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Geological Survey of Victoria

VICTORIA'S GROUNDWATER RESOURCE
A SUMMARY

by

J Leonard

Geological Survey Victoria
Unpublished Report 1988/13.

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DEPARTMENT OF INDUSTRY, TECHNOLOGY AND RESOURCES

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Report prepared for consideration for inclusion in the revised edition of the 'Geology of Victoria' to be published by the Geological Society of Australia during 1988.

INTRODUCTION

Groundwater is a widely distributed renewable natural resource of vital importance to the State's development. Its importance as a source of water is obvious but it is also a very important consideration in a number of environmental management problems including salinity and the land disposal of wastes. Groundwater contributes to such geotechnical problems as slope stability and land subsidence. Groundwater may also be a key to understanding a wide variety of geological processes, among them the generation of earthquakes, the migration and accumulation of hydrocarbons and the genesis of certain types of ore deposits, soil types and landforms. Where it is mineralized (mineral water) or occurs at elevated temperature (geothermal water) it may have added commercial potential.

Geological factors principal control the occurrence and movement of groundwater and in any area the number and type of aquifers, their location, lateral and vertical extent, and configuration including depth and outcrop patterns, hydraulic properties and degree of interconnection all depend on the geologic history. Surface geology controls the recharge/discharge regime of aquifer systems whilst subsurface geology controls the distribution and flow of groundwater.

Victoria's groundwater resources have been progressively developed mainly by private enterprise. The rate of development has increased markedly since the late 1960's aided by the improved technology for drilling bores and manufacturing construction materials such as stainless steel screens, and by the availability of high capacity bore pumps. Although the rate is influenced by prevailing economic conditions and agriculture and industrial practice, the largest single influence is the increased demand for water that during droughts which Victoria experiences about every seven to nine years.

Groundwater is used for a variety of uses including irrigation, industrial and stock and domestic purposes. It is also developed as a source of water for public supply. There are about 60 000 known water bores in Victoria including more than 6 000 licensed high yield bores used mainly for irrigation and town water supply. In detail, 33 towns including Sale, Portland and Nhill are dependent on groundwater for their water supply and another 28 towns the most notable of which is Geelong, use groundwater as an adjunct to surface water supplies. Many farms are dependent on groundwater as a supplement or as a primary source of water.

About 250 000 megalitres (ML) of groundwater are extracted annually, 150 000 ML of which are used for irrigation, 40 000 ML for town supplies and 30 000 ML for stock and domestic use.

Schemes to develop groundwater must be contingent upon the fact that the resource consists of a large store of water underground that is replenished by infiltration of a very small part of the annual rainfall. The total groundwater store is not known accurately but it is certainly hundreds and possibly thousands of times greater than the annual recharge (Lawrence, 1982). The estimated annual recharge for the major Groundwater Provinces in Victoria are given in Table 1.

TABLE 1 Estimated annual recharge

Groundwater province	m³/yr	ML/yr
Otway Basin	4.13 x 108	413 000
Murray Basin	9.8 x 107	98 000
Western Port Basin	1.9 x 107	19 000
Gippsland Basin	4.23 x 108	423 000
Port Phillip Basin	4.3 x 107	43 000
Highlands	4.36 x 108	436 000
Total	1.43 x 10	1 432 000

(After Lawrence, 1982)

The Groundwater Act (1969) provides for the exploration, conservation and beneficial use of the State's groundwater resources. A number of government agencies are involved in groundwater investigations, including research into salinity and groundwater pollution. Summaries of these investigations are published annually in the "Groundwater Investigation Program Report". Published reports discussing the regional groundwater resources of Victoria include Gloe (1947), AWRC (1965, 1974), Lawrence (1976, 1982) and DWR (1988). In 1982 the Geological Survey published a 1:1 000 000 scale map of Groundwater Resources of Victoria. This map indicates the generalized groundwater salinity and bore yield ranges of the main utilized aquifer in any given area which is generally the shallowest, unconfined aquifer.

The groundwater resources of Victoria can be considered in two sections, namely:

- the Palaeozoic and Lower Cretaceous sediments and igneous rocks, and
- the Upper Cretaceous and Cainozoic sediments and igneous extrusives that have infilled the major sedimentary basins.

The pre-Upper Cretaceous rocks are massive and are minor aquifers except where highly fractured and jointed. Outcrops of these rocks separate the major sedimentary basins.

The principal aquifers in the sedimentary basins both north and south of the Victorian Uplands are unconsolidated sand, gravel and limestone that possess dominantly intergrannular porosity. From deepest to shallowest, they are typically: Upper Cretaceous - Lower Tertiary quartzose sand and gravel, Upper Tertiary limestone and Pliocene to Recent marine sand and associated fluvial deposits.

Basalts of the Older Volcanic Series, are in places, intercalated with the Lower Tertiary units. Much at the Otway and Port Phillip basins are covered by younger, Newer Volcanic basalts. The basalt aquifers, where fresh, possess fracture porosity.

OTWAY BASIN

The onshore portion of the Otway Basin contains over 2 000 m of unconsolidated Upper Cretaceous, Tertiary and Quaternary sediments. These units wedge out to the north on the Palaeozoic rocks of the West and Central Uplands and to the east on the upfaulted, Lower Cretaceous rocks of the Otway Ranges. Much of the basin is covered by basalts of the Newer Volcanics.

Aquifers occur in a number of units in the stratigraphic sequence. The most developed are in the Tertiary sands, gravels and limestones of the Pebble Point, Dilwyn and Mepunga Formations and the Port Campbell Limestone, and the Newer Volcanic basalts. The Upper Cretaceous Waarre Sandstone and Timboon Sand also contain aquifers, however, they are not exploited as they are overlain by shallower, high yielding aquifers containing good quality groundwater. Minor aquifers are present in the other units in the stratigraphic column but for the most they behave as aquitards.

