history along the western margin of Australia: Quaternary Science Reviews, v. 10, p. 419–439.

KEVI, L., 1988, Total dissolved solid content estimation from resistivity well logs: Western Australia Geological Survey, Geophysical Report 5/88 (unpublished).

KEYS, W. S., and MacCARY, L. M., 1971, Application of borehole geophysics to water-resources investigations: Techniques of Water Resources Investigations of the United States Geological Survey, Chapter E1, p. 126.

KWINANA INDUSTRIES CO-ORDINATING COMMITTEE, 1987, Report of the Groundwater Management Working Group (unpublished).

LA BROOY, S. R., 1981, Nature of groundwater pollution and description of some sources of pollution, *in* Groundwater resources of the Swan Coastal Plain (1981) *edited by* B. R. WHELAN: Australia, Commonwealth Scientific and Industrial Research Organisation, Proceedings of Commonwealth Scientific and Industrial Research Organisation, and Water Research Foundation of Australia Symposium, p. 281–290.

LAWS, A. T., 1979, The hydrogeology of the proposed Jones Street sanitary landfill site: Western Australia Geological Survey, Hydrogeology Report no. 2065 (unpublished).

LAYTON GROUNDWATER CONSULTANTS, 1979, Cockburn Sound groundwater study: Cockburn Sound Study Group of the Department of Conservation and Environment, Report proposal.

LE PROVOST, I., SEMENIUK, V., and CHALMER, P., 1987, Environmental significance of wetlands in the Perth to Bunbury Region: Western Australia Water Resources Council, Report no. R164.

LOW, G. H., 1971, Definition of two new Quaternary formations in the Perth Basin: Western Australia Geological Survey, Annual Report 1970, p. 33–34.

McARTHUR, W. M., and BETTENAY, E., 1960, The development and distribution of the soils of the Swan Coastal Plain, Western Australia: Australia, Commonwealth Scientific Industrial Research Organisation, Soil Publication 16, p. 55.

McGHIE, D. A., 1980, The origins of water repellence in some Western Australian soils: University of Western Australia, PhD thesis (unpublished), p. 171.

McGHIE, D. A., and POSSNER, A. M., 1981, The effect of plant top material on the water repellence of fired sands and water repellent soils: Australian Journal of Agricultural Research, p. 609–620.

McLAUGHLAN, R. G., and KNIGHT, M. J., 1989, Corrosion and incrustation in groundwater bores — a critical review: Centre for Groundwater Management and Hydrogeology, University of New South Wales.

McWHAE, J. R. H., PLAYFORD, P. E., LINDNER, A. W., GLENISTER, B. F., and BALME, B. E., 1958, The stratigraphy of Western Australia: Geological Society of Australia, Journal, v. 4, pt 2, p. 161.

MAIN ROADS DEPARTMENT WESTERN AUSTRALIA, 1991, Main Roads Department Western Australia, Annual Report 1990–91.

MAITLAND, A. G., 1913, The artesian water resources of Western Australia, *in* Report of the Interstate Conference on Artesian Water, Sydney, 1912 *compiled by* J. E. SLADE: New South Wales, Government Printer, Appendix M, p. 115–129.

MARCHANT, N. G., WHEELER, J. R., RYE, B. L., BENNETT, E. M., LANDER, N. S., and MacFARLANE, T. D., 1987, Flora of the Perth region, Part one and Part two: Western Australian Herbarium, Department of Agriculture, Western Australia.

MARSILY, G. DE, 1986, Quantitative hydrogeology: Orlando, Academic Press Incorporated, p. 80–82.

MARTIN, M. W., and BADDOCK, L. J., 1989, Jandakot bore J270P pumping test: Western Australia Geological Survey, Hydrogeology Report no. 1989/41 (unpublished).

MONCRIEFF, J. S., 1981, Mirrabooka 285 production bore test pumping: Western Australia Geological Survey, Hydrogeology Report no. 2269 (unpublished).

MORGAN, K. H., 1964a, Progress report on drilling for water in the Gnangara Lake area near Perth: Western Australia Geological Survey, Annual Report 1963, p. 14–15.

MORGAN, K. H., 1964b, Hydrogeology of the southern part of the Gnangara Lake area, South-West Division, Western Australia: Western Australia Geological Survey, Record 1964/17.

MORGAN, K. H., 1969, Hydrogeology of the Swan Coastal Plain, Kwinana–Pinjarra area: Western Australia Geological Survey, Record 1969/11.

MORY, A. J., 1994, Geology of the Hill River – Green Head 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

NEWMAN, P. W. G., and MARKS, P. J., 1981, The removal of heavy metals by Perth sands, *in* Proceedings of the Groundwater Pollution Conference *edited by* C. R. LAWRENCE and R. J. HUGHES: Australian Water Resources Council, Conference Series no. 1, Perth, 1979, p. 267–289.

NIDAGAL, V., and DAVIDSON, W. A., 1991, North coastal groundwater investigation (Burns Beach–Pipidinny): Western Australia Geological Survey, Hydrogeology Report no. 1991/17 (unpublished).

PARKER, W. F., CARBON, B. A., and GRUBB, W. B., 1981, Coliform bacteria in sandy soils beneath septic tank sites in Perth, Western Australia, *in* Proceedings of the Groundwater Pollution Conference *edited by* C. R. LAWRENCE and R. J. HUGHES: Australian Water Resources Council, Conference Series no. 1, Perth, 1979, p. 402–414.

PASSMORE, H., 1912, The Canning Bore: The West Australian, Letters to the Editor (2nd August).

PASSMORE, J. R., 1967, The geology, hydrology and contamination of shallow coastal aquifers in the Rockingham district, Western Australia: University of Western Australia, PhD thesis (unpublished).

PASSMORE, J. R., 1970, Shallow coastal aquifers in the Rockingham District, Western Australia: Water Research Foundation of Australia, Bulletin 18, p. 83.

PIONKE, H. B., SHARMA, M. L., and HOSKING, J. A., 1990, Effect of irrigated horticultural cropping on groundwater quality, Swan Coastal Plain, Western Australia: Australia, Commonwealth Scientific and Industrial Research Organisation, Division of Water Resources, Water Resources Series no. 2, 19p.

PLAYFORD, P. E., COCKBAIN, A. E., and LOW, G. H., 1976, Geology of the Perth Basin, Western Australia: Western Australia Geological Survey, Bulletin 124.

PLAYFORD, P. E., COPE, R. N., COCKBAIN, A. E., LOW, G. H., and LOWRY, D. C, 1975, Phanerozoic, *in* Geology of Western Australia: Western Australia Geological Survey, Memoir 2, p. 223–433.

PLAYFORD, P. E., and LOW, G. H., 1972, Definitions of some new and revised rock units in the Perth Basin: Western Australia Geological Survey, Annual Report 1971, p. 44–46.

POLLETT, C. G., WIESE, I. D., and YUNG, F. H., 1979, Groundwater modelling in water resources planning for the Swan Coastal Plain, *in* Diamond Jubilee Conference, Perth, 1979 — Conference Papers: Institution of Engineers, Australia, Conference Papers, Event no. 404.2, 9p.

PUDOVSKIS, V., 1962, Subsurface geology of the Perth metropolitan area: West Australian Petroleum Pty Ltd., Report May 1962 (unpublished).

QUILTY, P. G., 1974, Cainozoic stratigraphy in the Perth area: Western Australia Royal Society, Journal, v. 57, p. 16–31.

REXILIUS, J. P., 1984, Late Cretaceous microfossil biostratigraphy of the southwestern Australian margin: University of Western Australia, PhD Thesis (unpublished).

ROCKWATER, 1987, Results of test-pumping bore CG2 Serpentine: Rockwater Pty Ltd.

SALAMA, R. B., DAVIS, G. B., and BARBER, C., 1989, Characterising the hydrogeological variability of a sand aquifer in the region of a domestic waste disposal site, *in* Proceedings of the IAHS Symposium on Groundwater Management, Quantity and Quality 1989: International Association of Hydrological Sciences, Publication no. 188, p. 215–226.

SANDERS, C. C., 1967, Exploratory drilling for underground water, Gingin Brook area, Perth Basin: Western Australia Geological Survey, Annual Report 1966, p. 27–33.

SEMENIUK, C. A., 1988, Consanguineous wetlands and their distribution in the Darling System, Southwestern Australia: Journal of the Royal Society of Western Australia, v. 70, p. 69–87.

SEMENIUK, V., and SEARLE, D. J., 1985, The Becher Sand, a new stratigraphic unit for the Holocene of the Perth Basin: Royal Society of Western Australia, Journal, v. 67, p. 109–115.

SHARMA, M. L., 1986, Measurement and prediction of natural groundwater recharge — an overview: Journal of Hydrology (N.Z.), v. 25(1), p. 49–56.

SHARMA, M. L., 1987, Groundwater recharge along a hillslope on the coastal plain of Western Australia, estimated by a natural chemical tracer, *in* Proceedings of the International Conference on Groundwater Systems Under Stress: Australian Water Resources Council, Conference Series no. 13, Brisbane, 1986, p. 43–52.

SHARMA, M. L., BARI, M., and BYRNE, J., 1991a, Dynamics of seasonal recharge beneath semi-arid vegetation on the Gnangara mound, Western Australia: Hydrological Processes, v. 5, p. 383–398.

SHARMA, M. L., BARRON, R. J. W., and CRAIG, A. B., 1988, Influence of landuse on natural groundwater recharge in the unconfined aquifers of the Swan Coastal Plain, Western Australia: Australia, Commonwealth Scientific and Industrial Research Organisation, Division of Water Resources, Project Report 1 July, 1985 to June 1988.

SHARMA, M. L., BYRNE, J. D. M., HERNE, D. E., and KIN, P. G., 1991b, Impact of horticulture on water and nutrient fluxes to a sandy aquifer: Australia, Commonwealth Scientific and Industrial Research Organisation, Division of Water Resources, Report 91/33, December, 1991.

SHARMA, M. L., and CRAIG, A. B., 1989, Comparative recharge rates beneath banksia woodland and two pine plantations on the Gnangara mound, Western Australia, *in* Groundwater recharge *edited by* M. L. SHARMA: Symposium on Groundwater Recharge, Mandurah, Western Australia; Rotterdam, A. A. Balkema, 1987, Proceedings, p. 171–184.

SHARMA, M. L., FARRINGTON, P., and FERNIE, M., 1983, Localized groundwater recharge on the 'Gnangara Mound', Western Australia, *in* Papers of the International Conference on Groundwater and Man — Volume 1; The Investigation and Assessment of Groundwater Resources: Australian Water Resources Council, Conference Series no. 8, v. 1, p. 293–302.

SHARMA, M. L., and HUGHES, M. W., 1985, Groundwater recharge estimation using chloride, deuterium and oxygen-18 profiles in the deep coastal sands of Western Australia: Journal of Hydrology, v. 81, p. 93–109.

SHARMA, M. L., and PIONKE, H. B., 1984, Estimating groundwater recharge from measurements of environmental tracers in the vadose zone, *in* NWWA/US EPA Conference on Characterisation and Monitoring of the Vadose (unsaturated) Zone *edited by* D. M. NIELSEN: December, 1983, Las Vegas, Nevada, Proceedings, p. 799–819.

SMITH, R. A., 1979, Shallow artesian pumping tests on Jandakot 45 and 105: Western Australia Geological Survey, Hydrogeology Report no. 1973 (unpublished).

SMITH, R. A., 1982a, Wanneroo aquifer evaluation test pumping of Wanneroo No 30 (W30): Western Australia Geological Survey, Hydrogeology Report no. 2481 (unpublished).

SMITH, R. A., 1982b, Pinjar aquifer evaluation test pumping of Gingin No 2 investigation well: Western Australia Geological Survey, Hydrogeology Report no. 2462 (unpublished).

SMITH, R. A., 1982c, Wanneroo aquifer evaluation test pumping of Wanneroo aquifer evaluation pumping bore No 1 (WEP1): Western Australia Geological Survey, Hydrogeology Report no. 2463 (unpublished).

SMITH, R. A., 1992, A bibliography of published reports on groundwater in Western Australia by staff of the Geological Survey of Western Australia: Western Australia Geological Survey, Record 1992/12.

SMITH, R. A., 1993, A bibliography of published reports on groundwater in Western Australia, excluding those by staff of the Geological Survey of Western Australia: Western Australia Geological Survey, Record 1993/2.

SMITH, R. A., and DAVIDSON, W. A., 1984, Pumping-test of Applecross investigation bore AI8B Gairloch Reserve: Western Australia Geological Survey, Hydrogeology Report no. 2621 (unpublished).

SMITH, R. A., and DAVIDSON, W. A., 1985, Pumping-test of Applecross investigation bore AI10B Shirley Strickland Oval: Western Australia Geological Survey, Hydrogeology Report no. 2648 (unpublished).

SWAN RIVER TRUST, 1992, Swan River Trust Annual Report for the year ended 30 June 1992: Perth, Swan River Trust.

TAYLOR, K. J., 1989, Effects of urbanisation on the quality of groundwater in the Perth metropolitan area: Land and Water Research News, no. 2, p. 6.

THIERRIN, J., DAVIS, G. B., BARBER, C., PATTERSON, B. M., PRIBAC, F., POWER, T. R., and LAMBERT, M., 1993, Natural degradation rates of BTEX compounds and napthalene in a sulphate reducing groundwater environment: Hydrological Sciences Journal, v. 38 (4), p. 309–322.

THORPE, P. M., 1989, Tritium as an indicator of groundwater recharge to the Gnangara groundwater mound on the Swan Coastal Plain, Perth, Western Australia, *in* Groundwater recharge *edited by* M. L. SHARMA: Symposium on Groundwater Recharge, Mandurah, Western Australia; Rotterdam, A. A. Balkema, 1987, Proceedings, p. 41–55.

THORPE, P. M., and DAVIDSON, W. A., 1991, Groundwater age and hydrodynamics of the confined aquifers, Perth, Western Australia, *in* Proceedings of the International Conference on Groundwater in Large Sedimentary Basins, Perth, Western Australia, 1990: Australian Water Resources Council, Conference Series no. 20, p. 420–436.

TODD, D. K., 1959, Ground water hydrology: New York, John Wiley and Sons, Inc., 1959, p. 279–282.

TOWNLEY, L., TURNER, J., BARR, A., TREFRY, M., WRIGHT, K., GAILITIS, V., HARRIS, C., and JOHNSTON, C., 1993, Wetlands of the Swan Coastal Plain, Volume 3; Interaction between lakes, wetlands and unconfined aquifers: Water Authority of Western Australia.

UPSON, R. A., 1992, Reintegrating fragmented landscapes; Chapter 5, changes in soil properties: Springer-Verlag, New York, Inc.; p. 107–145.

VENTRISS, H. B., 1988, Allocation of entitlements to groundwater in Western Australia, *in* Proceedings of the AWRC Workshop on Groundwater Allocation, Sydney, October 27–28, 1987: Australian Water Resources Council, Conference Series no. 15, p. 15–24.

VENTRISS, H. B., 1989, Groundwater management — the players and the process, *in* Swan Coastal Plain Groundwater Management Conference *edited by* G. LOWE: Western Australian Water Resources Council, Conference Proceedings, Perth, 1988, Publication no. 1/89, p. 31–39.

VENTRISS, H. B., 1990, General principles and policy for groundwater licensing in Western Australia: Water Authority of Western Australia, Water Resources Directorate, Groundwater Branch, Report no.. WG 90, 45p.

VENTRISS, H. B., and GREEN, R. E., 1987, Stressed groundwater systems in Western Australia — some management case histories, *in* Proceedings of the International Conference on Groundwater Systems Under Stress: Australian Water Resources Council, Conference Series no. 13, Brisbane, 1986, p. 177–187.

WATER AUTHORITY OF WESTERN AUSTRALIA, 1991, Jandakot groundwater scheme Stage 2 public environmental review: Water Resources Directorate, Groundwater Branch, Perth, Western Australia.

WATER AUTHORITY OF WESTERN AUSTRALIA, 1992a, Annual Report of the Water Authority of Western Australia, 1992.

WATER AUTHORITY OF WESTERN AUSTRALIA, 1992b, Gnangara Mound vegetation stress study — results of investigations: Water Authority of Western Australia, Water Resources Directorate, Groundwater and Environment Branch, Environmental Management Section, Report no.. WG 127, 30p.

WATERWAYS COMMISSION, 1992, Waterways Commission 15th Annual Report the year ending 30 June 1992: Perth, Waterways Commission Annual Report 1991–92.

WEBSTER, K. C., 1989, Groundwater management on the Swan Coastal Plain — an overview, *in* Swan Coastal Plain Groundwater Management Conference *edited by* G. LOWE: Western Australian Water Resources Council, Conference Proceedings, Perth, 1988, Publication no. 1/89, p. 21–29.

WESTERN AUSTRALIAN WATER RESOURCES COUNCIL, 1983, Lake Coogee area — review of groundwater problems: Western Australian Water Resources Council, Publication no. WRC 3/83, 53p.

WESTERN AUSTRALIAN WATER RESOURCES COUNCIL, 1992, Annual Report 1992 of the Western Australian Water Resources Council.

WETLANDS ADVISORY COMMITTEE, 1977, The status of wetland reserves in System 6: Wetlands Advisory Committee to the Environmental Protection Authority, Western Australia, Report (unpublished).

WHARTON, P. H., 1981a, Lake Thompson 50 constant-rate pumping test: Western Australia Geological Survey, Hydrogeology Report no. 2304 (unpublished).

WHARTON, P. H., 1981b, Lake Jandabup investigation–test pumping of Wanneroo W240 production bore April–May, 1981: Western Australia Geological Survey, Hydrogeology Report no. 2332 (unpublished).

WHARTON, P. H., 1991, Review of performance: Leederville and Yarragadee aquifers between Gingin and Mandurah: Rockwater Pty Ltd, September, 1991 (unpublished).

WHELAN, B. R., BARROW, N. J., and CARBON, B. A., 1981, Movement of phosphate and nitrogen from septic tank effluent in sandy soils near Perth, Western Australia, *in* Proceedings of the Groundwater Pollution Conference *edited by* C. R. LAWRENCE and R. J. HUGHES: Australian Water Resources Council, Conference Series no. 1, Perth, 1979, p. 391–401.

WHELAN, B. R., and PARKER, W. F., 1981, Bacterial and chemical transmission through sand — a field study in groundwater pollution from a septic tank in Perth, Western Australia, *in* Groundwater resources of the Swan Coastal Plain (1981) *edited by* B. R. WHELAN: Australia, Commonwealth Scientific and Industrial Research Organisation, Proceedings of Commonwealth Scientific and Industrial Research Organisation, and Water Research Foundation of Australia Symposium, p. 313–329.

WHINCUP, P., 1966, Hydrogeology of the Pinjar exploratory drilling, Western Australia: Western Australia Geological Survey, Annual Report 1965, p. 19–23.

Glossary

abstraction	pumping groundwater from an aquifer
aerobic	with oxygen
anaerobic	without oxygen
AHD	Australian Height Datum; equivalent to: Mean Sea Level (MSL) + 0.026 m; Low Water Mark Fremantle (LWMF) + 0.756 m
alluvium (alluvial)	detrital material which is transported by streams and rivers and deposited
AMG	Australian Map Grid; standard reference system whereby the first group of figures (eastings) and the second group (northings) together uniquely define the position
anisotropy	the degree of variation of hydraulic conductivity between the vertical and horizontal directions at a point in an aquifer
anticline	sedimentary strata folded in an arch
aquifer	a geological formation or group of formations able to receive, store and transmit significant quantities of water
unconfined	a permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure
confined	a permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability
semi-confined	a semi-confined or leaky aquifer is saturated and bounded above by a semi-permeable layer and below by a layer that is either impermeable or semi-permeable
semi-unconfined	intermediate between semi-confined and unconfined, when the upper semi-permeable layer easily transmits water
artesian	a confined aquifer under such pressure that water rises in a bore above the ground surface
artesian basin	a series of sedimentary beds disposed in such a way that an aquifer holds water under a pressure head between two less permeable beds.
base flow	that portion of river and streamflow coming from groundwater discharge
Becquerel	one nuclear transformation per second (SI unit)
biota	all plants and animals within a specified area
bioturbated	sediments stirred by organisms
BOD	biochemical oxygen demand
bore	small diameter well, usually drilled with machinery
colloid	suspended microscopic particles in water
colluvium (colluvial)	material transported by gravity downhill slopes
confining bed	sedimentary bed of very low hydraulic conductivity
conformably	sediments deposited in a continuous sequence without a break
unconformably	time break in sequence of deposition
Cretaceous	final period of the Mesozoic era; 65–144 million years ago
density	the mass of water per unit volume, usually stated in g/cm^3
doline	synonym of sinkhole or karst depression
effective porosity	drainable pore space, considered synonymous with specific yield of unconfined aquifer
eolian	wind-blown; deposit formed by wind action
ephemeral stream	stream or river that flows briefly in direct response to rainfall and whose channel is above the watertable
estuary (estuarine)	the seaward or tidal mouth of a river where fresh water comes into contact with seawater
eustatic	pertaining to worldwide changes of sea level that affect all the oceans
evapotranspiration	a collective term for evaporation and transpiration
facies	a mappable lithostratigraphic unit, differing in lithology from adjacent units deposited at the same time and in lithologic continuity
fault	a fracture in rocks or sediments along which there has been an observable displacement
field capacity	the quantity of water held by sediments in the unsaturated zone against the pull of gravity
fluvial	pertaining to streams and rivers
flux	outflow
formation (geological)	a group of rocks or sediments which have certain characteristics in common, were deposited about the same geological period, and which constitute a convenient unit for description
Gondwana	The Late Palaeozoic continent of the Southern Hemisphere
graben	an elongate, relatively depressed block that is bounded by faults on its long sides
group (geological)	includes two or more contiguous or associated formations with significant lithological features in common
hydraulic	pertaining to groundwater motion
conductivity (permeability)	the flow through a unit cross-sectional area of aquifer under a unit hydraulic gradient

gradient	the rate of change of total head per unit of distance of flow at a given point and in a given direction
head	the height of the free surface of a body of water above a given subsurface point
hypersaline	excessively saline; with a salinity substantially greater than that of sea water
isopotential	equipotential; having uniform hydraulic head
Jurassic	the second period of the Mesozoic era; 144–213 million years ago
karst	a type of topography that is formed on limestone by dissolution, and is characterized by sinkholes, caves, dolines, solution channels and underground drainage
lacustrine	pertaining to, produced by, or formed in a lake
leach (leaching)	remove soluble matter by percolation of water
levee	bank of a watercourse
member (geological)	a lithostratigraphic unit of subordinate rank, comprising some specially developed part of a formation
Mesozoic	an era of geological time; 65–253 million years ago
neritic	pertaining to the ocean environment or depth zone between low-tide level and the edge of the continental shelf
Neocomian	stage of geological time; earliest Cretaceous
oxidizing	combine with oxygen
palaeolake	ancient lake
palynology	study of pollen of seed plants and spores of other embrophytic plants, whether living or fossil, including their dispersal and applications in stratigraphy and palaeoecology
paralic	pertaining to interfingered marine and continental deposits laid down on the landward side of the coast or in shallow water (lagoonal or littoral) subject to marine invasion
permeable	ability to permit water movement
pH	measure of acidity and alkalinity given by the negative decimal logarithm of hydrogen ion concentration. For example, pure water at 25°C contains $10^{-7.00}$ g/L of H^+ ion; its pH is 7.00
piedmont	a plain or foothill at the base of a mountain or high range
plateau	an extensive land region considerably elevated (more than 150 m) above the adjacent country or above sea level
pore space	the open spaces in sediments, considered collectively
potentiometric surface	an imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a bore. The watertable is a particular potentiometric surface
Quaternary	relating to the most recent period in the Cainozoic era, from 2 million years to present
reducing	remove oxygen or undergo addition of electrons
salinity	a measure of the concentration of total dissolved solids (TDS) in water 0–500 mg/L, fresh 500–1500 mg/L, fresh to marginal 1500–3000 mg/L, brackish >3000 mg/L saline
scarp	a line of cliffs (steep slopes) produced by faulting or by erosion
solution channel	tubular or planar channel formed by solution of calcium carbonate in limestone
specific yield	the volume of water that an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable
storage coefficient	the volume of water that a confined aquifer releases from storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface
stratigraphy	the science of rock strata. Concerned with original succession and age relations of rock strata and their form, distribution, lithology, fossil content, geophysical and geochemical properties
surfactant	substance that reduces surface tension
swale	a slight depression, sometimes swampy, in generally level land
syncline	a basin-shaped fold in sedimentary strata
tectonic	pertaining to the forces that produce structures or features in rocks
Tertiary	the first period of the Cainozoic era; 2–65 million years ago
transmissivity	the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient
transpiration	the loss of water vapour from a plant, mainly through the leaves
trough (geological)	a linear depression or basin that subsides as it receives clastic material; located near the source supplying the sediment
type (locality, section)	the place at which a stratotype is situated and from which it derives its name
watertable	the surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere
well	large diameter bore, usually dug by hand; also petroleum bore

Plates (1–85)

Note: Where frequent reference is considered likely, several of the Plates have been simplified and placed in the body of the text.

These are included in the following section for completeness.

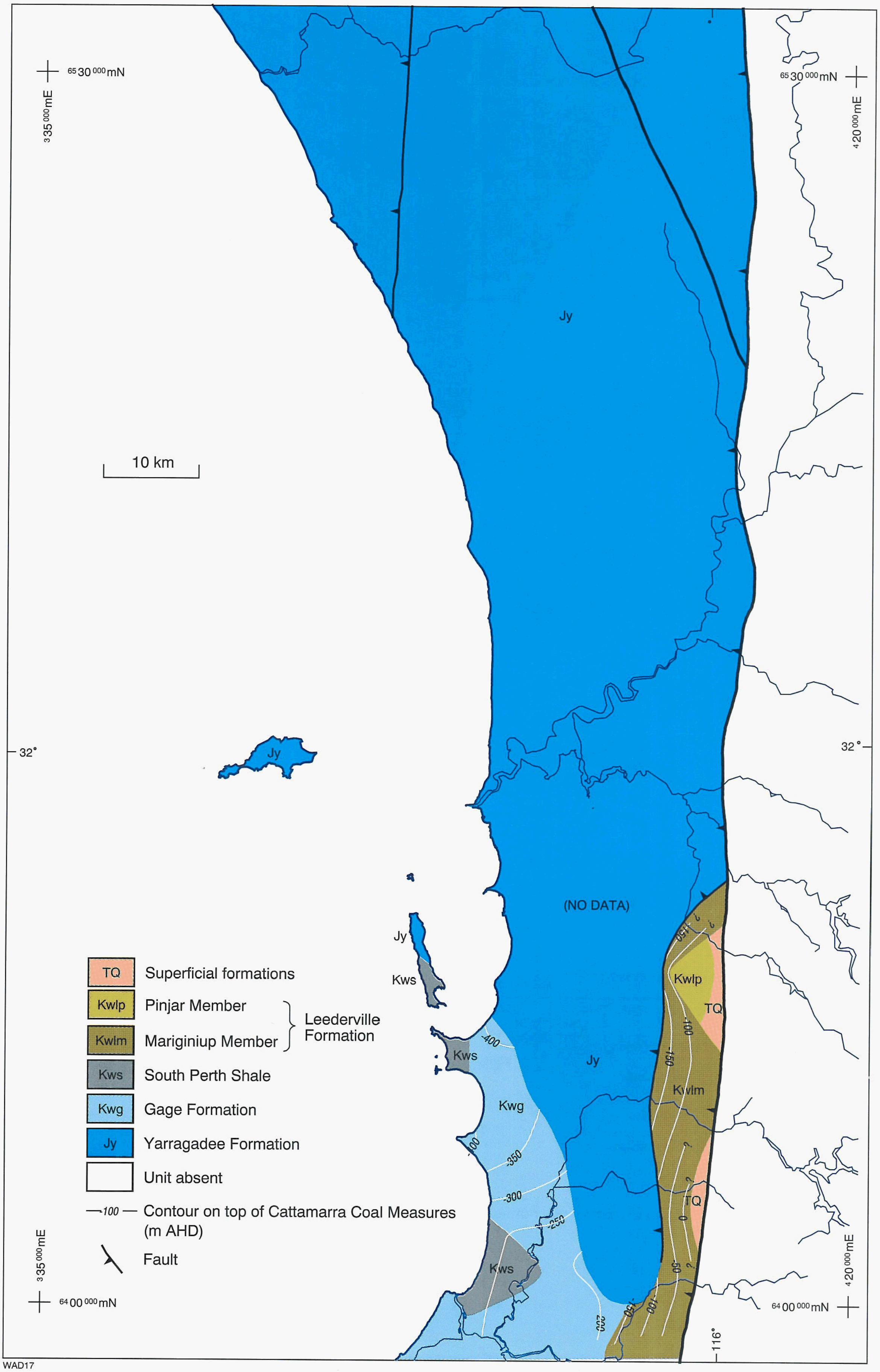


PLATE 1. Cattamarra Coal Measures: contours on top of unit; with overlying strata

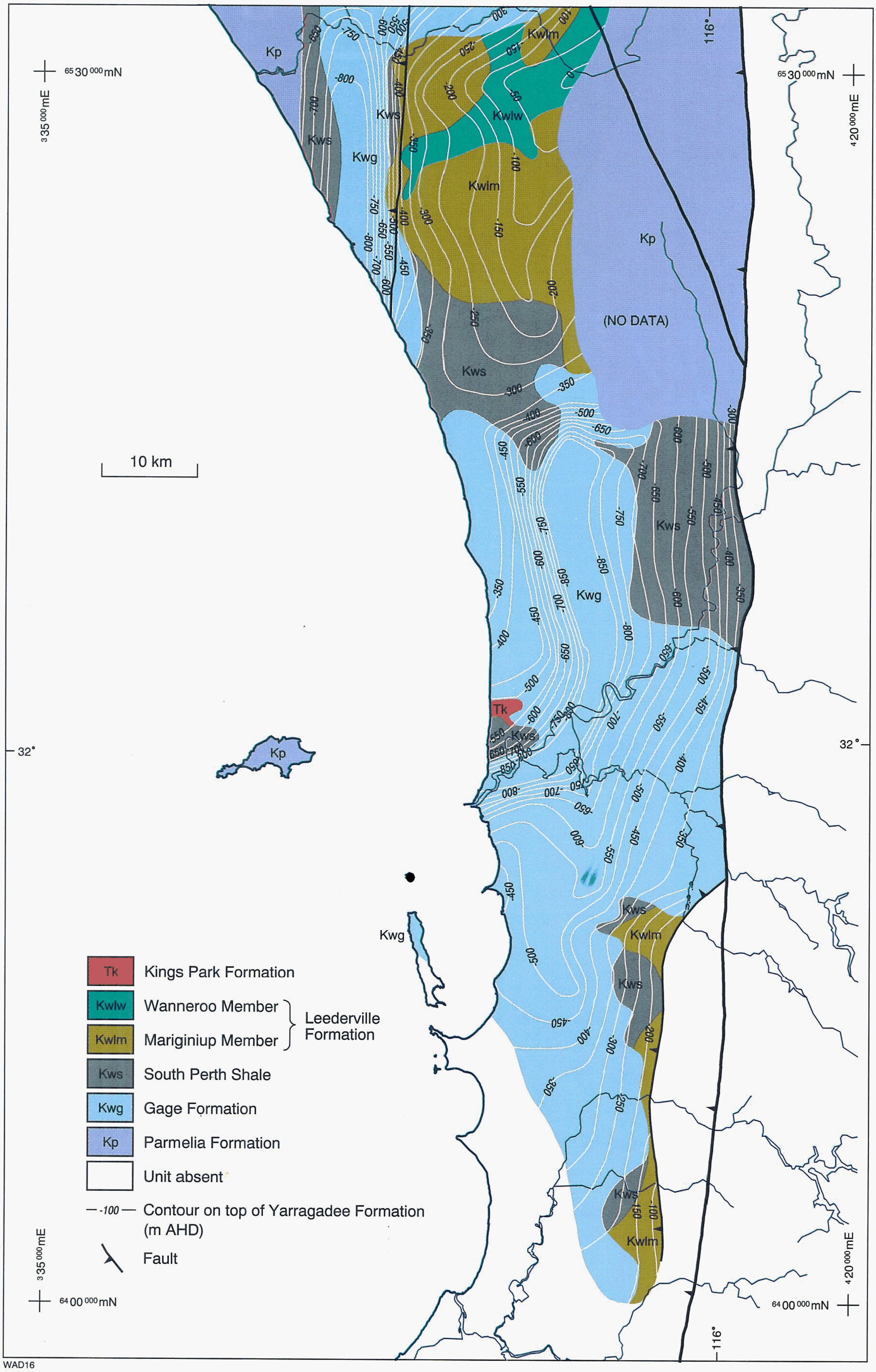
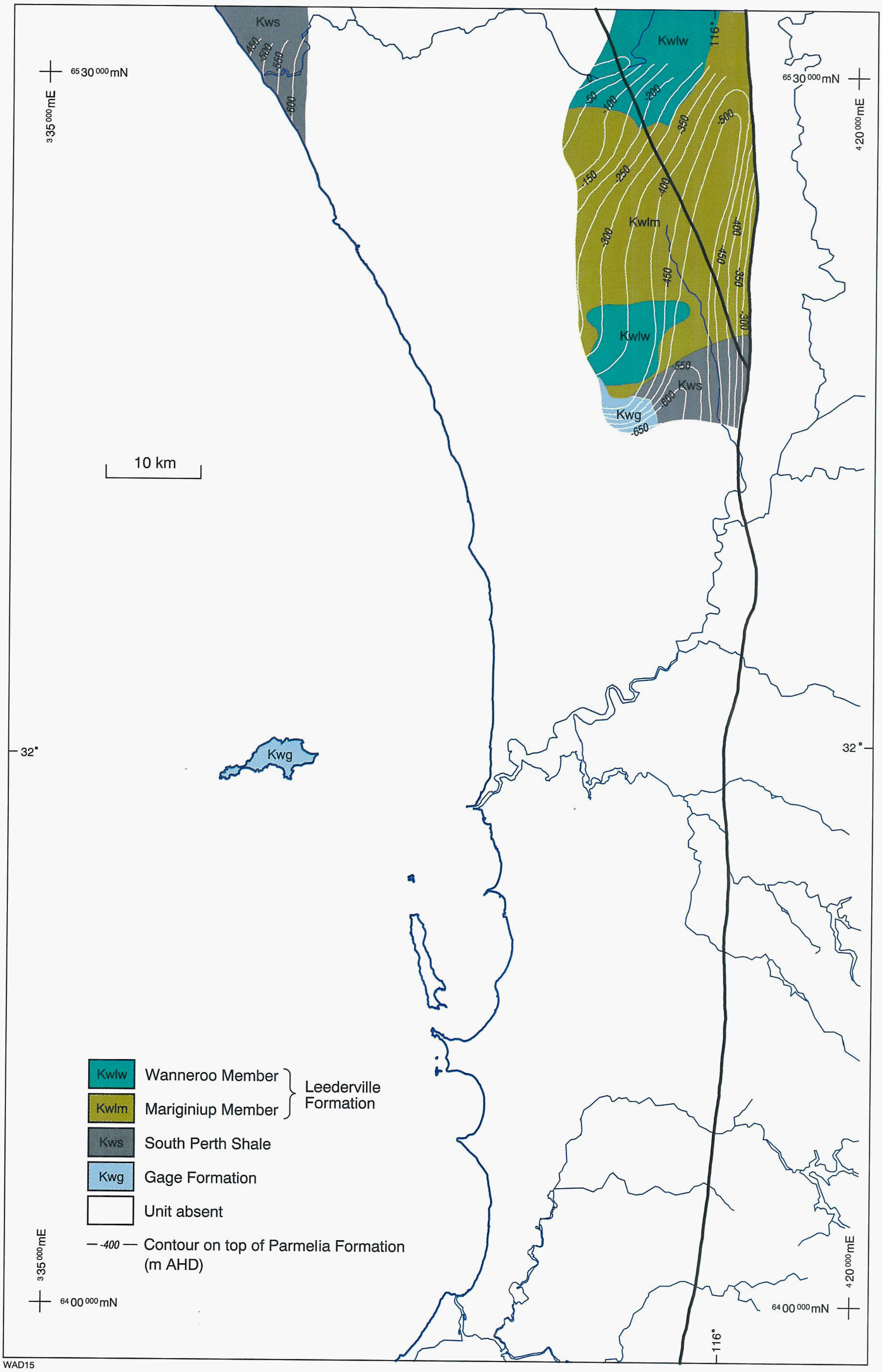


PLATE 2. Yarragadee Formation: contours on top of unit; with overlying strata



WAD15

PLATE 3. Parmelia Formation: contours on top of unit; with overlying strata

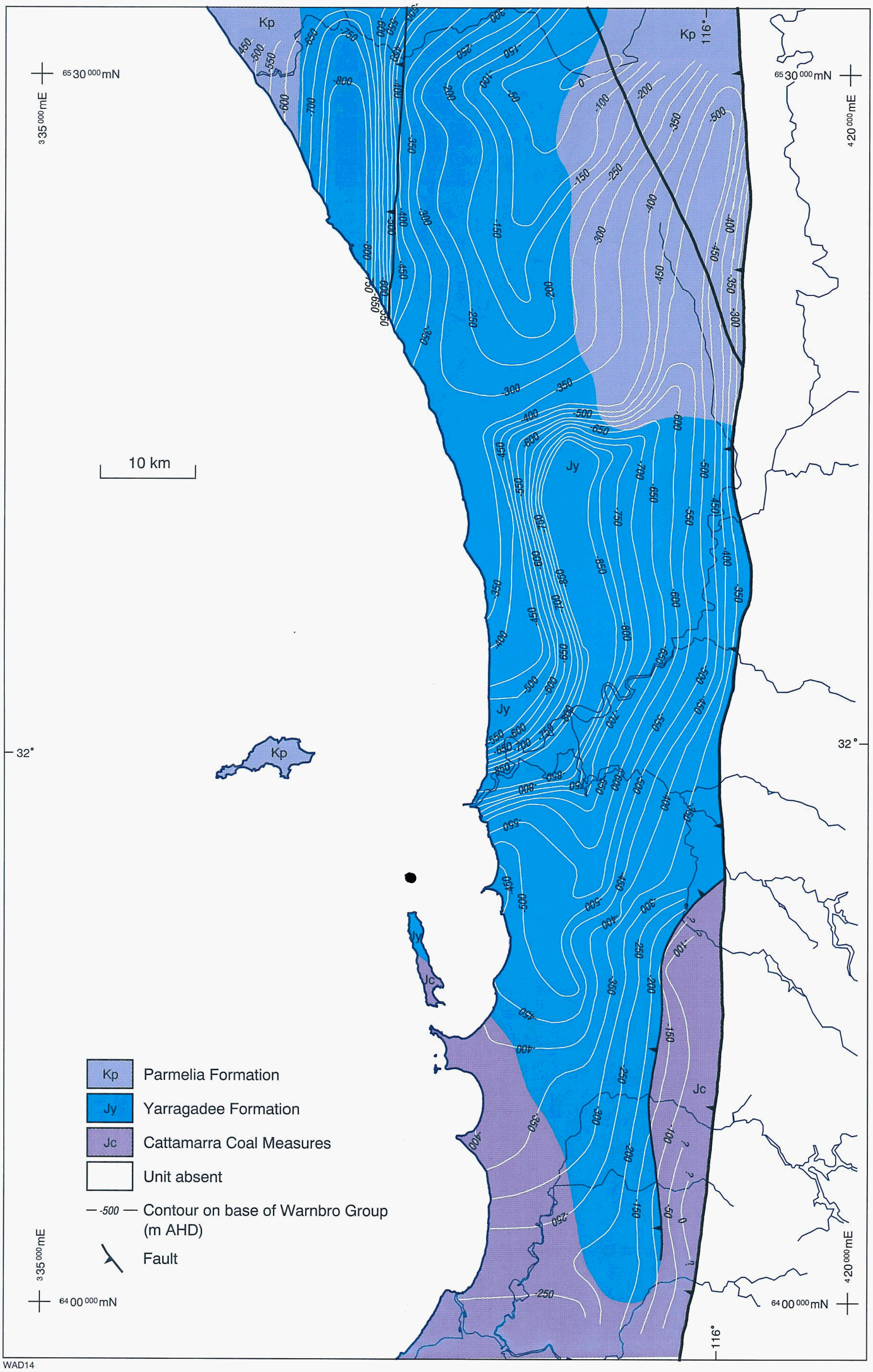
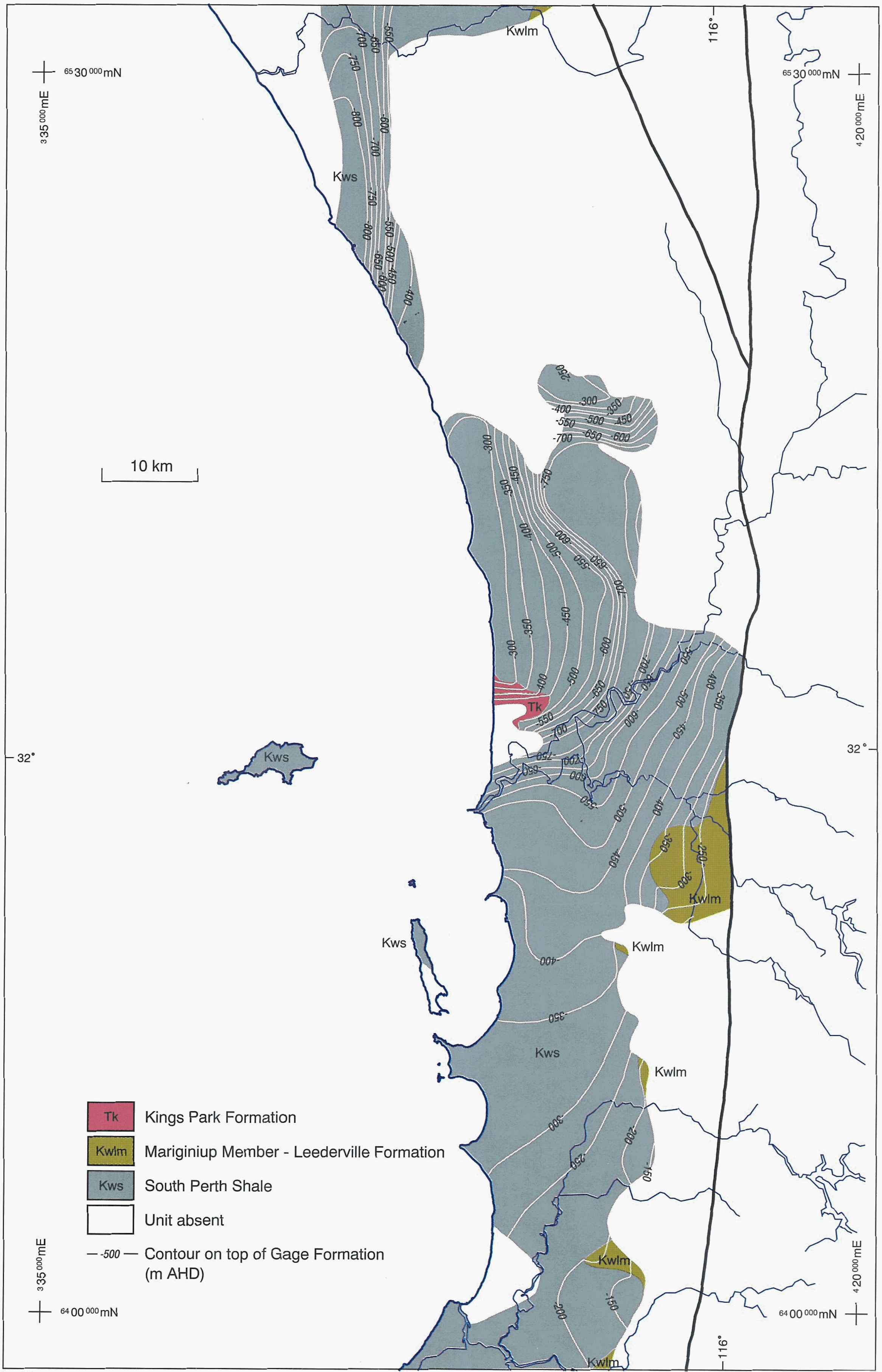


