Water Authority
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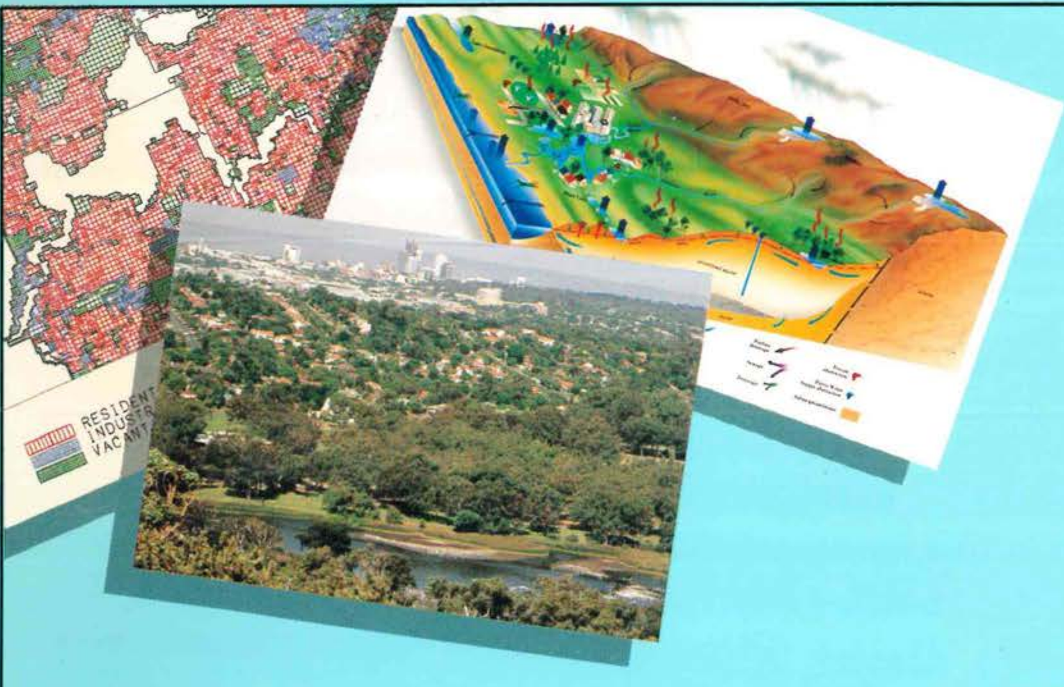

PERTH URBAN WATER BALANCE STUDY

Volume 1 - Findings

May 1987

CENTRE FOR WATER RESEARCH
UNIVERSITY OF WESTERN AUSTRALIA

GEOLOGICAL SURVEY
OF WESTERN AUSTRALIA

DEPARTMENT OF CONSERVATION
AND ENVIRONMENT

Water Authority of Western Australia

in conjunction with

Centre for Water Research
University of Western Australia

Geological Survey of
Western Australia

Department of Conservation
and Environment

PERTH URBAN WATER BALANCE STUDY

VOLUME 1
FINDINGS

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CONTRIBUTING ORGANISATIONS

The Perth Urban Water Balance Study was coordinated and funded by the Water Authority of Western Australia and was undertaken in collaboration with the Centre for Water Research at the University of Western Australia, the Geological Survey of Western Australia and the Department of Conservation and Environment.

The Steering Committee consisted of senior people from each of the participating organisations, each with particular experience relevant to the Study objectives. The Committee's role was to provide direction and to ensure the technical veracity of the Study.

Members of the Project Team were drawn from the participating organisations to work full-time on the Study.

The Water Authority provided funding, accommodation, computing facilities and administrative services. Centre for Water Research and Water Authority personnel provided technical and scientific expertise in modelling and reporting, Geological Survey personnel provided hydrogeological expertise and Department of Conservation and Environment personnel reviewed the role of wetlands in the urban environment of Perth.

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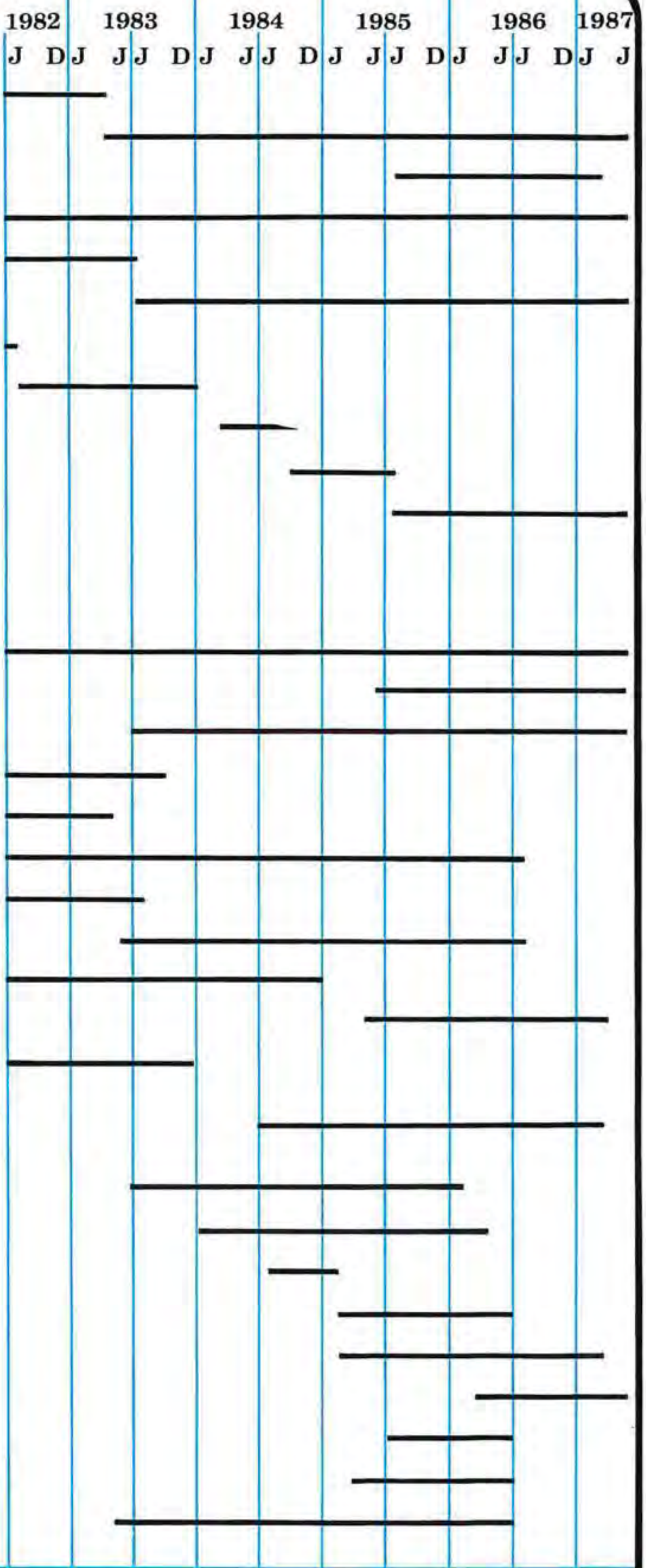

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The role of the many other people who provided assistance and advice is also gratefully acknowledged.

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GLOSSARY

abstraction	pumping from an aquifer
anion	an ion with a negative charge, e.g. Cl^-, SO_4^{2-}
anisotropy	the degree of variation of hydraulic conductivity between the vertical and horizontal directions at a point in an aquifer
aquifer	a geological formation or group of formations able to receive, store and transmit significant quantities of water
• confined aquifer	an aquifer, confined between an upper and lower layer of relatively impermeable material
• unconfined aquifer	an aquifer which has its upper boundary at the earth's surface (the upper surface of the groundwater within the aquifer is called the water table)
• artesian aquifer	a confined aquifer under sufficient pressure that water would rise in a bore above the ground surface
aquitard	a geological formation with low permeability forming a boundary between two aquifers
boundary condition	a condition which defines the behaviour of a system at its boundaries and must be specified for all boundaries of a model of that system
cation	an ion with a positive charge, e.g. Na^+, Fe^{2+}
class A pan evaporation	a measure of evaporation from a free water surface using a standard instrument called a class A pan evaporimeter
deep drainage	the vertical percolation of water through the unsaturated soil zone into the saturated zone below
Eh	a measure of the potential for chemical oxidation or reduction reactions
electrical conductivity	the rate of transfer of electric charge through a body (in water, electrical conductivity, E.C., increases with increasing concentration of dissolved salts and provides a measure of salinity)
eutrophication	the process by which water bodies become enriched with nutrients, leading to excessive plant growth
evapotranspiration	a collective term for evaporation and transpiration
finite element method	a method of solving spatial equations by dividing a region into finite increments of area
hectare (ha)	unit of land area equal to 10 000 m^2 or approximately 2.47 acres
heterogeneity	the degree of variation of hydraulic characteristics between different locations within an aquifer
horticulture	the growing and cultivation of gardens, including domestic and commercial
hydraulic conductivity	a constant of proportionality, K, such that the flow through a section of an aquifer is equal to the product of K, the cross-sectional area and the slope of the water table, i.e. it is the flow through a unit cross-sectional area of aquifer under a unit hydraulic gradient
impermeable	having zero or extremely low hydraulic conductivity
isohyet	a line on a map joining locations with equal rainfall
mAHD	metres above Australian Height Datum, which is approximately Mean Sea Level
macroinvertebrate	an invertebrate (animal without a backbone) of a size not able to pass through a 250 micron mesh net, excluding zooplankton

net vertical flux	the net vertical flow into the unconfined aquifer, incorporating the combined effect of recharge, direct evaporation from the water table, transpiration by phreatophytes, groundwater abstraction and leakage to or from the underlying confined aquifer
oligotrophic	containing few nutrients
permeability	see hydraulic conductivity
permeable	having a sufficiently large hydraulic conductivity to permit water to move perceptibly under head differences ordinarily found in groundwater
pH	a measure of acidity or alkalinity on a scale of 0 to 14 where 7 is neutral, less than 7 is acidic and greater than 7 is alkaline
phreatophytes	plants that can tolerate having their roots flooded by groundwater and can therefore gain their supply of water from below the water table
porosity	the ratio of volume of voids to total volume in a sample of aquifer material
recharge	the downwards flow of water through the water table, incorporating the combined effect of rainfall, canopy interception, evapotranspiration from the unsaturated zone, garden irrigation and septic tank effluent
runoff	that part of rainfall which flows off the land surface towards drainage lines
salinity	a measure of the concentration of total dissolved solids (T.D.S.) in water
saltwater intrusion	the inland intrusion of a layer of salt water into a fresh water aquifer
• saltwater interface	the interface between the layer of fresh groundwater and the underlying salt water
• saltwater wedge	a wedge-shaped layer of salt water which intrudes into a fresh water aquifer
sewage	the mixture of waste fluids and solids flowing in sewers from houses, factories, etc.
sewage effluent	the fluid discharged from a sewage treatment plant after purification and removal of solids
silviculture	the growing and tending of trees as a branch of forestry
storage coefficient	the ratio of the volume of water which will drain under gravity to the total volume of a sample of material near the water table in an unconfined aquifer
superficial formations	a collective term for surface geological formations which, beneath the Swan Coastal Plain, form a thin layer of late Tertiary and Quaternary age formations overlying older formations
transmissivity	the product of hydraulic conductivity and aquifer thickness, i.e. it is the flow through a unit width of aquifer under a unit hydraulic gradient
transpiration	the process where plants take water from the soil and pass it through their stems and leaves to the atmosphere while, at the same time, removing nutrients and trace elements
unconformity	a surface between two geological formations where the underlying formation was partially eroded before deposition of the overlying formation
water table	the level to which water rises in a bore tapping an unconfined aquifer

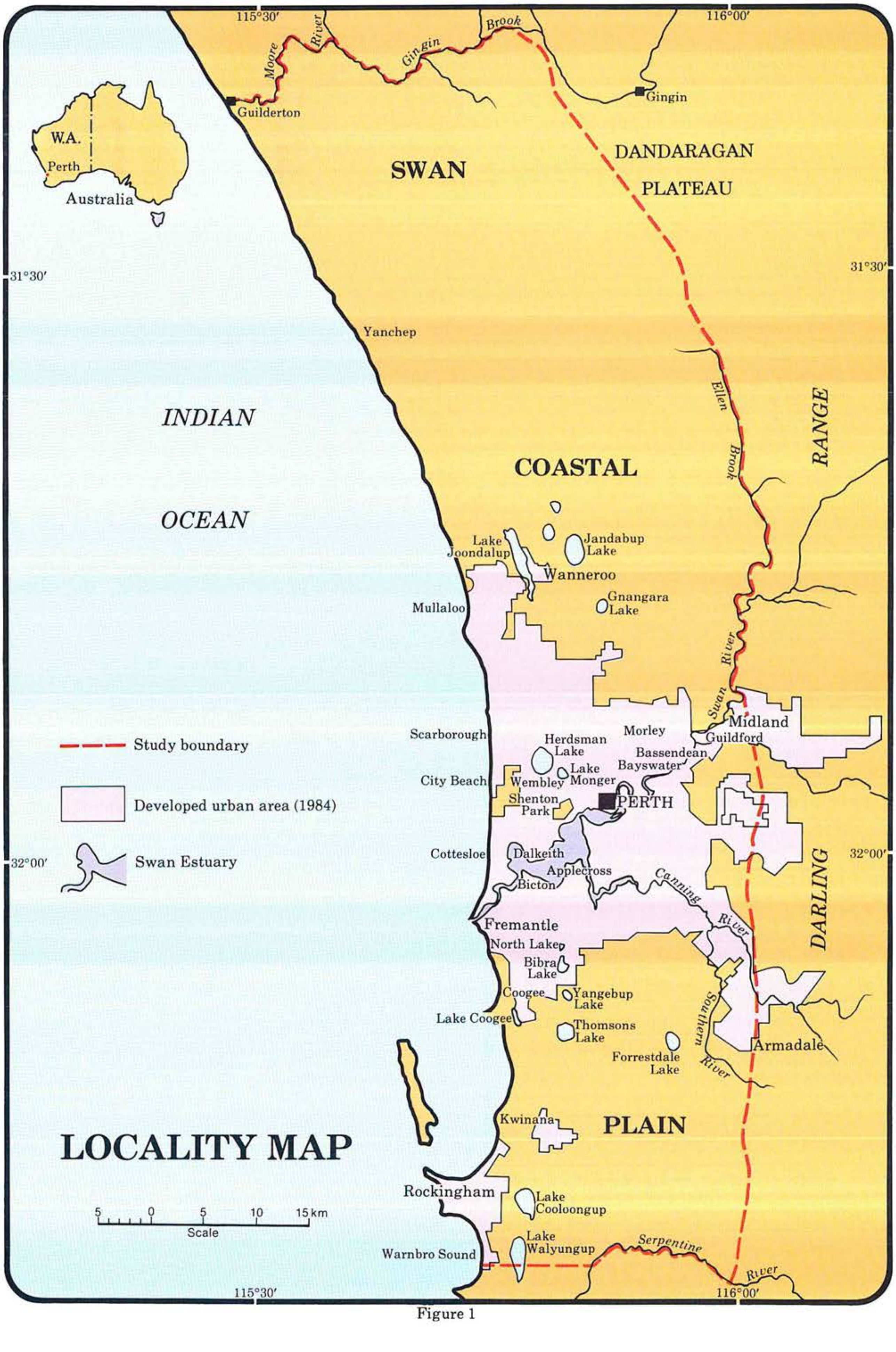

LOCALITY MAP
INDIAN
OCEAN
SWAN
COASTAL
PLAIN
DANDARAGAN
PLATEAU
DARLING
RANGE
Study boundary
Developed urban area (1984)
Swan Estuary
W.A.
Perth
Australia
115°30′
116°00′
31°30′
32°00′
Guilderton
Gingin
Moore River
Gingin Brook
Yanchep
Ellen Brook
Lake Joondalup
Jandabup Lake
Wanneroo
Gnangara Lake
Mullaloo
Swan River
Midland
Guildford
Morley
Scarborough
Herdsman Lake
Bassendean
Bayswater
Lake Monger
Wembley
City Beach
Shenton Park
PERTH
Cottesloe
Dalkeith
Applecross
Bicton
Canning River
Fremantle
North Lake
Bibra Lake
Coogee
Yangebup Lake
Lake Coogee
Thomsons Lake
Southern River
Forrestdale Lake
Armadale
Kwinana
Rockingham
Lake Cooloongup
Lake Walyungup
Warnbro Sound
Serpentine River
5 0 5 10 15 km
Scale

Figure 1

Chapter 1

INTRODUCTION

1.1 BACKGROUND

Perth is situated along the lower reaches of the Swan and Canning Rivers on the Swan Coastal Plain, which lies between the Darling Range and the Indian Ocean (Figure 1). The population of the metropolitan area is now about 1 million people and is expected to increase to about 1.4 million by the year 2010.

Perth's water supply is derived from two distinct sources: surface water collected in reservoirs in the Darling Range to the east and south-east of Perth (locally known as "hills water") and groundwater stored in the sediments of the Perth Basin beneath the Swan Coastal Plain.

The primary source of groundwater is a shallow unconfined aquifer which is a layer of permeable sediments containing the water table. Deeper permeable layers form confined aquifers separated by less permeable layers.

Groundwater from the unconfined aquifer satisfies a variety of community needs including domestic, irrigation and industrial water supplies. It is also an integral part of the natural coastal plain environment, supporting vegetation where the water table is shallow and flora and fauna at the many wetlands where the water table intersects, or is just below, the ground surface.

Groundwater has been an important consideration in the development of Perth since the Swan River Colony was founded in 1829, when water supplies were drawn from wells and springs. Towards the end of the 19th century, however, the use of shallow groundwater for public supplies ceased in favour of hills water and artesian groundwater. This situation continued until the mid-1960s when, with the rapid expansion of Perth and the increasing cost of developing the surface water resources, attention was again focused on shallow groundwater.

Reduced storage in surface reservoirs during the low rainfall years of the late 1970s led to an intensive public education program being implemented in 1976-77 and to restrictions being imposed on the use of reticulated supplies for domestic garden watering between 1977 and 1979. These restrictions reduced the total demand for public water supplies (Figure 2).

During the same period of the late 1970s, the quantity of groundwater being pumped by the Metropolitan Water Supply Sewerage and Drainage Board[1] for public supplies increased markedly. The water supplied from the unconfined aquifer increased from 18×10^6 m^3 (18 million cubic metres) in 1975-76 (9% of total supplies) to 35×10^6 m^3 in 1979-80 (24% of total supplies). Including water pumped from confined aquifers, the total groundwater component of public water supplies was 52×10^6 m^3 (45% of total supplies) during the first year of restrictions (1977-78).

About 57×10^6m^3 or 35% of the water supplied by the Water Authority to the Perth region in 1985-86 was groundwater, with about 60% of this being drawn from the unconfined aquifer. As Perth grows, it is proposed to further develop these resources to maintain the groundwater component of public water supplies at about 35%.

To protect their investment in landscaping, many householders have installed a privately operated bore or well to abstract water from the unconfined aquifer. Prior to the drought period, there were approximately 24 000 bores on private domestic properties. By 1980, their number had increased to 63 000, and currently there are estimated to be 77 000 private domestic bore users, abstracting about 77×10^6 m^3 of groundwater each year. The reduction in demand for water supplied by the Water Authority was more than offset by this increase in private abstraction, and the total use of water by the community continued to increase through the period of restrictions.

Abstraction by local authorities, institutions and schools for maintaining parks, gardens, golf courses and playing fields was estimated to be 55×10^6 m^3 in 1985 and, in the same year, about 38×10^6 m^3 was abstracted for agriculture. Virtually all irrigated public open space and farmland on the Swan Coastal Plain is irrigated with groundwater from the unconfined aquifer.

The total groundwater abstraction by all users including the Water Authority, local authorities, institutions, market gardeners, industry and private householders in 1985 was about 60% of all water used in Perth (Figure 3).

1. In July 1982, the Metropolitan Water Supply Sewerage and Drainage Board was reconstituted and renamed the Metropolitan Water Authority. In July 1985, this Authority was amalgamated with the Country Water Supply Section of the Public Works Department to form the Water Authority of Western Australia. The appropriate name for the time is used throughout this report.

1.2 MOTIVATION FOR THE PERTH URBAN WATER BALANCE STUDY

In a development study commissioned by the Metropolitan Water Board in 1977, it was recommended that the use of private wells for garden watering be encouraged in an effort to reduce the growth in demand for the Board's reticulated supplies (Binnie International, 1978).

By early 1978, when water restrictions were in force, concern was being expressed by the scientific community and by the public in general that the rapid growth in public and private abstraction of groundwater was having a significant impact upon the groundwater system underlying Perth. The drought had resulted in lowered water table elevations which led to the drying of lakes and wetlands, and there were reports of increased salinity in bores in coastal suburbs such as Applecross, City Beach, Cottesloe and Dalkeith (Figure 1).

Had groundwater levels fallen further, the considerable investment in private bores may have been placed at risk, and any failure in private bore development would have led to a dramatic increase in demand for public supplies, thus requiring the acceleration of the Water Board's source development program.

In response to these conflicts, the Water Board commissioned consultants to investigate whether concern was justified and to examine the feasibility of developing management strategies for the shallow unconfined groundwater resources in the Perth urban area. The consultants concluded that concern was justified and that practical management of the groundwater systems was feasible (Sinclair Knight Pigott and Eastwood, 1981). Consequently, in June 1982, the Metropolitan Water Board commenced the Perth Urban Water Balance Study.

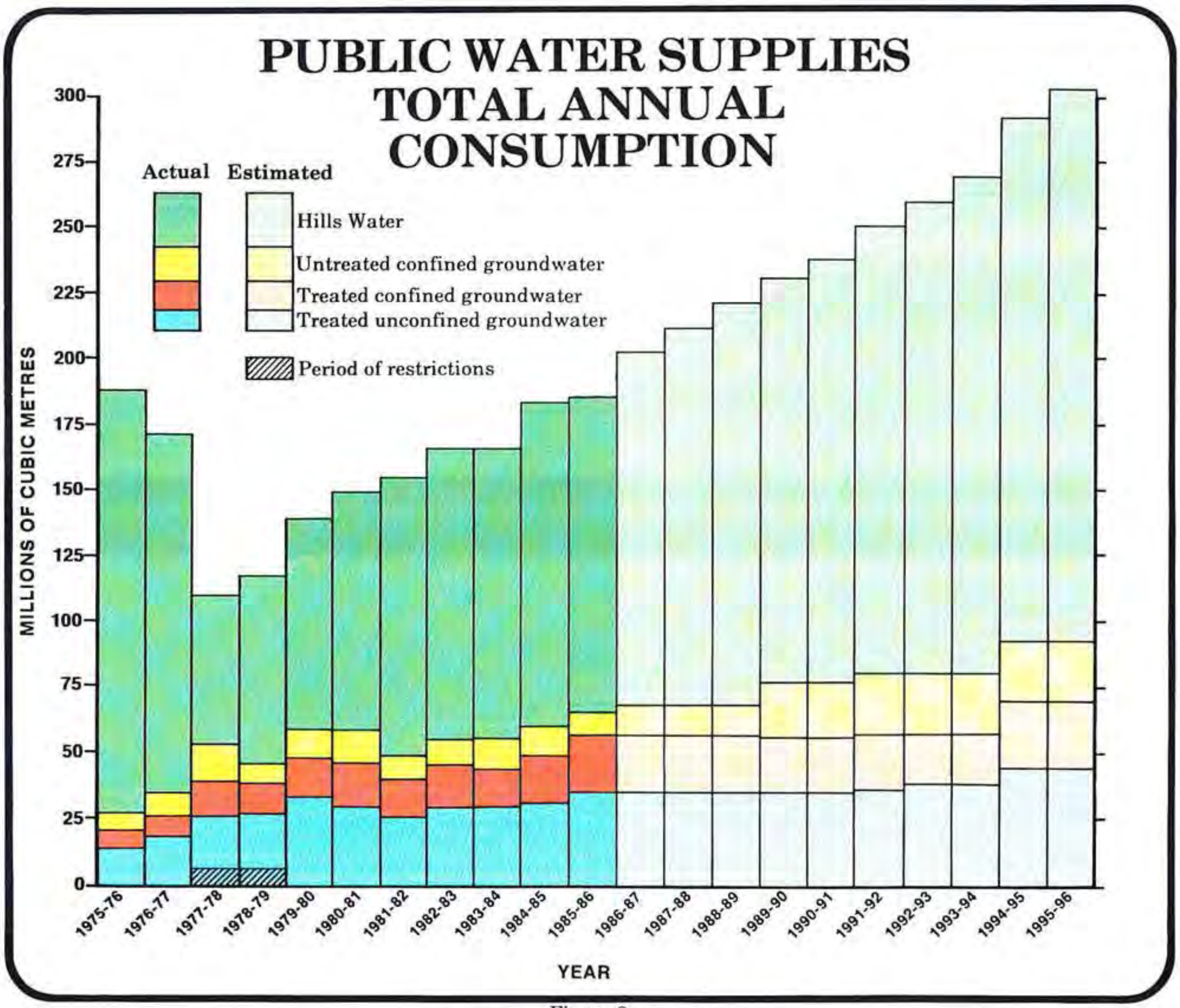


Figure 2

1.3 OBJECTIVES OF THE STUDY

The objectives of the Perth Urban Water Balance Study were:

(i) to identify areas where the groundwater resource may be at risk due to over-utilisation and/or degradation of water quality;
(ii) to investigate the areas at greatest risk; and
(iii) to identify groundwater management options for risk areas.

Risk areas were interpreted as being those areas where lowered water table elevations, drying of wetlands and increased saltwater intrusion had already occurred or could be expected to occur in the future.

To meet the objectives of the Study, it was necessary to develop an understanding of the groundwater system and its response to historical changes; to establish baseline groundwater quality data for future comparison; to develop a predictive computer model to evaluate groundwater movement within the study area; and to assess alternative groundwater management strategies.

The selection of a particular management strategy for implementation will require further evaluation of social, political, environmental and economic factors. In recognition of this need, the Western Australian Water Resources Council has established a Research Group on Groundwater Management to develop strategies for the Jandakot area taking these factors into account (Western Australian Water Resources Council, 1986*a*). It is anticipated that the results of that study will provide a framework for the further development of groundwater management strategies for the whole urban area.

1.4 STRUCTURE OF THE STUDY REPORT

To cater for a broad range of readers, the outcome of the Study is reported in the following forms:

- an executive summary, which contains brief explanations of the findings and recommendations; and
- the full report, which presents, in two volumes, a detailed analysis of the methods, findings and recommendations.

Volume 1 of the full report provides an account of the groundwater systems and their need for management, including the conclusions and recommendations of this Study. Analysis techniques are described briefly, where necessary, so that Volume 1 may be read independently of the rest of the report.

Volume 2 contains a full discussion of the techniques and methods used to derive the findings and recommendations of the Study. Volume 2 also contains, as an appendix, a detailed report of an independent study of groundwater quality transformations in the Perth region.

Figure 4 is a diagrammatic representation of the contents of each volume and shows the relationship between the different parts of the report.

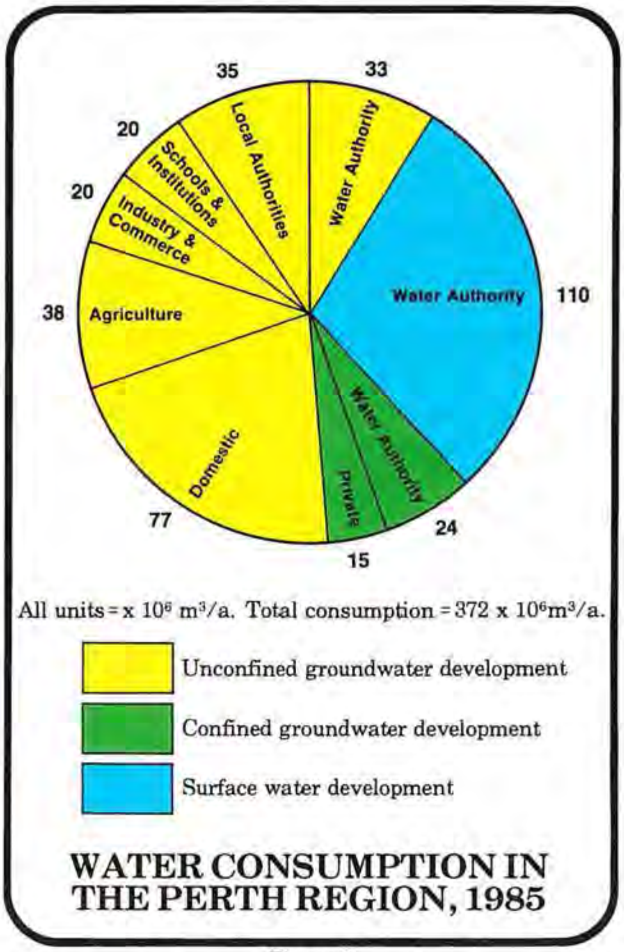
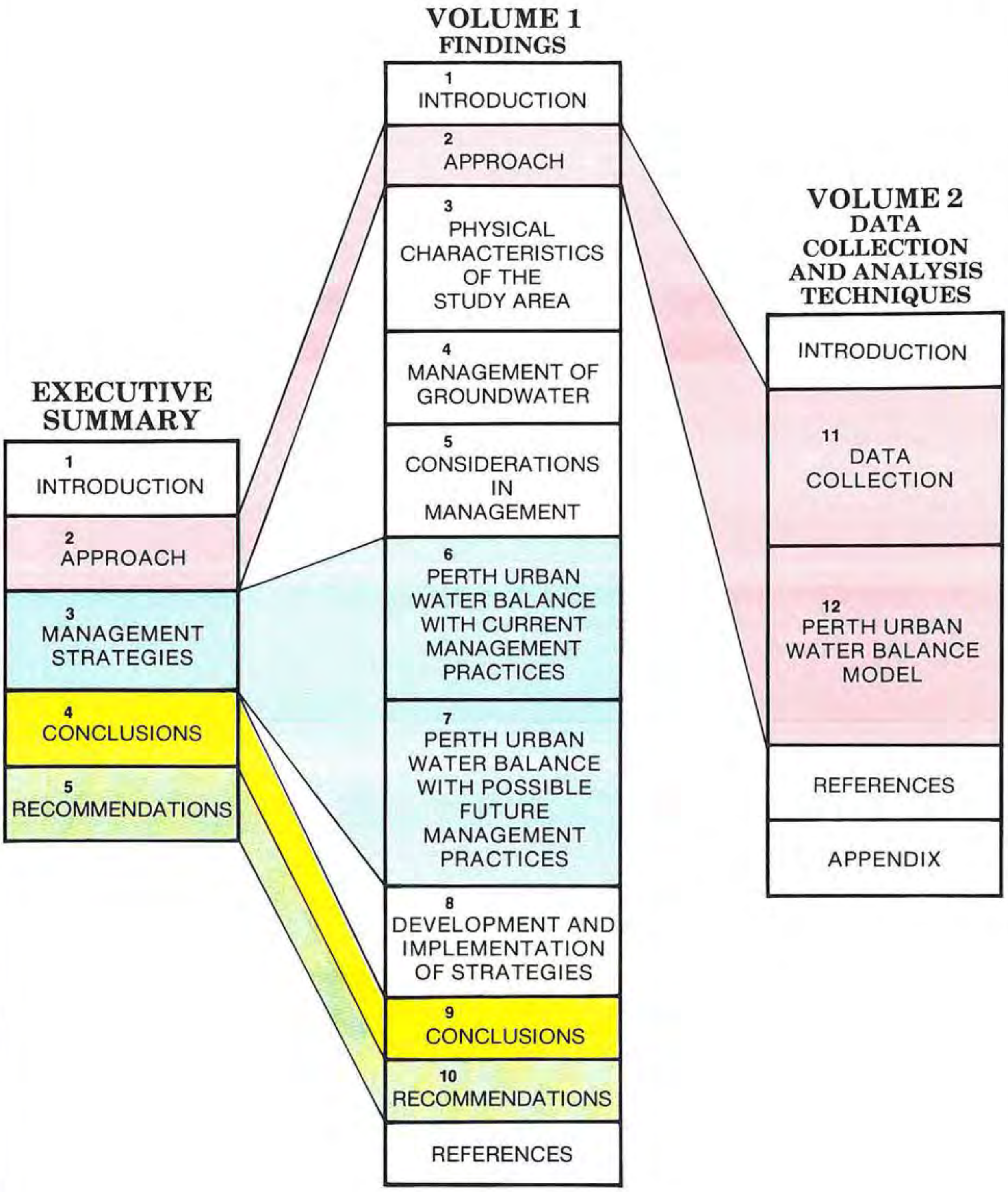


Figure 3



STRUCTURE OF THE PERTH URBAN WATER BALANCE STUDY REPORT

Figure 4

Chapter 2

APPROACH

The name of this Study refers specifically to an assessment of the water balance of the Perth urban area. The groundwater underlying this area is contained in only a small part of a regional aquifer system which extends well beyond the urban fringes. The occurrence of groundwater in urban areas may be influenced by factors in nearby areas because of the lateral movement of groundwater. The study area was therefore chosen to include the aquifer system beneath the Swan Coastal Plain between Moore River in the north and Serpentine River in the south (Figure 1).

To identify and evaluate areas at risk, it is important to evaluate the water balance for the region. Field investigations are equally important in determining the current state of the groundwater system and were an important part of the Study.

The approach involved three significant tasks. Firstly, all available data were collected and interpreted. Secondly, additional field and other investigations were conducted as necessary to collect new data. Thirdly, a computer model was developed to evaluate the urban water balance, so that the effect of various management strategies could be assessed.

Full details of data collection and model development are provided in Volume 2 of this report. The concept of a water balance is introduced and the data collection and model development carried out as part of the Study are summarised, in general terms, in this chapter.

2.1 INVESTIGATING WATER BALANCES

The concept of a water balance is fundamental to the management of a groundwater resource. In essence, a hydrologist carrying out a water balance is equivalent to an accountant balancing his books; that is, a water balance is a procedure by which all the flows of water into and out of a hydrological system (in this case a groundwater system) are balanced against changes in the volume of water stored within the system.

The important flows are components of the hydrological cycle and are depicted in Figure 5. Rainfall, infiltration, surface runoff, evaporation, transpiration, and groundwater flow are all natural processes, and are modified in an urban environment by the presence of sealed surfaces such as roofs and roads. The effects of water supply, pumping, sewerage and drainage must also be accounted for in urban situations.

A detailed review of the effect of urbanisation on the hydrological cycle in parts of Perth was presented by McFarlane (1984).

When investigating a water balance, it is necessary at the outset to define an area of interest with accurately specified boundaries and to define sub-areas and time intervals within which changes are to be examined. For a given sub-area (perhaps a hectare or a square kilometre) and time interval (perhaps a week or a month), the water balance equation can be expressed as:

Change in storage =
Sum of inflows — Sum of outflows

In a water balance for the sub-area represented in Figure 6*a*, for example, inflows include rainfall, water supply and groundwater inflow, and outflows include evapotranspiration, surface drainage, sewage disposal and groundwater outflow. Leakage between aquifers can be either an inflow or an outflow, depending upon its direction. Infiltration and pumping do not appear in the water balance equation, since they are internal flows that do not cross the boundary of the sub-area. If the inflows and outflows do not balance in one time interval, the result is a change in the volume of water stored within the sub-area, i.e., a change in water table elevation.

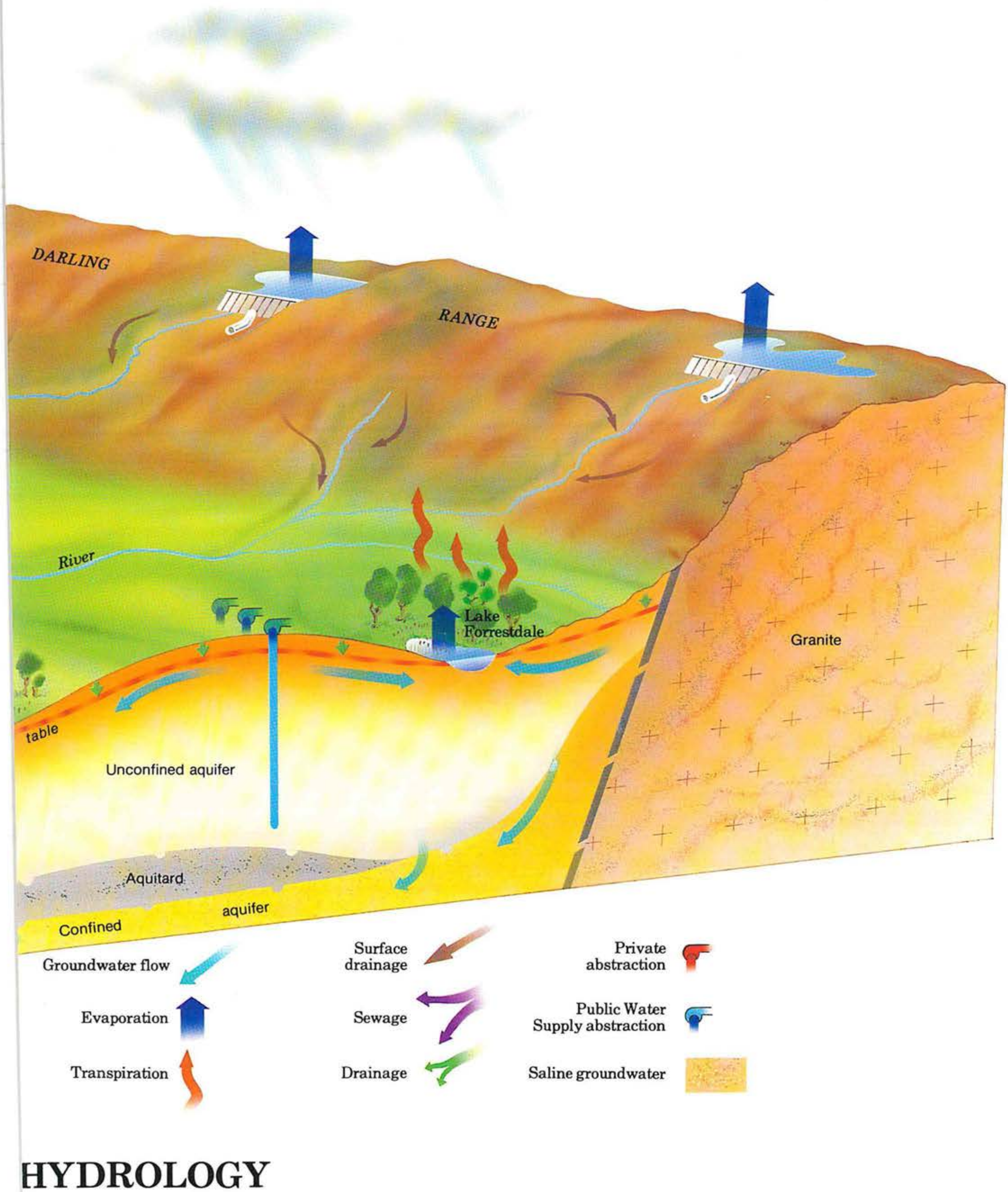
A regional groundwater system functions both as a storage reservoir and as a natural distribution system, capable of carrying water from one location to another. The total storage of water depends on the water table elevation and on the porosity of aquifer. Flows into and out of the groundwater system are often small compared to the total storage.

Although not included in a water balance for Figure 6*a*, pumping for garden irrigation does affect total evapotranspiration. To obtain better estimates of the evapotranspiration, it is convenient to further divide the sub-area of interest so that pumping becomes a flow across a boundary. This can be achieved by creating a boundary at the water table (Figure 6*b*). Water balances for a given time interval can then be performed separately for an upper layer (the atmosphere and the unsaturated soil zone) and for the saturated aquifer, although the calculations are coupled because they each involve the same pumping and deep drainage terms.

Horizontal sub-divisions can be selected to allow water balances to be performed for sub-areas with relatively uniform landuse characteristics (Figure 6*c*). It also allows for the


Lake Joondalup
Swan River
Bibra Lake
Water
Rain
Irrigation
Infiltration

STUDY AREA


DARLING
RANGE
River
Lake Forrestdale
Granite
table
Unconfined aquifer
Aquitard
Confined
aquifer
Groundwater flow
Evaporation
Transpiration
Surface drainage
Sewage
Drainage
Private abstraction
Public Water Supply abstraction
Saline groundwater

HYDROLOGY

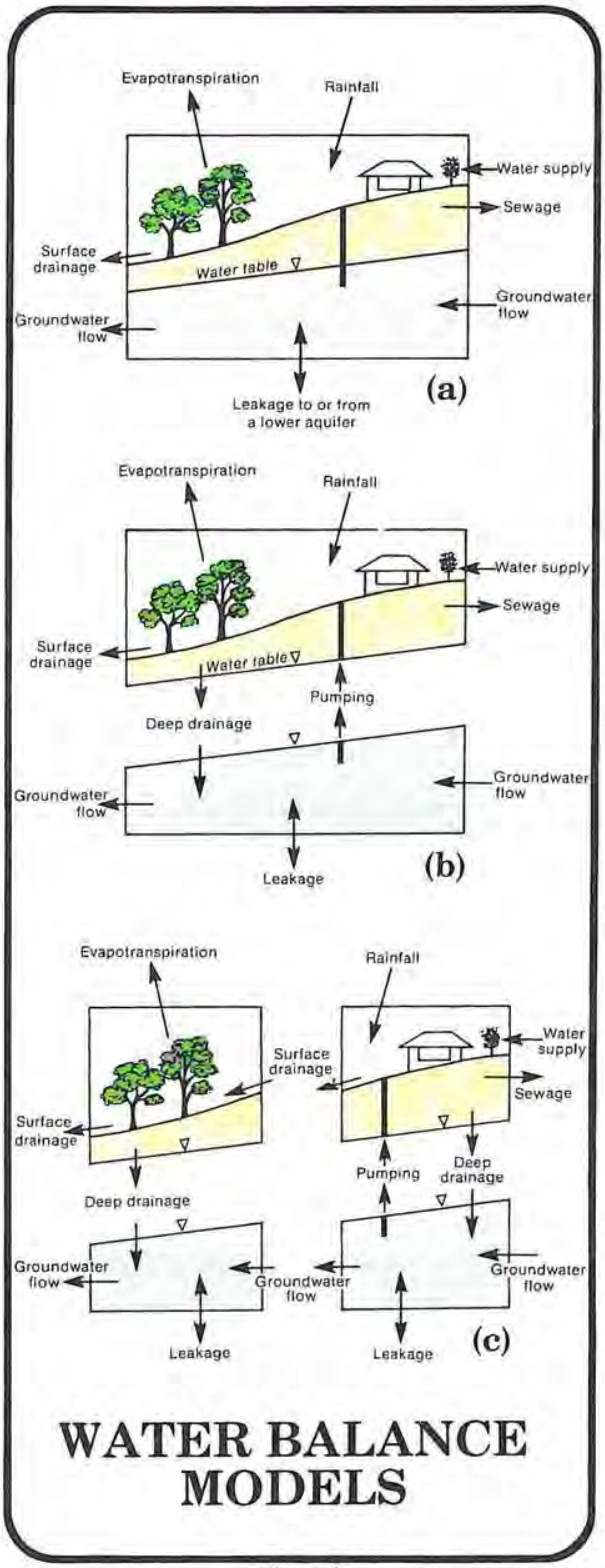


Figure 6

calculation of water table variations throughout a region.

There have been many assessments of the long-term average water balance of the Swan Coastal Plain. Water balances have been carried out for the aquifers to the North and South of the Swan estuary (Bestow, 1976; Allen, 1981); for the suburbs of Applecross, Bassendean and Wembley (Sinclair Knight Pigott and Eastwood, 1981); and for small areas in Shenton Park and Dalkeith (McFarlane, 1983, 1984). More intensive computer modelling, capable of accounting for horizontal groundwater flows, has also been carried out for large areas to the north of Perth (Burton, 1976; Pollett and Wiese, 1977; Pollett et al., 1979; Pollett, 1981).

Detailed computer modelling requires large amounts of data. The remainder of this chapter summarises the assimilation of data and the unique characteristics of the water balance model developed for this Study.

2.2 AVAILABLE DATA

An extensive amount of data existed prior to the Study and was available in a variety of forms such as detailed maps, tabulations, published reports and computer data files.

Topographic data were provided by the Department of Lands and Surveys of Western Australia in the form of contour plots used to prepare their topographic survey map series. The plots were digitised and a representative elevation was calculated for each hectare of the study area for use in modelling analyses.

Data on urban land use were obtained from the State Energy Commission, which had recently compiled accurate, current landuse information for its Computer Aided Distribution Planning and Design system. The Commission used 1984 aerial photographs (Department of Lands and Survey, 1984) at a scale of 1:5000 to plot the occurrence of 22 different urban landuse categories.

Land use outside the urban area was determined with similar accuracy. Market garden areas, which had not previously been mapped in detail, were plotted from the same series of aerial photographs; the Department of Conservation and Land Management provided detailed maps showing the history of pine plantation development; and vegetation cover on rural and uncleared land was estimated and mapped from Landsat imagery.

Landuse data produced and collated for this Study is at this time the most comprehensive regional assembly of landuse information available for the Perth Region.

Accurate estimates of abstraction from public and institutional bores and detailed maps of urban drainage systems were obtained from the Water Authority, from other government departments and from local government authorities.

Information on water consumption and the distribution of the metropolitan sewerage system was obtained from the Water Authority's Customer Data Base.

A significant source of groundwater level data was the Water Authority's existing groundwater level monitoring system (GROWLS) — a regional network of monitoring points at which groundwater levels are recorded each month. The system was established in the early 1960s to monitor the regional variations in the water table, the effects of drainage and the effects of Water Authority groundwater abstraction schemes. Since then the network has been expanded and now comprises about 1400 monitoring points.

Hydrogeological information on the study area, which was updated with information gathered during this Study, was provided by the Geological Survey of Western Australia.

2.3 DATA COLLECTION

2.3.1 Regional Data

Groundwater level monitoring. Selected bores from the GROWLS system were included in a regional monitoring network established during this Study for detailed analysis of groundwater level variations. Urban areas were sparsely covered by monitoring points within the GROWLS system, so the network was augmented by gaining access to bores operated by local government authorities, other government departments and some private householders. Additional monitoring bores were drilled where the available network was sparse. In all, the regional monitoring network consists of 360 bores at which water levels were recorded twice yearly between March 1983 and October 1985.

Groundwater quality monitoring. In the past, water quality monitoring was carried out at a few selected Water Authority monitoring points, but the data collected could not be integrated to provide regionally synoptic information. A regional water quality monitoring program was conducted during the Study to assess non-point-source pollution. A selection of about 190 bores from the regional network was sampled annually from 1983 to 1986 to assess the existence and extent of groundwater quality problems, to provide a basis for comparing future changes in groundwater quality and to highlight any areas where further research may be warranted. Water quality parameters included pH, Eh, temperature, electrical conductivity, nutrients (nitrogen and phosphorus compounds), chloride, sulphate and iron. Some analyses were also performed for organic carbon, heavy metals and pesticides.

Aquifer properties. Transmissivity in the superficial formations was mapped using results of aquifer pumping tests conducted at three locations during the study, permeameter tests on core samples from a number of bores and data available from previous tests.

2.3.2 Intensive Studies

Applecross water balance study. The suburb of Applecross, which is situated on a peninsula projecting into the Swan Estuary (Figure 1), was selected for intensive study. It was selected because of observed increases in groundwater salinity and the availability of a significant amount of hydrological data. Water levels were measured at 36 bores each month, between September 1983 and November 1985, and water quality analyses were performed twice yearly. Surface drainage was assessed and rainfall and runoff were measured continuously for two small sub-catchments. The hydrogeological investigations included tritium sampling to provide information about long-term recharge rates.

Inner urban monitoring. To provide a more detailed picture of groundwater levels within the urban area, a total of 254 bores were established in an inner urban network. This network includes the 36 bores on the Applecross peninsula[1], 45 monitoring bores on the Cottesloe peninsula[1] and an additional 130 bores which were not already included in the regional monitoring network. All of these bores are located in areas where the water table elevation is less than 5 m above sea level.

Saltwater interface monitoring. Fifteen multiport bores, which allowed sampling of groundwater at multiple depths, were installed around the estuary and along the coast for a study of saltwater intrusion. Salinity data were collected monthly between April 1984 and December 1985 and were complemented by data available from three existing sites.

Wetland review and biological monitoring. The Department of Conservation and Environment[2] established two projects to provide the Study with information about the role of groundwater in the maintenance of the region's wetlands. Both projects were full-time studies conducted in parallel with the Perth Urban Water Balance Study and were published as separate reports.

The first project provided an overall review of metropolitan wetlands (Arnold, 1987). Its aims were:

- to review and consolidate existing administrative, geological, biological and hydrogeological information on wetlands;
- to identify criteria for establishing quality and conservation values of metropolitan wetlands;

1. For convenience, the terms Applecross peninsula and Cottesloe peninsula are used in this report to describe the peninsulas which contain the suburbs of Applecross and Cottesloe, respectively.

2. In February 1987, the Department of Conservation and Environment and the previously existing Environmental Protection Authority were reconstituted to form the new Environmental Protection Authority

- to examine the relationships between environmental quality and landuse pressures; and
- to recommend ways in which water availability and quality should and could be managed to protect and enhance the key wetlands.

The second project provided a detailed biological examination of macroinvertebrates in five urban wetlands (Davis and Rolls, 1987). The project assessed wetland ecosystem viability and diversity and assessed the value of biological monitoring as a wetland monitoring technique.

Groundwater quality transformations. A research project, conducted in the Geology Department at the University of Western Australia as a component of this Study, assessed the changes in groundwater quality as groundwater moved along flow lines beneath various types of land use and through different rock types. The movement of contaminants and the variation in quality with depth below the water table were assessed. A report of that study is included as an appendix in Volume 2.

2.4 ANALYSIS AND ASSESSMENT TECHNIQUES

Data accumulated during the Study were stored in extensive data bases on the Water Authority's Facom M380S computer. Large spatial data sets were stored using the IMGRID geographic data base system (Sinton, 1977) and were manipulated using a high-level statistical analysis package (SAS Institute, 1982). Computer graphics were used extensively for data checking and for presentation of results (SAS Institute, 1985*a*).

Data analysis, which was not directly related to water balance calculations, included the use of regression and factor analysis for relating water quality parameters to landuse characteristics (SAS Institute, 1985*b*).

The water balance model developed for assessing the effects of alternative management strategies is described in detail in Volume 2. Fundamentally, the computer model is an extension of the concept illustrated in Figure 6*c*. It consists of two coupled models, a Vertical Flux Model which produces an estimate of the net vertical flow into the unconfined aquifer in a given time interval, and an Aquifer Flow Model which accounts for horizontal flows below the water table (Figure 7).

Net vertical flux is the net vertical flow into the unconfined aquifer, incorporating the combined effect of recharge, direct evaporation from the water table, transpiration by phreatophytes, groundwater abstraction and leakage to or from the underlying confined aquifer. Recharge is the downwards flow of water across the water table, incorporating the combined effect of rainfall, canopy interception, evapotranspiration from the unsaturated zone, garden irrigation and septic tank effluent. The direction of leakage varies, and leakage may therefore be a positive or negative component of net vertical flux.

The Vertical Flux Model can operate on areas as small as one hectare, which is the finest scale at which regional data sets were established. It carries out separate water balance calculations for a grass root zone (O m to 1 m below ground level), a tree root zone (1 m to 6 m below ground level) and a root free zone (from 6 m below ground level to the water table).

The Aquifer Flow Model is a finite element package which uses triangular sub-areas over the area of interest (Golder Associates, 1979; Marlon-Lambert et al., 1979). Since the triangles may cover up to several square kilometres, a large number of vertical flux calculations are made for each triangle and the fluxes are distributed to the nodes of the Aquifer Flow Model. The model predicts the water table elevation at each node at monthly time intervals.