The Dilwyn Formation is an extensive sand aquifer that is utilized mainly for urban water supply. Towns currently supplied by high yielding bores (up to 125 L/sec) developing this aquifer include Portland, Port Fairy and Heywood in the western Otway Basin and Port Campbell, Peterborough, Timboon and Geelong (in part) in the eastern Otway Basin. Leonard (1985) proposed to utilize this aquifer at Curdie Vale to augment the water supply for Warrnambool.

The Dilwyn Formation is a confined to semi-confined aquifer that is overlain by up to 1 000 m of younger sediments and basalt. In the western Otway Basin, the aquifer is recharged around the margins of the Merino Block where it outcrops or subcrops beneath limestones and calcarenites of the Bridgewater Formation and Port Campbell Limestone. Groundwater flow in this part of the basin is in a general southerly direction. In the eastern Otway Basin, recharge mainly occurs where the aquifer outcrops along the western flanks of the Otway Ranges. Here, the groundwater flows is mainly westly and southwestly away from the intake area. Groundwater salinity increases along the flow paths from less than 500 mg/L TDS in the intake areas up to about 1 500 mg/L TDS towards the coast. The exception is over the Warrnambool High where the salinity is as high as 5 600 mg/TDS. The chemical evolution of the groundwater downdip has been discussed by Johns (1968, 1971) and Blake (1980). The groundwater chemistry in the western Otway Basin is strongly influenced by recharge from the overlying calcareous sediments. Groundwater temperatures range from 15 to over 60 °C.

In the relatively small Barwon Downs Graben (Blake, 1974a) adjoining the western flanks of the Otway Ranges, the Dilwyn Formation aquifer is in hydraulic connection with aquifers in the underlying Pebble Point Formation and overlying Mepunga Formation. These units together form an aquifer system referred to as the basal Tertiary Aquifer System by Leonard et. al. (1981). The aquifer system is confined to semi-confined by up to 500 m of marl, silt and clay in the graben (Leonard, et. al., 1983). Its recharge area is on the adjoining Barongarook High where the aquifer sediments outcrop. Groundwater quality is very good (less than 300 mg/L TDS). The resource is being harvested as a source of water to augment the supply to the City of Geelong. Yields from production bores in the Barwon Downs borefield are about 110 L/sec (Lakey and Leonard, 1984; Leonard and Lakey, 1987).

The Port Campbell Limestone aquifer is unconfined where it outcrops and confined to semi-confined where it is overlain by Newer Volcanic basalts. Bore yields are highly variable ranging from less than 1 L/sec up to 25.0 L/sec; the higher yields are obtained from zones of more cavernous limestone. Groundwater salinities range from around 500 to 7 000 mg/L TDS but are mostly less than 1 500 mg/L TDS. The groundwater is hard due to dissolution of calcareous material. It is used for domestic and stock supplies, and irrigation. The water supply for the township of Koroit is drawn from this aquifer and until 1957, the City of Portland also obtained its supply from this Limestone.

The calcareous sand and limestone of the Bridgewater Formation and the weathered top of the Gellibrand Marl both act as minor aquifers which yield small supplies (less than 2 L/sec) of moderate quality (600 to 1 500 mg/L TDS) groundwaters. Groundwater from these units is used mainly for stock and domestic supplies.

Extensive sheets of Upper Cainozoic basalt of the Newer Volcanics series cover much of the Otway Basin to the north of an approximate west-east line from Warrnambool, through Colac to Geelong. The basalts range up to 120 m in thickness where the lava has completely infilled old valleys but are mostly less than 70 m thick. The complex hydrogeology of the basalt aquifers in this area was discussed by Newton (1954), Lawrence (1969), and Thompson (1972a, 1974). Recharge to the unconfined basalt aquifer can take place over much of its occurrence but is higher in the areas of younger, less weathered flows such as the 'stony rises'. Discharge is mostly into low lying depression and lakes of the internal drainage systems. Bore yields vary widely, up to about 60 L/sec where the basalts are highly fractured, but are typically less than 1.5 L/sec. Groundwater salinities range from less than 100 to 8 000 mg/L TDS but are mostly greater than 2 000 mg/L TDS. The lower salinity groundwater occurs where local recharge rates are high, however, these waters are characterized by high nitrate content (Johns and Lawrence, 1973; Lawrence, 1983). Groundwater from the basalts is used extensively for stock watering. Where the quality and bore yields are suitable, such as occurs in the area to the west of Colac, it is used for irrigation. Towns that use groundwater from the basalt for their supply include Mortlake, Skipton and Caramut.

TORQUAY BASIN

The relatively small Torquay Basin contains more than 600 m of Cainozoic sediments being mostly representatives of the Eastern View, Demons Bluff and Jan Juc Formations. The majority of units in the stratigraphic sequence are minor aquifers which contain poor quality groundwater. The exception are the sands of the Eastern View Formation which are capable of yielding large quantities of good quality groundwater. However, this resource is not used except at the Anglesea coal mine where about 25 ML/day of groundwater is withdrawn for use in power generation for the refining of aluminium at Point Henry.

GIPPSLAND BASIN

The Gippsland Basin has an Upper Cretaceous to Recent sequence that attains a maximum thickness of 1 500 m onshore but thickens considerably to in excess of 4 500 m offshore (Thompson, 1986). The sequence contains numerous interbedded and interconnected aquifers. A number of major structural elements, each with broady representative hydrostratigraphic sequences, are recognized.

The Latrobe Valley Depression and the adjoining smaller Moe Swamp Basin have been infilled by up to at least 770 m of continental sediments and Older Volcanic basalts (Thorpdale Volcanics) of the

Traralgon, Morwell and Yallourn Formations. The unconsolidated sands and gravels of these formations, and the basalts where unweathered and fractured are aquifers that are confined to semi-confined by intercalated clay, silt and coal aquitards. Existing data indicates the existence of a lower, Traralgon Formation aquifer system and an upper, Morwell Formation aquifer system (Brumley, et. al., 1981). Recharge occurs where the aquifers outcrop or subcrop along the flanks of the surrounding uplands, particularly the Strzelecki Ranges and along the Baragwanath Anticline, and by vertical leakage through the aquitard units. The Yallourn Monocline forms a hydraulic barrier that restricts groundwater flow between aquifers in the Moe Swamp Basin and the LaTrobe Valley Depression (Brumley and Holdgate, 1983). The aquifers contain low salinity groundwater, less than 900 mg/L TDS and are capable of yielding up to 150 L/sec. Groundwater temperatures up to 70 °C have been recorded.