PLATE 4. Intra-Neocomian unconformity surface showing strata subcrop and contours on base of Warnbro Group



WAD13

PLATE 5. Gage Formation: contours on top of unit; with overlying strata

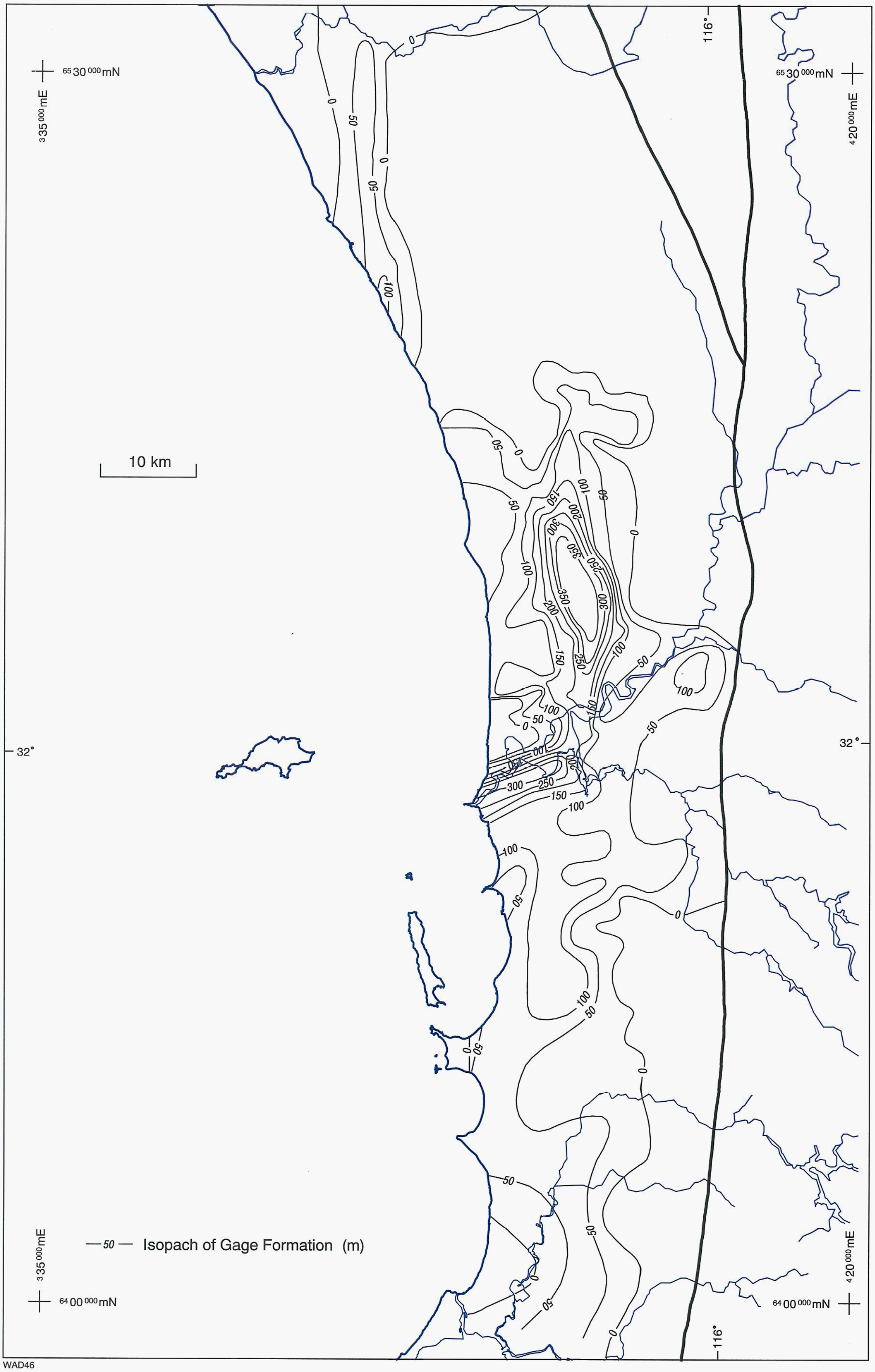


PLATE 6. Gage Formation: isopachs

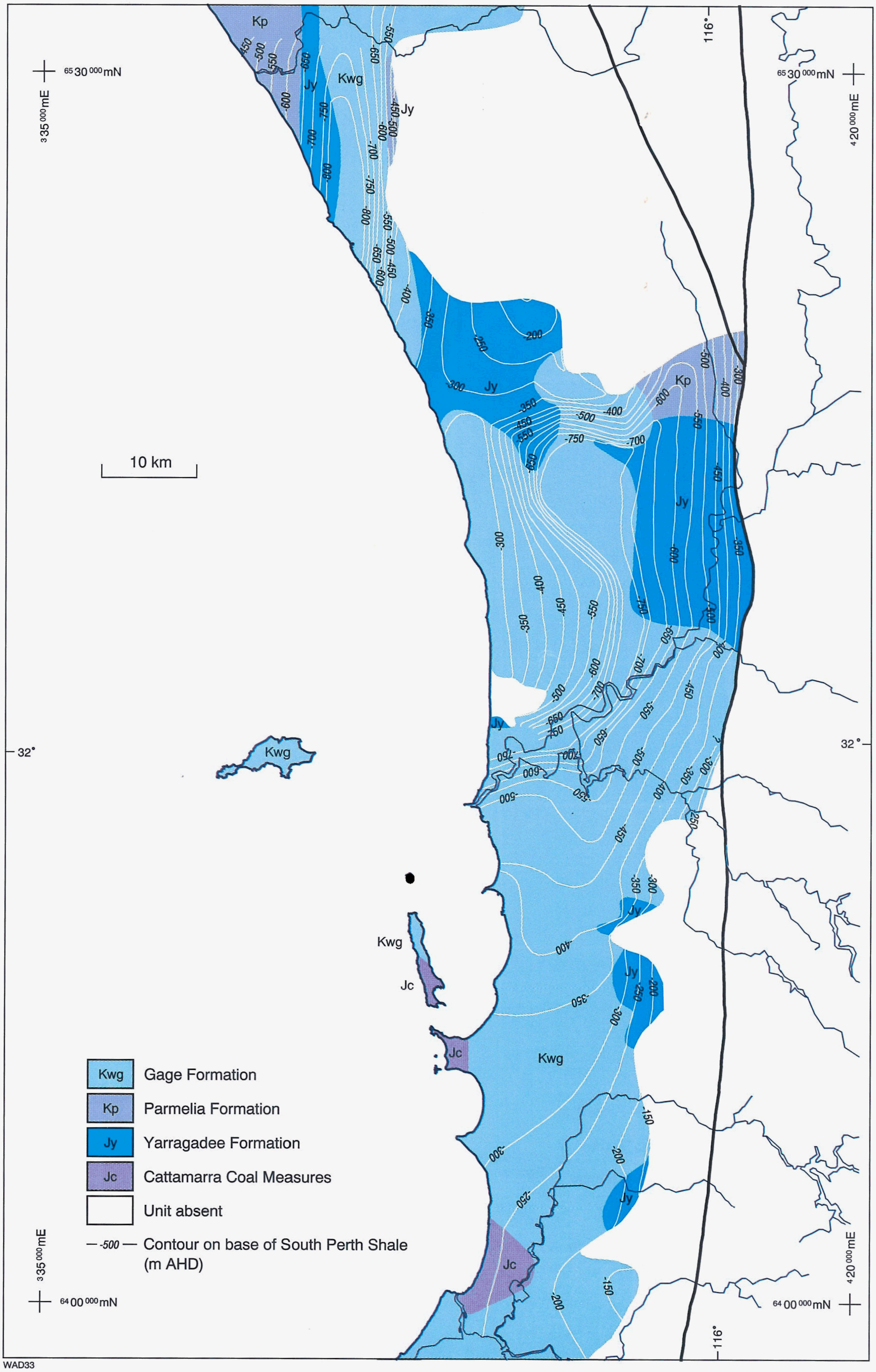


PLATE 7. South Perth Shale: contours on base of unit; with strata subcrop

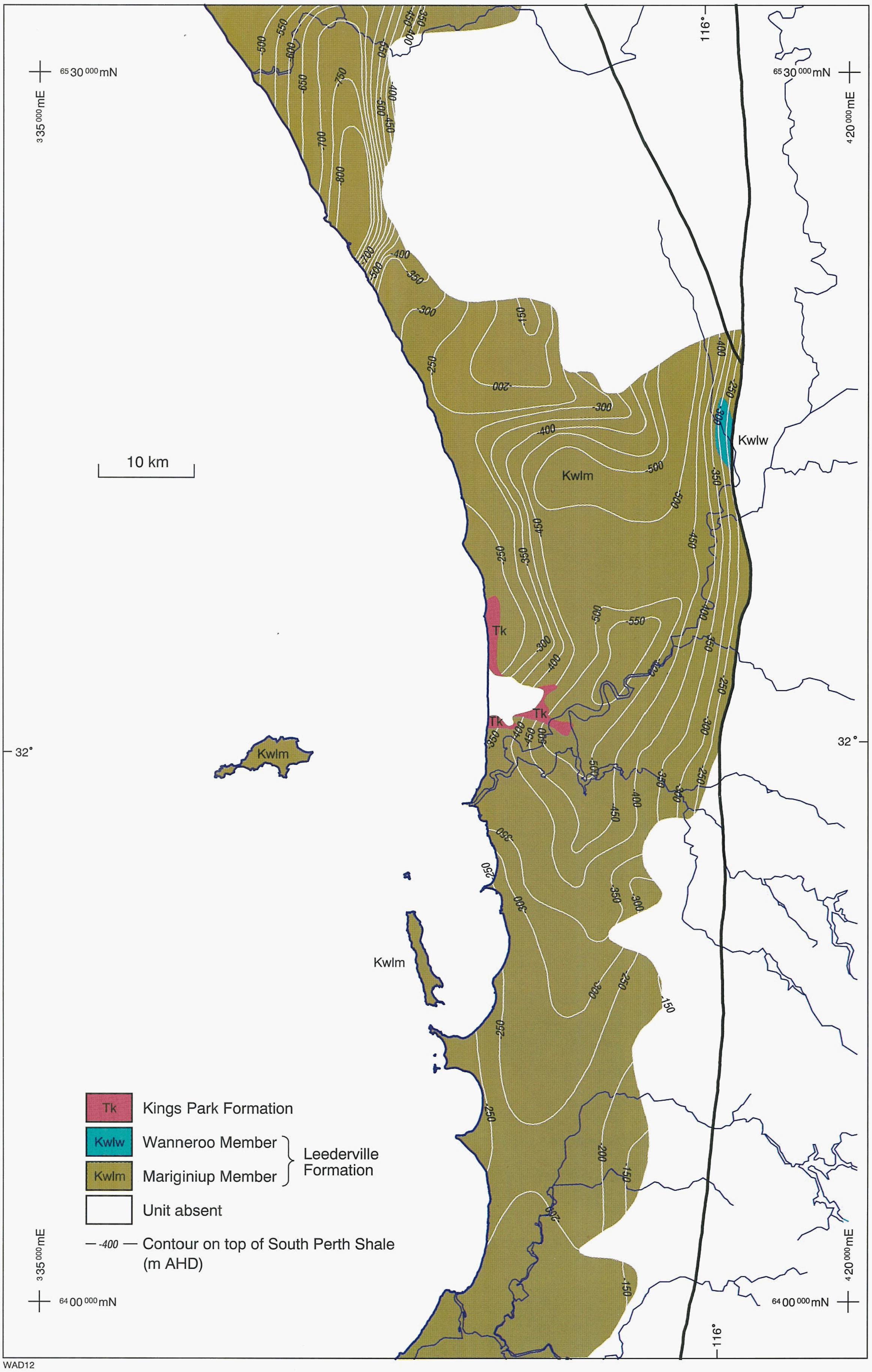
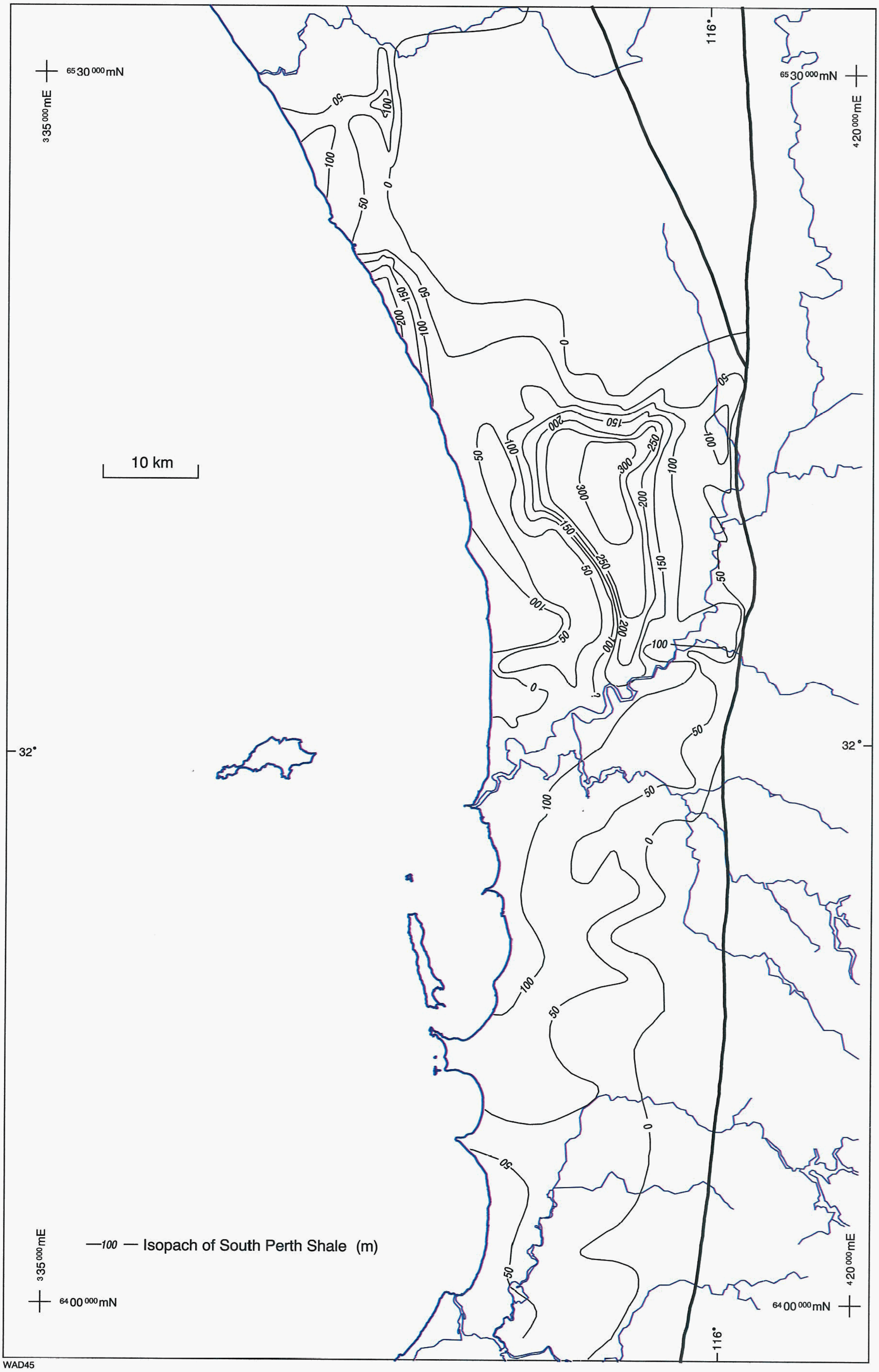


PLATE 8. South Perth Shale: contours on top of unit; with overlying strata



WAD45

PLATE 9. South Perth Shale: isopachs

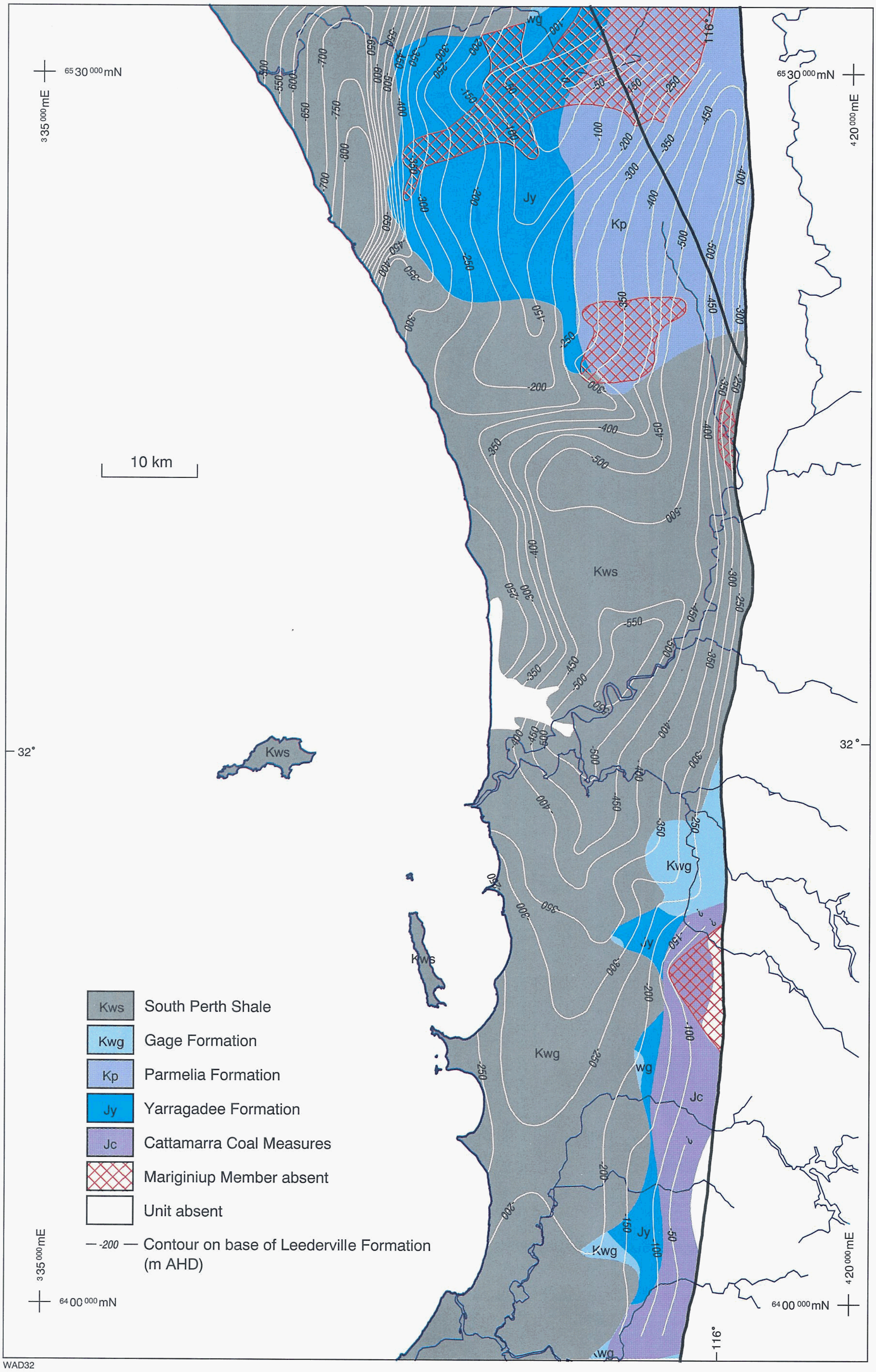


PLATE 10. Leederville Formation (Mariginiup Member): contours on base of unit; with strata subcrop

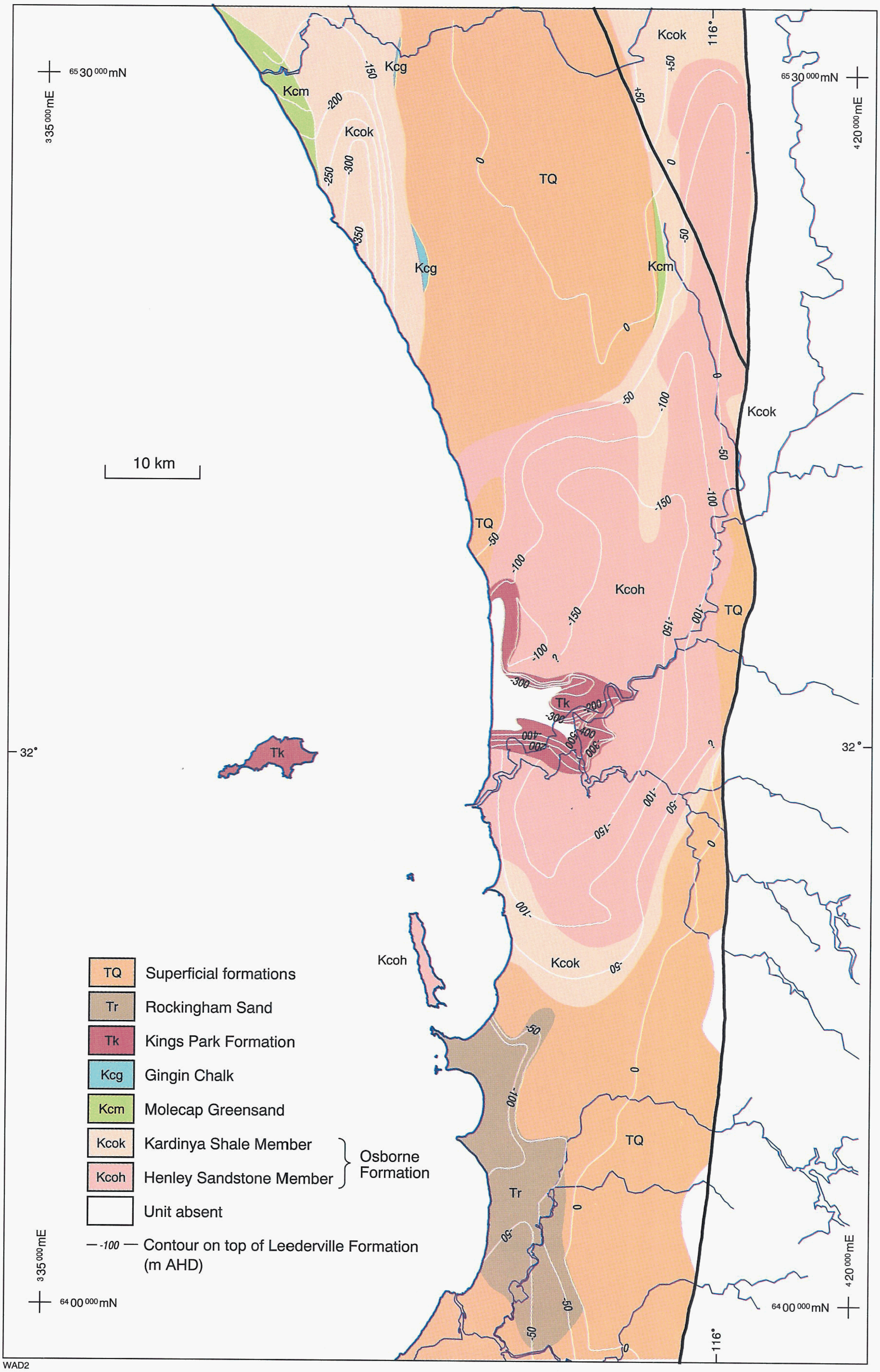


PLATE 11. Leederville Formation: contours on top of unit; with overlying strata

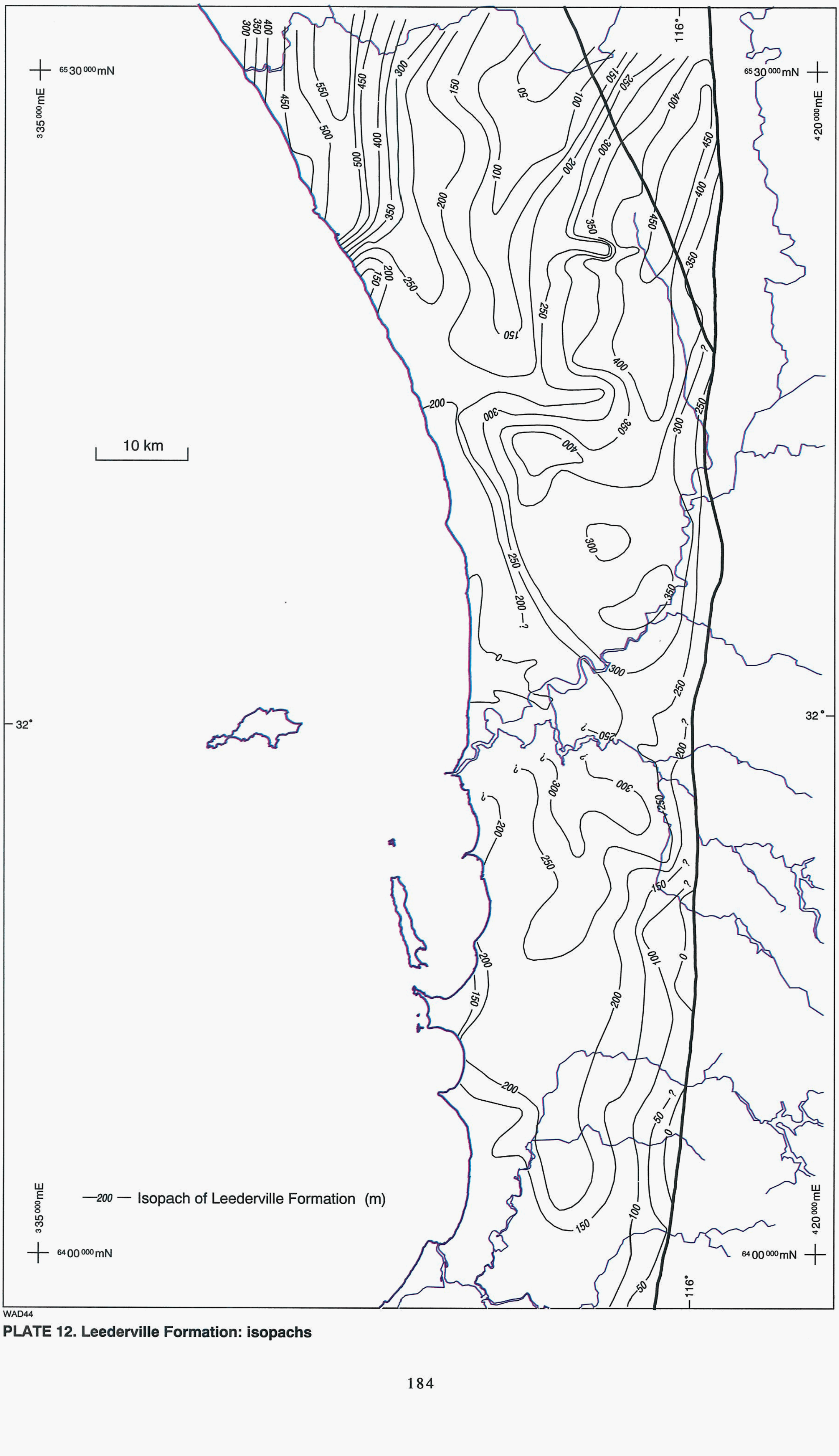


PLATE 12. Leederville Formation: isopachs

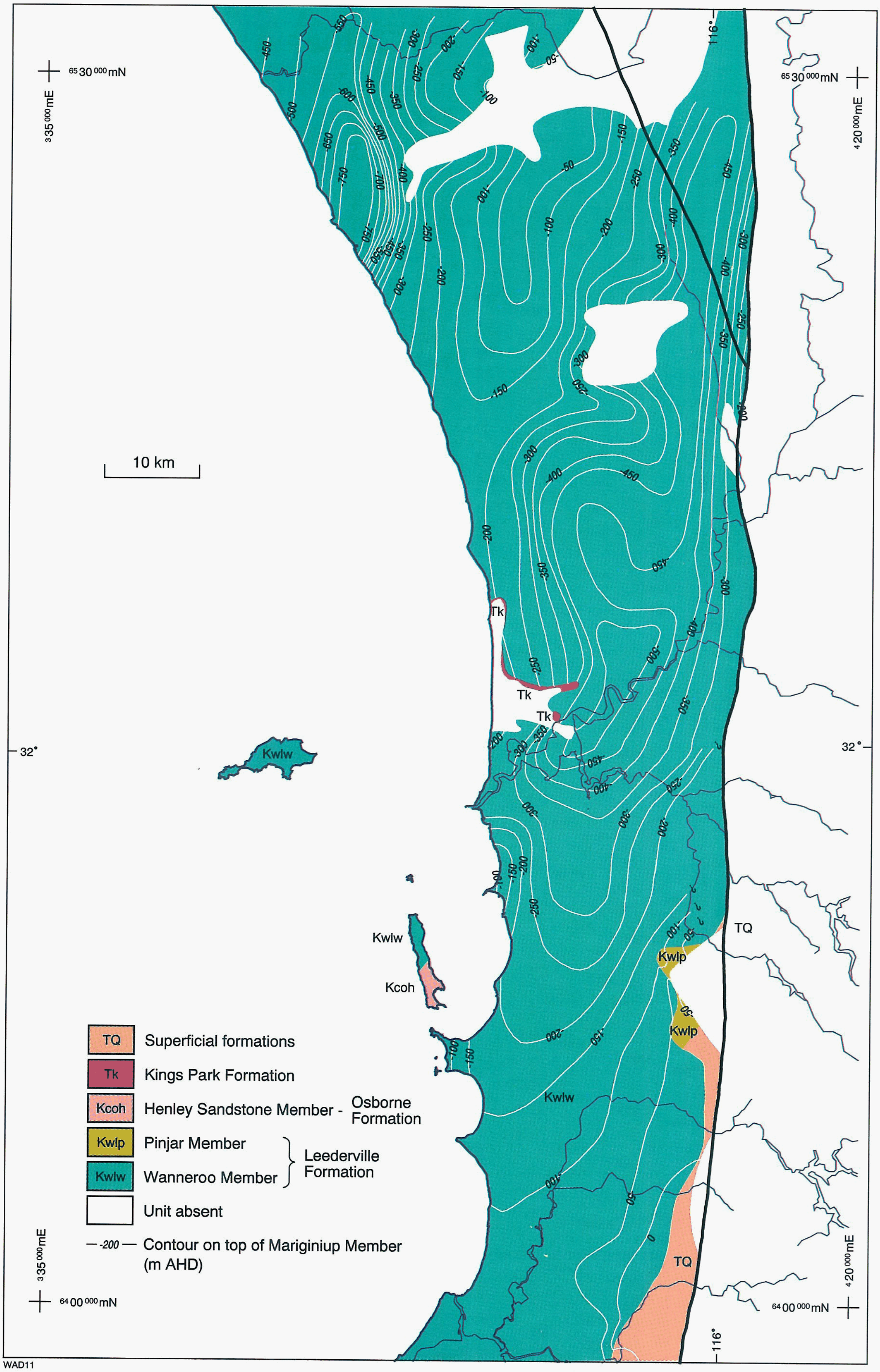


PLATE 13. Mariginiup Member: contours on top of unit; with overlying strata

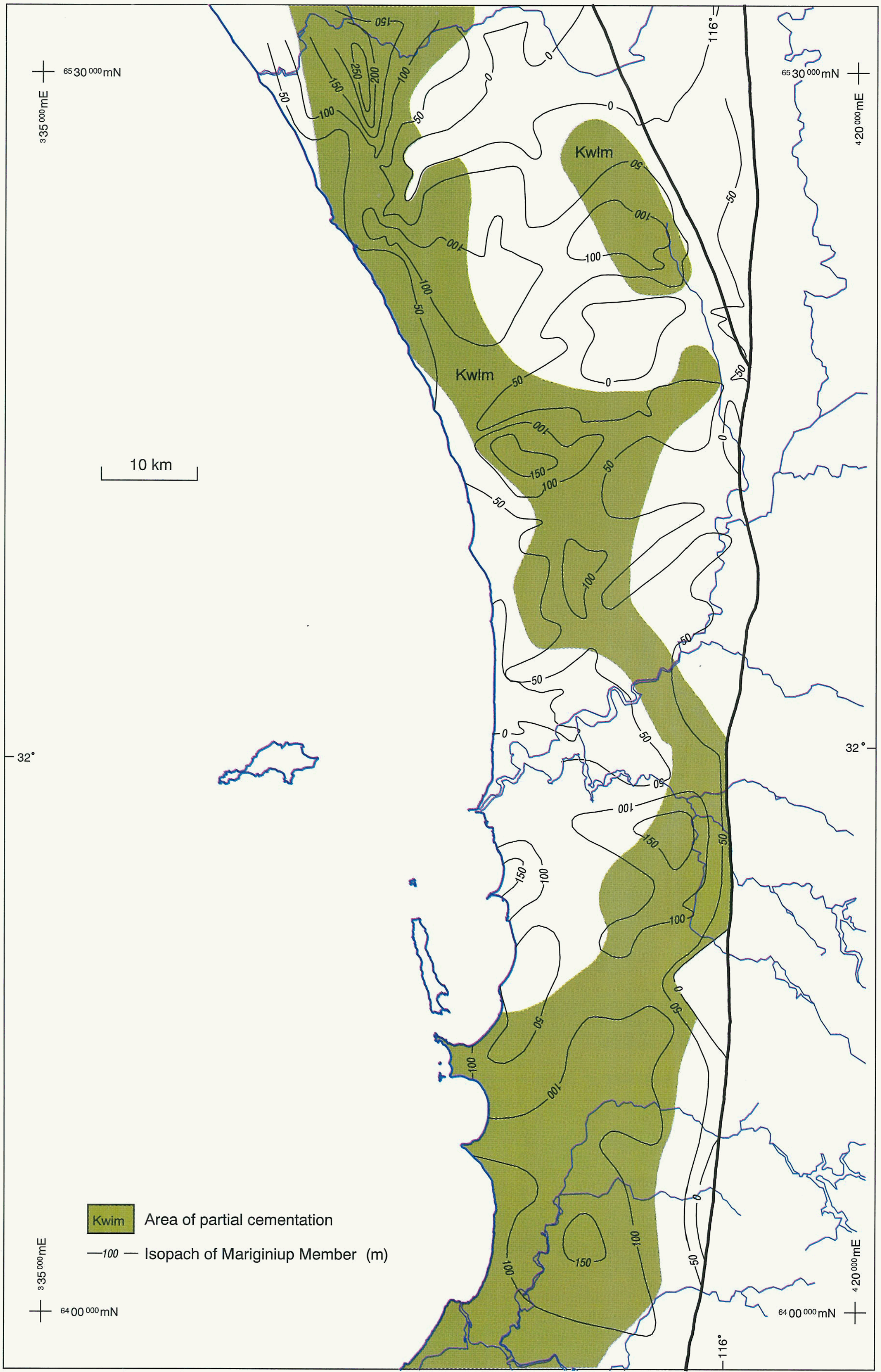


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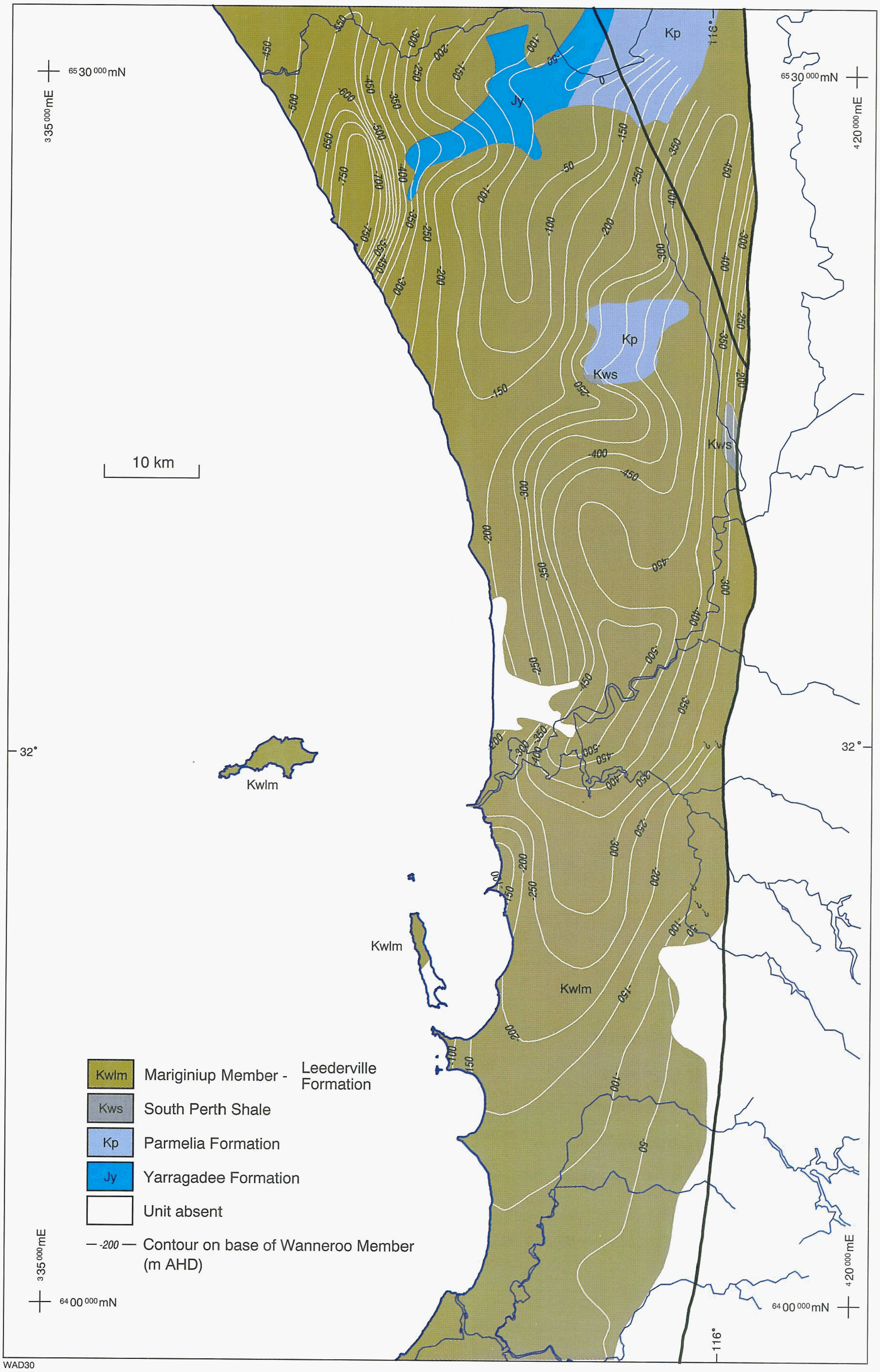
PLATE 14. Mariginiup Member: isopachs