2.5 MANAGEMENT STRATEGIES

Maintenance of groundwater levels was identified as the fundamental issue in managing the unconfined groundwater system. The Urban Water Balance Study model was used to predict the likely effect of continuing urbanisation under a variety of climatic conditions. Management strategies were then devised to manipulate extraction from and recharge to the aquifer and their effects were predicted using the model.

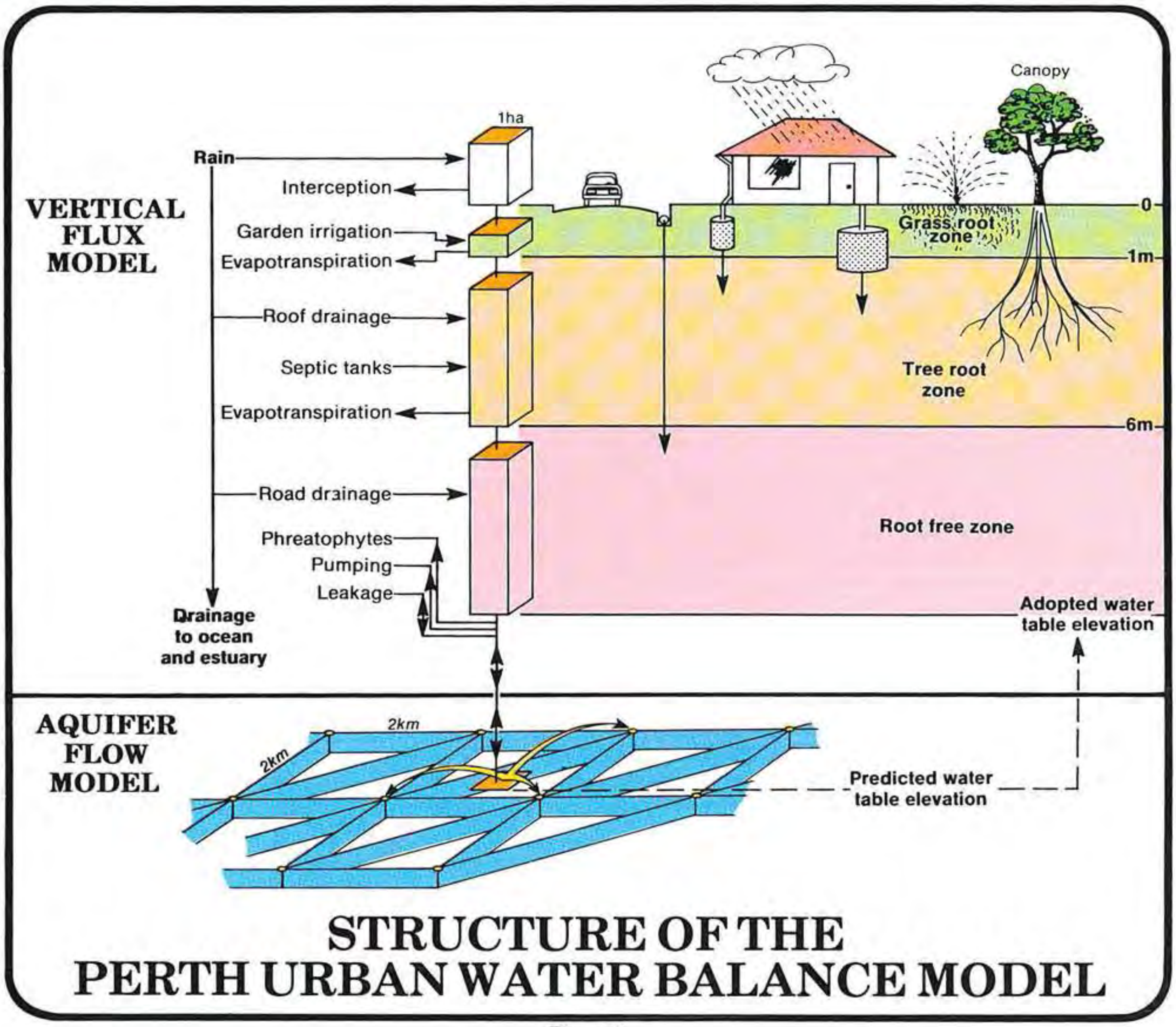

Canopy
1ha
Rain
Interception
VERTICAL FLUX MODEL
Garden irrigation
Evapotranspiration
Roof drainage
Septic tanks
Evapotranspiration
Road drainage
Phreatophytes
Pumping
Leakage
Drainage to ocean and estuary
Grass root zone
Tree root zone
Root free zone
0
1m
6m
Adopted water table elevation
AQUIFER FLOW MODEL
2km
2km
Predicted water table elevation
STRUCTURE OF THE PERTH URBAN WATER BALANCE MODEL

Figure 7

Chapter 3

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

3.1 SETTING

The area considered by the Perth Urban Water Balance Study is a part of the Swan Coastal Plain which is bounded in the east by the Darling Range and the Dandaragan Plateau and in the west by the Indian Ocean (Figure 1). The study area extends about 100 km from Moore River and Gingin Brook in the north to Warnbro Sound and Serpentine River in the south. This part of the plain is about 30 km wide and about 3150 km^2 in area. For convenience it is referred to as the coastal plain, with the area north of the Swan River referred to as the Northern Perth Area (2100 km^2), the area south of the Canning River as the Southern Perth Area (810 km^2) and the area bounded by the Swan and Canning Rivers and the Darling Range as the Eastern Perth Area (240 km^2).

3.2 CLIMATE

The region has a mediterranean climate with a cool wet period from May to October and a warm dry period from November to April. About 90% of annual rainfall occurs in the wet period and rainfall only exceeds Class A pan evaporation in the 4-month period from May to August (Figure 8). The annual average rainfall and pan evaporation for Perth are 870 mm and 1819 mm, respectively.

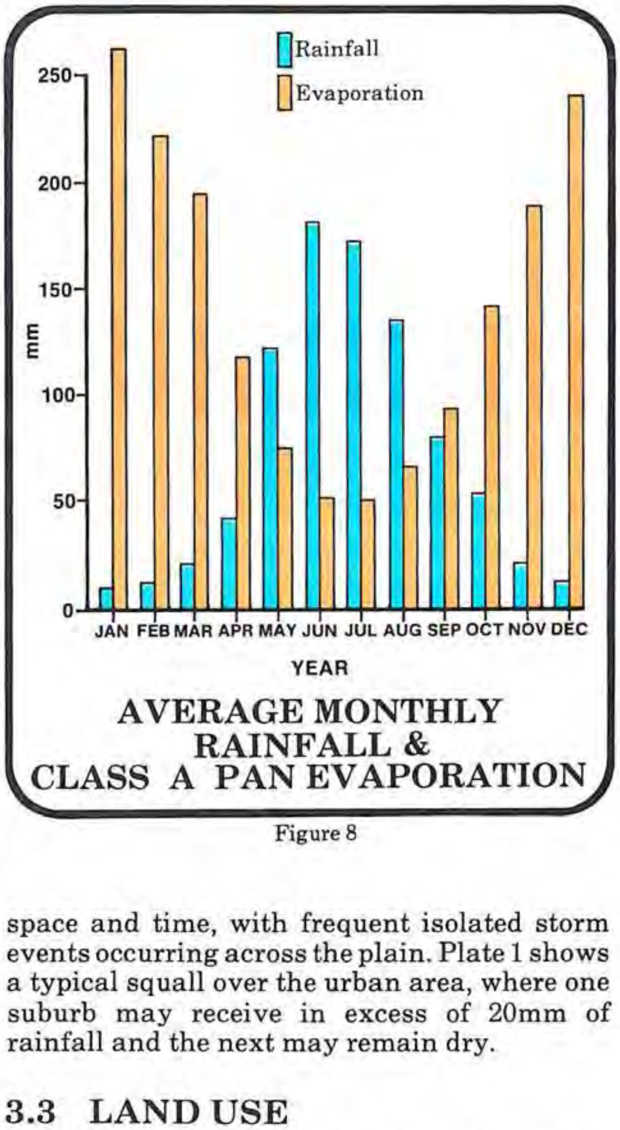


Figure 8

Average annual rainfall increases towards the range and from north to south along the plain (Figure 9). The annual rainfall is variable from year to year, with extended periods of above-average or below-average rainfall being common (Figure 10). The period 1976-85 was the driest ten-year period on record and, since 1971, there have been only four years with above-average rainfall.

Individual rainfall events are highly variable in space and time, with frequent isolated storm events occurring across the plain. Plate 1 shows a typical squall over the urban area, where one suburb may receive in excess of 20mm of rainfall and the next may remain dry.

Jenni Bartle

Plate 1 Isolated rain squall over Perth

3.3 LAND USE

Most of the study area has been cleared for pastoral, horticultural, silvicultural or urban purposes (Figure 11). The remaining bushland is largely in Crown land in the north or in reserves or undeveloped land adjacent to the coast.

The urban areas of Perth are adjacent to the Swan estuary and extend along the coast from Wanneroo in the north to Rockingham in the south, covering an area of approximately 755 km^2. A heavy-industrial region is located between Coogee and Kwinana, south of Fremantle, and many smaller commercial and light-industrial regions exist in the metropolitan area.

A view of the study area, as recorded by the Landsat satellite in 1980 from an altitude of over 900 km (Plate 2), shows the variability of land use in the Perth region.

Plate 2 Landsat image of the Perth region, 1980

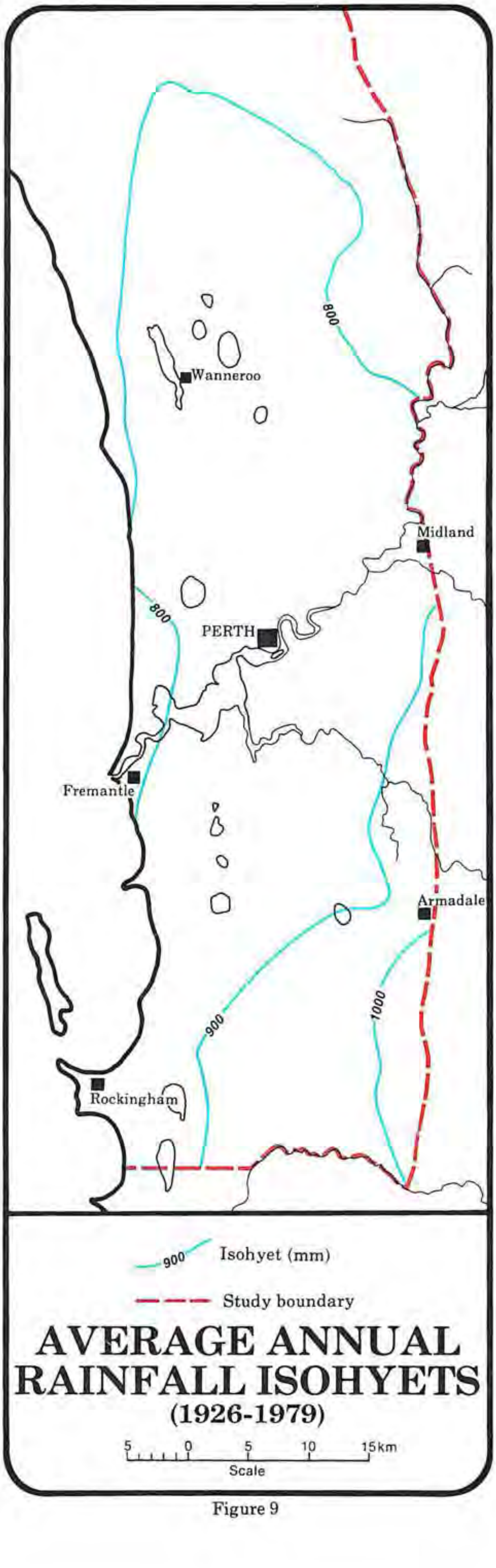


Figure 9

3.4 GEOMORPHOLOGY

The Swan Coastal Plain near Perth consists of a series of distinct landforms roughly parallel to the coast and extending from the coast to the Darling Fault and Gingin Scarp (Figure 12). The most easterly feature is formed by the colluvial slopes which are the dissected remnants of a sand-covered, wave-cut platform forming the foothills to the Darling Range. Along the foot of the colluvial slopes is the flat Pinjarra Plain, partly built up of alluvium brought down from the Darling Range. Further west are the Bassendean Dunes which form a gently undulating sand plain about 20 km wide (Plate 3). Fringing the present coastline are the irregular Spearwood and Quindalup Dune systems which are about 10 km wide (Plates 4 and 5). The rivers which presently cross the plain are flanked by flood plains and river terraces of recent origin. Wetlands have formed in interdunal swales of the Bassendean Dunes (Plate 6) and in interbarrier depressions between the Spearwood and Bassendean Dunes and within the Spearwood Dunes (Plates 7 and 8).

Surface elevations increase from south to north, reaching local maxima of 100 mAHD over the central Northern Perth Area. There is also a general west-to-east increase in elevation (Figure 13).

3.5 DRAINAGE

Because the region is generally formed of permeable, undulating dunes, rain water infiltrates the sandy soils or, where the ground is paved, drains towards local depressions rather than towards regional drainage systems.

The study area is crossed by three major drainage systems:

- the Gingin Brook — Moore River System, which forms the northern boundary to the area;
- the Swan River — Canning River System, which drains into the Swan estuary; and
- the Serpentine River, which forms the southern boundary to the area.

These rivers originate on and carry runoff from the Darling Range and the Dandaragan Plateau; they also carry some groundwater discharge from the coastal plain.

Several minor watercourses originate on the coastal plain. The largest of these is Ellen Brook which is fed from groundwater discharge from the coastal plain and runoff from the Darling Range and the Dandaragan Plateau and forms the eastern boundary of the Northern Perth Area.

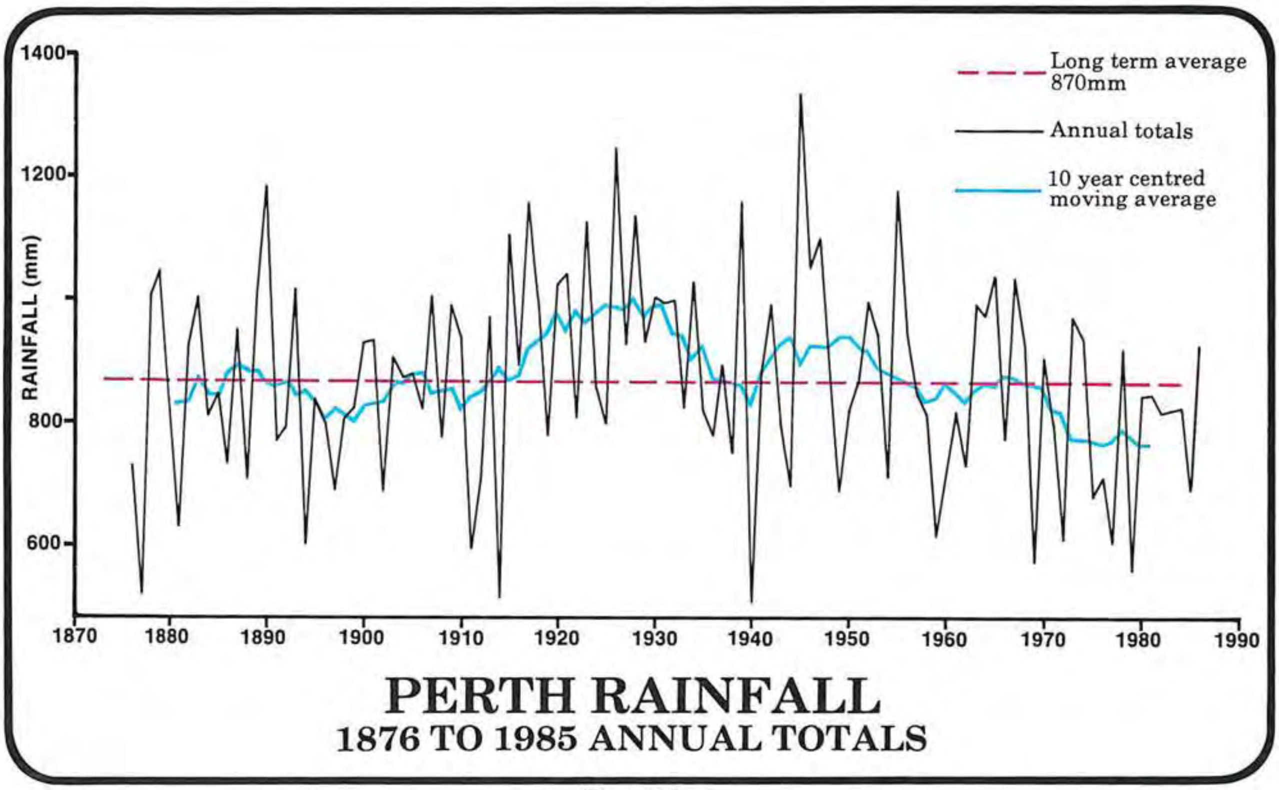
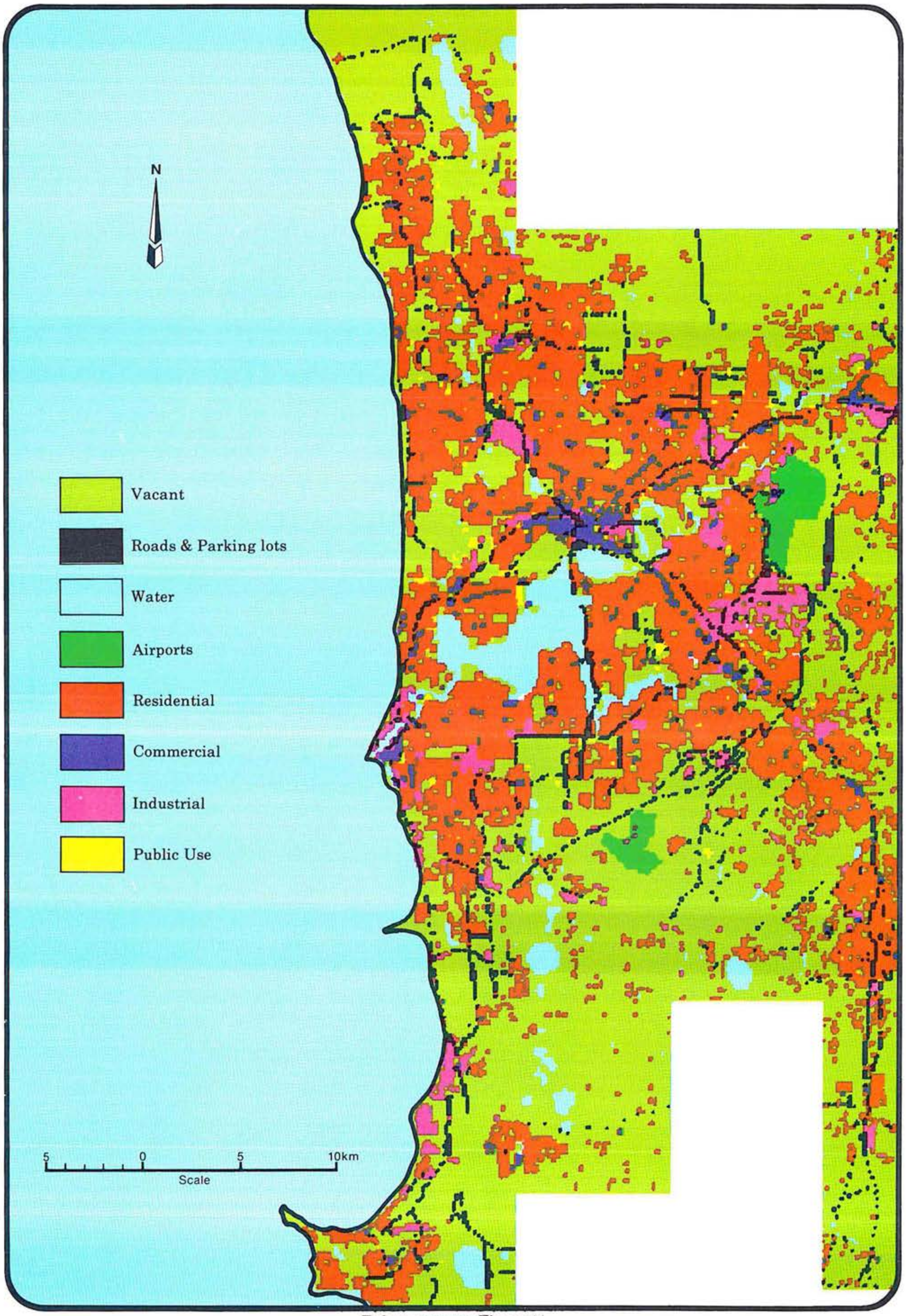


Figure 10

Plate 3 Gently undulating Bassendean Dune System

Plate 4 Spearwood Dune System

Plate 5 Quindalup Dune System



Enlargement to Figure 11

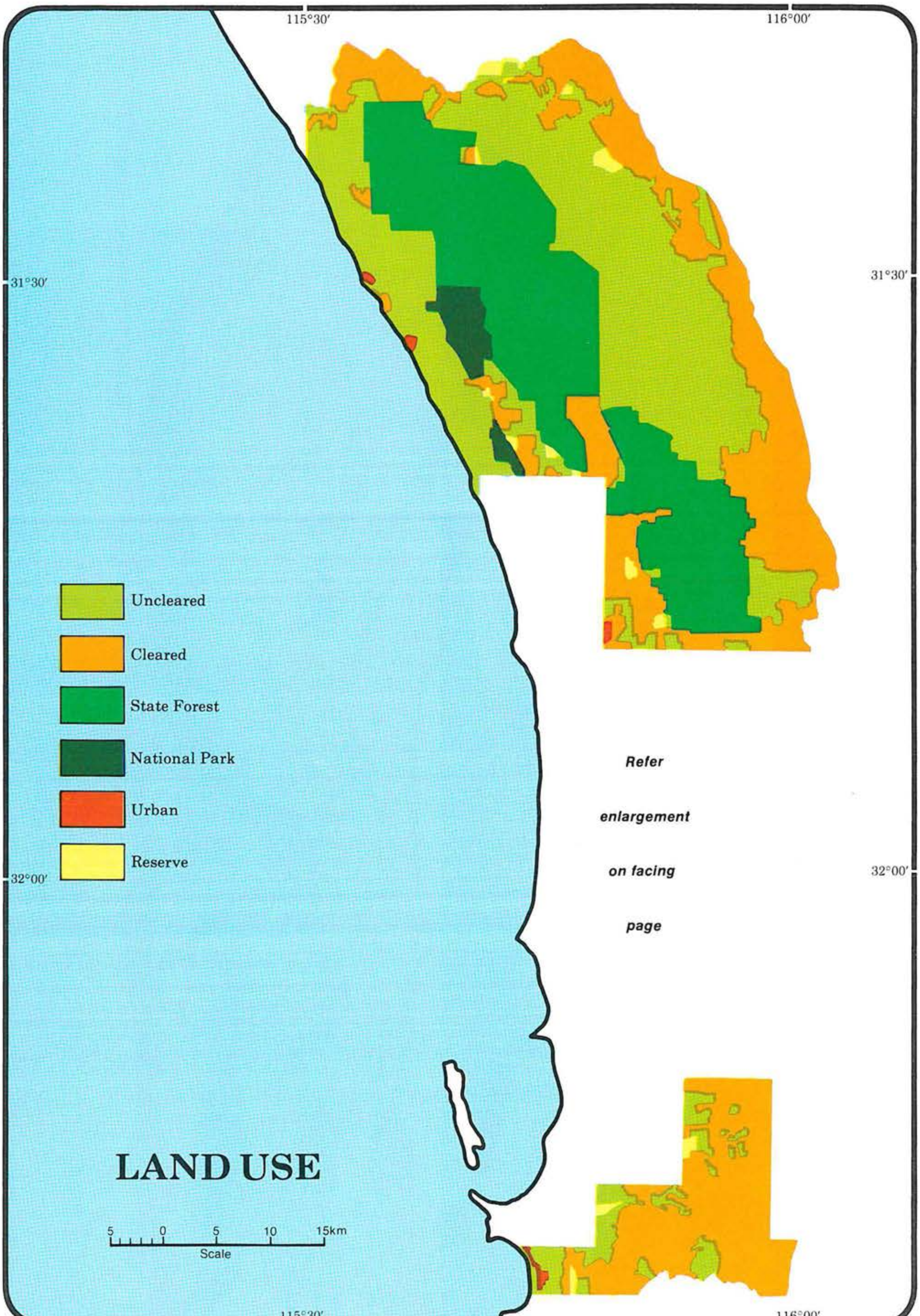

115°30′
116°00′
31°30′
31°30′
32°00′
32°00′
Uncleared
Cleared
State Forest
National Park
Urban
Reserve
Refer enlargement on facing page
LAND USE
5 0 5 10 15km
Scale
115°30′
116°00′

Figure 11

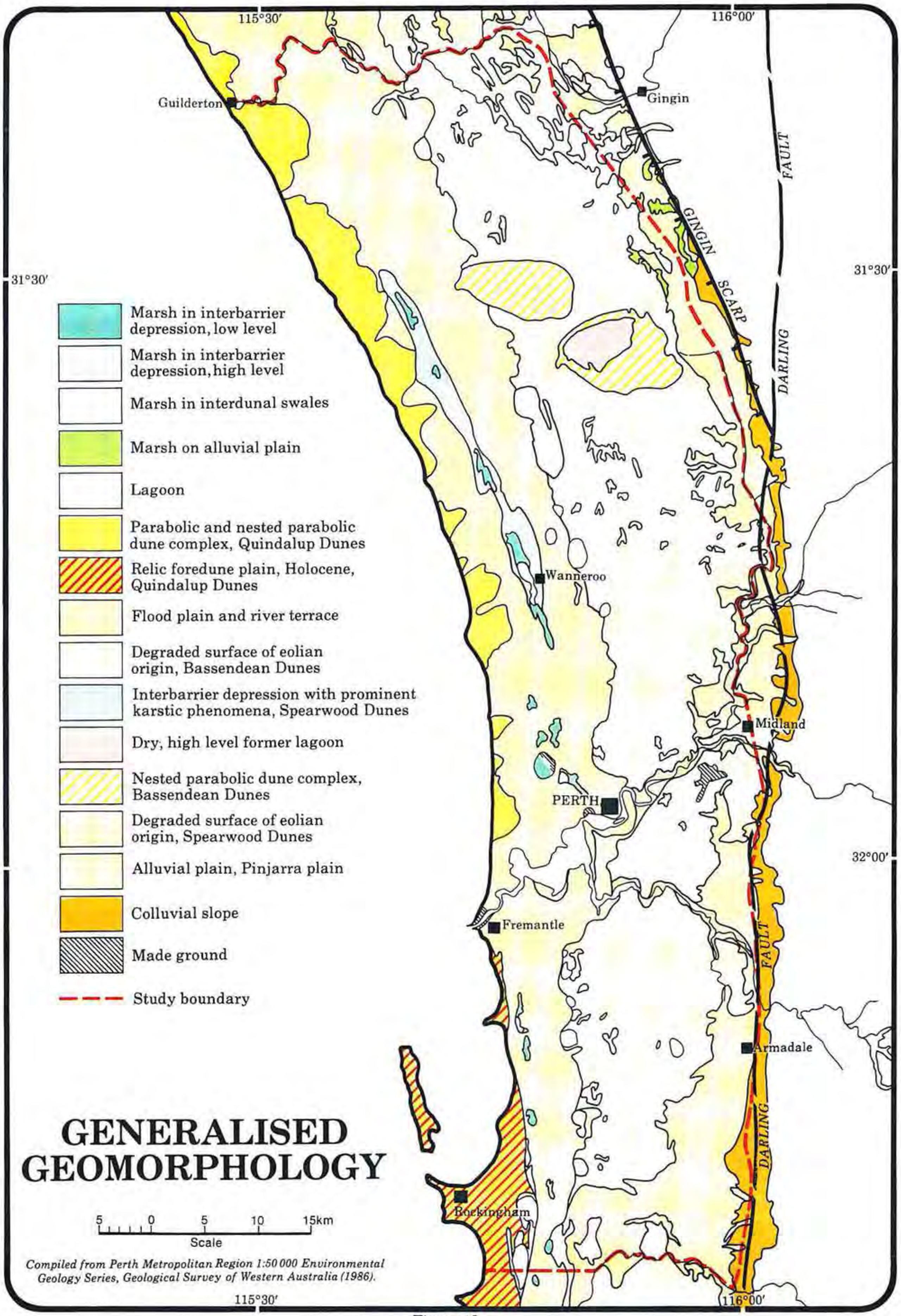

115°30′
116°00′
31°30′
31°30′
32°00′
Guilderton
Gingin
Wanneroo
Midland
PERTH
Fremantle
Armadale
Rockingham
GINGIN SCARP
DARLING FAULT
DARLING FAULT
Marsh in interbarrier depression, low level
Marsh in interbarrier depression, high level
Marsh in interdunal swales
Marsh on alluvial plain
Lagoon
Parabolic and nested parabolic dune complex, Quindalup Dunes
Relic foredune plain, Holocene, Quindalup Dunes
Flood plain and river terrace
Degraded surface of eolian origin, Bassendean Dunes
Interbarrier depression with prominent karstic phenomena, Spearwood Dunes
Dry, high level former lagoon
Nested parabolic dune complex, Bassendean Dunes
Degraded surface of eolian origin, Spearwood Dunes
Alluvial plain, Pinjarra plain
Colluvial slope
Made ground
Study boundary
GENERALISED GEOMORPHOLOGY
5 0 5 10 15km
Scale
Compiled from Perth Metropolitan Region 1:50 000 Environmental Geology Series, Geological Survey of Western Australia (1986).
115°30′
116°00′

Figure 12

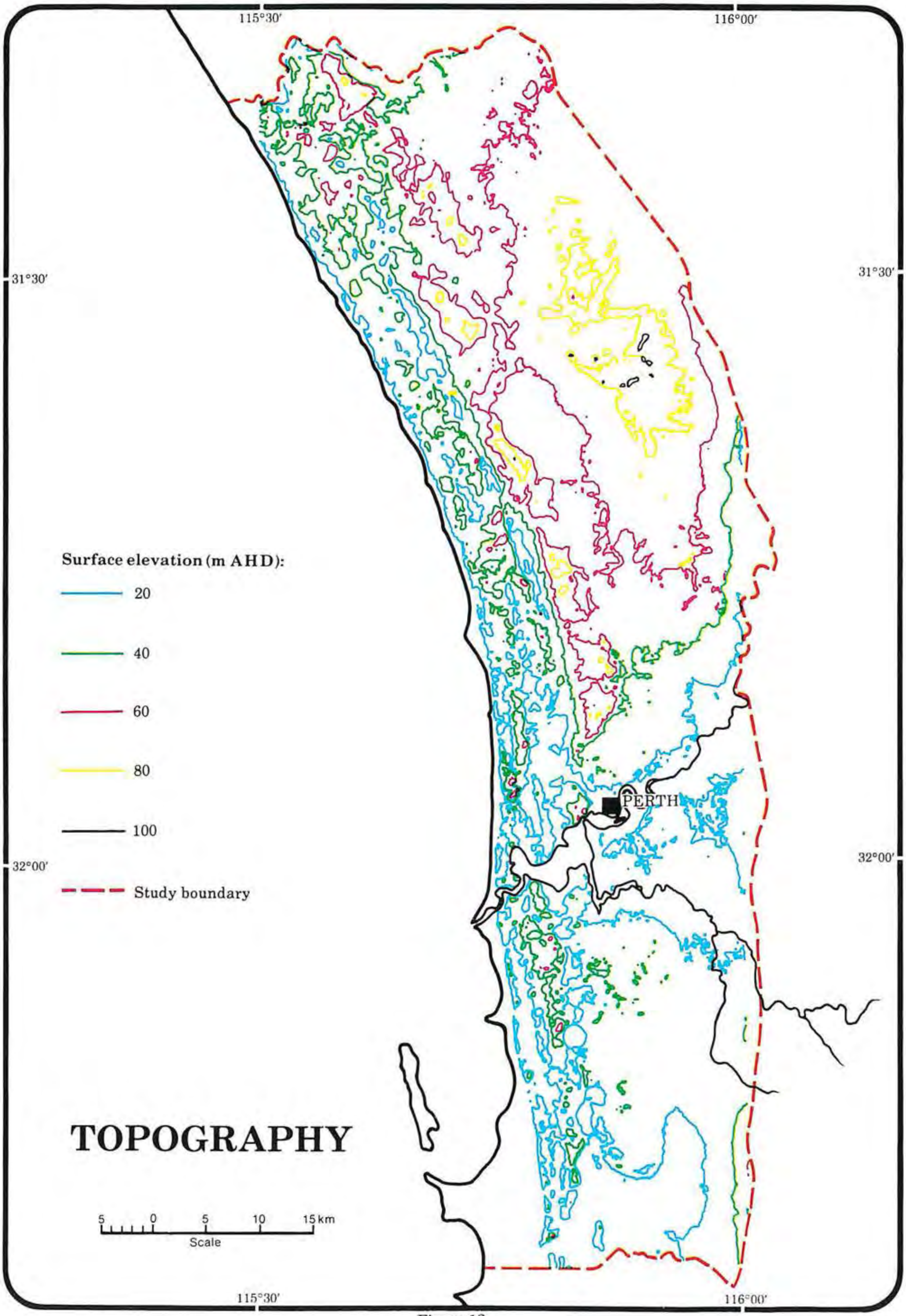

115°30'
116°00'
31°30'
31°30'
32°00'
32°00'
PERTH
Surface elevation (m AHD):
20
40
60
80
100
Study boundary
TOPOGRAPHY
5 0 5 10 15 km
Scale
115°30'
116°00'

Figure 13

3.6 GEOLOGY

3.6.1 Swan Coastal Plain

The Swan Coastal Plain is developed on the eastern, onshore edge of the Perth Basin. Near Perth, the basin contains about 13 000 m of Permian to Quaternary age sedimentary rocks, separated from the Archaean crystalline rocks of the Yilgarn Block by the Darling Fault (Allen, 1981).

The coastal plain is underlain by a thin layer of Late Tertiary and Quaternary formations which are, for convenience, collectively referred to as the superficial formations. The superficial formations lie unconformably on and obscure the irregular, seaward sloping, erosional surface of older sediments (Figure 14). The level of this surface ranges from 20 m above AHD in the east to 30 m below AHD near the coast.

The stratigraphic units of importance to this Study are given in sequence in Table 1.

3.6.2 Superficial Formations

This Study is concerned with the groundwater resources of the superficial formations. They range in thickness from about 10 m to 100 m and consist of sand, limestone and discontinuous beds or lenses of silt and clay, deposited in various environments during world-wide changes in sea level.

The surface geology of the study area is shown in Figure 15 and the generalised stratigraphy is represented in Figure 16.

The lowest units of the superficial formations are the discontinuous Ascot Limestone, Rockingham Sand and Jandakot Beds. The areal extent of these formations is not well known but they are generally 5 to 10 m thick and consist of poorly sorted gravels, sands and clays with frequently occurring shelly layers. Calcareous cementation of these sediments is common.

Unconformably overlying these units is the Guildford Formation which consists of fine to coarse sand with discontinuous beds or lenses of silt and clay which occur particularly in the eastern parts. Overlying the Guildford Formation is a thin layer of wind-blown fine to coarse sand referred to as the Bassendean Sand.

At about the level of the water table, iron oxides have deposited on the sand grains of the Bassendean Sand and parts of the Guildford Formation. In some areas, these oxides have cemented the sand to form the locally termed "coffee rock".

Unconformably overlying and abutting the Guildford Formation in the west is the Tamala Limestone. This unit is commonly leached at the surface leaving behind pale brown to yellow,

Plate 6 Wetlands of the Bassendean Dune System

Plate 7 Wetlands in inter-barrier depressions between the Spearwood and Bassendean Dune Systems — North, Bibra and Yangebup Lakes.

Plate 8 Wetlands in inter-barrier depressions within the Spearwood Dune System — Loch McNess

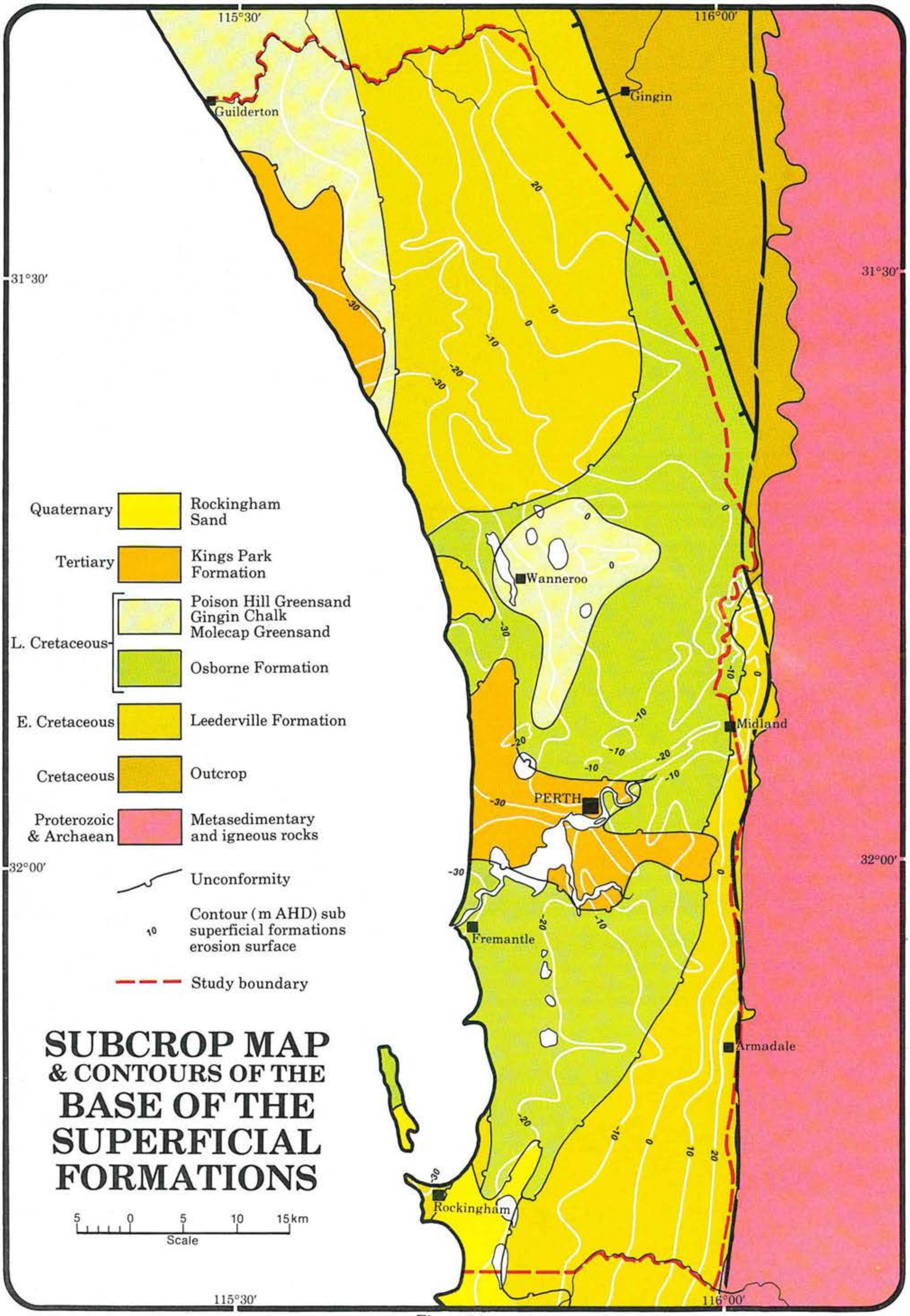
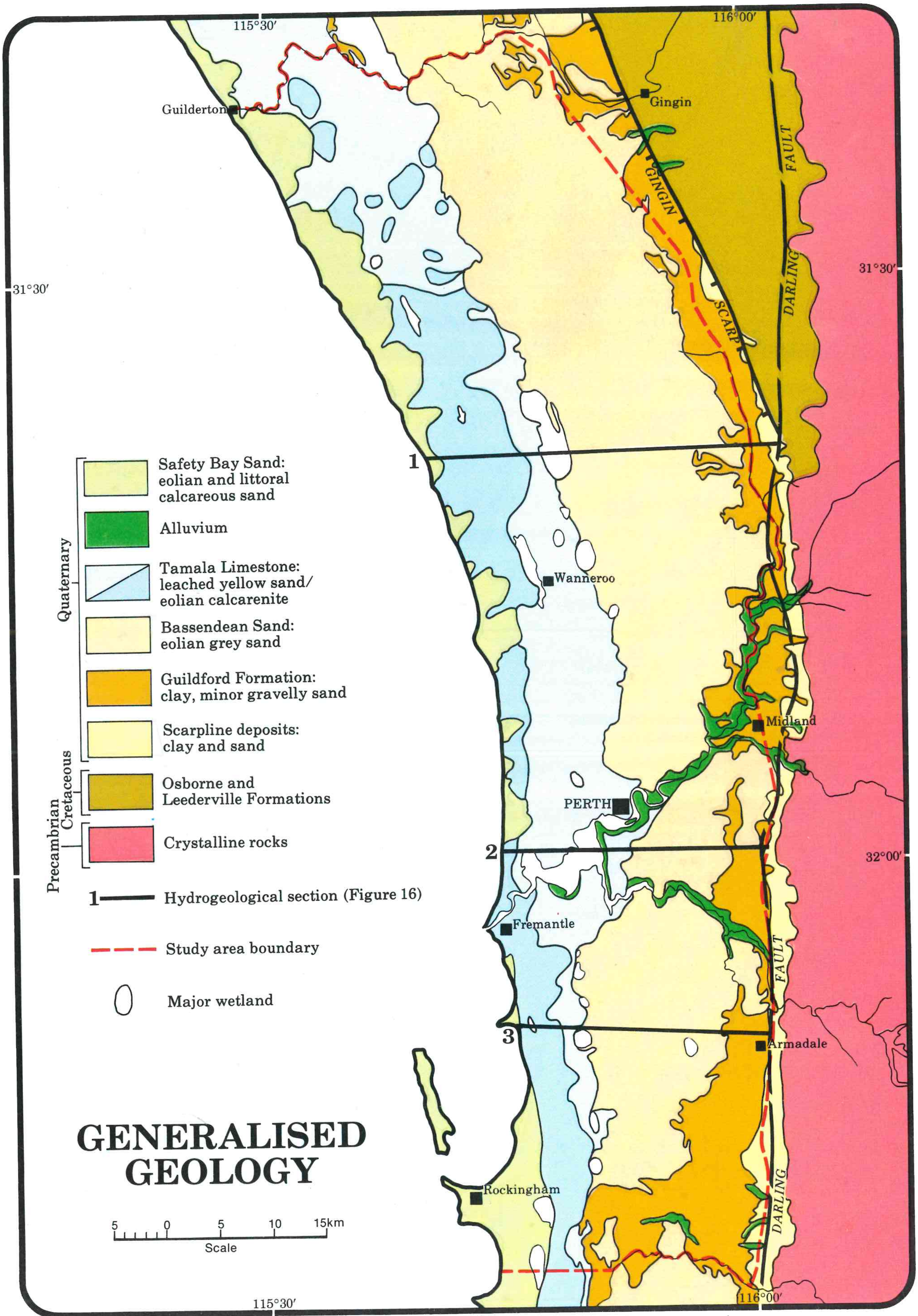

115°30'
116°00'
Guilderton
Gingin
31°30'
Wanneroo
Midland
PERTH
Fremantle
Armadale
Rockingham
32°00'
Quaternary
Rockingham Sand
Tertiary
Kings Park Formation
L. Cretaceous
Poison Hill Greensand
Gingin Chalk
Molecap Greensand
Osborne Formation
E. Cretaceous
Leederville Formation
Cretaceous
Outcrop
Proterozoic & Archaean
Metasedimentary and igneous rocks
Unconformity
Contour (m AHD) sub superficial formations erosion surface
Study boundary
SUBCROP MAP
& CONTOURS OF THE
BASE OF THE
SUPERFICIAL
FORMATIONS
5 0 5 10 15km
Scale

Figure 14



115°30′
116°00′
Guilderton
Gingin
GINGIN SCARP
DARLING FAULT
31°30′
31°30′
1
Wanneroo
Midland
PERTH
2
32°00′
Fremantle
FAULT
3
Armadale
Rockingham
DARLING
115°30′
116°00′
Quaternary
Cretaceous
Precambrian
Safety Bay Sand: eolian and littoral calcareous sand
Alluvium
Tamala Limestone: leached yellow sand/ eolian calcarenite
Bassendean Sand: eolian grey sand
Guildford Formation: clay, minor gravelly sand
Scarpline deposits: clay and sand
Osborne and Leederville Formations
Crystalline rocks
1 Hydrogeological section (Figure 16)
Study area boundary
Major wetland
GENERALISED GEOLOGY
5 0 5 10 15km
Scale

Figure 15

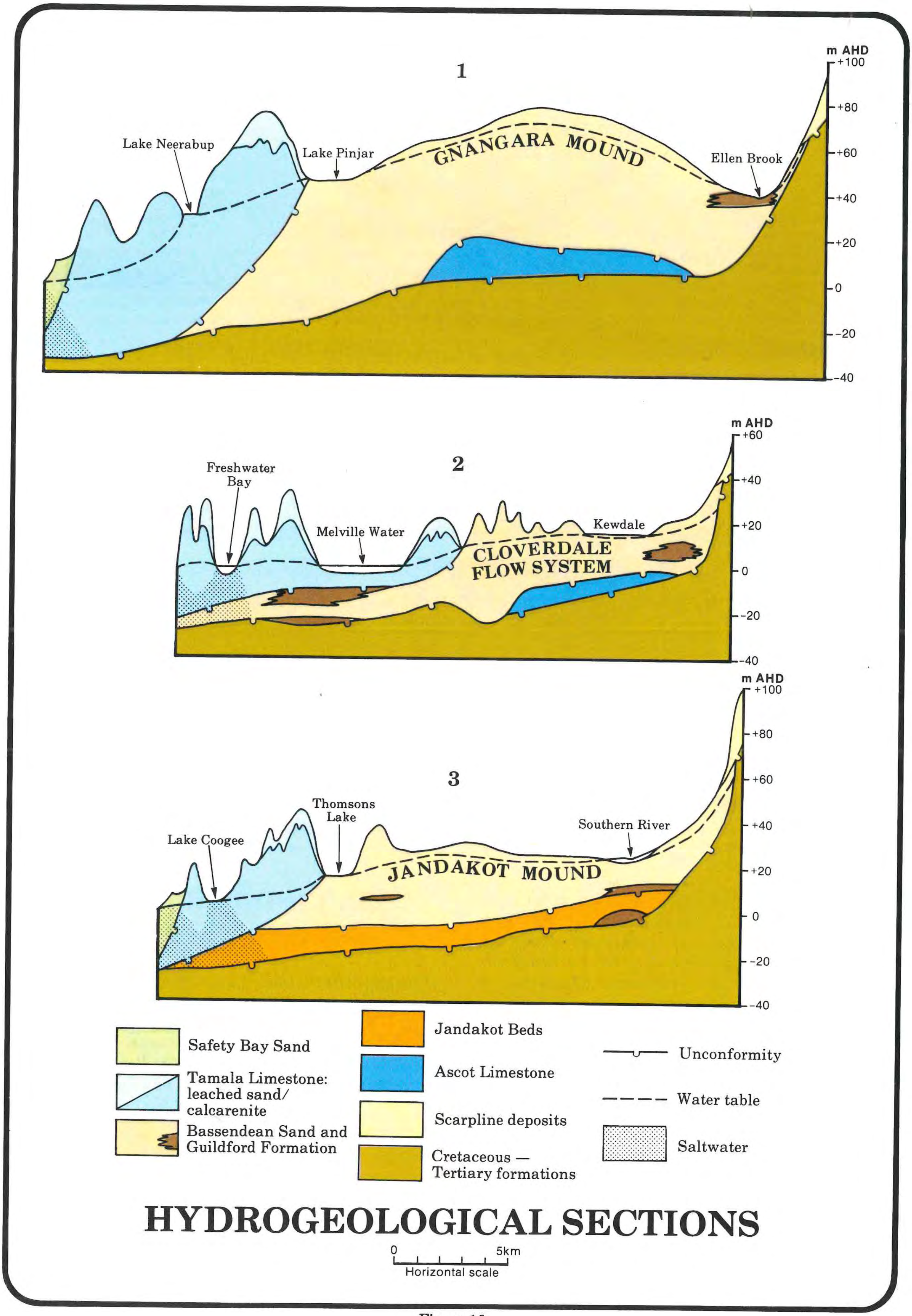

1
m AHD
+100
+80
+60
+40
+20
0
-20
-40
Lake Neerabup
Lake Pinjar
GNANGARA MOUND
Ellen Brook
2
m AHD
+60
+40
+20
0
-20
-40
Freshwater Bay
Melville Water
Kewdale
CLOVERDALE FLOW SYSTEM
3
m AHD
+100
+80
+60
+40
+20
0
-20
-40
Thomsons Lake
Lake Coogee
Southern River
JANDAKOT MOUND
Safety Bay Sand
Tamala Limestone: leached sand/ calcarenite
Bassendean Sand and Guildford Formation
Jandakot Beds
Ascot Limestone
Scarpline deposits
Cretaceous — Tertiary formations
Unconformity
Water table
Saltwater
HYDROGEOLOGICAL SECTIONS
0
5km
Horizontal scale

Figure 16

Age	Formation	Maximum Thickness	Lithology	Groundwater Potential
Late Tertiary to Quaternary	superficial formations	100m	Sand, limestone, clay	Major unconfined aquifer; fresh groundwater
UNCONFORMITY				
Early Tertiary	Kings Park Formation	540m	Shale, calcareous and glauconitic siltstone and minor sand	Local unconfined and confined aquifer; fresh groundwater
UNCONFORMITY				
Late Cretaceous	Poison Hill Greensand Gingin Chalk Molecap Greensand	40m	Glauconitic shale, siltstone and sand	Minor, locally confined aquifer
	Osborne Formation	260m	Glauconitic Sand and chalk	Semi-confining bed; local aquifer; fresh groundwater
UNCONFORMITY				
Early Cretaceous	Leederville Formation	500m	Sandstone, siltstone and shale, locally calcareous and glauconitic	Major confined aquifer; fresh to brackish groundwater

STRATIGRAPHIC SEQUENCE OF THE SWAN COASTAL PLAIN
Table 1

fine to very coarse sand, very slightly calcareous at depth. Below the leached section, the unit consists of limestone and calcareous cemented, fine to coarse sand. The contact between the leached sand and the unleached limestone is irregular, with pinnacles of limestone extending upwards into the sand.

Along the coast, the Tamala Limestone is unconformably overlain by Safety Bay Sand, consisting of calcareous sand up to 20 m thick. Alluvial deposition of Safety Bay Sand is continuing today.

Alluvial deposits of silt, clay, sand and gravel brought down from the Darling Range overlie the Guildford Formation and form the flood plains and terraces adjacent to the major rivers.

Colluvial scarpline deposits of clay, sand and gravel exist along the Darling Fault and Gingin Scarp.

3.7 GROUNDWATER

3.7.1 Occurrence

The superficial sediments form a heterogeneous unconfined aquifer which varies in composition both laterally and vertically (Figure 16). The aquifer has a saturated thickness of up to 60 m and contains 10% to 35% by volume of groundwater.

The aquifer is recharged from rainfall which is distributed, on an annual basis, fairly evenly across the coastal plain. Recharge leads to a build-up of water, forming mounds of groundwater in the sediments. This groundwater drains towards the boundaries of the aquifer under the action of gravity since the water table is higher than sea level. Groundwater mounds which have formed in the Northern and Southern Perth Areas are referred to as the

Gnangara Mound and the Jandakot Mound, respectively. The small Cloverdale Flow System has developed in the Eastern Perth Area (Davidson, 1984), where groundwater flows generally westward toward the Swan and Canning Rivers.