The groundwater resources in the Traralgon and Morwell Formation aquifer systems are little utilized. However, in excess of 27 000 ML of groundwater is extracted annually to reduce hydrostatic pressures to stabilize the brown coal open cuts at Morwell and Loy Yang. The resultant depressurized cone extends for more than 35 km to the east (Brumley,1984). Dewatering of the aquifer has resulted in land subsidence (Evans, 1986). In the eastern part of the Latrobe Valley Depression the groundwater is used for irrigation.

Further to the east in the Lake Wellington and Seaspray depressions the Morwell Formacion is not present, however, the Traralgon Formation occurs at depths greater than 600 to 900 m. The groundwater in this latter unit is not tapped because of its depth although its quality and yield potential are suitable for most purposes including town supply. Over the past decade there has been a decline in groundwater pressure levels in the Traralgon Formation on-shore due to the extraction of hydrocarbons and associated fluids in the off-shore Gippsland Basin.

The strata the aquifers above the Traralgon Formation are in places hydraulically connected and thus, on a regional scale, they can be regarded as an aquifer system, referred to here as the Gippsland Aquifer System. The two systems are effectively separated by the Traralgon coal seam and aquitards in the Lakes Entrance Formation.

The narrow, north-south trending barrier sand sequence of the Balook Formation (Thompson, 1980) is an important aquifer in that it provides hydraulic connection laterally between the Morwell Formation aquifer system in the Latrobe Valley Depression and the Gippsland Limestone aquifer to the east, and vertically with the, at least in part, overlying Boisdale Formation aquifer. However, the Balook Formation is only of minor importance as a source of water because of its limited extent.

The hydraulic properties of the Gippsland Limestone vary; where it is mainly marl to marly limestone it is a poor aquifer both in terms of bore yields and groundwater quality, however, where it consist of limestone and shelly sands it can yield up to 10 L/sec of groundwater with a salinity in the range 1 000 to 2 500 mg/L TDS. In the area to the south of Longford where the Rosedale Monocline has brought the limestone close the surface, it is used as an irrigation and Industrial water supply (AGC, 1983).

The Boisdale Formation consists of a sequence of sand and clay, with the sand becoming more predominant with depth. The formation commonly contains several aquifer horizons which are, in places, confined to semi-confined beneath clays that occur towards the top of the unit or in the overlying Haunted Hill Gravels and Quaternary alluvium; bores developing this aquifer particularly in the Sale area are known to flow. Recharge is achieved via direct infiltration where the formation outcrops or subcrops beneath sandy units, and by lateral throughflow and vertical leakage from surrounding strata. The formation yields large quantities of good quality, less than 500 mg/L TDS, groundwater. It is extensively utilized for irrigation and as a source of water for the City of Sale.

Much of the Gippsland Basin is overlain by gravel, sand, clay and silt of the Haunted Hill Gravel and/or Recent alluvium. Yields from these units vary considerably with higher yields generally being obtained from the alluvium as for example along the Mitchell River. The salinity from both units is generally less than 1 000 mg/L TDS.

Tarwin Basin

The Tarwin Basin is a small fault bounded graben situated to the south of Leongatha. It has been infilled by a relatively thin Tertiary sequence consisting of sand, gravel and clay of the Childers Formation and Haunted Hill Gravels separated by Older Volcanic basalts. The Older Volcanics which outcrop extensively to the north of Leongatha in the Woorayl Graben, where unweathered and fractured is the main aquifer (Pratt, 1985). Groundwater salinities range from 250 mg/L to 3 000 mg/L TDS but are generally less than 1 000 mg/L. Bore yields are mostly less than 5 L/sec. The groundwater resources in this basin are not greatly utilized.

MURRAY BASIN

The Victorian portion of the Murray Basin contains up to 640 m of unconsolidated, marine and terrestrial, Cainozoic sediments which dip gently towards the northwest corner of the State. The sedimentary sequence is essentially water saturated and contains a number of partial or minor aquifers which are locally productive, in addition to the major, regional aquifers. At a regional scale all of the aquifers are interconnected to varying degrees being either in direct contact or separated by leaky confining layers (aquitards). Minor, 'perched' aquifers sometimes occur above the main water table where imperable layers locally restricts downward groundwater flow (Tickell and Humphrys, 1987).

Groundwater is extensively utilized for stock and irrigation purposes and increasingly for town water supplies. It has been intensively investigated, particularly in terms of its role in land and water salinity. Major reports on the hydrogeology of the Murray Basin include those of Lawrence (1975), Macumber (1983) and Tickell and Humphrys (1987). Reference to numerous, more localized studies are given in these reports.

The basal aquifer system in the Murray Basin is the fluviatile Renmark Group comprised of the Warina Sand which is dominantly a quartz sand and the younger Olney Formation which tends to be a more carbonaceous and silty to clayey unit. These sediments form a large sheet-like deposit which is almost continuous across the entire basin having infilled the valleys of the pre-Tertiary drainage system; they have been traced up into the Highland tracts of many valleys

(Tickell, 1977). The Olney Formation is the lesser aquifer of the two units in the Renmark Group. Aquifers in these units are confined to semi-confined beneath the overlying thick sequence of Geera Clay and Ettrick Marl aquitards. Groundwater flow is mainly north and northwesterly. Groundwater salinities increase along flow paths from around 1 000 mg/L TDS around the highland front up to 12 000 mg/L TDS. Bore yields up to 50 L/sec have been obtained (Lawrence, 1982) but because of its greater relative depth the aquifer has not been exploited. It has been tested as a source of water to supplement the supply to Nhill but the water quality (4 400 mg/L TDS) rendered it unsuitable.