WAD30

PLATE 15. Wanneroo Member: contours on base of unit; with strata subcrop

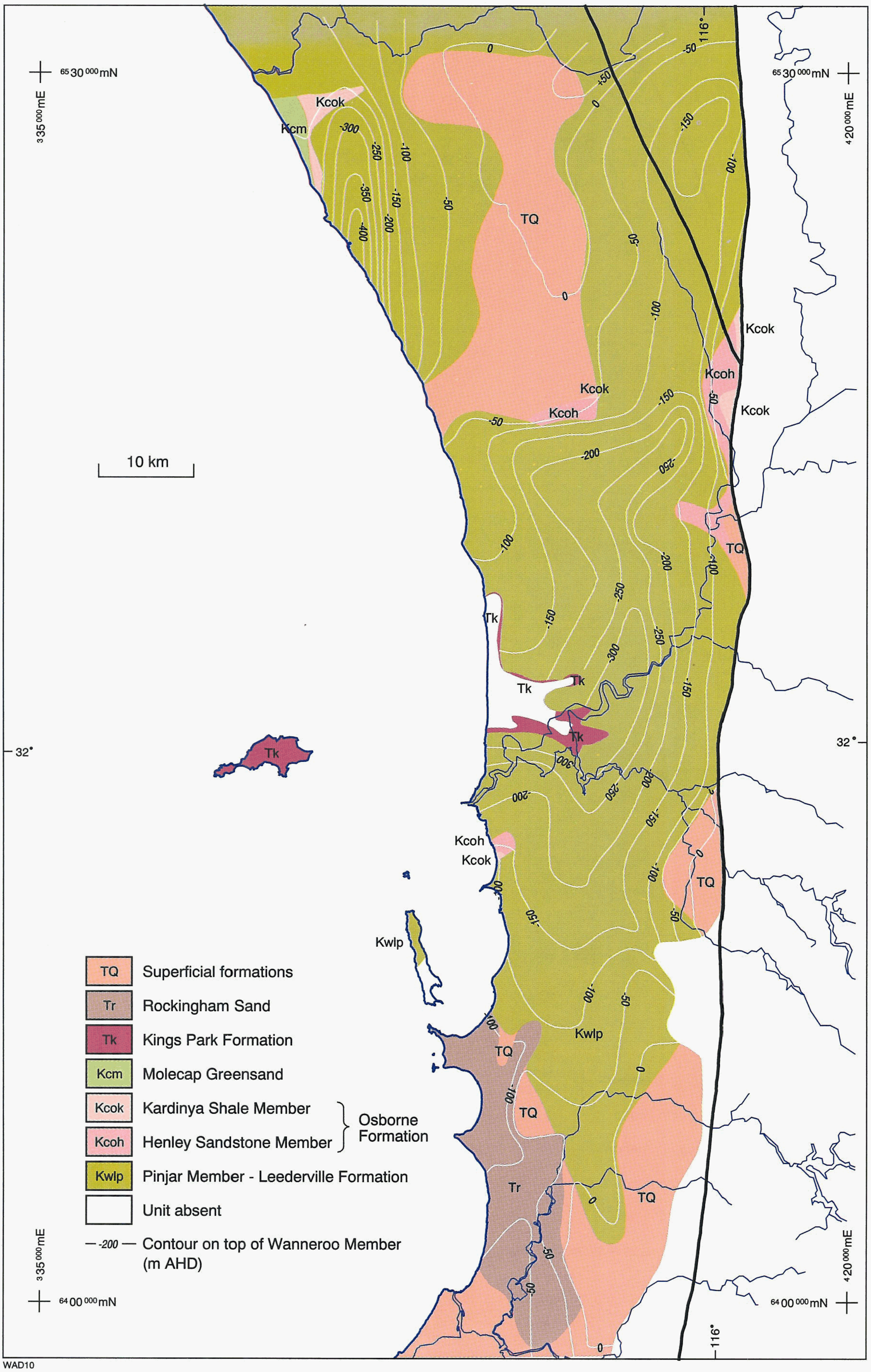


PLATE 16. Wanneroo Member: contours on top of unit; with overlying strata

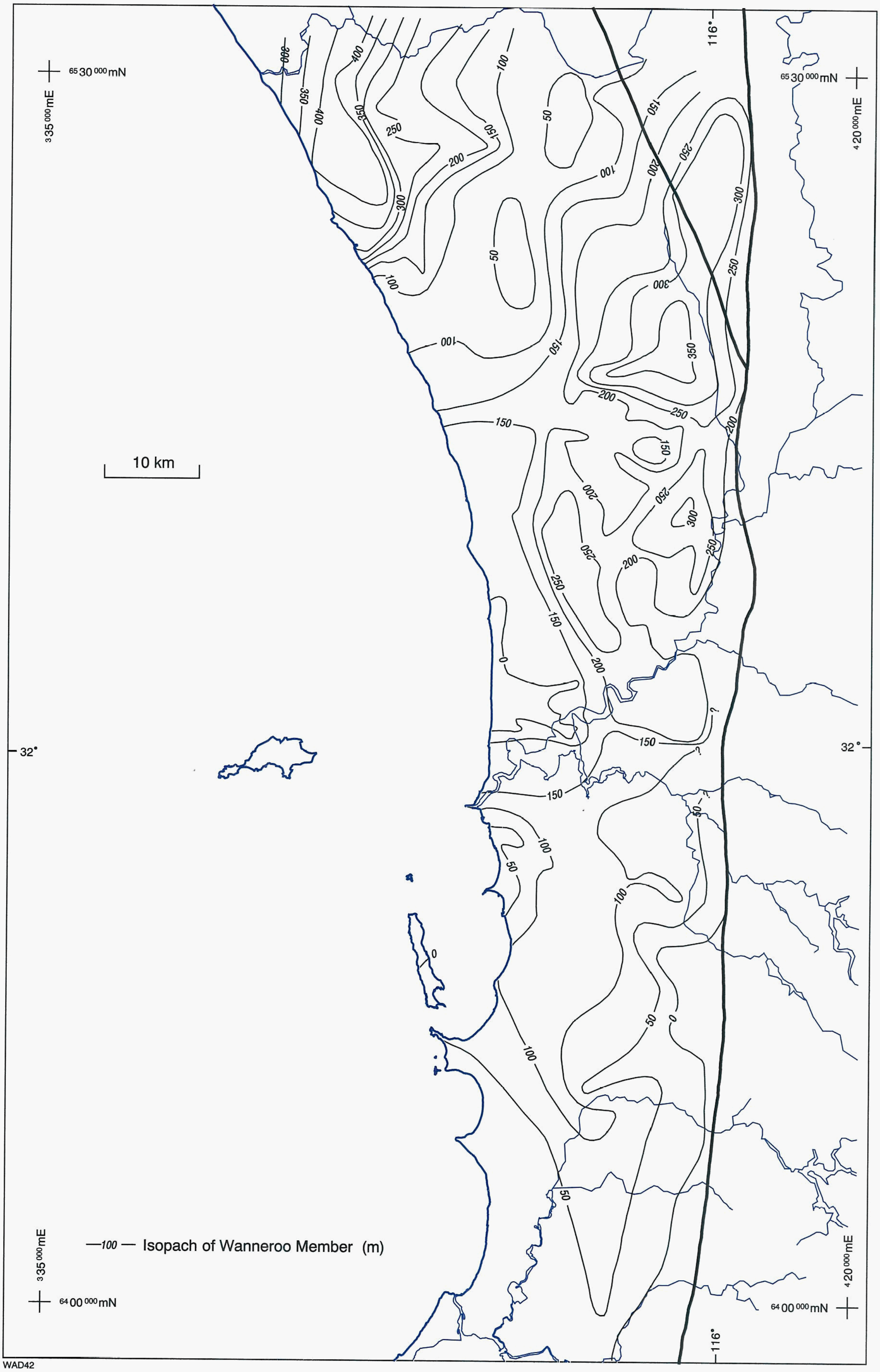


PLATE 17. Wanneroo Member: isopachs

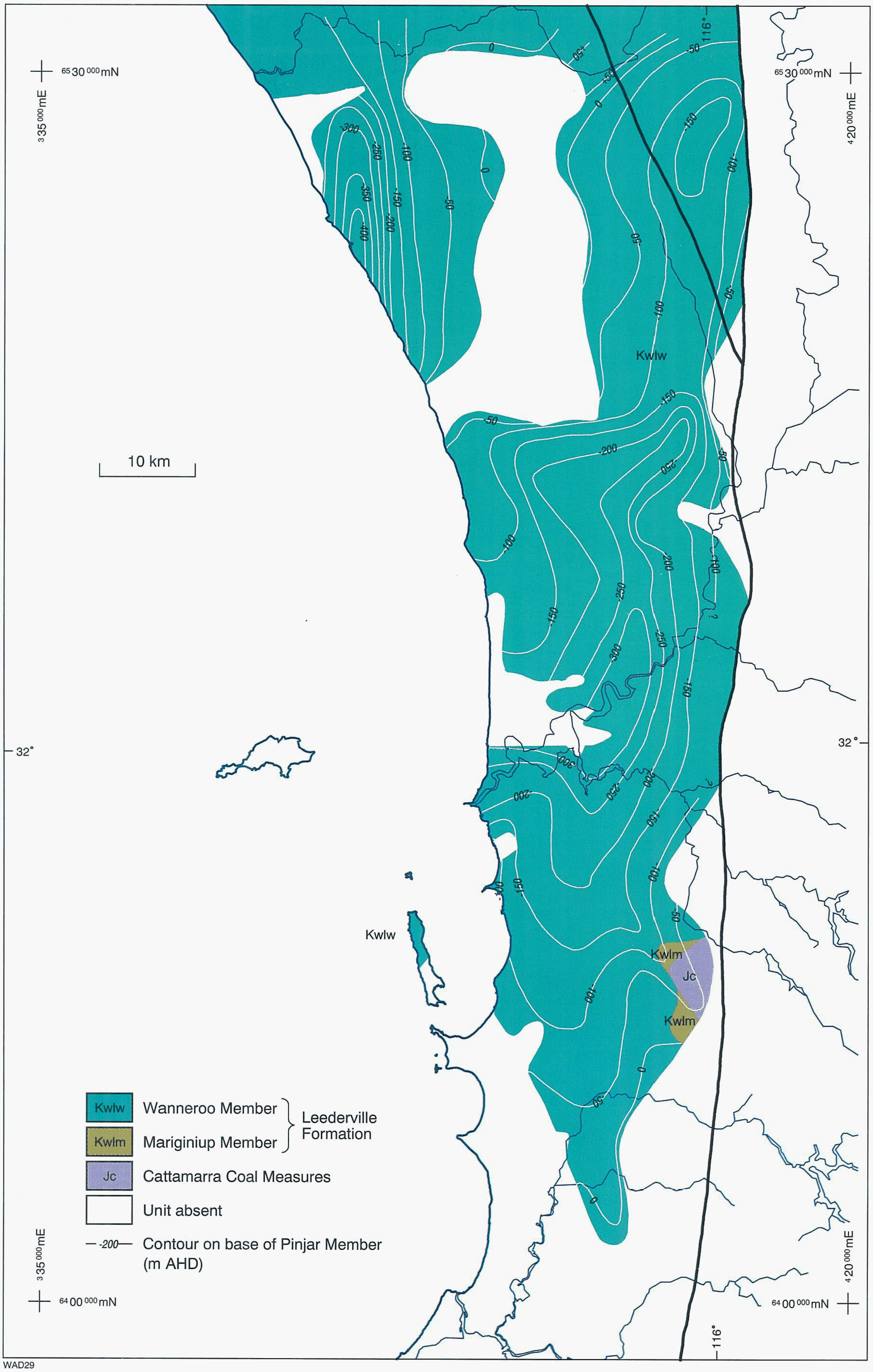


PLATE 18. Pinjar Member: contours on base of unit; with strata subcrop

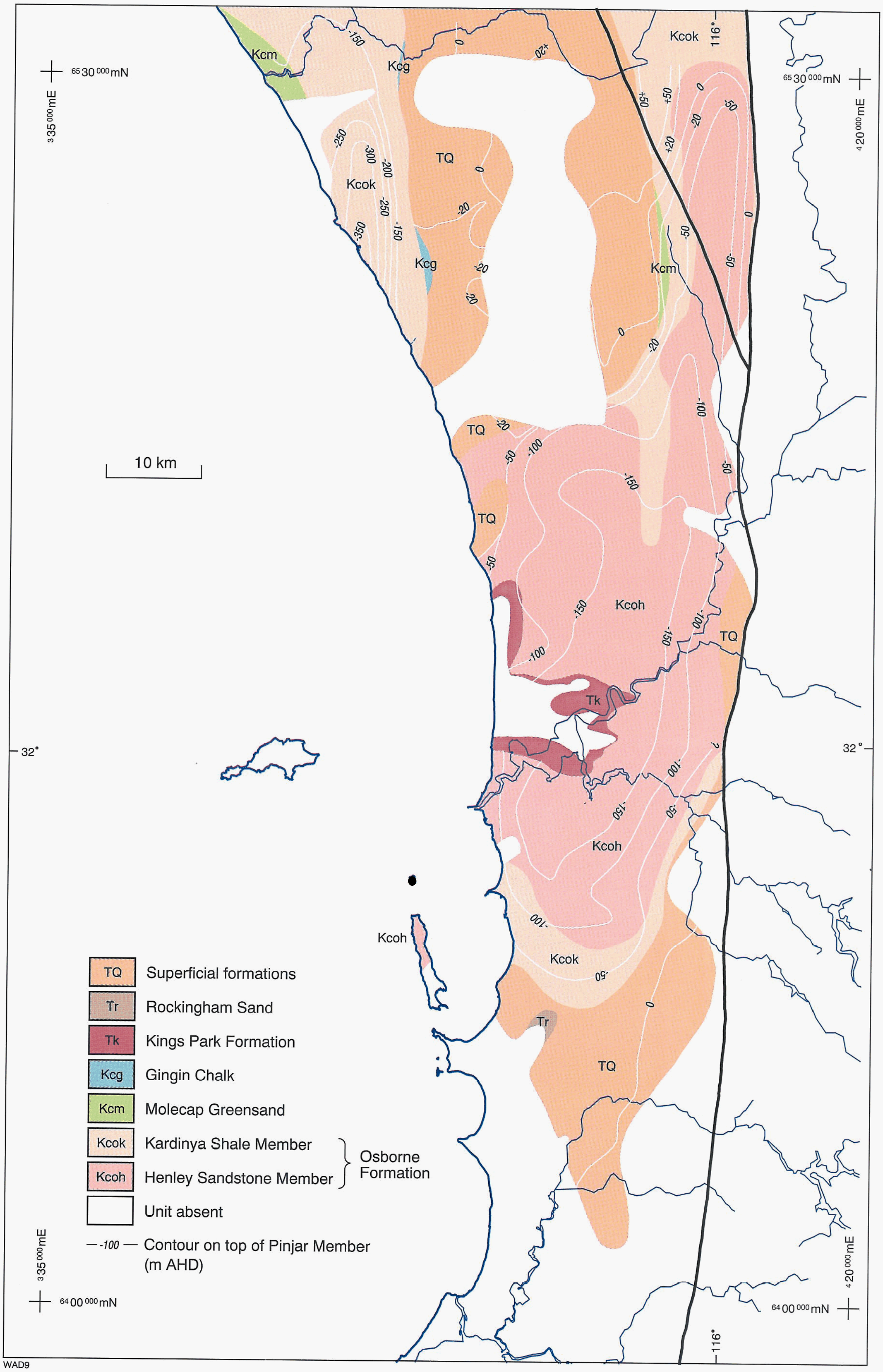
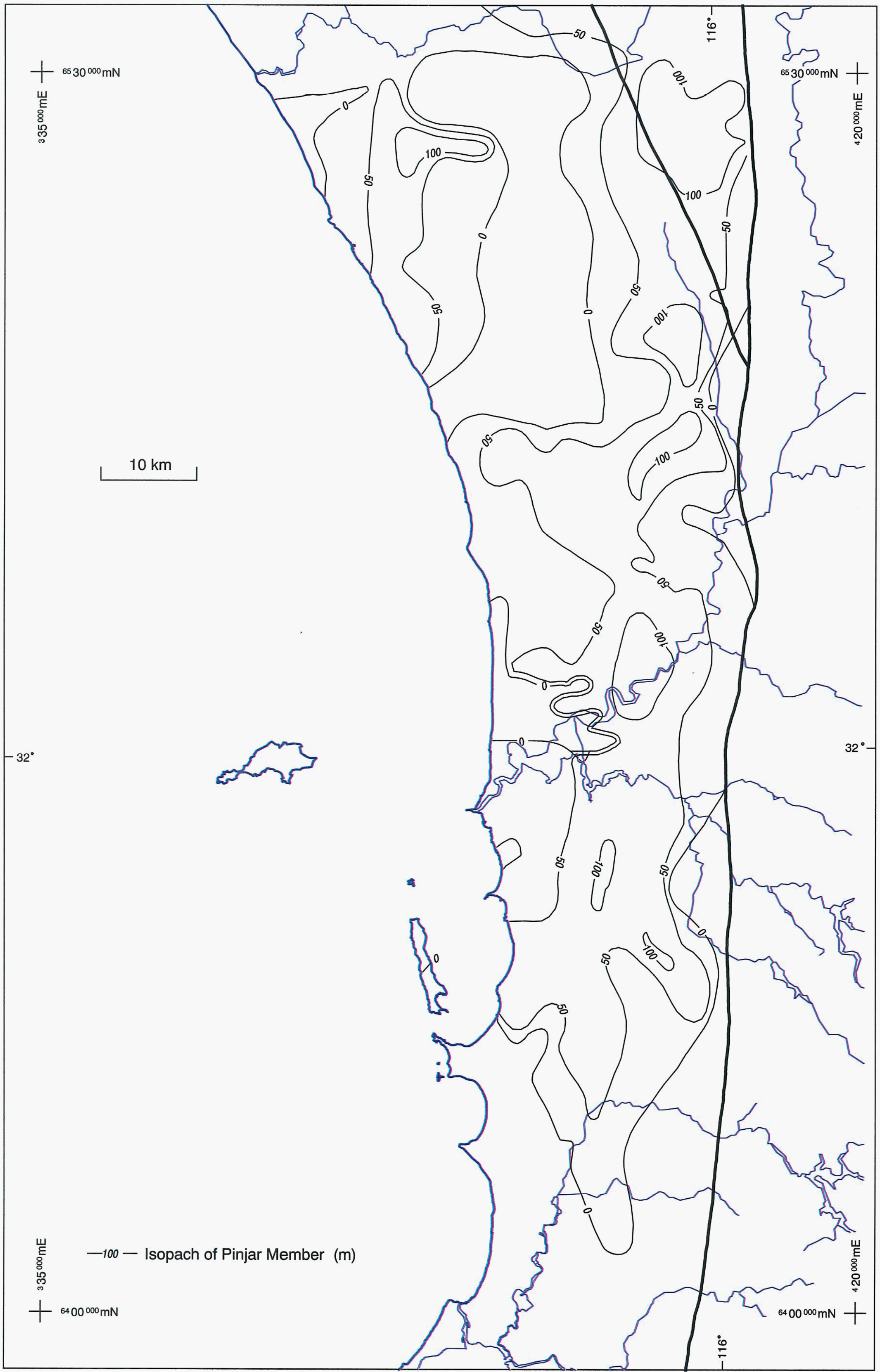


PLATE 19. Pinjar Member: contours on top of unit; with overlying strata



WAD41

PLATE 20. Pinjar Member: isopachs

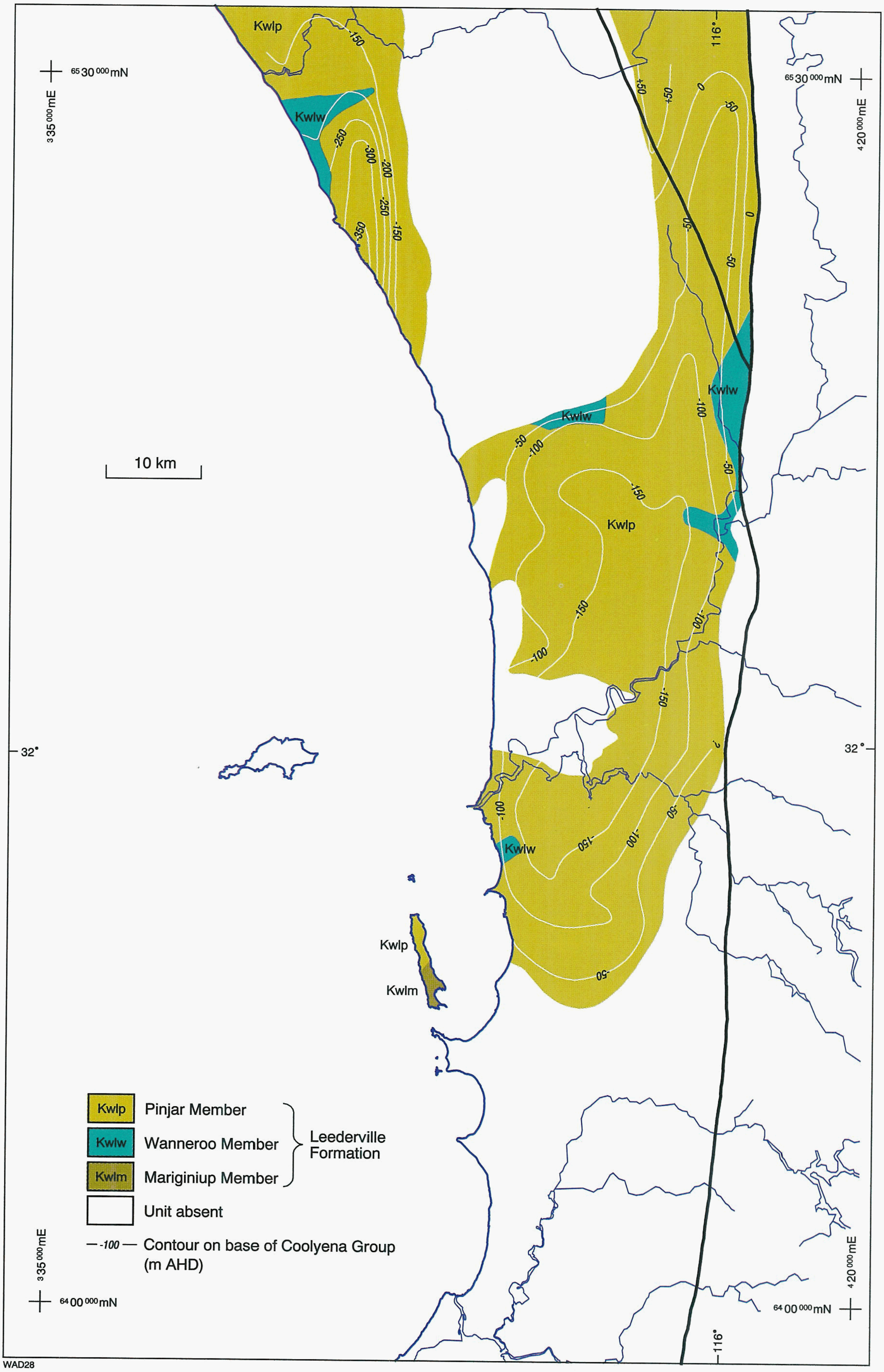


PLATE 21. Coolyena Group: contours on base of group; with strata subcrop

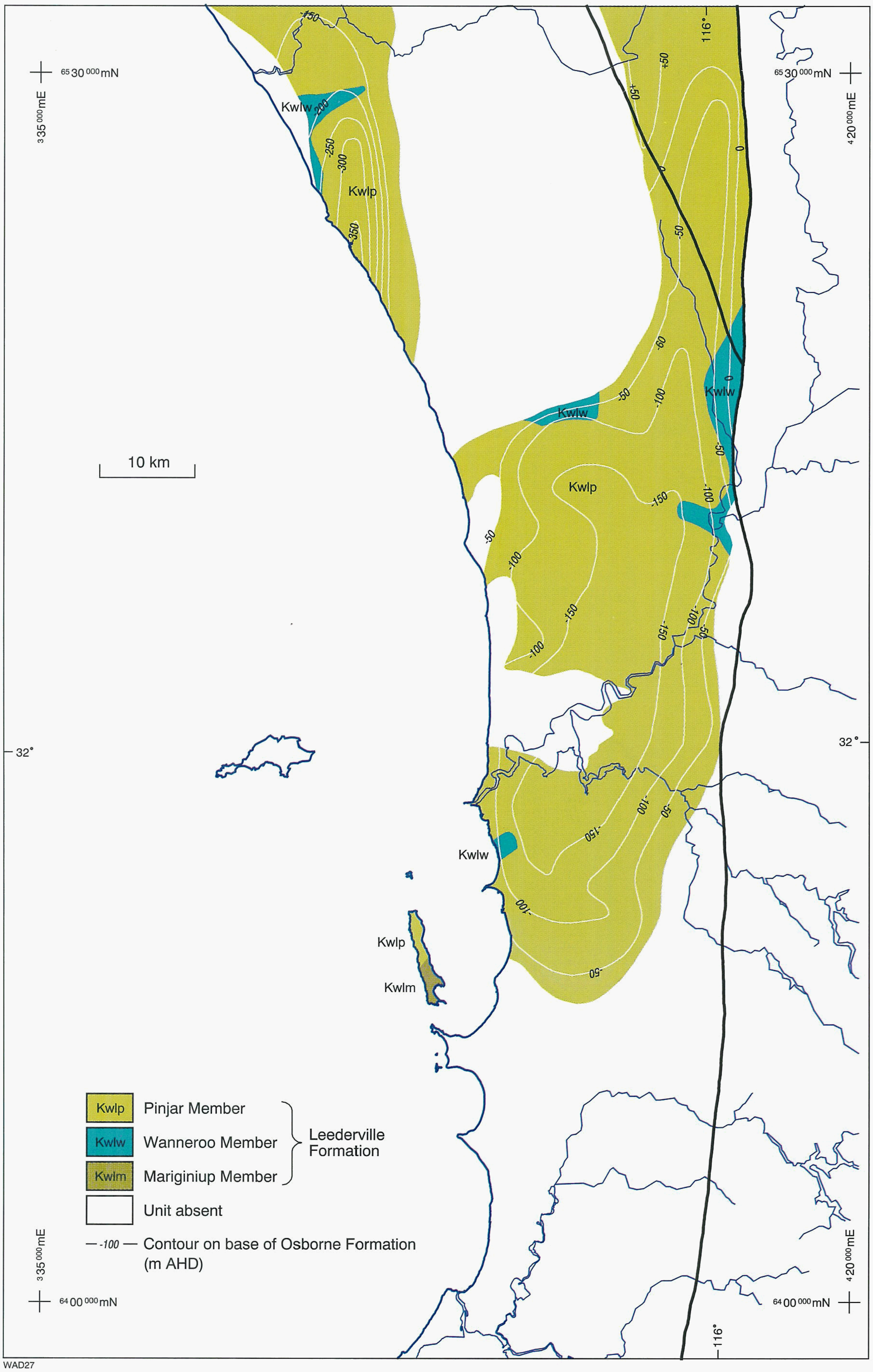


PLATE 22. Osborne Formation: contours on base of unit; with strata subcrop

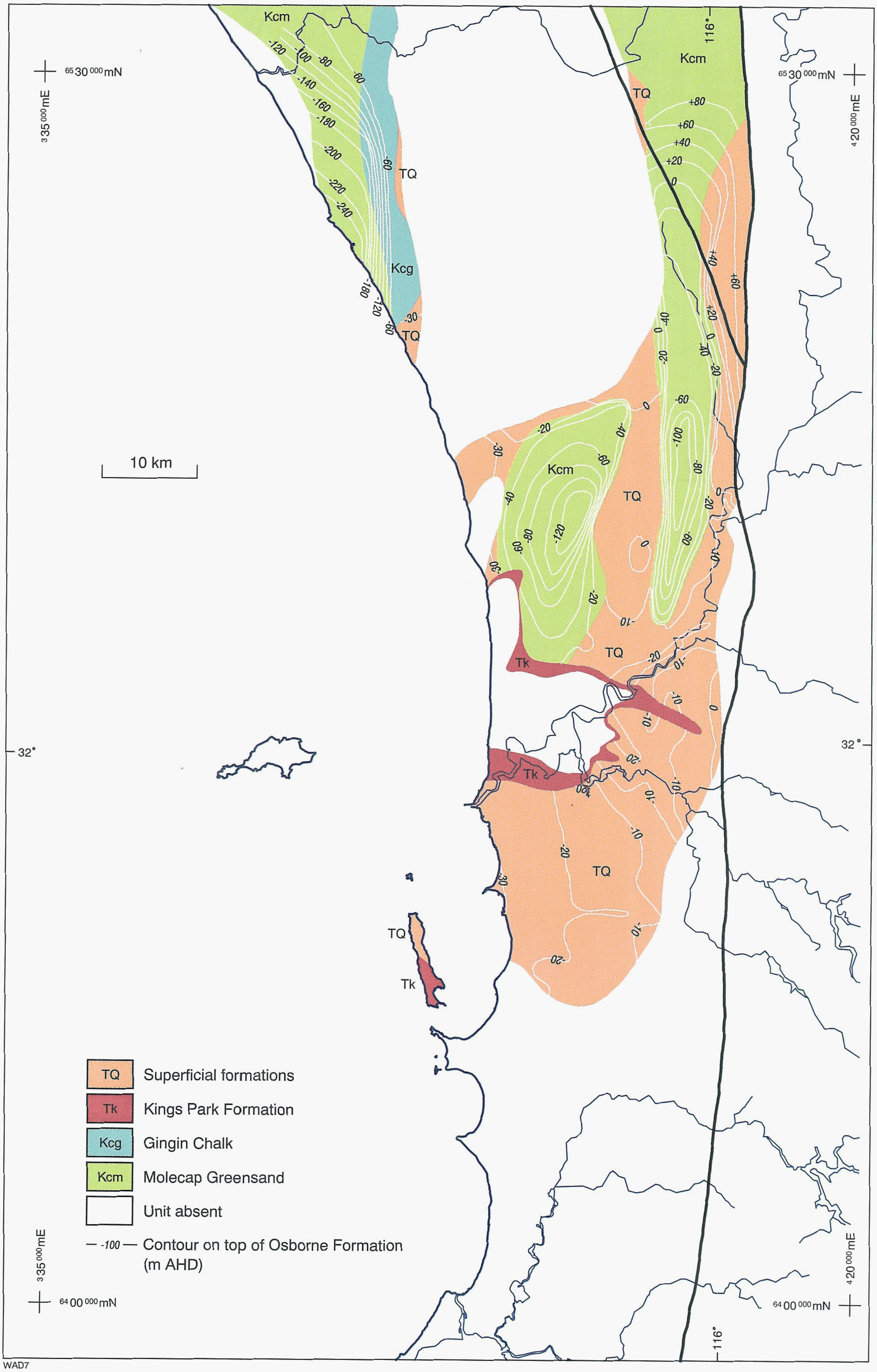
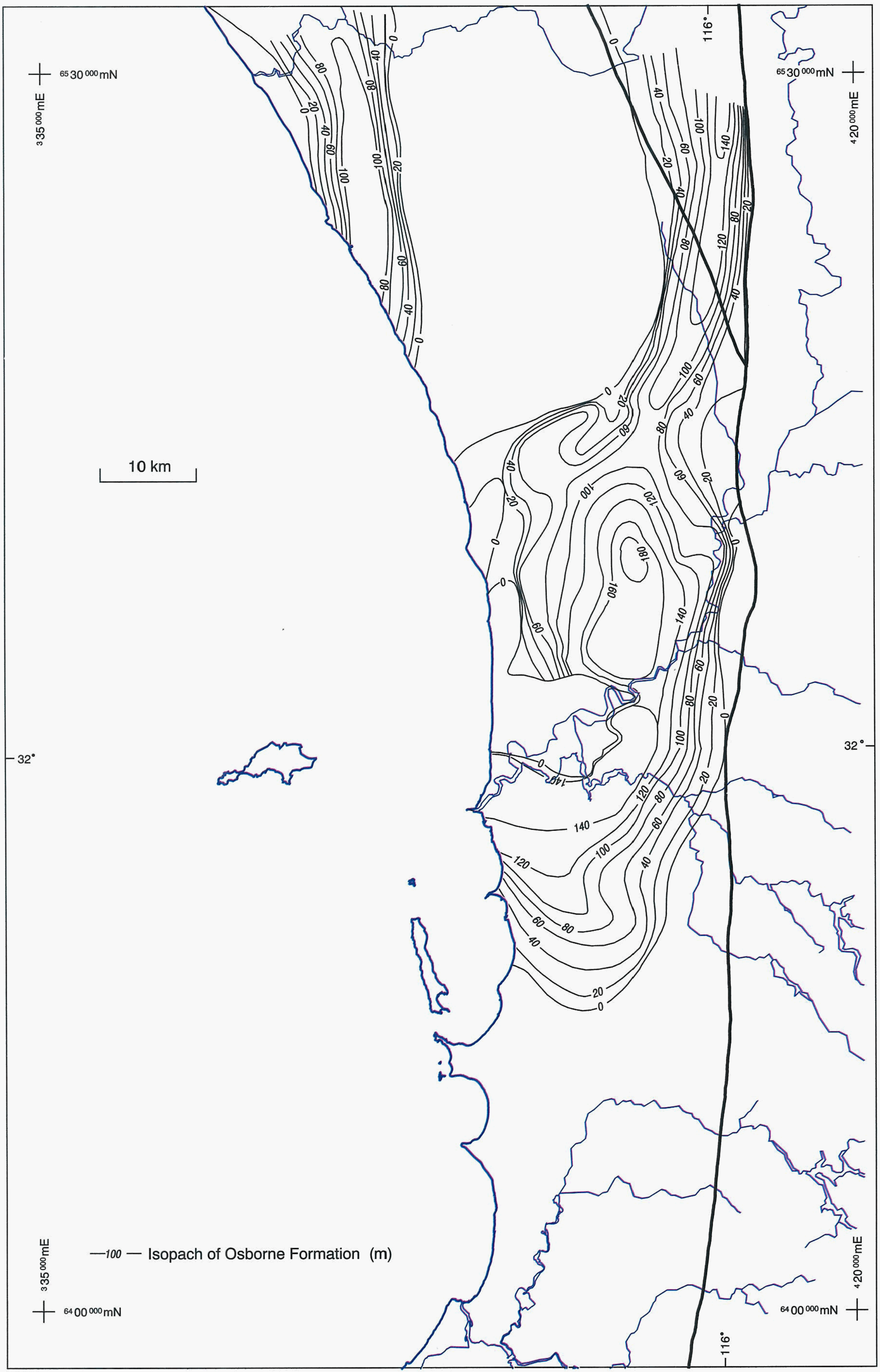
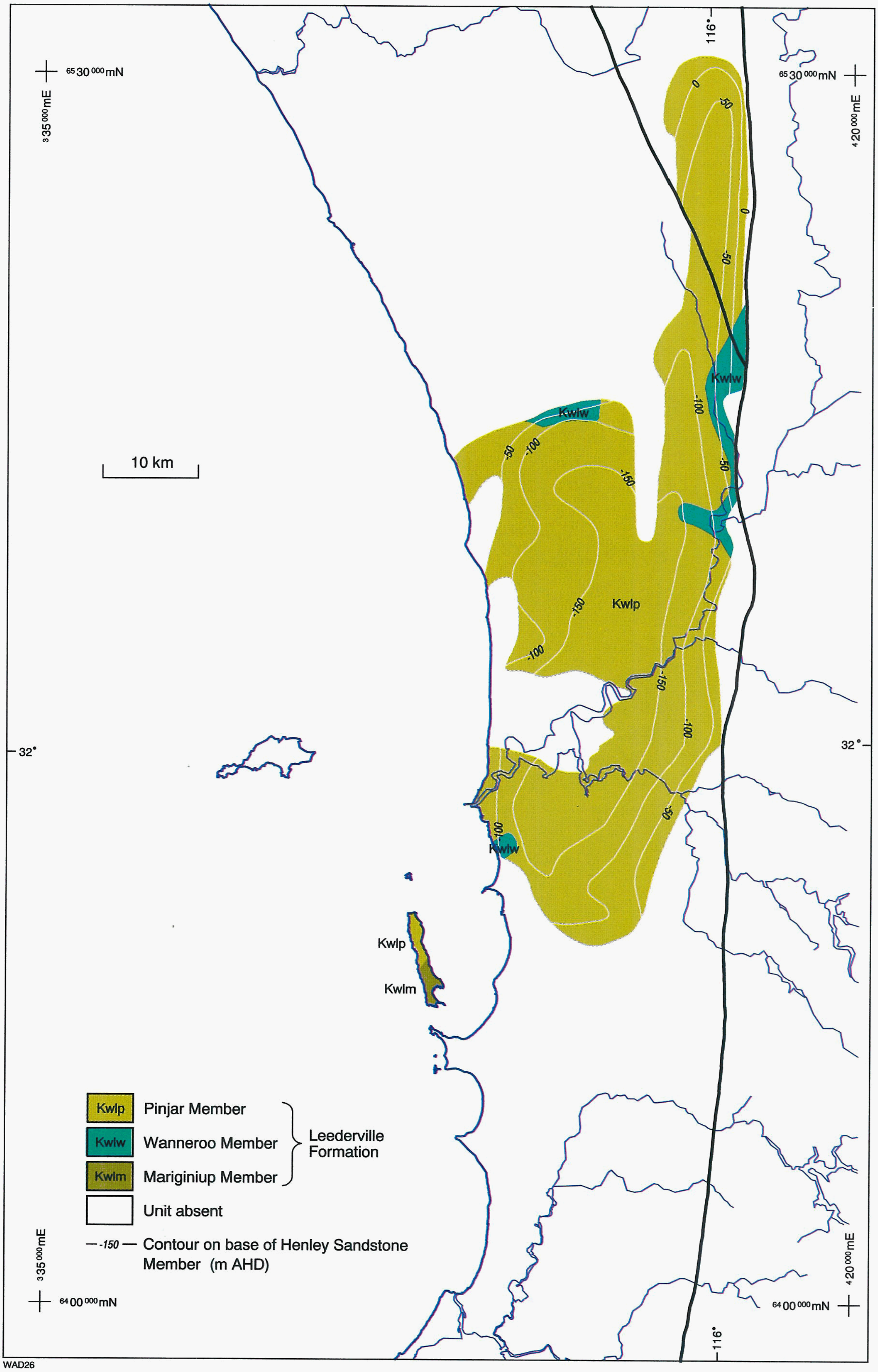


PLATE 23. Osborne Formation: contours on top of unit; with overlying strata



WAD40

PLATE 24. Osborne Formation: isopachs



WAD26

PLATE 25. Henley Sandstone Member: contours on base of unit; with strata subcrop

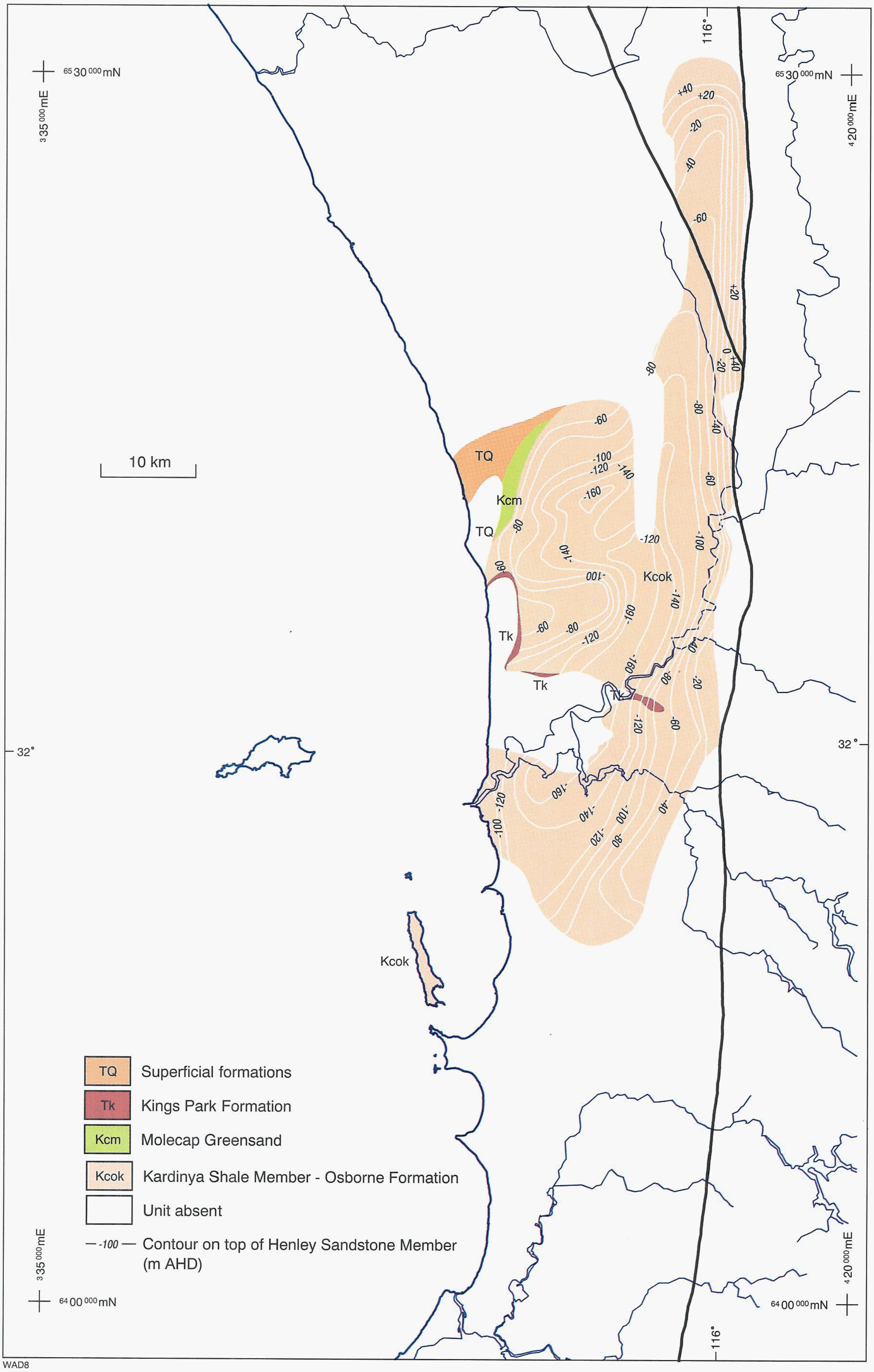


PLATE 26. Henley Sandstone Member: contours on top of unit; with overlying strata