Figure 17 shows the October 1985 water table contours which indicate the mounds. Groundwater movement is perpendicular to these water table contours and occurs at an average rate of 50 to 100 metres per year.

The shape of the water table contours reflects the hydrogeological properties of the aquifer and the spatial distribution of net vertical flux to the aquifer. The water table rises gradually from the coast and reaches an elevation of 5 mAHD approximately 3 to 5 km inland. Over the next 5 km, the water table is much steeper and rises to 35 mAHD. The lower slope of the water table occurs in the highly permeable Safety Bay Sand and eolian calcarenite of the Tamala Limestone. The sandy sediments which comprise the leached sands of the Tamala Limestone, the Bassendean Sand and the Guildford Formation are less permeable, and the groundwater flows more slowly towards the sea. Hence, the slope of the water table along the boundary of these sandy sediments is higher. The variation in aquifer hydraulic conductivity across the study area (Figure 18) reflects the distribution of the different geological formations.

Drainage along the eastern boundary of the Gnangara Mound is to Ellen Brook. The water table elevation is therefore determined by the elevation of Ellen Brook. In this area, which is fairly flat, the water table is close to natural surface level and many wetlands have formed.

The shape of the water table contours in the western suburbs, north of the Swan estuary, indicates that lateral flow through peninsular areas like Cottesloe is a minor component of the local water balance. Groundwater resources in these areas are heavily dependent upon local recharge.

3.7.2 Recharge

Recharge to the aquifer is largely from rainfall which occurs in the winter months, and leads to a seasonal variation in the water table elevation of between 1.5 m and 7.5 m (Allen, 1981), depending upon the year and the location. Maximum and minimum water table elevations in the Applecross peninsula in 1984-85 are shown in Figure 19 and a plot for the whole study area of the differences which occurred in water table elevation between April and October 1985 are shown in Figure 20. In general, the water table is highest in September-October and lowest in March-April.

Seasonal recharge first occurs through lakes and swamps and later by infiltration from the land surface. Upward leakage into the superficial formations from the Leederville Formation also occurs in some areas.

Recharge to the aquifer varies annually, depending upon seasonal and climatic factors. Water balance modelling of the study area has shown that, for the climatic sequence experienced over the decade from 1976 to 1985, the recharge to the aquifer over the whole study area was approximately 19% of actual rainfall. Had average rainfall been experienced over that decade, the recharge would have been about 23% of average rainfall. With above-average rainfall (as defined in Section 6.3), up to 27% of that rainfall would have reached the groundwater system. The percentage of rainfall that reaches the water table can be seen to increase as rainfall increases.

The actual depth of recharge, averaged over the whole study area, would be 130 mm, 200 mm and 260 mm for below-average, average and above-average rainfall, respectively. Recharge during above-average rainfall periods would be twice that which would occur during below-average rainfall periods.

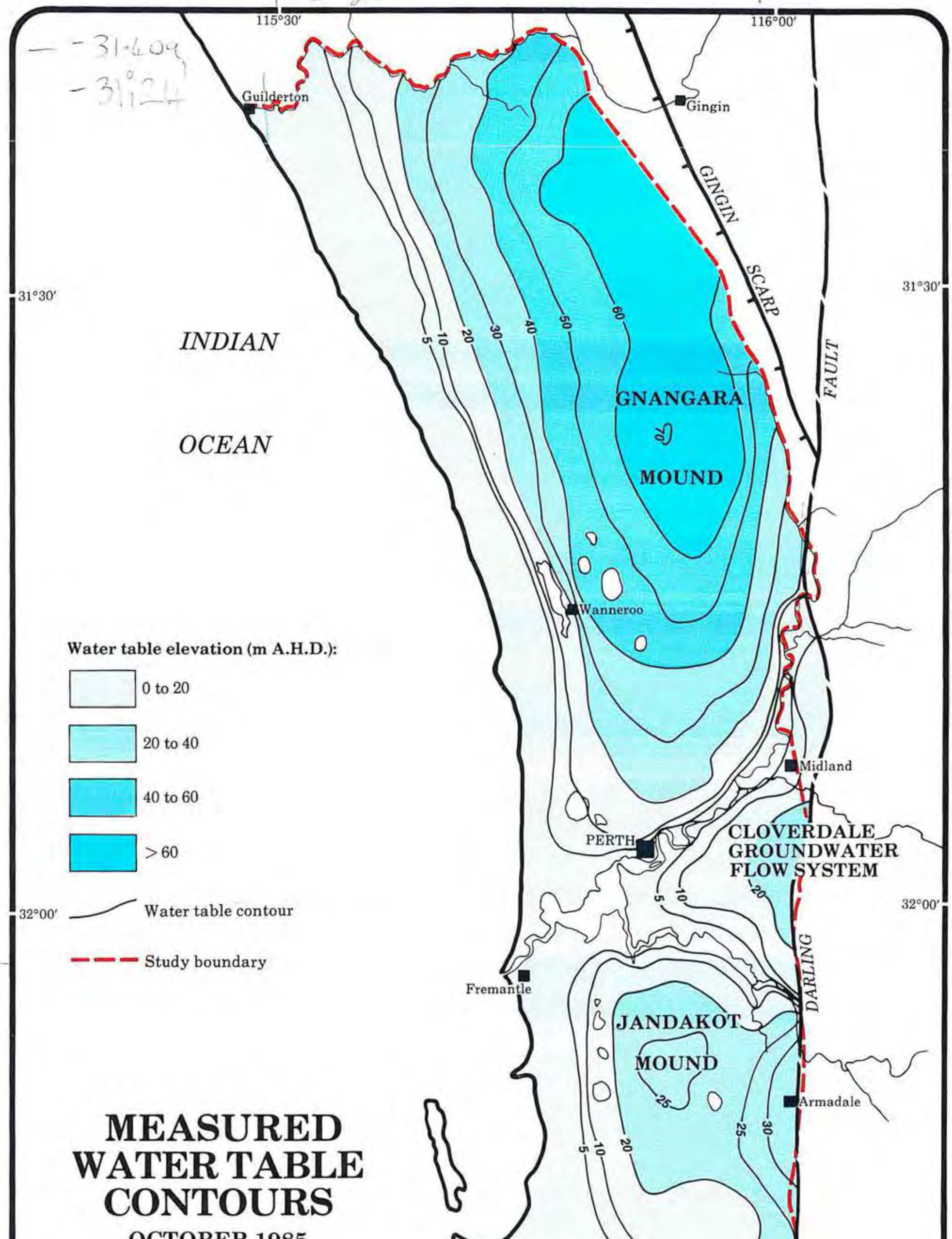
Recharge also varies spatially, depending upon land use, vegetation cover and depth to the water table. Recharge in urban areas, for example, includes roof runoff, which is concentrated in household "soak wells", and road runoff which is concentrated in larger "infiltration basins". Septic tanks and garden irrigation also contribute to recharge. From 1976 to 1985, recharge across the urban area of Perth was estimated to be 21% of rainfall, compared with 19% for the whole study area, i.e. 150 mm per year compared with 130 mm per year.

3.7.3 Discharge

Groundwater is discharged or extracted from the unconfined aquifer by evaporation from lakes and wetlands, by transpiration from vegetation with roots reaching the capillary fringe of the water table, by outflow to the ocean and major rivers and by leakage into the Leederville Formation (Allen, 1981). It also discharges to surface drains that intersect the water table and is abstracted by pumping from bores and wells.

3.7.4 Saltwater Wedge

Groundwater flowing to the ocean or the estuary discharges over a wedge of saltwater. When an aquifer is in hydraulic connection with the sea or an estuary, the salt water, being more dense than fresh water, forms a wedge extending inland underneath the fresh groundwater. The water within the wedge is derived from the sea



115°30'
116°00'
Guilderton
Gingin
GINGIN SCARP
FAULT
INDIAN
OCEAN
31°30'
5
10
20
30
40
50
60
70
GNANGARA
MOUND
Wanneroo
Midland
PERTH
CLOVERDALE GROUNDWATER FLOW SYSTEM
32°00'
DARLING
Fremantle
JANDAKOT
MOUND
25
Armadale
Rockingham
Water table elevation (m A.H.D.):
0 to 20
20 to 40
40 to 60
> 60
Water table contour
Study boundary
MEASURED WATER TABLE CONTOURS
OCTOBER 1985
5 0 5 10 15km
Scale

Figure 17

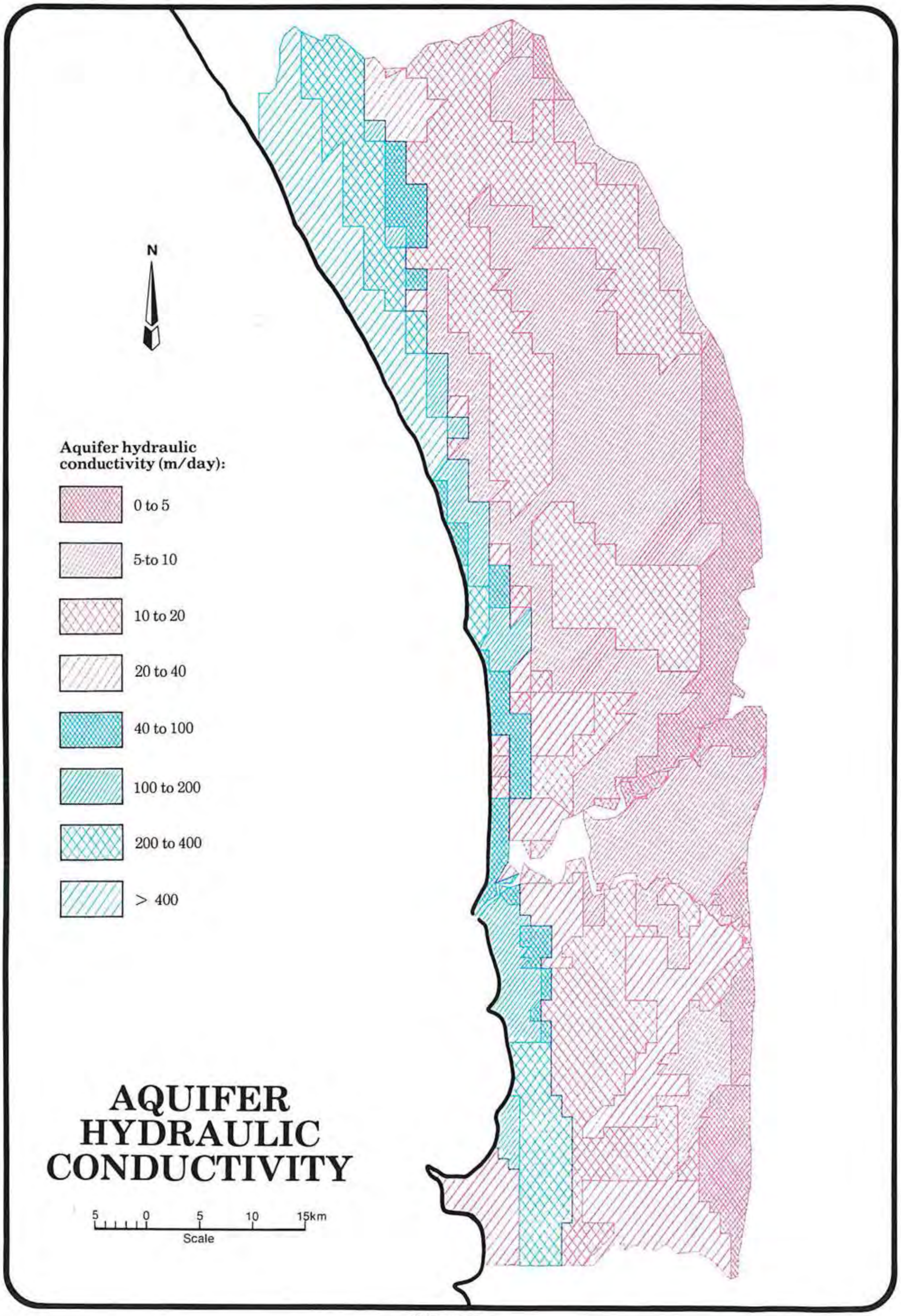
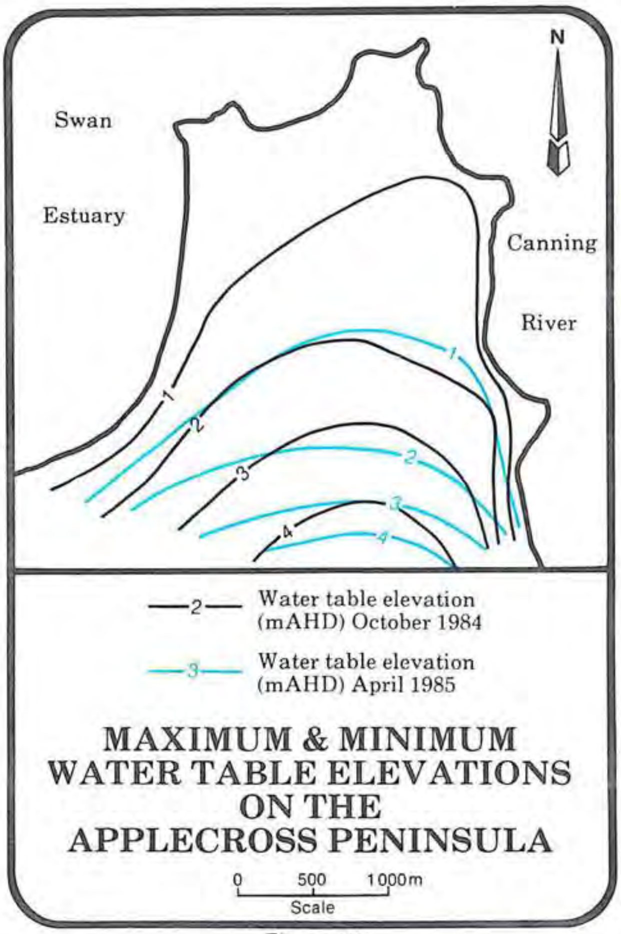

N
Aquifer hydraulic conductivity (m/day):
0 to 5
5-to 10
10 to 20
20 to 40
40 to 100
100 to 200
200 to 400
> 400
AQUIFER
HYDRAULIC
CONDUCTIVITY
5 0 5 10 15km
Scale

Figure 18

or estuary and remains essentially stagnant. The ionic composition of the water within the wedge may be different from that of sea water because of interaction with the aquifer host rocks. The interface between the fresh groundwater and the wedge is a diffuse zone, 5 to 15 m thick, across which the groundwater salinity increases from about 1000 mg/L to levels similar to sea water, i.e. over 30 000 mg/L.

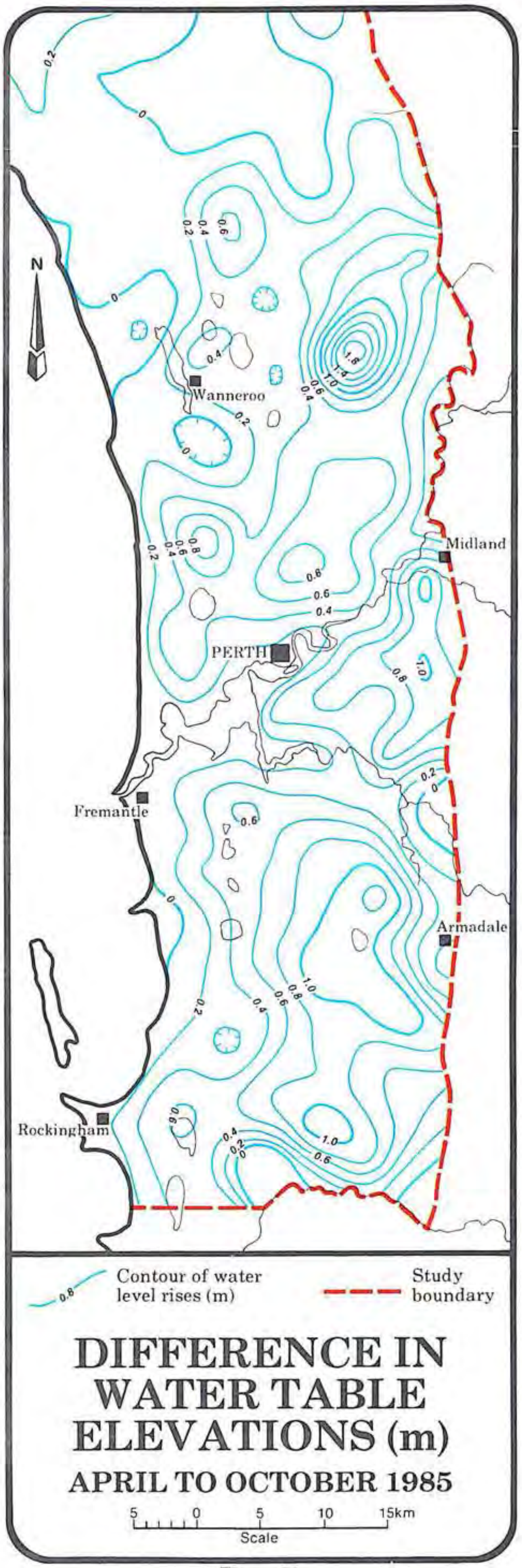
Within the inner urban area, a saltwater wedge only occurs in the unconfined aquifer in a narrow strip along the estuary and the coast. A wedge has not been observed where the water table elevation exceeds 1 mAHD (Figure 21). Outside the inner urban area, a relatively stable saline wedge has been observed at Kwinana (Haselgrove, 1981), Yanchep (Davidson, 1981) and inland of Lake Coogee (Western Australian Water Resources Council, 1983).

The shape of the wedge and its seasonal behaviour vary considerably around the shores of the estuary. A saltwater wedge was not detected in the unconfined aquifer at saltwater intrusion investigation sites DBN1/DBN3, BSM1/BSM2, IF10, IF11, IF13 or IF14, possibly because groundwater flows are sufficiently large to hold back the intrusion of salt water. Sites IF07 and IF12 showed elevated salinities at depths exceeding 18 m and 10 m, respectively. The Cottesloe peninsula is completely underlain



MAXIMUM & MINIMUM WATER TABLE ELEVATIONS ON THE APPLECROSS PENINSULA

Figure 19



DIFFERENCE IN WATER TABLE ELEVATIONS (m)

APRIL TO OCTOBER 1985

Figure 20

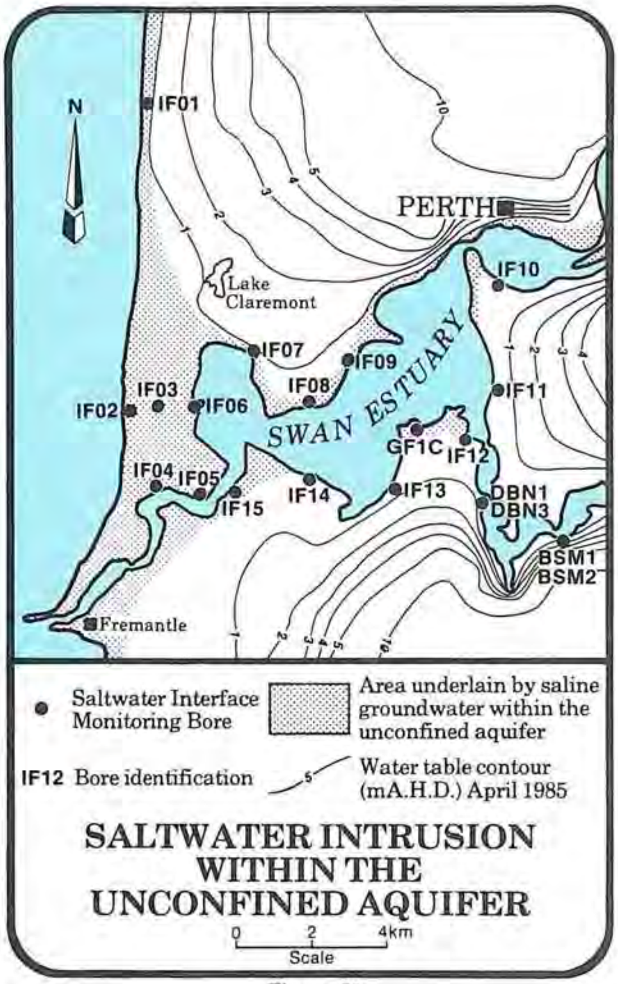


Figure 21

by salt water, the maximum thickness of fresh water being about 15 m, halfway between the estuary and the ocean. Salt water was observed over the full saturated thickness of the aquifer at site IF04 which is located approximately 70 m from the river bank.

3.7.5 Quality

Salinity. Groundwater salinity is generally lowest near the crest of the mounds and increases as groundwater flows towards the coast and estuary. Elevated concentrations of groundwater salinity occur down-gradient of wetlands (Section 3.8.1).

Groundwater with an electrical conductivity (E.C.) of less than 25 milliSiemens per metre (mS/m) [corresponding to a salinity of 140 mg/L total dissolved solids (T.D.S.)] is generally only found near the crests of the Gnangara and Jandakot Mounds. Near the coast, however, E.C. exceeds 100 mS/m (550 mg/L T.D.S.; Figure 22).

The anion composition of groundwater changes as the groundwater flows towards the coast. Near the crest of the Gnangara Mound, chloride is the dominant anion whereas in the Tamala Limestone there is a greater proportion of the bicarbonate ion. The cation composition is fairly uniform and is dominated by sodium.

pH. The hydrogen ion concentration (pH) of groundwater is generally higher in the limestone along the coast than further inland in the sand (Figure 23). Near the coast, the pH ranges between 6.5 and 7.5 and is probably controlled by the dissolution of calcite to form the weak acid bicarbonate ion. Further inland, it generally ranges between 4.5 and 6.5, possibly due to the hydrolysis and oxidation of dissolved ferrous iron and the presence of organic acids.

Eh. Groundwater with a high oxidation-reduction potential (Eh > 0.3 V) is found in the central part and near the coast of the Northern Perth Area, in the Eastern Perth Area and along the coast of the Southern Perth Area (Figure 24). Factors which may contribute to high Eh values in these areas include high porosity in the unsaturated zone, low depth to the water table and low concentrations of dissolved organic compounds.

Nitrate. The concentration of nitrate ions in groundwater commonly exceeds 1 mg/L within the urban area and is generally low outside urban areas (Figure 25). Levels are within standards set for drinking water.

Phosphorus. Total phosphorus concentrations in excess of 0.1 mg/L (Figure 26) are found in groundwater near the eastern margin of the coastal plain in the clayey parts of the Guildford Formation. Throughout the metropolitan region such phosphorus concentrations occur at only a few locations.

Sulphate. Sulphate ion concentrations generally range up to about 100 mg/L in the Perth region, however concentrations in excess of 200 mg/L were recorded along the coast between Woodman Point and Kwinana Beach and east of Cape Peron (Figure 27).

Normalising the concentration of sulphate ion against the chloride ion, to remove the effects of evaporative concentration, indicates areas where sulphate has been added to the groundwater (Figure 28). High values of the sulphate/chloride ratio near Kwinana are probably due to industrialisation, whereas high values near the crests of the Gnangara and Jandakot Mounds may be due to the oxidation of sulphides associated with wetland soils.

Monthly sampling across the Applecross peninsula indicated that the groundwater sulphate concentration may vary seasonally. Peak concentrations appear to occur in both summer and winter months and variations are greatest near the Swan estuary. Variations adjacent to the estuary may be due to seasonal movements of the saltwater wedge.

Iron. The distribution of total dissolved iron at

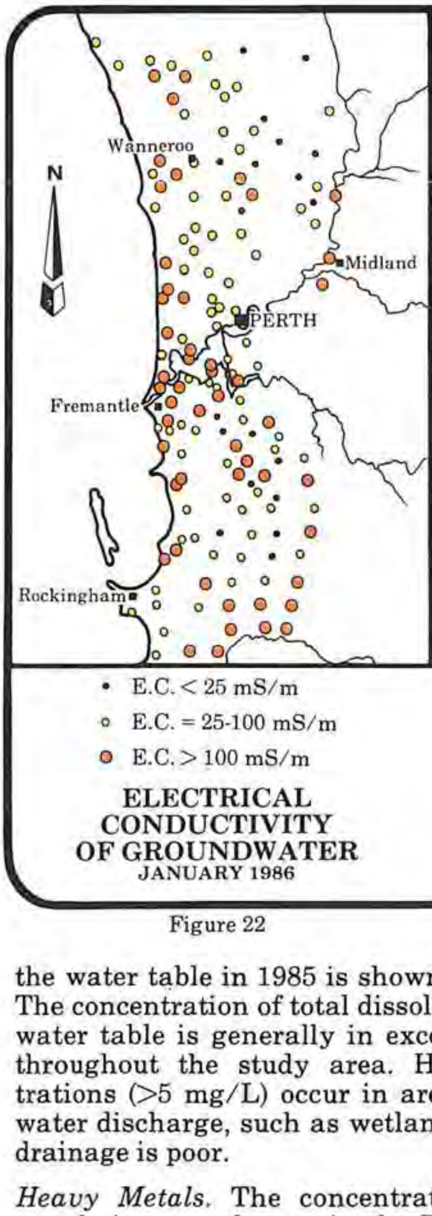


Figure 22

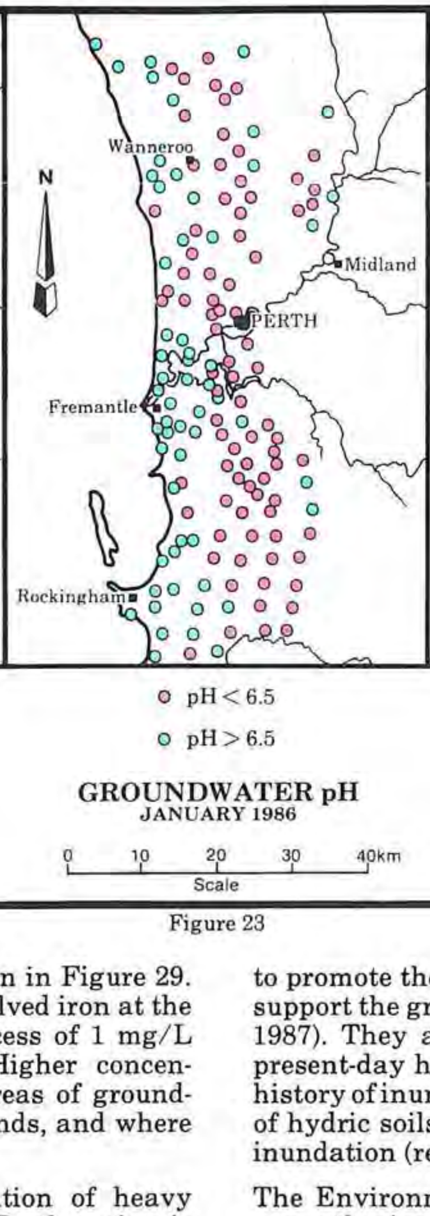


Figure 23

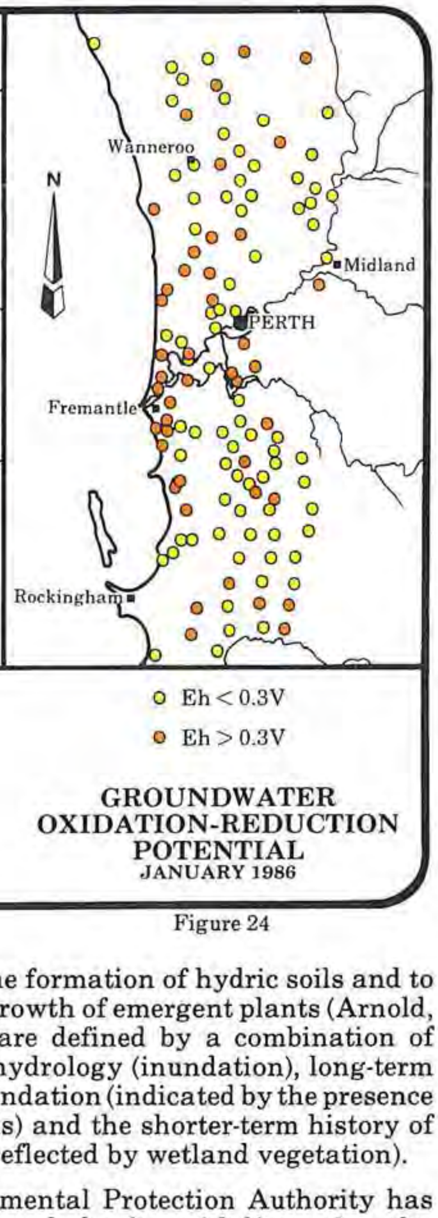


Figure 24

the water table in 1985 is shown in Figure 29. The concentration of total dissolved iron at the water table is generally in excess of 1 mg/L throughout the study area. Higher concentrations (>5 mg/L) occur in areas of groundwater discharge, such as wetlands, and where drainage is poor.

Heavy Metals. The concentration of heavy metals in groundwater in the Perth region is generally low. Localised elevated concentrations do occur, probably from point sources of contamination. These do not pose a threat to current or planned drinking water supplies.

Total Organic Carbon. The concentrations of total organic carbon recorded during the Study, which may include traces of organo-chloride pesticide compounds, were generally between 1 and 10 mg/L (Figure 30). In all samples tested for pesticides, the concentration was well below potable limits.

Water Temperature. The temperature of water at the water table varies seasonally, between 19°C and 23°C.

3.8 WETLANDS

For the purposes of this Study, wetlands are defined as areas where the water table is at or near the land surface for long enough each year to promote the formation of hydric soils and to support the growth of emergent plants (Arnold, 1987). They are defined by a combination of present-day hydrology (inundation), long-term history of inundation (indicated by the presence of hydric soils) and the shorter-term history of inundation (reflected by wetland vegetation).

The Environmental Protection Authority has recently issued draft guidelines for the management of Perth's metropolitan wetlands following growing recognition over the last 15 years of the importance of wetlands (Environmental Protection Authority, 1986).

3.8.1 Physical Characteristics

The Swan Coastal Plain in the Perth metropolitan region, has many shallow freshwater and saline wetlands and is crossed by the Swan estuary (Plate 9). The wetlands include shallow permanent and seasonal lakes and swamps (Plates 10, 11 and 12). Based on the occurrence of peats and other soils formed in waterlogged conditions, wetlands occupy a significant area of the coastal plain. The major wetlands of the region, with an approximate area of 9000 ha, were reviewed for this Study (Arnold, 1987).

The lakes and swamps of Perth's wetlands are expressions of the unconfined groundwater above the ground surface and water levels vary

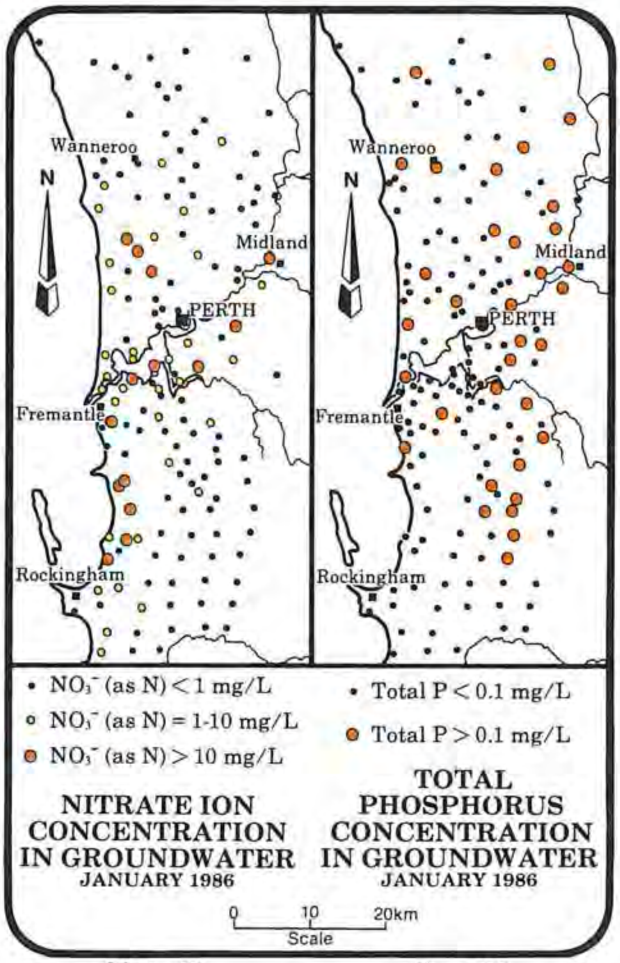


Figure 25 Figure 26

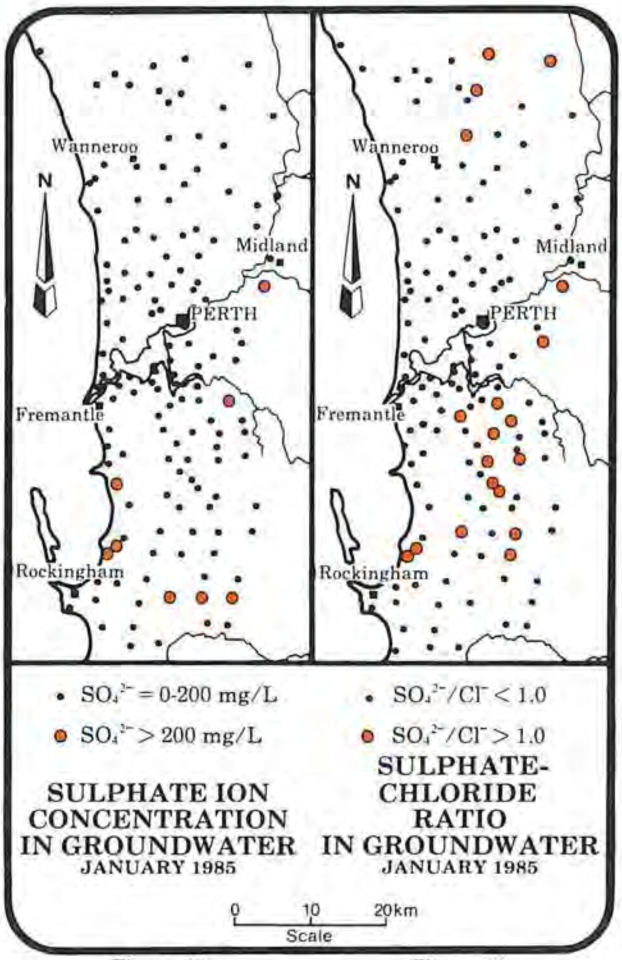


Figure 27 Figure 28

in sympathy with the elevation of the water table. Since they are shallow water bodies (with depth less than 3 m), long-term changes in the water table elevation from the normal seasonal variations may present a serious stress to wetland ecosystems.

Wetlands often act as compensating basins within local drainage systems and most lakes have at least one, and often several, drains discharging to them.

Groundwater salinity is affected by wetlands where the concentration of solutes is increased by evaporation and transpiration. Detailed studies of groundwater movement near some wetlands in the Perth area have shown that groundwater salinity down-gradient of wetlands is significantly higher than up-gradient (Figure 31; Allen, 1980; Davidson, 1984; Hall, 1985).

The range of wetland types occurring within the study area is limited, according to classification systems designed for large regional or continental inventories of aquatic systems. Nevertheless there are many subtle differences between the lakes and swamps which reflect differences in their origin and history, as presented in the following examples (see Figures 12 and 32):

- the Wanneroo chain of wetlands are associated with karstic formations of the Tamala Limestone;
- chains of lakes are formed in interbarrier depressions on old shorelines, e.g. East Beeliar chain, Lake Pinjar to Gnangara Lake;
- Lakes Cooloongup, Walyungup and Richmond are lagoons of marine origin, isolated from the ocean by the beach ridges of the relic foredune plain around Rockingham; and
- seasonal wetlands in the Bassendean Dunes have formed in interdunal swales where the water table intersects the ground surface. Along the eastern edge of the Bassendean Dunes, they have formed where groundwater discharges to streams such as Gingin and Ellen Brooks, north of the Swan River, and Southern River, south-east of the metropolitan region. Small mounded springs occur in some of these discharge zones.

3.8.2 Biological Significance

The wetlands are areas of high biological productivity and directly or indirectly support most of the wildlife of the Swan Coastal Plain.

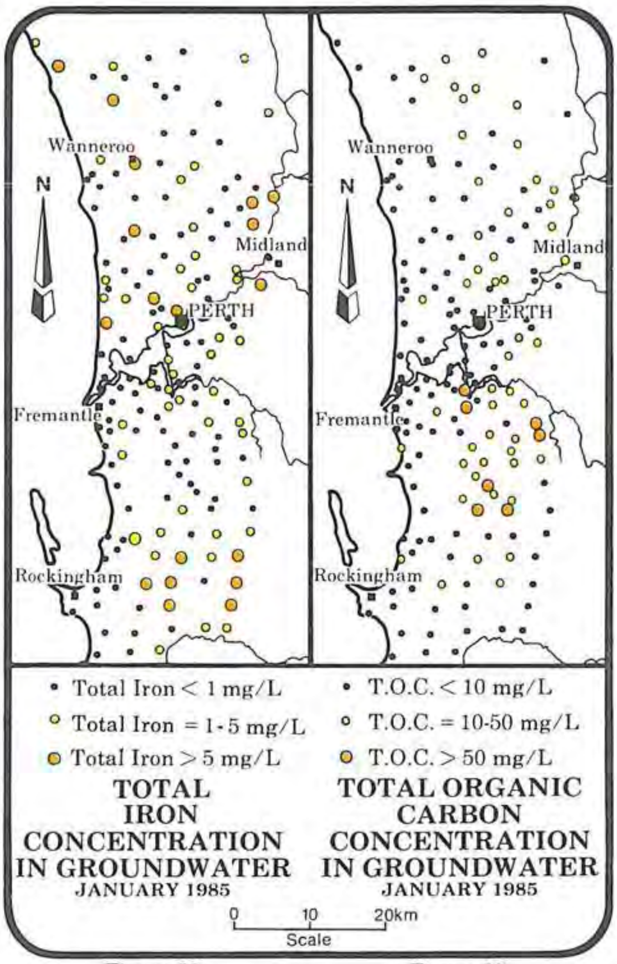


Figure 29 Figure 30

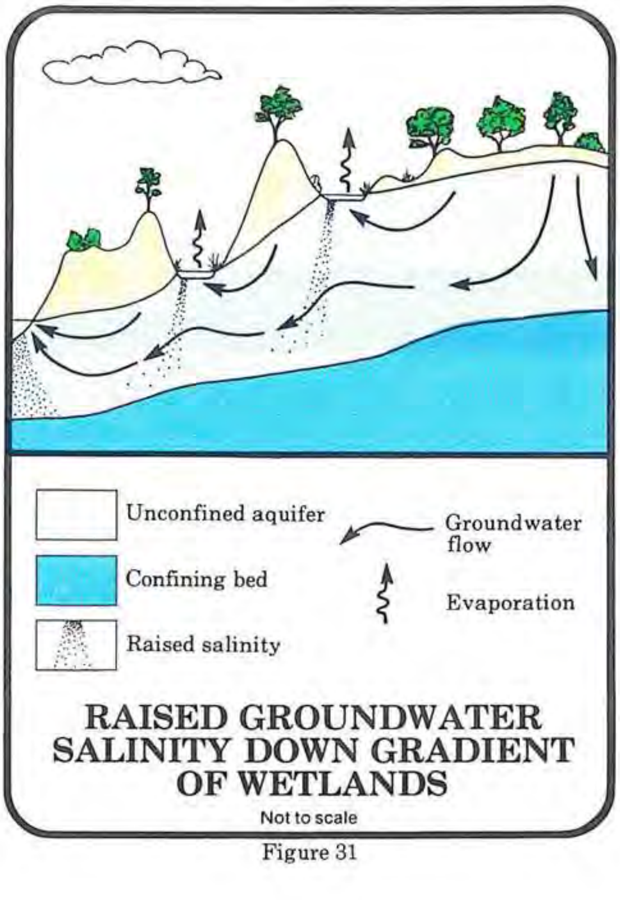


Figure 31

Plate 9 Perth on the Swan Estuary

Their importance extends beyond the coastal plain, however, as they are visited each year by large numbers of migratory wading birds from the northern hemisphere (Australia is signatory to international treaties which oblige it to protect the habitats of many of these species) and by water birds which move to the coast as inland water bodies contract during summer.

Wetland vegetation is central to all wetland processes (Plate 13). It extracts nutrients from the water and the atmosphere, provides the primary production for wetland ecosystems and provides a range of habitats for aquatic and terrestrial fauna. The wetland plant communities have been significantly altered by clearing, grazing and fire (Plate 14) and there have been notable expansions in the distribution of invasive species such as *Typha orientalis* (Plate 15).

Birds are very conspicuous in their wetland habitats. The diversity of bird species using wetlands is determined by the complexity of the wetland environment, which depends mainly upon water depth and vegetation structure. A wide range of wetland habitats exist in the Perth region, satisfying the specific requirements of a large number of species.

The microscopic flora and fauna are important but poorly known elements of wetland ecosystems. They include free swimming and sediment dwelling invertebrates, phytoplankton and zooplankton and the fungi and bacteria involved in breaking down detritus.

Aquatic macroinvertebrates are responsible for a significant proportion of the secondary production occurring in wetlands. Much of the documented waterfowl diversity and abundance is likely to be a direct consequence of the macroinvertebrate food supply.

WETLANDS OF THE PERTH REGION

Index to wetlands:

Adams	B3
Alfred Cove	B5
Badgerup	B4
Balannup	B6
Banganup	B6
Banjup	B6
Beenyup	B4
Bennett Brook	C4
Beonaddy	A3
Bibra	B6
Blue Gum	B5
Bollard Bullrush	B7
Booragoon	B5
Brownman	B6
Canning River	B5
Carabooda	A3
Careniup	B4
Carine	B4
Claremont	B5
Coogee	B6
Coogee Springs	A3
Cooloongup	B7
Emu Swamp	B4
Forrestdale	B6
Gnangara	B4
Goolelal	B4
Gwelup	B4
Hazelmere	C4/5
Herdsman	B5
Hyde Park	B5
Interchange Wetlands	B5
Jackadder	B4
Jandabup	B3
Joondalup	B3/4
Karrinyup	B4
Kogolup	B6
Little Mariginiup	B3
Little Rush	B6
Loch McNess	A2
Long Swamp	B6
Mabel Talbot Park	B5
Malaga	B4
Manning	B6
Mariginiup	B3
Mary Carroll Park	C6
Melaleuca Park	B3
Mindarie	A2
McDougall Park	B5
Monger	B5
Mt. Brown	B6
Mussel Pool	C4
Neerabup	A3
North Lake	B6
Nowergup	A3
Perry Lakes	B5
Piney	B5
Pinjar	B3
Pipidinny	A2
Pickle Swamp	B7
Richmond	A7
Roe Swamp	B6
Shenton Park	B5
Sloan's Reserve	B7
Snake Swamp	B4
South Lake	B6
Star Swamp	A4
Swan River Foreshore	B5
Tamworth	B7
Thomsons	B6
Tomato	B5
The Spectacles	B6
Twin Swamps	C3
Walluburnup	B4
Walyungup	B7
Wattleup	B6
Wilgarup	A2
Wright	C6
Yangebup	B6
Yule Brook Reserve	C5
Yonderup	A2

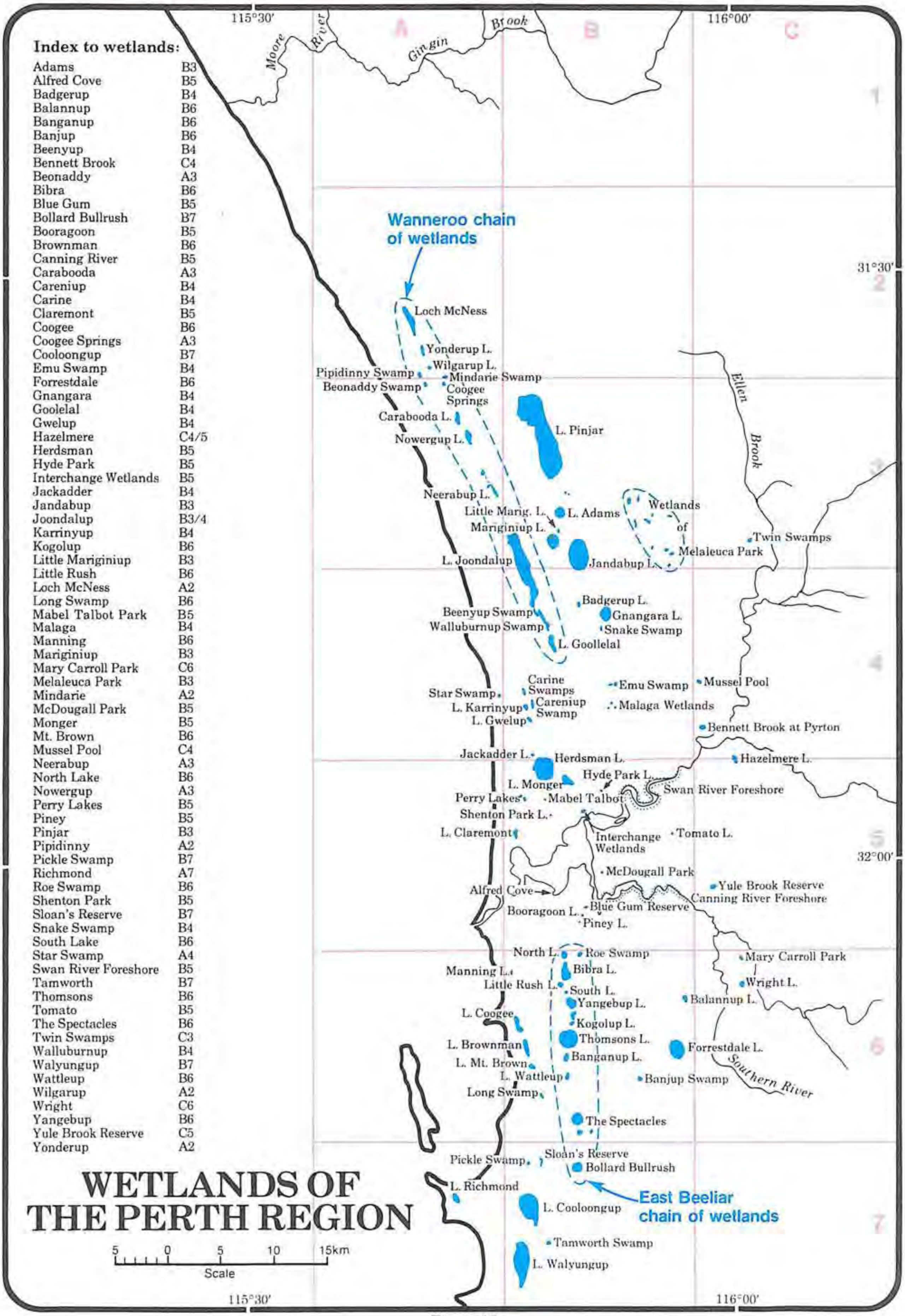


Figure 32

Plate 10 Lake Monger

Plate 11 The Spectacles

Plate 12 Forrestdale Lake at the end of summer, 1986

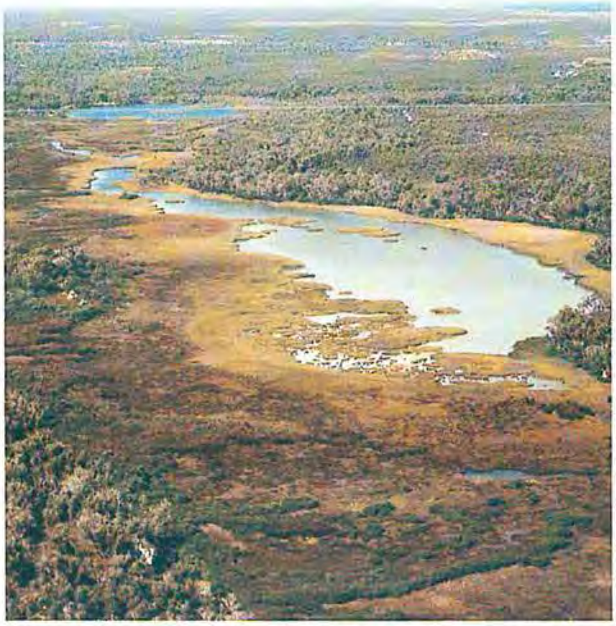


Plate 13 Vegetation of Loch McNess

Plate 14 Clearing for recreational purposes — Big Carine Swamp

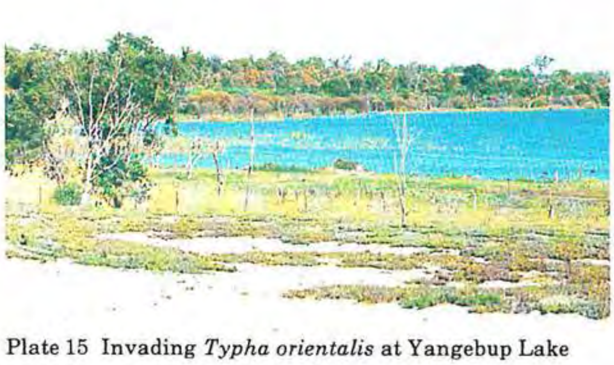


Plate 15 Invading *Typha orientalis* at Yangebup Lake

MANAGEMENT OF GROUNDWATER

4.1 AN HISTORICAL OVERVIEW

The management of Perth's groundwater resource is largely influenced by community attitudes to drainage, wetlands, sanitation and water supply. These attitudes gradually evolved from colonial concern for adequate sanitation, drainage and water supply into the attitudes of today's environmentally conscious society, which is concerned for the remaining urban wetlands as well as for the maintenance of a readily available groundwater resource.

Water has been a major preoccupation with the people of the Perth region, at least since European settlement (Morony,1980). The colony was founded on the strength of Captain James Stirling's optimistic reports of his 1827 exploration in which he concluded that "the Swan River area's supply of fresh water from springs and lagoons is abundant". It did not take long, however, for the early settlers to see how over-optimistic Stirling had been. In the first summer of the Swan River Colony, in 1829, they existed on meagre rations from shallow wells, lakes and small streams; in the summer of 1833, the lakes dried up, leaving the settlers to depend on their wells and a few springs (Gentilli, 1979).

By the early 1870s there was an increasing concern in the colony about sanitary conditions and their link with disease. The general system of sewage disposal in the town was a closet with an unbricked adjoining cesspit, often only a few metres from a well.

In 1885, in response to growing community concern, a Commission of Enquiry established what could be considered the first management guidelines for groundwater. The Commission recommended that, in addition to a good supply of water being introduced in both Perth and Fremantle, dry-earth closets should be made compulsory within certain limits; that cesspits in defined areas should be emptied and filled in within six months; and that sewage be disposed of outside municipalities or in areas approved by inspectors.

Wetlands were regarded as a nuisance and as an obstruction to development. In 1847, a major medical report on the link between the swamps and diseases in the town was made to the Governor by the Colonial Surgeon, Dr L. Ferguson, who concluded that the lakes were prejudicial to the health of the community and that as Perth's population increased they should be completely drained (Bekle, 1981).

Flooding was another problem necessitating drainage works. There were frequent petitions seeking government action to overcome flooding. Drainage work was undertaken over the years but problems continued and on-going expenditure is still being incurred in upgrading and maintaining drainage facilities.

At the beginning of this century the official view of wetlands was of "many small fresh-water lakes, the majority of which are nothing more than swamps during the dry season, and none of them are of any economic importance" (Bekle, 1981). The history of Shenton Park Lake (Plate 16) is presented as an example of the evolution of the community attitudes towards wetlands and groundwater management in the Perth region (from Spillman, 1985).

What is now Shenton Park Lake is known to have been a popular gathering place for local aborigines prior to European settlement. At the time of European settlement the "lake" was a large reedy swamp that dried up completely during summer leaving only a flat of mud and brownish reeds. Known as Dyson's Swamp, it was frequently used as a stopping off point by settlers travelling between Perth and Fremantle. In 1877 the property was sold to George Shenton who recognised the potential of the area for future development.