There are also aquifers in the calcareous, marine Duddo Limestone and its eastern (sourceward) lateral equivalent, the more marly Winnambool Formation of the Murray Group. These units are only developed in the part of the Murray Basin to the west of an approximate north-south line from Robinvale to Murtoa. The aquifers are confined to semi-confined beneath the clay, marl and silt of the Bookpurnong Beds. The combination of skeletal debris and quartz sand in the calcarenites of the Duddo Limestone has resulted in high intergrannular porosity and permeability which has been increased locally by the development of solution cavities. Yields from this unit range up to 15 L/sec and salinities vary from less than 1 000 mg/L TDS up to about 3 500 mg/L TDS. The groundwater from this aquifer is tapped as a source of water for several towns including Nhill and Kaniva as well as for irrigation and stock supplies. The Winnambool Formation is less permeable and contains poorer quality (up to 15 000 mg/L TDS) groundwater due largely to incomplete flushing of the connate water from this aquifer: Johns and Lawrence (1964) noted that the groundwater from this formation has a closer chemical affinity to sea water than that in the Duddo Limestone from which connate water has been substantially flushed.

The sediments of the Wunghnu Group form an important regional aquifer system that is restricted in occurrence to the Riverine Plain of the eastern Murray Basin. The principal aquifer in this group is the fluviatile sand and gravel of the Calivil Formation (Macumber, 1983). Minor aquifers occur in the buried stream channel deposits of the Shepparton Formation.

The sands and gravels of the Calivil Formation infilled the former valleys of the Avoca, Loddon, Campaspe and Goulburn drainage systems that were incised into the Renmark Group. These sediments mark the downstream extension of the 'deep leads' that emanated in the highlands (Macumber, 1984). The aquifer is well developed close to the highlands where coarser grained sediments were deposited. Basinwards, towards the Murray River, the formation is represented by more poorly sorted sands which persist as sheet deposits beyond the former valleys. The aquifer is semi-unconfined to semi-confined in the southern part of the Riverine Plain but becomes increasingly more confined to the north; the degree of confinement depends mainly on local lithologic variations in the overlying Shepparton Formation (Macumber, 1983). Bore yields as high as 125 L/sec have been obtained (Lawrence, 1976, 1982). The salinity of the groundwater close to the highland front is usually less than 500 mg/L TDS but it increases to the north along flow paths to be highly saline (up to 40 000 mg/L TDS) beneath much of the Riverine Plain. Groundwater from the Calivil Formation is exploited locally around the basin margins for irrigation and stock water but it is too saline for irrigation about 80 km from the highland front.

The Shepparton Formation contains a system of thin, irregular and discontinuous sand and gravel beds which are locally important aquifers, however, because of their mode of occurrence and lithologic variations, their potential as aquifers varies considerably with location. The aquifer sediments were deposited along the channels of ancestral (prior) streams and are interspersed in a matrix consisting principally of clay and silt overbank and lacustrine sediments. The aquifers have forms ranging from isolated ribbon-like bodies to semi-continuous sheets and are mostly less than 5 m thick; because of their often considerable length, yet limited width and thickness they are referred to as 'shoe-string sands'. They are well developed in the Murray, Ovens, Goulburn and Campaspe Valleys and in the southern portion of the Loddon Valley but are only poorly developed in the Avoca Valley (ACIL, 1983). The shallower aquifers in the Shepparton Formation are essentially unconfined whilst the majority are semi-confined by overlying silty clays (Tickell and Humphrys, 1987). Bore yields are generally less than 5 L/sec. The groundwater shows a wide variation in salinity even on a local scale, however, salinities generally increase towards the north west and also downstream within each of the main river valleys. Groundwater is pumped from aquifers shallower than 25 m, not only for irrigation and stock and domestic purposes but also for water table control to assist in mitigating salinity problems. The deeper aquifers are mainly only exploited in the Murray and Ovens Valleys because salinities are generally too high elsewhere.

The Wunghnu Group Aquifer System is recharge primarily in the alluviated valleys in the highlands and around the basin margins. Groundwater flow is in a general northerly direction towards the Murray River. Discharge to the surface occurs to the north of an approximate east-west 'hinge-line' through Calivil into salt lakes and streams such as Barr Creek and Bears Lagoon. Regional discharge also occurs into the Murray River. A component of throughflow in the southern Loddon Valley, recharges the hydraulically connect Parilla Sand aquifer.

The marine sands and silts of the Parilla Sand are the down-basin continuation of the fluviatile Calivil Formation (Lawrence, 1966). It forms an extensive sheet-like aquifer in the Mallee Region of the western Murray Basin. It is essentially unconfined, becoming semi-confined only where it is overlain by thick development of lacustrine Blanchetown Clay which infilled the inter-ridge corridors (Macumber, 1983). The aquifer is recharged by direct infiltration of rainfall as well as by lateral throughflow from up-basin areas beyond the Mallee and by upward leakage from deeper aquifers. Groundwater discharge occurs in the northern Mallee and produces complex patterns of salines, salt lakes, gypsum flats and seepage salting termed 'boinkas' by Macumber (1980). However, the bulk of the regional groundwater discharge is into the Murray River. The salinity of the groundwater varies widely but is generally within the range of 5 000 to 40 000 mg/L, TDS. The groundwater is not greatly exploited because of its poor quality.

Quaternary aeolian and fluviatile sediments re scattered throughout the Murray Basin. In a few places the coarser grained sediments in the basal section of the Coonambidgal Formation overlying the Shepparton Formation, can provide useful quantities of good quality water (ACIL, 1983).

WESTERN PORT BASIN

The Western Port Basin is a small (900 km^2), relatively shallow basin which has been infilled by Cainozoic sedimentary and volcanic rocks. The thickness of this sequence ranges from less than 50 m to over 300 m in the southeastern part of the basin.