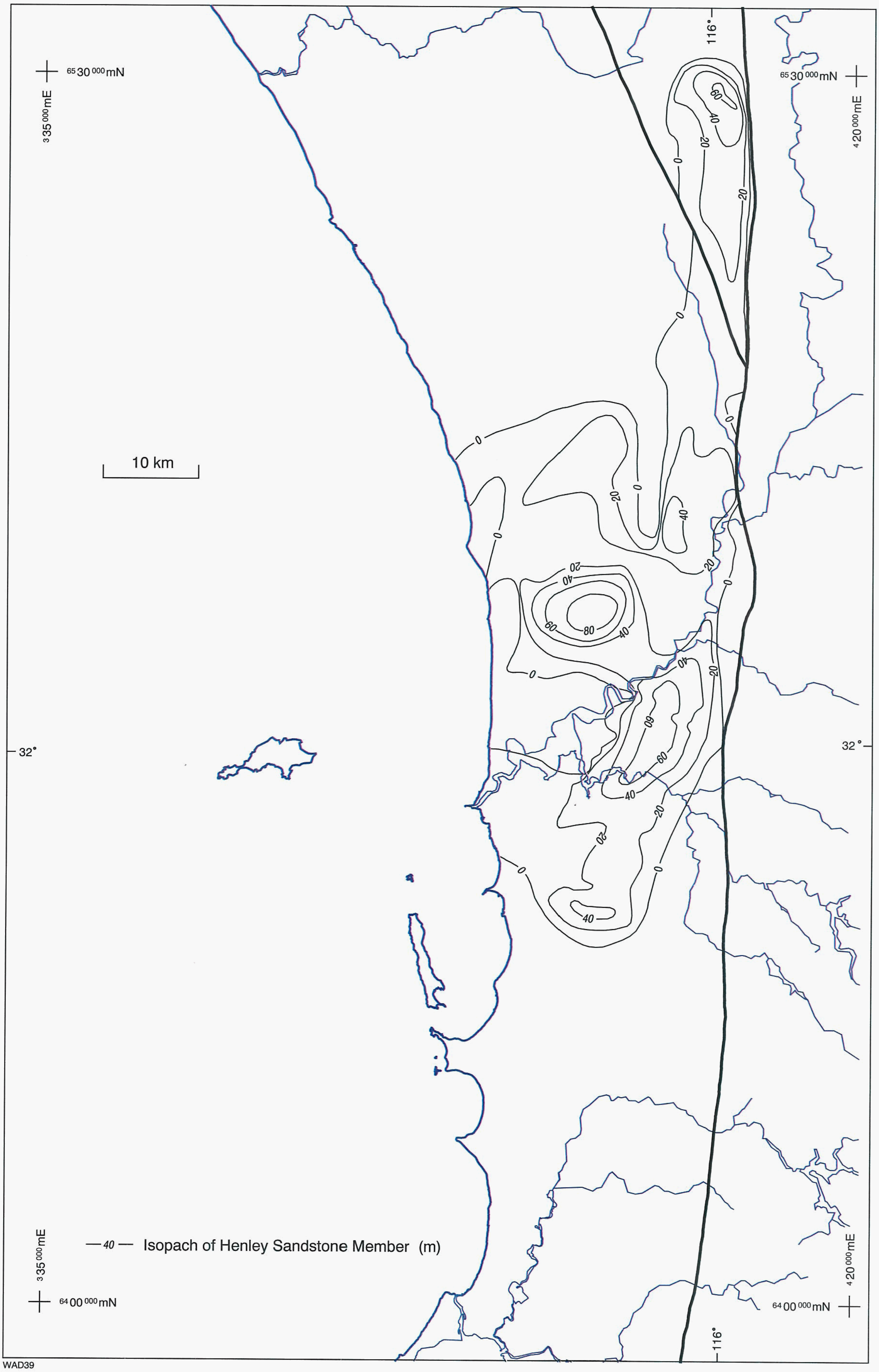


PLATE 27. Henley Sandstone Member: isopachs

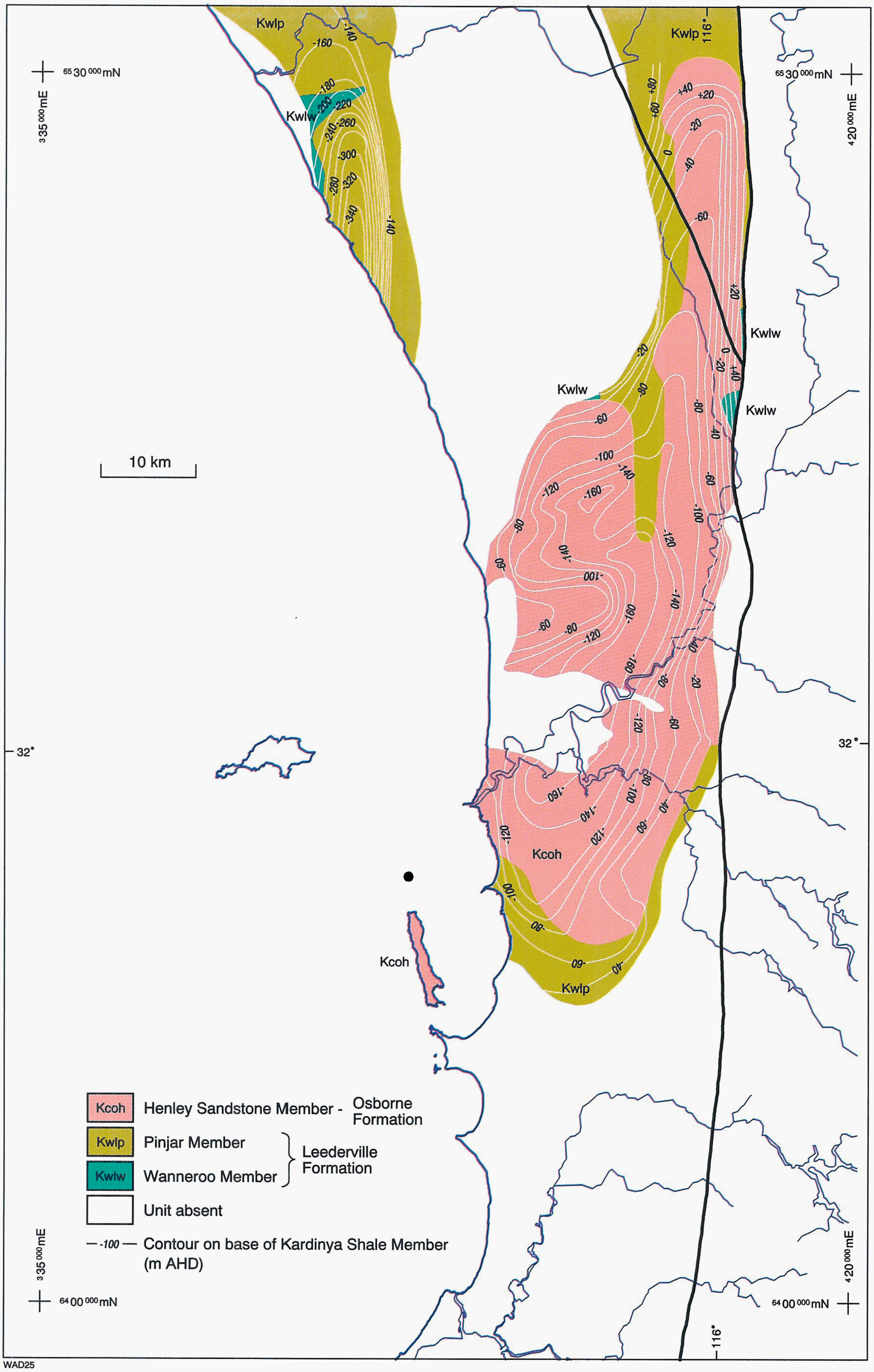


PLATE 28. Kardinya Shale Member: contours on base of unit; with strata subcrop

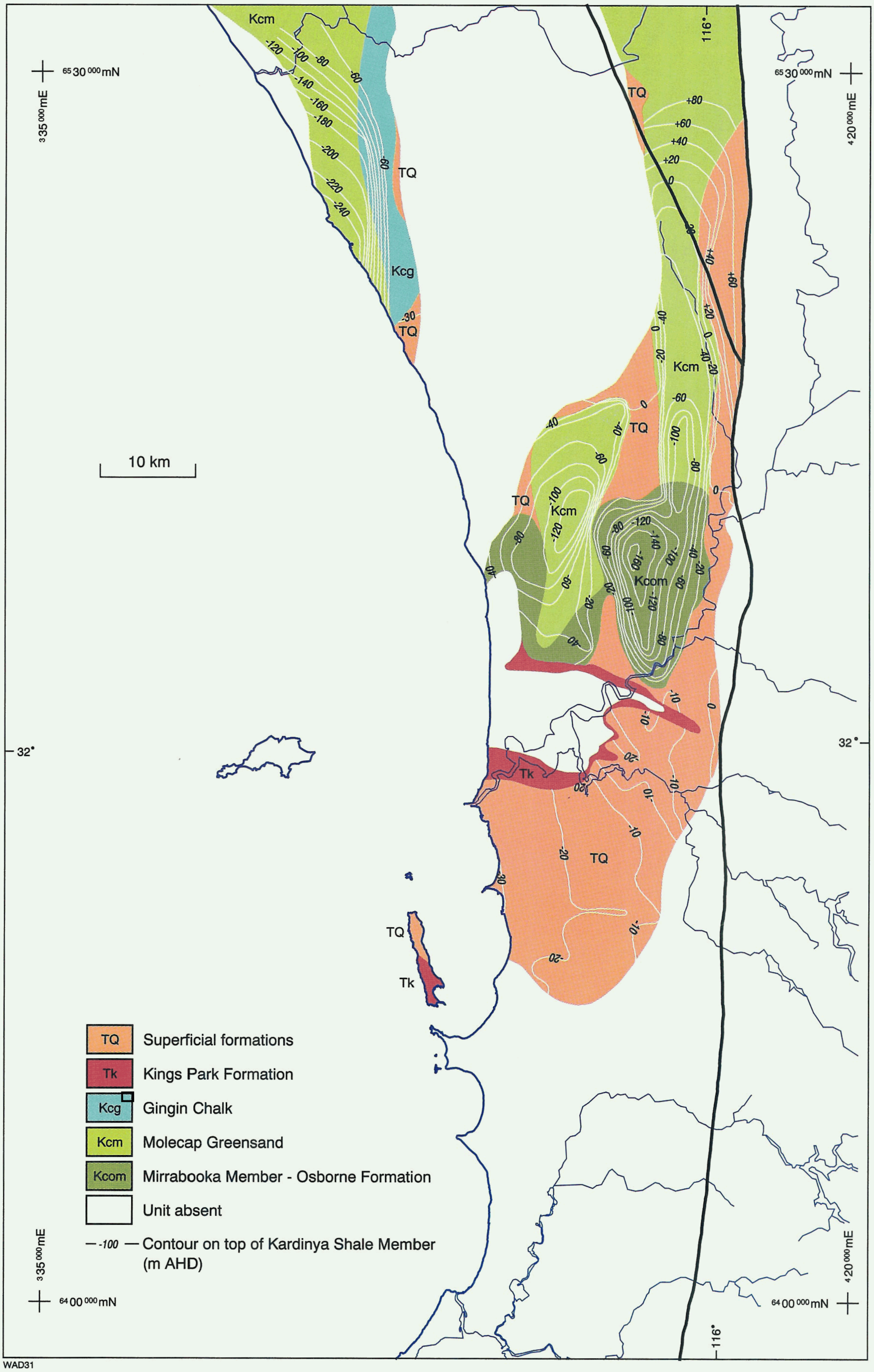
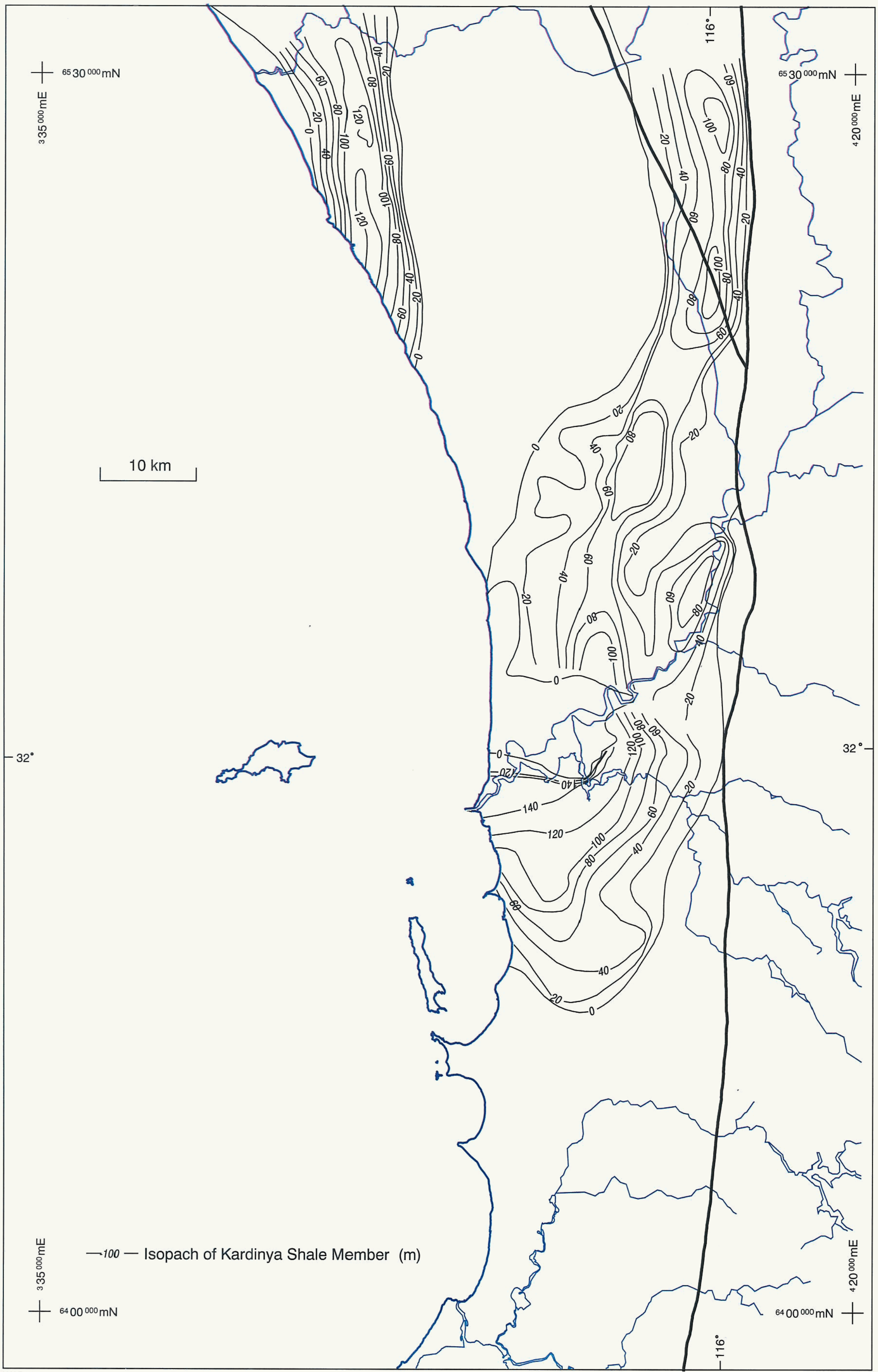


PLATE 29. Kardinya Shale Member: contours on top of unit; with overlying strata



WAD38

PLATE 30. Kardinya Shale Member: isopachs

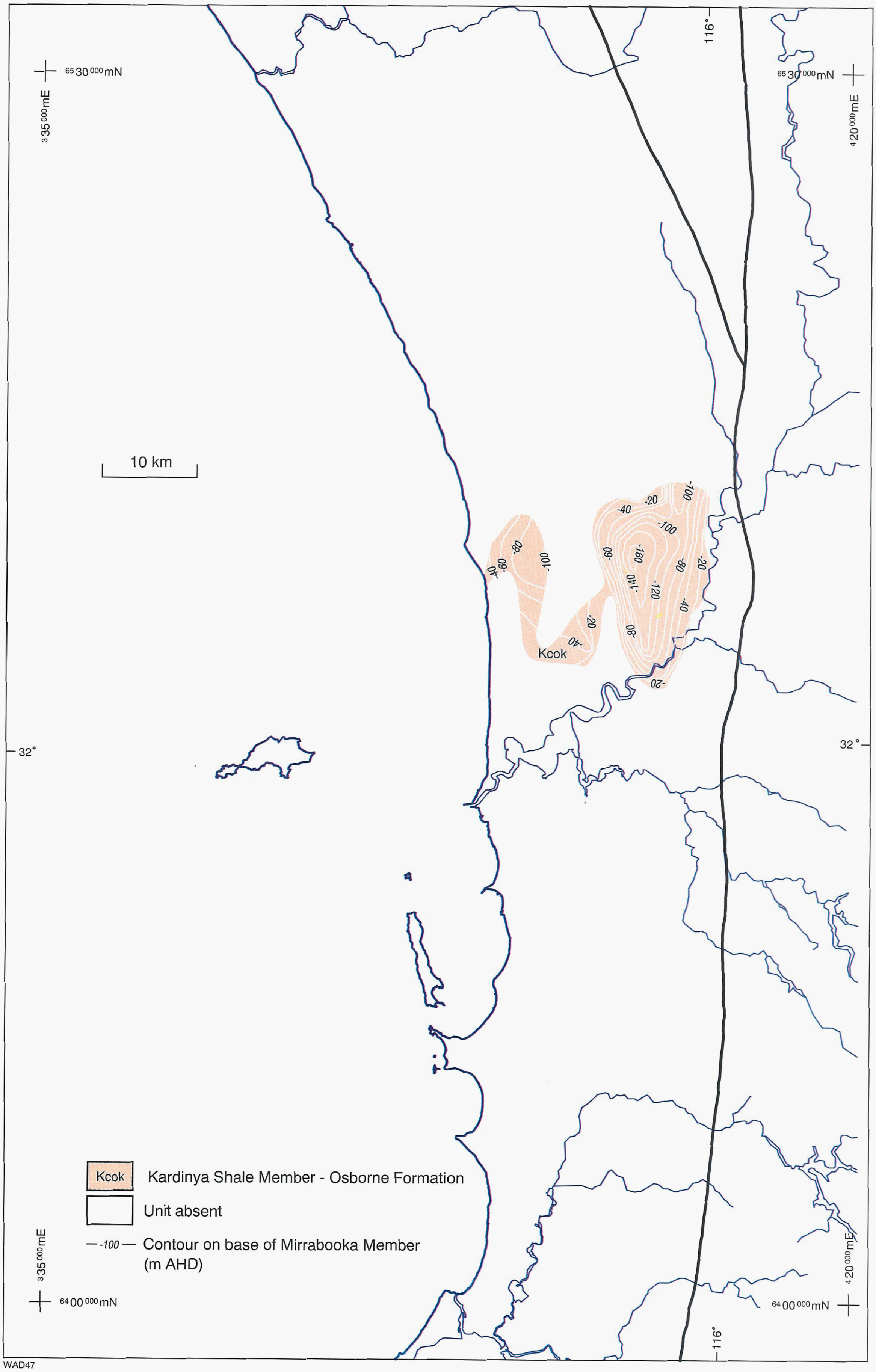


PLATE 31. Mirrabooka Member: contours on base of unit; with strata subcrop

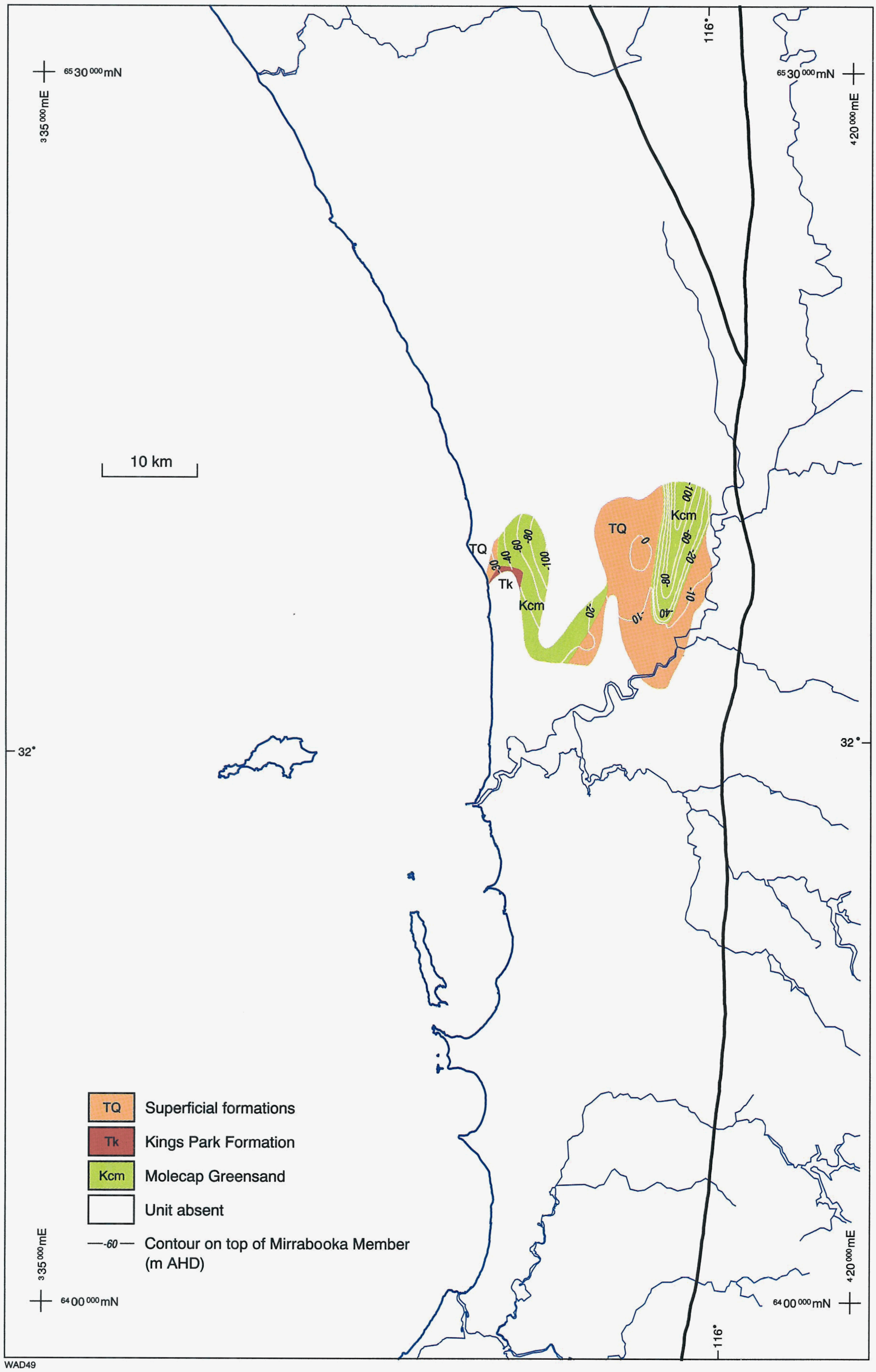
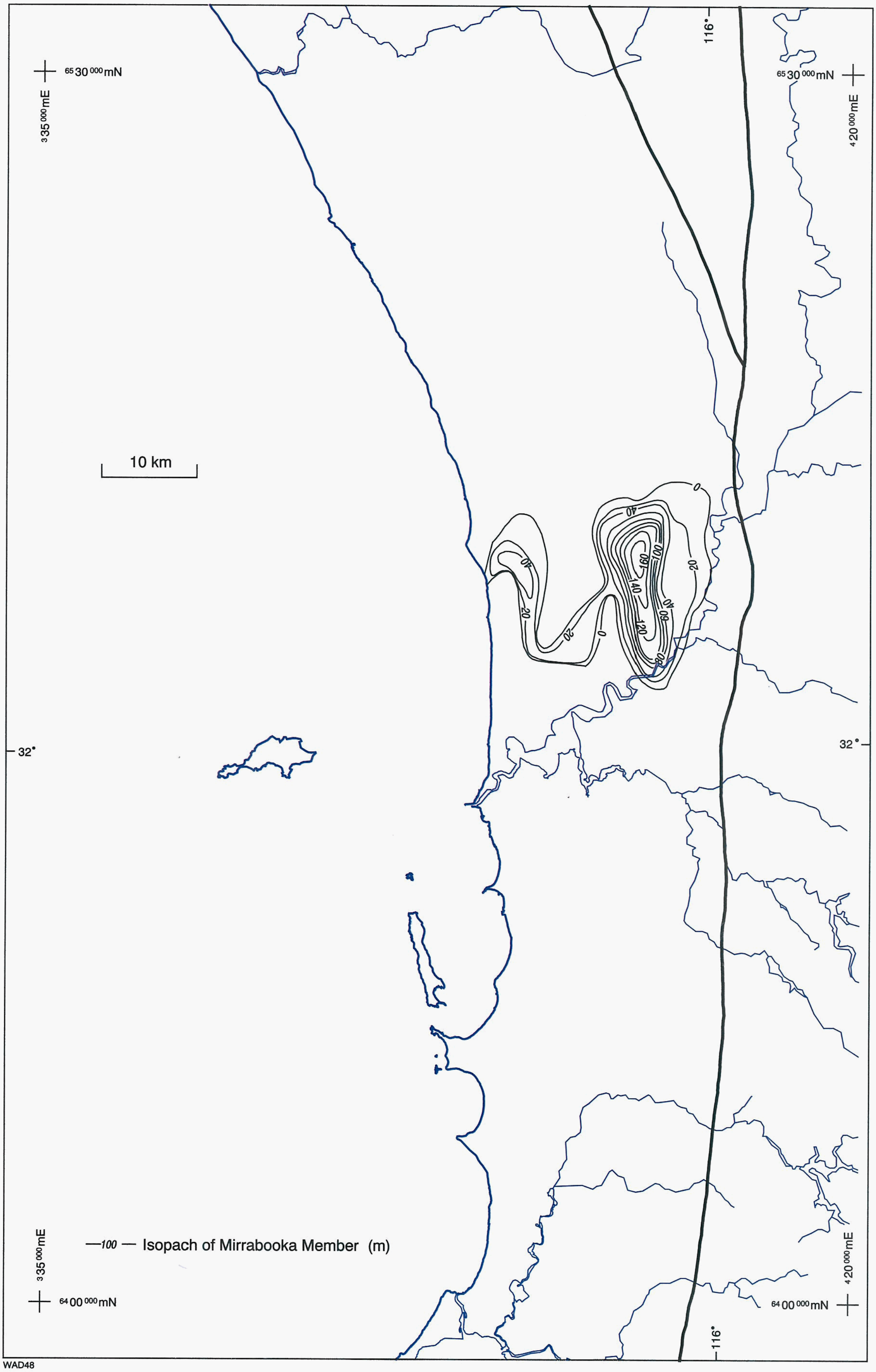