In 1897 the local residents made the first moves to have the area developed and "improved"; eight hectares of land around the swamp were transferred to Council ownership and it soon became known as Shenton Park Lake.

It was not uncommon for some of the young families of the area to take advantage of the

Plate 16 Shenton Park Lake

locality's wildlife for food and to many the lake became a convenient dumping ground for rubbish.

As development increased in the area, groundwater levels rose and the smallish seasonal marsh became a permanent and expanding swamp. Old, shady trees by the swamp's edge were drowned by the higher water levels.

Flooding soon became a problem and residents from all parts of the municipality were encouraged to dump their rubbish at the lake in a sustained effort to keep houses habitable and roads traversable. By such primitive means, the total area of the swamp was gradually reduced; but flooding was not brought under control until 1929, when a pump house was erected. In 1933, the Metropolitan Water Supply, Sewerage and Drainage Department commenced a permanent drainage scheme for the Lake.

During the decade after 1955, Shenton Park Lake reserve was developed as an intensely managed recreation area. A sprinkler system was installed and lawn and trees were established.

In 1963 the Subiaco Council removed an extensive bed of reeds, causing a public furore, with nature lovers claiming that bird-life at the lake would be adversely affected. To some, however, all this fuss seemed absurd: Shenton Park Lake reserve had, after all, been a rubbish dump for more than forty years.

In spite of these periodic controversies, Shenton Park Lake has become one of modern Subiaco's show places.

Before 1880, water supplies for the colony were drawn largely from shallow wells, and there were proposals from time to time to develop the lakes to the north of Perth for public water supplies. By the late 1870s, the focus of water supply development for Perth shifted to the "hills" sources and, in 1891, the Victoria Reservoir on Munday Brook was opened. Since 1897, the water for Perth has also been supplied from artesian bores.

Despite the development of better quality water supplies, many people could not afford connections and most people in the city still used wells and water bags. Following public pressure in the early 1920s to improve the supply of water to Perth, the Government proposed a rapid development of the hills resources. After completion of the Churchman's Brook and Wungong Brook pipehead dams, the consumption of bore water decreased from 2.3×10^6 m^3 in 1925/26 to 1.5×10^6 m^3 the following year. (The consumption of hills water increased from 0.6×10^6 m^3 to 1.6×10^6 m^3 in the same period.)

The hills sources were further developed with the construction of the Canning Dam in 1940, the Serpentine pipehead dam in 1957 and the Serpentine Dam in 1961.

It was soon after the completion of the Serpentine Dam that government interest in the use of shallow groundwater as a water resource was renewed. In 1963 a special Hydrogeology Section of the Geological Survey Division of the Mines Department was established to engage in groundwater investigation. Thus, the systematic assessment of the State's water resources and the use, again, of unconfined groundwater to supplement the State's water supplies commenced.

The first groundwater to be drawn from the extensive shallow groundwater resources of the Perth region was from the Mirrabooka scheme, commissioned in 1970. Schemes were later constructed at Gwelup (1974), Wanneroo (1976) and Jandakot (1979) (Figure 33).

In response to water restrictions during the mid-1970s, private domestic abstraction from the unconfined aquifer increased dramatically. There are now approximately 77 000 private domestic wells, plus bores from which water is drawn for market gardens, public open space and industry. Private unconfined groundwater development forms a valuable secondary water supply system that has reduced the demand for reticulated supplies and has therefore meant lower costs to the Water Authority's customers.

4.2 FACTORS AFFECTING THE URBAN WATER BALANCE

Clearly there have been a number of changes of attitude towards water in Perth since early settlement. Water management, at various times, responded to demands for increased water supply, for control of potential sanitary problems, and for control of flooding. Different responses had different effects on the water balance.

Many of the factors which affect the urban water balance are related to the expansion of urban areas. The transition in land use, from natural-to-rural-to-urban, causes changes in groundwater recharge and discharge processes, leading to changes in the volume of water stored in the aquifer and, hence, to changes in the water table elevation.

Any actions which influence the movement of significant quantities of water can affect the regional water balance. Management strategies are a collection of planned actions which may be implemented to control recharge or discharge to alter the regional water balance so that problems or potential problems can be avoided.

The Water Authority draws water from the unconfined aquifer in four Public Water Supply

Areas: Mirrabooka, Gwelup, Wanneroo and Jandakot. The total abstraction from each of these schemes is plotted for the period 1979 to 1984 (Figure 34) to show the fluctuations in quantities of groundwater drawn for public supplies. Extensions to the public water supply schemes are proposed in the Pinjar, Yeal, Barragoon, Lexia and Jandakot areas as shown in Figure 33. When complete, the water supply system will cater for the needs of urban Perth under full Corridor Plan development.

Bores operated by local authorities, institutions and private householders are distributed across the entire urban area and large horticultural areas exist in the Northern and Southern Perth Areas (Figure 35).

The Metropolitan Water Authority (1985*a*) estimated that each private domestic bore user abstracts an average of 1000 m^3 from the aquifer each year, applying 12.7 mm of groundwater to their garden each day during summer. This is well in excess of the Department of Agriculture recommendation of 4 mm per day needed to maintain an adequate lawn (Department of Agriculture, pers. comm., 1985) and the CSIRO recommendation of 16 mm per week (CSIRO, 1979).

With irrigation rates as high as are currently used, vegetation transpires at the maximum possible rate (at the rate of potential evapotranspiration) and excess irrigation water returns to the aquifer. Since plants can be maintained at less than their potential evapotranspiration rates (Western Australian Water Resources Council, 1986*b*), the amount of water that needs to be pumped from the aquifer can be reduced (Figure 36). By avoiding the recirculation of irrigation water, the cost of pumping and the leaching of contaminants and fertilisers to the aquifer are reduced. The latter reduces the cost of fertilising and has a beneficial effect on the regional groundwater quality. By applying only the minimum amount of water sufficient for adequate growth of the garden, less water needs to be pumped from the aquifer so that regional water levels will be higher and pumping costs will be reduced.

The type, density and distribution of vegetation also affect the water balance. Plants have root systems which extract water mainly from the unsaturated soil zone, however some species known as phreatophytes may extract water directly from the saturated zone. Actions which affect evapotranspiration include the clearing of natural vegetation for urban development (Plate 17) and the development and management of pine plantations (Plate 18). In the former case, there is a significant temporary reduction in evapotranspiration, often leading to local rises in groundwater levels. Replacement with urban garden vegetation will reverse the

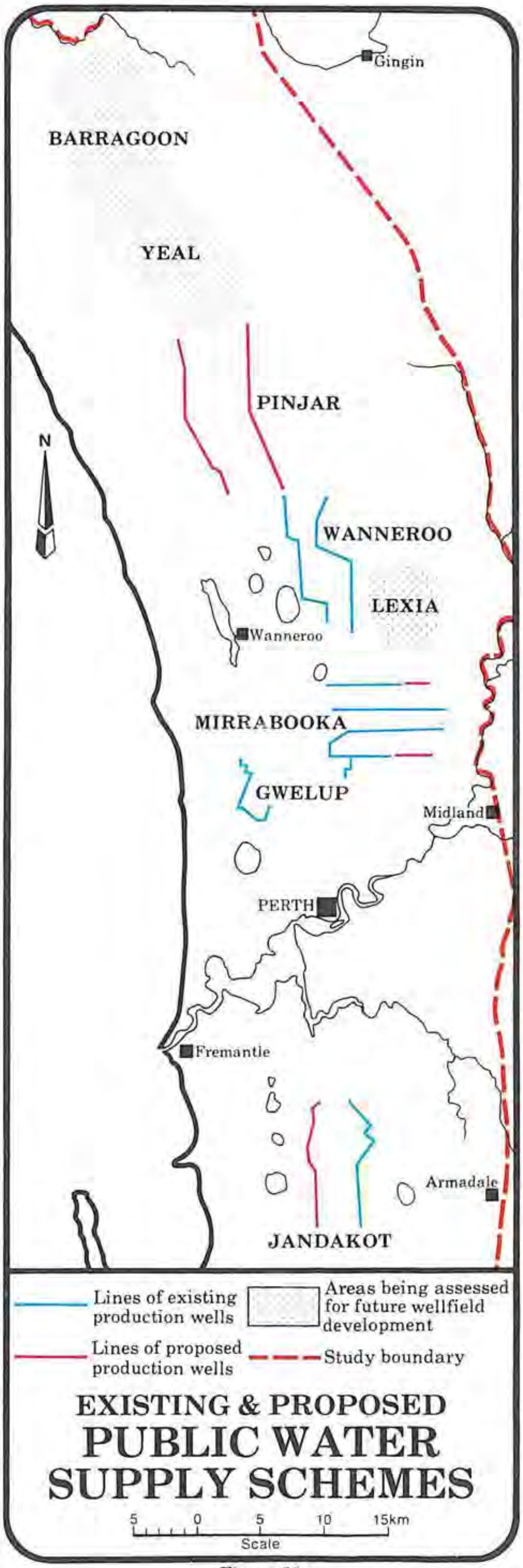


Figure 33

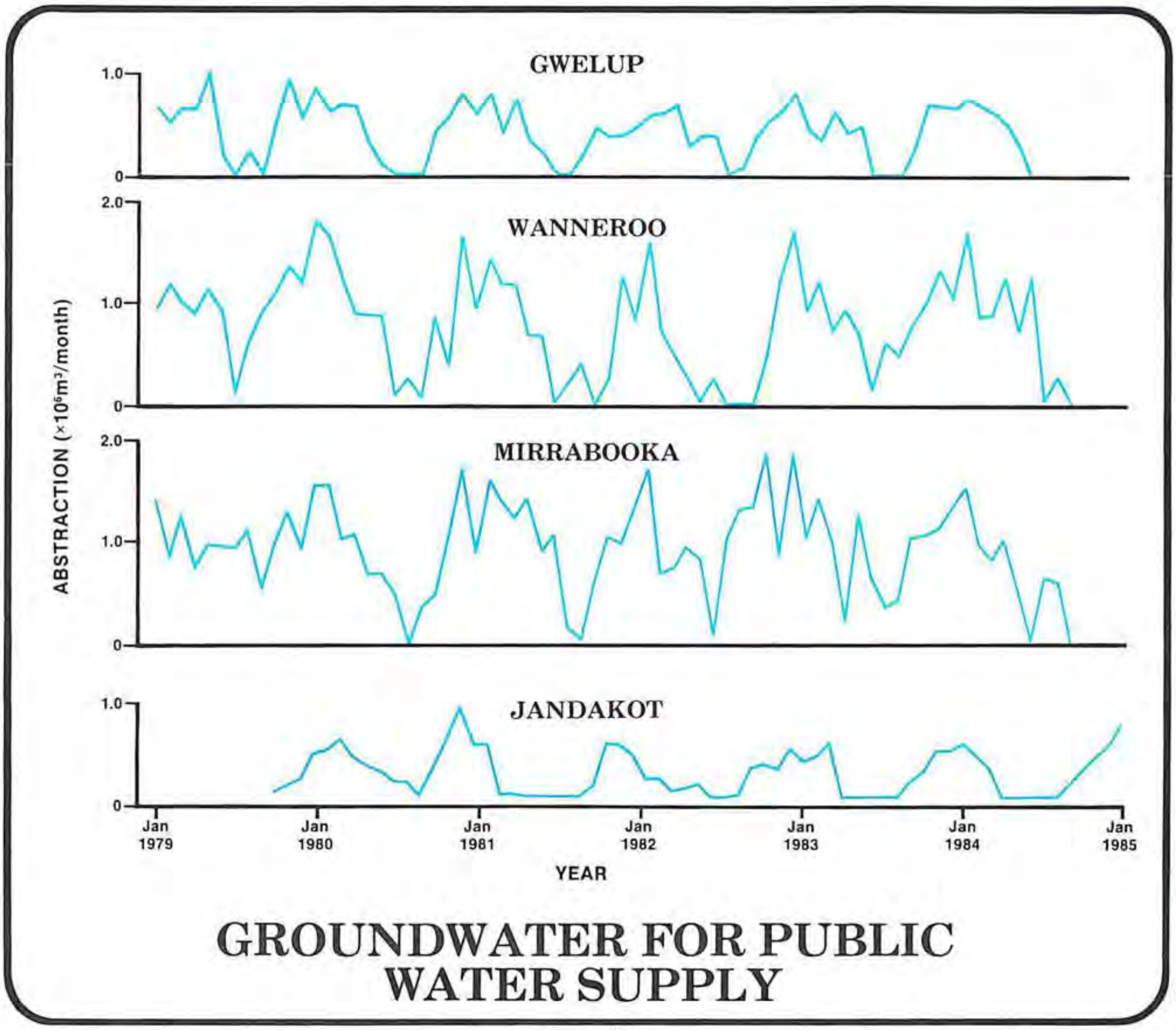


Figure 34

trend in water table movements and may ultimately lead to a return to original or higher evapotranspiration rates. Pine forests have been established in the Northern Perth Area and are currently in various stages of growth, from seedling to fully mature stands. Evapotranspiration varies significantly as the pine forest matures.

Figure 37 shows a hydrograph of recorded levels in an observation bore in Piercy Way, Kardinya, in the Southern Perth Area. The maximum water levels recorded each year in this bore tended to rise despite below-average rainfall occurring in the period from 1970 onwards.

Piercy Way is within stage 1 of three stages in the development of a land subdivision at Kardinya and, in the groundwater flow system, it is immediately downgradient of Murdoch University. Before 1973, all areas now covered by Murdoch University and the residential development of Kardinya and Winthrop were covered by about 880 ha of mature pine forest. From 1973, these pines were cleared in stages.

Despite the period of below-average rainfall, recharge to the aquifer has remained high because of the large reduction in evapotranspiration following clearing of the pine forest. Rising water levels in the area have placed many of the older homes at risk of flooding and immediate action is needed to protect these homes.

A second water table hydrograph (Figure 38) shows the effect of clearing the native vegetation, and subsequent revegetation with pine trees. Observation bore GN20 is within 1500 ha of pine forest east of Lake Pinjar in the Northern Perth Area. The forest was planted in 1973 after the area was cleared of native banksia woodland vegetation over the previous two years. The observation bore is at the north-eastern extremity of the Wanneroo Public Water Supply Area, near a production bore from which groundwater has been pumped since 1985.

From 1972 to 1974, the water table rose sharply due to the combined effect of clearing and above-average rainfall. It has steadily fallen since, due

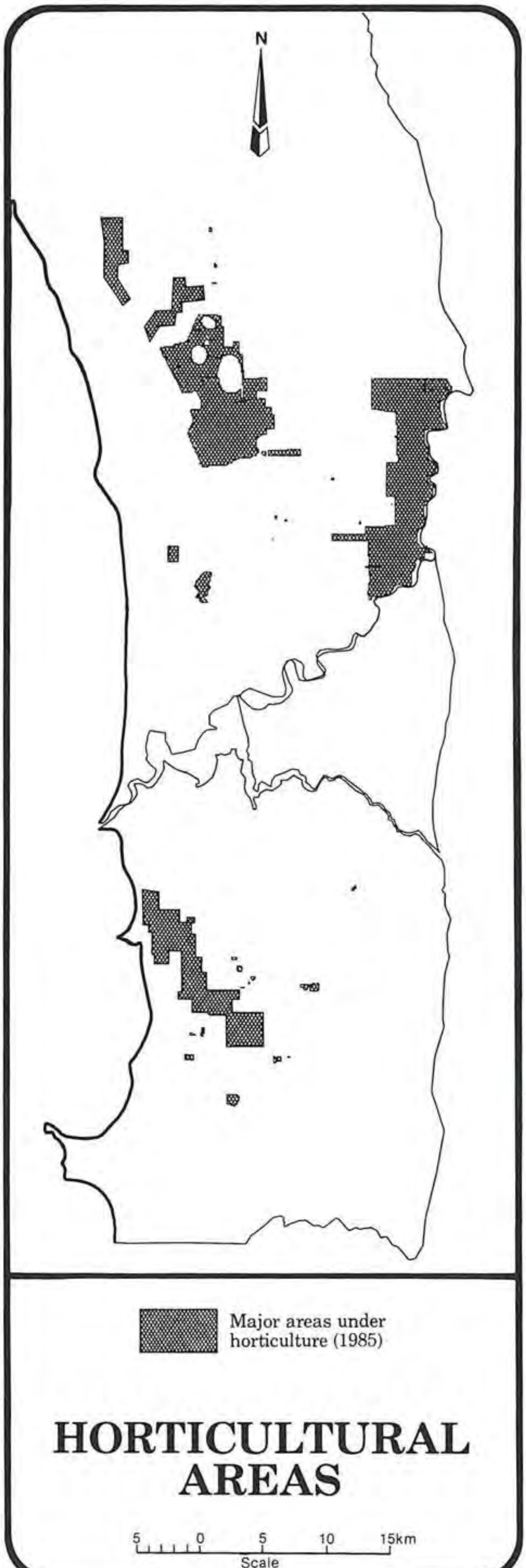


Figure 35

to increasing interception and transpiration losses from the growing pine trees. A noticeable fall in the water level occurred in 1985 following commissioning of the nearby production bore. Before then, there may have been a slight effect on water levels at bore GN20 from the more distant production bores. In the few years prior to clearing, the water table fell in response to below-average rainfall.

The distribution of sewered and non-sewered areas has a small effect on recharge to the water table. Most of the water supplied by the Water Authority to householders using septic tanks is discharged into the ground and increases

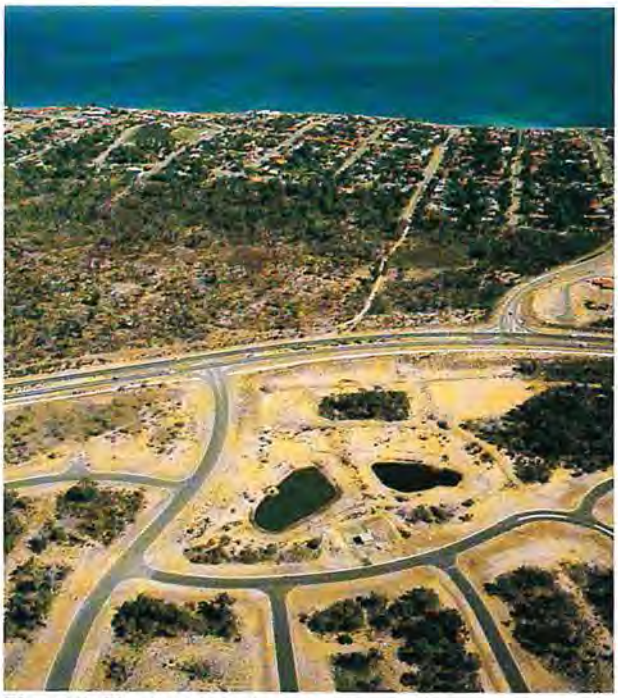


Plate 17 Clearing for urban development

Plate 18 Pine plantations in the Northern Perth Area

recharge to the aquifer. In sewered areas, water used in the house is exported through the sewerage system and discharged to the ocean, although it may be feasible in future for treated sewage to be used to artifically recharge the aquifer in areas where additional recharge would be beneficial. Current sewered areas are shown in Figure 39. Septic tanks are still in use in the recently sewered established urban areas and it is expected that individual septic tanks will remain in use until major maintenance becomes necessary, justifying the expense of connecting to sewer.

Roof runoff in urban areas is discharged either to the ground surface or to soak wells, the latter providing more effective recharge. Road runoff is discharged either to the ocean, to the Swan estuary, to some wetlands or to infiltration basins. Infiltration basins are extremely effective for recharging the aquifer. Drainage systems have been constructed by the Water Authority to serve the area shown in Figure 40, although in many of these areas, infiltration basins and soak wells are also in use.

In some urban areas lying on the less permeable parts of the Guildford Formation near the Swan estuary, water-logging problems have been experienced because the water table commonly reaches the ground surface. To make the area suitable for residential and industrial development, an extensive network of drains has been installed to maintain the water table below ground level (Plate 19).

Nearly all of the above factors can be managed, either locally or regionally, to alter the water balance.

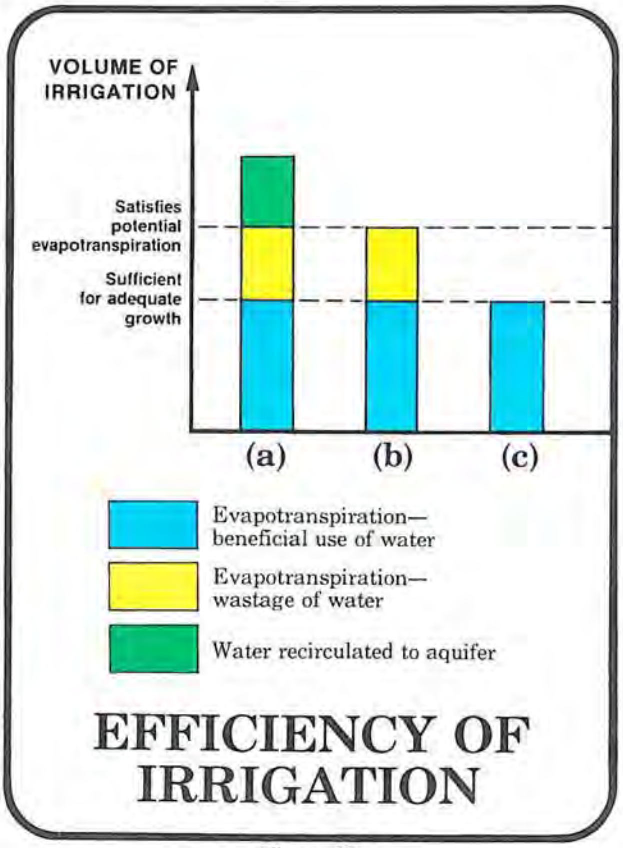


Figure 36

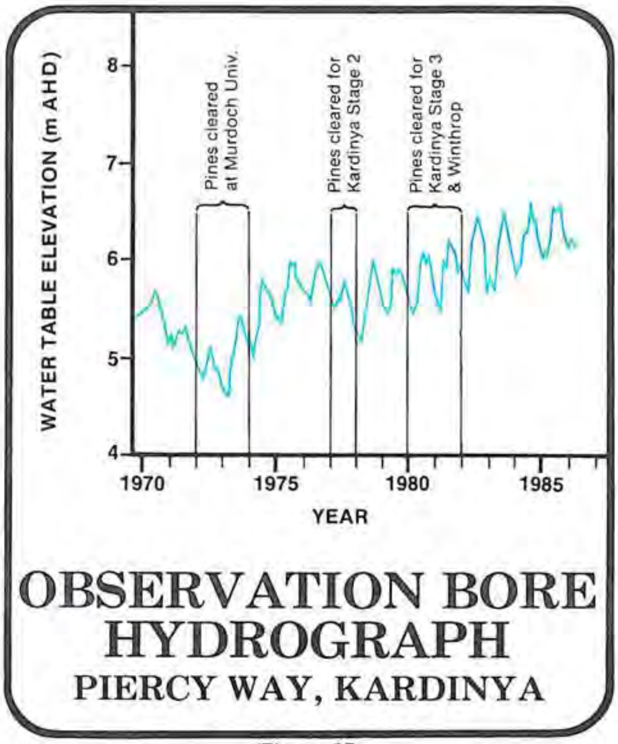


Figure 37

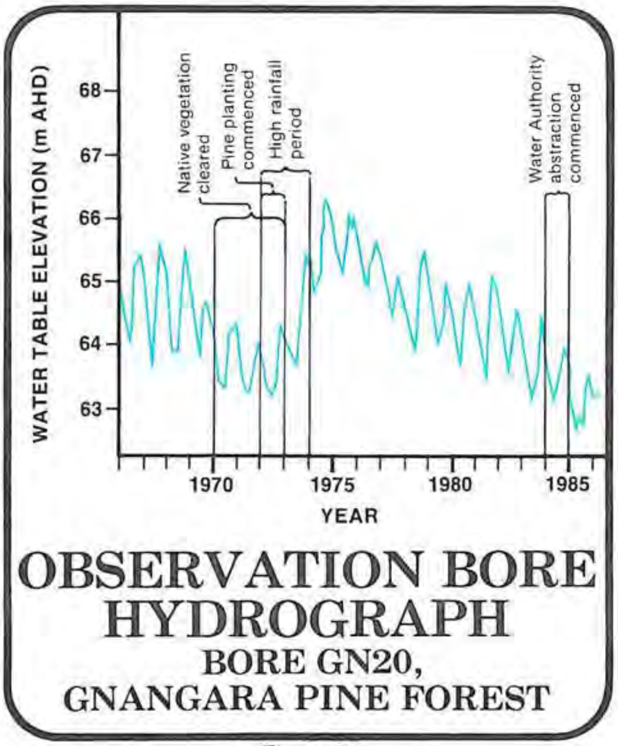


Figure 38

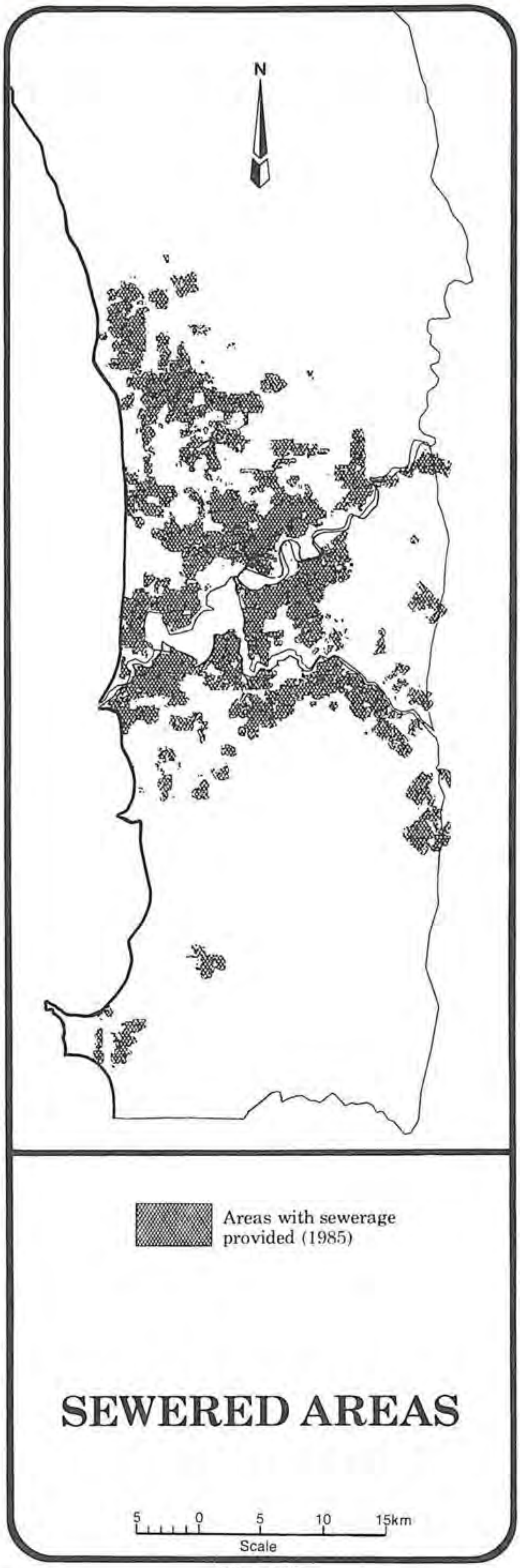


Figure 39

Plate 19 The Bayswater Main Drain

4.3 PRESENT CONTROL OF THE MANAGEABLE FACTORS

Control of pumping is usually considered to be the principal water management technique. Pumping is an important component of the overall water balance, but control of pumping should always be considered in conjunction with control of other components. All current controls affecting the groundwater system are outlined below.

4.3.1 Pumping

The principal uses of groundwater from the unconfined aquifer are private domestic use, local government and institution irrigation, commercial irrigation, industrial use, public water supplies and rural supplies.

The Water Authority supplies potable water to Perth's residents. The metropolitan area has a single integrated supply system drawing from both surface and groundwater sources. Public, private and environmental requirements for groundwater are taken into account in the development of management strategies, which are implemented for the overall benefit of the community and to maintain a continuity of supply to groundwater users.

Once the Water Authority has developed a groundwater source, the effects of abstraction are monitored and the abstraction program is regularly reviewed to ensure that the impacts are contained within acceptable limits. If necessary, the Authority's abstraction program can be varied at short notice.

The Water Authority is responsible for the management of all water resources in Western Australia.

The Water Authority administers the Rights in Water and Irrigation Act and the Metropolitan Water Supply Sewerage and Drainage Act,

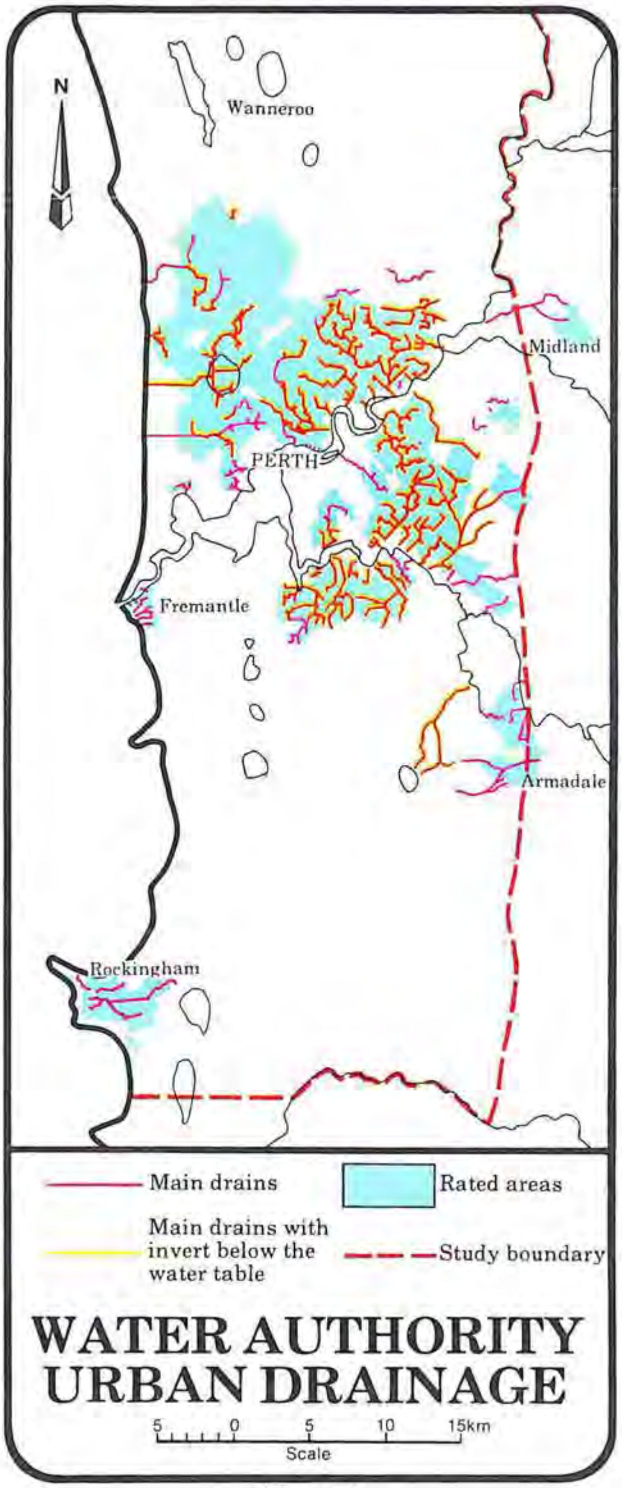


Figure 40

which provide the legislative framework for the control of all groundwater use in the State. The Water Authority of Western Australia is currently preparing legislation for the consolidation of all Acts pertaining to the management of water resources into one comprehensive Water Act.

While all groundwater resources of Western Australia are vested in the Crown, the Government only exercises control of unconfined aquifers in areas it has proclaimed for that purpose. In the remainder, the individual has the common law right to use groundwater from unconfined aquifers without restriction. The Government actively manages all artesian groundwater resources in the State.

The Rights in Water and Irrigation Act requires that all bores and wells be licensed within proclaimed Groundwater Areas, although bores from which groundwater is abstracted from the unconfined aquifer for stock and domestic purposes are exempted in parts of some proclaimed areas. Advisory Committees, e.g. the Swan Groundwater Area Advisory Committee and the Wanneroo Groundwater Area Advisory Committee, may be established to give the community the opportunity to influence the allocation and management of the resource. The Act also makes it possible to control pumping from surface water resources throughout the State.

The Metropolitan Water Supply Sewerage and Drainage Act provides for protection of groundwater quality and quantity in areas proclaimed as Public Water Supply Areas or Underground Water Pollution Control Areas in the Perth region. All bores in Public Water Supply Areas are required to be licensed. Water Reserves can also be proclaimed so that the Authority can protect the quantity and quality of both surface and underground water resources for possible future public supplies.

Conditions attached to groundwater abstraction licences generally relate to bore construction, intended use, permissible or allocated volumes and rates of abstraction. Licence conditions may be varied at any time and meters may be fitted if considered necessary.

Areas in the Perth region which are proclaimed for the control and management of unconfined groundwater resources are those areas where groundwater is drawn for public supplies or where there are identified conflicts in the private development of the resource. The proclaimed groundwater management areas in the Perth region are generally located outside urban areas (Figure 41).

The vast majority of unconfined groundwater used within the Perth region is abstracted from privately owned bores within the developed urban areas. In these areas there is no control or management of abstraction, and a landowner has the right to take water in such quantities and for such purposes as he sees fit. A landholder has no legal recourse against a neighbour whose pumping prevents water from flowing to his bore, and the abstraction of water from beneath the land of a neighbour cannot form the grounds for an action between landowners. An established or potential groundwater user has no assurance of continuity of supply and there is no mechanism for

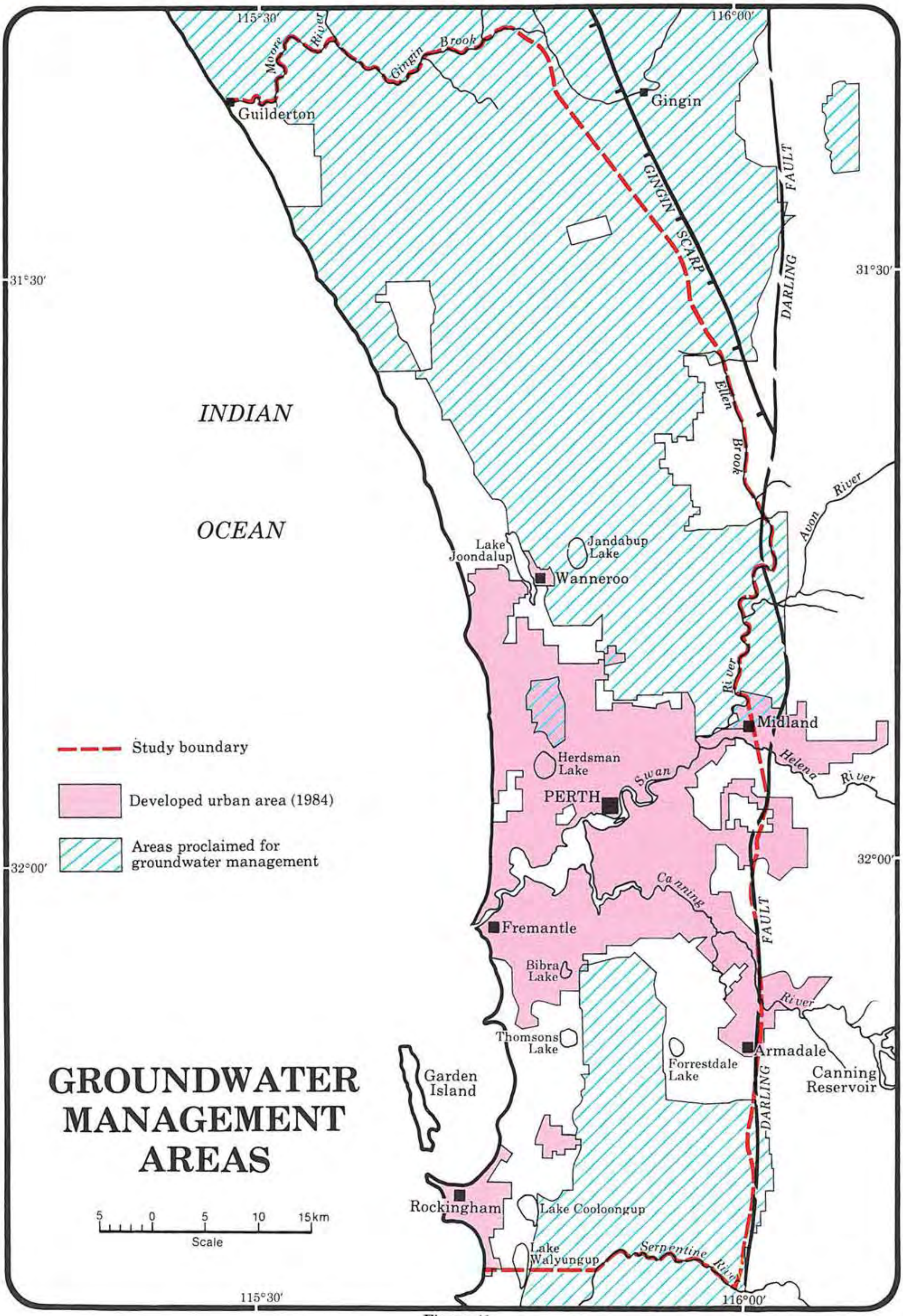

115°30′
116°00′
Moore River
Gingin Brook
Guilderton
Gingin
GINGIN SCARP
DARLING FAULT
31°30′
INDIAN
OCEAN
Ellen Brook
Avon River
Lake Joondalup
Jandabup Lake
Wanneroo
River
Midland
Study boundary
Developed urban area (1984)
Areas proclaimed for groundwater management
Herdsman Lake
Swan
Helena River
PERTH
32°00′
Canning
Fremantle
FAULT
Bibra Lake
River
Thomsons Lake
Forrestdale Lake
Armadale
Canning Reservoir
Garden Island
DARLING
GROUNDWATER MANAGEMENT AREAS
Rockingham
Lake Cooloongup
5 0 5 10 15km
Scale
Lake Walyungup
Serpentine River

Figure 41

protection of the environment. This is in contrast to the proclaimed areas where the resource is managed for equitable distribution and protection of the environment.

Local government authorities draw water from the unconfined aquifer for irrigating reserves, parks and gardens under their jurisdiction. In the past, local authorities did not use efficient watering practices and there appeared to be scope for improvement. Local authorities are now more carefully considering water conservation in their design of reticulation systems because of the increasing cost of pumping. Although the Water Authority does not currently have direct control of local authority abstraction, it is expected that local authorities would cooperate with the Water Authority in developing efficient watering practices.

Demand for groundwater by organisations and amenities, such as schools (primary, secondary and tertiary), hospitals, industries and the Perth Zoo, has been collectively referred to in this report as "institutional demand". Abstraction by institutions is not controlled in areas outside proclaimed management areas and their operation of irrigation systems depends on individual requirements and practices. Often, little consideration is given to efficiency of water use.

Abstraction for private domestic purposes is also uncontrolled outside proclaimed management areas. Control of abstraction is determined by the individual requirements and conservation attitudes of bore owners.

4.3.2 Vegetation

Transpiration of water by vegetation is a significant component of the hydrological cycle.

In the Perth region, the largest single manager of vegetation is the Department of Conservation and Land Management (C.A.L.M.), which controls about 23 000 ha of pine forest. The forest is managed for multiple uses, including water production, timber production and conservation.

Within pine forests, optimum growth rate and wood quality is achieved by thinning inferior trees while maintaining canopy closure. The optimum tree density, which is expressed as the basal area of tree stems in square metres per hectare of plantation, is related to the water and nutrient supply at the site, and a tree density which uses a similar amount of water to the native woodland formerly on the site is believed to optimise growth. A target stand density of between 7 and 15 m^2/ha, with an average of 11 m^2/ha, has been proposed by C.A.L.M. to provide the optimum benefit for wood and water production (Water Authority of Western Australia, 1986*a*).

Canopy cover in existing pine forests ranges between 0 and 75%, depending upon age and thinning. The age of pine forests in the study area is shown in Figure 42. For the purposes of predicting future water balance changes, it was assumed that C.A.L.M. will implement its target stand density of 11 m^2/ha which is approximately equivalent to a canopy cover of 20%.

Vegetation is also controlled in more than 2500 ha of agricultural development, worth more than $40 million in annual production, by the individual farmers. Advice is offered by the Department of Agriculture on the quantities of water that should be applied to meet the needs of crops. Direct management is not practised, but because the costs of abstracting groundwater are a significant component of the cost of vegetable production, farmers avoid pumping more groundwater than they require.

The vegetation of household gardens and community parks and gardens is controlled by the aspiration and desires of the local community. There is little control of vegetation in terms of water requirement although some councils are now rationalising their areas of grassed parkland because of the expense involved in watering and maintaining them.

4.3.3 Septic Tanks and Sewerage Systems

The Water Authority of Western Australia has control over the planning and development of sewerage systems within the Perth urban area. When a sewerage extension is installed, the residents served by that extension are charged a sewerage rate. They are not, however, compelled to connect to the system and it is expected that some septic tanks in currently sewered areas will remain in service until the end of this century.

The State Government Sewerage Policy for the Perth metropolitan region requires that reticulated sewerage be provided for all new subdivisions of land unless special conditions exist relating to areas where sewerage facilities are not available nor in reasonable prospect and provided that the site conditions are suitable for safe, efficient, long-term use of septic tanks.

4.3.4 Surface Drainage

A property owner has a common law responsibility to prevent drainage from his property from passing to his neighbour's. He should contain stormwater on-site or he should dispose of it via a specially constructed discharge point, if provided by his local authority.

The Main Roads Department provides drainage facilities to remove stormwater from its road systems, directing runoff to local authority drains, Water Authority main drains, infiltration basins or directly to the estuary or the ocean.

Local government authorities are responsible for the control of surface drainage within their area. The surface drainage may come from stormwater falling on public land under their control (including road reserves), from stormwater falling on private property in areas where on-site disposal is impractical or from water table control drains constructed for the prevention of flooding in low-lying areas.

Surface drainage is discharged to local infiltration basins, to Water Authority main drains or directly to some wetlands, the estuary or the ocean. The locations of all local authority infiltration basins are shown in Figure 43. Local authorities have control over the discharge of drainage from private properties; they may require that stormwater be disposed of on-site, that any discharge off-site must be via a specified discharge point or that on-site compensating facilities be provided before discharge off-site.

The Water Authority is responsible for the provision of main drainage facilities where drainage lines cross local authority boundaries. Local authorities then discharge runoff to the Water Authority main drains (Figure 40). The Authority may also become involved in large drainage schemes within local authority areas where the local authority has requested assistance and where the scheme would return the costs of construction through drainage rates.

Main drains are constructed by the Water Authority for both the removal of stormwater and for the control of high groundwater levels.

4.3.5 Urban Development

The Metropolitan Region Scheme is the statutory basis for the control of urban development by the State Planning Commission. The Commission recognises the economic, physical and climatic features of a region when zoning land for development. The current, government-adopted strategy for the development of Perth is the Corridor Plan (Figure 44) which guides development along four corridors — the North-West Corridor, the Eastern Corridor, the South-East Corridor and the South-West Corridor (Metropolitan Region Planning Authority, 1971). This plan is currently under review to reassess its appropriateness for the future development of Perth, however, predictions of landuse development used in this Study are based upon the Corridor Plan. The effects of any alternative plan on the groundwater resource may, in principle, be readily assessed using the Perth Urban Water Balance Model, however substantial resources are needed for any modelling exercise, for both the preparation of additional data sets and for

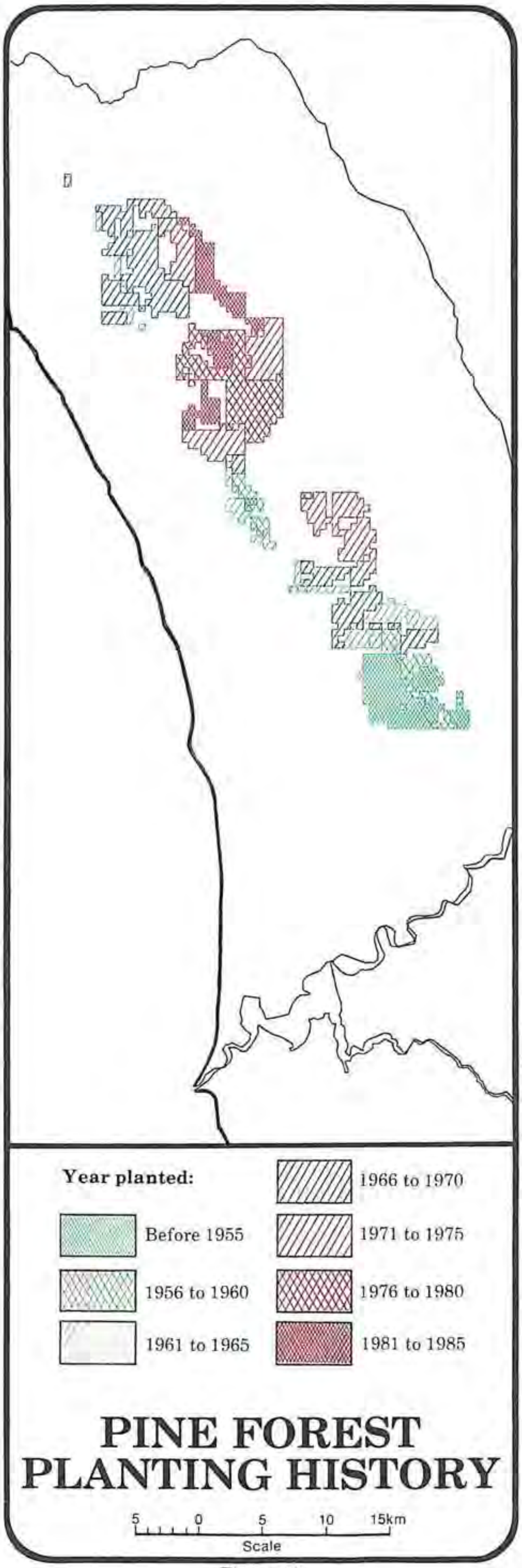
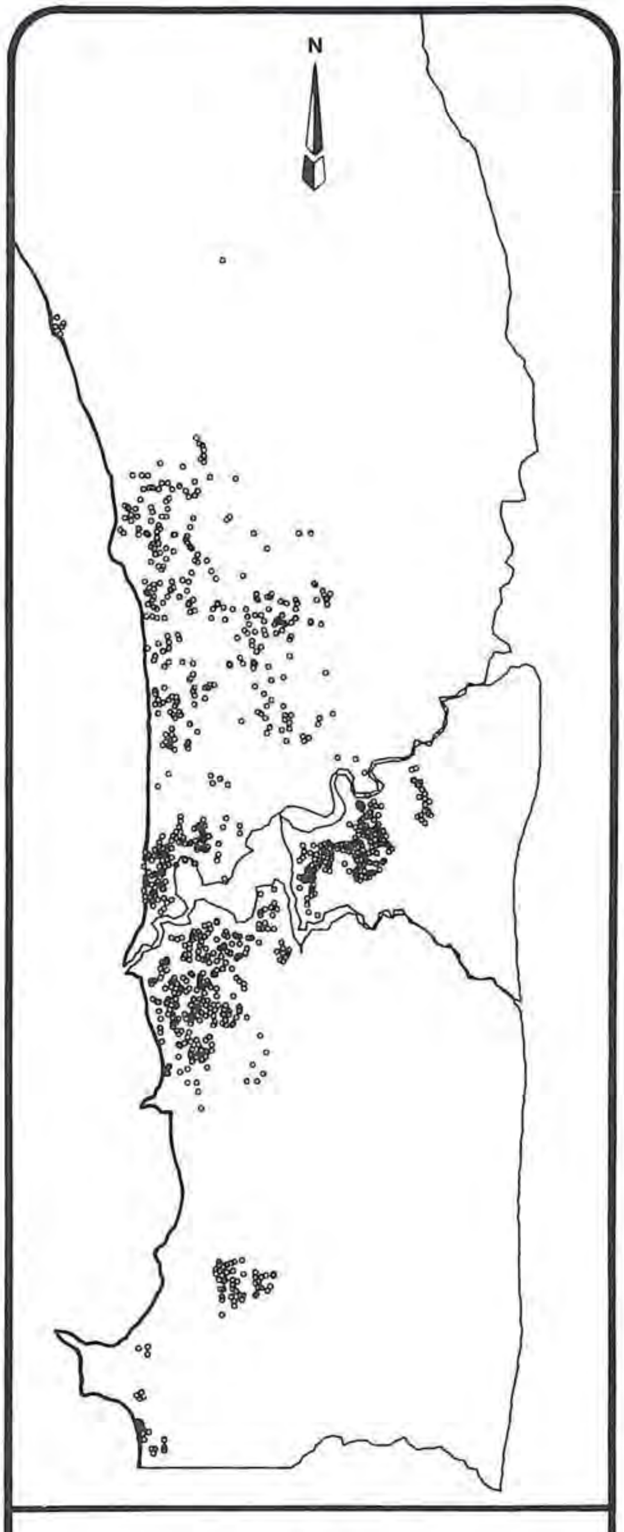


Figure 42



Local authority infiltration basin (1985)

LOCAL AUTHORITY INFILTRATION BASINS

5 0 5 10 15
Scale

Figure 43

the modelling itself.

Local authorities also have the responsibility to control landuse development within the broad zoning requirements of the Metropolitan Region Scheme.

4.3.6 Groundwater Quality

The Environmental Protection Act provides for the protection of all groundwater resources and for the control of polluting discharges to surface and underground water resources.

4.3.7 Climate

Climate has a region-wide influence on the groundwater system. Temperature and rainfall influence recharge, evapotranspiration and abstraction for irrigation. It is not possible to control climate and management of the groundwater system can only be achieved within the limits imposed by climatic variations.