The groundwater resources in this basin have been extensively investigated (Threader; 1952; Jenkin 1961, 1962a; Carillo-Rivera, 1974; Thompson, 1974). A detailed hydrogeological map of the Western Port Basin (Lakey and Tickell, 1980) and explanatory notes (Lakey and Tickell, 1981) have been published. (The description of the resource given here is taken largely from this latter reference). The natural recharge characteristics of the Western Port Groundwater Basin and the potential sea water intrusion problem were described by Lakey (1981, 1983).

The Western Port Groundwater Basin has a limited annual recharge component that is controlled by direct infiltration into the small area of outcropping Tertiary aquifer along the eastern and western basin boundaries, and infiltration via Quaternary sediments in the northeast along the Bunyip and Tarago Rivers. Before the groundwater resources in this basin were tapped, groundwater flow was radially towards Western Port Bay from these recharge areas. Discharge was offshore and also onshore into the extensive low lying swamps.

Since the late 1960's the groundwater resources have been extensively exploited principally for irrigation of stock and domestic uses. The resource is also used for industry, dairy washing, in piggeries and poultry farms and also as a water supply for the township of Lang Lang. Withdrawals from these bores had depleted the groundwater store, creating a risk of intrusion of sea water into the aquifer system. In 1971, this basin was declared a Groundwater Conservation Area to enable resource development to be controlled to the benefit of all users (Baker et. al., 1986).

The combined units of the Cainozoic sequence in the Western Port Groundwater Basin behave as a leaky confined, horizontally stratified aquifer system, all members of which are capable of yielding supplies of groundwater. Apart from the Childers Formation which is of limited extent and consequently of limited groundwater potential, the main aquifers are the Older Volcanics and the overlying Western Port Group. Over much of the area the Childers Formation, Older Volcanics and the Western Port Group are in hydraulic continuity. It is only in those areas where a weathered volcanic clay persists between the fresh basalt of the Older Volcanics and the Western Port Group that the aquifers demonstrate a degree of hydraulic independence.

The Quaternary alluvial deposits (shoe-string sands) form a complex network, extending from Langwarry, where they are best developed, to Dalmore. These prior stream deposits provide shallow stock and domestic supplies but yields are inadequate for irrigation. Dune deposits occur in the Cranbourne and Lang Lang areas and have an important role as intake beds for the underlying formations, but do not provide a direct source of groundwater for extraction.

The Western Port Group includes the Baxter, Sherwood and Yallock Formations. These sediments provide more than 80% of the total extraction from the basin.

The Baxter Formation has been extensively utilized and is particularly important throughout the major irrigation areas in the Dalmore-Cora Lynn area. Clay lenses interdigitate with coarse sand and gravel and yields in excess of 25 L/sec have been obtained.

The coarse sand and gravel of the Yallock Formation are highly developed in the Cora Lynn area and form the major sand aquifer throughout the western part of the sedimentary basi. Over much of this area the aquifer is covered by up to 75 m of Quaternary clay and consequently is relatively unexploited. Yields in excess of 40 L/sec have been obtained from well designed bores situated in the coarse sand and gravel in the Lang Lang area.

The Sherwood Formation is of considerable importance in the area to the east of Koo-wee-rup. Much of the formation consists of fine calcareous sand, but irrigation supplies of 10 to 15 L/sec are obtained from coarse shelly horizons and occasional lenses of fractured limestone which act as drains for the bulk of the formation.

The Older Volcanics are developed in the Nar-nar-goon and Clyde-Devon Meadows areas where the Western Port Group is either absent or consists mostly of clay that fail to produce satisfactory yields. In Nar-nar-goon, Pakenham and Cranbourne areas, the basalt aquifer comprises a series of narrow valley flows separated by ridges of Silurian basement and overlain by a thin veneer of Tertiary sand and clay. Pumping tests indicate multiple complex boundary conditions, and yields depend upon local recharge conditions (ie the infiltration and drainage characteristics of adjacent sediments). The basalt flows in the Nar-nar-goon area and the northeastern part of the basin are relatively dense, have not developed high secondary porosity and generally possess poor yield characteristics. In the central and eastern basin the basalt aquifer is relatively thick (up to 100 m) and several test bores have produced relatively high yields of 25 L/sec and more for small drawdowns of the order of 2 m. However, because of the depth of occurrence (150 to 200 m) no private bores have been sunk into the basalt aquifer in this area.

PORT PHILLIP BASIN

The Port Phillip Basin, including the Ballan Graben, has been infilled by Cainozoic sediments and volcanics which attain a maximum thickness in excess of 1 000 m beneath the Nepean Peninsula but for the most its onshore thickness is less than 250 m. The Cainozoic sequence contains a number of aquifers, the most important of which occur in the sand, gravel and limestone of the Werribee, Fyansford and Bridgewater Formations and the Brighton Group, basalts of both the Older Volcanics and Newer Volcanics and the superficial dune and deltaic deposits. Many of these aquifers are hydraulically interconnected. The hydrogeological characteristics of the geological units in the Port Phillip Basin are discussed in more detail in Leonard (1979, 1988) and the reference therein.

Recharge of the aquifers in the Port Phillip Basin is mainly by direct infiltration of rainfall into the unconfined aquifers or into the outcrops of the confined aquifers. The latter aquifers are also recharged via vertical leakage and lateral inflow from adjacent strata. Onshore discharge occurs into the streams draining the basin or into low lying swamps and coastal wetlands where it is removed by evapotranspiration. Some dischage also occurs offshore in Port

Phillip Bay and Bass Strait.

The Werribee Formation has mainly only subsurface occurrence. It is laterally continuous from its outcrop area in the Ballan Graben and the Bacchus Marsh area towards the Bay, extending at depth under the Nepean Peninsula. Its onshore occurrence to the southeast of Melbourne is restricted to a small area south of the Beaumaris monocline between Mentone and Frankston. Bore yields vary widely generally being in excess of 10 L/sec. Groundwater salinities are also highly variable but are typically greater than 2 500 mg/L TDS. This aquifer is largely unexploited except for some irrigation bores in the Bacchus Marsh area where the formation subcrops, and watering of golf course in the southeastern suburbs of Melbourne.