PLATE 32. Mirrabooka Member: contours on top of unit; with overlying strata



WAD48

PLATE 33. Mirrabooka Member: isopachs

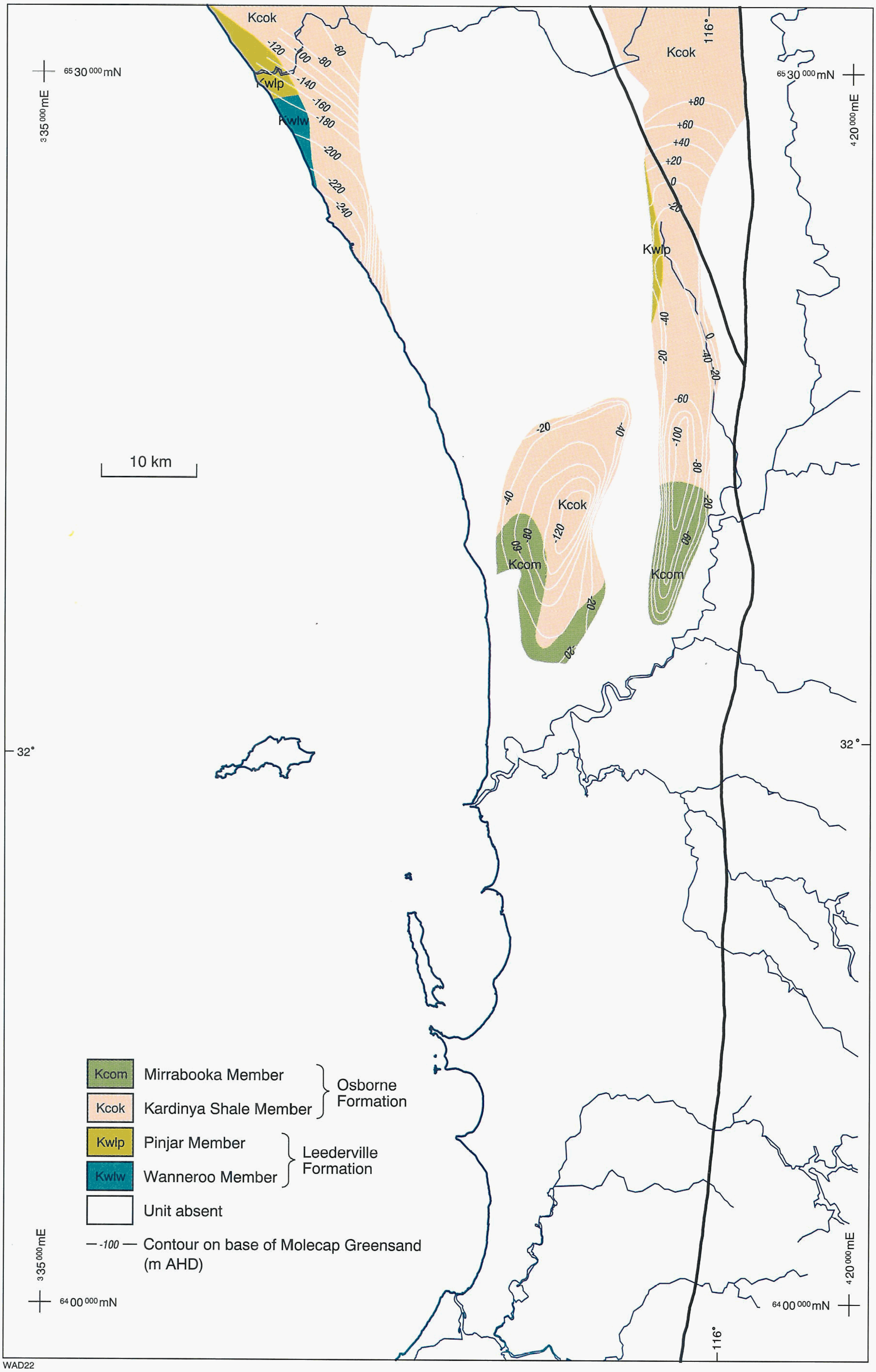


PLATE 34. Molecap Greensand: contours on base of unit; with strata subcrop

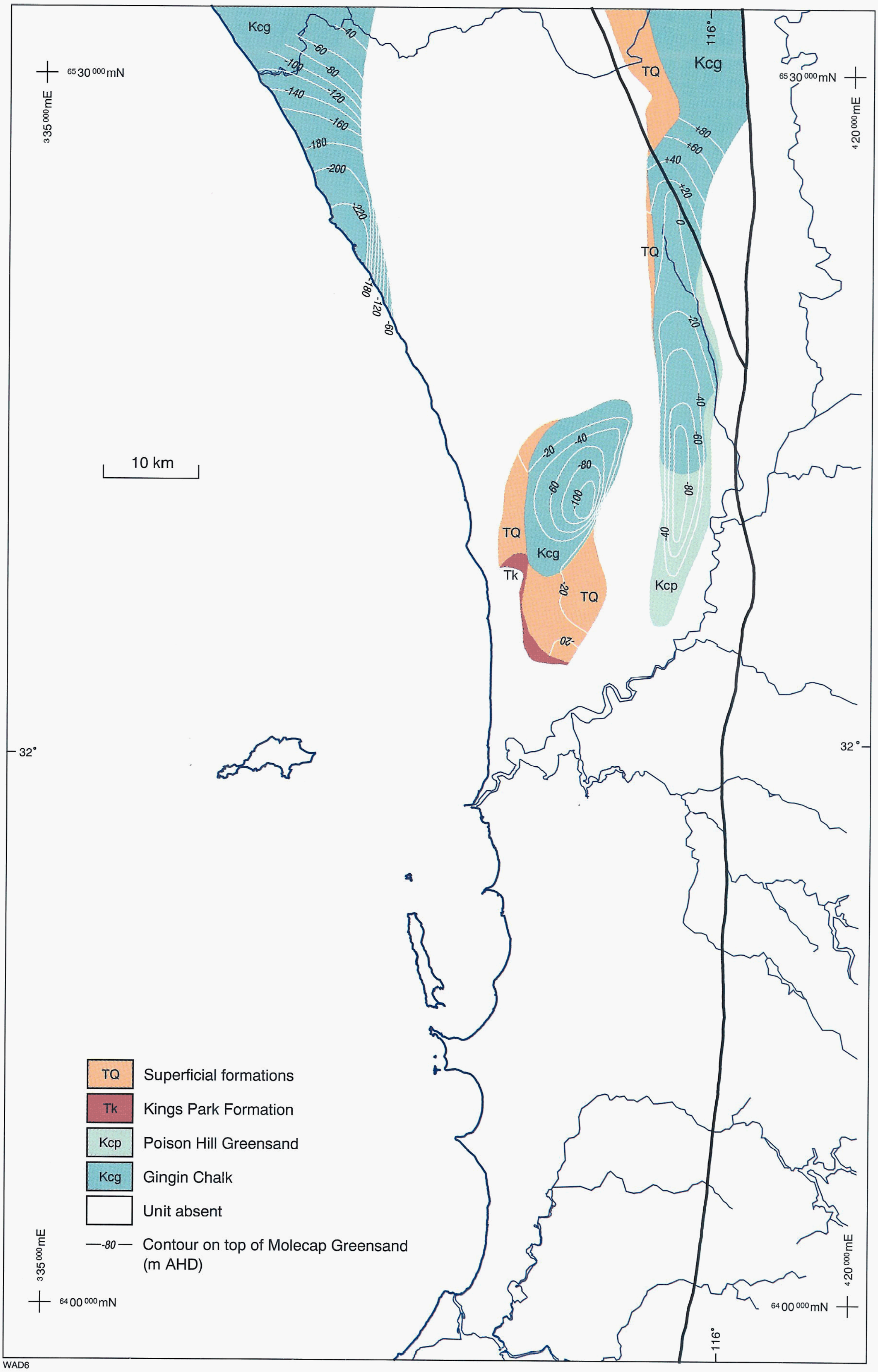


PLATE 35. Molecap Greensand: contours on top of unit; with overlying strata

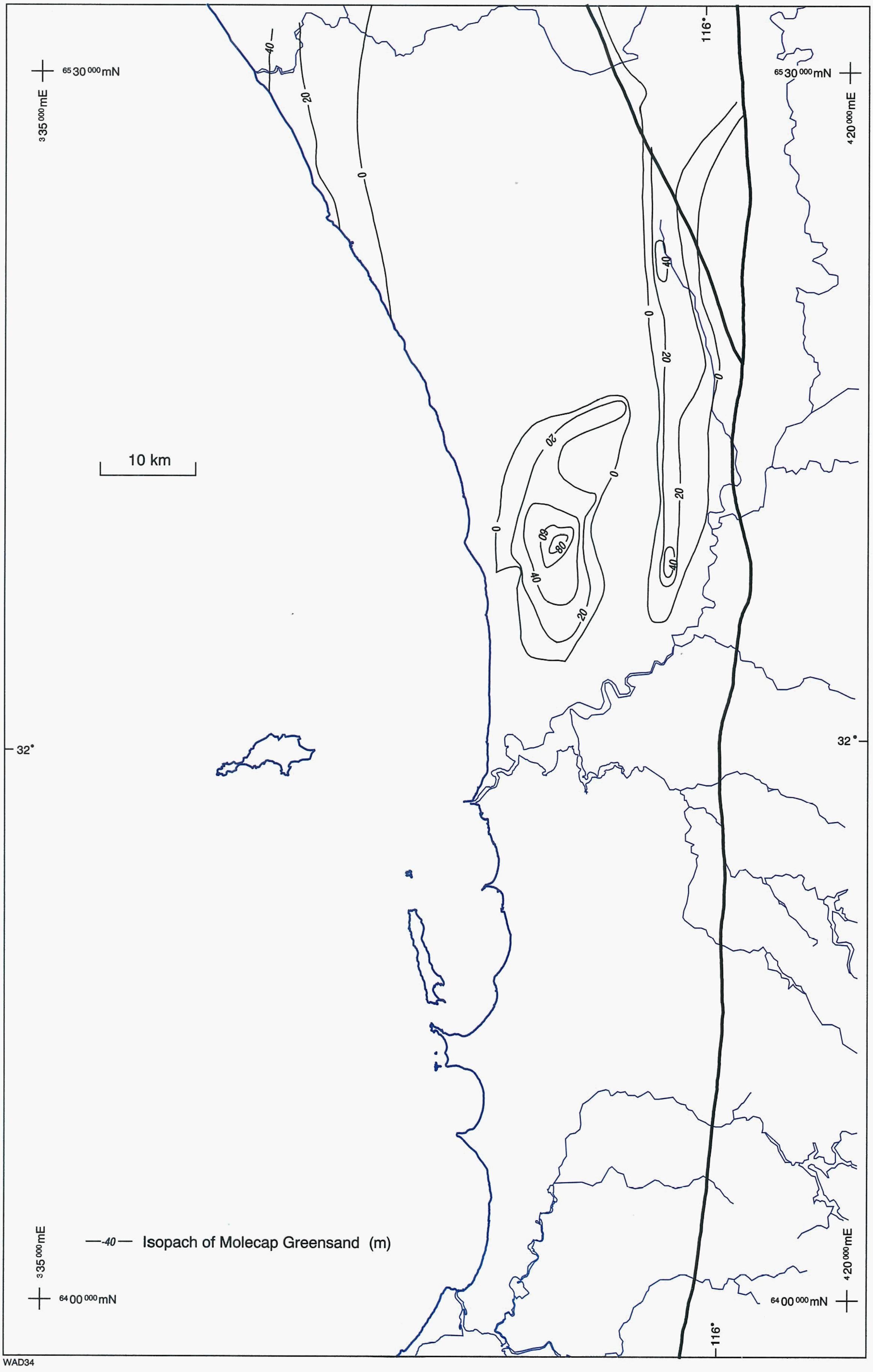


PLATE 36. Molecap Greensand: isopachs

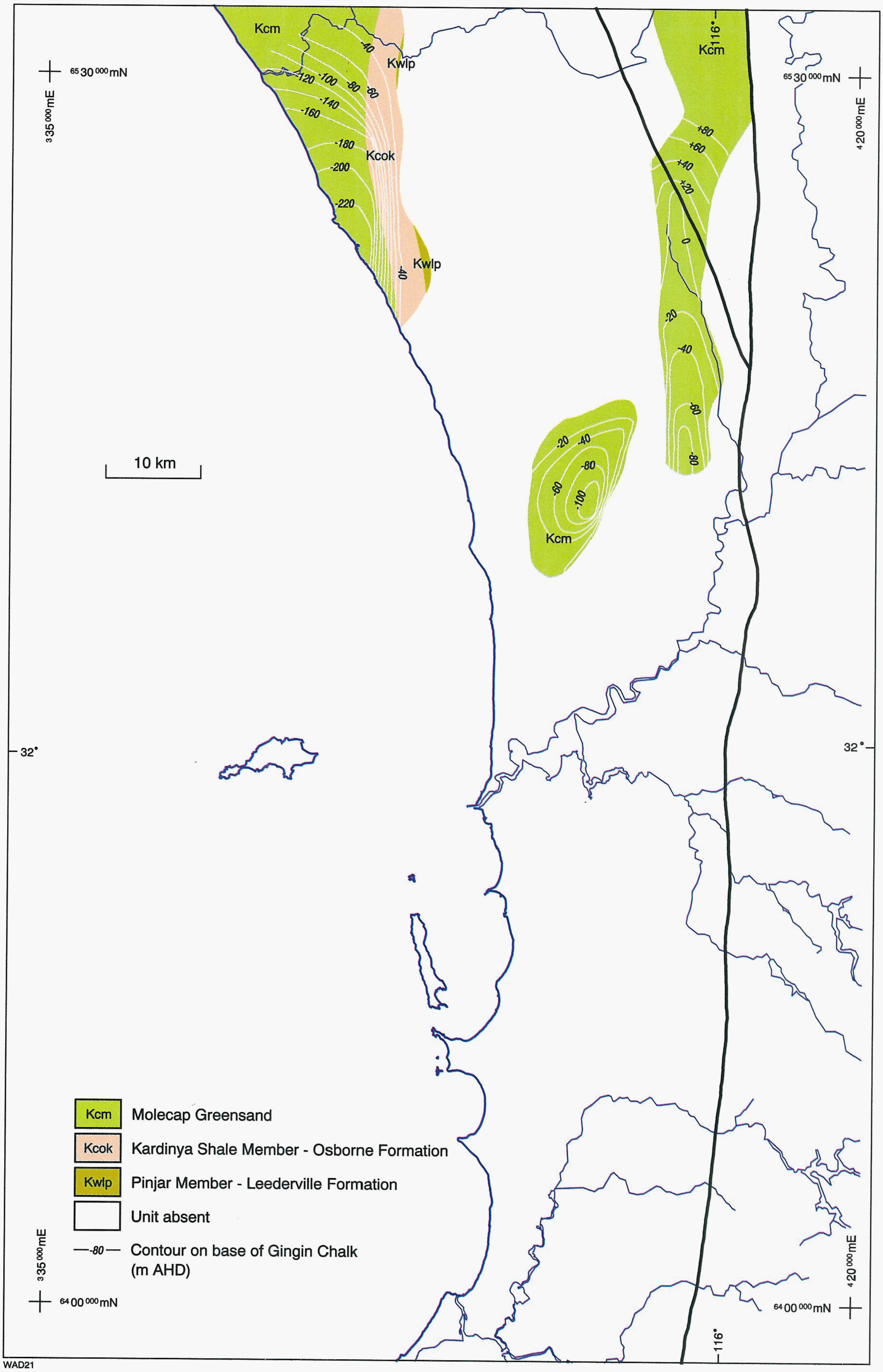


PLATE 37. Gingin Chalk: contours on base of unit; with strata subcrop

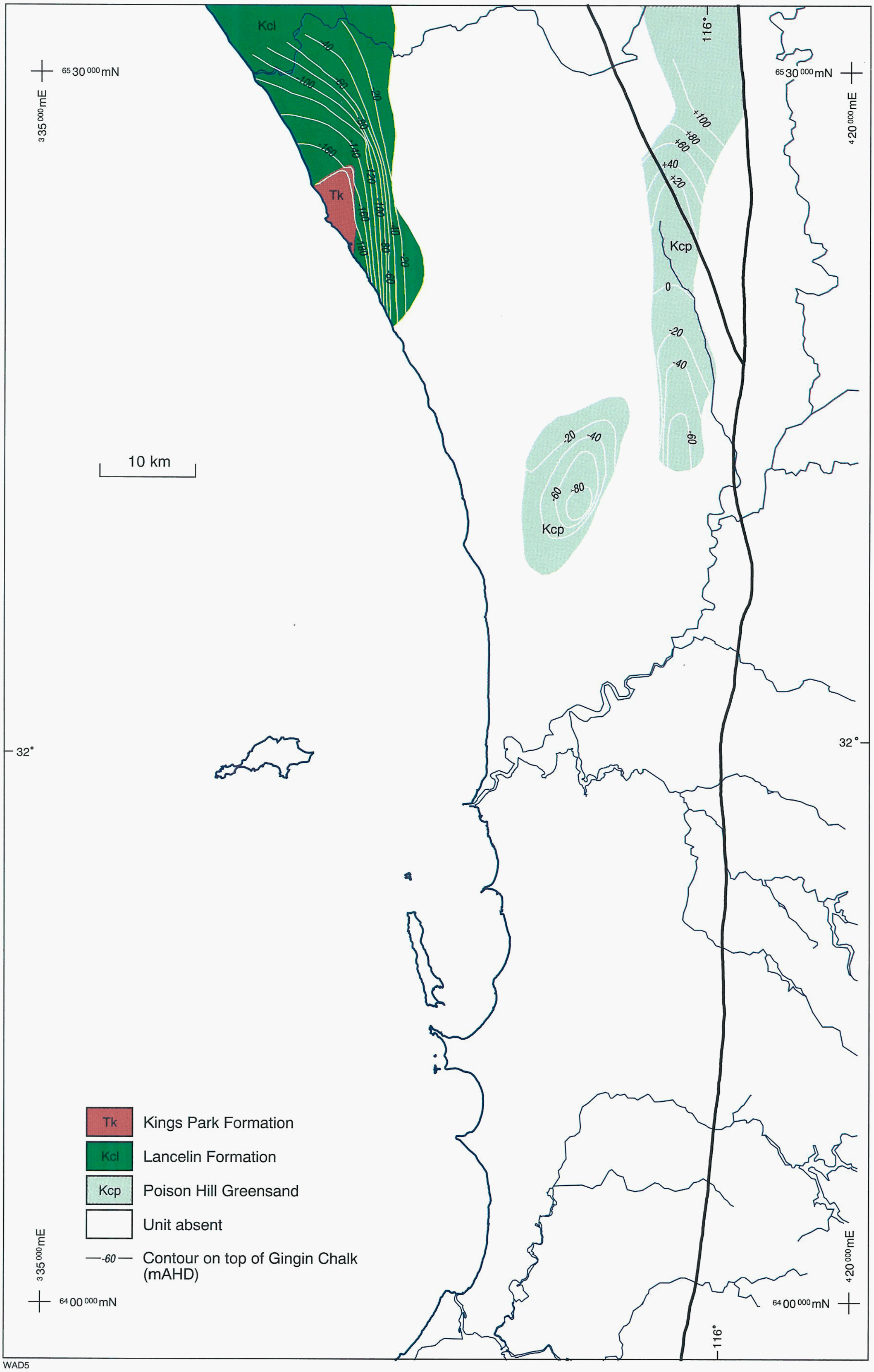


PLATE 38. Gingin Chalk: contours on top of unit; with overlying strata

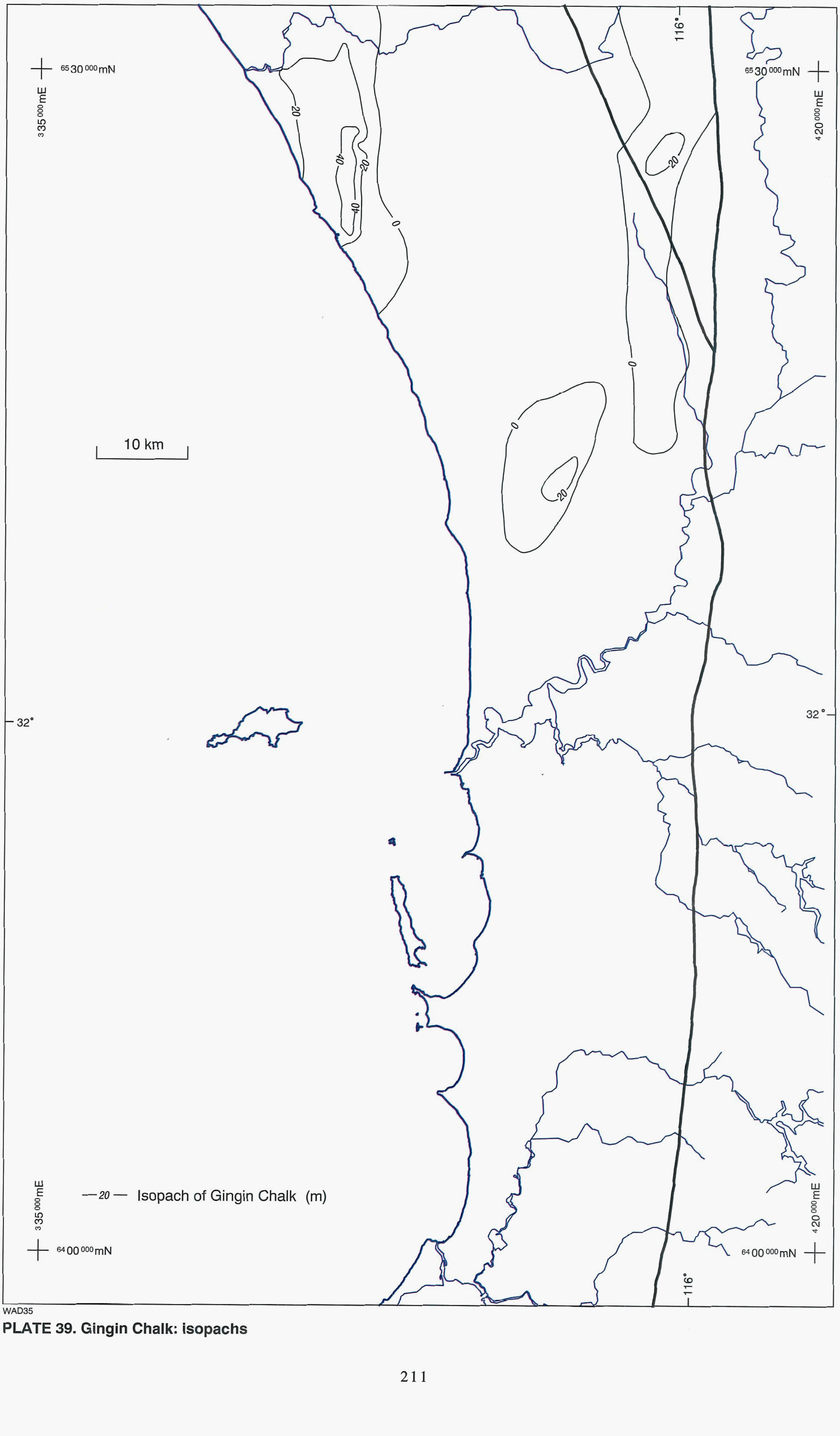


PLATE 39. Gingin Chalk: isopachs

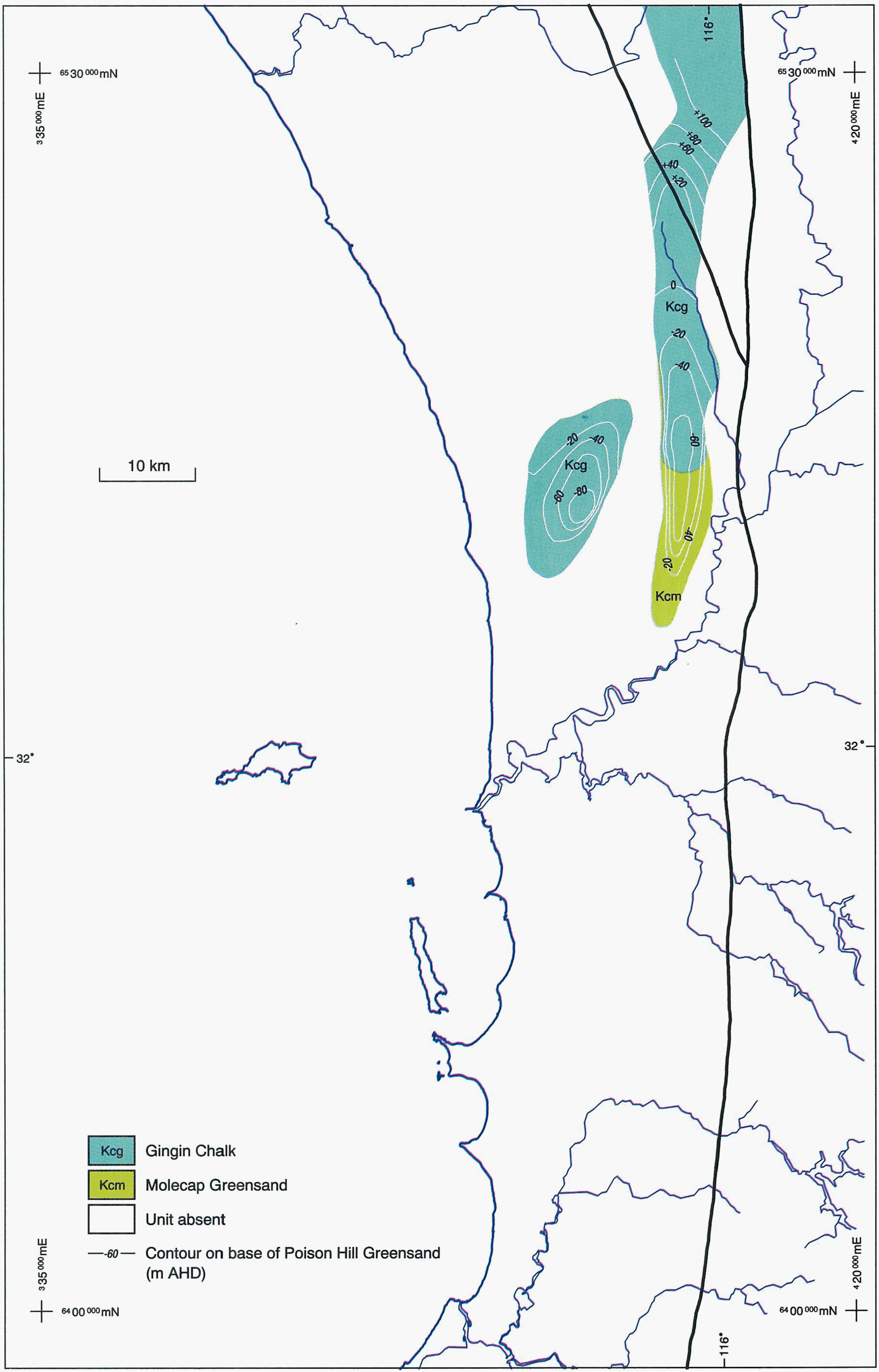


PLATE 40. Poison Hill Greensand: contours on base of unit; with strata subcrop

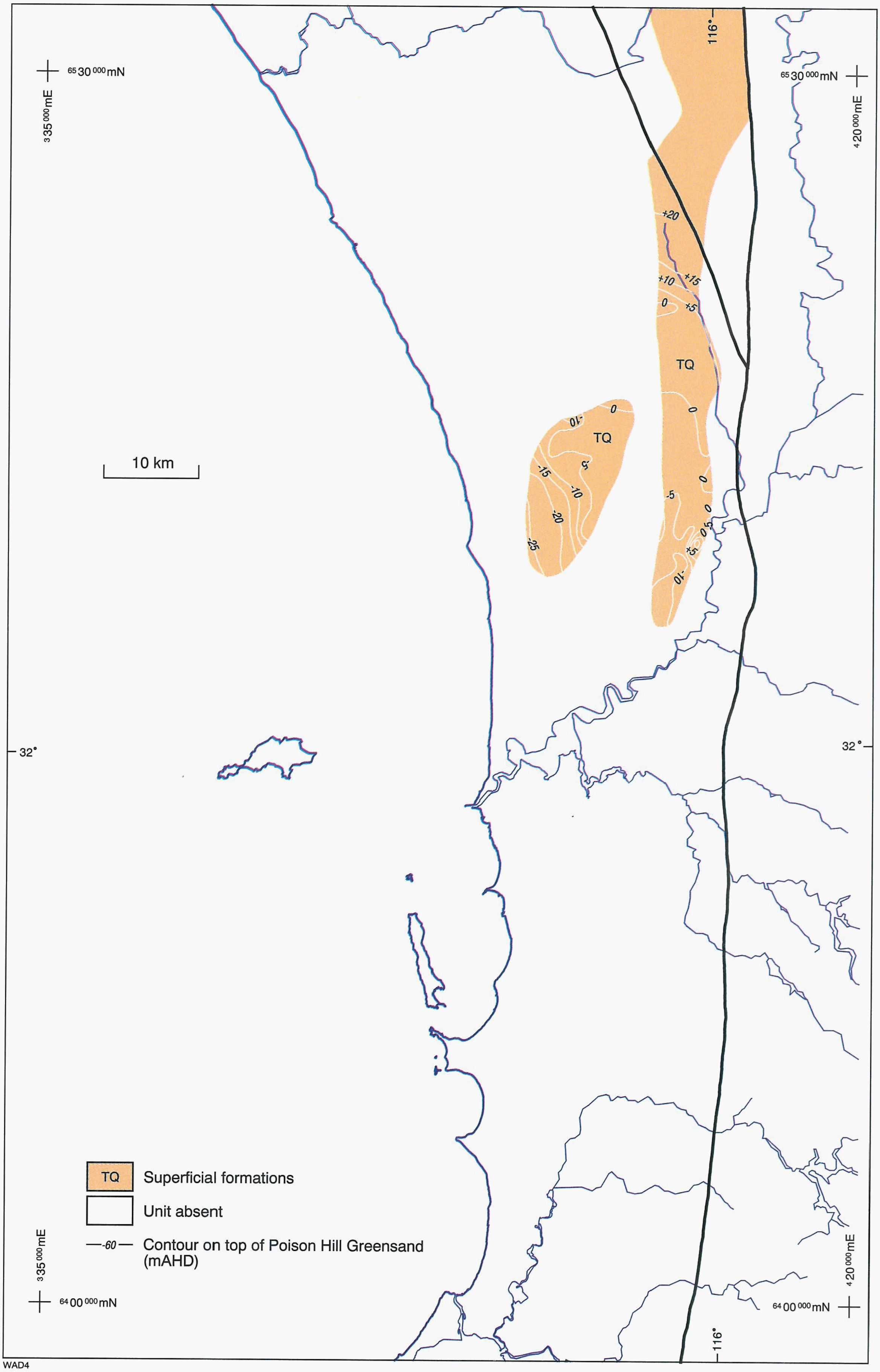


PLATE 41. Poison Hill Greensand: contours on top of unit; with overlying strata

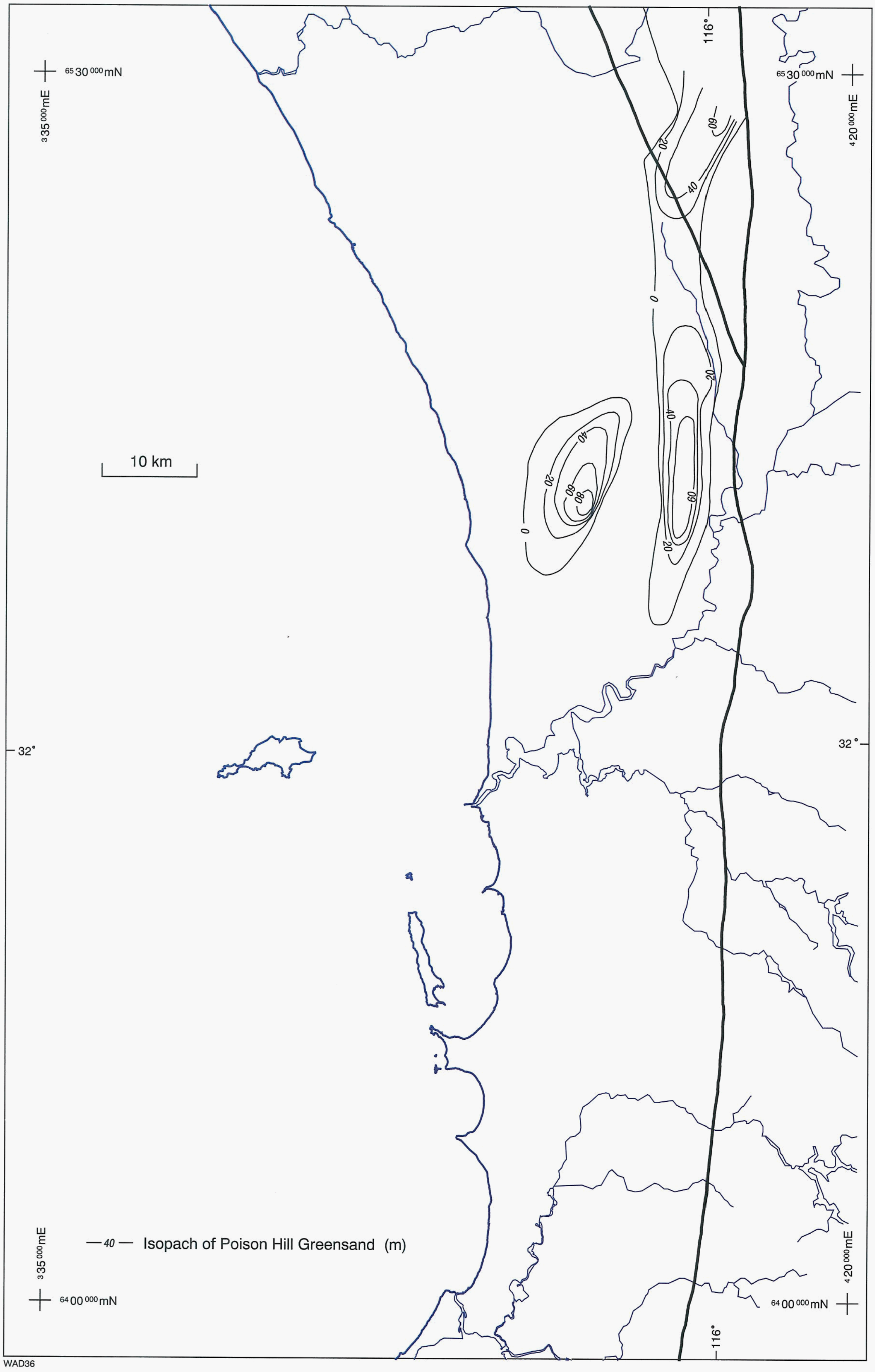


PLATE 42. Poison Hill Greensand: isopachs

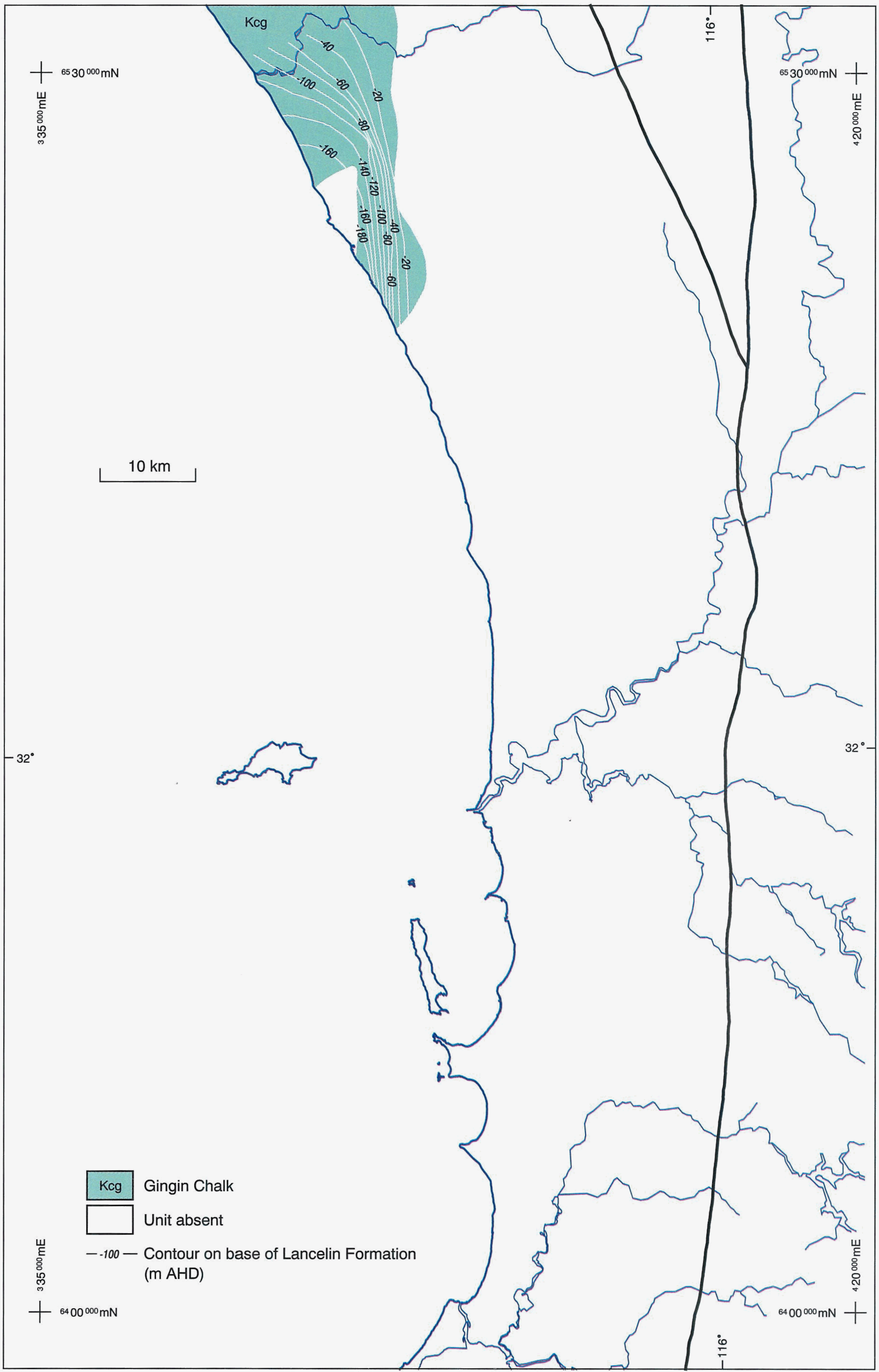


PLATE 43. Lancelin Formation: contours on base of unit; with strata subcrop

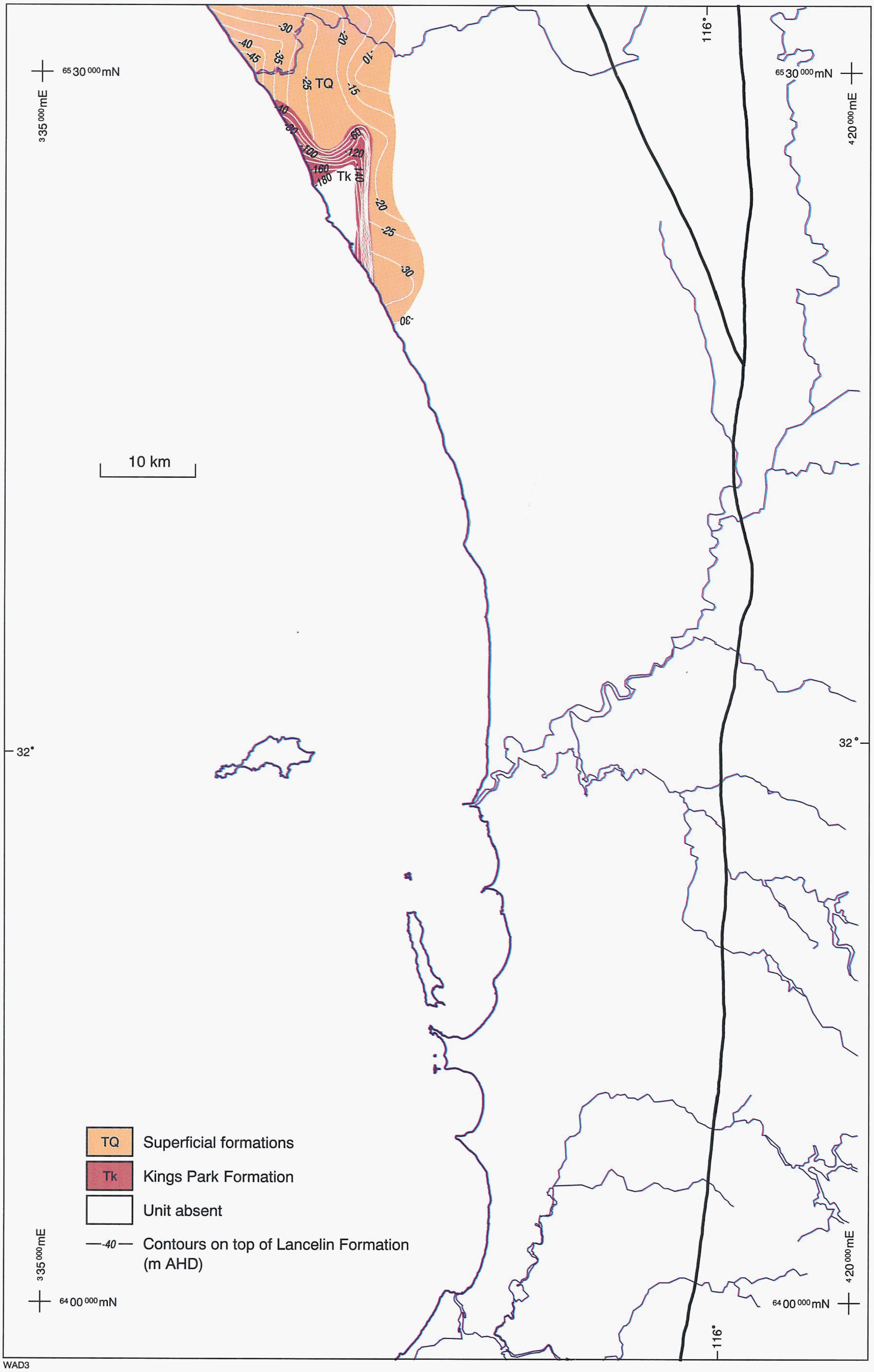


PLATE 44. Lancelin Formation: contours on top of unit; with overlying strata

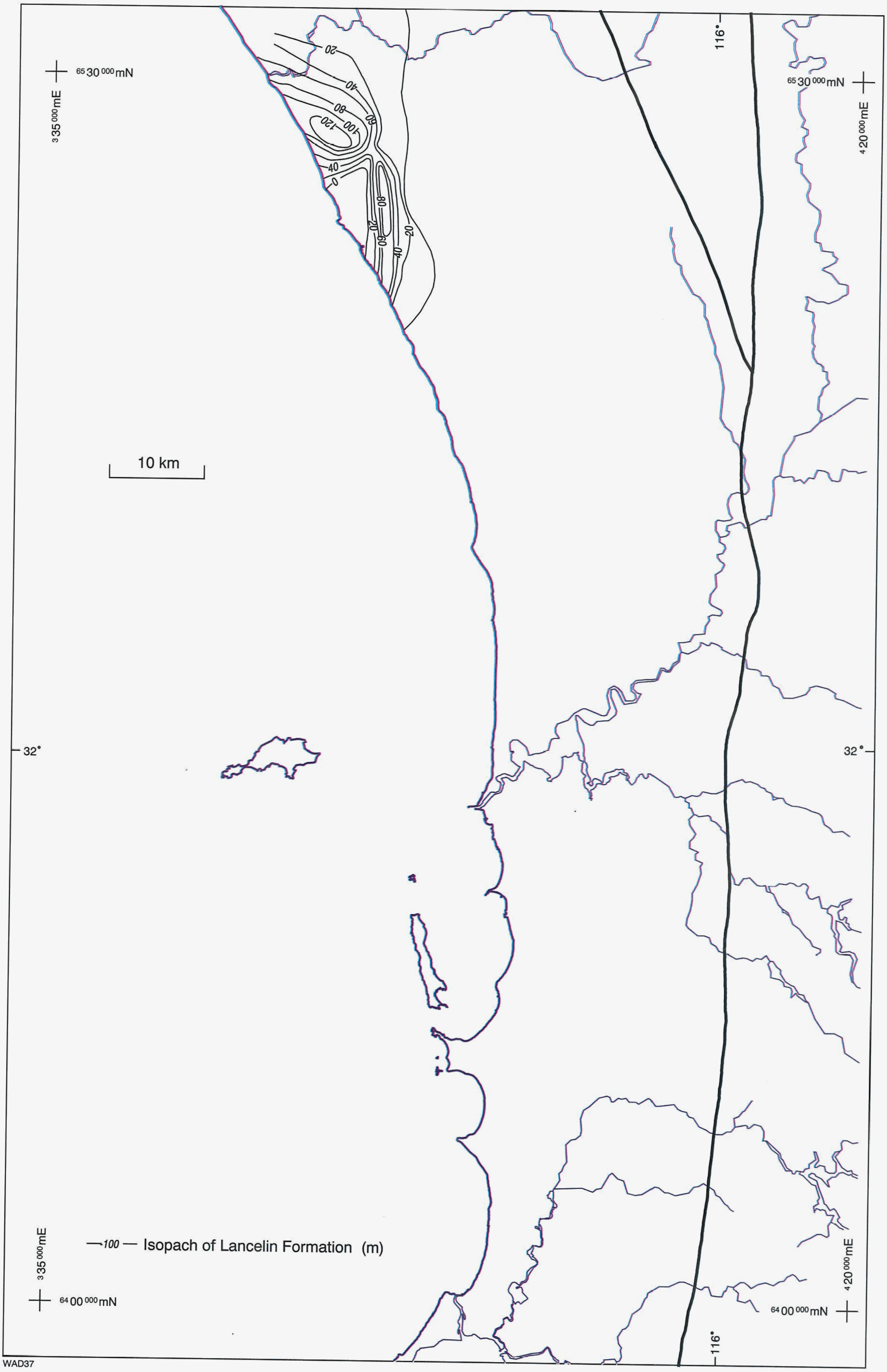
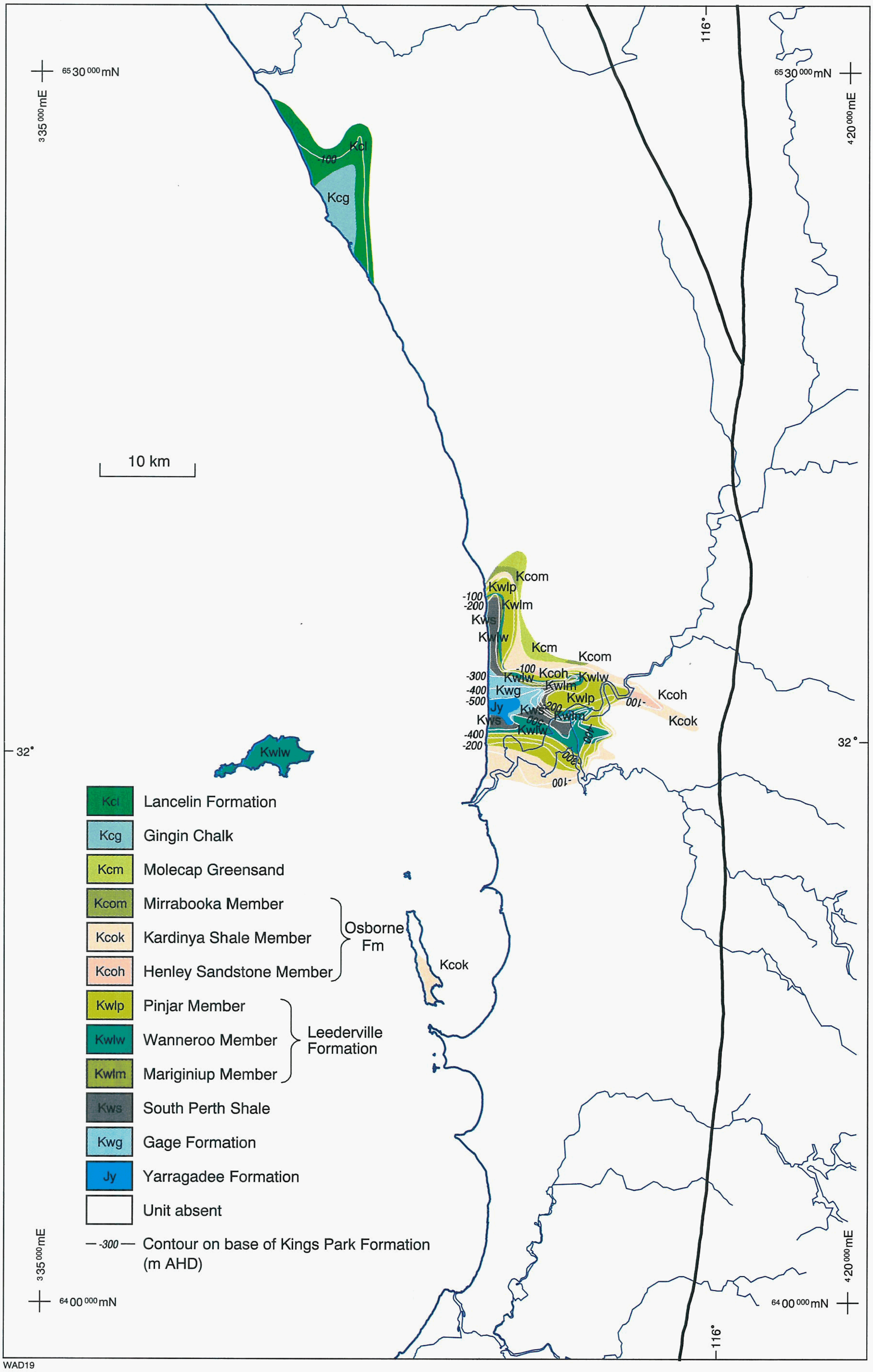


PLATE 45. Lancelin Formation: isopachs



WAD19

PLATE 46. Kings Park Formation: contours on base of unit; with strata subcrop

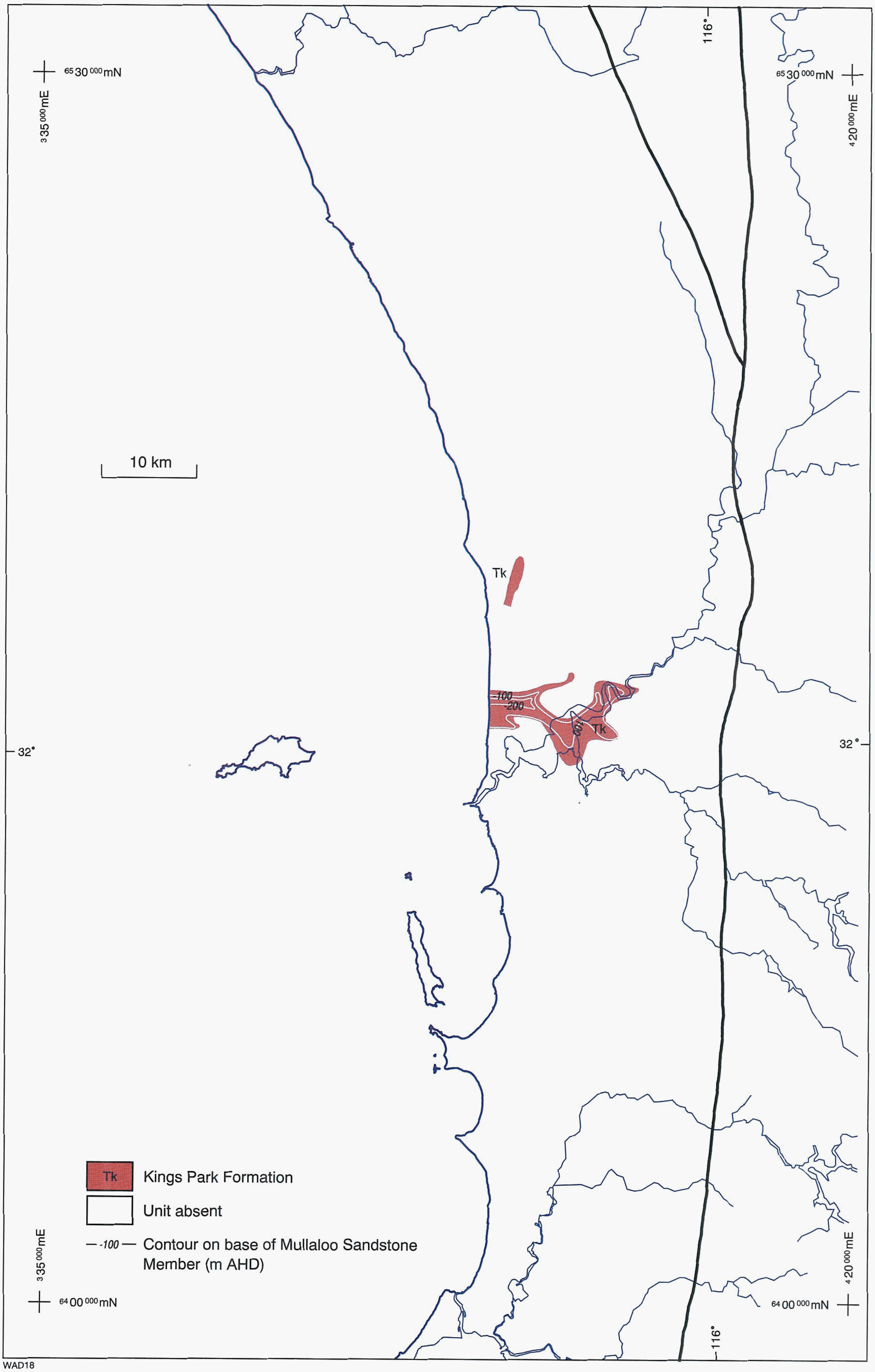
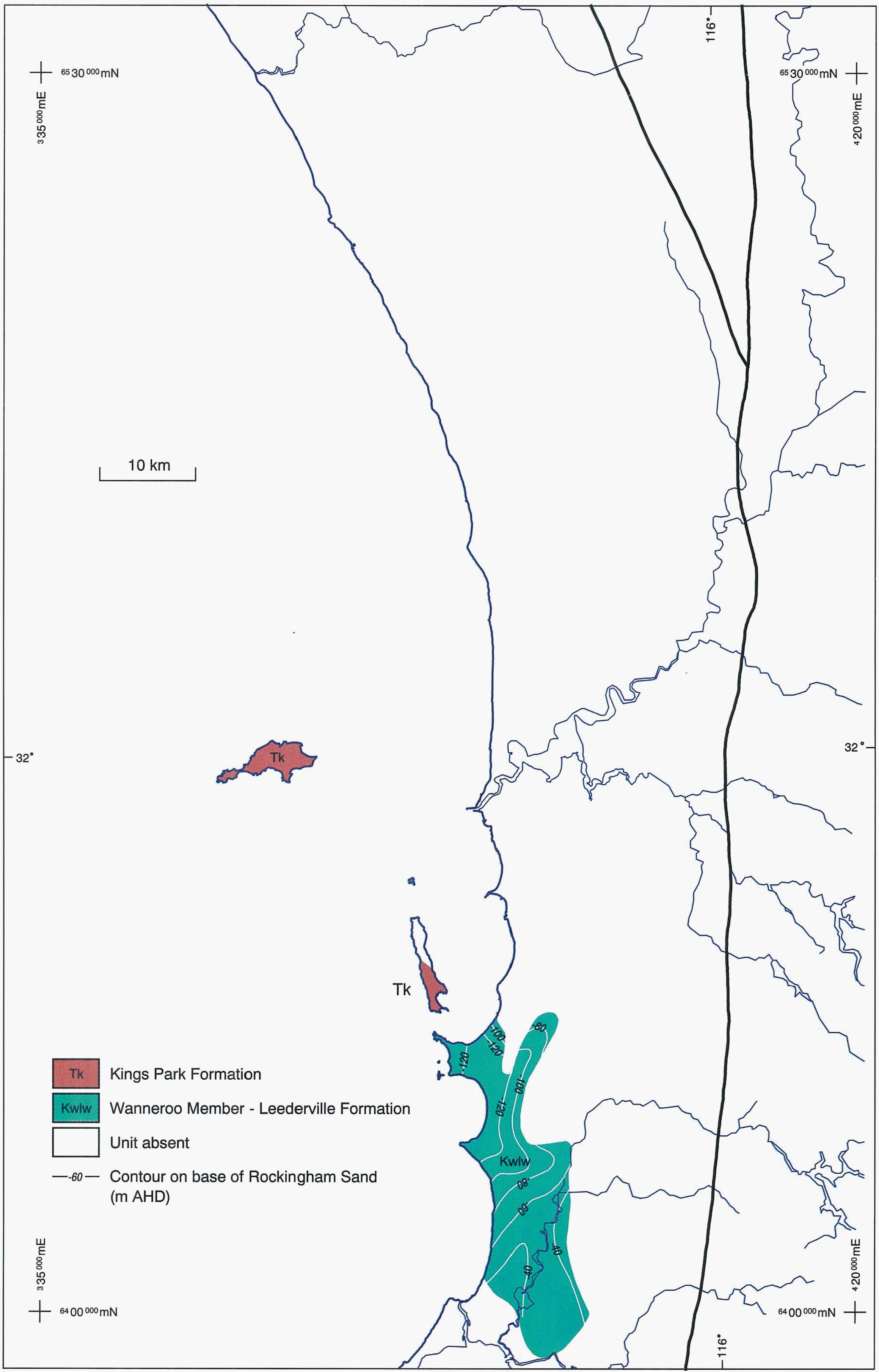


PLATE 47. Mullaloo Sandstone Member: contours on base of unit; with strata subcrop



WAD24

PLATE 48. Rockingham Sand: contours on base of unit; with strata subcrop

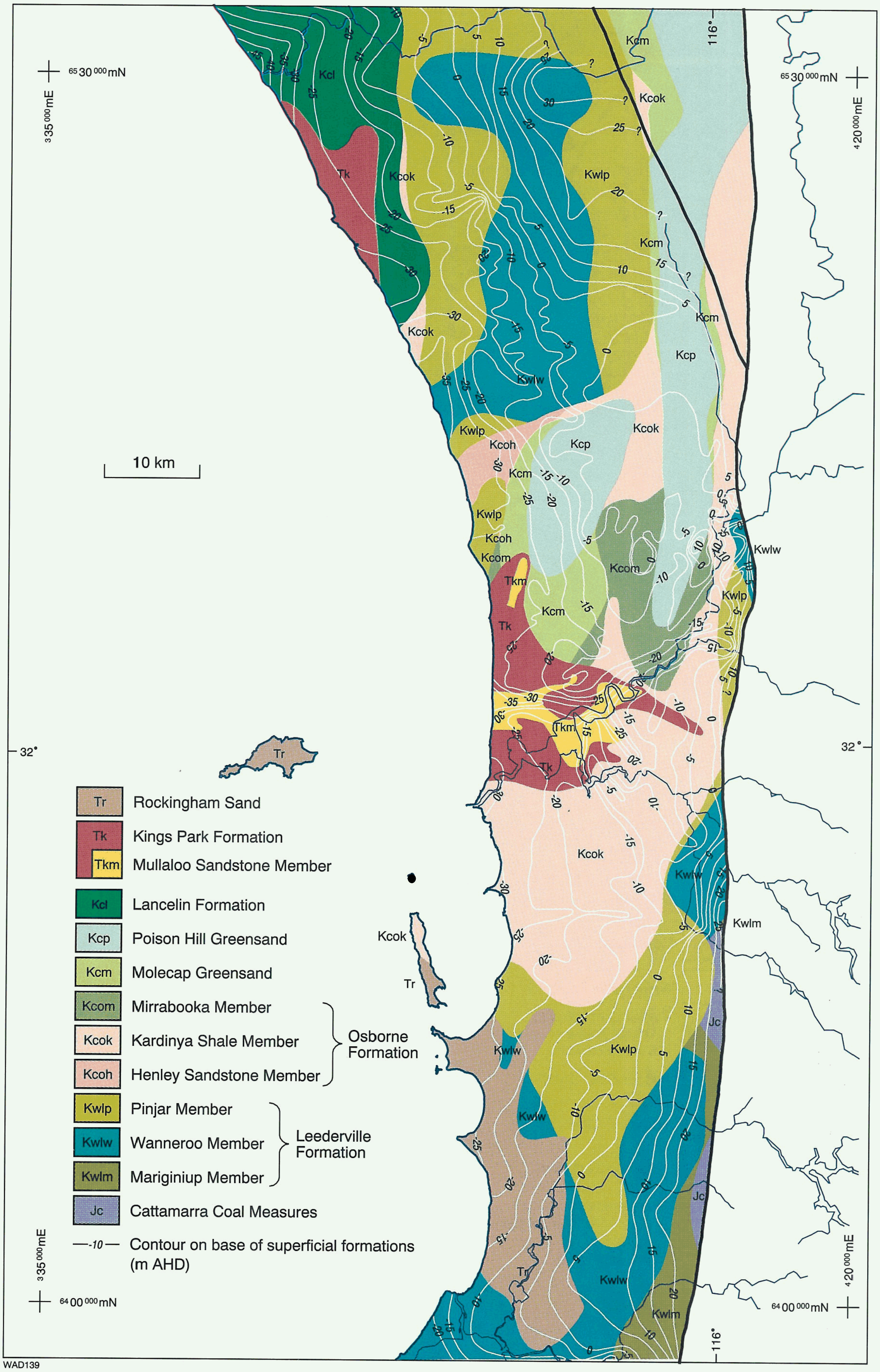
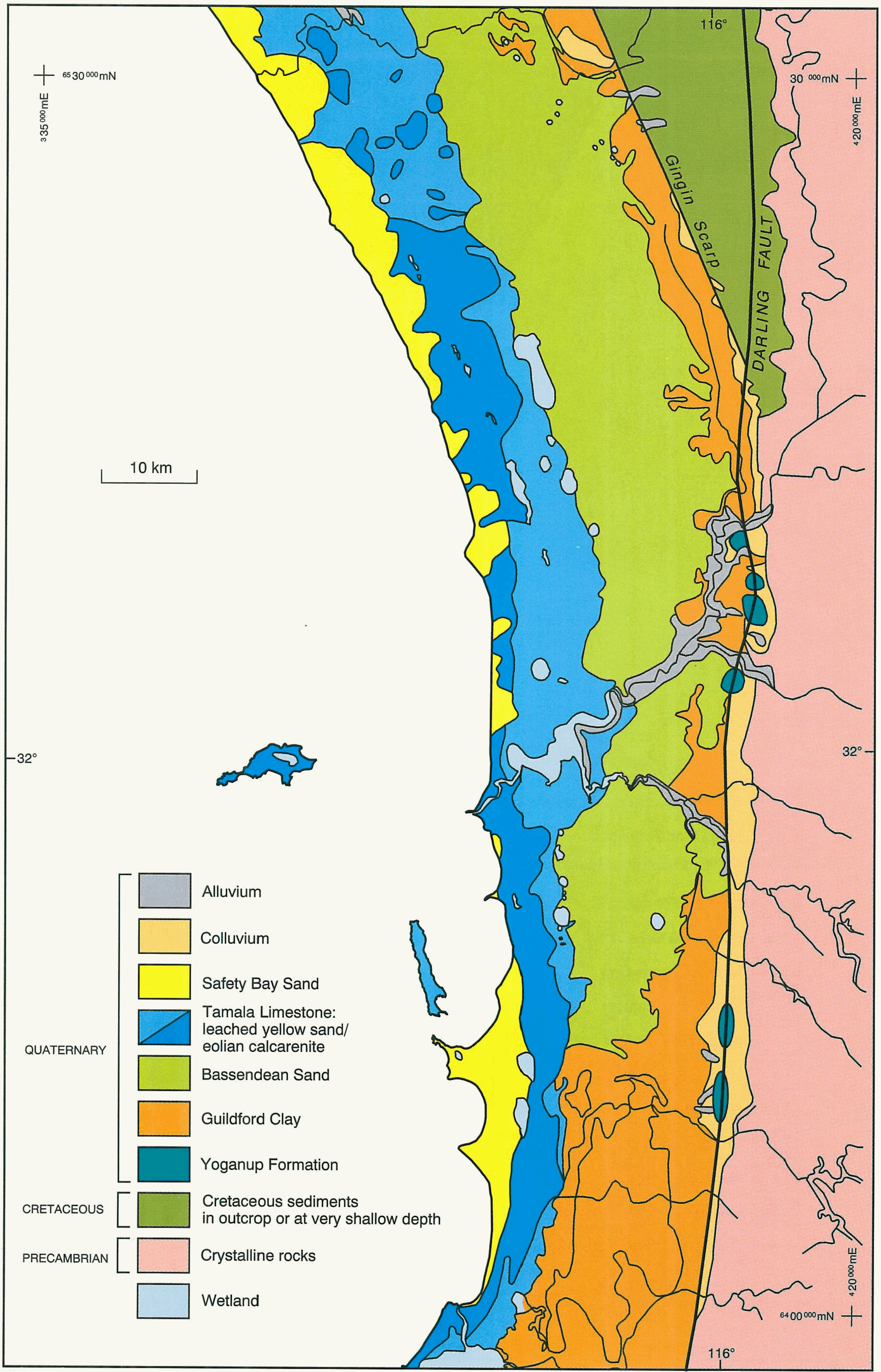