4.4 PHILOSOPHY AND OBJECTIVES OF MANAGEMENT

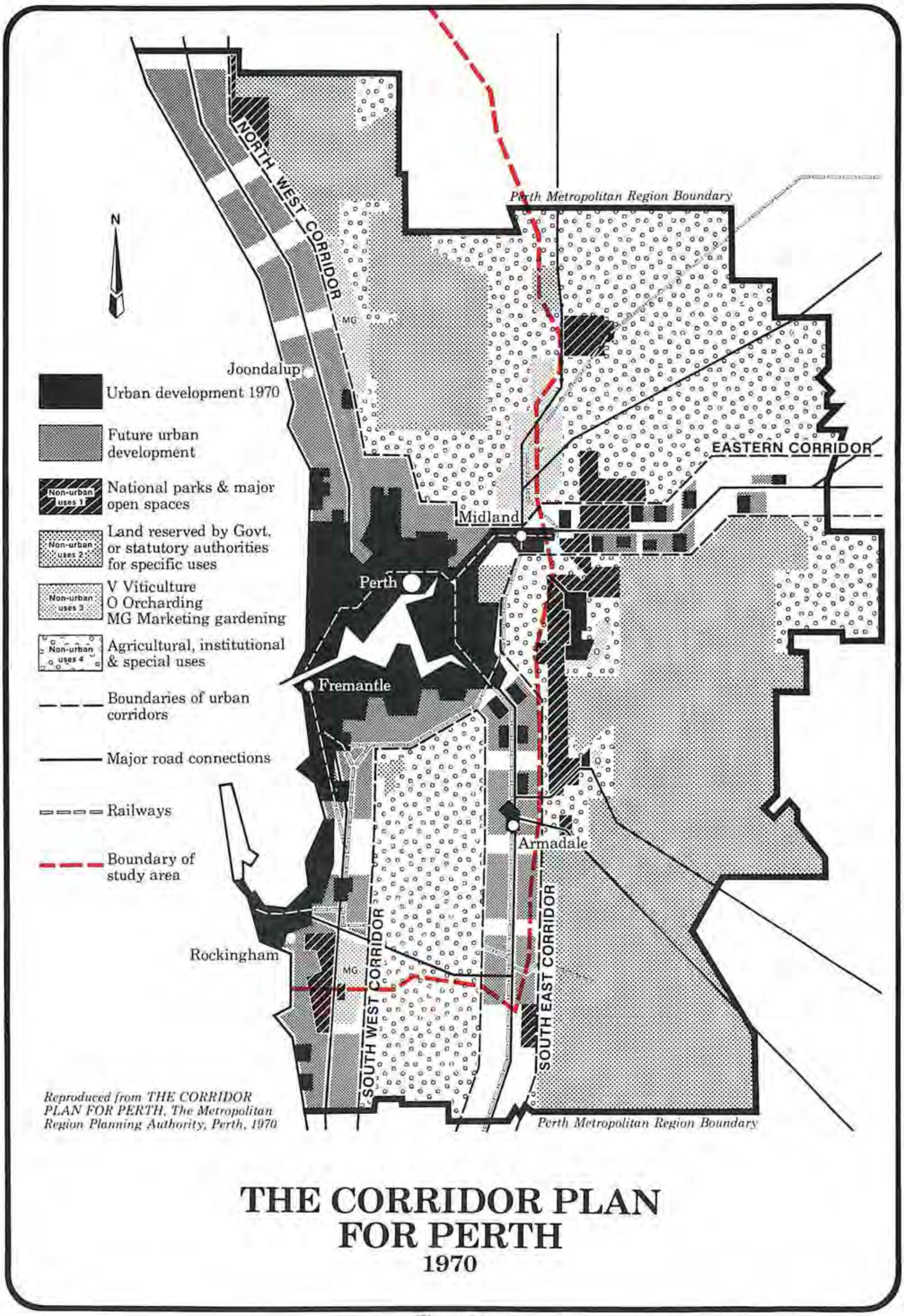
Of the many organisations with control over factors affecting the urban water balance, the Water Authority has the major influence through its control of abstraction for public water supplies, through its potential for control of other abstraction and through its control over sewerage and drainage systems. A Water Authority corporate objective is "to assess, plan and manage the use and conservation of the State's water resources for the continuing benefit of the community" (Water Authority of Western Australia, 1986*b*). The Water Authority therefore has a leading role in the development of groundwater management strategies and must involve other organisations in the planning of those strategies.

While the tradeoffs involved in groundwater management have long been recognised within the Water Authority, a concise external review is presented by McFarlane (1980). Extensions to the recent work by the Western Australian Water Resources Council (1986*a*) will further explore the development of management strategies.

The Water Authority's philosophy for management of water resources is based on "prevention rather than cure", that is, to introduce controls that prevent problems from arising. Preventative action taken to date has proven to be acceptable to the community (Ventriss and Green, 1986).

To achieve the above aims according to the overall philosophy, a four-stage approach to management has been adopted:

Stage 1: to be alert to any agricultural, mineral, municipal, town planning or



Perth Metropolitan Region Boundary
N
NORTH WEST CORRIDOR
MG
Joondalup
Urban development 1970
Future urban development
Non-urban uses 1
National parks & major open spaces
Non-urban uses 2
Land reserved by Govt. or statutory authorities for specific uses
Non-urban uses 3
V Viticulture
O Orcharding
MG Marketing gardening
Non-urban uses 4
Agricultural, institutional & special uses
Boundaries of urban corridors
Major road connections
Railways
Boundary of study area
EASTERN CORRIDOR
Midland
Perth
Fremantle
Armadale
Rockingham
MG
SOUTH WEST CORRIDOR
SOUTH EAST CORRIDOR
Reproduced from THE CORRIDOR PLAN FOR PERTH, The Metropolitan Region Planning Authority, Perth, 1970
Perth Metropolitan Region Boundary
THE CORRIDOR PLAN FOR PERTH
1970

Figure 44

industrial developmentwhich poses a threat to the utility of the resource or to established groundwater users;

Stage 2: to proclaim areas, where necessary, to facilitate monitoring the use of the resource and the behaviour of the aquifer;

Stage 3: to introduce regulatory or restrictive controls where monitoring indicates that the aquifer has been adversely affected; and

Stage 4: to monitor the effectiveness of the management strategy in terms of the objectives for the area and modifying management as appropriate.

Regulatory controls are aimed at:
- maintaining abstraction at a level sustainable in the long term without deleterious effects,
- allocating available resources for beneficial public and private purposes and environmental requirements, and
- sharing the resource equitably in a non-contentious manner.

If on-going water availability is to be assured for the current lifestyle, it is vital that the current approach to management be continued. This will help prevent the State from having to embark on rescue operations, such as the provision of alternative supplementary supplies, at considerable cost to the community.

CONSIDERATIONS IN MANAGEMENT

A large number of issues have the potential to affect the range of options available for future management of groundwater resources. Some of these issues could be viewed as constraints on future management, however whether or not they are constraints may depend on social and political pressures at the time management decisions are made. For this reason, they are described here as considerations, rather than as constraints.

Three important considerations are the likelihood of effects on wetlands, increasing saltwater intrusion and lowering of the water table in the vicinity of existing bores. These issues were identified as potential problems in the late 1970s and were prominent when the Perth Urban Water Balance Study was initiated. Another consideration is groundwater quality, as it affects both the environment and the utility of the groundwater resource.

A large number of social, economic and political issues need to be considered in the implementation of management strategies, but evaluation of these was considered to be beyond the scope of the Study.

5.1 WETLANDS

Drying of wetlands and degradation of wetland water quality are visible indicators of stress on a groundwater system. Since wetlands are important features of the urban environment, their maintenance is an important consideration in the development of future groundwater management strategies.

Management objectives for wetlands do not directly correspond with management objectives for a regional groundwater system, however responsible groundwater management needs to take them into account.

5.1.1 The Value of Wetlands

In defining objectives for the management of wetlands, the Environmental Protection Authority (1986) categorised 79 wetlands in the study area in terms of their "natural" and "human use" attributes (see also Arnold, 1987).

A checklist of natural attributes included:
- the degree of modification of the wetland and its surrounding landform;
- the degree of alteration of its hydrology;
- water quality;
- the condition and extent of fringing vegetation;
- the presence of rare or unusual plant and animal species;
- the use of the area by water birds;
- the range of habitat types available; and
- wetland and reserve size as a measure of effectiveness as a conservation area.

A checklist of human use attributes included:
- the type and vesting of the wetland reservation and of the level of management applied;
- the uses catered for, e.g. facilities for cycling and walking, picnics and barbecues, active sports, education and research;
- any drainage or other service function;
- the aesthetic qualities of the wetland, e.g. diversity and quality of the landscape and whether the area retained some ambience of peacefulness and wilderness;
- whether residences around the wetland were placed to take advantage of the area; and
- the area's potential to fulfill social functions in the future.

On the basis of the importance of individual attributes, the wetlands were grouped into five broad classifications (Figure 45). Recommendations were then made for the management of each of the groups of wetlands.

5.1.2 Water Level Requirements

To set management criteria, it would be desirable to define limits on the range of permissible water levels in wetlands and then to manage the water balance of surrounding areas appropriately. The wetland review (Arnold, 1987) summarised all existing hydrological data on major wetlands of the region, and demonstrated that a variety of human activities, such as modification of vegetation and drainage to or from lakes, can have significant effects on wetland water levels. Similar effects can be caused by long-term climatic variations.

To assist in the maintenance of wetland ecosystems, guidelines for desirable or acceptable water levels or water level variations could, in principle, be developed based on the relationship between water levels and the species composition of wetland flora and fauna.

Apart from the large amount of data available on the biology and ecology of birds, considerably more data are available on flora than on fauna (Arnold, 1987). However, the study of the aquatic invertebrate fauna of five urban wetlands (Davis and Rolls, 1987) has helped to reduce this deficiency.

Quantitative and qualitative sampling of the aquatic invertebrate fauna of Jandabup, North and Thomsons Lakes and Lakes Joondalup and

PERMANENT & SEASONAL WETLANDS WITH WELL-DEFINED BOUNDARIES

Wetland	code to Figure 45
Star Swamp	1
Brownman Swamp	2
Lake Mt Brown	3
Walyungup	4
Cooloongup	5
Joondalup	6
Jandabup	7
Forrestdale	8
Loch McNess	9
Yonderup	10
Nowerup	11
Melaleuca Park	12
Bennett Brook at Pyrton	13
Thomsons	14
Banganup	15
Monger	16
Jackadder	17
Perry Lakes	18
Claremont	19
Shenton Park	20
Manning	21
Richmond	22
Bibra	23
Yangebup	24
North	25
Carine	26
Gwelup	27
Herdsman	28
Booragoon	29
Blue Gum	30
McDougall Park	31
Tomato	32
Mary Carroll Park	33
Coogee	34
Mariginiup	35
Gnangara	36
Careniup	37
Goollelal	38
Carabooda	39
Neerabup	40
Adams	41
Pipidinny	42
Beonaddy	43
The Spectacles	44
Piney	45
Bollard Bullrush	46
Little Rush	47
Roe Swamp	48
Wright	49
Hazelmere Lakes	50
Snake Swamp	51
Wilgarup	52
Mindarie	53
Coogee Springs	54
Pinjar	55
Tamworth Hill	56
Anstey's Swamp	57
Alfred Cove (M6)	58
Canning River Wetlands (M68)	59
Belmont/Maylands (M51)	60
Maylands (M50)	61
Heirisson Island	62
Queens Gardens	63
Interchange wetlands	64

SEASONAL & EPISODIC WETLANDS WITH POORLY-DEFINED BOUNDARIES

Wetland	code to Figure 45
Little Mariginiup	501
31°42′N 115°50′E	502
Pickle Swamp	503
32°14′N 115°50′E	504
Banjup	505
Balannup	506
Yule Brook Reserve	507
Twin Swamps	508
Malaga	509
32°08′N 115°56′E	510
32°10′8″N 115°57′E	511
Yangedi Swamp (east)	512
Yangedi Swamp (west)	513
32°08′7″N 115°54′20″E	514
32°22′N 115°52′E	515

CODES TO FIGURE 45

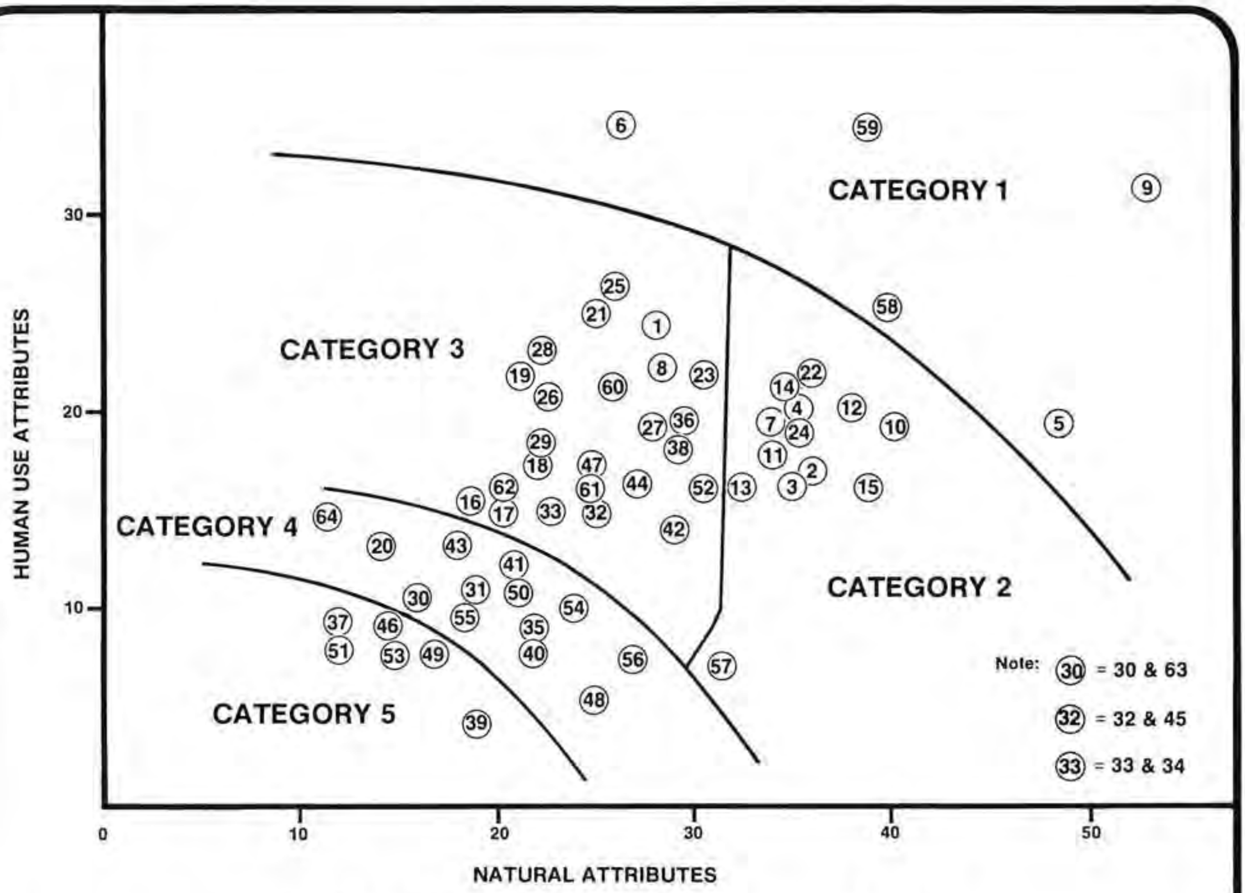
Table 2

Monger emphasised the extent to which each wetland is a unique ecosystem. The five wetlands were chosen to include some with high natural value and some with substantially degraded environments. Quantitative measurements taken at three-monthly intervals between April 1985 and March 1986 were of:

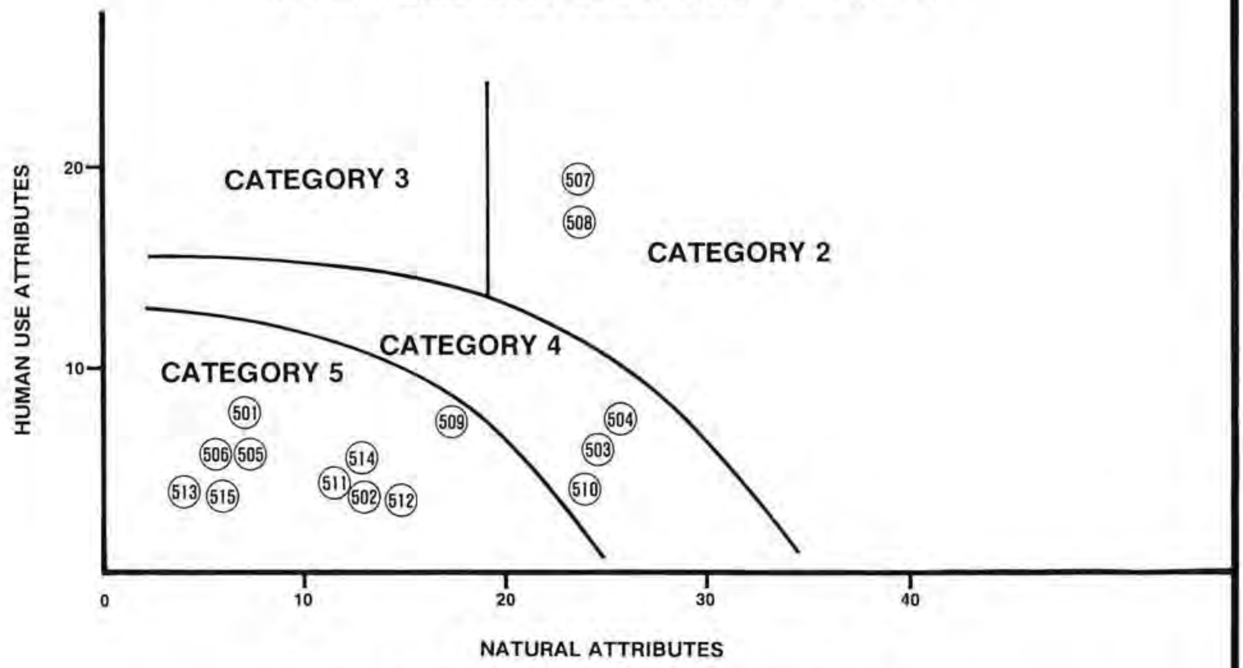
- species richness (the number of species recorded at each site);
- abundance of organisms (the density of individuals of all species); and
- trophic structure (the relationship between species at different levels in the food chain).

Observations at Thomsons and Jandabup Lakes indicated that lakes which dry completely each summer may possess a rich and abundant macro-invertebrate fauna as the lakes fill. These ecosystems therefore appear to be well adapted to seasonal drying due to resistant eggs or dormant phases in the fauna life cycles or to well-developed mechanisms for the transfer of organisms from permanent lakes as the seasonal lakes refill.

The summer drying of wetlands may be an important factor in the natural protection of the



PERMANENT & SEASONAL WETLANDS WITH WELL-DEFINED BOUNDARIES



SEASONAL & EPISODIC WETLANDS WITH POORLY-DEFINED BOUNDARIES

CLASSIFICATION OF WETLANDS

Figure 45

environment because the wetlands are dry during the period when they would otherwise be subject to high nutrient and salt concentrations together with warm, highly productive conditions for the growth of algae (Section 5.1.3). Permanent wetlands are also important, however, as refuges and faunal reservoirs.

Hydrographs of wetland water level data and evidence from lake bed sediments indicate long-term variations in the water table elevation. Long-term variations in annual maximum and minimum wetland water levels may result from changing land use, changing climatic conditions, the use of wetlands as drainage basins or changing groundwater abstraction practices. These long-term changes may lead to stresses developing within a wetland ecosystem or they may lead to a transition to a different, but stable, ecosystem. All wetlands which have been influenced by urbanisation show definite signs of long-term changes in water levels and/or trophic states. Wetlands unaffected by urbanisation lie well north of Perth in the Yanchep National Park or on the eastern flank of the Gnangara Mound near Gingin.

Evidence also exists at many of the inner urban wetlands that water levels have increased over a considerable period of time. Lake Claremont and Bluegum Reserve, for example, have many dead eucalypt and melaleuca trees standing in permanent water, indicating that at one time the normal water level was significantly lower (Plate 20). Information from early accounts of the Swan River colony (e.g. Evans and Sherlock, 1950; Grey, 1841) indicates that many of the lakes now with an open water surface were once swamps, bogs and marshes, e.g. Shenton Park Lake (Section 4.1), Mabel Talbot Park Lake, Lake Monger and Lake Claremont.

Plate 20 Drowned eucalypts in Bluegum Reserve on the Applecross peninsula

Water levels required for wetland maintenance form the most restrictive constraints upon the management of the groundwater systems of the Swan Coastal Plain because small level changes can have significant effects upon wetland environments.

The major problem facing urban wetlands is considered to be a combination of low water levels and high nutrient levels, rather than low water levels alone. The Water Authority is continuing its work with the Environmental Protection Authority to establish appropriate water level criteria for the wetlands of the Swan Coastal Plain.

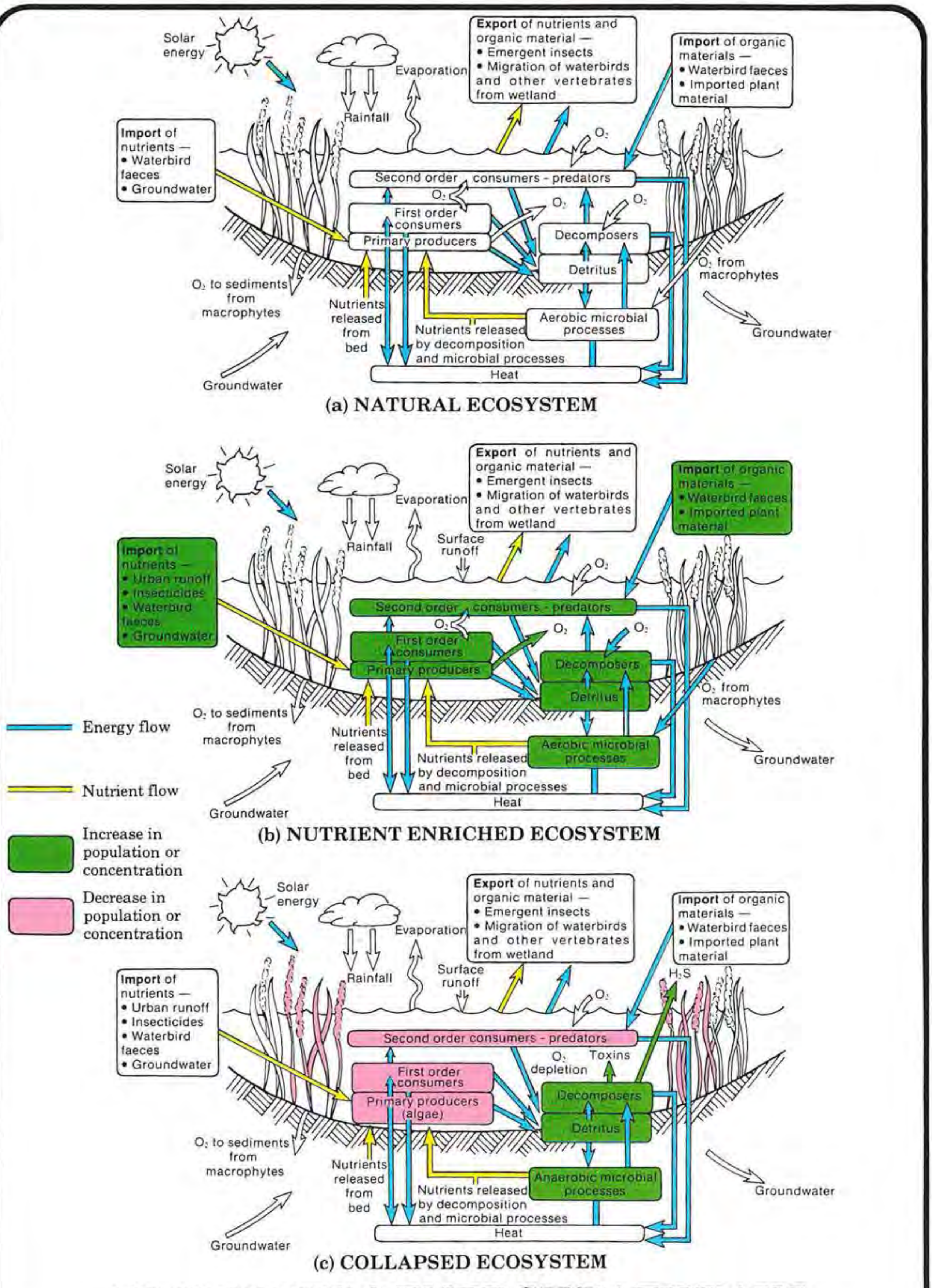
5.1.3 Water Quality

Existing wetland water quality data were summarised by Arnold (1987) and additional data were collected seasonally at the five wetlands discussed above (Davis and Rolls, 1987). Wetlands and the groundwater system should be managed together so that the water quality is sufficient to maintain viable, or "healthy", freshwater ecosystems for the preservation of aesthetic values, water bird habitat and scientific and educational resources.

The most significant water quality problem in urban wetlands is the input of large amounts of nutrients from groundwater inflow and from surface stormwater runoff. Groundwater under urban areas contains significant concentrations of nitrate, and drainage into wetlands, which form important discharge points in the urban drainage network, contains nutrients and other contaminants from the surrounding urban area.

The biological response to increased nutrient input is increased plant and algal growth followed by increased secondary production and decomposition. These last two may become so great that the oxygen demand of decomposing organic matter can exceed the rate of oxygen supply, leading to a depletion of dissolved oxygen and the development of anaerobic decomposition processes (Figure 46). The consequences of such ecological changes include:

- odours,
- choking due to massive growth (blooms) of plant material,
- changes in populations and species of fauna,
- oxygen depletion leading to death of fish,
- high populations of pathogenic and other bacteria, and
- high concentrations of algal and bacterial toxins leading to death of water birds and fish.



NUTRIENTS & ENERGY PATHWAYS IN WETLANDS

Figure 46

Algal blooms (see e.g. Congdon, 1979; Plate 21), and algae-related fauna deaths (Arnold, pers. comm., 1987; Aplin, 1983) have occurred on many lakes in the Perth area.

The water quality in Lakes Joondalup and Monger is very poor compared with other lakes, as indicated by their lower species richness. The biological monitoring technique of Davis and Rolls (1987) exposed a highly stressed ecosystem in Lake Joondalup, despite chemical analyses indicating that the water quality was not poor. Biological monitoring is a complementary technique to chemical monitoring, because it effectively integrates the influence of many stress factors in wetland ecosystems and indicates how severe the effect of water quality problems may be on the biota.

Nutrients in wetlands come from urban drainage, groundwater inflow and fauna. To estimate the input of nutrients to a wetland, the water balance of the wetland, the nutrient concentrations in the water flowing into and out of the wetland and the surface area and bathymetry of the wetland are required. Nutrient balances have been estimated for a small number of wetlands in the Perth area.

Estimates for Lake Jandabup, which is considered to be oligotrophic (Davis and Rolls, 1987), suggest that nutrients entering the lake in groundwater do not exceed its capacity to assimilate them. In contrast, Lake Joondalup, 5 km to the west of Lake Jandabup, does show symptoms of eutrophication (Congdon, 1979; 1986) although nutrient loads entering the lake via the groundwater are estimated to be lower than the expected assimilative capacity. In this case, substantial loads of phosphorus are carried to the lake by surface flow from swamplands to the south.

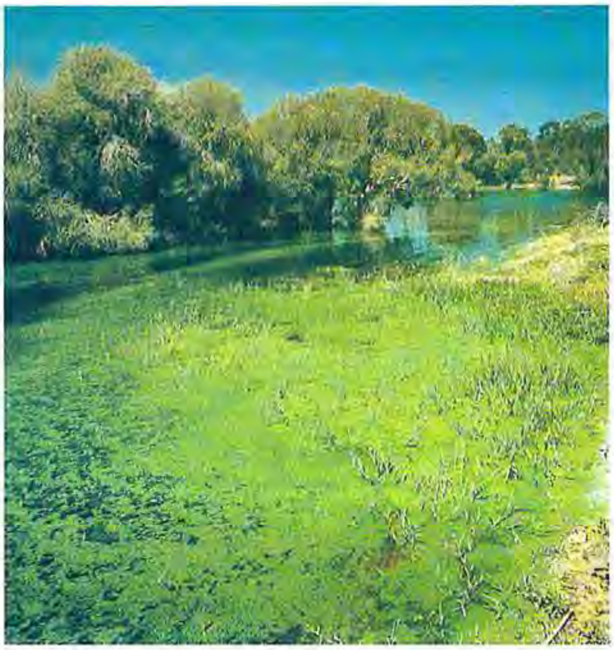


Plate 21 Algal bloom in North Lake

The high invertebrate species richness observed at Thomsons and Jandabup Lakes indicates the value of protection afforded by the vegetation buffer surrounding them and the general protection afforded by their status as reserves.

5.2 SALTWATER INTRUSION

5.2.1 Occurrence

The occurrence of a saltwater wedge along the ocean and estuary boundaries of the unconfined aquifer is defined in Chapter 3. The following information is presented, however, to assist in assessing the extent to which saltwater intrusion may become a problem in the future.

Saltwater intrusion is a water quality problem caused by physical changes in the regional groundwater flow system. Landward movement of a saltwater wedge occurs when groundwater flow to the coast, and consequently groundwater levels near the coast, are reduced. Saltwater intrusion can be managed by controlling groundwater flows and levels in the vicinity of the coast.

Serious saltwater intrusion problems have occurred in coastal aquifers around the world. Active management, sometimes involving artificial recharge near the coastline, has been implemented in many instances e.g. the barrier projects constructed in the Los Angeles Flood Control District. Such remedial action is very expensive.

In an ideal aquifer with steady flow and uniform permeability, a theoretical result known as the Ghyben-Herzberg principle indicates that the depth below sea level to the saltwater-freshwater interface is approximately 40 times greater than the elevation of the water table above sea level (Bear, 1979). This situation is illustrated in Figure 47*a*.

Halving the long-term average water table elevations near the coastline could be expected, according to the Ghyben-Herzberg principle, to lead to an approximate doubling of the length of the saltwater wedge. Observations of a number of coastal aquifers in Australia, however, have indicated that the extent of saltwater intrusion is not as great as predicted by the Ghyben-Herzberg principle (e.g. Baker et al., 1986). In aquifers which contain some clay materials, it is possible that dispersion of colloidal clay particles, due to freshwater flushing of the aquifer in geologic time, may impede the landward movement of the wedge (Goldenberg et al., 1983).

Steady flow is rarely encountered and is particularly unlikely in the mediterranean climate of Perth, where seasonally varying water levels result in fluctuations in through-flow and fluctuations in the location of the interface (Figure 47*b*). Aquifer heterogeneity and anisotropy also greatly affect the position of the interface (Figure 47*c*).

Detailed investigations at the sites shown in Figure 21 showed varying conformity with the Ghyben-Herzberg principle. Three-dimensional plots showing the variation of salinity with time and depth below the water table at each of the investigation sites are presented in Figure 48. Site IF08 showed a sharp interface but no clear indication of seasonal movements. Site IF01 showed a relatively thin layer of water with increased salinity in the middle of a deep freshwater profile; this is indicative of aquifer heterogeneity (Figure 47*c*), however the seasonal fluctuation showing maximum salinity in winter requires further investigation. Site IF03 showed that the entire Cottesloe peninsula is underlain by a layer of salt water.

A saltwater wedge occurs in all areas adjacent to the coast and in many areas adjacent to the estuary. Removal of this wedge is not possible and management of saltwater intrusion into coastal and near estuary bores involves the careful design and spacing of bores so that fresh water may be withdrawn from above the wedge without drawing salt water up from below (Figure 49). Peninsular areas are particularly at risk from saltwater intrusion problems; areas such as Applecross and Cottesloe, which were investigated in detail, and South Perth, Maylands, Dalkeith and Rockingham/Safety Bay, which require further investigation to determine the extent of the risk.

Saltwater intrusion may be significant in some local areas and is therefore an important consideration in the development of groundwater management strategies.

5.2.2 On-going Monitoring

Long-term and seasonal movement of the saltwater wedge can only be accurately studied with long-term monitoring of the interface bores. The results of the Study program were used to select appropriate bores at which monitoring should be continued.

Further monitoring is not considered necessary at IF04, which contains salt water for its full depth, and at IF02, IF05 and IF06, because the behaviour of the saltwater wedge under the Cottesloe peninsula may be effectively monitored at IF03, now that it is established that a layer of salt water extends under the entire peninsula.

Twice yearly monitoring of all other bores would detect seasonal and long-term move-

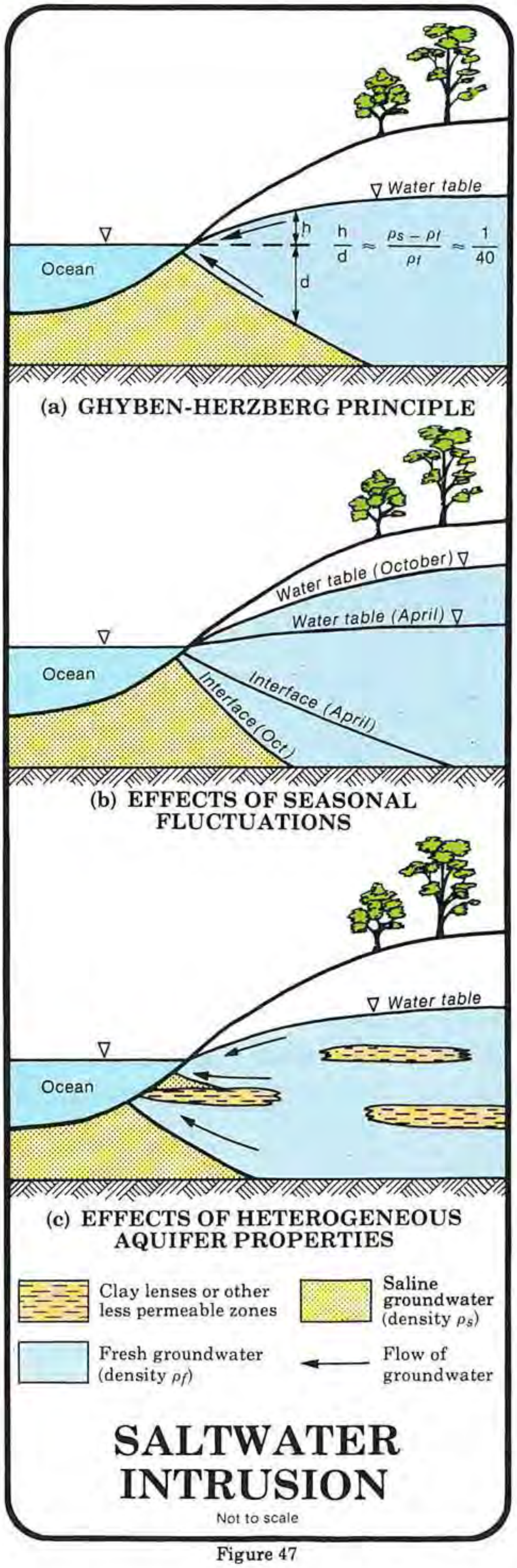
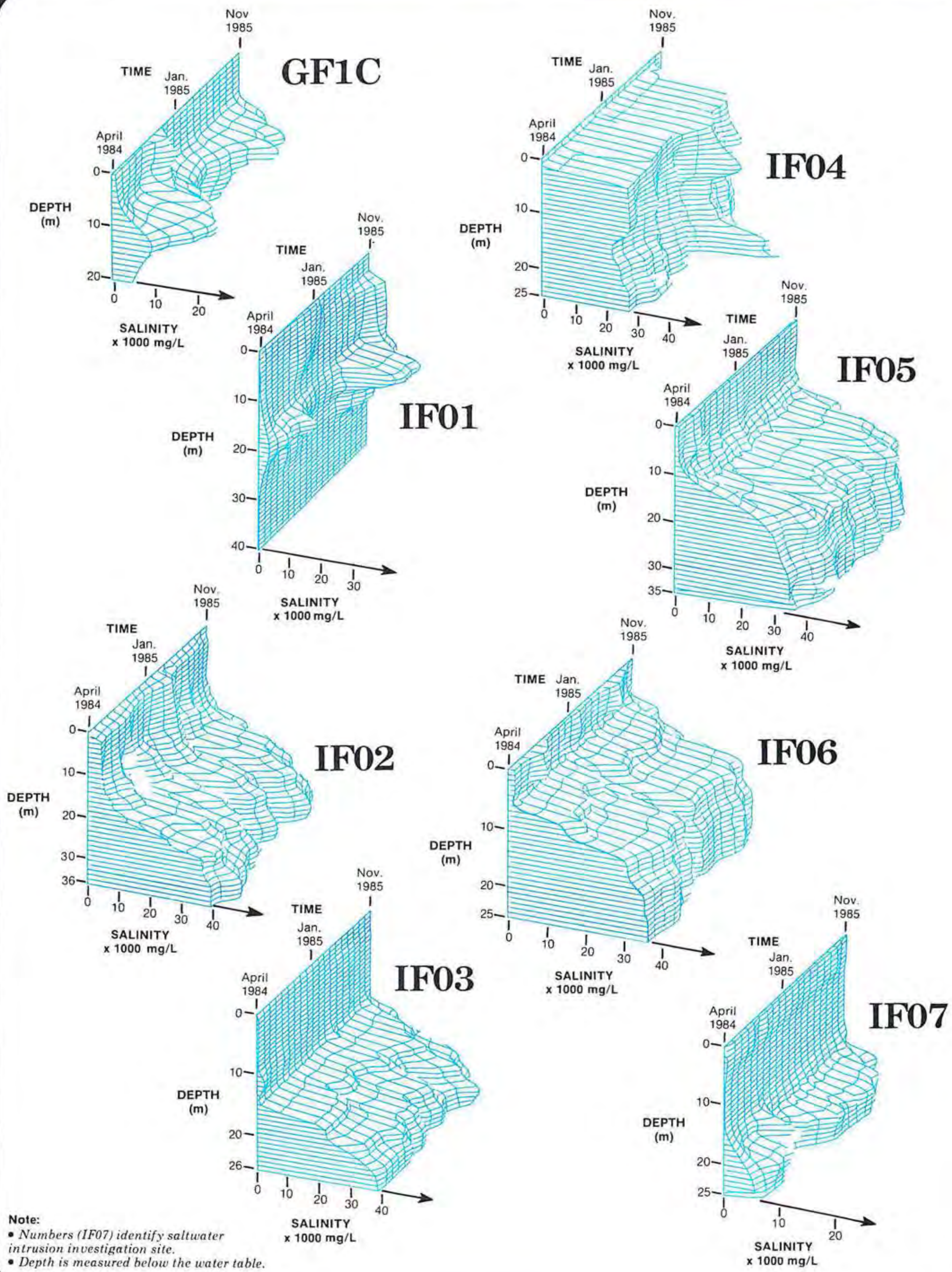
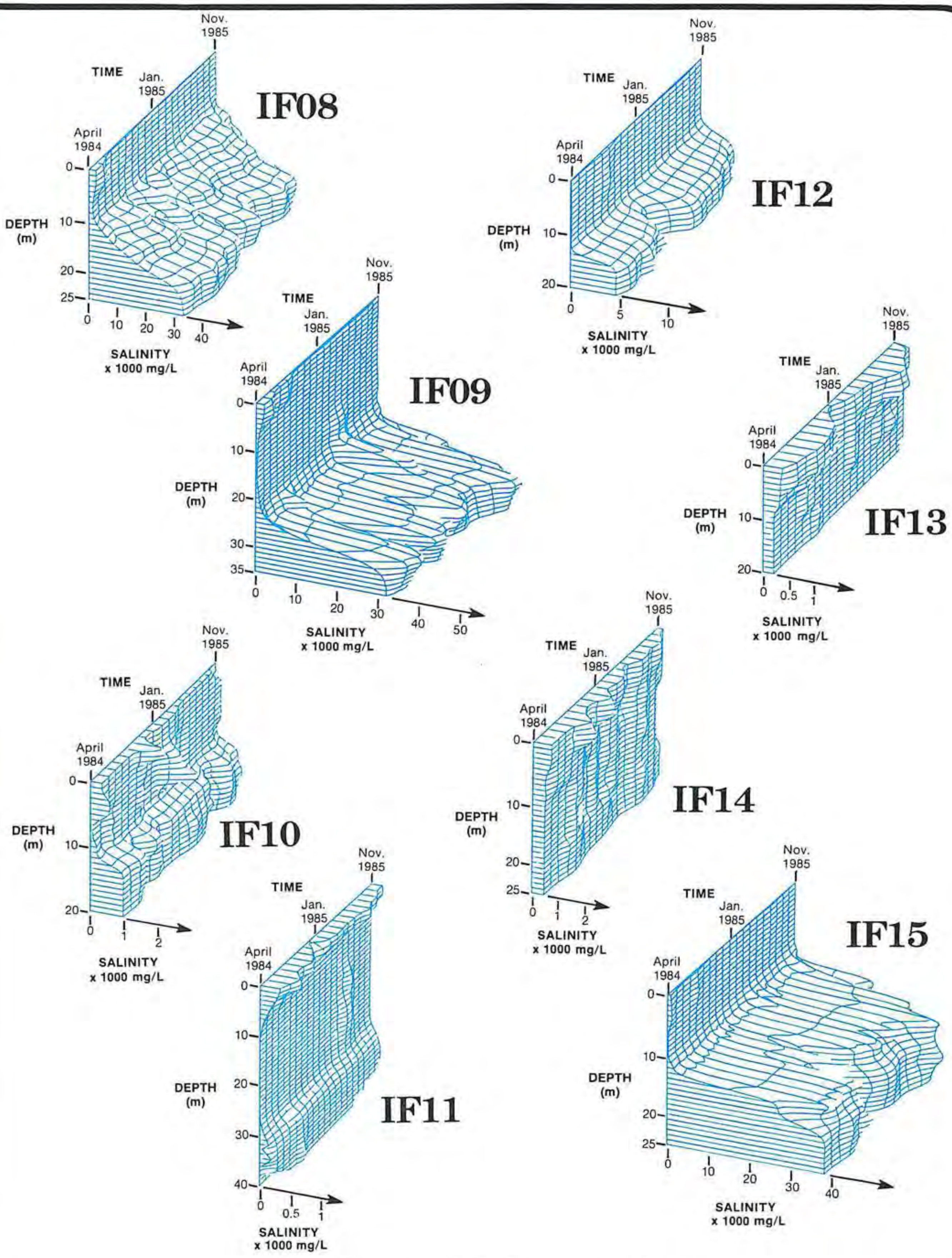


Figure 47



Note:
- *Numbers (IF07) identify saltwater intrusion investigation site.*
- *Depth is measured below the water table.*



SALINITY PROFILES

Figure 48

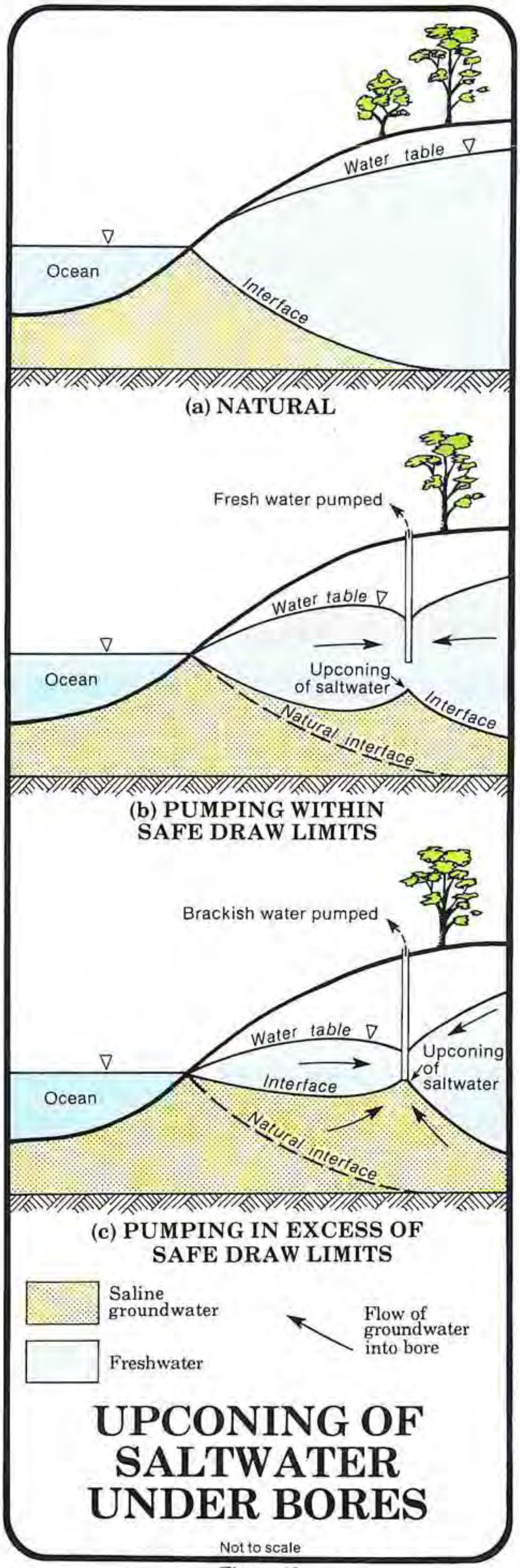


Figure 49

ments in the saltwater wedge or detect whether a wedge appears. In addition, three-monthly monitoring of IF13 would allow investigation of the occurrence and seasonal variation of brackish water which has appeared at the top of the aquifer.

Bores IF01 and GF1C returned results with variations in the position of the saltwater wedge which could not be explained and evidence of a layer of fresh water under the wedge. Two-monthly monitoring of these bores will be necessary to investigate any patterns which may become evident over a number of years.

5.3 WATER FOR DRINKING

The utility of groundwater as a drinking water resource is controlled by water quality constraints. The components most likely to constrain its use for drinking are the concentrations of nitrogen and phosphorus compounds, heavy metals and pesticides.

5.3.1 Nitrate

A relationship has been shown to exist between the occurrence of high nitrate levels and urbanisation. Nitrogen compounds entering the soil are subject to nitrification and denitrification processes which can affect groundwater nitrate levels. Nitrification occurs when reduced nitrogen compounds (ammonia, proteins etc.) undergo oxidation by soil microbes to form nitrite and nitrate. Whelan and Parker (1981; see also Parker, 1983) found that, under aerobic conditions, almost all ammonium in septic tank effluent in sands within the Perth metropolitan area was oxidised to nitrate over a distance of 0.7 m from the leach drain. Denitrification occurs when nitrate is biologically reduced to form gaseous nitrous oxide and nitrogen. This process requires an anaerobic, organic-rich environment to be effective. The sandy Perth soils do not provide such an environment and nitrogen remains free to be leached to the groundwater at the same concentration as in the effluent (Whelan and Parker, 1981).

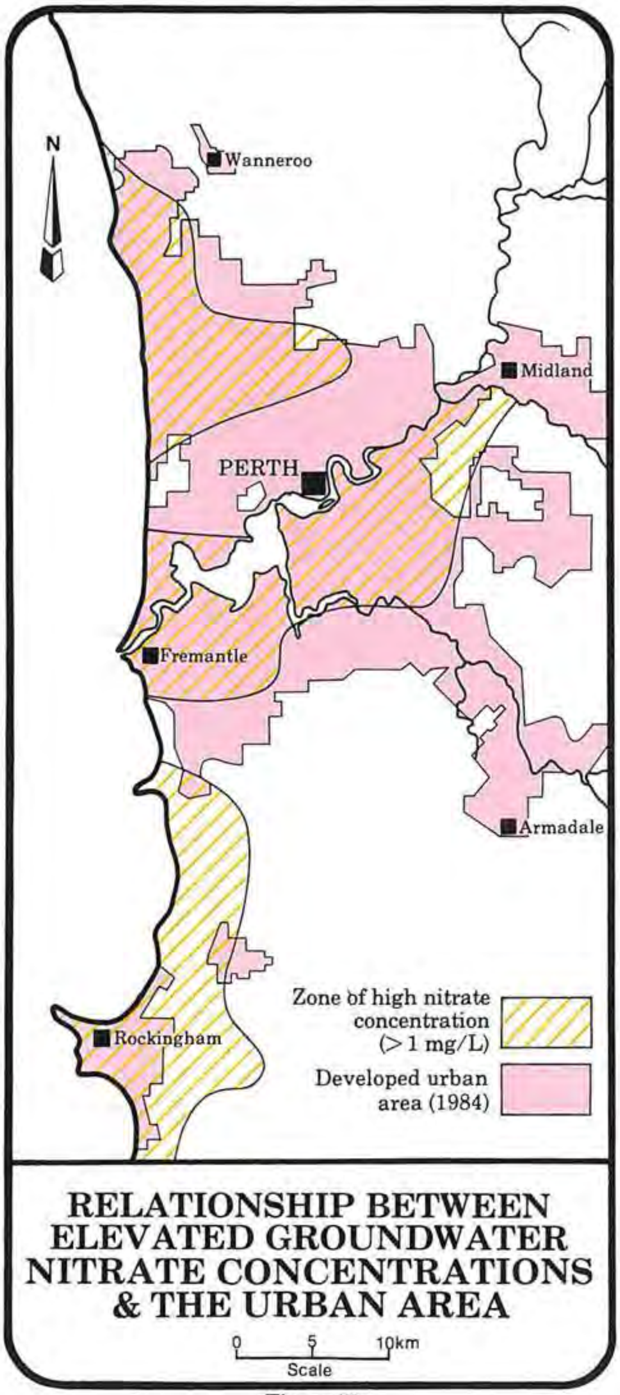
Groundwater nitrate concentrations in excess of 1 mg/L (expressed as N) occur almost exclusively in urban areas (Figure 50) and levels have been recorded up to and above the Department of Health (1980) recommended potable limit of 10 mg/L (Figure 25). The major sources of groundwater nitrates in urban areas are septic tank effluent, fertilisers, landfill, waste disposal sites and industrial effluent. A reasonable association between the distribution of nitrate concentrations exceeding 1 mg/L and the occurrence of septic tanks within the suburb of Applecross was identified (Figure 51).

The vertical distribution of nitrate recorded along two groundwater flow lines (Figure 52) is shown in Figure 53.

Along the Gwelup flow line in the Northern Perth Area, nitrate concentrations exceeding 1.0 mg/L, and up to 29 mg/L, were recorded near the surface of the aquifer under urban areas. High nitrate was also recorded at the water table at bore MX1, which is within an area of hobby farms and a few horticultural farms. Under the newer urban area of Ballajura (around bores MM28 and MX2), nitrates, probably derived from fertilisers, pass directly through the leached sand of the Tamala Limestone. Further south, in the older urban areas which have only recently been sewered (around bores GM32 and GM20), effluent from septic tanks may also be a significant source of nitrates.

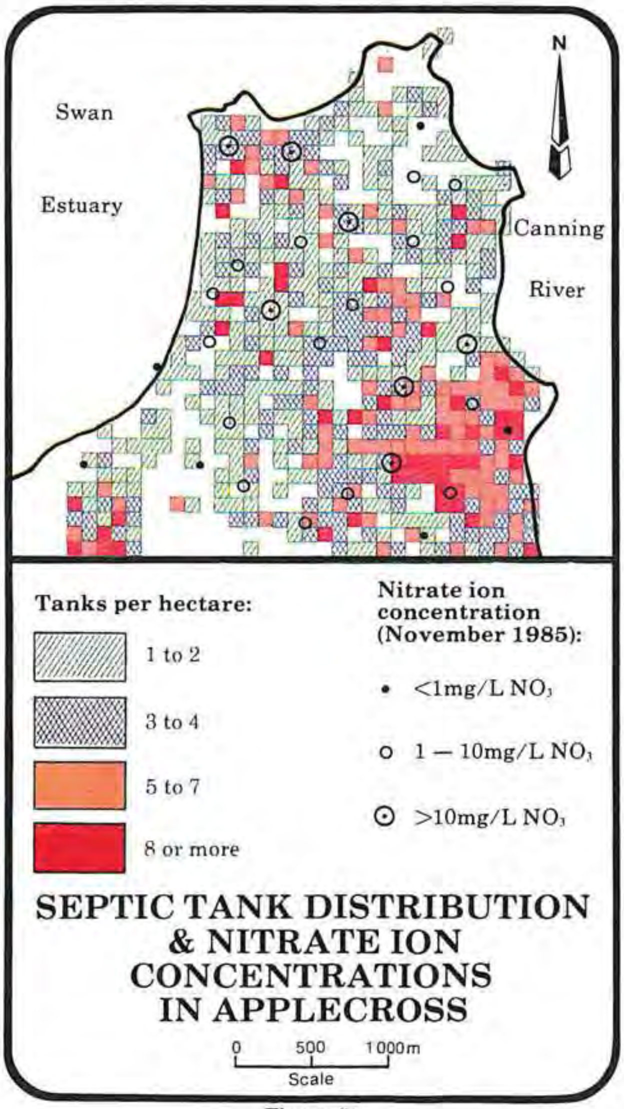
Within the interbarrier depression around bores JS4, GM31, GX1 and G80, nitrate concentrations were found to be less than 1.0 mg/L. Low-nitrate groundwater flowing at depth within the aquifer rises towards the wetlands in this region because of the large evapotranspirative losses. It may also be possible that nitrates applied to the soil or to the wetlands are reduced to nitrogen or nitrous oxide in the organic soils and wetland sediments.