Basalts of the Older Volcanics occur mainly subsurface on the Mornington Peninsula in the Cranbourne-Mordialloc-Mentone and the Mount Eliza areas, and in the Melbourne area, and outcrop in the Ballan Graben. Bore yields up to 12.5 L/sec have been obtained in the Carrum area (Lakey, 1978) but they are generally less than 2.0 L/sec. Water salinity is extremely variable ranging from 300 to 8 000 mg/L TDS with an average value of around 2 000 mg/L TDS. The groundwater is used for irrigation and stock and domestic usage mainly towards Cranbourne where the basalts outcrop.

The Fyansford Formation is of variable lithologic character; to the west of Melbourne it is dominantly clay, silt and marl and is only a minor aquifer which yields small supplies of poor quality groundwater. Southeast of Melbourne the sand, sandy limestone and gravel horizons in this formation are very important semi-confined aquifers (Shugg, 1976) which have been harveted for a variety of uses including watering of golf clubs, irrigation, industrial and commercial applications. Bore yields are generally less than 2.6 L/sec although higher yields up to 18 L/sec have been obtained. Groundwater salinities are in the range 800 to 2 000 mg/L TDS.

The clay, silt and fine sand of the Brighton Group are generally poor aquifers, however, coarser sand and gravel horizons that occur particularly towards the base of the upper terrestrial unit are better aquifers. Bore yields are mostly less than 1.6 L/sec. The groundwater in the occurrence of the Brighton Group to the west of Melbourne is of poor quality (greater than 3 000 mg/L TDS) and is suitable mainly only for stock watering. However, the groundwater in this unit underlying the Oakleigh-Dingley-Black Rock and Seaford to Frankston areas has a salinity of generally less than 1 000 mg/L TDS. The poorer quality groundwater (up to 6 800 mg/L TDS) underlying coastal wetlands such as the Carrum Swamp reflects the local discharge of groundwater with the higher salinities at least in part due to the concentrating effects of evapotranspiration. Groundwater in the vicinity of waste disposal sites in disused sand pits in the southeastern suburbs of Melbourne is locally contaminated (Harris, 1972; Shugg 1976; Craigie, 1977; Leonard, 1979, 1980, 1983). The better quality groundwater is extensively utilized for garden watering, particularly during droughts.

The Newer Volcanics consist of a number of superposed basalt flows that cover much of the Port Phillip Basin forming a virtually continuous sheet around the Bay from Melbourne to Geelong and inland to the Central Uplands. The thickness of the basalts varies in sympathy with the buried topography and is greatest (up to 150 m) along pre-basaltic drainage lines. The basalt thins towards the Bay.

Aquifers occur where the basalts are highly vesicular and strongly jointed. Bore yields range from 0.4 to 40.0 L/sec but are generally less than 1.2 L/sec (Leonard 1979). Salinities are in the range 100 to over 6 000 mg/L TDS; the variation in quality reflects the recharge/discharge regime with the better quality water occurring in close proximity to the intake areas. The quality of the groundwater in the Newer Volcanics underlying the western suburbs of Melbourne is seriously impaired by pollution (Riha, 1969; Riha and Kenley, 1978; Leonard, 1979, 1980; Shugg, 1981). Groundwater from this aquifer system is extensively utilized for stock watering, but it is also used for irrigation of more salt tolerant crops and by a number of industries which do not require good quality water.

The calcareous and quartzose sand of the Bridgewater Formation on the Nepean Peninsula is a very important aquifer. Yields from individual bores up to 25 L/sec have been recorded but the average recorded yield is 1.2 L/sec. The quality of the groundwater is mostly very good (less than 300 mg/L TDS), however, it does deteriorate in the swampy discharge zones and in the salt-wedge along the coast. The local groundwater resource is intensively utilized for irrigation, watering of recreation reserves and importantly for domestic supply. Increased concentrations of nitrate is a serious problem locally. Shugg (1985) noted that the higher concentration of nitrate exhibits a positive correlation with unsewered urban development which indicates that septic tanks are major sources of nitrate in the groundwater.

Deltaic sediments

Small deltas have developed near the mouth of the Yarra and Werribee Rivers. The main aquifers in the Werribee Delta are in the sand and gravel of the elongated former river channels (shoe-string sands) with the surrounding clay and silt behaving as aquitards. Bore yields are in the range 5 to 15 L/sec and salinities range from about 500 to 6 000 mg/L TDS (Leonard, 1979). The higher yields and lower salinity groundwater is extracted from the coarse aquifer horizons. The groundwater is used extensively for irrigation and washing dairies as well as for stock watering and general domestic purposes. Groundwater in the Yarra Delta is of poor quality and is not utilizes.

Dune deposits

The most significant occurrences of dune deposits are in the southeastern suburbs of Melbourne between Mordialloc and Frankston where they border the coastal wetlands, and the remnant strand-line dunes that trend parallel and close to the present coastline mainly to the north of the Beaumaris Monocline. The dunes are generally less than 15 m thick and are elevated from 4 to 6 m above the surrounding land surface. These deposits generally contain good quality groundwater. Bore yields are small around 0.2 L/sec. Numerous shallow bores extract water from these dunes for watering household gardens particularly during drought periods.

VICTORIAN UPLANDS

The Uplands are relatively elevated areas of outcropping "basement" rocks that separate the major sedimentary basins. The Upland includes the Dundas Tableland and Crampian Ranges in the west, the central and eastern Victorian Highlands, and the Otway and Strzelecki

Ranges of southern Victoria. The present terrain of the Uplands is the result of fault movement and differential erosion.

The Uplands of west, central and eastern Victoria consist of a spine of Palaeozoic sedimentary rocks intruded in places by granitic and acid volcanic rocks which have locally metamorphosed the adjacent rocks. The South Victoria Uplands are composed of younger, Lower Cretaceous aged sedimentary rocks. Igneous extrusive rocks (Older and Newer Volcanics) cap the basement sediments at a number of locations throughout the Uplands. Many of the streams have significant alluvial deposits along their valley tracts.