PLATE 49. Superficial formations: contours on base of unit; with strata subcrop



WAD85

17.06.94

PLATE 50. Surface geology; generalized

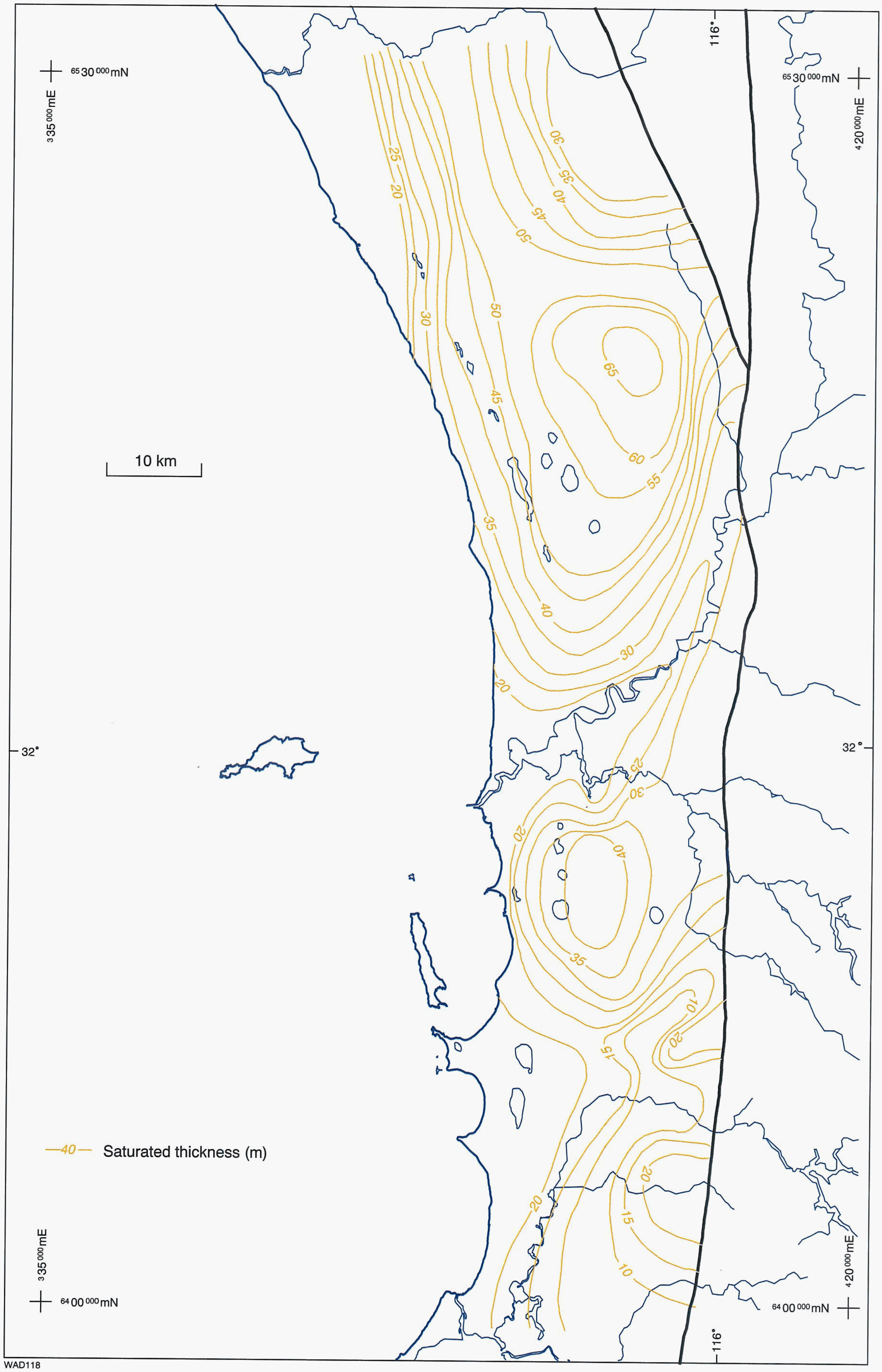


PLATE 51. Superficial aquifer saturated thickness

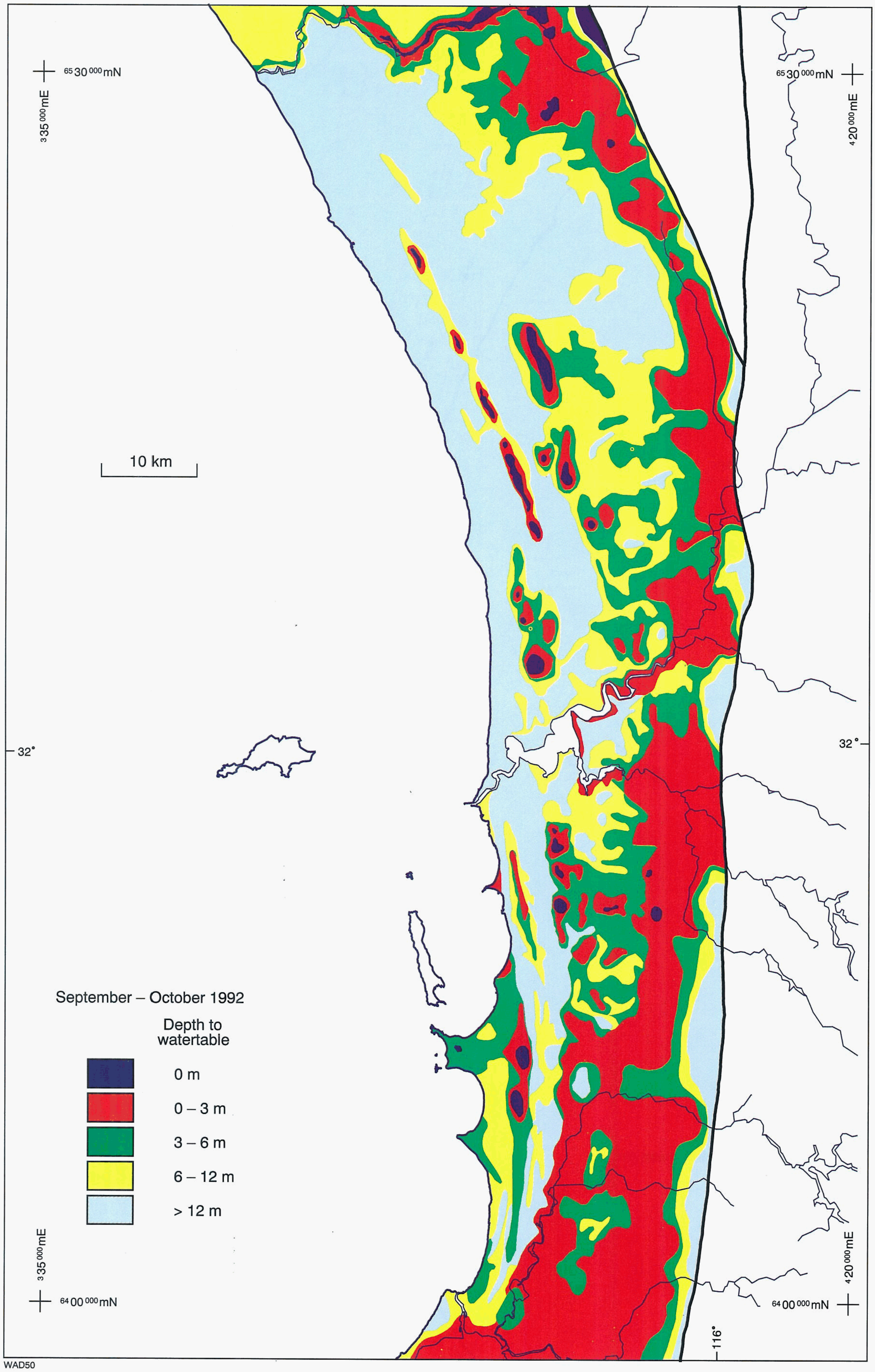


PLATE 52. Superficial aquifer depth below groundlevel to the watertable

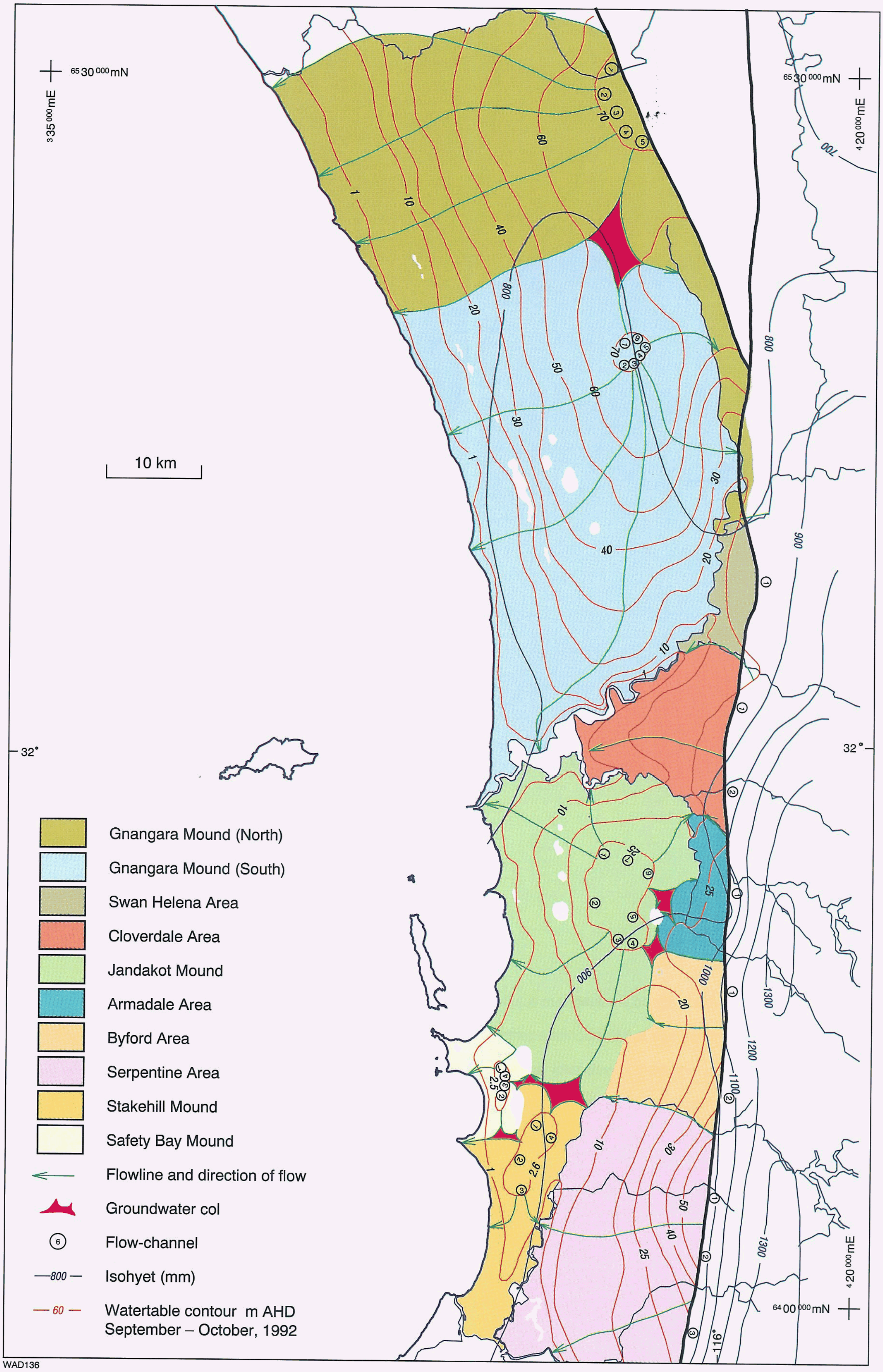


PLATE 53. Superficial aquifer groundwater flownet

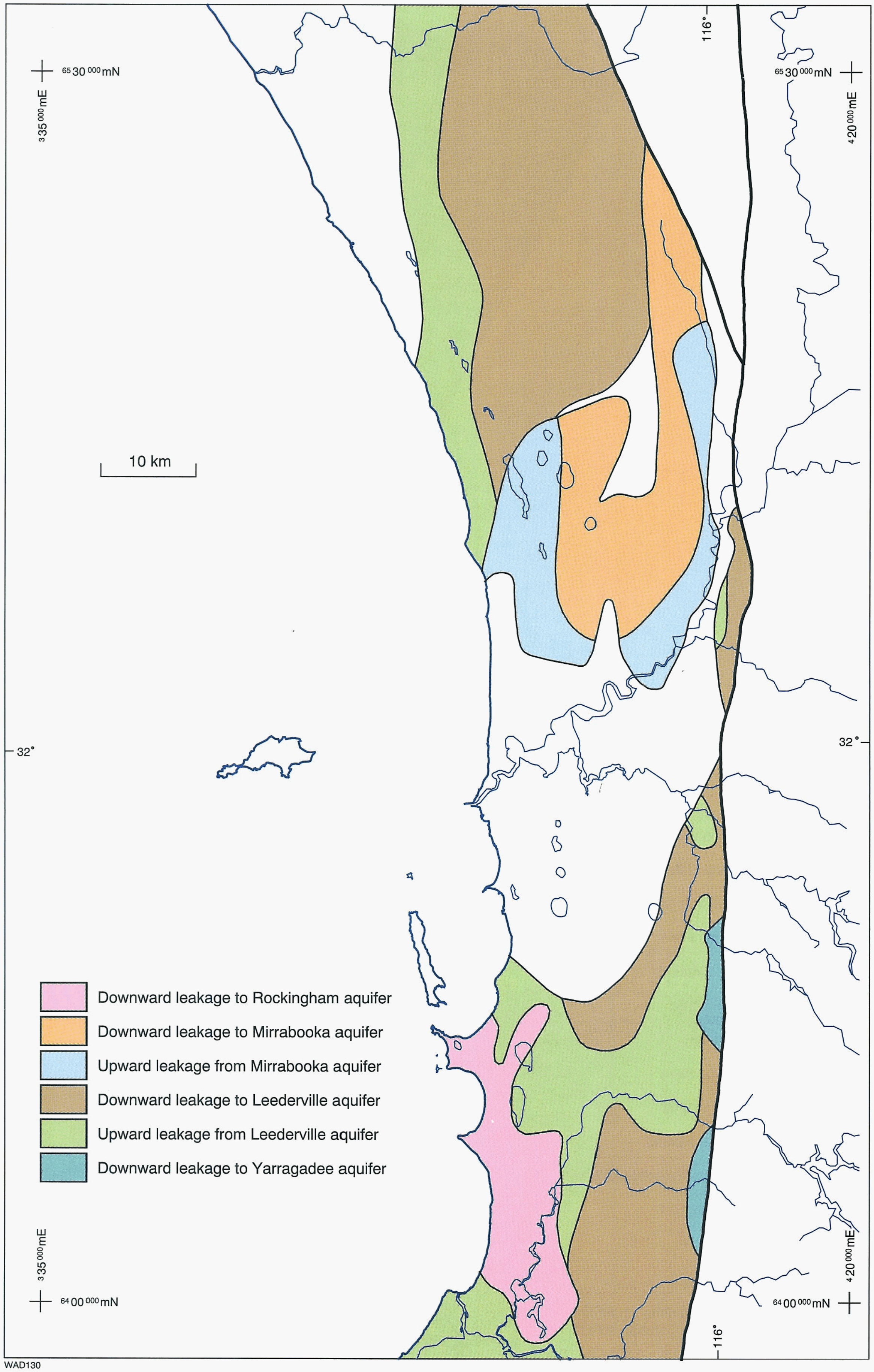


PLATE 54. Superficial aquifer; areas of downward discharge from and upward recharge to the aquifer

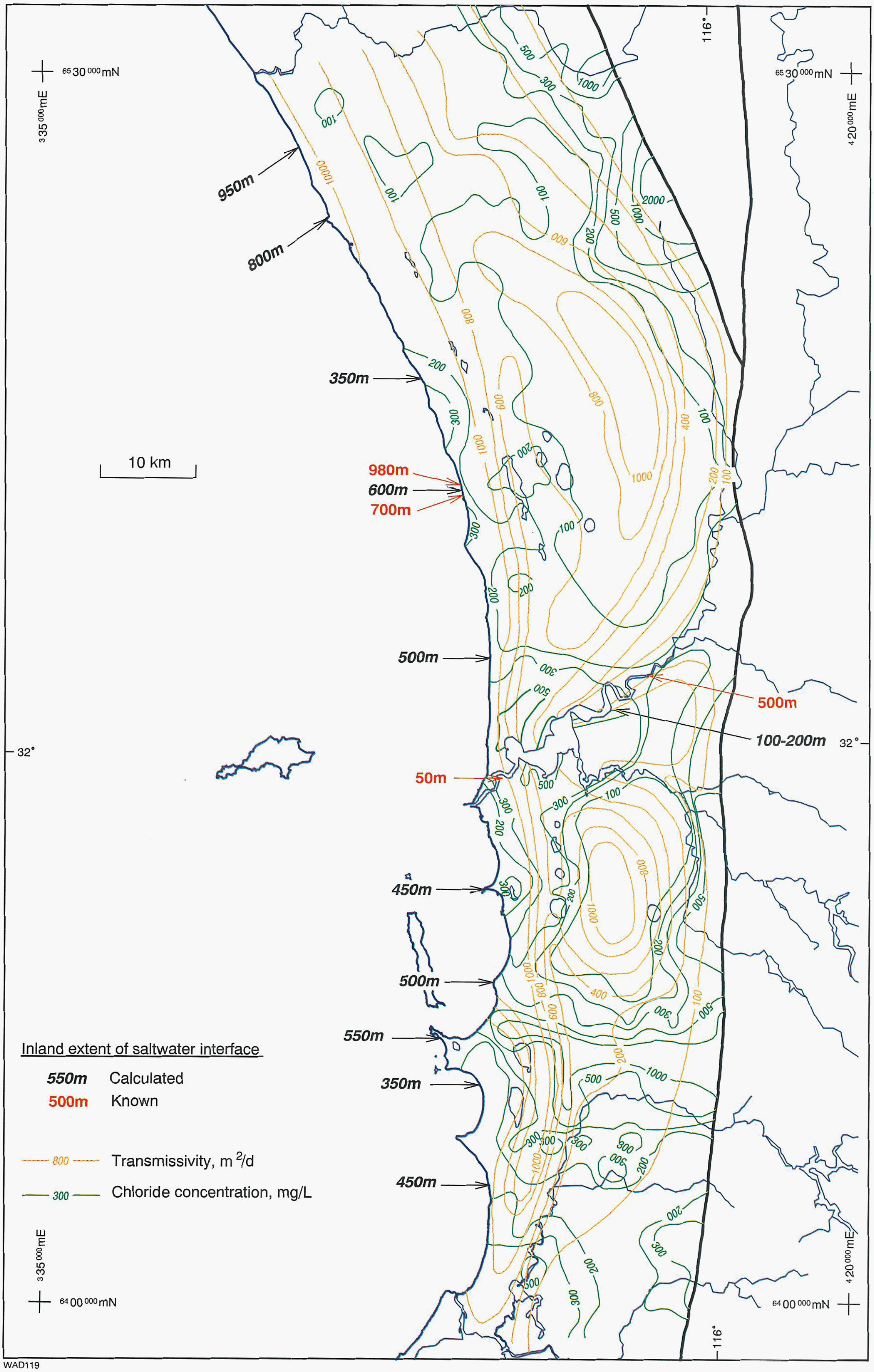


PLATE 55. Superficial aquifer contours of transmissivity and chloride concentration

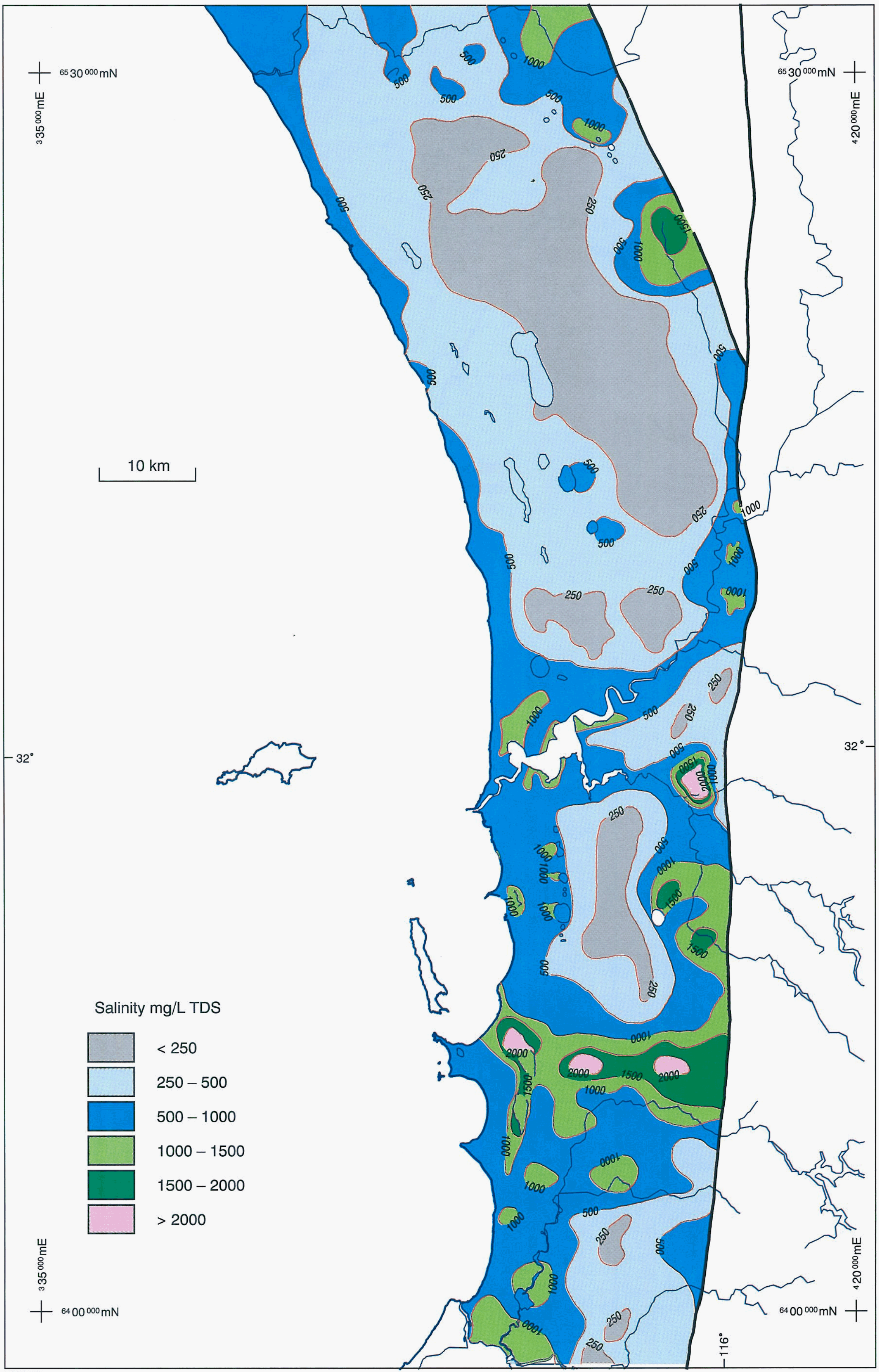


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PLATE 56. Superficial aquifer groundwater salinity

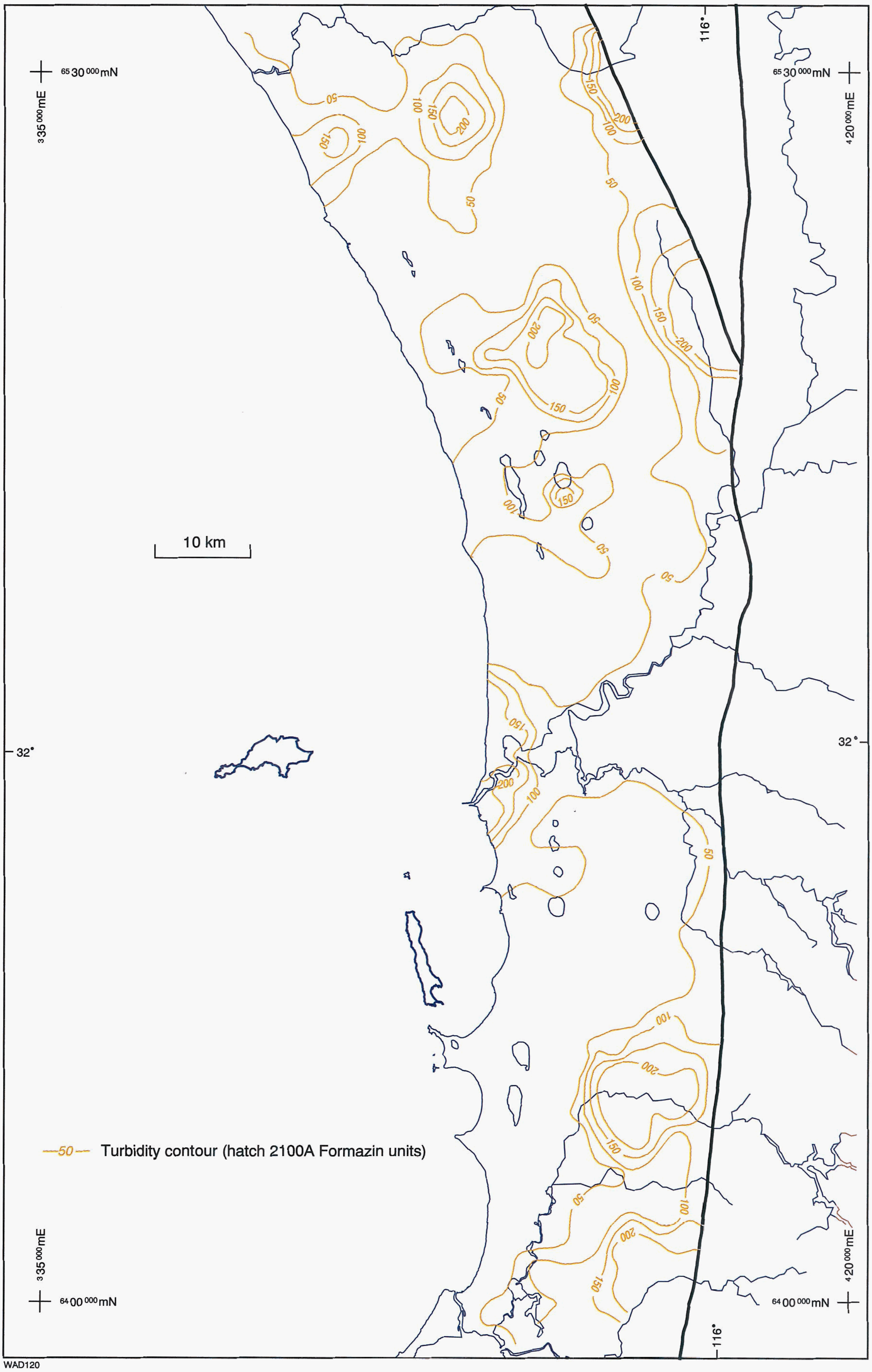

PLATE 57. Superficial aquifer groundwater turbidity

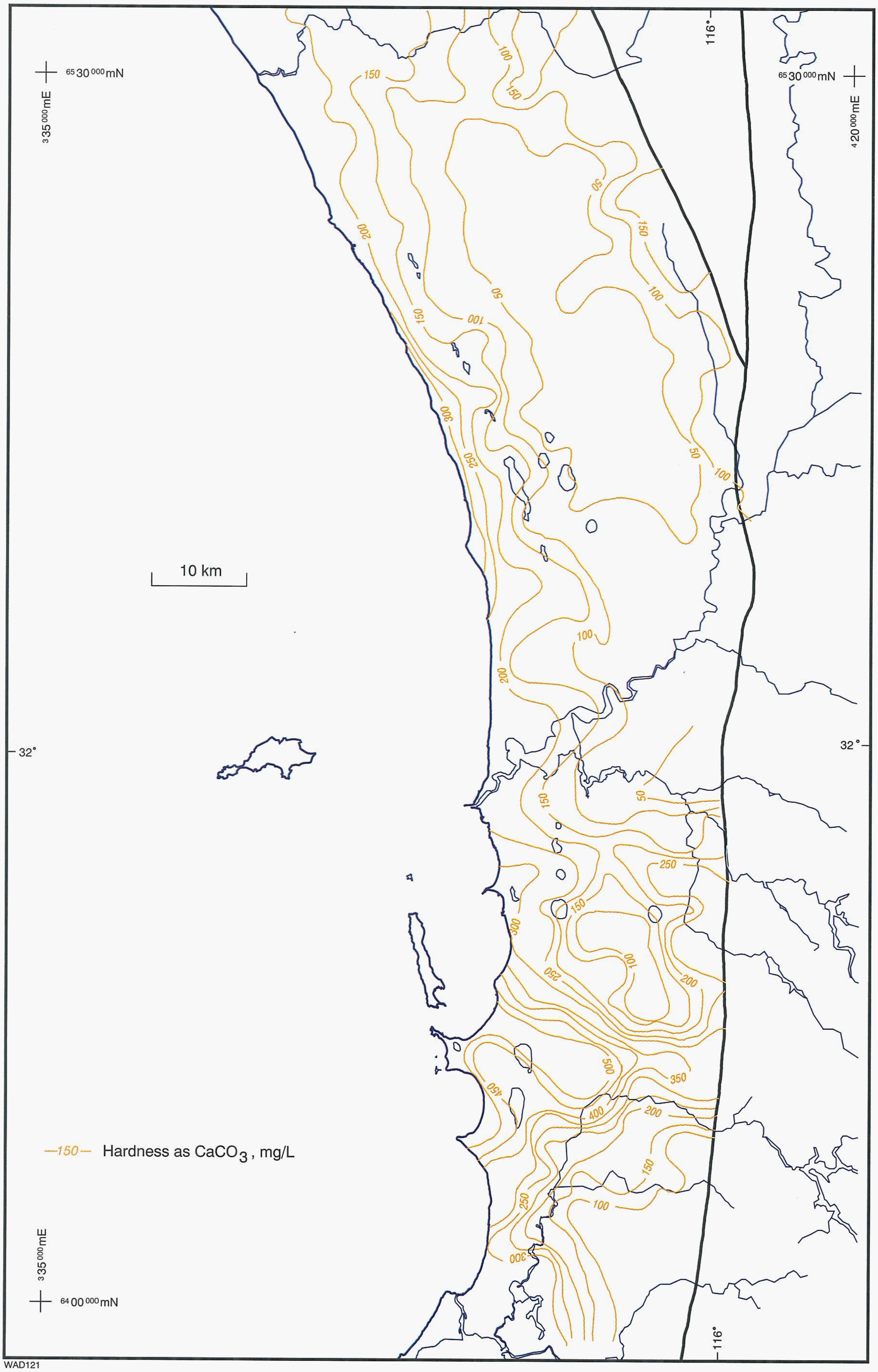

PLATE 58. Superficial aquifer groundwater hardness

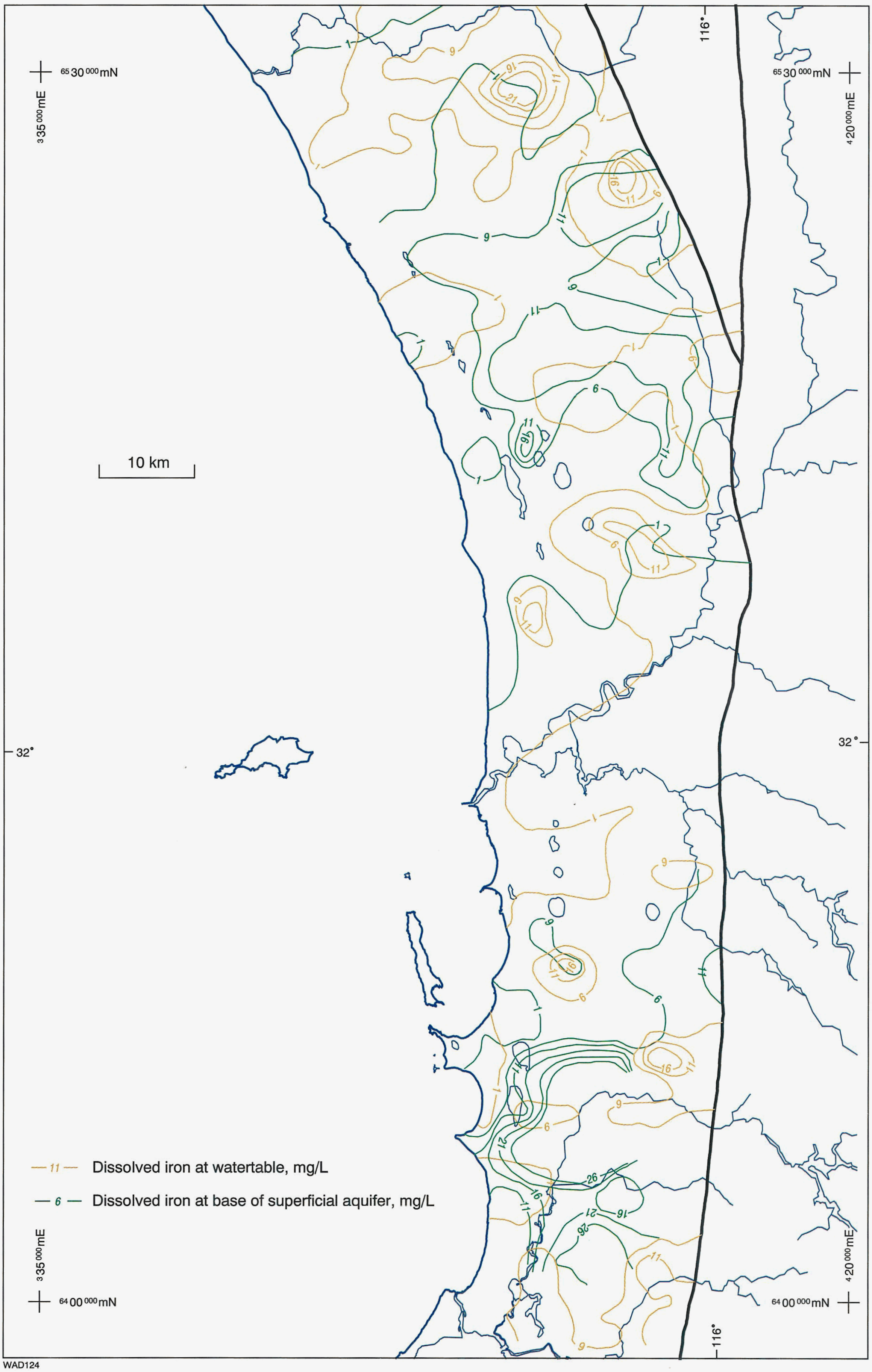

PLATE 59. Superficial aquifer dissolved iron concentrations

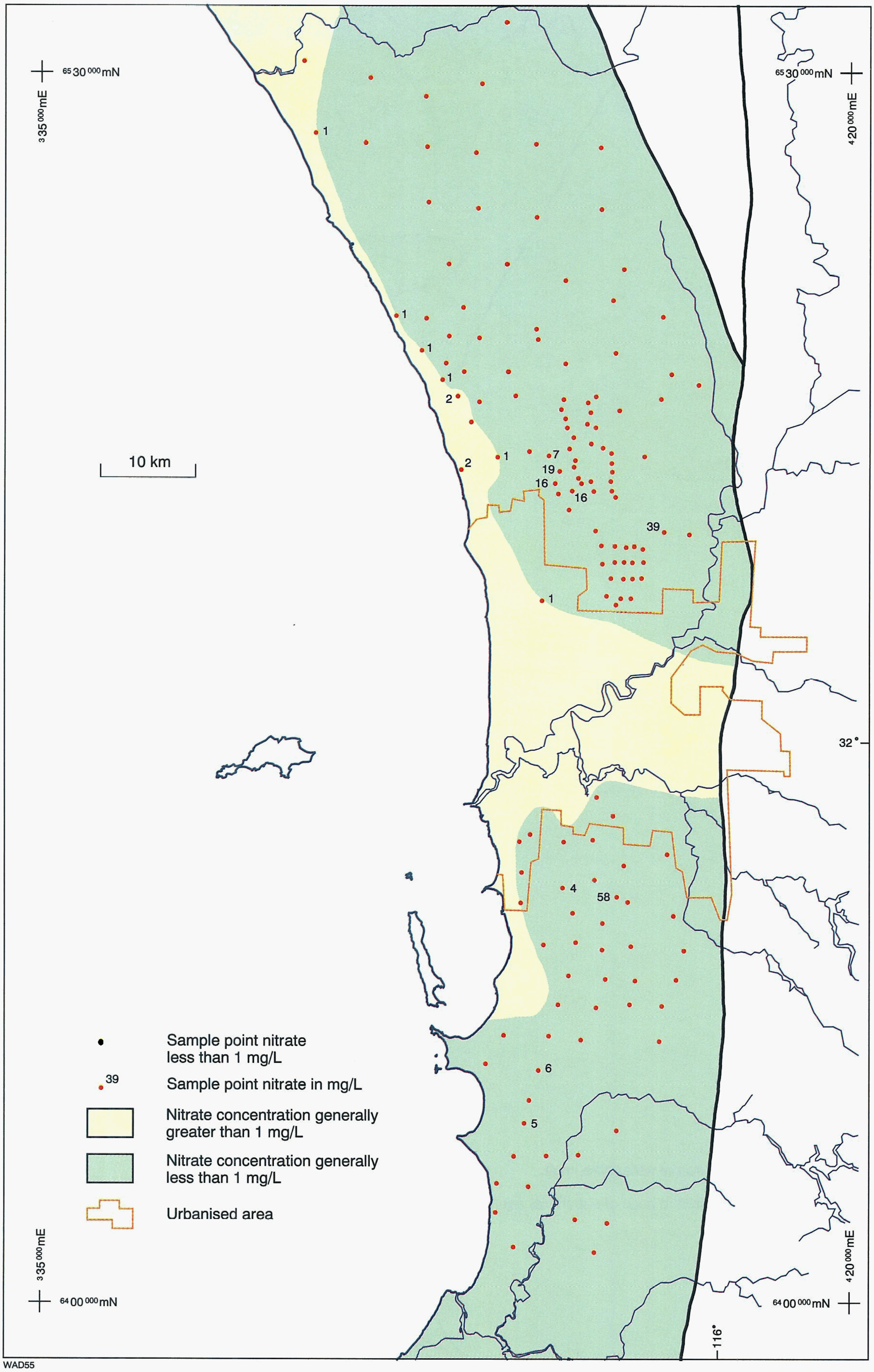

PLATE 60. Superficial aquifer groundwater nitrate concentrations (from Davidson and Jack, 1983)