Along the Applecross flow line in the Southern Perth Area, nitrate concentrations are generally low in groundwater under native bush and under new urban areas. In the older areas of the Applecross peninsula, elevated nitrate concentrations extend to the full depth of the aquifer (Bore A12), probably because of the combination of high septic tank density, mixing within the aquifer caused by heavy private pumping [up to 75% of householders use bore-water for their gardens (Metropolitan Water Authority, 1985*a*)], and because throughflow of low-nitrate groundwater in this area, being a peninsula, is



RELATIONSHIP BETWEEN ELEVATED GROUNDWATER NITRATE CONCENTRATIONS & THE URBAN AREA

Figure 50



SEPTIC TANK DISTRIBUTION & NITRATE ION CONCENTRATIONS IN APPLECROSS

Figure 51

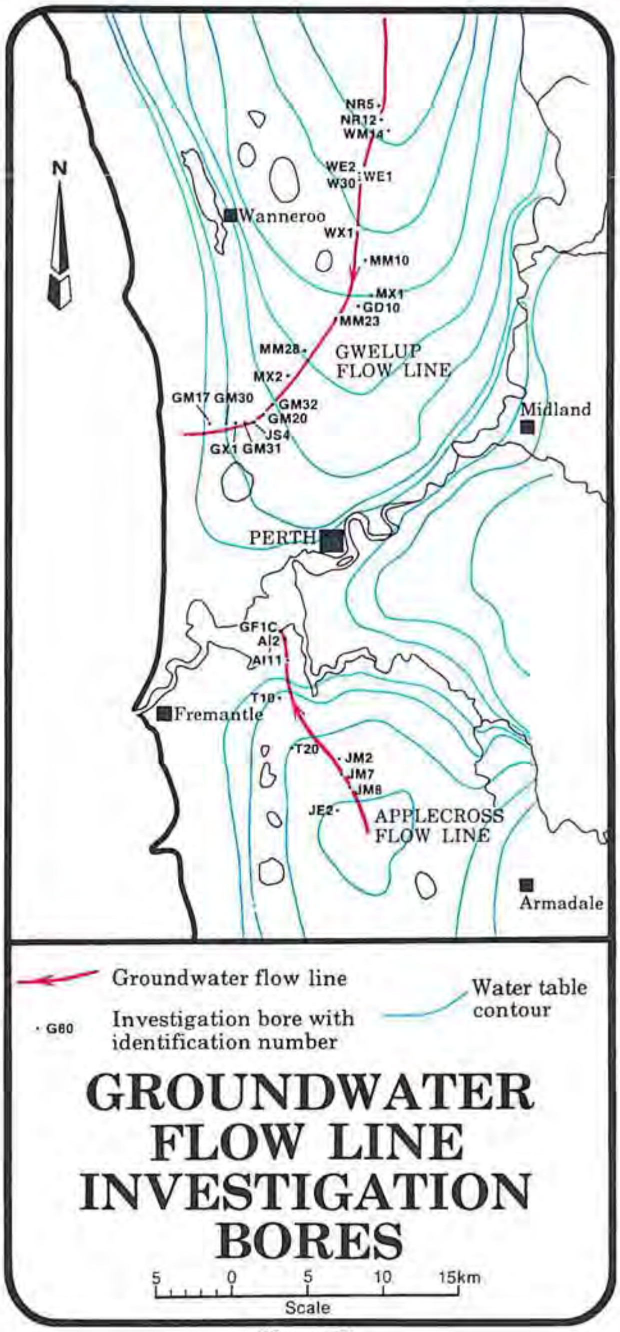


Figure 52

limited. Nitrates may also be derived from fertilisers but low concentrations of sulphates recorded in the groundwater under Applecross (see Section 5.3.3) indicate that excessive application of fertilisers may not be a problem.

At present, nitrate concentrations in public water supply areas located outside the urban area are well below potable limits. Higher concentrations have been recorded in some public water supply bores in the Gwelup area but concentrations in reticulated supplies are maintained well below Department of Health (1980) criteria for drinking water because water from all bores is mixed prior to distribution.

5.3.2 Phosphorus

There is no limit specified by the Health Department for phosphorus concentrations in drinking water, however the Canadian Government has specified 0.2 mg/L as a desirable limit. Total phosphorus concentrations in excess of 0.2 mg/L (Figure 26) are commonly found near the eastern margin of the coastal plain in clayey sediments of the Guildford Formation. Throughout the metropolitan region, such concentrations occur only sporadically and show no obvious relationship with areas where significant phosphorus inputs to groundwater might be expected, such as residential areas with large gardens or industrial areas.

Elevated concentrations were also recorded in eastern suburban areas, where the water table is generally shallow, and in areas of low aquifer permeability.

5.3.3 Sulphate

Sulphate ion concentrations in excess of the Department of Health long-term objective for drinking water of 200 mg/L have only be recorded in the Southern and Eastern Perth Areas (Figure 27). Concentrations in excess of the desirable limit of 400 mg/L were not recorded. The variation of sulphate ion concentrations with depth along the Gwelup and Jandakot flow lines is shown in Figure 54.

High sulphate ion concentrations were only recorded beneath an area of hobby farms and horticultural farms in the vicinity of bores MX1 and GD10, beneath the wetlands of the interbarrier depression between bores JS4 and GM17 and very close to the estuary at Applecross.

Elevated concentrations of sulphate ion in groundwater can result from oxidation of sulphides and organo-sulphur compounds, contained in peaty sediments associated with wetlands; from saltwater intrusion; from evapotranspirative concentration in areas where the water table is shallow; from contamination in industrial areas where sulphuric acid, sulphur dioxide or soluble sulphate salts are used or produced; from the leaching of fertilisers; and from rainfall.

Normalising the concentration of sulphate ion against the chloride ion to remove the effects of evaporative concentration has shown areas where sulphate has been added to the groundwater (Figure 28). High values of the sulphate/chloride ratio near Kwinana are probably due to industrialisation, whereas high values near the crests of the Gnangara and Jandakot Mounds may be due to the oxidation of sulphides associated with wetland soils.

The distribution of the sulphate/chloride ratio with depth along the Gwelup and Applecross

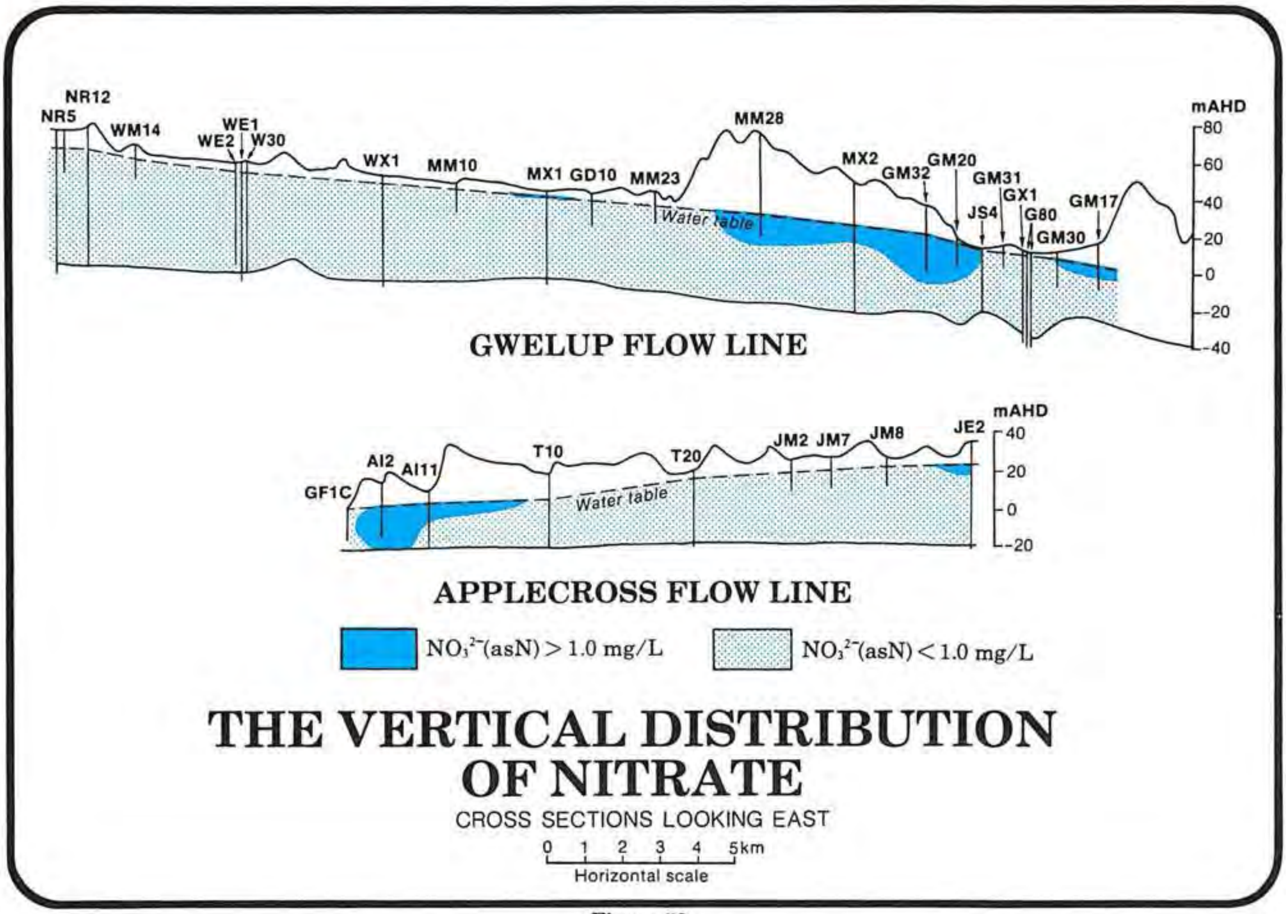


Figure 53

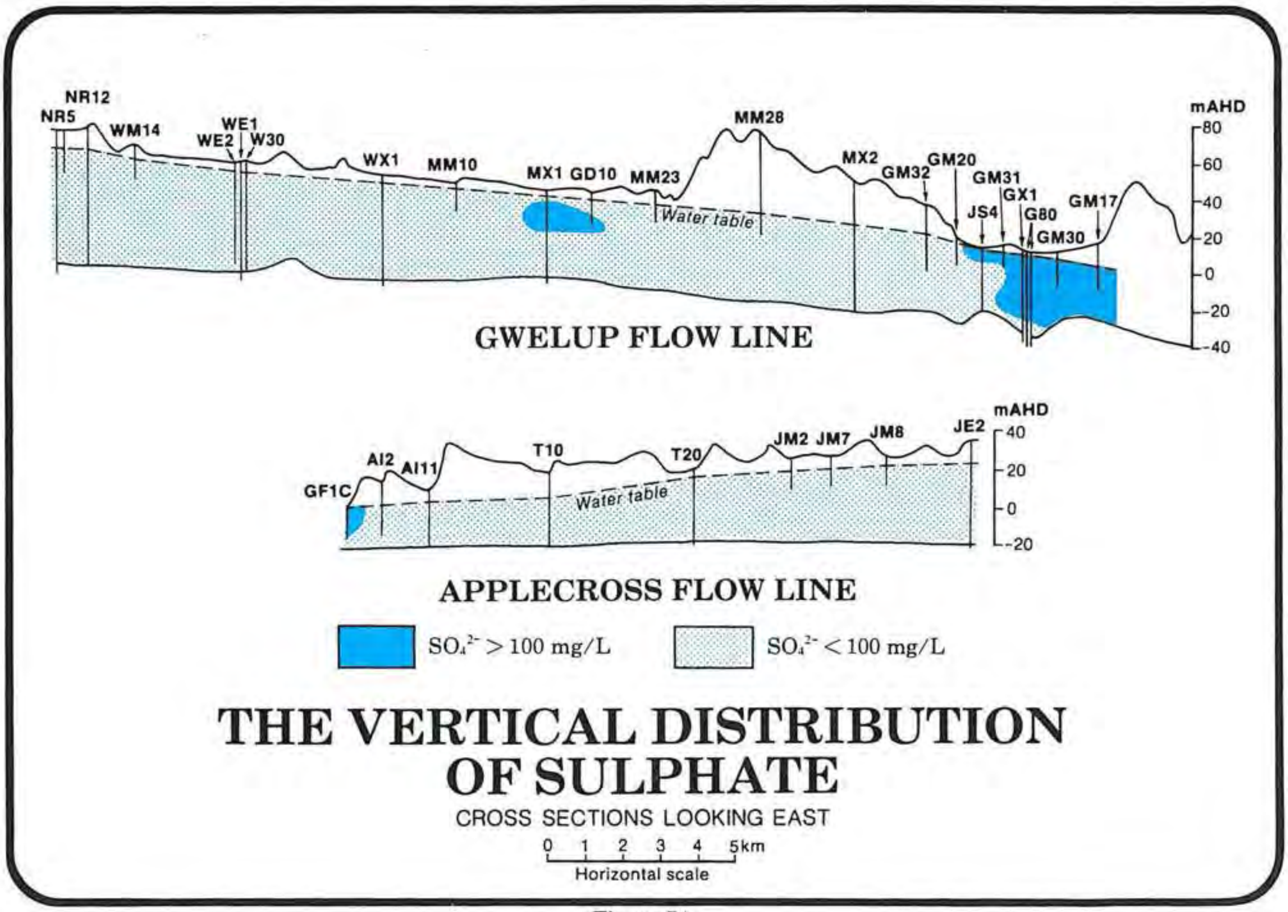


Figure 54

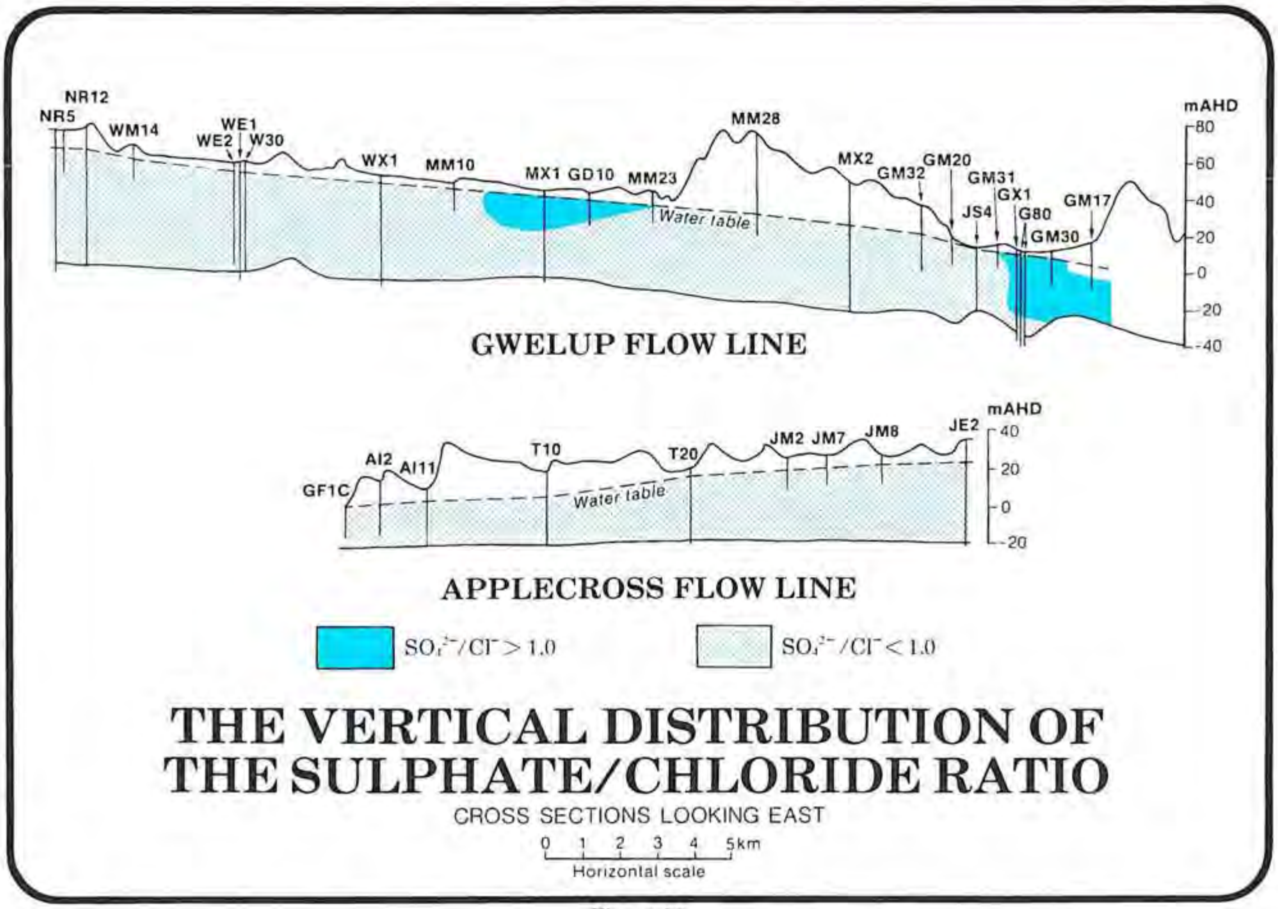


Figure 55

flow lines are presented in Figure 55. Along both flow lines, the ratio is generally greater than 0.14, which is the value of the ratio in Perth's rainfall, indicating that sulphates in groundwater have been derived from sources other than rainfall. In the vicinity of bores MX1, GD10 and MM23 and bores JS4 to GM17 along the Gwelup flow line, the ratio was above 1.0, indicating significant input of sulphates from sources other than rainfall.

Fertilisers applied in the horticultural areas and in urban areas along the Gwelup flow line may be the source of sulphate, although in the same area the concentration of nitrate was found to be low. Groundwater conditions may be such that nitrate is reduced to ammonia and nitrogen in these areas, but that the reducing conditions are not sufficiently strong to reduce sulphates to sulphides.

In Applecross, low sulphate/chloride ratios recorded under urban areas where high nitrate concentrations were recorded could indicate that nitrates are principally derived from septic tank effluent rather than from fertilisers.

5.3.4 Heavy Metals

Heavy metals including cadmium, chromium, copper and lead are toxic in drinking water at very low concentrations. The major sources of these metals in an urban environment are the disposal or spillage of industrial wastes, leachates from landfill sites and road runoff. Samples collected from 34 bores distributed throughout developed areas (Figure 56) showed that concentrations were generally well below potable limits. Isolated high concentrations were recorded in the vicinity of Kwinana, probably from point sources of pollution. The effluent disposal provisions of the Environmental Protection Act provide a mechanism for the management of point sources of pollution.

5.3.5 Total Organic Carbon

The total organic carbon (T.O.C.) concentration in groundwater indicates the presence of any organic material. This material may include small amounts of toxic organic pesticides. The T.O.C. concentration of groundwater in the region was generally less than 20 mg/L but the concentration recorded for a number of isolated samples collected in January 1984 was in excess of 50 mg/L. These samples were collected near market gardening areas in the Southern Perth Area. Groundwater was resampled at these sites and specifically analysed for organo-chloride pesticides which are extremely toxic and biologically non-degradable.

The concentrations of all pesticides measured were found to be well below potable limits.

5.3.6 Iron

The presence of iron in domestic water supplies causes problems of staining of clothes, and clogging of pipes and has an unpleasant taste. It is, however, easily removed from the water prior to distribution by the Water Authority and does not limit the utility of groundwater for public water supplies.

5.3.7 Testing Water for Drinking

There is risk of degradation of water quality in urban areas and water drawn for drinking purposes should be periodically tested to ensure that it meets drinking water standards. The Water Authority maintains a rigorous treatment and testing facility for its public water supply schemes to ensure that water delivered complies with drinking water standards.

5.4 IRON STAINING AND BORE ENCRUSTATION

High concentrations of iron in groundwater can cause problems for users of groundwater resources. These include the staining of walls, fences and pavements, the staining of leaf vegetable crops and the reduction of water yield through iron encrustation on bore screens. These problems are caused by the oxidation of dissolved iron to form insoluble precipitates.

Iron exists in nature in two oxidation states: ferrous iron (Fe^{2+}) and ferric iron (Fe^{3+}). Ferrous iron is highly soluble in water whereas ferric iron has low solubility (except in acidic solutions). Upon exposure to oxygen, ferrous iron precipitates from solution as ferric oxides and hydroxides. Staining problems are widespread throughout the urban area, however the community appears to be resigned to staining as an unavoidable consequence of using groundwater.

A severe economic problem is the encrusting of bore screens with ferric oxides produced by iron bacteria from ferrous iron dissolved in the groundwater. When chemical and biological conditions are ideal, heavy encrustations form and cause substantial reductions in yield. Removal of the encrustation requires frequent treatment at considerable expense. The reductions recorded in some local authority bores may be due to this problem and bore screens and collector mains of the Gwelup public water supply scheme require cleaning every one to five years to remove encrustation produced by iron fixing bacteria.

Factors which probably affect the distribution of iron in the unconfined aquifer in the Perth area are depth below the water table, the presence of organic material, and the presence of iron bacteria.

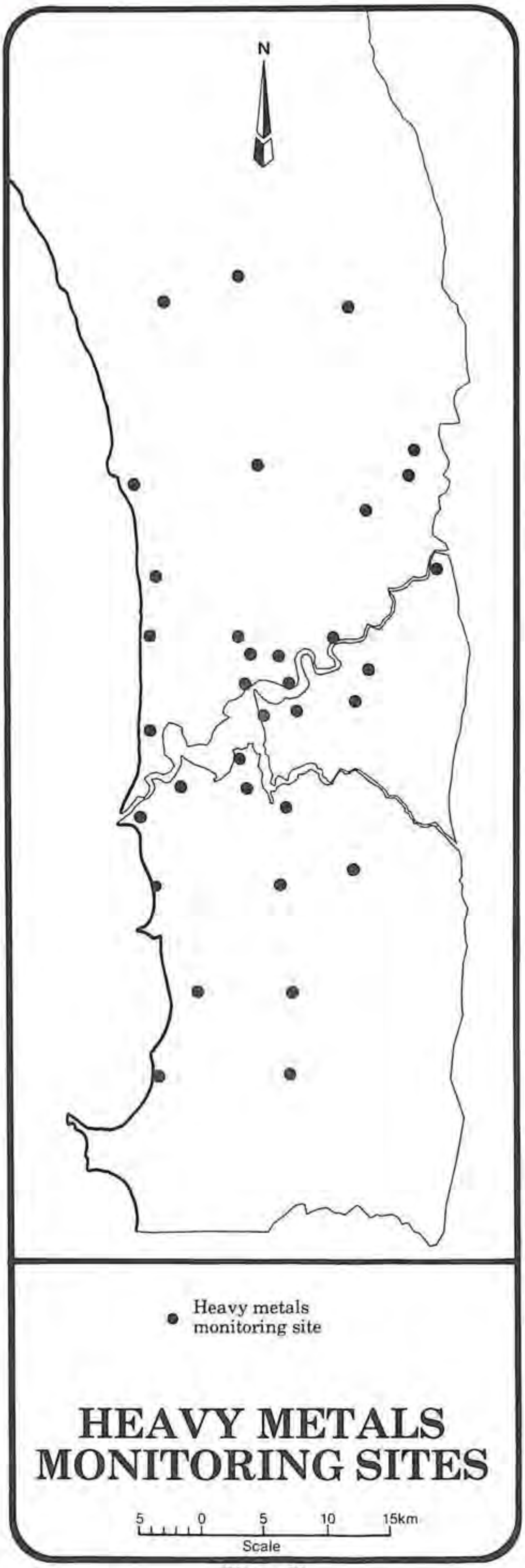
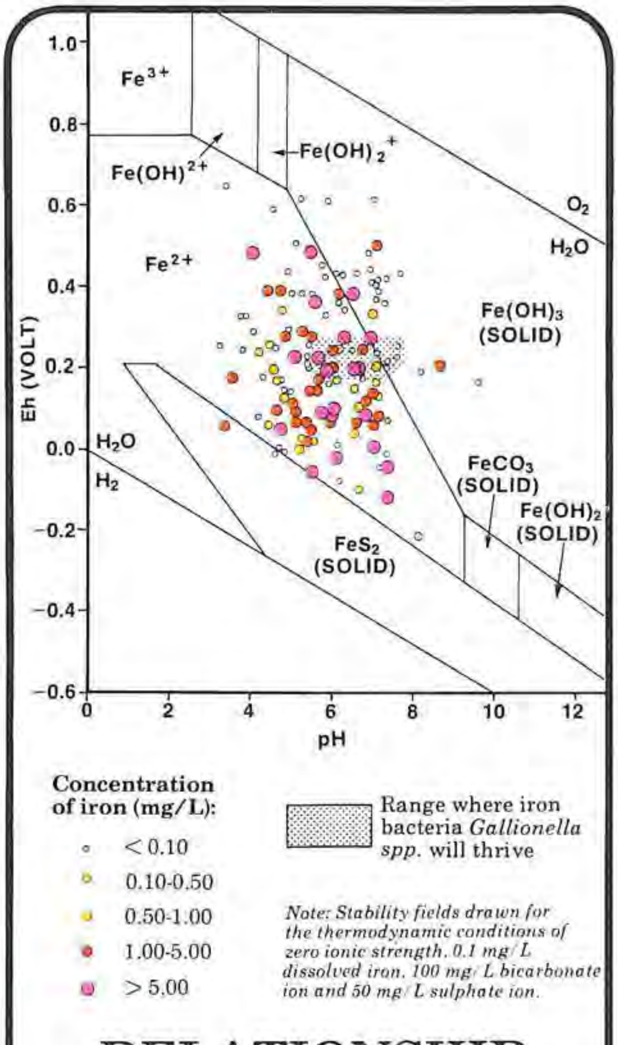


Figure 56

Under equilibrium conditions, the solubility of iron is strongly influenced by the oxidation potential (Eh) and the pH of the groundwater. The stable form of iron under various conditions of Eh and pH can be shown on an Eh-pH (Pourbaix) diagram (Garrels and Christ, 1965). The Pourbaix diagram in Figure 57 shows the ion concentration of samples collected during the January 1985 regional sampling round plotted according to the Eh and pH of the sample.

Total iron concentrations generally increase with depth in the aquifer due to decreasing Eh values (Martin and Harris, 1982). This trend was observed in this Study, although many local variations exist.

The distribution of dissolved iron with depth along the Gwelup and Applecross flow lines is shown in Figure 58. Total iron concentrations greater than 5 mg/L occur near the surface of the aquifer under the horticultural and pine forest areas around bores MM10 and MX1 and at mid-depth in the aquifer in the Tamala Limestone.



RELATIONSHIP OF IRON CONCENTRATION TO Eh & pH
JANUARY 1985 DATA

Figure 57

Near the top of the aquifer in the Tamala Limestone, iron is probably present as iron oxide precipitate on the sand grains and is not extracted during pumping. The stable form of iron at mid-depth in the aquifer is ferrous iron in solution. Iron recorded at high concentrations near the surface of the aquifer beneath the wetlands and shallow water table of the interbarrier depression between bores JS4 and G80 may exist as a chemical complex with ammonium or phosphate or as a colloidal oxide suspension.

Near the base of the aquifer, where the oxidation-reduction potential is low, the stable form of iron is the solid pyrite. Siderite may also exist in the Tamala Limestone.

Along the Applecross flow line, the concentration of dissolved iron is everywhere less than 5.0 mg/L, but concentrations exceed 1.0 mg/L at mid-depth for most of the flow line (Figure 58).

Organic material in soils provides a nutrient source for the mobilisation of iron by bacteria, provides chelating agents (substances which have the ability to form strong bonds with metal ions so that the ions are not free to form insoluble salts) and maintains the reducing conditions necessary to hold iron in solution. High iron concentrations observed in groundwater in the Southern Perth Area are generally found in swampy areas which contain peat.

Bacteria such as *Gallionella* spp., which use the oxidation of ferrous iron to ferric iron as an energy source, can control the concentration of dissolved iron. The population of bacteria fluctuates seasonally depending on the availability of nutrients and the existence of an appropriate growth environment (Smith and Tuovinen, 1985). This and several other genera of iron-fixing bacteria have been recorded in local groundwater (Grey, 1976).

The range of Eh and pH for which iron bacteria *Gallionella* spp. will thrive has also been plotted on the Pourbaix diagram in Figure 57, to show that there are a number of locations where high concentrations of dissolved iron co-exist with an appropriate growth environment for *Gallionella* spp. These locations are shown in Figure 59. Bore encrustation problems are, in fact, far more widespread in the Perth region than is suggested by the concentration of dissolved iron and the Eh and pH of groundwater. Many other factors, such as the presence of nutrients and organic material, are also important factors in the distribution of iron fixing bacteria.

Bacteria that cause bore clogging problems are endemic within aquifers. It has been suggested in the USA that bacterial problems are spreading at a noticeable rate through aquifers in a number of parts of North America (Smith and Tuovinen, 1985). These problems could be caused by bacteria migrating to and multiplying in different parts of the aquifer, by drawing water through the aquifer at bores, providing ideal local conditions for bacteria to multiply, or by transferring bacteria on drilling rigs. Further specific research is needed to assess the distribution of given bacteria species in Perth and the extent of any problems resulting from migration of bacteria in the aquifer.

Periodic changes in iron concentration were apparent at some bores, e.g. UA10 (Figure 60), where peak concentrations at least twice the minimum were observed between April and June. The length of record was insufficient, however, to identify long-term trends.

5.5 WATER LEVELS IN THE VICINITY OF BORES

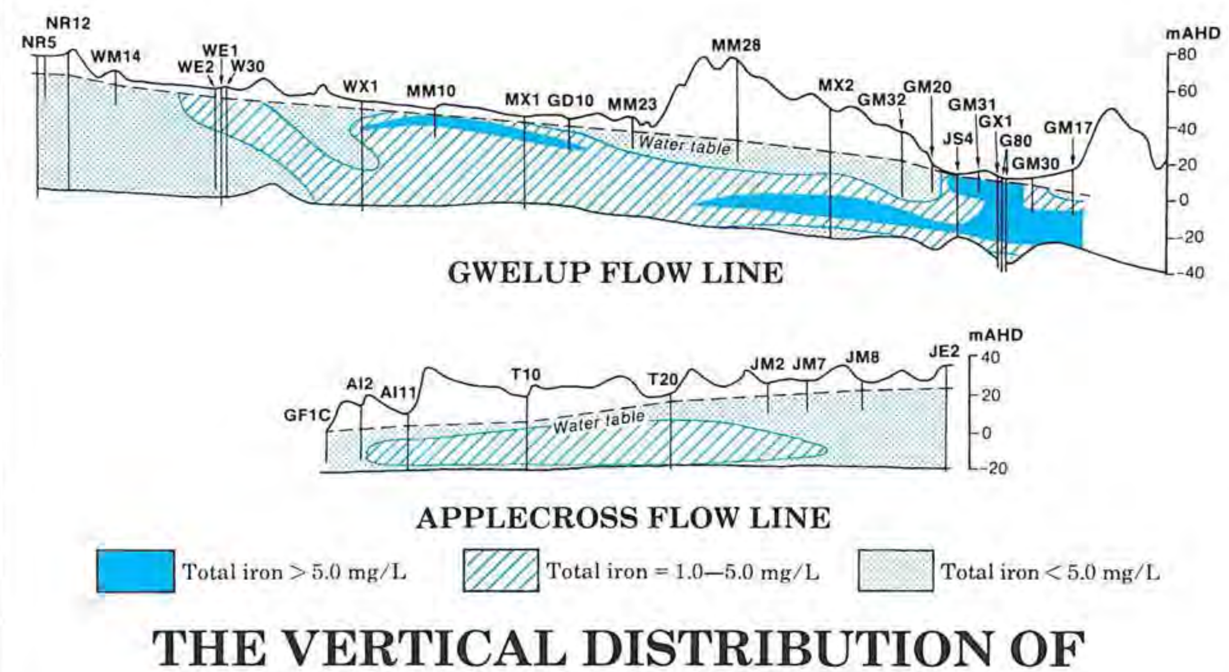
Variations in the water table elevation may affect the ability of bore users to pump water from the aquifer.

Bores are constructed to varying depths, ranging between the water table and the base of the aquifer. Those that are constructed to draw water from the top of the aquifer are at greatest risk of malfunction if the groundwater level falls below the pump intake. Domestic bores are at greatest risk because they are usually constructed no deeper than necessary to gain a supply. Local authorities and other institutions extend their bores deeper into the aquifer because of their need for high yields. They are therefore not as susceptible to problems caused by water level changes.

A bore may also malfunction with a lowered water table if the head against which the pumping equipment must draw water exceeds the maximum design suction head of the pump. In this case, the pump is no longer able to raise groundwater the extra distance to the pump. In areas where the water table is shallow, most domestic bore users use centrifugal pumps mounted near the ground surface. These pumps have a limited suction head, and they are therefore at risk of malfunction should the water table fall significantly.

5.6. EQUITABLE DISTRIBUTION OF THE RESOURCE

In keeping with the Water Authority's corporate objective of managing the use and conservation of the State's water resources for the continuing benefit of the community, an important consideration is the equitable distribution of the

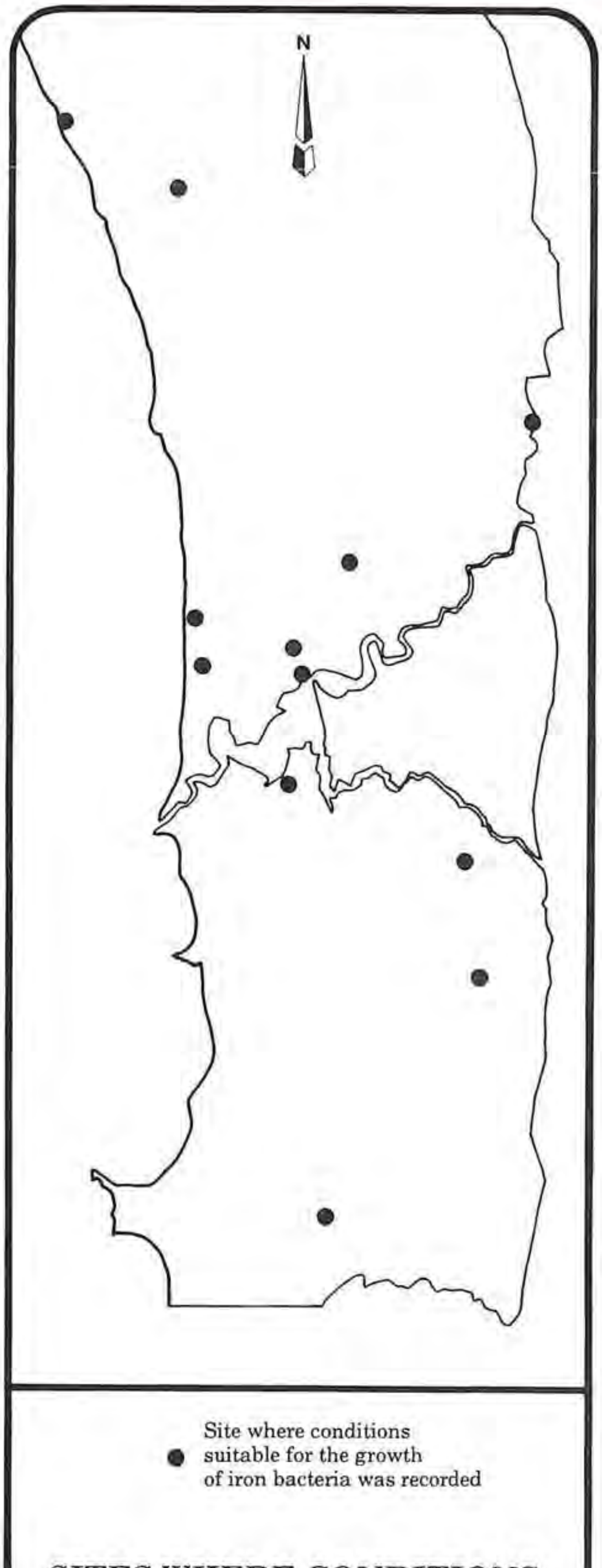


THE VERTICAL DISTRIBUTION OF TOTAL DISSOLVED IRON

CROSS SECTIONS LOOKING EAST

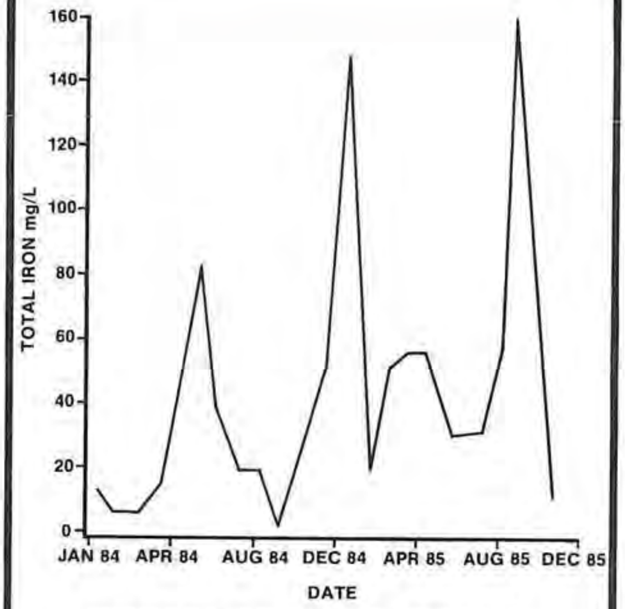
0 1 2 3 4 5km
Horizontal scale

Figure 58



SITES WHERE CONDITIONS SUITABLE FOR THE GROWTH OF IRON BACTERIA WERE RECORDED

Figure 59



PERIODIC VARIATIONS IN IRON CONCENTRATION
AT BORE UA10

Figure 60

resource between competing users. This distribution needs to be managed to ensure that no individual uses the resource to the disadvantage of others and that the security of the resource is not prejudiced.

Once the amount of water that can be safely taken from a resource is determined, the sharing of that water between competing users needs to be resolved. Competition may be between any combination of private use, public water supply use and the environment. The issue becomes more complex when considerations such as drainage and the import or export of water to or from an area are superimposed.

Resolution of the problem of equitable sharing, therefore, requires both the technical evaluation of the physical responses of the system together with the evaluation of the social, economic and political considerations.

Water resource management plans are prepared taking into account the role of the groundwater resource in meeting part of Perth's water supply needs and private irrigation needs whilst continuing to sustain the region's environment.

Evaluations of these groundwater management strategies now use sophisticated water balance and aquifer simulation models (Metropolitan Water Authority, 1985*b* and 1985*c*) and future evaluations will be based on the model developed during this Study. These models can be used to test and evaluate groundwater management strategies formulated from the non-technical social, economic and environmental considerations.

PERTH URBAN WATER BALANCE WITH CURRENT MANAGEMENT PRACTICES

Declining groundwater levels in the late 1970s aroused concern that the rapid growth in public and private abstraction would have a significant impact upon the groundwater system (Section 1.2). To assess the severity of the impact, water level changes for a number of different climatic and urban development scenarios were predicted using a computer model, known as the Perth Urban Water Balance Model.

As outlined in Section 2.4, the computer model was developed in two parts. The first part is the Vertical Flux Model, which produces an estimate for a given time interval of the net flow into the saturated zone of the aquifer from the unsaturated zone above and from the underlying Leederville Formation. The Aquifer Flow Model computes horizontal flow and change in storage in the saturated zone. Change in storage in the aquifer is reflected as a change in the water table elevation. Details of the development and calibration of the model are presented in Volume 2. Methods of presenting model output are summarised in Section 6.1.

In this chapter, attention is focussed on a situation in which groundwater use is not controlled and recharge processes are not enhanced by management beyond the level currently practised by the Water Authority. The results of this investigation indicate some areas where the groundwater resource may be at risk and where more active management may be required.

The situation which has developed within the groundwater system over the period 1976 to 1985 reflects the historical development of the groundwater resource under historical climatic conditions and is referred to as the "current situation". Variations in the components of the water balance during that period, as evaluated with the computer model, are described in Section 6.2.

To demonstrate the influence of climatic conditions, the urban water balance was evaluated assuming different climatic conditions to those which actually occurred in the period 1976 to 1985 (Section 6.3).

In Section 6.4, the effects of different levels of abstraction from bores are assessed.

The effects on the urban water balance of the expansion of urban areas are considered in Section 6.5.

6.1 MODEL OUTPUT

Results of computer simulations can be displayed in many different ways to allow assessment of the water balance. Contours of the simulated water table elevation and net vertical flux were plotted for the "current situation" to show their spatial variation across the entire study area. When looking at different scenarios for the development of the groundwater system, however, predictions were compared with the "current situation" by plotting contours of water level differences and contours of differences in net vertical flux. "Difference plots" highlight small variations that would not be evident on plots of absolute values.

Because of the irregular shape of the coast and estuary boundaries, the contouring package used to produce water level difference plots sometimes shows finite (i.e. non-zero) differences along these boundaries. Such values should be ignored. In all cases, it should be realised that the computer model is capable of predicting regional variations over distances of 1 or 2 km, and should not be believed at every point in the study area.

To smooth the effects of short-term variations in rainfall, all water level plots show the average of the previous twelve monthly values of the water table elevation.

Since the primary aims of this Study relate to the *urban* water balance, water level difference plots are restricted to areas which are currently urban or which will be urban if the region develops fully according to the Corridor Plan for Perth. Although areas outside the urban area were modelled, water level variations in these areas were not assessed in detail. More detailed studies are already being undertaken by the Water Authority to assess water level variations across the Gnangara and Jandakot Mounds. The effects predicted for areas towards the crest of the Gnangara Mound, for example, were the subject of an Environmental Review and Management Programme which was recently prepared by the Water Authority (Water Authority of Western Australia, 1986*a*). Only the effects within current and future urban areas are considered in detail in this report.

The temporal variation of each component of the water balance was assessed for different areas of interest within the study area. The areas of particular interest in this report are the whole study area, the whole urban area and the Applecross peninsula. For each month of a four-year period, the values of each component of the water balance were spatially averaged across the area of interest and the average values plotted as a time series. The different components are described in detail for the "current situation" in Section 6.2.2.

6.2 CURRENT SITUATION

6.2.1 The Spatial Distribution of Water Levels and Net Vertical Flux

Water levels and recharge vary across the study area as a result of the combined influences of aquifer properties, topography and land use (see Section 3.7).

The measured distribution of water levels is depicted as a water table contour map as shown in Figure 17. The elevation of the water table at any location depends upon the distributions of recharge to the aquifer and aquifer properties throughout a nearby region. The water table tends to rise where local recharge is high but, under the influence of gravity and depending upon the permeability of the aquifer, groundwater moves laterally to smooth the shape of the water table.

The first application of the computer model was to simulate the water table elevation and the net vertical flux for the "current situation", resulting from historical influences of climate and land use during the period 1976 to 1985. The simulated water table elevations (Figure 61) agree closely with measured water table elevations for October 1985 (see Figure 17).

The net vertical flux varies across the study area depending upon land use and topography and is far more spatially variable than water level (Figure 62).

Net vertical flux is higher under areas which have been cleared for farming or urban development since evapotranspiration is much less than from uncleared land. Also, infiltration basins in developed urban areas are very effective recharge sites. Net vertical flux is lower under dense forest, particularly under forests of species not adapted to the dry Perth environment, such as pines.

Net vertical flux is low in low-lying areas where the ground surface is close to the water table, because phreatophytes have more ready access to groundwater below the water table and because direct evaporation occurs from the aquifer at wetlands. In these areas, however, recharge, which does not include extraction by phreatophytes or by direct evaporation, is high because there is a smaller distance for water to travel before it reaches the water table. Conversely, where the depth to the water table is greater than the penetration of phreatophytes, net vertical flux is higher.

Figure 62 shows the distribution of net vertical flux across the urban areas for the year ending in October 1985. Net vertical flux was in excess of 500 mm/a, or 60% of rainfall, in the North West Corridor, an area which is currently undeveloped land covered by low dune vegetation (see Plate 5). Around Gwelup, in the centre of the Northern Perth Area, net vertical flux was negative due to high rates of abstraction of groundwater by the Water Authority, market gardeners and golf courses (Plate 22). In the Eastern Perth Area, net vertical flux ranged between zero and 200 mm/a, or between zero and 25% of 1985's rainfall. In the north western part of the Southern Perth Area, where few householders own bores and where vegetation tends not to be lush (Plate 23), net vertical flux was up to 500 mm/a. Futher inland, high evapotranspiration from Bibra Lake led to negative net vertical flux. In the eastern urban areas of Ferndale, Gosnells and Armadale, net vertical flux was low, the area being low-lying with high evapotranspiration. Along the west coast near Kwinana, net vertical flux under cleared industrial land was high, and in the vicinity of Lakes Cooloongup and Walyungup, in the far southwest of the study area, net vertical flux was negative.

6.2.2 Temporal Variations in the Water Balance

The temporal variation of all components of the water balance during the last four years of the historical simulation is shown in Figure 63. The components of the water balance have been spatially averaged over the whole study area, the whole urban area and the Applecross peninsula, respectively, and flows have been presented in units of m^3/ha/month (these units can be converted to mm/month by dividing by 10).

The components plotted are divided into those pertaining to the unsaturated soil zone and those pertaining to the saturated zone, just as in Figure 6. Flows such as deep drainage and private pumping from bores appear for each zone, since they represent flows from one zone to the other. Flows shown in green above the axis represent flows into a zone and those shown in orange below the axis represent flows out of a zone.

Rainfall. The first curve for the unsaturated zone represents rainfall reaching the land surface. Rainfall varies seasonally with strong peaks in winter and few events in summer.

Irrigation. Irrigation water from private bores (for public and private garden watering and commercial irrigation) and irrigation water

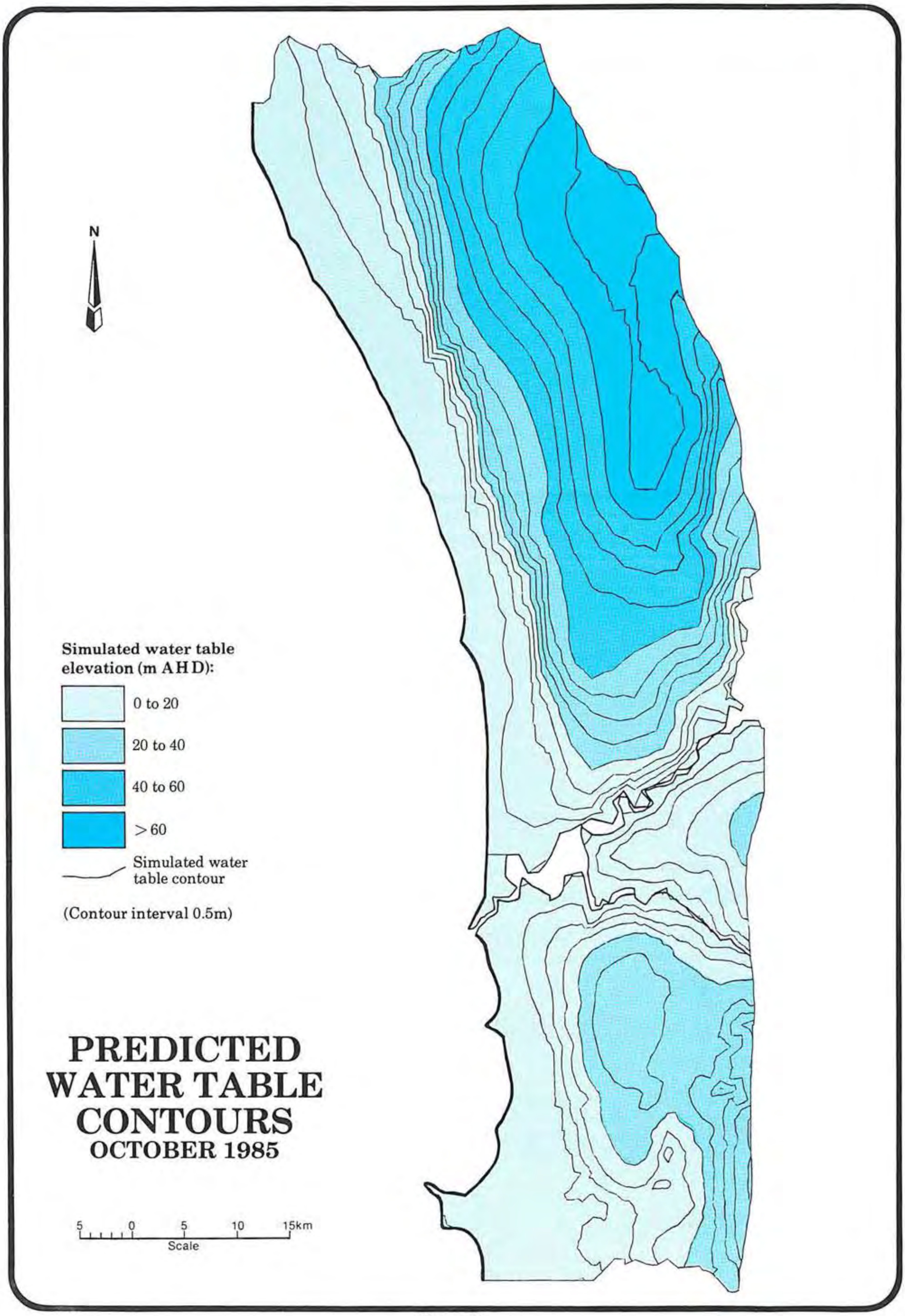
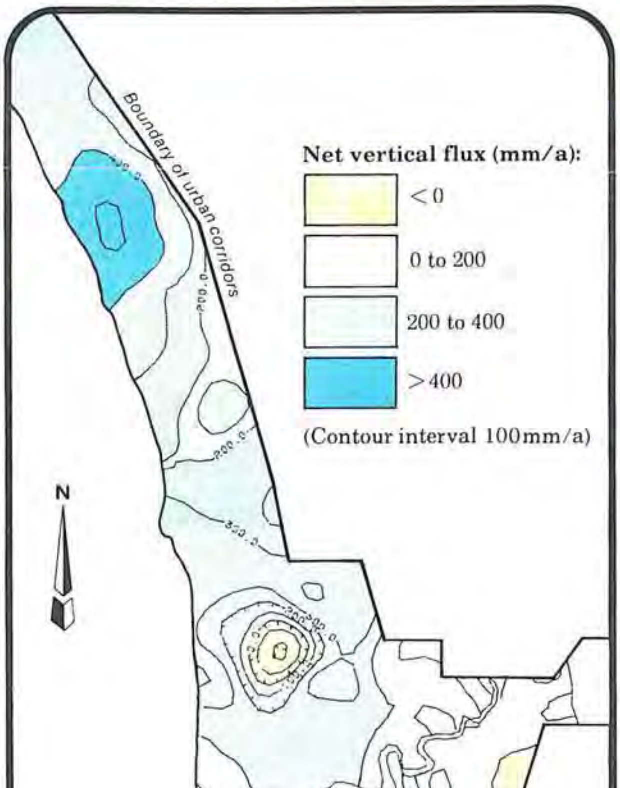

N
Simulated water table elevation (m AHD):
0 to 20
20 to 40
40 to 60
> 60
Simulated water table contour
(Contour interval 0.5m)
PREDICTED WATER TABLE CONTOURS
OCTOBER 1985
5 0 5 10 15km
Scale

Figure 61



NET VERTICAL FLUX TO THE AQUIFER

NOVEMBER 1984 TO OCTOBER 1985

5 0 5 10 15km
Scale

Figure 62

Plate 22 Market gardens and Lake Karrinyup Country Club in the Gwelup Public Water Supply Area

from Water Authority reticulated supplies (for private garden watering) has the same distribution each year, reflecting the assumptions made in distributing these components throughout the year. The regularity of the irrigation components is shown more clearly in Figures 63*b* and 63*c*, which show the water balance for urban areas. Irrigation is more significant in the developed urban areas and, in particular, suburbs like Applecross because of the high density of domestic bores.

Septic tanks. The discharge of septic tank effluent to the unsaturated soil zone is insignificant relative to other flows and cannot be seen at this scale.

Excess runoff is a loss, or output, from the system to the ocean or the estuary and represents that part of all runoff from roads and paved surfaces that does not reach the unsaturated soil zone via infiltration basins. This curve is a percentage of the rainfall curve and was determined from the percentage of the area which is covered by paved surfaces that drain out of the system.