Recharge is achieved by direct infiltration of precipitation. Much of the discharge occurs locally into surface streams providing the base flow component which, for many upland streams persists throughout summer. Some discharge also occurs at lower elevations into aquifers in the adjoining younger sedimentary basins.

The yields obtained from bores developing outcropping basement aquifers in the Uplands are generally less than 3 L/sec but can vary considerably often over short distances. Yields are dependent on the number, "openess" and degree of interconnection of the secondary joints and fractures intersected by the bores. The extent of weathering can also affect bore yields by changing the local hydrologic properties of these rocks. For example, sandstone weathers to sand which can result in increased storage and transmitting capacity whereas mudstone and shale weathers to clays which have lower hydraulic properties than their parent rocks.

Groundwater salinities reflect the recharge/discharge regime; in the Uplands, salinities are dominated by the effects of local rainfall. Where the rainfall exceeds 1 000 mm/yr such as occurs over much the central and eastern Uplands and the Grampians and Otway Ranges, the groundwater in the basement rocks generally has a salinity of less than 1 000 mg/L TDS. In this respect, the Strzelecki Ranges are an exception as the rainfall is mostly greater than 1 000 mm/yr but the groundwater salinities are generally in the range 1 500 to 3 000 mg/L TDS.

In the lower rainfall areas of the central Uplands the groundwater quality is usually greater than 3 000 mg/L TDS. In the Dundas Tableland where the rainfall is less than 700 mm/yr, the topographic relief is low and remnants of lateritic weathering are preserved, the salinity is often greater than 7 000 mg/L TDS.

Groundwater from the outcropping basement rocks is mainly used for stock and domestic purposes. Exceptions occur such as in the Kinglake and Monbulk areas, where basement aquifers are heavily utilized for irrigation. The highly mineralized groundwater emanating from the Palaeozoic sediments in the Daylesford-Hepburn district of central Victoria (Lawrence, 1969; Laing, 1977, 1981; Schaefer and Kecskemeti, 1981) is used locally for drinking and bathing. The water from several mineral springs is also bottled commercially for an expanding market.

Yields from Acid Volcanic rocks and associated metamorphic (hornfel) aureoles are usually less than 0.5 L/sec. Groundwater salinity, although variable, is normally lower than that in the surrounding sedimentary rocks.

The Older Volcanics and sub-basaltic sands that cap the basement rocks notably in the Silvan-Wandin-Monbulk and Drouin-Warragul-Thorpdale areas are locally very important aquifer systems that are utilized intensively, mainly for irrigation. The groundwater quality from these aquifers is very good, mostly less than 500 mg/L TDS. Bore yields are typically around 5.2 L/sec.

The sand and gravel alluvial deposits of the Uplands are important aquifers not only because of their high groundwater development potential but also because they are intake beds for aquifer in the adjoining sedimentary basins. In places, particularly in the Central Highlands, the alluvium is covered by Newer Volcanic basalts. Alluvial aquifers are more extensive in the valleys of the Murray, Mitta Mitta, Kiewa, Ovens, Goulburn and Loddon Rivers (Lawrence, 1976). Bore yields as high as 125 L/sec have been recorded. The salinity of the groundwater is mostly between 100 and 1 000 mg/L TDS with the higher salinities in the more westerly valleys. Groundwater from these aquifers is used mainly for irrigation and stock watering, with the most significant development in the Ovens River valley.

Aquifers also occur in the Newer Volcanic basalts that cover much of the basement rocks in the Central Highlands. Bore yields up to 15 L/sec of groundwater with salinity of less than 1 000 mg/L TDS are obtained in the high rainfall areas around Ballarat. The groundwater in this area is intensively utilized for irrigation. It is also used as a source of water for the townships of Learmonth, Gordon and Mount Egerton. Elsewhere, the generally higher salinities, (greater than 3 000 mg/L TDS) and smaller bore yields (around 1 to 2 L/sec) limits the use mainly to stock watering.

SALINITY

The term 'salinity' is used to describe the accumulation of dissolved salts in groundwater in the soil zone (soil/land salinization) and in the surface drainage system (stream salinity). Salinity problems have emerged as major problems of environmental management which necessitate continuing programs of investigation. These investigations are studying the interaction between saline groundwaters and the surface drainage system. The effects on the waters of the Murray River which supplies Adelaide in addition to many towns in the Murray Basin are being investigated as well as its effects on agricultural activities.

A number of researchers notably Macumber (1968, 1978b, 1983), Lawrence (1975), Jenkin (1980), Tickell and Humphrys (1987), Dyson and Jenkin (1981), Jenkin and Dyson (1983) and Ife (1983) have recognized that salinity problems are to groundwater behaviour particularly the recharge/discharge regime which is strongly affected by man's activities. A series of reports examining the causes, extent and effects of salinity and salinity control measures have been prepared for the Salinity Committee of the Victorian Parliament. These include ACIL (1983), Gutteridge, Haskin and Davey (1983) and Dwyer Leslie (1984). The physical controls options and Victoria's strategy for managing the salinity of land and water resources have also been discussed by the Salinity Committee (1984), Salt Action (1987) and, Macumber and Fitzpatrick (1987).

The natural equilibrium between groundwaters and surface waters is such that a small increase in recharge or reduction in discharge can result in significant rises in groundwater pressures and in the level of the water table. Increased groundwater recharge can result not only from climatic changes but also from changes in land use that facilitate recharge and/or decrease discharge: Large scale irrigation developments and land clearing result in excess water infiltrating to the saturated zone causing the water table to slowly rise. Land clearing, in removing trees and other vegetation that would otherwise remove subsurface water by evapotranspiration results in decreased discharge.

As the water levels rise, the groundwater dissolves naturally occurring salts in soil and rocks and bring them towards the surface, where the salt is concentrated by evaporation. The increase in salt and water levels near the surface causes land salinization and water-logging that can damage vegetation and soils, resulting in decreased agricultural productivity. High salt levels also increase erosion, damage water-using appliance, and lead to loss of wildlife habitat and recreational areas. Discharge of saline groundwater also result in deterioration of stream water quality.