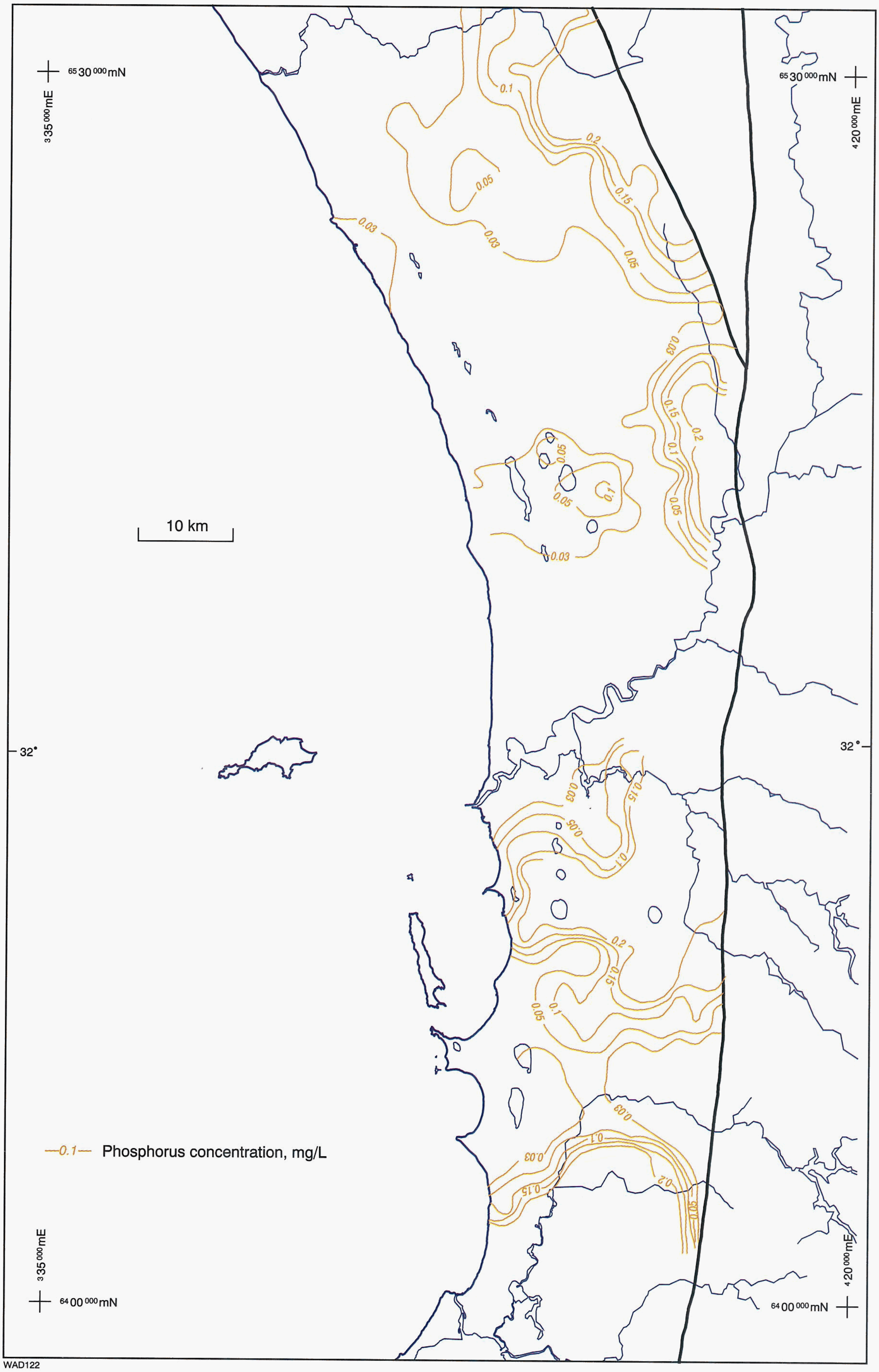

PLATE 61. Superficial aquifer watertable phosphorus concentrations

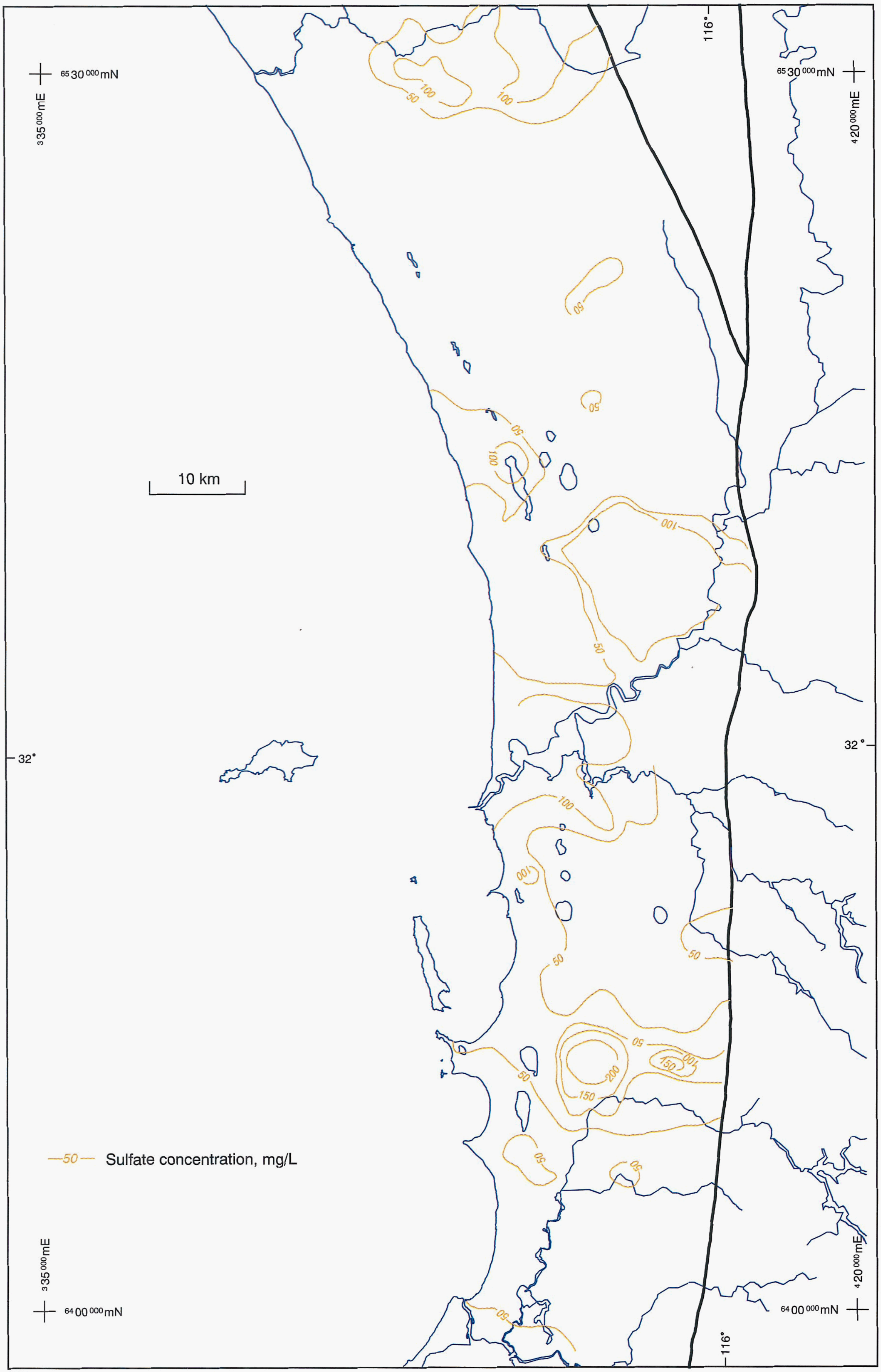

Plate 62. Superficial aquifer groundwater sulfate concentrations

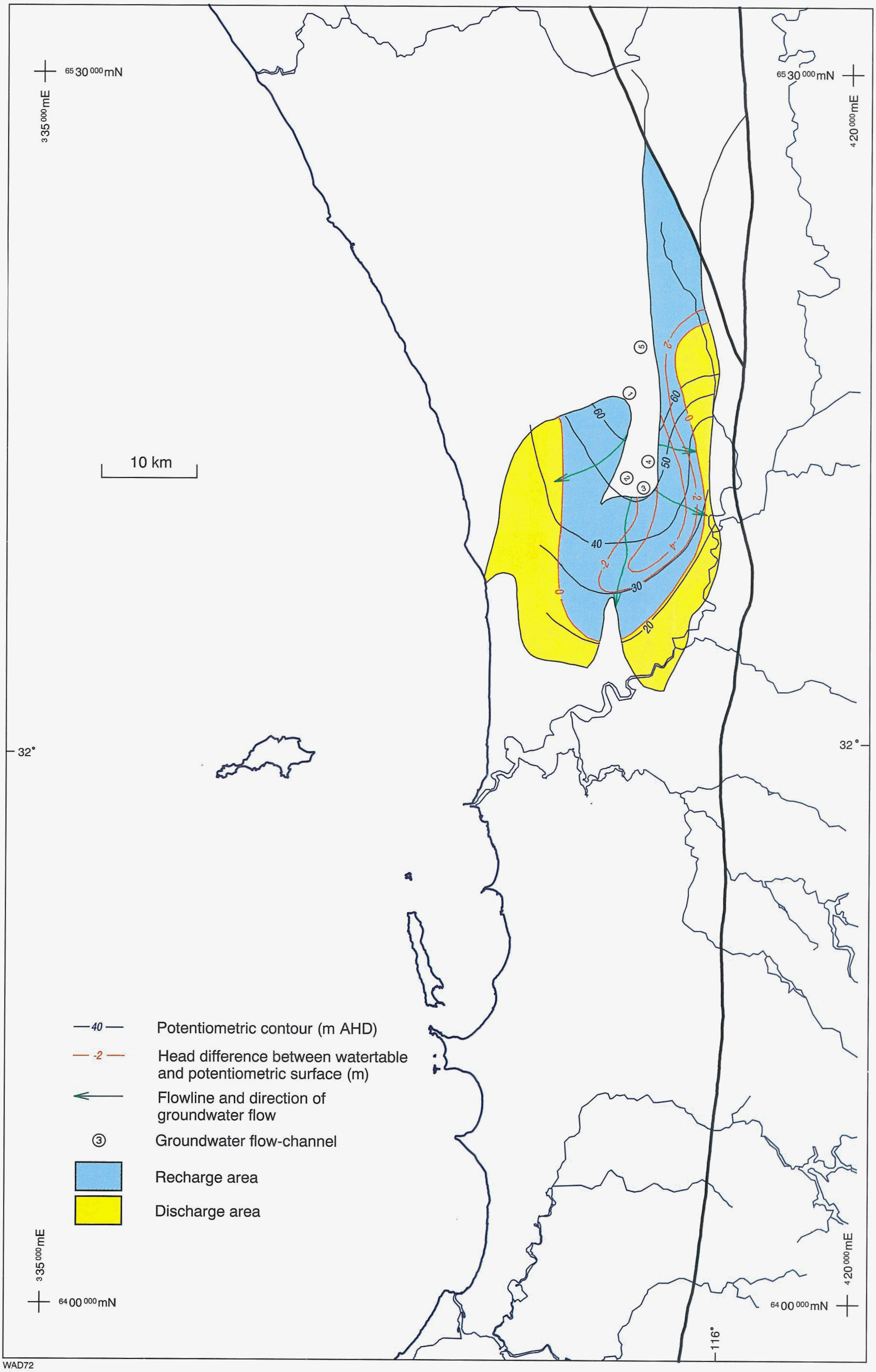

PLATE 63. Mirrabooka aquifer groundwater flownet September – October 1992

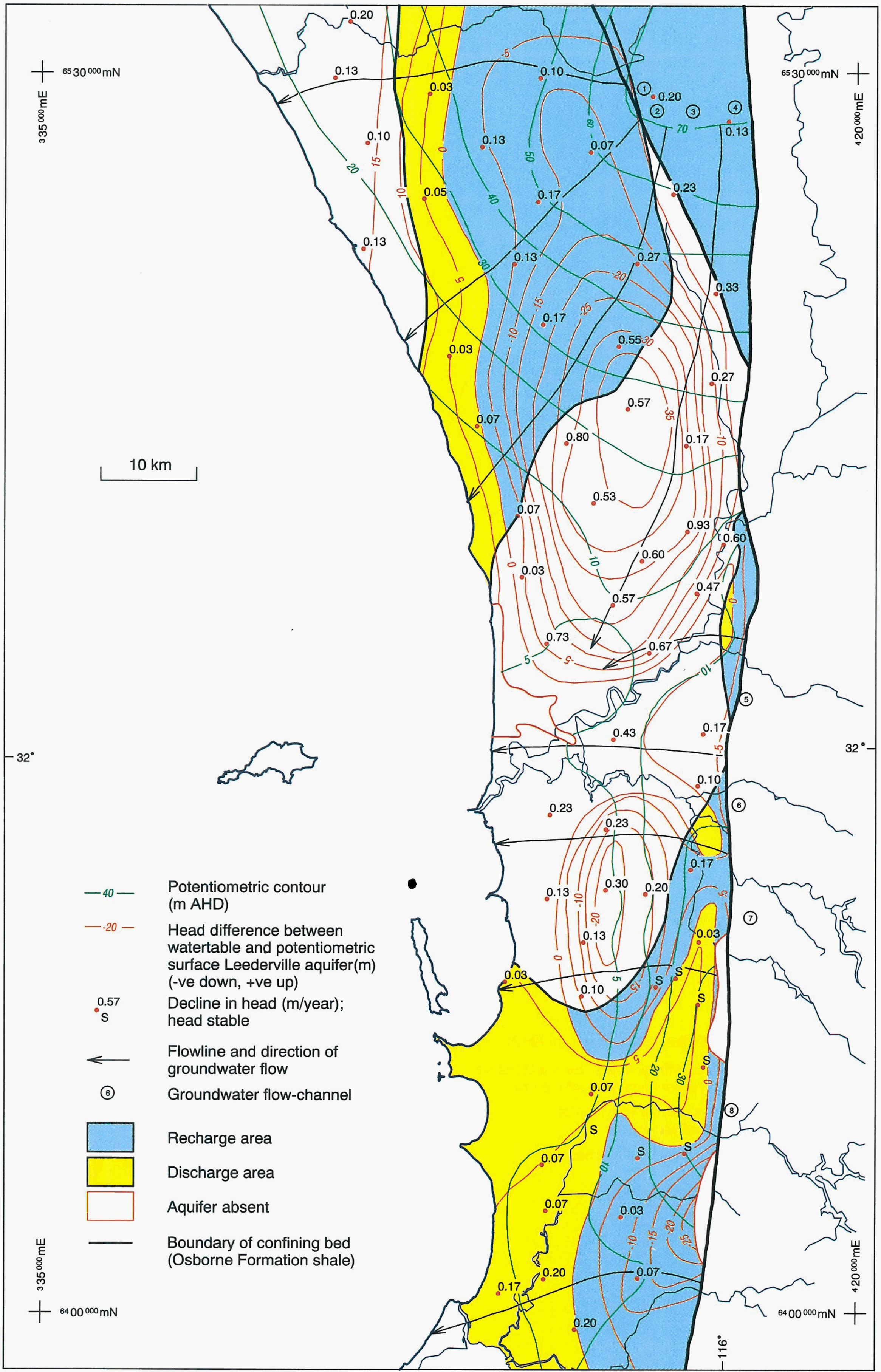

PLATE 64. Leederville aquifer groundwater flownet September – October 1992

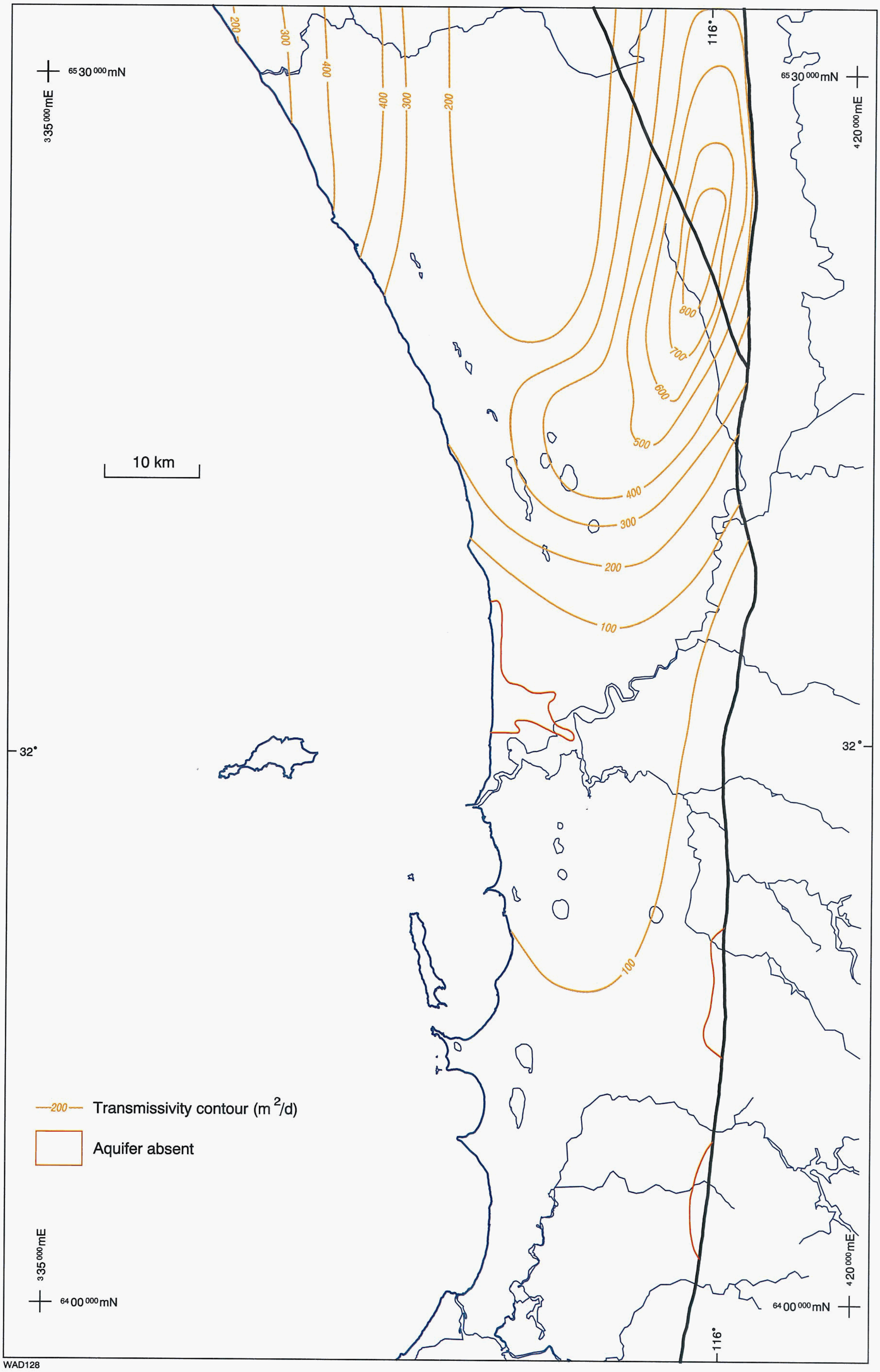

PLATE 65. Leederville aquifer transmissivity contours

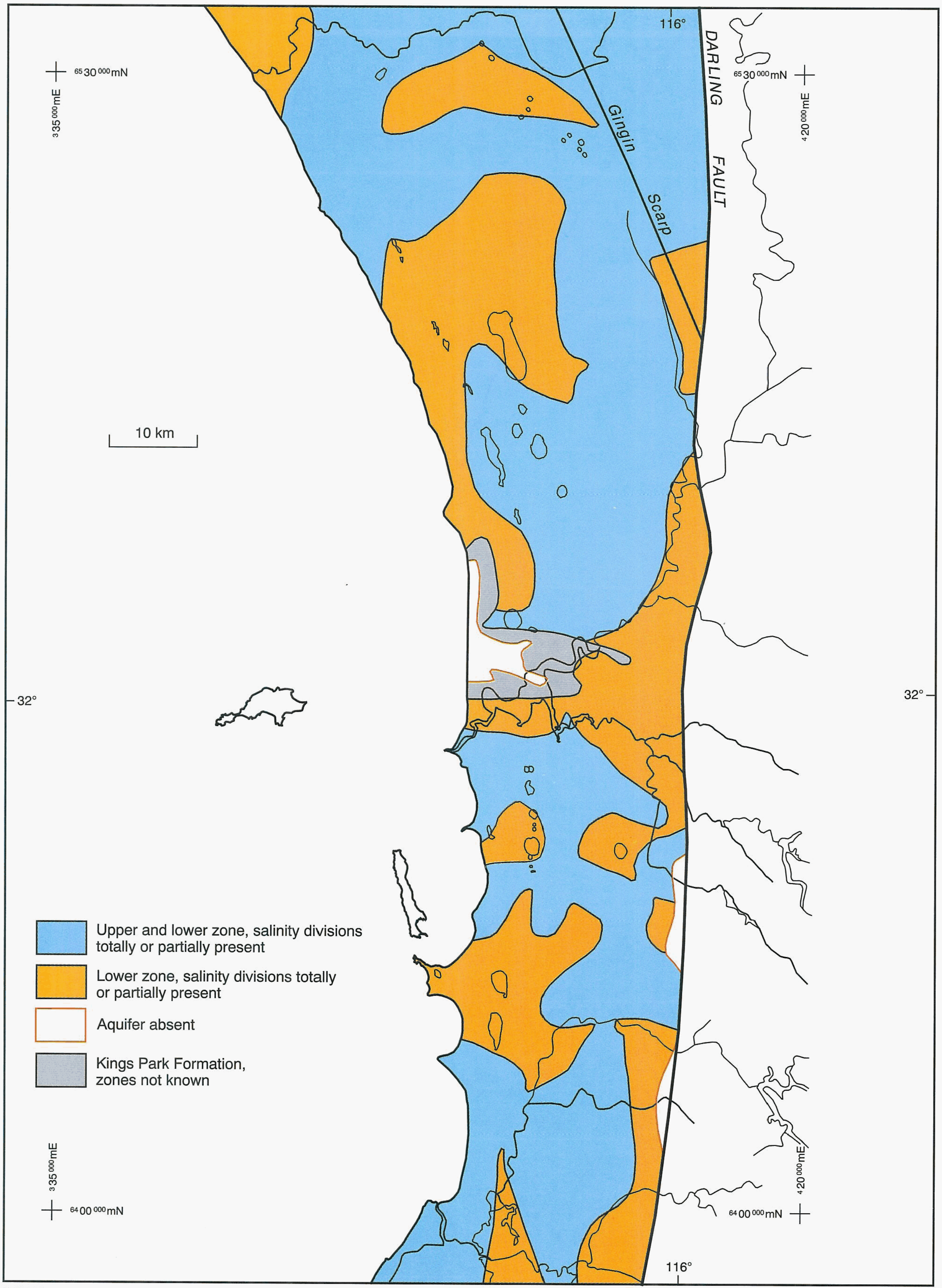

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PLATE 66. Leederville aquifer salinity zones

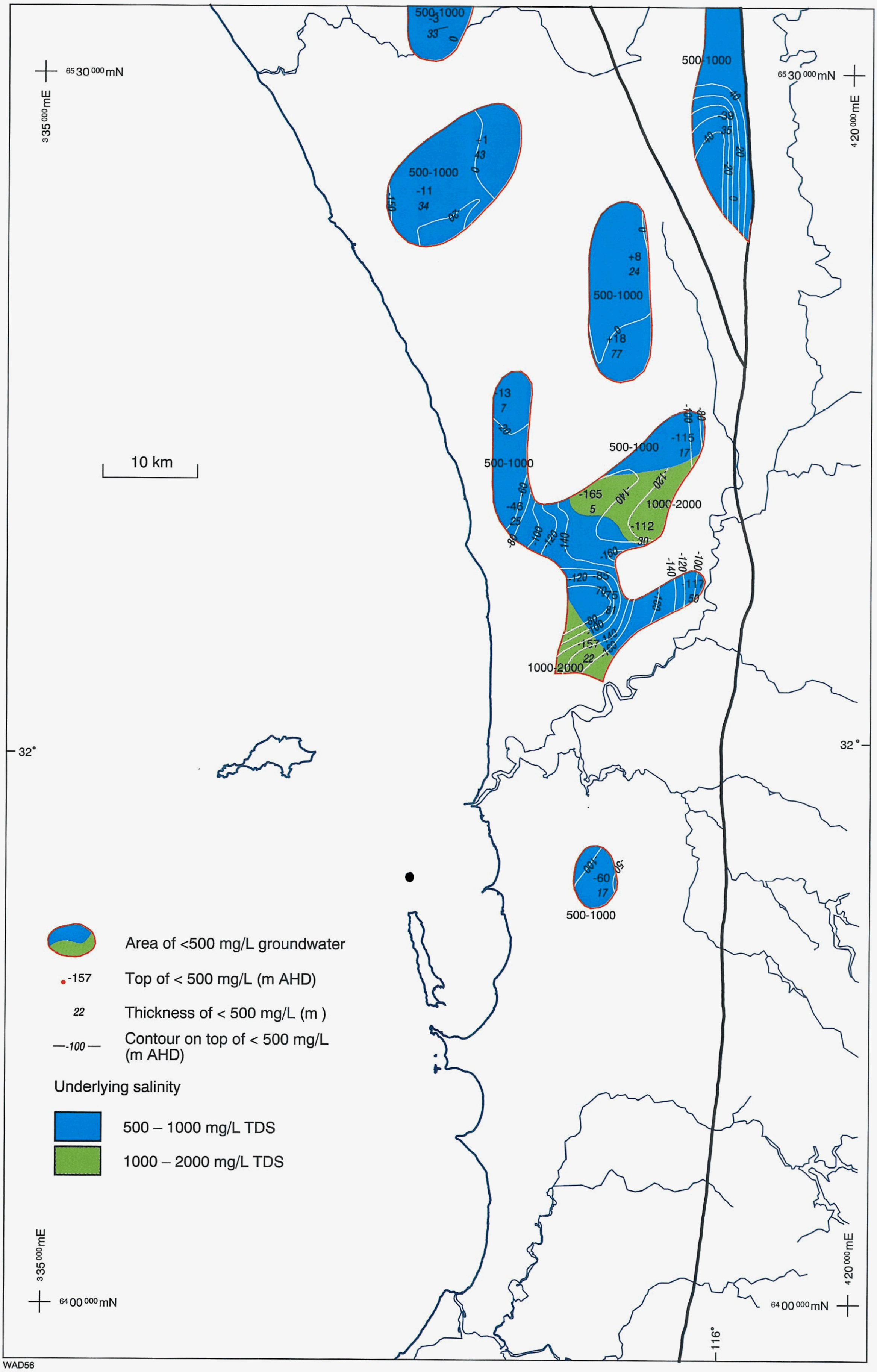

PLATE 67. Upper Leederville aquifer groundwater salinity less than 500 mg/L TDS

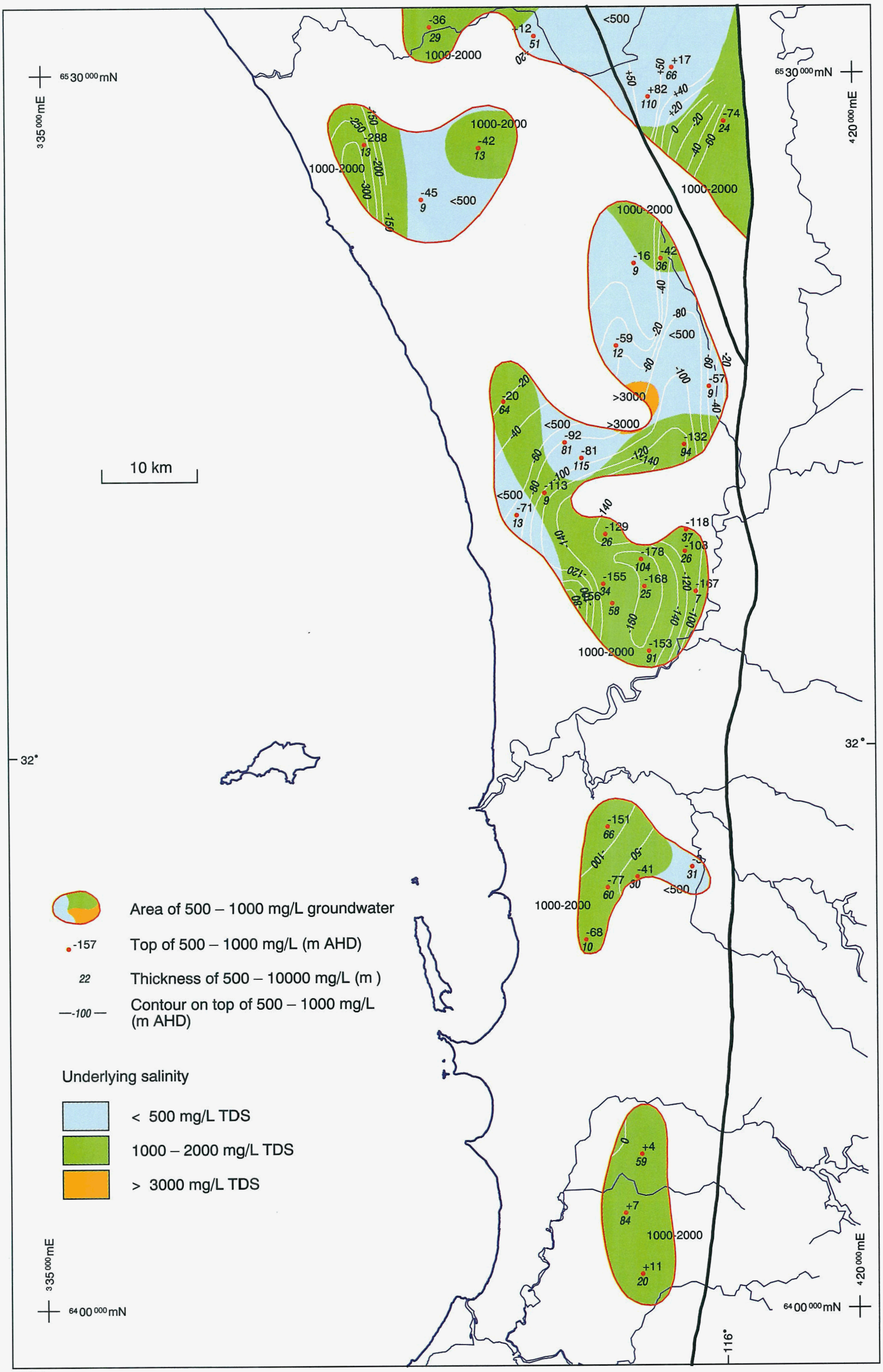

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PLATE 68. Upper Leederville aquifer groundwater salinity 500 – 1000 mg/L TDS

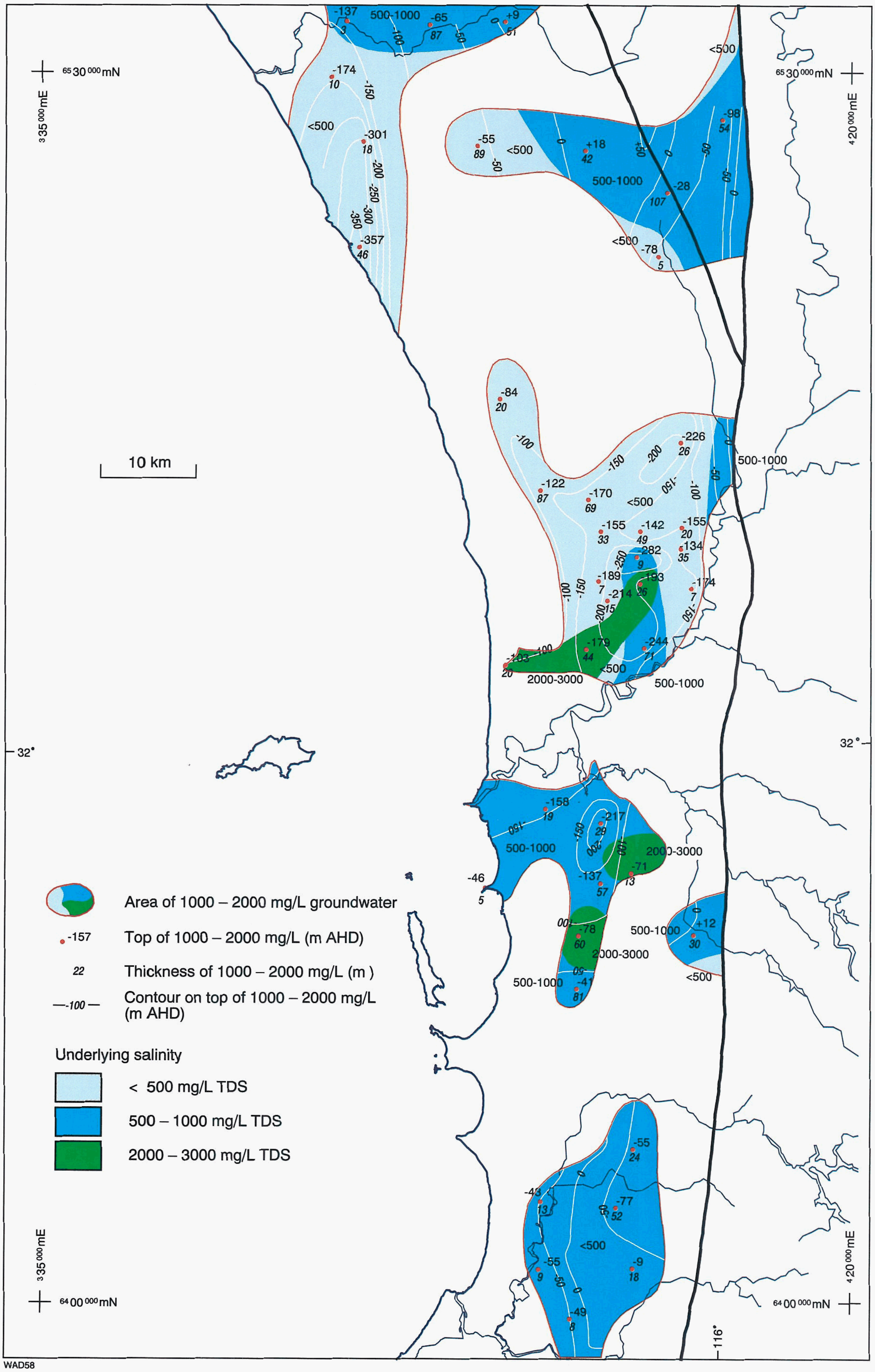
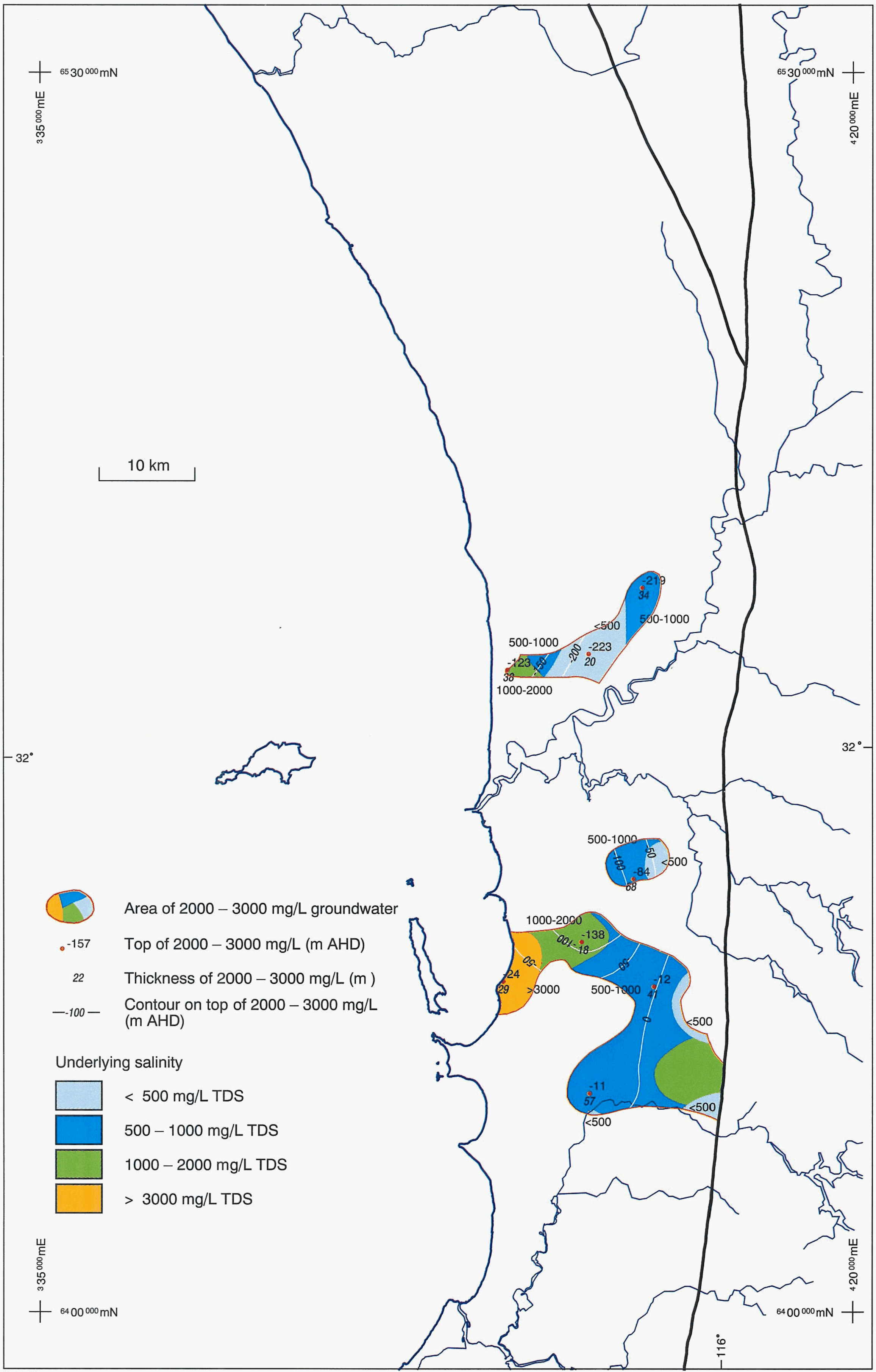


PLATE 69. Upper Leederville aquifer groundwater salinity 1000 – 2000 mg/L TDS



WAD59

PLATE 70. Upper Leederville aquifer groundwater salinity 2000 – 3000 mg/L TDS

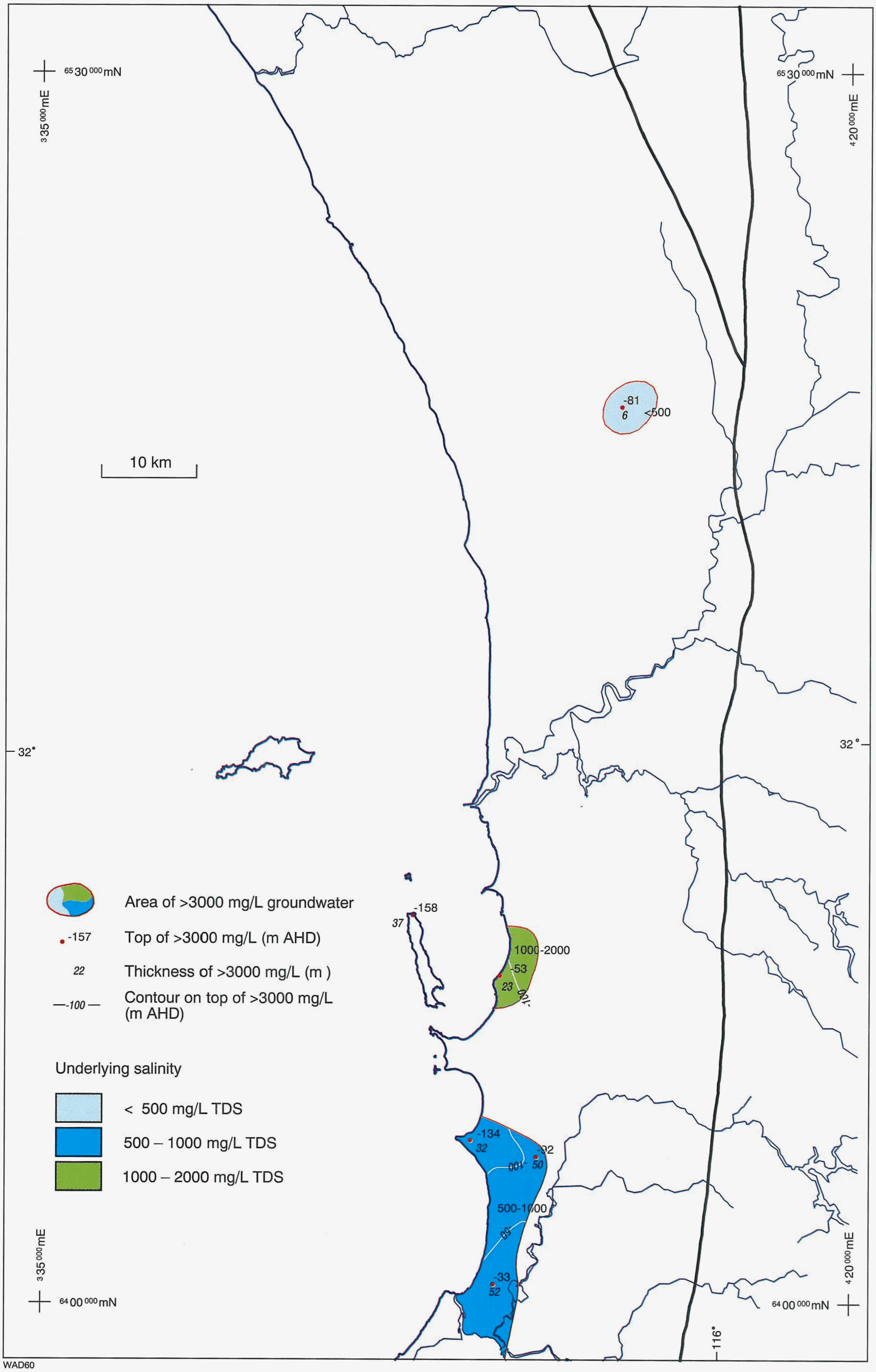


PLATE 71. Upper Leederville aquifer groundwater salinity greater than 3000 mg/L TDS