Deep drainage is the vertical percolation through the unsaturated soil zone into the saturated zone below. The variation of deep drainage is strongly seasonal and peaks between June and August, lagging behind the peak in rainfall by one or more months. The shape of the curve shows a relatively rapid rise to its peak each year as the moisture content of the zone increases and a slower exponential decay following the conclusion of the season's rainfall. Deep drainage is generally referred to as recharge.

Evapotranspiration from the unsaturated zone depends on both the available soil moisture, which is highest in winter, and on the atmospheric demand for moisture, which is highest in summer. The net result fluctuates from month to month but maintains a strong seasonal variation. For the study area as a whole (Figure 63*a*), the peak evapotranspiration from the unsaturated zone occurs in the winter months, indicating that available soil moisture is more important than the atmospheric demand for moisture in determining evapotranspiration.

The sum of all components in the unsaturated zone, shown blue in Figure 63, represents the month-to-month *change in soil moisture content.* This term is strongly seasonal, being positive in winter and negative in summer, following the rainfall distribution.

A quick scan down all curves shows that rainfall is the most significant component and that the variation of rainfall has the most significant effect upon the overall water balance.

The water balance of the saturated soil zone, is presented in the same way.

Deep drainage is an input to the saturated zone and is equal to the deep drainage from the unsaturated zone, above.

Leakage between the superficial formations and the Leederville Formation is an extremely small component which in many cases cannot be seen at this scale. This component can be positive or negative depending upon whether the net flow over the area being analysed is into or out of the superficial formations.

Lateral groundwater flow is the net horizontal flow of groundwater into the area being analysed. Generally, the flow from the "downstream" end of the system exceeds the flow into the "upstream" end because local net vertical flux is positive. The net flow into the area is therefore negative. When the groundwater outflow is less than the inflow, as occurs in summer months in urban areas (Figures 63*b* and 63c), the groundwater users of the area are partially dependent upon groundwater flowing from upstream. Areas with a high density of private bores are more dependent on lateral inflows from upstream in the aquifer. Water balance plots of this type, if prepared for each municipality in the Perth metropolitan area, would indicate the extent to which some areas rely on lateral inflows and may assist in determining management strategies for local areas after regional strategies have been evaluated.

Pumping. Water pumped by the Water Authority and water pumped by all other users is distributed regularly each year, reflecting the assumptions made in distributing the total annual abstraction during the year. The importance of these terms varies for different

Plate 23 Urban development in the north western part of the Southern Perth Area

areas under consideration. For the study area as a whole (Figure 63*a*), they are minor components of the overall water balance, but in local areas such as Applecross, they become more significant (Figure 63c). Water pumped for private purposes is used primarily for irrigation; the same curve therefore appears as a private irrigation input to the unsaturated zone.

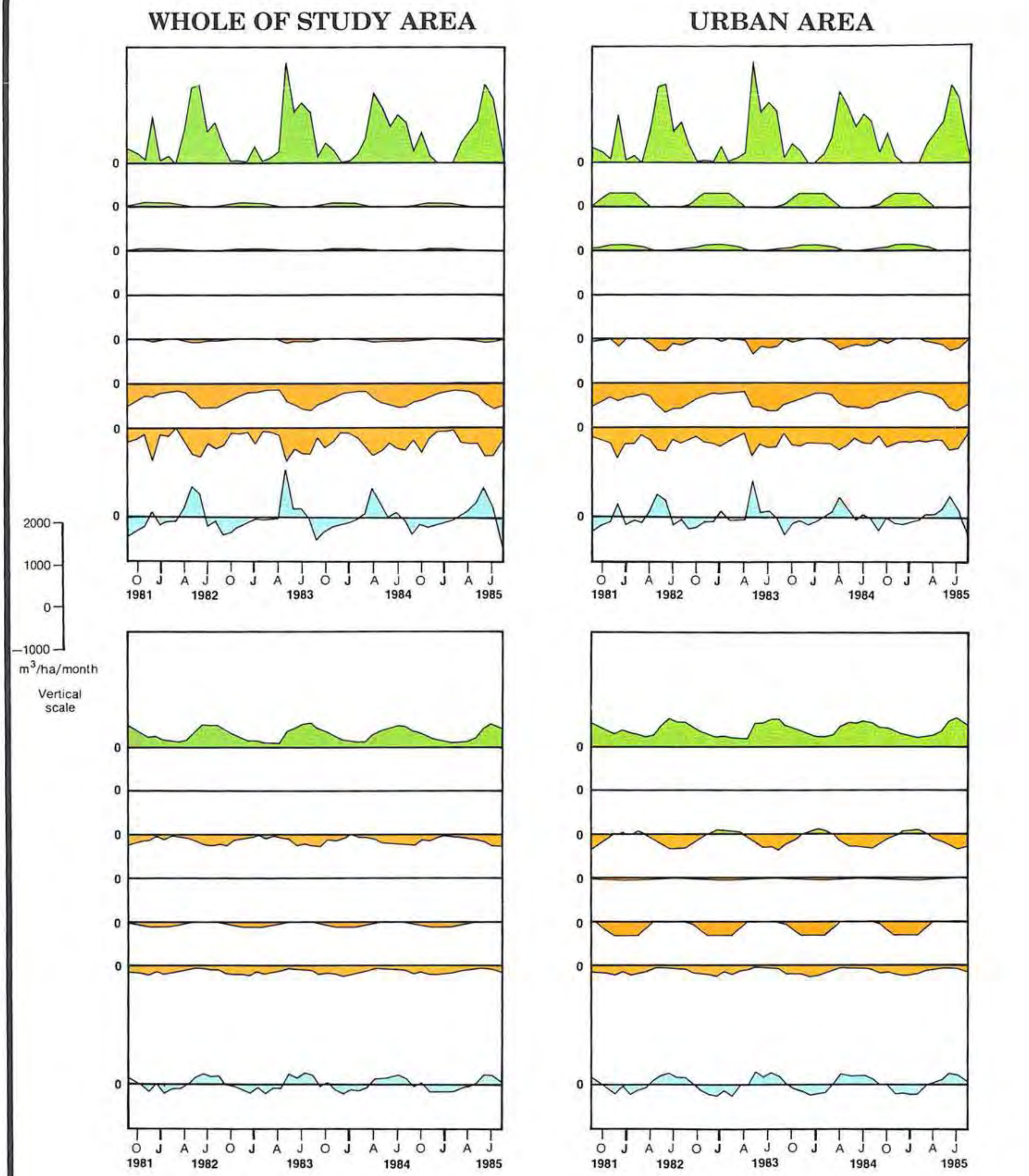
Evapotranspiration from the saturated zone is comprised of evaporation from lakes and swamps, where the ground surface is just above or below the water table, and transpiration by phreatophytes. Extraction by phreatophytes only occurs where the roots of the phreatophytes penetrate to the water table. Because water is always available below the water table, evapotranspiration is controlled by atmospheric conditions and, unlike evapotranspiration from the unsaturated zone, this loss is always higher during the summer months.

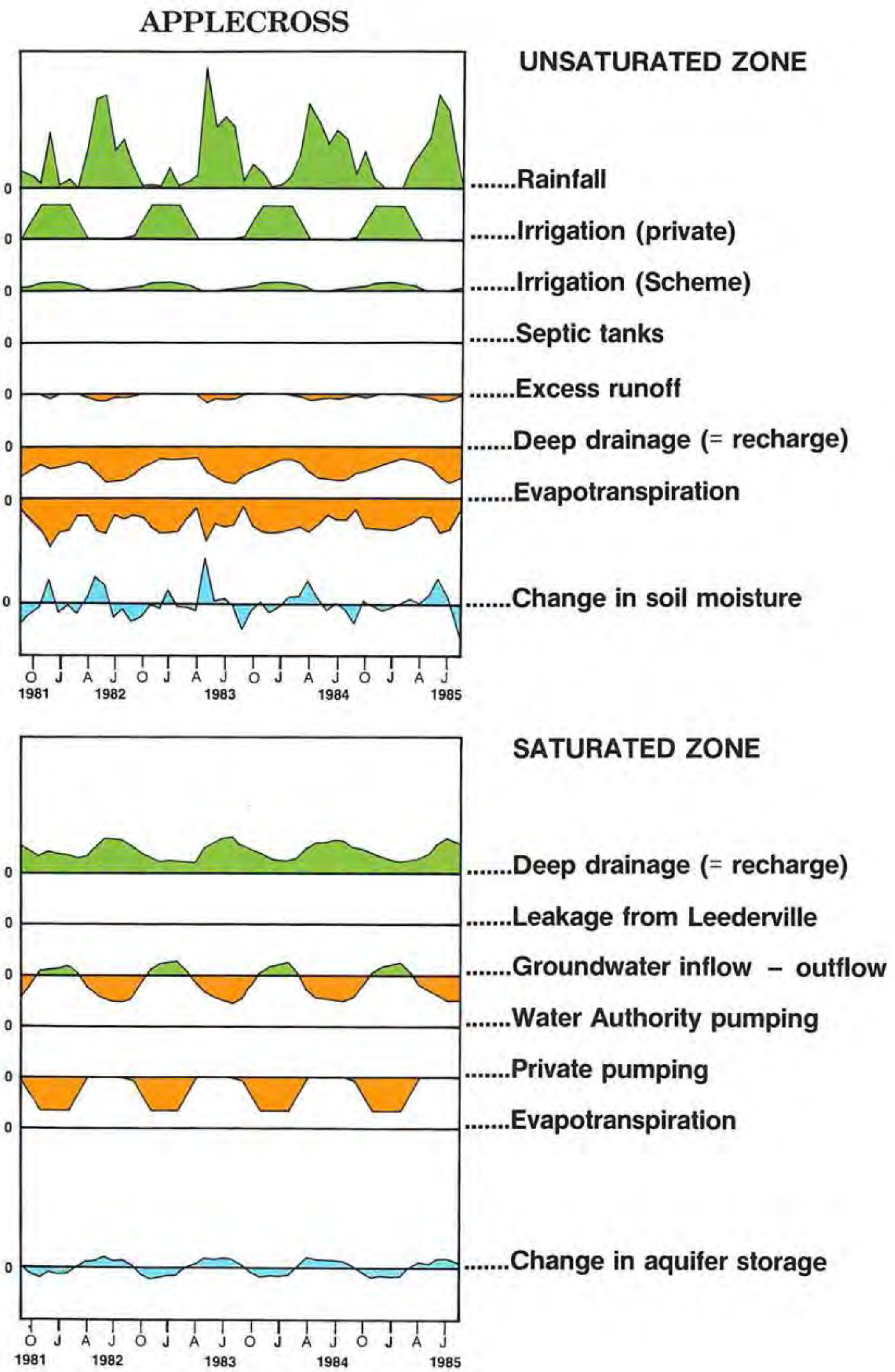
Change in storage. The overall change in storage in the saturated zone is equivalent to the difference between total inflow and total outflow from the zone (see Section 2.1). Change in storage is manifested as a change in the elevation of the water table. It is strongly seasonal and is generally positive until September or October each year and negative until April or May.

6.2.3 The Current Water Balance

The spatial distribution of water levels was shown to be fairly smooth across the study area. The shape of the water table depends largely upon the distribution of aquifer properties and the distribution of recharge. Recharge is extremely variable across the study area and varies with topography and land use.

Strong seasonal trends were shown to occur in


WHOLE OF STUDY AREA
URBAN AREA
0
2000
1000
0
−1000
m³/ha/month
Vertical scale
O J A J O J A J O J A J O J A J
1981
1982
1983
1984
1985



VARIATIONS IN THE WATER BALANCE
1981 TO 1985

Figure 63

most components of the water balance and the components vary in their importance depending upon the area being assessed. (Time series plots, such as those in Figure 63, can be used to show the variation in the water balance components for any area or region so that, for any local area under investigation, the most significant components can be identified).

Deep drainage to the water table continues throughout the year. In winter, this is derived from recent rainfall whilst, in summer, it consists of delayed percolation of earlier rainfall as well as the excess of irrigation over evapotranspiration in the unsaturated zone. The latter is often described as recirculated irrigation water.

In urban areas, private irrigation is a significant component because of the high density of private bores. During summer, high abstraction rates may result in a negative lateral flow of groundwater, indicating that the area is partially dependent upon groundwater flowing from upstream (Figure 63*b* and 63*c*).

Evapotranspiration from the saturated zone varies depending upon the proportion of the area covered with lakes and swamps. This component is significant for the whole urban area but in Applecross, where the depth to the water table is generally large, it is virtually zero.

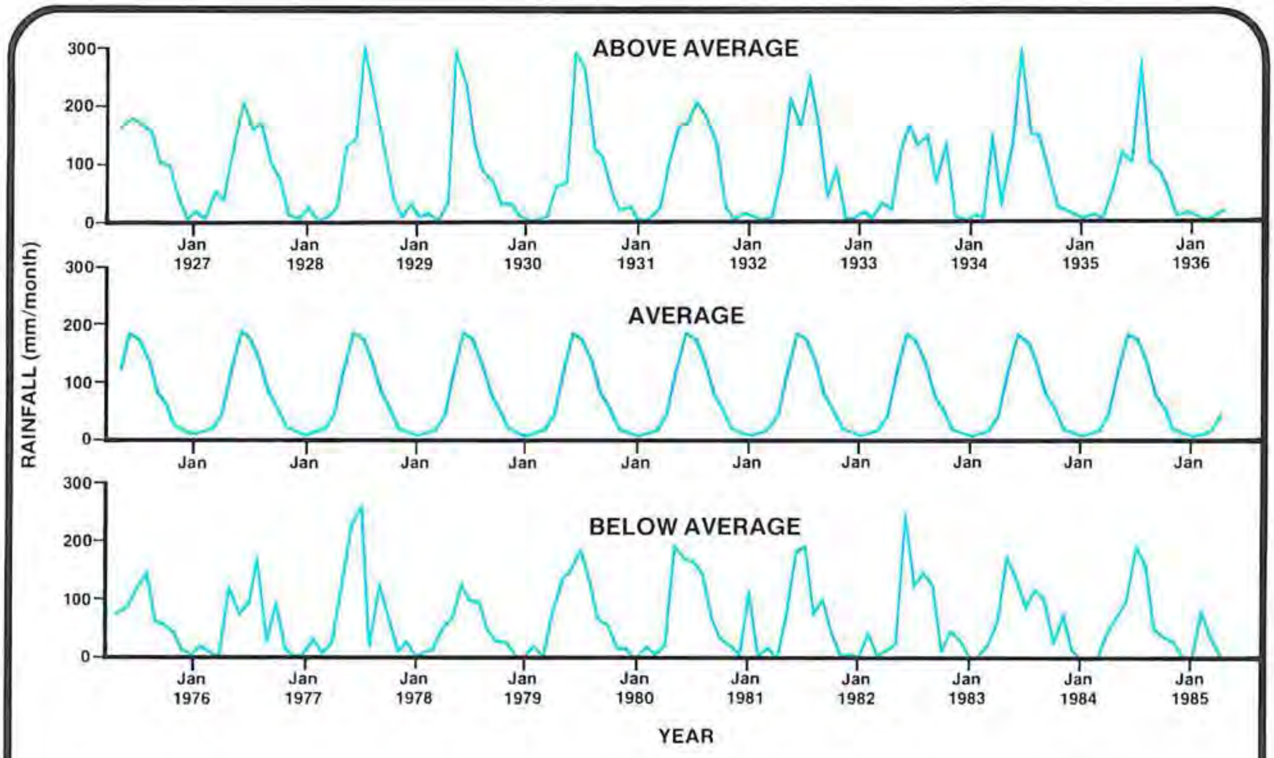
Evapotranspiration from the unsaturated zone is higher in Applecross than for the whole urban area because of the high density of private bores and the high application rates of irrigation water per bore.

The urban water balance is primarily driven by climatic effects but is modified by changes in land use. There is a need to manage land use to ensure that equitable distribution of the available resource is maintained for all climatic conditions.

6.3 EFFECTS OF CLIMATE

During the period from 1976 to 1985, below-average rainfall in the Perth region (Figure 10) led to a reduction in groundwater utility in some areas. To quantify the effect of climate on the water balance, the computer model was used to simulate variations in water level during the same period, under conditions of average and above-average rainfall.

An average-rainfall sequence was generated by setting each month's rainfall equal to the long-term average for that particular month. The high rainfall sequence adopted was the historical rainfall for the period 1926 to 1935. The average and high-rainfall sequences are compared with actual 1976-1985 rainfall in Figure 64.



RAINFALL SEQUENCES USED IN MODEL SIMULATIONS

Figure 64

Statistical analysis of annual rainfall volumes between 1876 and 1985 shows that annual rainfalls are, statistically, almost independent, with an average of 870 mm and a standard deviation equal to 165 mm. If annual rainfalls are assumed to be "normally distributed", it can be shown that the probabilities of occurrence of 10-year periods drier than 1976-1985 and wetter than 1926-1935 are 2.3% and 6.2% respectively. Considerable care is required in interpreting these probabilities, particularly for overlapping 10-year periods. If two successive years are drier than average, for example, the chance of a ten-year sequence, starting with these two years, being drier than 1976-1985 depends on the actual rainfalls already recorded for the first two years. Nevertheless, it is clear that the adopted sequences are certainly drier and wetter than average.

6.3.1 Average Rainfall

The predicted differences between water levels which would have occurred in 1985 had average rainfall been received during the previous ten years and actual 1985 water levels are shown in Figure 65. As expected, regional water table elevations in many areas would have been higher than they are now.

Groundwater levels would have been up to 0.5 m higher across most of the urban area, and up to 1.0 m higher in the northern suburbs. Of particular interest is the result that water levels in the inner western suburban lakes would have been about 0.5 m higher than at present and in the Wanneroo chain of wetlands they would have been about 1.0 m higher. Low water levels experienced in these wetlands in the last few years would not have eventuated.

6.3.2 Above-average Rainfall

If the region had received above-average rainfall between 1976 and 1985, water levels would have been even higher than with average rainfall.

In the Southern Perth Area, levels would have been up to 2.5 m higher in the Winthrop and Bateman areas (Figure 66). Levels would have been generally up to 1.0 m higher in the Eastern and Northern Perth Areas, with the localities between Marangaroo and Bayswater experiencing levels up to 4.0 m higher.

The large response in the groundwater system between Marangaroo and Bayswater reflects the low permeabilities in the aquifer underlying these areas (Figure 18). Larger rises of the water table in these areas occur because the groundwater cannot flow quickly to the estuary.

The higher water table would be close to the ground surface in many urban areas and would be likely to cause flooding and waterlogging problems.

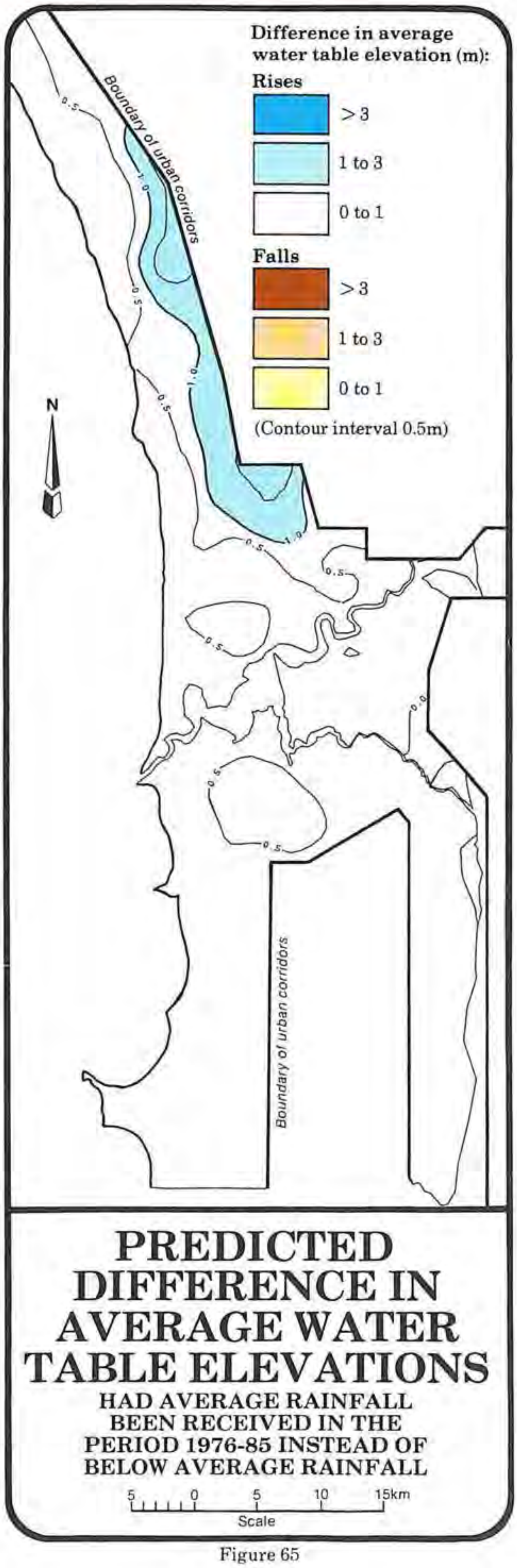
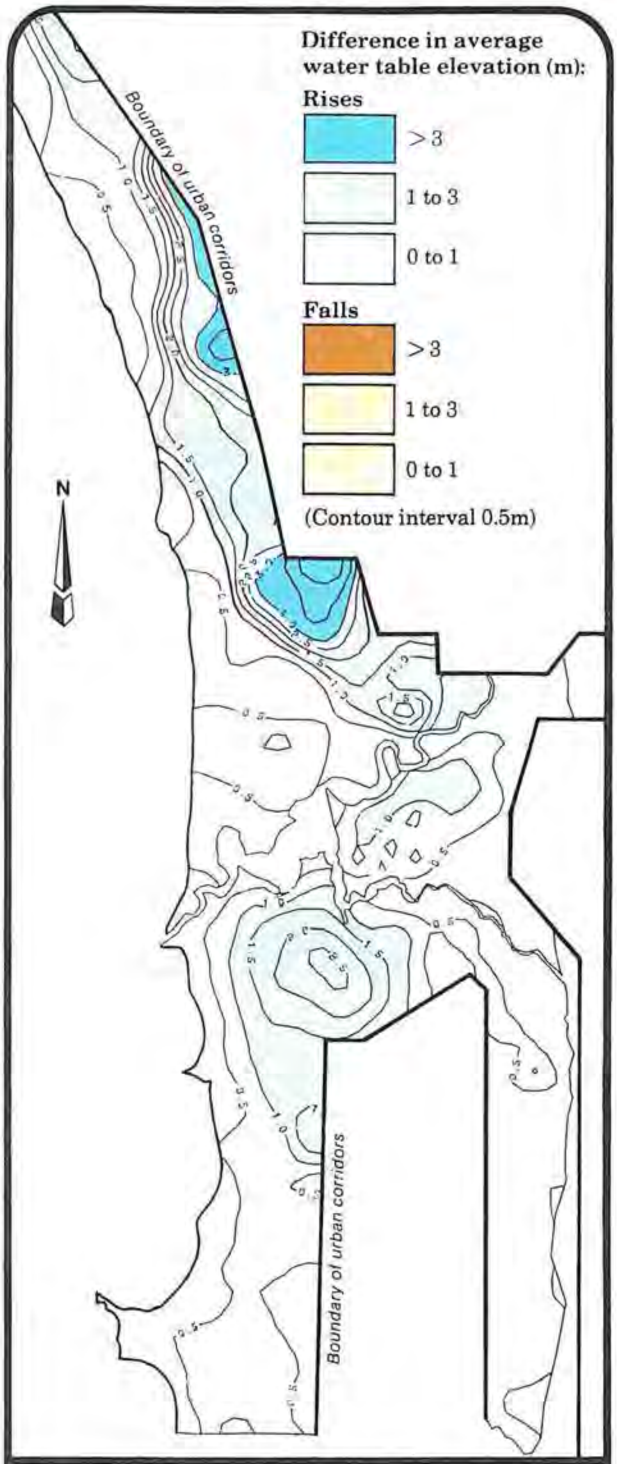


Figure 65



PREDICTED DIFFERENCE IN AVERAGE WATER TABLE ELEVATIONS
HAD ABOVE AVERAGE RAINFALL BEEN RECEIVED IN THE PERIOD 1976-85 INSTEAD OF BELOW AVERAGE RAINFALL

5 0 5 10 15km
Scale

Figure 66

6.4 EFFECTS OF INCREASED BORE DENSITY

Below-average rainfall during the last ten years has produced some adverse effects on the utility of the groundwater resource. It is possible that below-average rainfall will continue in the near future and if it does, private use of groundwater could also be expected to increase.

In this section, the effects of a further ten years of below-average rainfall, starting from 1985, are assessed. It is assumed there would be a gradual increase in private domestic pumping to 150% of current rates and a gradual increase in local authority and institution pumping to 120% of current rates within the existing urban area.

The results of this simulation are shown with water level difference contours in Figure 67. Water table elevations would be lower across most of the urban area. In particular, declines of up to 1.0 m could be expected in the Northern Perth Area (between Marangaroo and Morley) and in the Eastern Perth Area (centred on the City of Belmont). Water levels in the Southern Perth Area and in the inner western suburbs around Wembley would be less than 0.5 m lower than in 1985, however wetlands in these areas (such as Perry Lakes) are already identified as being under stress from lowered water levels and even a small further lowering would exacerbate the problems.

The greatest variations in water levels are in areas where the aquifer permeability is low.

6.5 EFFECTS OF URBAN DEVELOPMENT

In Section 6.3, it was shown that average rainfall over the last ten years would have prevented problems of drying wetlands and reduced water table elevations. As the urban area expands in the future, however, changes in the water balance will occur. To see whether any of these problems will persist with urban expansion, the water balance was evaluated under conditions of full urban development according to the Corridor Plan for Perth (see Section 4.3.5).

Associated with full Corridor Plan development are a number of factors which may affect the regional water balance. The following assumptions were made to account for these factors:

- all planned Water Authority public water supply schemes will be fully developed;
- abstraction by market gardeners will be almost double the current rates;
- all current pine forests will have matured, but will be managed at 20% canopy cover (canopy cover in pine forests currently ranges from 0 to 75%); and

- abstraction for domestic, local authority and institution bores for all urban areas in the future will be at the same rates as in current urban areas.

It is important to note that full urban development would not be reached until well into the 21st Century, hence this scenario is not related to the current water balance regime.

Three situations with different climatic conditions were modelled with full Corridor Plan development, i.e. with average rainfall, above-average rainfall and below-average rainfall. Domestic, local authority and institution pumping rates were linked with the different rainfall conditions. With average and above-average rainfall, it was assumed that domestic bores would be installed in all new urban areas but that pumping rates would be the same as for current urban areas. With below-average rainfall, the adopted private domestic pumping rates were 150% of 1985 rates and the adopted local authority and institution pumping rates were 120% of 1985 rates for the expanded urban area. This accounted for both a larger number of bores and longer periods of pumping because of the drier conditions and possible restrictions on the use of scheme water.

6.5.1 Average Rainfall with Full Corridor Plan Development

With average rainfall and full Corridor Plan development, water levels in urban areas would be similar to those that were predicted for average rainfall and current urban development. Predicted water table differences for this scenario are shown in Figure 68, and can be compared with Figure 65 in current urban areas.

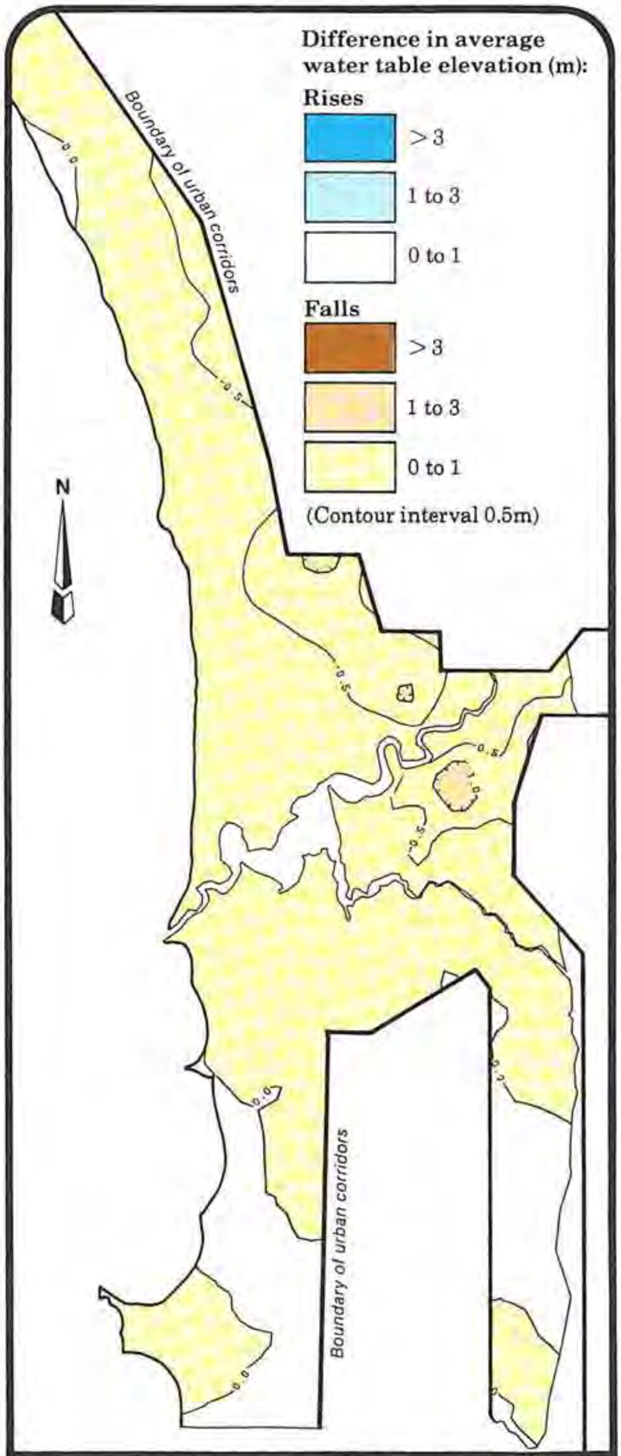
The only significant changes predicted for water levels were outside the current urban areas and are associated with extensions to Water Authority wellfields and changes in pine forest transpiration. These influences did not extend to urban areas.

The results of this simulation indicate that localised responses in the groundwater system result only from influences occurring in nearby areas. The system is not sensitive to influences at a distance from a particular point of interest.

It is predicted that problems of drying wetlands, saltwater intrusion and reduced water table elevations would not generally occur if average rainfall is received. However, careful management in the vicinity of the Wanneroo chain of wetlands will be necessary to ensure that reduced water levels, resulting from increased market garden and Water Authority abstraction, do not adversely affect the environment.

6.5.2 Above-average Rainfall with Full Corridor Plan Development

With above-average rainfall and Full Corridor



PREDICTED DIFFERENCE IN AVERAGE WATER TABLE ELEVATIONS
SHOWING THE EFFECTS OF HIGHER DOMESTIC, LOCAL AUTHORITY & INSTITUTION GROUNDWATER USE DURING A CONTINUED BELOW AVERAGE RAINFALL PERIOD

5 0 5 10 15km
Scale

Figure 67

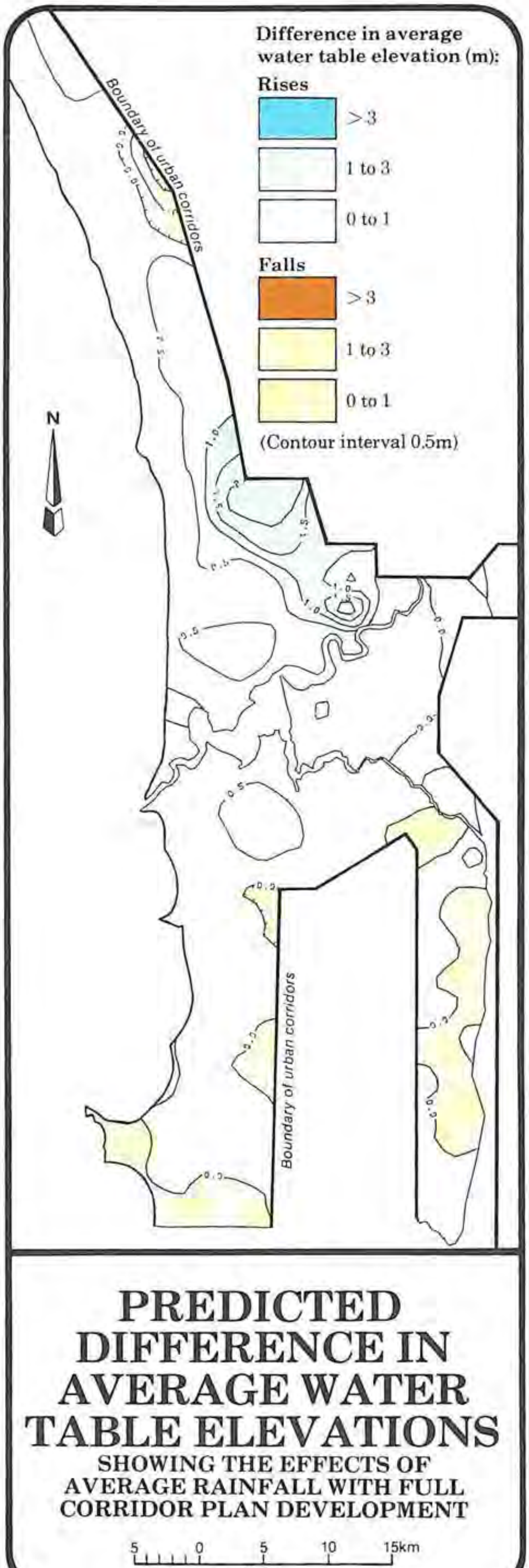


Figure 68

Plan development, water levels are predicted to be significantly higher than they were in 1985 in all urban areas (Figure 69). Levels would be up to 4.0 m higher in the low-permeability area between Marangaroo and Morley, more than 1.0 m higher around Belmont and more than 2.5 m higher in the Southern Perth Area around Winthrop.

The water table in these areas would rise to the ground surface and the main drainage system would need to remove excess water to prevent flooding.

Water levels in the inner-western suburbs of the Northern Perth Area would be up to 1.0 m higher, indicating that wetlands of that region would have ample water. Levels in the Wanneroo chain of wetlands and in the East Beeliar chain of wetlands would also be significantly higher.

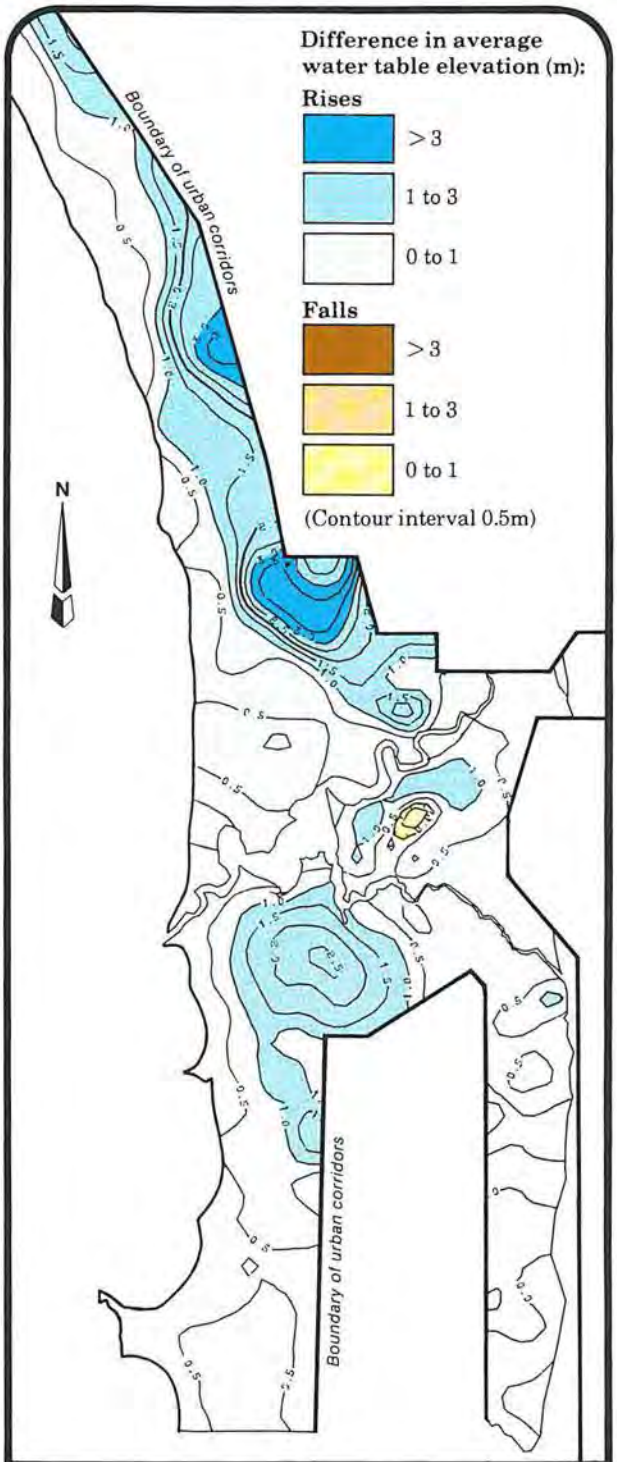
6.5.3 Below-average Rainfall with Full Corridor Plan Development

A sequence of dry years caused adverse effects on the urban water balance during the period 1976 to 1985. The severity of these effects was also assessed for below-average rainfall with full Corridor Plan development. Because of the low rainfall sequence, it was assumed that domestic pumping would expand to 150% of current rates and that local authority and institution pumping would expand to 120% of current rates. The predicted differences in average water levels between this scenario and the "current situation" are shown in Figure 70.

Significantly lower water levels would be experienced in urban areas overlying low permeability parts of the aquifer. Water levels would be more than 2.0 m lower in the Northern and Eastern Perth Areas around Morley and Belmont. In the Southern Perth Area, levels in urban areas would be up to 1.0 m lower. Wetlands in the inner-western suburbs around Wembley would be under stress with average water levels up to 1.0 m lower than in 1985. Levels in the Wanneroo chain of wetlands would be significantly lower as a result of the reduced rainfall and also because of increased Water Authority and private abstraction to the east. These lower levels indicate that the shallower wetlands would dry out during summer, or if they are already normally dry in summer, would be dry for a longer period each year.

The differences in water levels between this scenario and the "current situation" occur because the net vertical flux to the aquifer would change. Figure 71 is a contour plot of the differences in the annual net vertical flux at the end of the simulation period between this scenario and the "current situation".

Net vertical flux would be less than the "current

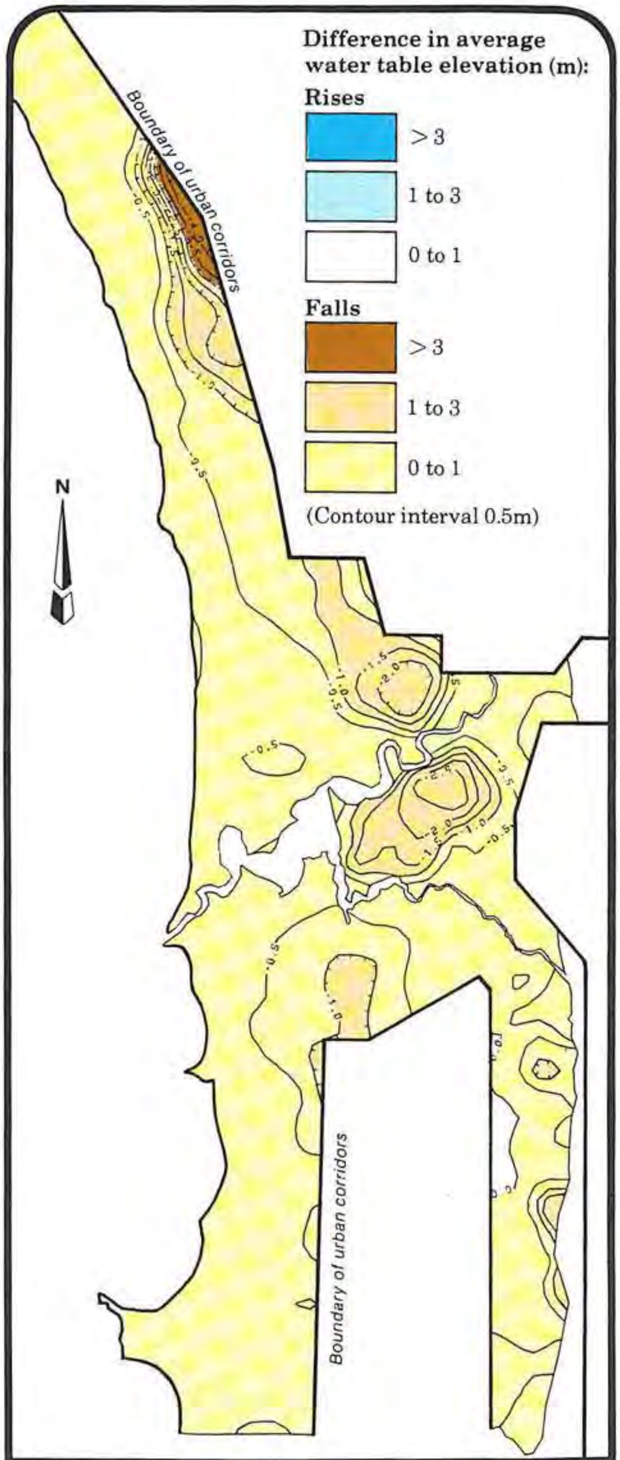


PREDICTED DIFFERENCE IN AVERAGE WATER TABLE ELEVATIONS

SHOWING THE EFFECTS OF ABOVE AVERAGE RAINFALL WITH FULL CORRIDOR PLAN DEVELOPMENT

5 0 5 10 15km
Scale

Figure 69

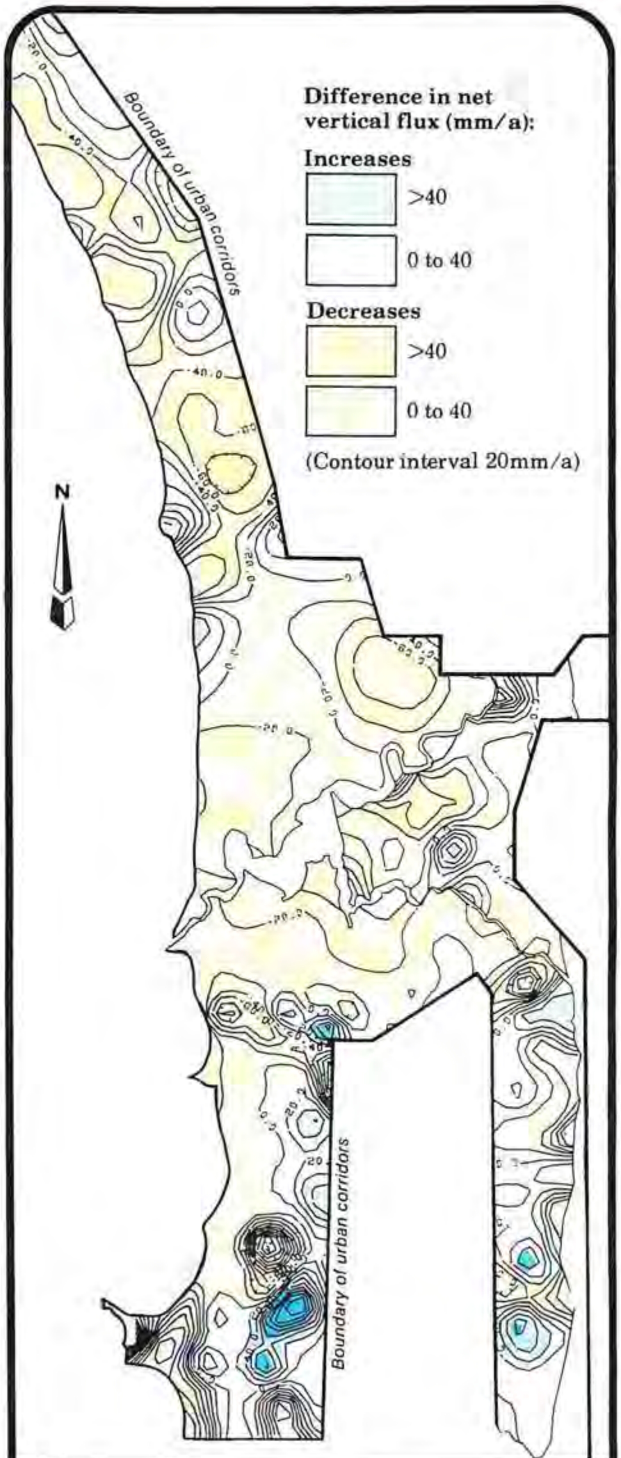


PREDICTED DIFFERENCE IN AVERAGE WATER TABLE ELEVATIONS

SHOWING THE EFFECTS OF BELOW AVERAGE RAINFALL WITH FULL CORRIDOR PLAN DEVELOPMENT

5 0 5 10 15km
Scale

Figure 70



DIFFERENCE IN NET VERTICAL FLUX
SHOWING THE EFFECTS OF BELOW AVERAGE RAINFALL WITH FULL CORRIDOR PLAN DEVELOPMENT

Figure 71

situation" in existing and future urban areas because of the increased private pumping from the aquifer. In the Eastern Perth Area, in the vicinity of Cannington and Kewdale industrial areas, the net vertical flux would be slightly higher. In this area, where the water table is shallow, evapotranspiration from the saturated zone is the dominant extraction process. As the water table elevation across the region falls during a below-average rainfall period, evapotranspiration from the saturated zone decreases. The decrease in evapotranspiration would be likely to exceed the decrease in recharge from rainfall so the net vertical flux would increase. A similar variation would occur in the southern Perth Area, along the East Beeliar chain of wetlands.

This scenario may be considered as an extreme because it relates to a period of below-average rainfall occurring after full Corridor Plan development, and the accompanying high groundwater use, is achieved. Hydrographs plotted from the model run of this scenario show that most changes would occur during the first ten to twelve years of below-average rainfall. A state of dynamic equilibrium in the groundwater system would then be reached.

The ten-year sequence of below-average rainfall used in the simulation is not unrealistic as it is derived from a recorded rainfall sequence. Also, full urban development relates to a predicted ultimate population for Perth of about 2 million by the third or fourth decade of the next century. This is a realistic prediction based upon research by the State Planning Commission. Whilst this scenario may be considered as extreme, it is nonetheless a plausible scenario.

In the near future, full urban development will not be achieved. Management of the groundwater system for the near future should be based upon predictions for urban development in the near future, but taking into account the requirements of long-term development. Computer simulations of the groundwater system should be used in the current review of the Corridor Plan so that alternative regional landuse plans may be developed such that the demands for groundwater will match its availability.

6.6 THE NEED FOR MANAGEMENT

In this chapter, it has been shown that, during periods of below-average rainfall, it is likely that reductions in groundwater utility would occur because of reduced water levels. This situation currently exists, and it will exist in the future as the urban area expands and groundwater use increases.

To avoid problems of reduced groundwater utility, management of the resource is needed to reduce abstraction from the aquifer or to increase recharge.

With extended periods of average rainfall, problems of reduced groundwater utility would not occur. Higher recharge rates in this situation would ensure adequate groundwater levels for all purposes for both the "current situation" and with expanded urban development.

During above-average rainfall periods, water levels would be significantly higher across most of the urban area. The water table would reach the ground surface in some areas and, if not for the extensive drainage systems in those areas, would cause flooding and water-logging problems. The design of drainage systems is therefore critically important for managing the urban water balance during high rainfall periods.

The consequences of a high water table and flooding are likely to have a more direct impact on the community than the consequences of a low water table. However, drainage systems should be designed to maximise recharge to the aquifer and disposal of stormwater to the estuary should be considered only when there is no further capacity for recharging the aquifer.

Chapter 7

PERTH URBAN WATER BALANCE WITH POSSIBLE FUTURE MANAGEMENT PRACTICES

This chapter focusses on strategies appropriate for managing the resource when rainfall is below average. This situation is considered to be more difficult to manage than the high rainfall situation because the latter is readily managed by constructing appropriate drainage systems.

The strategies analysed were selected to demonstrate a range of options and to demonstrate the sensitivity of the groundwater system to different options. Each model run simulated the effect of only one strategy in order to isolate its benefits. It is recognised, however, that realistic management will involve a combination of strategies. In practical situations, the model would be used to assess the simultaneous effects of a number of strategies.

The strategies analysed in this chapter, were selected to control the adverse effects of below-average rainfall with full Corridor Plan development. The different strategies require:

- reducing domestic abstraction to 50% of current rates;
- reducing domestic abstraction to 50% of current rates and reducing local authority and institution abstraction to 70% of current rates;
- reducing Water Authority abstraction to 50% of current rates;
- removing pine forests;
- directing all road drainage to infiltration basins; and
- recharging the aquifer with sewage effluent.

Finally, a strategy was considered to assess whether immediate implementation of management strategies would be effective in controlling problems which may occur over the next ten years if below-average rainfall were to continue.

The results of each analysis are presented as water level difference plots to show the differences in water levels between the situation being assessed and the "current situation". Management strategies are applied together with ultimate urban development, so the water level differences reflect the influence of both urban development and the management strategy.

To isolate the effects of each management strategy, the plots should be compared with Figure 70, which shows the water level differences resulting from the urban development alone. To make this comparison easier, Figure 70 has been reproduced as a foldout inside the back cover of this volume, together with a tabulated guide to all water level difference maps.

7.1 VARIATIONS IN EXTRACTION RATES

7.1.1 Reducing Domestic Groundwater Use following Full Corridor Plan Development

A sequence of dry years occurring after full urban development would have an adverse effect upon the urban water balance (Section 6.4.3). To avert any problems, it may be possible to reduce domestic bore use and so limit abstraction in existing and future urban areas.

If groundwater application rates for garden areas were reduced from 12.7 mm/d, which is the rate that domestic bore owners were estimated to apply in 1984 (see Section 4.2), to 4 mm/d, which is recommended by the Department of Agriculture, the reduced abstraction from bores would cause the net vertical flux to the aquifer in Applecross to increase from 490 m^3/ha to 1680 m^3/ha (all vertical fluxes are spatially averaged across the peninsula). If application rates were only reduced to 8 mm/d, the net vertical flux would increase to 1090 m^3/ha/a. In both cases the effect is dramatic, indicating the impact of private abstraction on the groundwater resource.

Water table elevations resulting from a reduction in domestic pumping to 50% of 1985 rates would be at or slightly above current water levels across most of the urban area, even during extended periods of below-average rainfall (Figure 72). Water levels would be up to 2.0 m higher than at present in the Bayswater and Morley area and in the City of Belmont, because of the low permeability of the aquifer.

By comparing Figure 72 with the foldout in the back of this volume, it can be seen that the management strategy would lead to levels being above current levels instead of well below. The effect of this strategy alone, therefore, is to produce levels up to 3.5 m higher in Morley and up to 4.5 m higher in Belmont. Wetlands of the inner western suburbs would have water levels up to 0.5 m higher.

7.1.2 Reducing Domestic, Local Authority and Institution Groundwater Use following Full Corridor Plan Development

Reducing domestic pumping was shown in Section 7.1.1 to have a pronounced effect upon water table elevations in some urban areas. Groundwater use may be further reduced by controlling local authority and institution pumping as well. To demonstrate this, local authority and institution pumping were reduced to 70% of their 1985 rates.

Even after an extended period of below-average rainfall, water table elevations would be generally higher than at present, as shown in Figure 73. In the Bayswater and Morley areas, water levels would be more than 2.0 m higher, compared with 1.5 m resulting from the control of only private domestic bore users (Figure 72). Similarly, in the urbanised parts of the Southern and Eastern Perth Areas, levels would be slightly higher than if only domestic pumping was controlled.