Salt affected areas (Fig. 1) occur throughout Victoria; in the Riverine Plain and the Mallee in northern Victoria; in the Highlands extending from the Strathbogies in the east to the Crampians in the west; the Dundas Tablelands and the basaltic plains of western Victoria; and in parts of Gippsland, notably in the vicinity of Lake Wellington. Groundwater discharge is responsible for the high salinity of streams throughout southwestern Victoria and in the tributary system that feed the major rivers of northern Victoria.

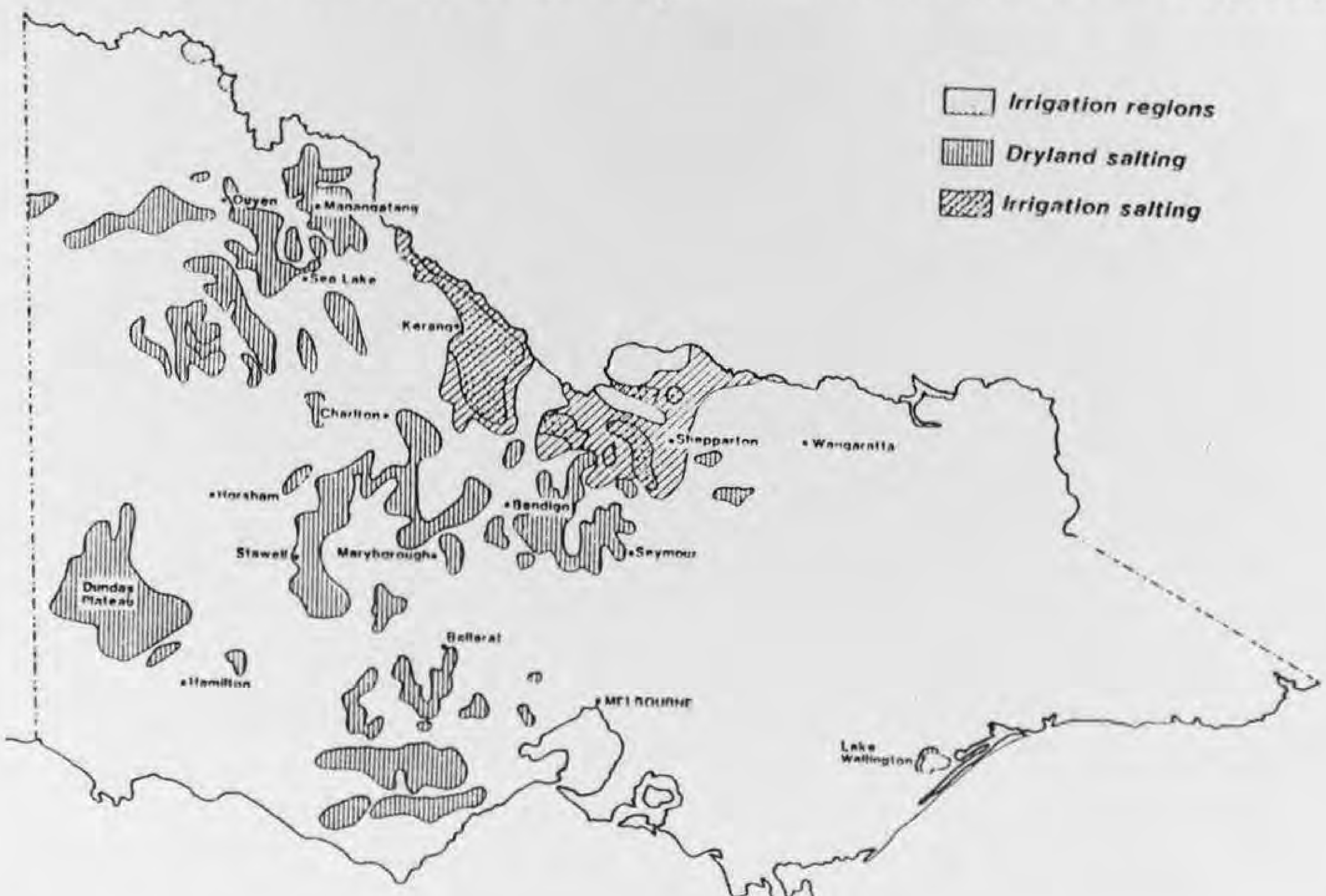

FIGURE 1 Areas prone to salinity (After Salt Action, 1987)

Shallow watertables threaten about 385 000 hectares of Australia's largest irrigation area, the Goulburn-Murray Irrigation District. This salt prone area includes 72% of the Kerang Region and 22% of the

Shepparton Region. Already about 140 000 hectares of land in these regions is damaged by salt.

Areas of dryland (non-irrigation) are scattered throughout the State. A total of 45 000 hectares of dryland farming land is affected and an equivalent area is in the early stages of salinization (Salt Action, 1987).

The research, particularly in the more susceptible areas in the north of the State, into the dynamics of salinity has found that salts are so abundant in the landscape that they will not be flushed out in the foreseeable future, and that control measures are needed in both recharge and discharge areas (Rowan, 1982). A number of technical options exist for the control of land and stream salinity, the applicability of which depends on local hydrogeological, and geomorphological characteristic and on land use practices.

Fifteen salinity provinces have been identified in Victoria on the basis of the characteristics of the groundwater system (Salt Action, 1987). Each province has its own range of technically feasible control options which can be incorporated into salinity control strategies. The salinity control options fall into three broad categories namely:

- i measures designed to reduce accessions to the water table;
- ii measures controlling water tables such as subsurface drainage and pumping from bores; and
- iii measures designed to optimize farm productivity under saline conditions - the 'saline agriculture' option.

In some cases, none of the control options may work; in these situations it may be necessary to have sacrificial areas which become further salinized.

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