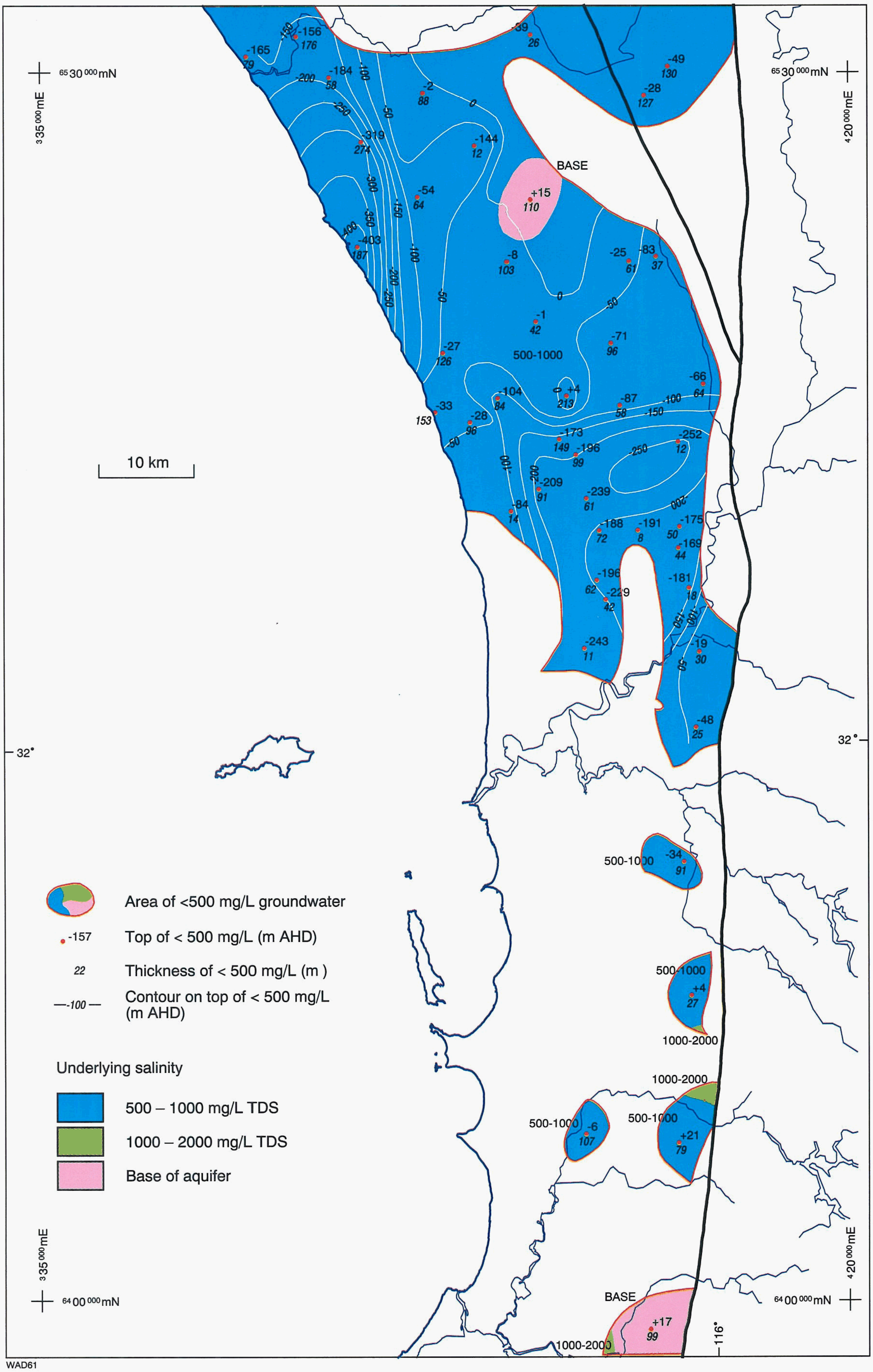


PLATE 72. Lower Leederville aquifer groundwater salinity less than 500 mg/L TDS

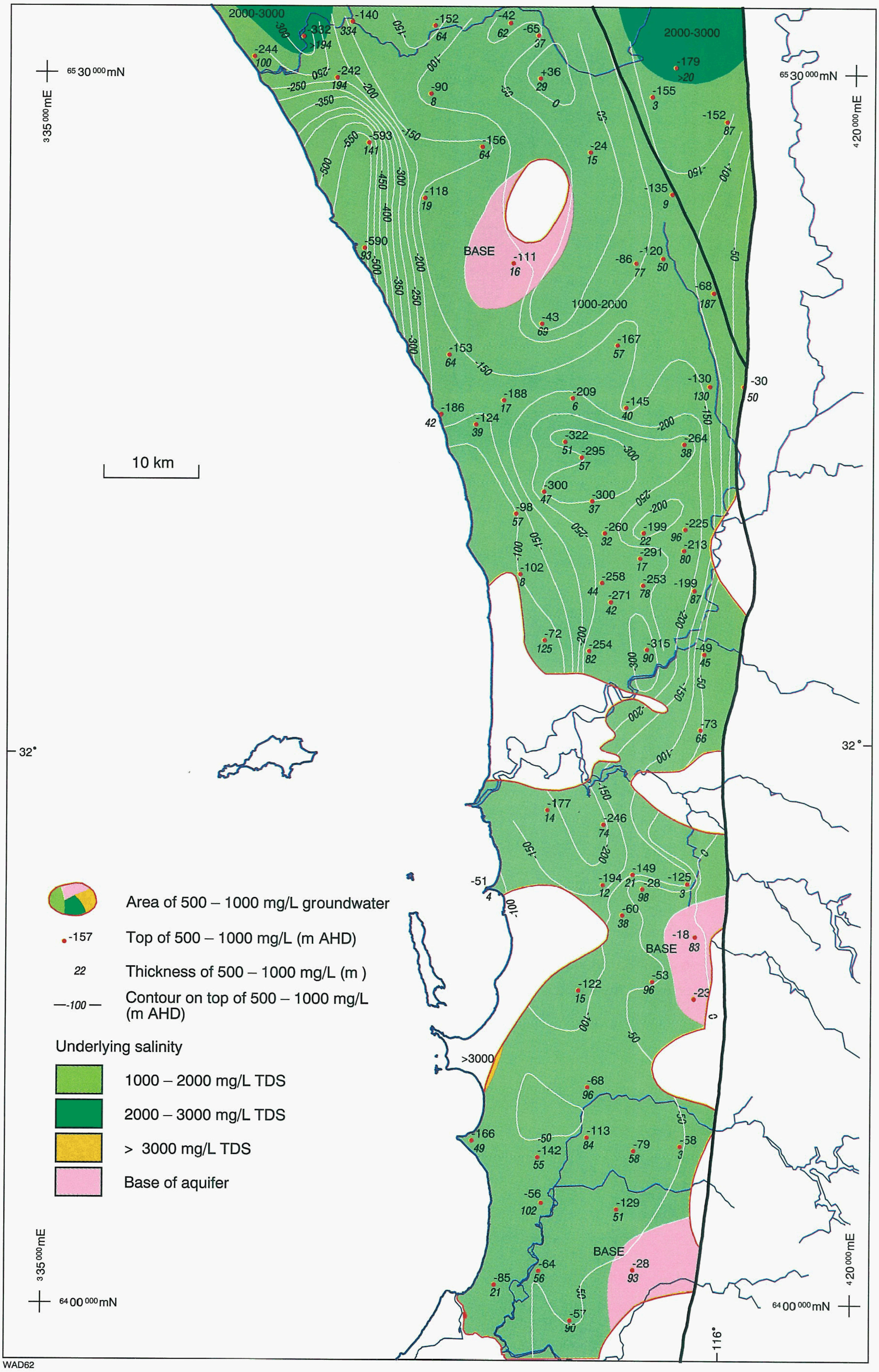


PLATE 73. Lower Leederville aquifer groundwater salinity 500 – 1000 mg/L TDS

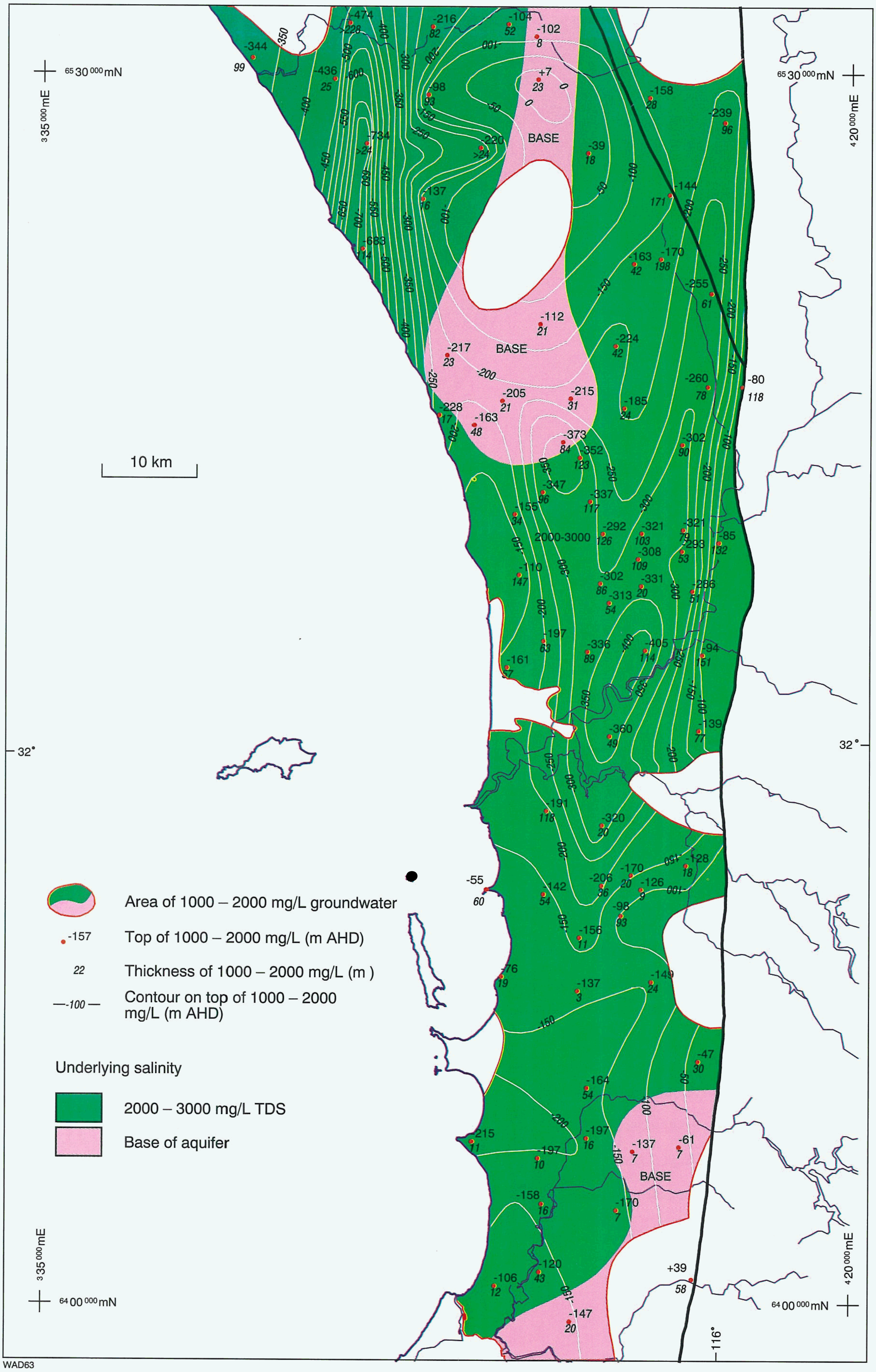


PLATE 74. Lower Leederville aquifer groundwater salinity 1000 – 2000 mg/L TDS

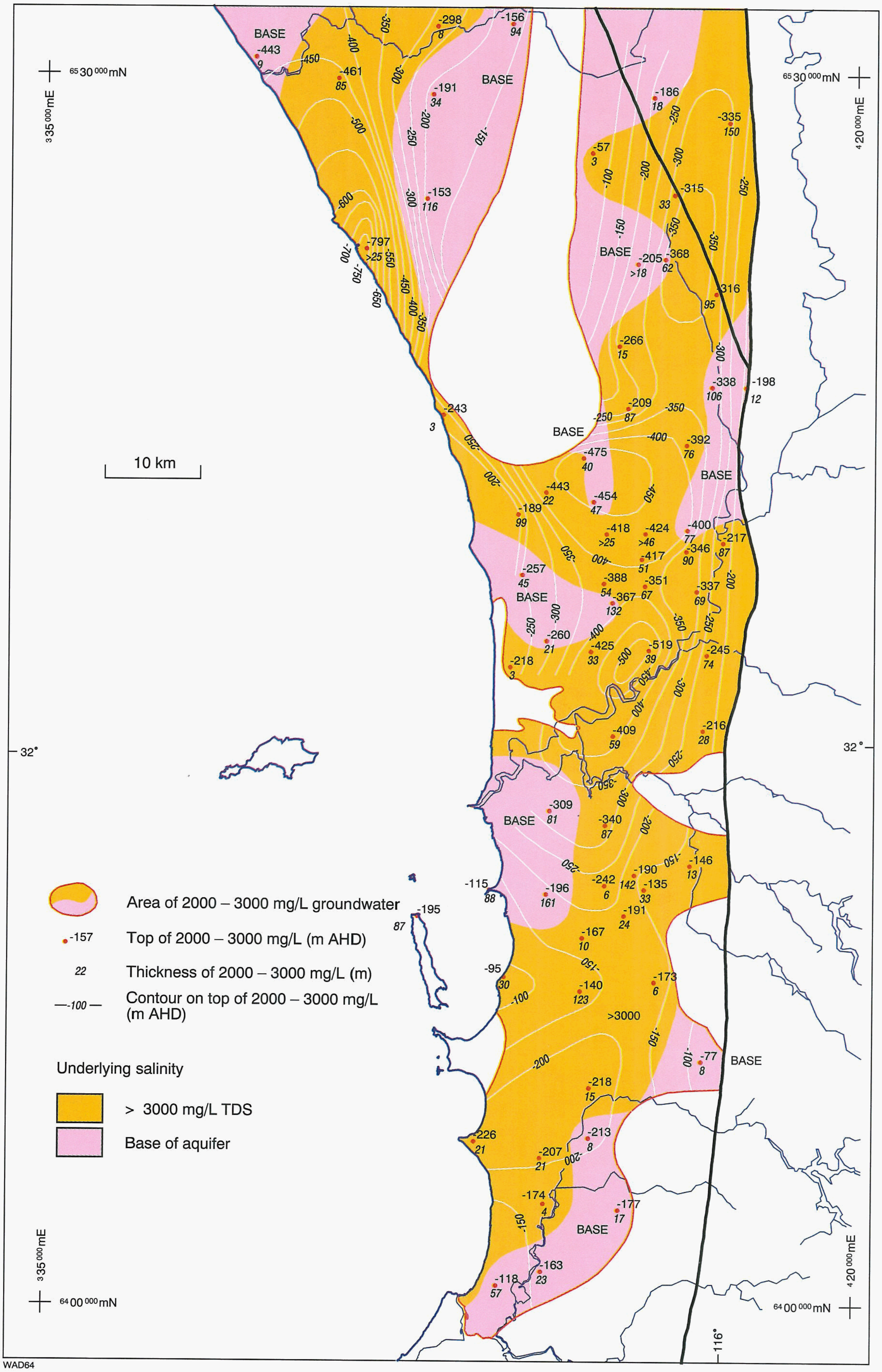


PLATE 75. Lower Leederville aquifer groundwater salinity 2000 – 3000 mg/L TDS

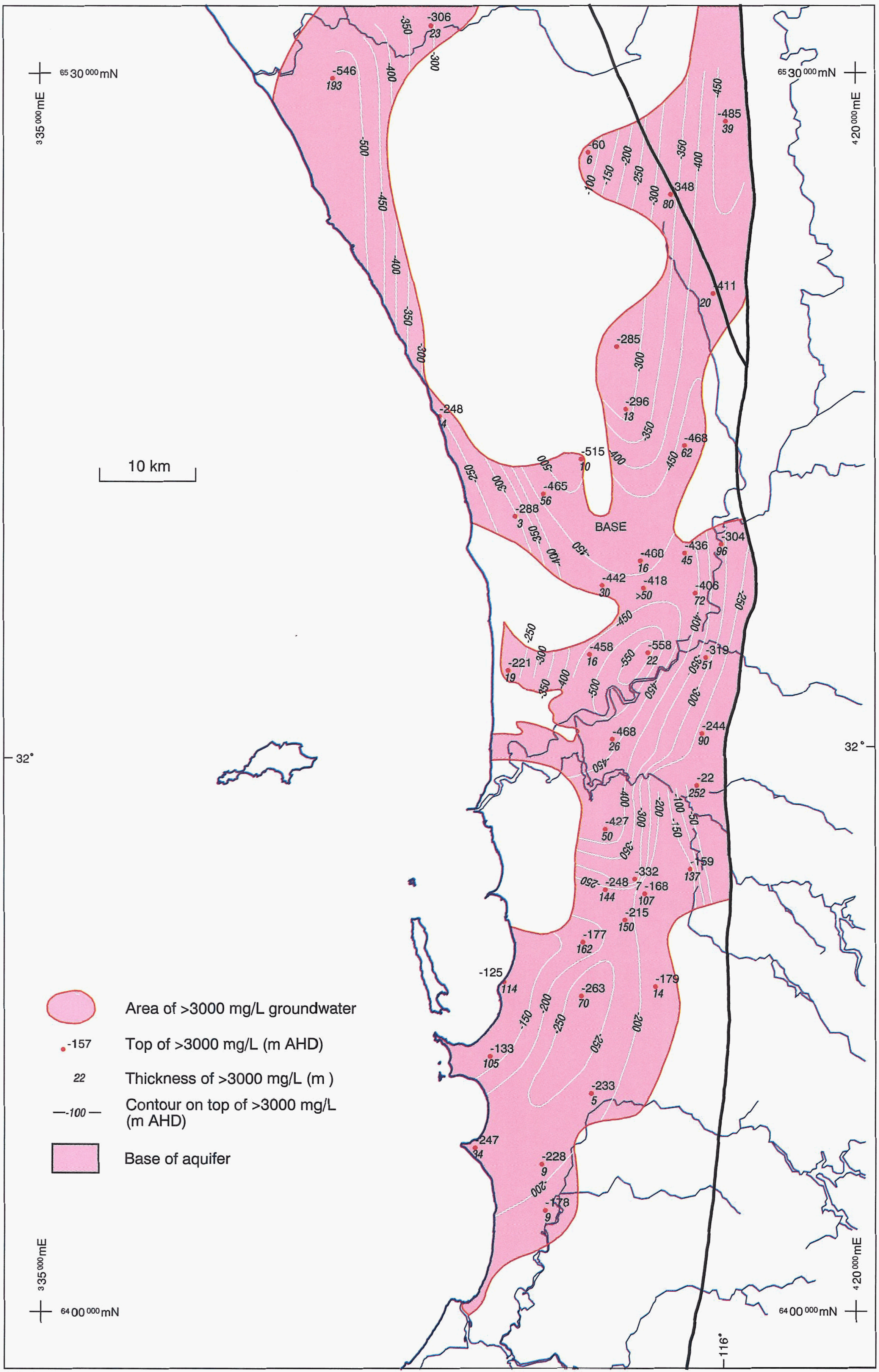


PLATE 76. Lower Leederville aquifer groundwater salinity greater than 3000 mg/L TDS

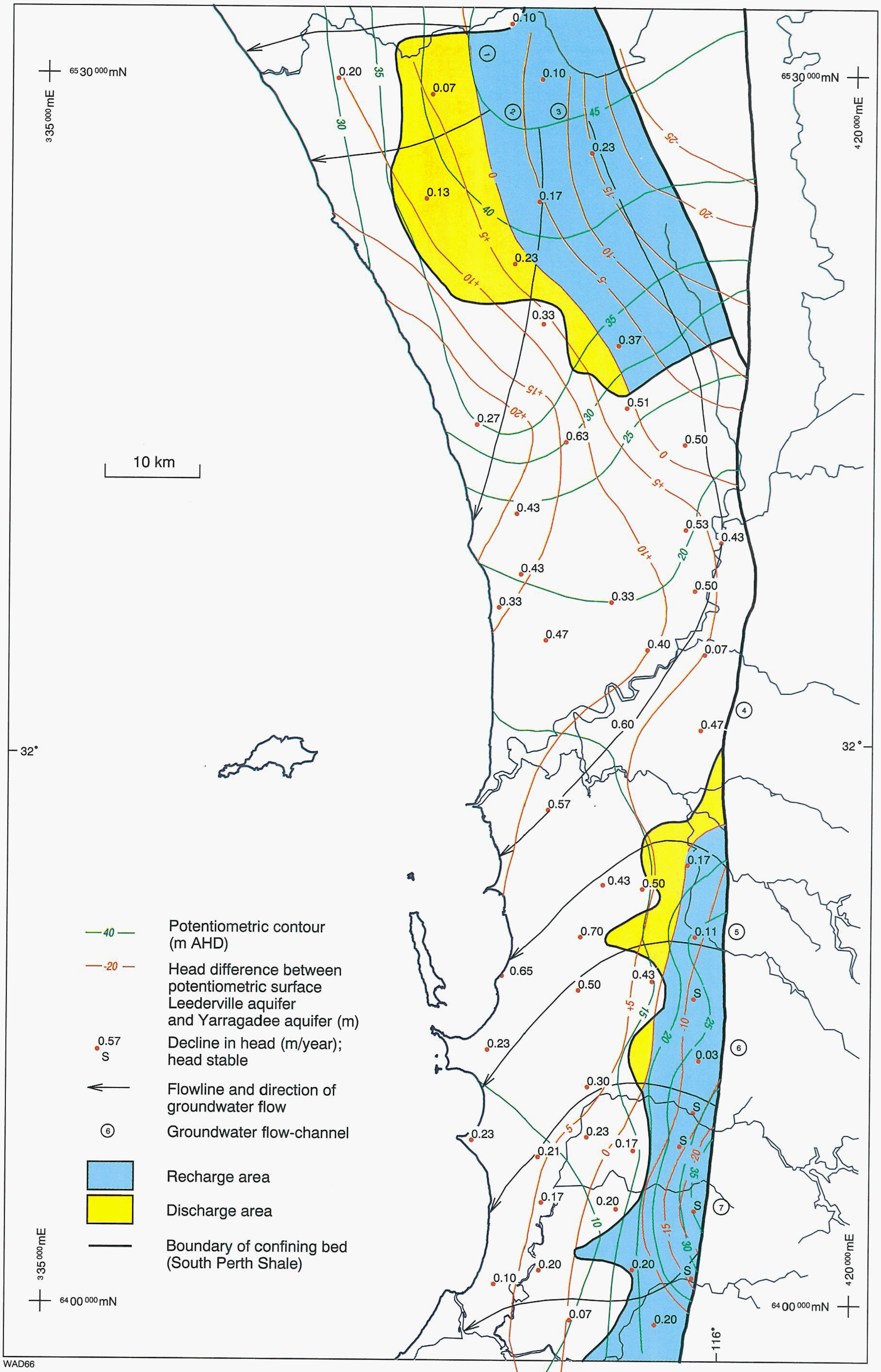


PLATE 77. Yarragadee aquifer groundwater flownet September – October 1992

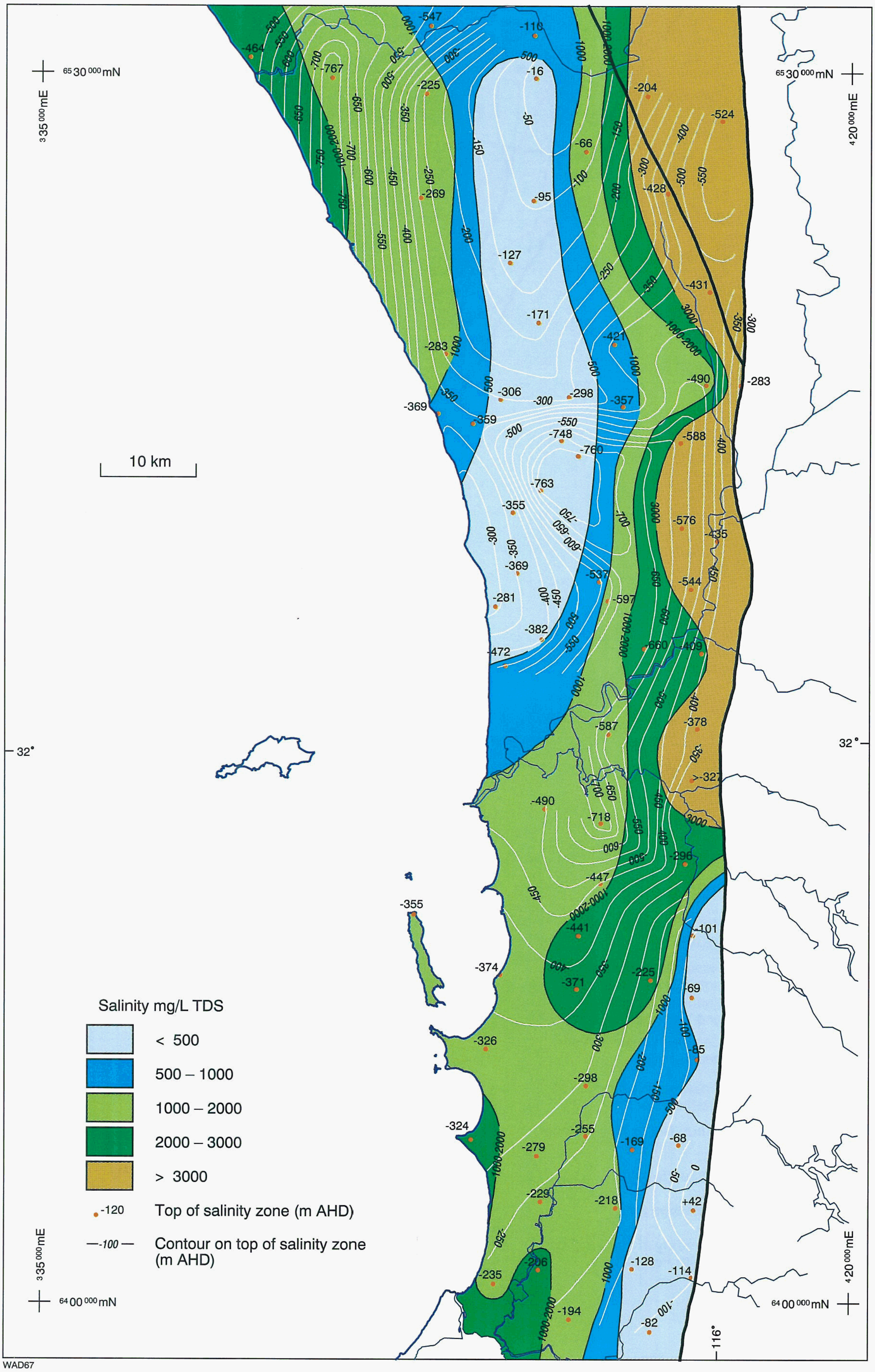


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PLATE 78. Yarragadee aquifer lowest salinity groundwater

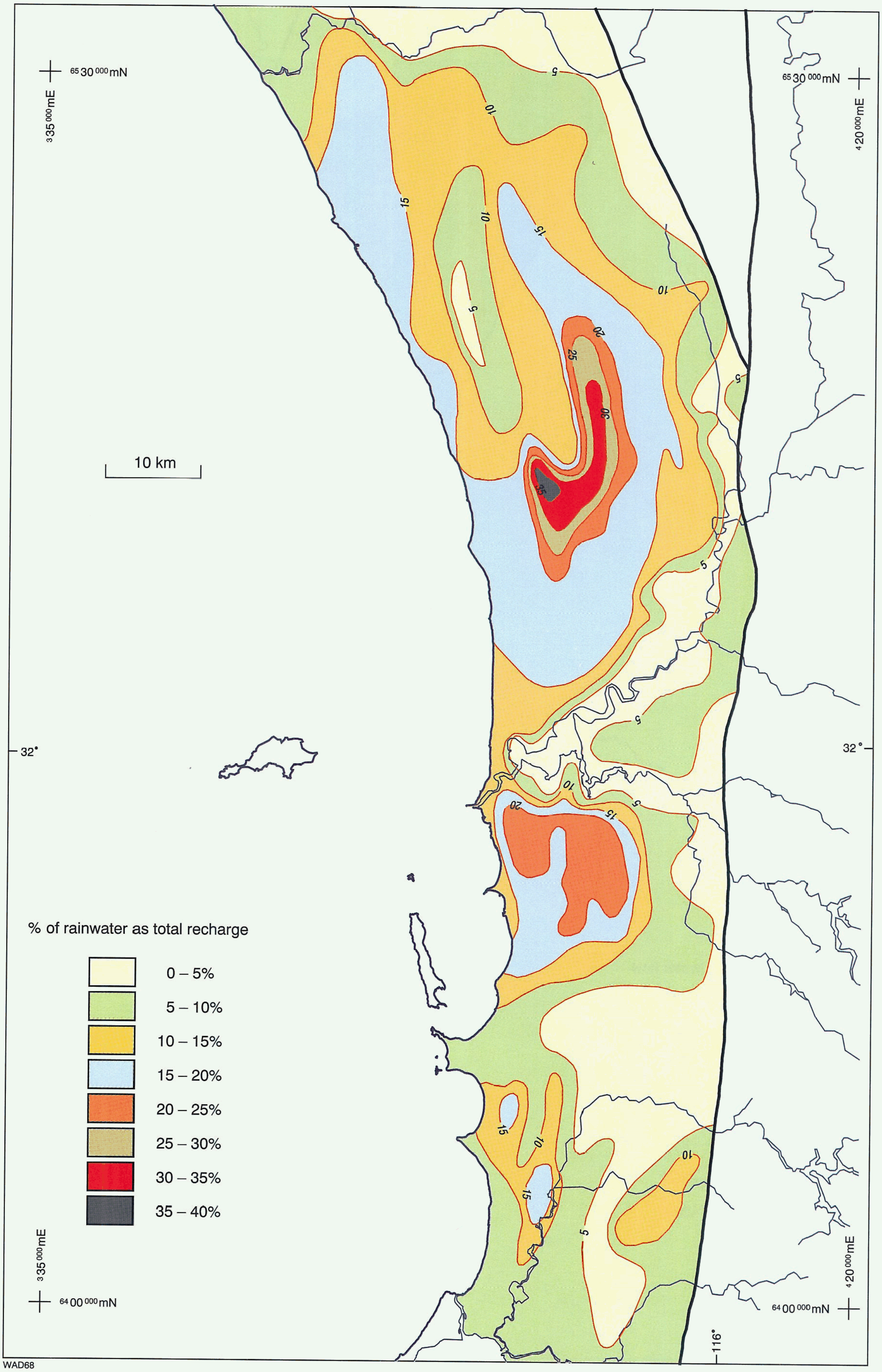

PLATE 79. Superficial aquifer total rainfall recharge

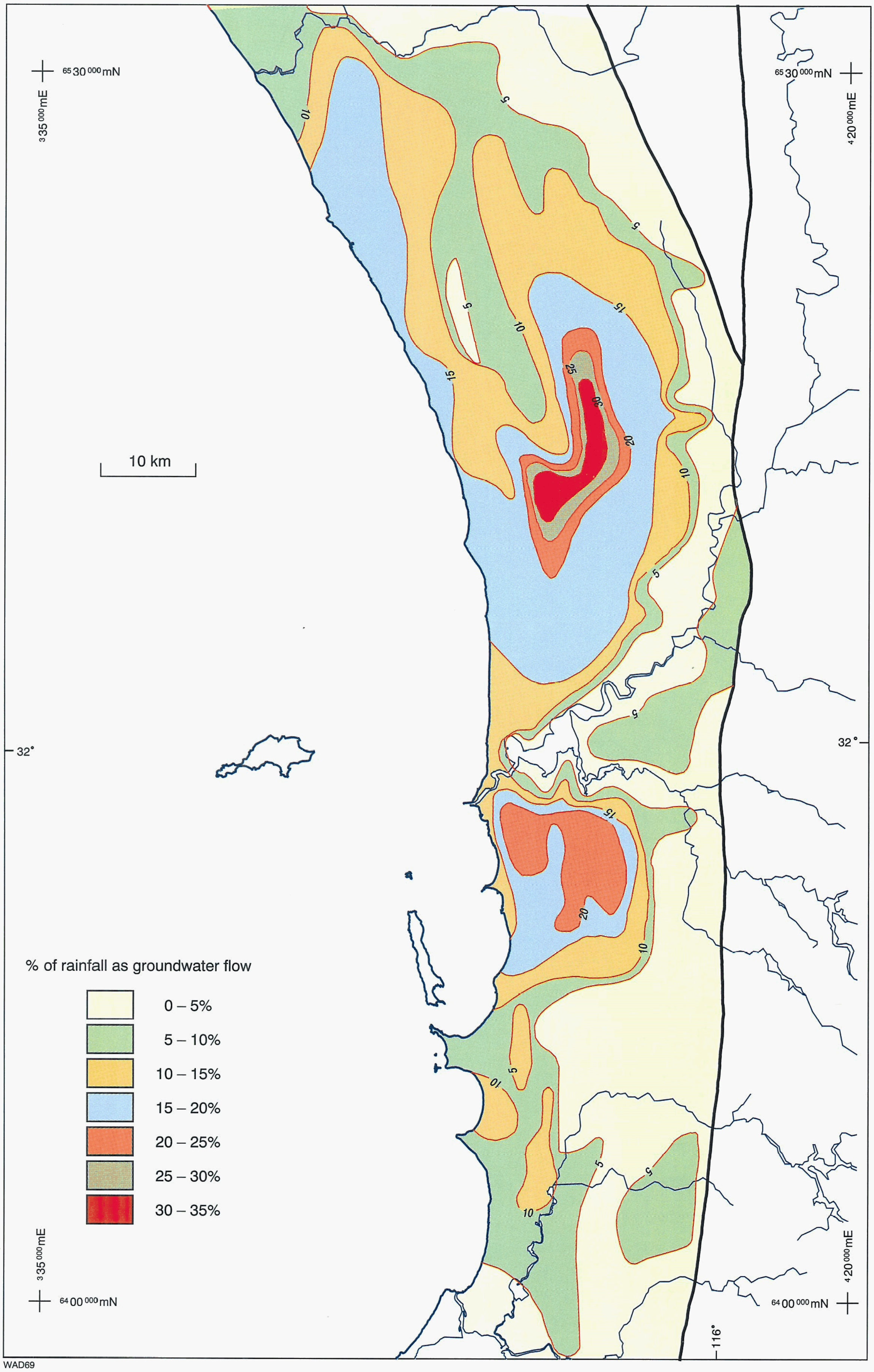

PLATE 80. Superficial aquifer percentage of rainfall recharge contributing to groundwater throughflow

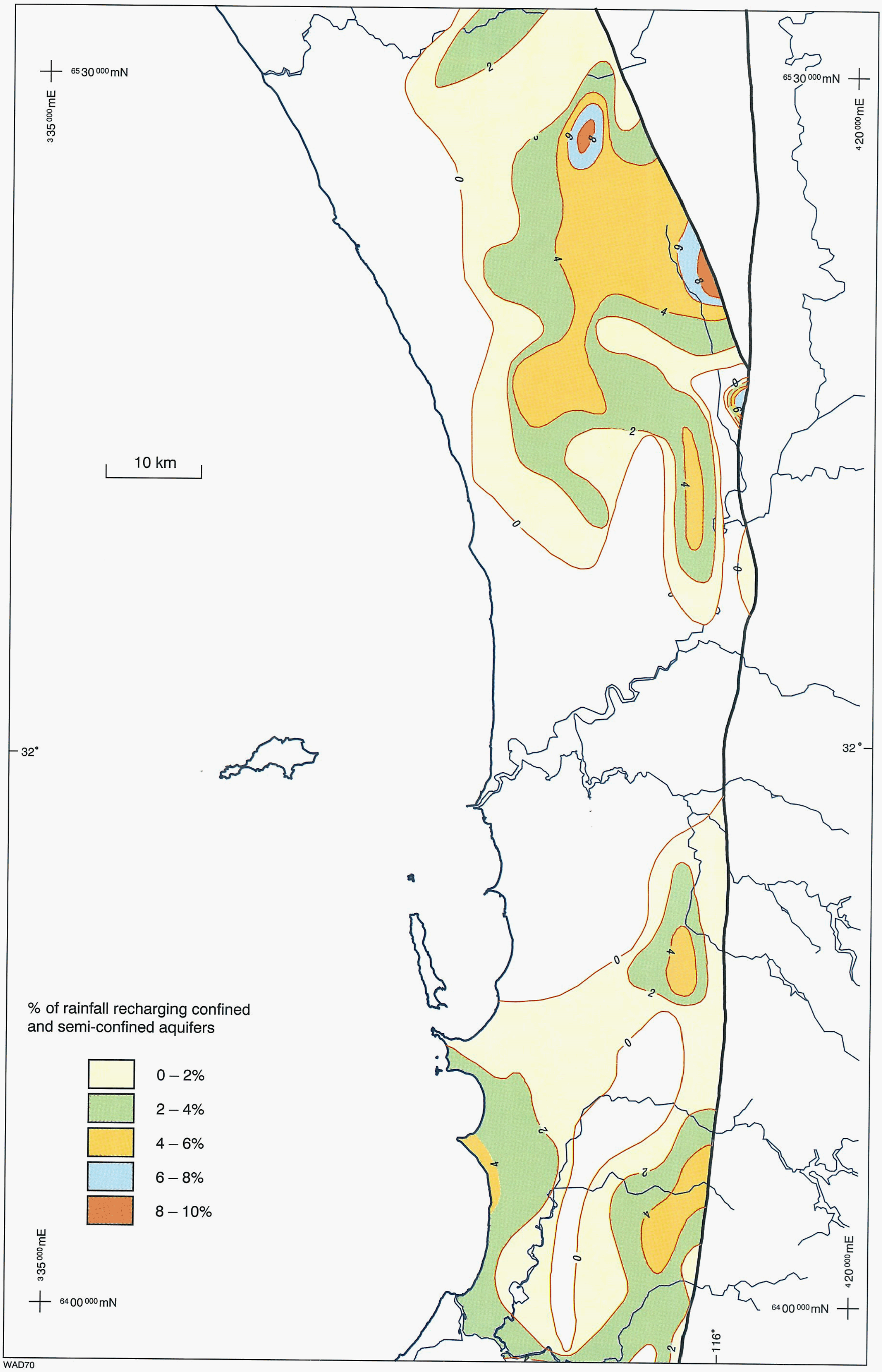

PLATE 81. Percentage of rainfall recharge to confined and semi-confined aquifers

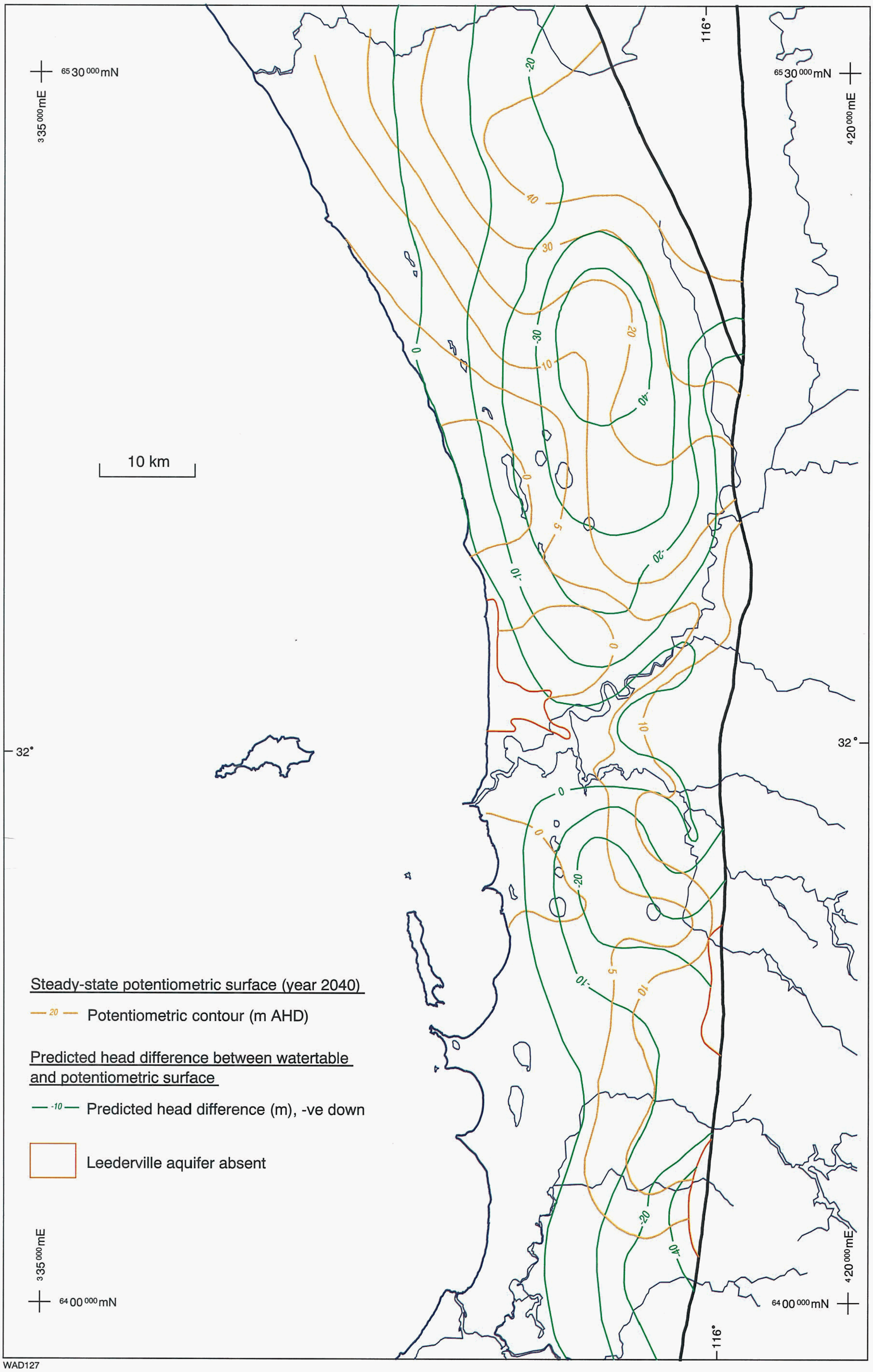

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PLATE 82. Leederville aquifer: predicted year 2040 steady-state potentiometric surface (at 1992 combined abstraction rates from Leederville and Yarragadee aquifers)

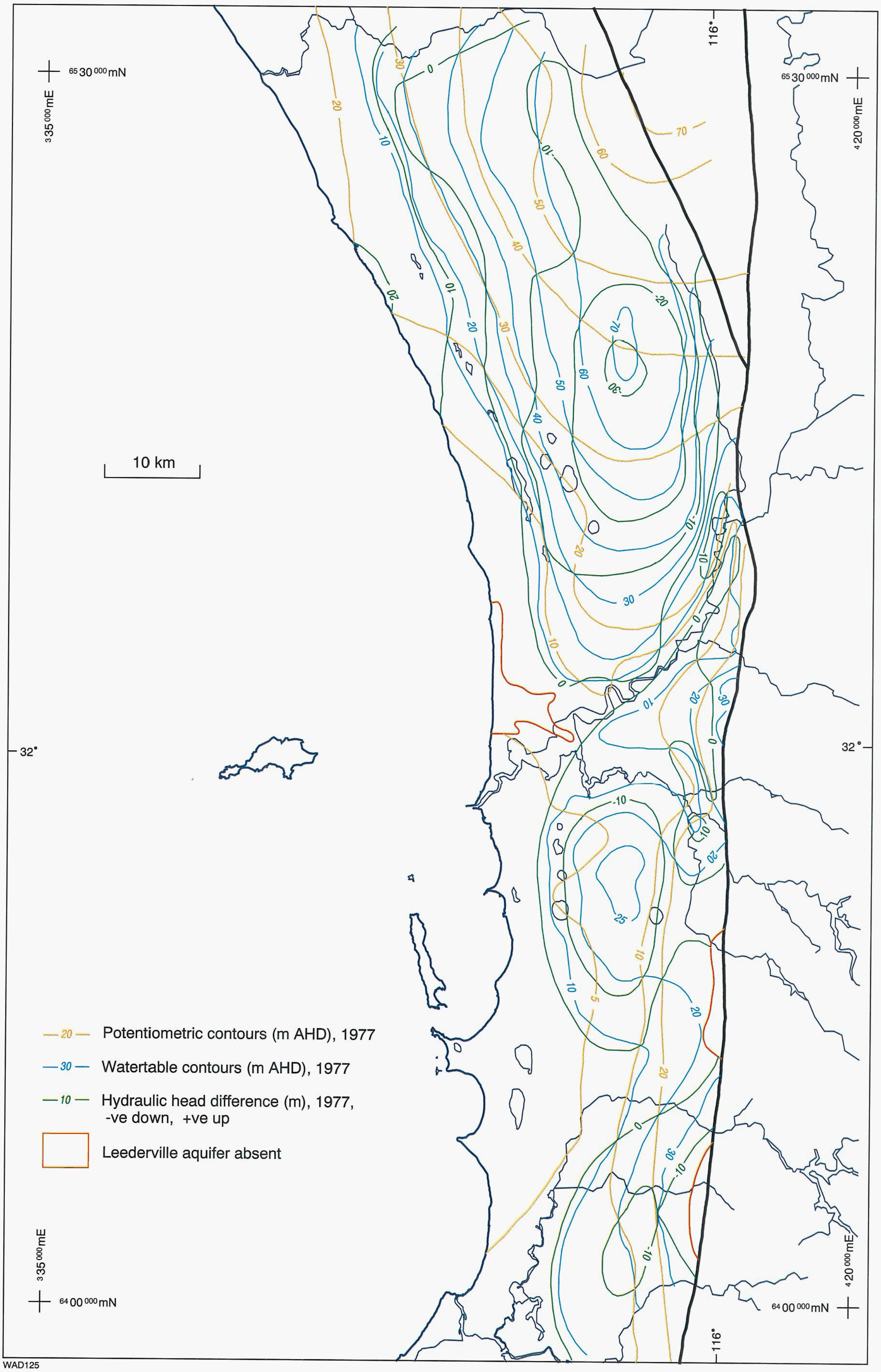

PLATE 83. Hydraulic-head difference between watertable and potentiometric surface of the Leederville aquifer, 1977

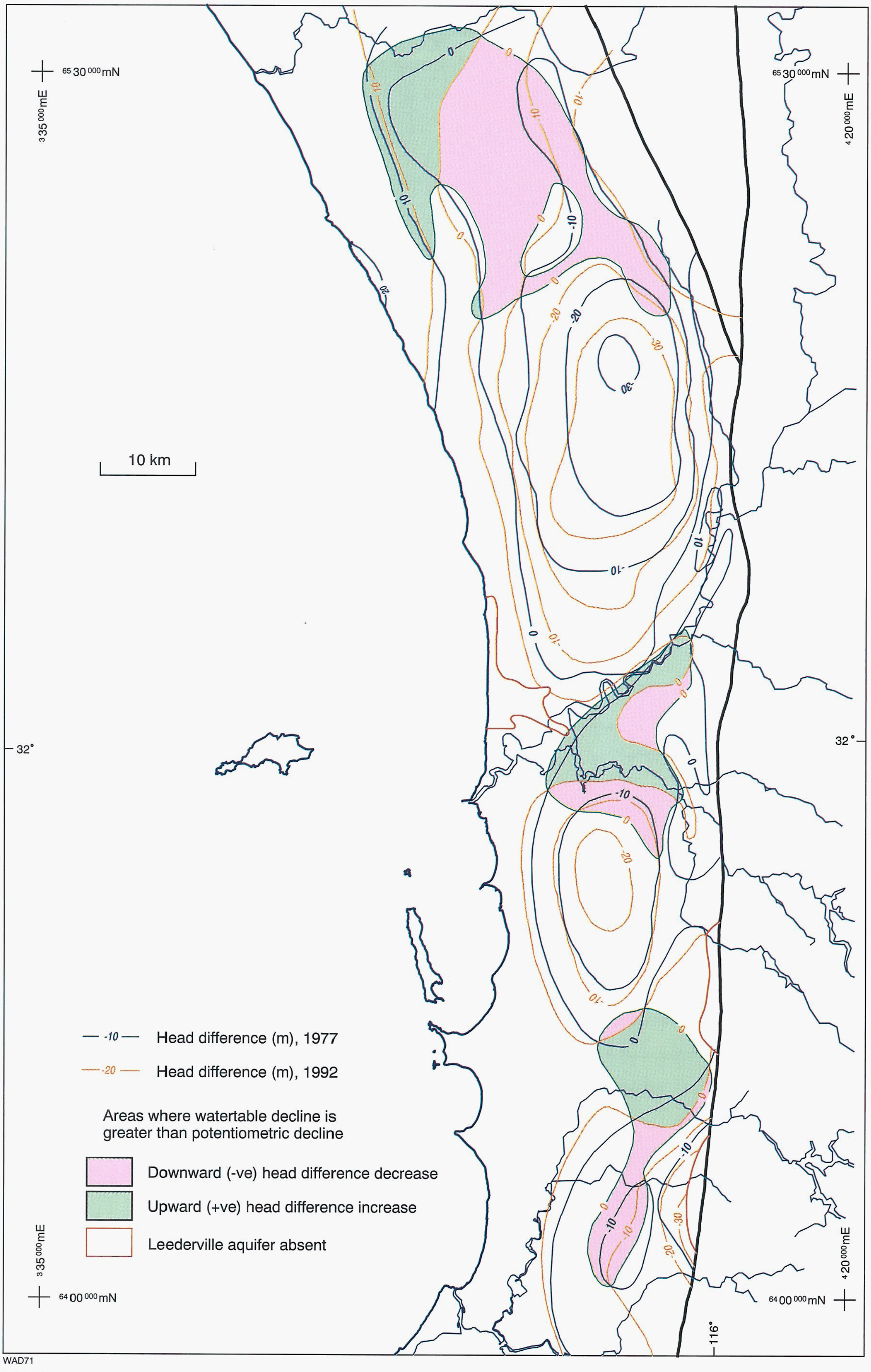

PLATE 84. Change in hydraulic-head difference between watertable and potentiometric surface of the Leederville aquifer from 1977 to 1992

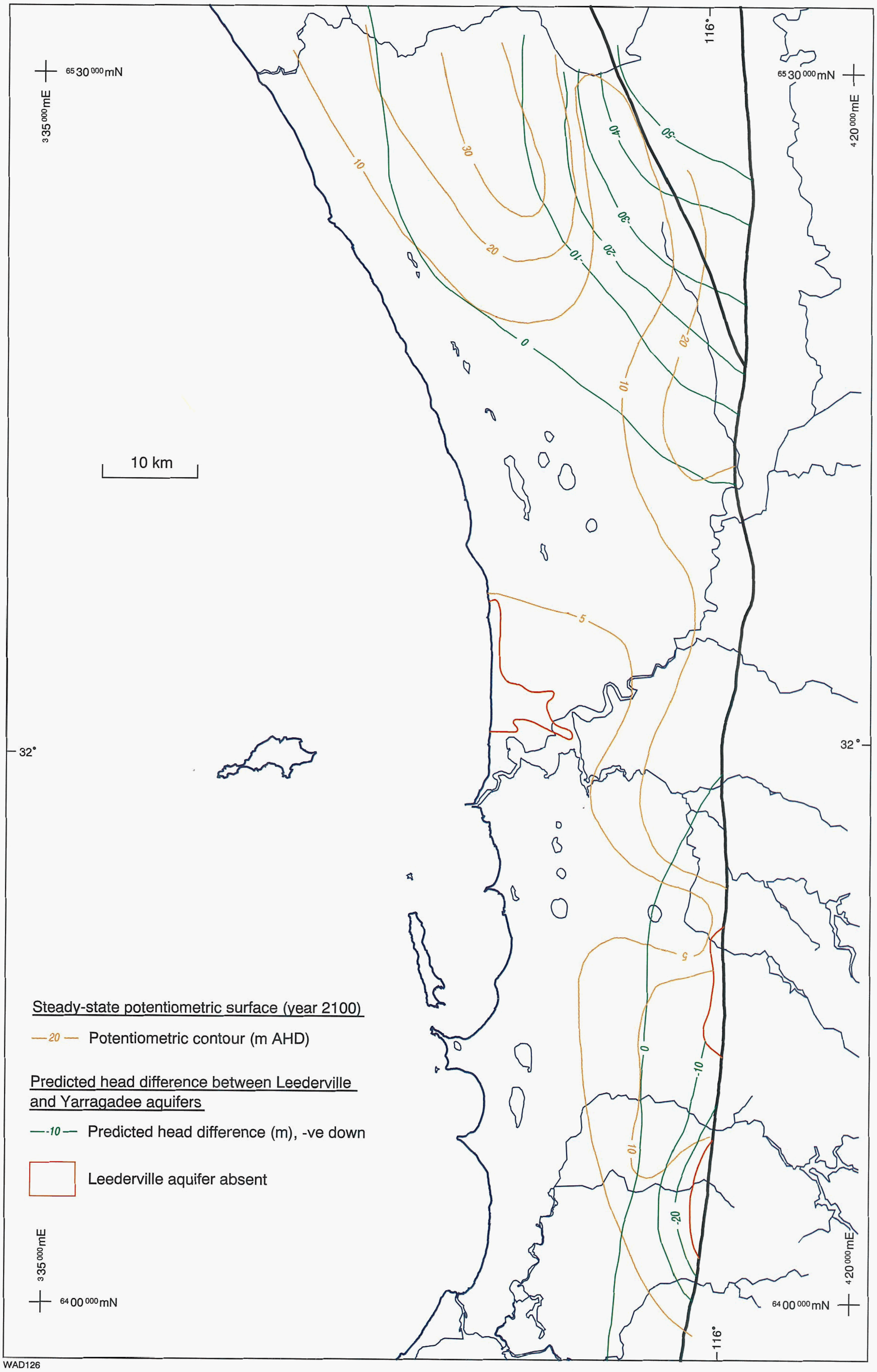

PLATE 85. Yarragadee aquifer: predicted year 2100 steady-state potentiometric surface (at 1992 abstraction rates)