7.1.3 Reducing Water Authority Groundwater Abstraction following Full Corridor Plan Development

It may be possible to reduce the growth in groundwater abstraction for public water supplies provided alternative sources are available to meet the community's needs. Assuming the Water Authority could reduce abstraction from its existing and proposed groundwater schemes to 50% of the planned ultimate rate, water table elevations would still be significantly lower than they were in 1985 in the northern and eastern suburbs and along the Wanneroo chain of wetlands. They would also be slightly lower in the western suburbs as shown in Figure 74. Water levels in urban areas would not improve from the levels induced by an adverse climatic situation.

By comparison with the foldout inside the back cover, it can be seen that water levels would be almost as low with limited Water Authority abstraction as they would be without it. The limitation would only affect water levels where Water Authority production wells are located, i.e. to the east of the Wanneroo chain of wetlands, in the Gwelup area and in the Jandakot area. This management strategy does not otherwise influence water table elevations in urban areas.

7.1.4 Clearing Pine Forests following Full Corridor Plan Development

Pine forest densities currently vary from 0 to 75% canopy cover, depending upon forest age and thinning. The "extreme" scenario presented in Section 6.5.3, however, incorporates pine forest management practices which maintain the density of pines such that canopy cover is about 20%.

If it were feasible to clear all the existing pine forests, water table elevations would be less than 1.0 m lower than in 1985 in the Bayswater area, compared with levels more than 2.0 m lower without the strategy (Figure 75; Foldout). Levels would also improve slightly to the west of the Wanneroo chain of wetlands. The areas

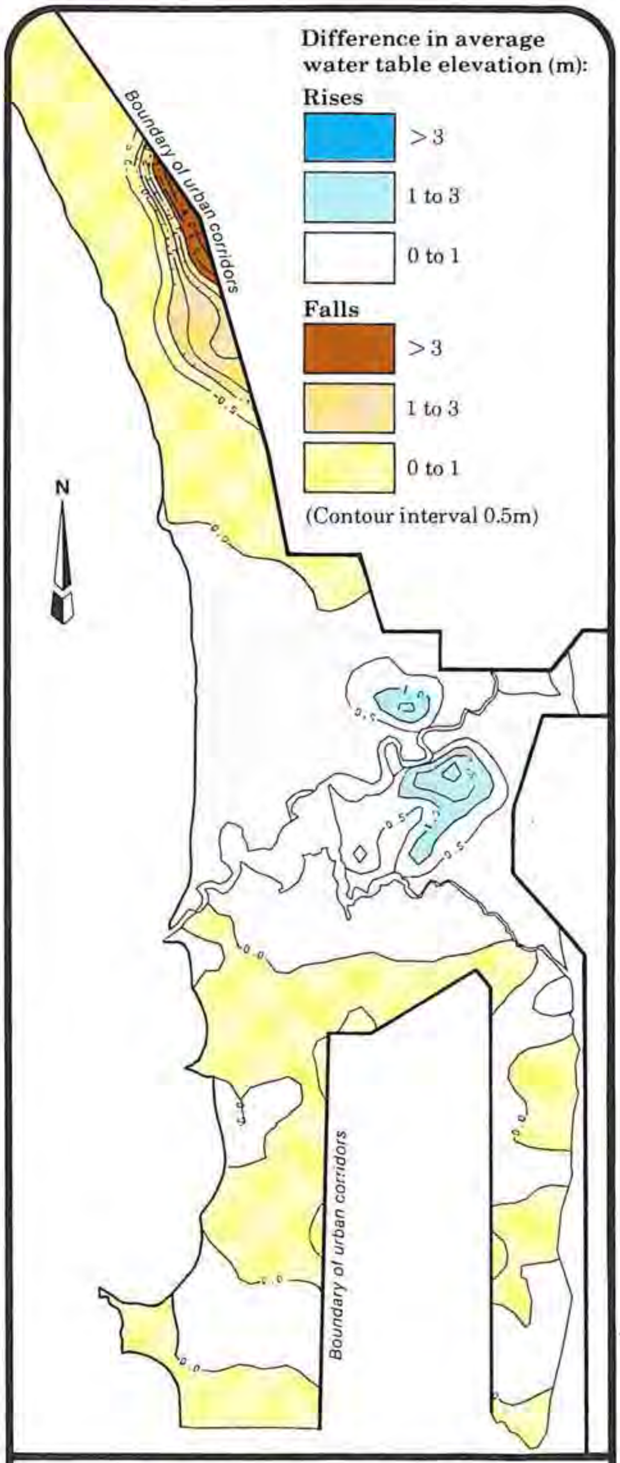
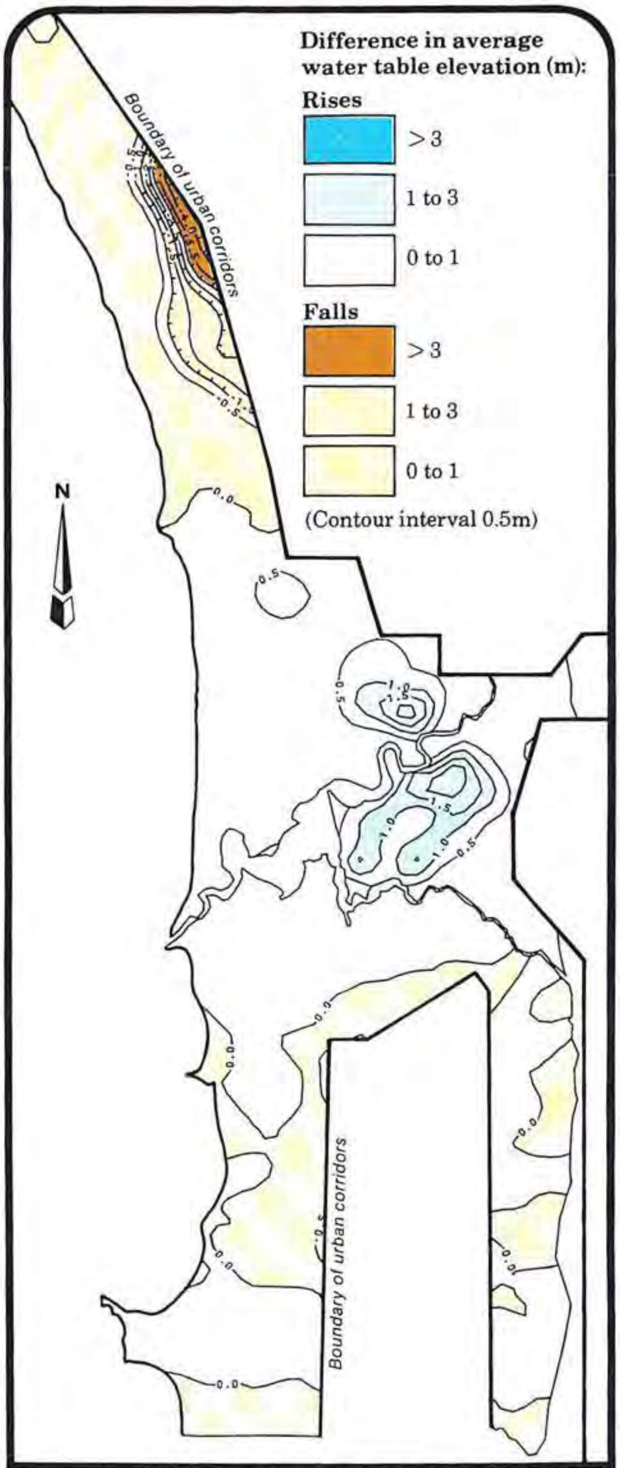


Figure 72

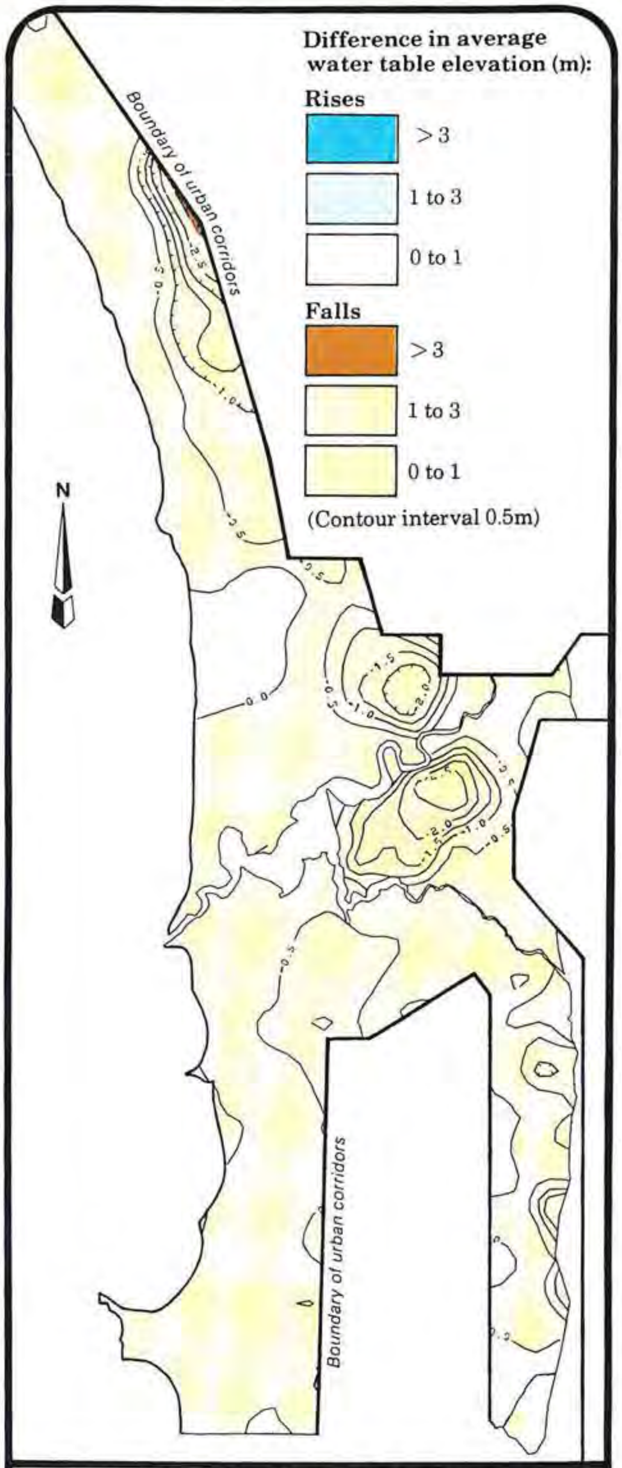


PREDICTED DIFFERENCE IN AVERAGE WATER TABLE ELEVATIONS

SHOWING THE EFFECTS OF REDUCED DOMESTIC, LOCAL AUTHORITY & INSTITUTION GROUNDWATER USE WITH BELOW AVERAGE RAINFALL & FULL CORRIDOR PLAN DEVELOPMENT

Scale: 5 0 5 10 15km

Figure 73



PREDICTED DIFFERENCE IN AVERAGE WATER TABLE ELEVATIONS

SHOWING THE EFFECTS OF REDUCED WATER AUTHORITY GROUNDWATER ABSTRACTION WITH BELOW AVERAGE RAINFALL & FULL CORRIDOR PLAN DEVELOPMENT

Scale: 5 0 5 10 15km

Figure 74

where levels would improve are down-gradient of the pine forests along groundwater flow lines. In the Southern and Eastern Perth Areas there would be no effect as there are no pine plantations.

This strategy is presented to demonstrate the sensitivity of water levels in the urban area to changes in the cover of pine forests. Even with this rather extreme strategy, water level improvements in urban areas would be small.

7.2 VARIATIONS IN RECHARGE

7.2.1 Directing Road Drainage to Infiltration Basins following Full Corridor Plan Development

There are many areas where a significant amount of stormwater is allowed to drain away from the groundwater system to the ocean or to the estuary (Plate 24). If all this stormwater were directed to local infiltration basins, there would be significant improvements in the level of the water table in some areas, even following extended periods at below-average rainfall (Figure 76).

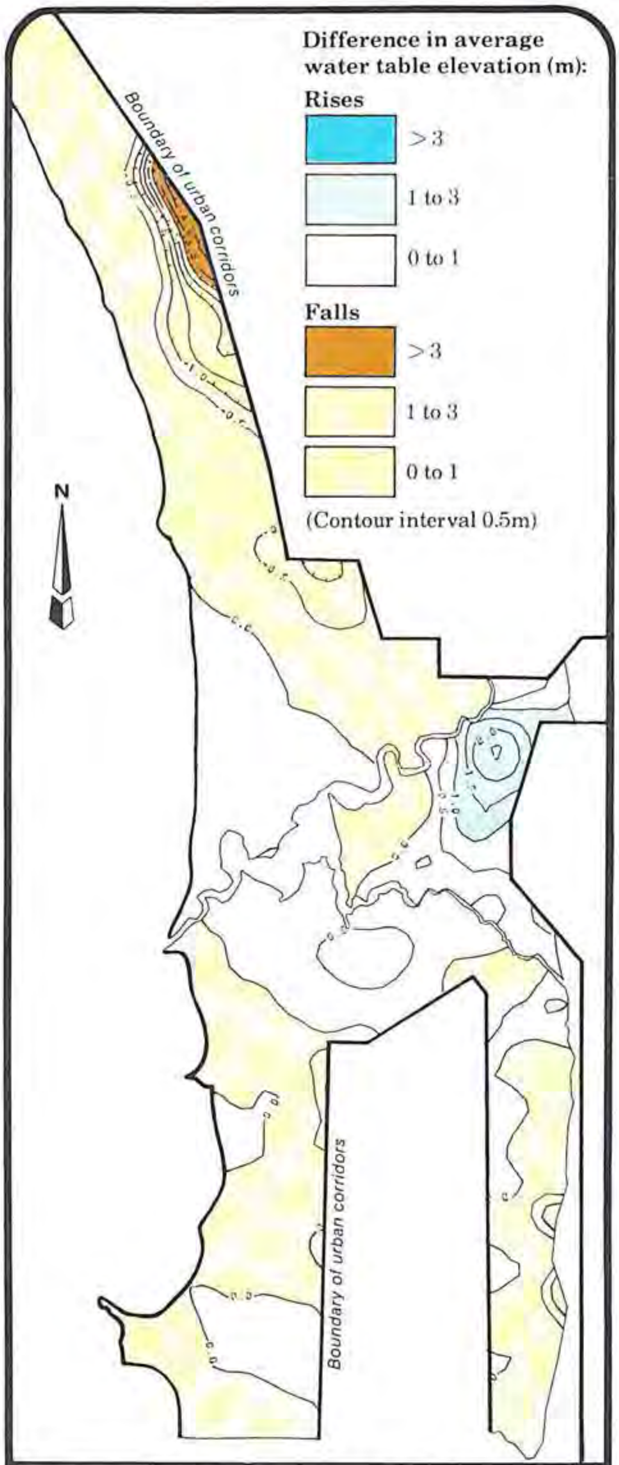
Geoff Boughton

Plate 24 Stormwater drainage to Scarborough Beach

In the Bayswater and Morley areas, the water table would be less than 1 m below 1985 levels, compared with levels more than 2.0 m lower without the increased infiltration (Foldout). There would be some improvement in the inner western suburbs where water levels would be at 1985 levels. The effect in the north, near the Wanneroo chain of wetlands, would be small.

These aquifer responses are related to the local aquifer permeability. In the aquifer underlying the area between Bayswater and Marangaroo, the permeability is low compared to that along the coast. The extra recharge under Bayswater would not flow as quickly towards the estuary as groundwater under coastal areas, and the water table would rise more significantly.

Figure 75



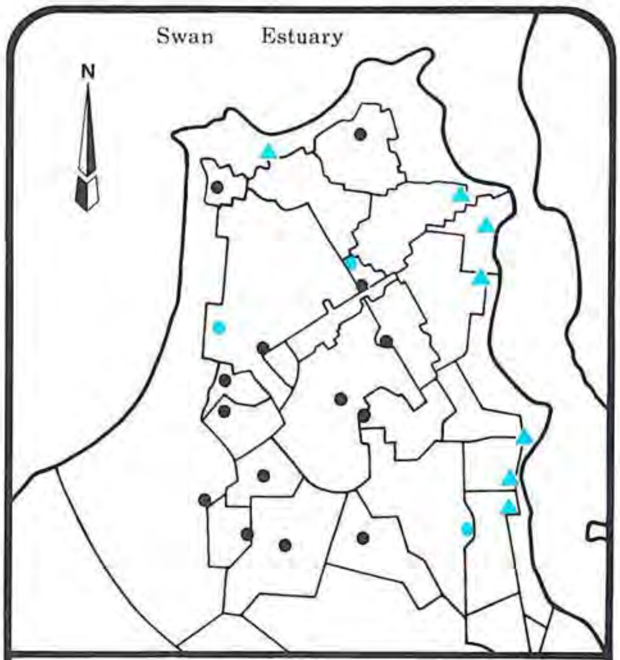
PREDICTED DIFFERENCE IN AVERAGE WATER TABLE ELEVATIONS

SHOWING THE EFFECTS OF MAXIMISING STORMWATER RECHARGE WITH BELOW AVERAGE RAINFALL & FULL CORRIDOR PLAN DEVELOPMENT

5 0 5 10 15km
Scale

Figure 76

Local recharge is a significant component of the water balance of the Applecross Peninsula. Currently, stormwater from 60% of road reserves on the peninsula drains to the estuary. Two possible management strategies for the area might be to construct infiltration basins in all catchments where the depth to groundwater is at least 5 m (the bottom of these sumps would normally be dry) and to construct infiltration basins in all catchments (the ones close to the estuary would intersect the water table). The extra basins constructed with the first strategy would collect stormwater from 55% of the area currently drained to the estuary and with the second strategy the remaining catchments, excluding a narrow strip around the foreshore, would be drained to basins (Figure 77).



- Existing infiltration basins
- Potential sites for infiltration basins with depth to groundwater >5m
- Potential sites for infiltration basins which would intersect the water table

DRAINAGE SYSTEMS ON THE APPLECROSS PENINSULA

500 0 500 1000m
Scale

Figure 77

The annual vertical flux to the aquifer was estimated to be 490 m^3/ha in 1985. The first strategy would increase this to 630 m^3/ha and the second to 720 m^3/ha, i.e. increases of 29% and 47%, respectively. It is interesting to note that the first strategy would only involve the construction of four extra basins and the second, twelve.

Unfortunately there are problems associated with increasing local recharge where aquifer permeability is low. Infiltration basins would need to be extremely large to allow sufficient ponding of stormwater as it slowly infiltrates the soil. Also in these areas, drains have been constructed to prevent flooding from an elevated water table in wet years. If this management strategy was adopted to increase recharge in below-average rainfall periods, the drainage systems developed would need to be able to cope with higher flows in above-average rainfall periods.

The increase in recharge is only minor along the coast, in the Tamala Limestone and Safety Bay Sand. In the western suburbs, Perry Lakes would still be lower than at present. Infiltration basins have already been constructed in urban areas in the coastal regions to receive most of the stormwater, and implementation of this management strategy would not lead to the construction of many additional basins.

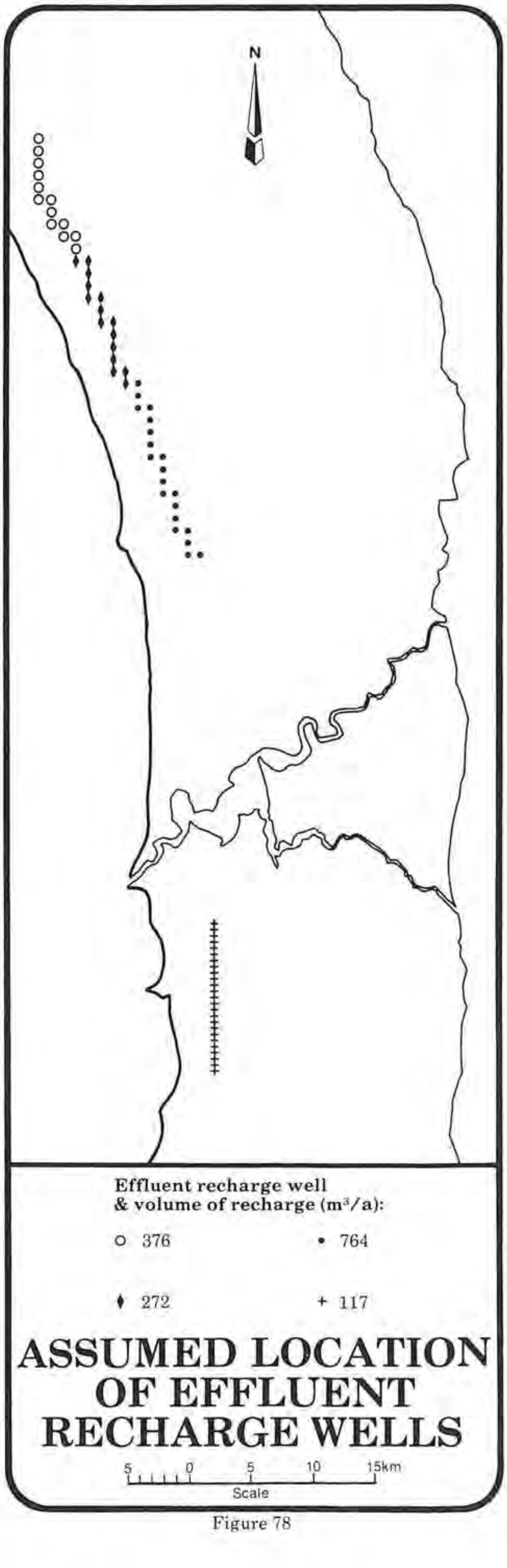
The implementation of this strategy, involving the modification of drainage systems, would have little effect on water levels in the Wanneroo chain of wetlands.

7.2.2 Recharge of Sewage Effluent following Full Corridor Plan Development

Artificially recharging the aquifer with treated sewage effluent has been suggested as a possible strategy to raise groundwater levels, although it is often not considered acceptable from a water quality point of view.

A strategy was devised to demonstrate the value of wastewater recharge, involving the recharge of effluent from the Beenyup and the proposed Alkimos sewage treatment plants in a line of wells just to the west of the Wanneroo chain of wetlands, and the recharge of effluent from the Woodman Point treatment plant in a line of wells just to the west of the East Beeliar chain of wetlands. The location of the recharge wells and the annual volumes pumped to them are shown in Figure 78.

With recharge of sewage effluent as above, water levels in the northern wetlands of the Wanneroo chain would be similar to 1985 levels and levels in the southern Wanneroo wetlands would be up to 4.0 m higher (Figure 79). Water levels would be up to 1.0 m higher in the East Beeliar chain of wetlands. Without this management strategy (Foldout), groundwater levels in the vicinity of these wetlands would be significantly lower. The magnitude of the effect on groundwater levels reflects the volume of water recharged at each well and the distribution of permeabilities in the vicinity. If this strategy was considered feasible, there are many options available for the location and quantity of recharge of sewage effluent.



ASSUMED LOCATION OF EFFLUENT RECHARGE WELLS

Figure 78

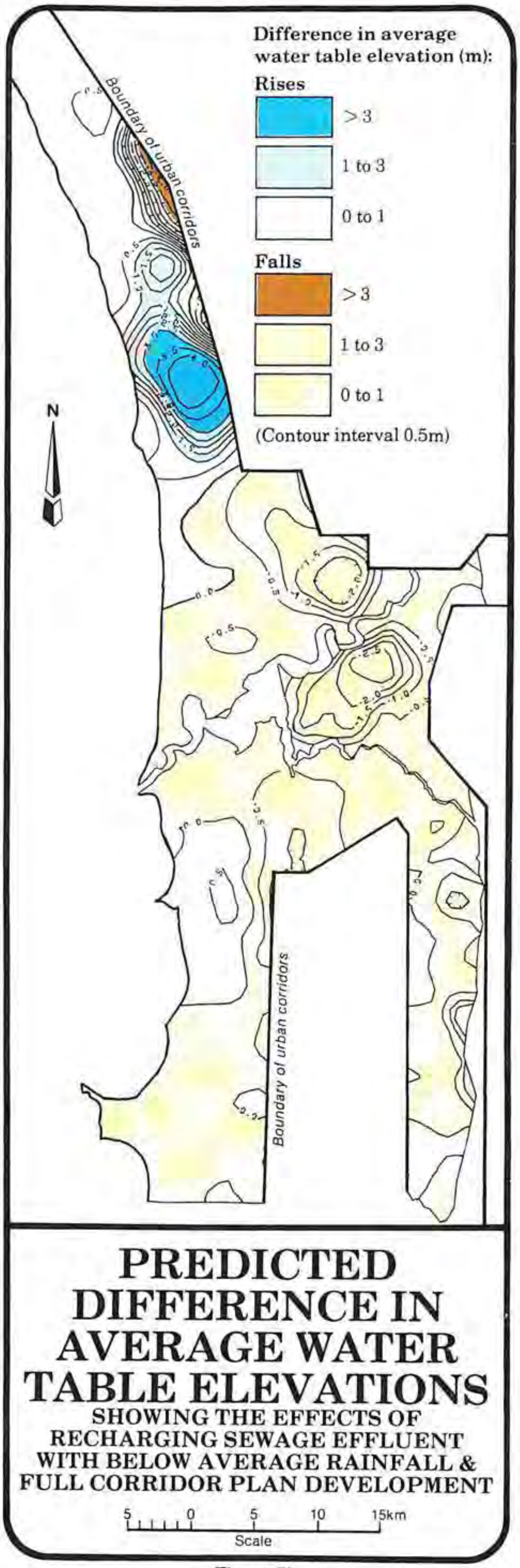


Figure 79

The influence of this recharge strategy is local but would be effective in protecting the Wanneroo and East Beeliar wetlands.

Recharging the aquifer in a line parallel to the water table contours, down-gradient of the wetlands, has the effect of reducing the water table gradient across the wetlands, making them less susceptible to changes in water level caused by climatic variations. Placing the line of recharge wells down-gradient of the wetlands also has the advantage, from a water quality point of view, that recharged water would flow away from the wetlands towards the ocean. The majority of groundwater users along the coast are domestic and local authority users pumping water for irrigating parks and gardens, and increased nutrients from effluent recharge may even be an advantage by reducing the need to apply fertilisers. The recharge of effluent does, however, preclude development of public water supply schemes along the coast unless the sewage effluent is treated to a high standard.

7.2.3 Using Septic Tanks Instead of Sewerage in Corridor Areas still to be Developed

In an effort to hold the water table at a higher elevation during periods of low rainfall, a strategy was considered which would require all dwellings in new areas to have septic tanks installed as an alternative to a sewerage system. The resulting water level differences were immeasurable.

This result was expected, based upon the magnitude of the septic tank component of the water balance plotted in Figure 71.

This option would also have the disadvantage of precluding development of public water supply schemes in unsewered urban areas.

7.3 THE VALUE OF THE STRATEGIES ASSESSED

7.3.1 Groundwater System Responses

The impact of the various management strategies which were assessed in the Study depends largely upon the local aquifer permeability, the depth to the water table and the distance from the area where the strategy is applied.

In general, areas overlying low permeability parts of the aquifer respond well to local management strategies. Where the permeability is less, the water level variations are smaller, although small responses may still be significant. The wetlands of the Wanneroo chain and the inner western suburban wetlands, whilst overlying higher permeability parts of the aquifer, can be seriously affected by long-term falls in water levels of only 1 m.

Efforts to raise the water table are less effective where the water table is within a few metres of the ground surface than in areas where the water table is deep because, in the former case, phreatophytes are able to make use of some of the extra water available to them.

Where a management strategy is applied in a local area, the response of the aquifer tends to be limited to that and nearby areas. The extent of the response beyond the area of application depends upon the magnitude of the extra recharge or extraction resulting from the strategy. For example, water levels in Perry Lakes would not be influenced by a strategy to increase recharge or reduce private abstraction in the outer urban areas. Instead, recharge should be increased or private abstraction reduced in the Wembley and Floreat areas. Removing pine forests would have some effect on water levels in areas down-gradient at Wanneroo, Bayswater and Morley.

The Southern Perth Area appears to be relatively insensitive to changes in extraction and recharge. This may be because the water table over a large part of the area is controlled by extensive drainage systems. Even in years with below-average rainfall, the water table rises sufficiently in winter to allow groundwater to discharge to surface drainage systems. Also, the south-western urban corridor overlies a high permeability part of the aquifer and water level variations from urban management strategies are small.

7.3.2 Management in the Short Term

Many of the strategies investigated during this Study will involve long lead-times for developing the system and infrastructure for their implementation. A strategy which could be implementated immediately, however, is the reduction of domestic, local authority and institution abstraction, provided it could be achieved with public education programs.

To assess whether it would be worth implementing such a strategy immediately, water levels were predicted for 1995, assuming that domestic, local authority and institution use of groundwater could be gradually reduced from now until 1995 to 50%, 70% and 70%, respectively, of 1985 rates.

Figure 80 shows that, with controlled abstraction, water levels in 1995 would be slightly higher than in 1985 throughout the urban area, even if the current period of below-average rainfall were to continue for another ten years. Hence, local problems of low water levels in wetlands and low water levels in areas such as Bayswater and Belmont would not be as serious.

It is interesting to compare this result with the

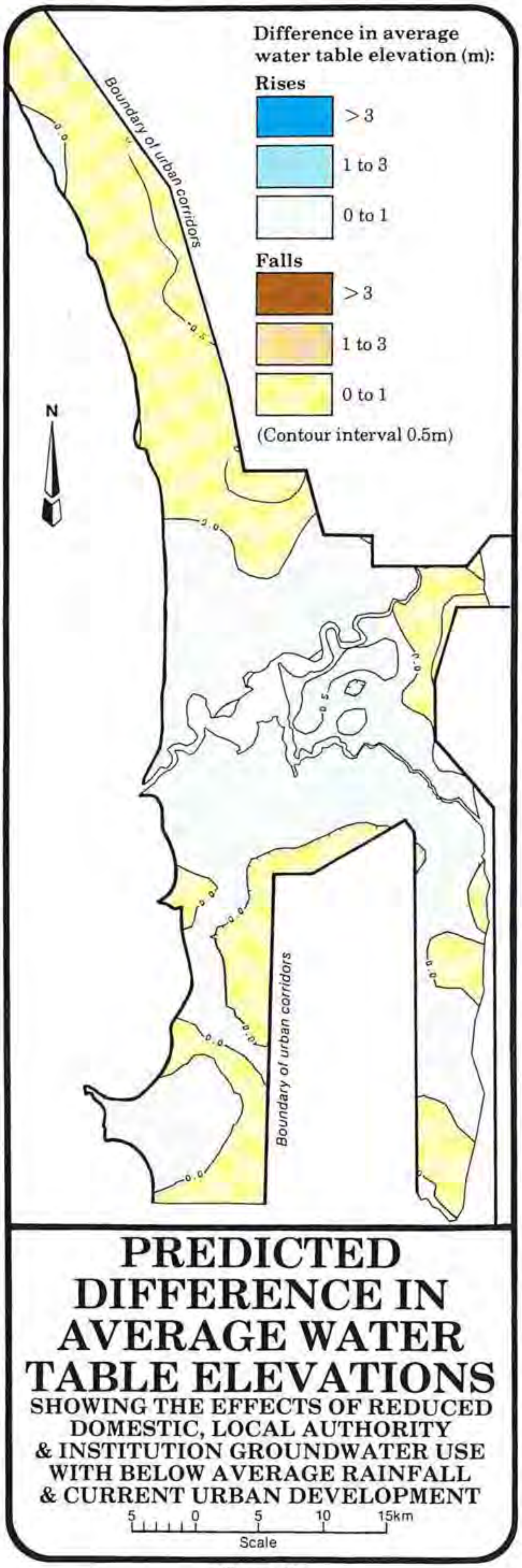


Figure 80

significant fall in the water table predicted for an increase in abstraction (Figure 67): a rise in pumping during dry conditions would produce a significant drop in the water table but a reduction in pumping would produce only a small rise in the water table. The results indicate that some immediate reduction in abstraction may be necessary, just to maintain water levels at or slightly higher than 1985 levels.

In outer urban areas and in areas beyond the urban fringe, water levels would fall, even with controlled abstraction because there is currently very little domestic, local authority and institution pumping to control. The extended below-average rainfall period would lead to further reductions in water levels. Reducing abstraction in inner urban areas would not have a significant effect on water levels outside the urban area.

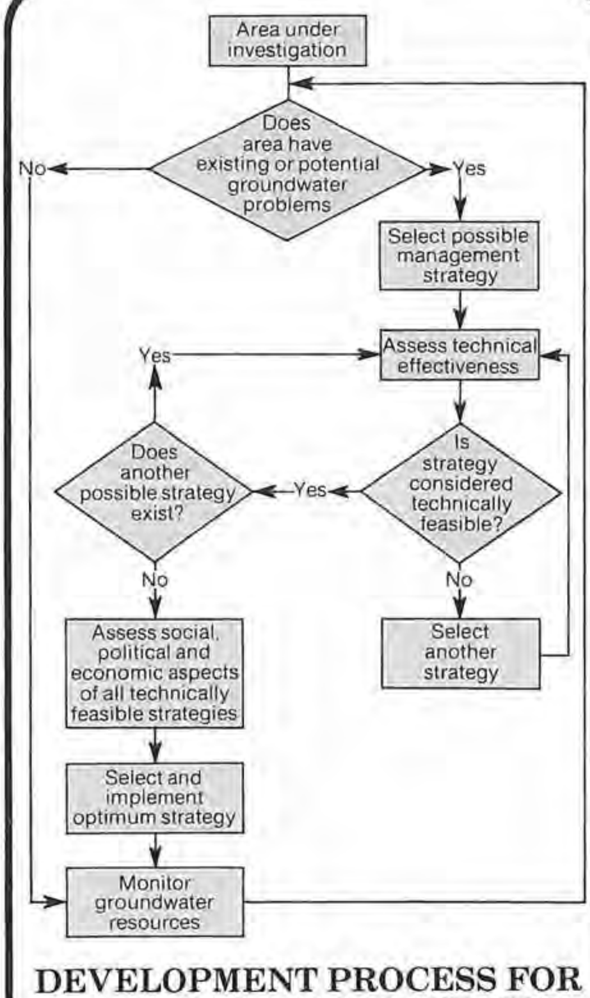
DEVELOPMENT AND IMPLEMENTATION OF MANAGEMENT STRATEGIES

A procedure for developing strategies for managing a groundwater system is shown diagrammatically in Figure 81.

For an area under investigation, it is necessary to identify whether there are existing or potential groundwater problems by identifying existing or potential users, quantifying their requirements and then determining the availability of the resource.

If there is no foreseeable reduction in groundwater utility, there is no need for direct management of the resource. There is, however, a need to monitor the resource and to regularly reassess potential problems.

If a potential problem is identified, management strategies to protect the beneficial uses of the resource need to be devised and assessed for technical feasibility. Those considered technically feasible are then subjected to social, political and economic evaluation to determine an optimum strategy for implementation.



DEVELOPMENT PROCESS FOR MANAGEMENT STRATEGIES

Figure 81

Although it is concluded that immediate implementation of an active regional management program is essential based upon the outcome of this Study, it is recognised that strategies implemented immediately may not prove to be the optimum strategy. Detailed assessment of social, political and economic factors will enable the management strategies to be refined. However, expertise and experience exists to enable the immediate implementation of acceptable management strategies.

The control of factors affecting the urban water balance is spread throughout many government departments and organisations. Management strategies must therefore be developed with communication and co-operation between those groups.

The management process is not static. It is necessary to regularly monitor the response of the resource to management, to reassess the potential problems and to modify the adopted strategy, based upon up-to-date information.

Direct management of groundwater resources may be achieved by any combination of legislative control, technical solutions and public education. The option also exists for indirect management without imposing any controls. The development of strategies within each of these categories is examined in more detail in the following sections.

There is a significant lead time involved in the implementation of management strategies. It is affected by the time needed to devise, assess and implement the strategy and the time needed for the strategy to take effect. The time required for implementation of a strategy may range from a few months to a year or two, depending upon the preparedness of management authorities. The time required for the strategy to take effect may be many years, however, as it depends on the sensitivity of the groundwater system to changes in recharge and extraction parameters.

Strategies should be implemented well in advance to be prepared for possible problems so that they may be avoided or satisfactorily managed and to allow management strategies to be implemented in readily accepted stages. This is preferable to having to mount a rescue operation after problems have developed, a course which is usually socially and economically unpalatable. Effective planning allows efficient handling of possible problems and, through staged implementation of strategies, allows the community to gradually become conscious of the need for management.

8.1 INDIRECT MANAGEMENT

Current levels of management may be preferred where the resource utility is not considered to be at risk or where use of the resource is self-regulating. In the first instance, expanded management is not needed and in both instances, close monitoring is required to ensure that the resource does not deteriorate and that some sections of the community are not disadvantaged.

A self-regulating resource is protected by the direct costs to the user of using the resource, which may become more difficult to obtain or may suffer from reduced quality.

The advantages of minimum government intervention in the management of the groundwater systems are that the community is not encumbered by regulation and control and that costs to the community are generally low. If, however, the system cannot cope with all demands, the cost to affected parties may be high and any remedial action may be expensive.

8.2 DIRECT MANAGEMENT

8.2.1 Legislative Control

Legislation may be used to achieve a positive response from the community to the control of groundwater use. Legislation may be used to control groundwater use, to increase the rate of recharge to the aquifer using absorption systems and to ensure that anticipated groundwater demand matches the available resource by the control of landuse development. Legislative control would have a significant impact upon the activities of individuals and would require a substantial administrative structure.

Control of bores. Groundwater use may be controlled by limiting some or all bore users. The level of control may be varied depending upon the necessary reduction in use and may range from general restrictions on hours of use, to specific controls on individual users.

Because of the large number of bores and the consequent high cost of controlling their use, controlling all bore users would be difficult and expensive. Legislative control of all bores would have a large impact on private citizens and may be seen as a bureaucratic imposition upon their rights. Considerable manpower would be required to locate all bores, to implement controls and to police restrictions. The most difficult group to control would be private domestic bore users, being large in number and having low individual groundwater requirements.

By controlling only the bore owners who use large quantities of water, approximately two-thirds of all groundwater abstraction from the unconfined aquifer would be brought under control (Figure 82). Such users are few in number and would be easier to control and, because they have larger requirements for groundwater, they each have a larger impact upon the groundwater system. These users generally derive an economic return or provide a community service from their use of groundwater, and licence fees can therefore be passed on to the consumer or beneficiary and consequently to the community.

In specific areas, however, it may be necessary to control abstraction from private domestic bores.

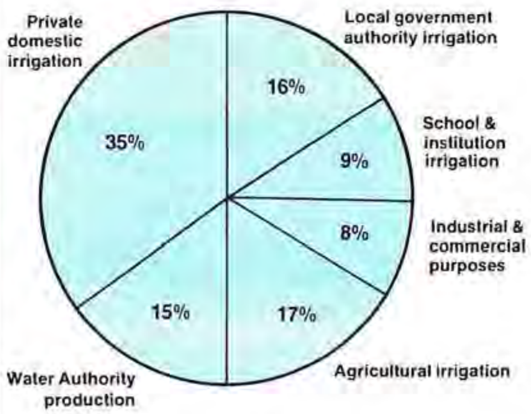


Figure 82

Control of stormwater discharge. The amount of water recharged to the aquifer may be controlled by restricting the discharge of stormwater to the ocean or the estuary.

Local stormwater drainage is currently the responsibility of local government authorities who generally dispose of it in the cheapest, most convenient manner such that flooding problems are avoided. Stormwater is discharged to infiltration basins, the ocean, the estuary and main drains. Stormwater recharge may be maximised by requiring that all stormwater be discharged to infiltration basins unless shown to be technically impractical.

Control of land use. Land development in the State is administered by the State Planning Commission and local government authorities.

The groundwater requirement for different land uses should be compared with the predicted availability of groundwater before re-zoning of land proceeds. This would allow land use to be matched with groundwater availability in developing areas.

Under the current review of the Corridor Plan, the State Planning Commission may consider more intense development in the regions between the urban corridors. The effect of such a plan on groundwater and on the current users of groundwater can and should be assessed with the predictive model developed during this Study. It must be recognised, however, that preparation of spatial data sets and predictive modelling involves considerable time and expense.

Vegetation density and type may be varied to increase or decrease net recharge in any area by decreasing or increasing transpiration losses from the unsaturated zone. Legislative control of vegetation may be possible but the imposition of this sort of limitation is likely to be received unfavourably and therefore to be ineffective.

8.2.2 Technical Solutions

Technical solutions to groundwater problems include strategies which could be implemented by government authorities to improve recharge and extraction processes directly under their control. Such solutions would have little direct impact upon members of the community, who may be unaware of the strategies being followed. Technical solutions would generally incur costs which would be borne by the community as a whole through rates and charges.

Drainage. The Water Authority currently controls extensive systems of main drains which were constructed to alleviate flooding problems. Water carried through the drainage system may be available for recharge via infiltration basins in areas with depressed groundwater levels.

It may also be feasible to transport stormwater from areas with low soil permeability to areas with high permeability or from areas where groundwater is plentiful to areas with depressed groundwater levels. With these strategies, drainage design objectives would need to include maximising recharge as well as mitigating floods.

Drains have been constructed to prevent flooding in areas where the water table is close to the ground surface and water is removed from the groundwater system and discharged to the Swan or Canning Rivers. As an alternative, the land surface may be raised to avoid the need to drain water from the aquifer. In some semi-rural areas (e.g. in the City of Armadale) houses are required to be built on a "house-pad", which is a small area of filled ground large enough for the house alone.

Wastewater recharge. In areas where low groundwater levels or saltwater intrusion may cause concern, the resource could be augmented by recharging effluent from sewage treatment plants. The feasibility of this strategy will depend on the effects of nutrient input upon wetlands, the level of treatment required, the volume of wastewater available, the location of the wastewater relative to the disposal site and the cost of implementation.

Irrigation with wastewater. Demand on the groundwater system could be reduced by irrigating parks and gardens with treated wastewater, subject to consideration of health and cost aspects, as an alternative to recharging the aquifer with the wastewater. This is not direct recharge to the aquifer, but the effect is similar because the amount of water abstracted from the aquifer is reduced.

Dual water supply system. The Water Authority could consider providing a dual water supply system to areas where groundwater quality has been made unacceptable by previous heavy abstraction. For example, there may be a risk of groundwater in the Cottesloe peninsula becoming permanently salty if demands in that area continue to increase. The dual system would include the existing drinking water system and a second low-quality water system for outdoor use. Dual systems are, however, expensive to install and operate.

Design of wells. The problem of pumping saline water in near-estuary or coastal regions could be minimised by careful design and location of wells and well fields. Low pumping rates from shallow, well-spaced, large-diameter wells will assist in minimising saltwater intrusion problems.

Vegetation. The manipulation of vegetation density is possible, especially in the large areas of pine plantation controlled by the Department of Conservation and Land Management. Reducing vegetation density would lead to locally increased recharge because of reduced evapotranspiration losses.

Wetlands. The most significant consideration in managing Perth's unconfined groundwater system is the water requirement of wetlands. This consideration may become less significant in some areas if wetland management can be modified. In areas where groundwater demand may be causing water levels to drop, wetlands may be foresaken, they may be deepened or lined, they may be topped up with imported water or they may be replaced by wetlands serving similar functions nearby. Wetland management will require thorough evaluation to ensure that the best interests of the community are served in each individual case.

8.2.3 Public Education

Public education can modify community expectations for an "English garden" city and increase public awareness of the value and availability of water. Public education may be a low cost means of achieving reductions in groundwater use and increases in recharge to the aquifer. If the community took voluntary action, there may be no need for legislative control.

Householders with access to a bore need to be made aware that they can maintain a healthy garden using only one third of the water they currently apply. Many householders water at inappropriate times of the day, and with fine sprays, causing significant evaporation losses and causing plant stress from salt burning (Plate 25).

Reducing extraction by night-time watering appears to be achievable through public education, judging by results of a survey conducted for the Domestic Water Use Study (Metropolitan Water Authority, 1985*a*). The survey found that 53% of respondents would find it relatively easy to adjust their habits and to water at night or in the early morning. Because plants would appear healthier, with less salt burning, people would also tend to water less.

Education programs would be able to highlight the personal benefits of night-time watering, which are that less water would be needed, less time would be required in the garden and the costs of power for pumping or excess water bills for those using scheme water would be reduced. With the wind-free conditions, which prevail in Perth during summer evenings, iron-staining

Plate 25 Domestic garden watering with a fine spray during daytime hours

from wind-drift would also be reduced. These direct benefits to the householder would improve the effectiveness of education programs.

Water demand can be reduced significantly by growing dry-climate species of plants and by using appropriate watering techniques for those species.

Government and local government authorities, that often water open space in daytime hours or in windy conditions when evaporation losses are high (Plate 26), also need to improve the efficiency of their watering habits.

Plate 26 Local authority watering in the middle of a hot windy day

8.3 MONITORING

The need for monitoring is important whether current groundwater management practices are maintained or management is expanded.

If the Water Authority maintains current management practices or if it expands its management of the groundwater resource, the decision to do so should be based upon a current assessment of the urban water balance. The information available at any time for that assessment is derived from extensive monitoring and predictive analysis of the groundwater system. The monitoring program should provide regionally synoptic and locally detailed water level, water quality, abstraction and saltwater intrusion data which are relevant for assessing management strategies.

If components of the urban water balance change, or if our understanding is improved with additional information, management strategies may need to be amended. It is therefore essential that the groundwater system be monitored regularly to enable regular updating of predictions so that management may respond to potential problems in time to prevent them occurring.

Chapter 9

CONCLUSIONS
OF THE PERTH URBAN WATER BALANCE STUDY

9.1 THE RESOURCE

CONCLUSION 1

Groundwater is vital for maintaining the lifestyle of the Perth region.

Groundwater meets about one third of the public water supply requirements of the region's one million inhabitants and provides about two thirds of all the water used in Perth.

About 77,000 or one in four households in Perth rely on private groundwater supplies for garden irrigation.

On the Swan Coastal Plain, virtually all irrigated public open space is irrigated with groundwater.

Groundwater supports much of the natural environment of the Swan Coastal Plain in the Perth region, including the 9000 hectares of major wetlands which were reviewed for this Study.

More than 2500 hectares of commercial agriculture, worth $40 million per annum, and some major industries, which contribute significantly to the economy of the region, depend upon readily available groundwater of suitable quality.

CONCLUSION 2

Without active management, the groundwater resource of the Perth region cannot meet the expanding public and private demands whilst continuing to sustain the region's environment.

Lowered water levels in some urban wetlands and increased salinity in some coastal and near-estuary bores since the mid-1970s are indications that the resource is locally under stress from current levels of development.

Uncontrolled expansion of groundwater use will lead to further problems of lowered water levels in wetlands and increased saltwater intrusion in coastal and near-estuary suburbs.

Management of factors affecting the water balance is necessary to ensure that groundwater continues to play its role in maintaining the lifestyle of the region.

CONCLUSION 3

Water level variations within the groundwater system of the Perth region are dominated by climate.

Water levels rise and fall significantly each year as rainfall varies with the seasons, and successive years of above-average or below-average rainfall cause longer-term fluctuations in groundwater levels. Of the many influences that affect groundwater levels, climatic variations are the most significant.

Recharge to the groundwater resource during the extended period of below-average rainfall between 1975 and 1985 was about two thirds of that which would occur during periods of average rainfall and only about half of that which would occur during periods of above-average rainfall. Had average rainfall occurred in the period 1975 to 1985, water levels across the urban area would generally have been about 0.5 m higher than those recorded in 1985.

Evidence from lake bed sediments indicates that fluctuations in water levels have occurred over long periods of time. There is no doubt that some of the existing urban wetlands dried out occasionally due to variations in climate, prior to any land development by man. The ecosystems of many of the lakes in the region have adapted to this occasional drying out. This must be taken into account when developing management plans for wetlands. Wetlands which dry out almost annually sustain a diverse flora and fauna, reflecting their adaptation to the strongly seasonal climate.

Changes in groundwater levels induced by urbanisation and development of groundwater resources should be considered in the context of natural, long-term fluctuations in groundwater levels.

CONCLUSION 4

Within the Perth region, land use has a significant influence on variations in both groundwater levels and groundwater quality.

Urban development can cause either a rise or a fall in water levels, depending on the local aquifer conditions and the nature of the development. There is evidence, including drowned fences across lakes and drowned trees within lakes, supporting the conclusion that long-term water level changes have occurred since European development of the region commenced in 1829. Urban development also affects groundwater quality through leaching of fertilisers and recharge of contaminated runoff and septic tank effluent.

Recreational developments, both passive and active, may have significant groundwater requirements. Passive recreation areas may require groundwater for the maintenance of natural or created environments while active recreation areas require groundwater for irrigation of playing fields and surrounds.

Large evapotranspirative losses of groundwater occur from wetlands and, in some areas, wetlands are the dominant influence on the groundwater system.

Large scale modification of vegetation, such as pine plantations and regional open space, may have a considerable effect on evapotranspiration and recharge processes, and consequently on groundwater levels.

Industrial developments may place a significant demand on groundwater resources and are potential sources of pollution.

Irrigated agricultural development involves intense use of groundwater resources. On average, every hectare of land irrigated for market gardening requires an amount of water equivalent to the recharge occurring over ten hectares. Agricultural development also affects groundwater quality through the leaching of fertilisers and pesticides. Therefore, despite the potential economic returns, there is a finite limit to how much agricultural irrigation can be undertaken without conflict with other demands or activities.

Landuse planning should aim to develop urban forms that take account of impacts on groundwater resources so that demands remain compatible with availability of water.

CONCLUSION 5

Immediate implementation of an active regional groundwater management program, recognising all components of the water balance, is essential.

Management should be implemented to avoid problems. It is not satisfactory to wait until problems become evident before strategy development commences. With effective management, many of the problems associated with climatic variations, landuse development and uncontrolled use of the resource will be avoided.

Should appropriate strategies not be implemented in sufficient time to ensure that problems are avoided, the costs to the community to undertake rehabilitation activities would be considerable and may involve the expenditure of millions of dollars.

9.2 AREAS AT RISK

CONCLUSION 6

Urban wetlands are at risk due to hydrological changes associated with urban development.

Reduced water levels have been experienced in recent years in some urban wetlands, such as Shenton Park Lake and Perry Lakes.

The existence of dead trees within some urban lakes, such as Blue Gum Reserve and Lake Claremont, indicates elevated water levels resulting from urbanisation. Similar problems are likely to occur in Bibra, Yangebup and Thomsons Lakes following urban development in surrounding regions. These high water levels may require a regional drainage system to be established to protect environmentally significant wetlands from local flooding, although it must be recognised that artifically linking wetlands together with a drainage system may have undesirable ecological side effects.

Many lakes and wetlands form important discharge points in the urban drainage network. Much of the drainage water discharging to the wetlands contains contaminants from the surrounding urban area. The diversity of fauna and flora and the stability of lake ecosystems are at risk from degraded water quality from this contaminated drainage. This is already evident in Lakes Joondalup and Monger. Whilst the impact of these contaminants on the wetlands is not well understood, it may be possible to remove some of them using settling basins, for example, prior to discharging stormwater to the wetlands.

The maintenance of water levels in wetlands, which are important elements of the region's natural environment, is the most significant consideration in the regional development of the groundwater resource.

CONCLUSION 7

Saltwater intrusion is a significant risk in local areas adjacent to the coast and the Swan estuary.

Along the foreshore of the suburb of Applecross, saltwater intrusion has already occurred to the extent that the salinity of water drawn from the deeper bores in the unconfined aquifer has increased. In some cases, the salinity has increased to above levels considered tolerable for garden plants. Similar situations exist in other peninsulas, such as at South Perth, Maylands, Dalkeith and Rockingham/Safety Bay.

Management of the intrusion of salt water into bores in risk areas may be assisted by strategies which increase the flow of groundwater towards the ocean or estuary. Many problems experienced to date, however, are the result of inappropriate bore construction and high pumping rates. Users of groundwater in risk areas should be advised of the correct bore construction and pumping techniques to ensure that only good quality groundwater is pumped from above the saltwater wedge.

CONCLUSION 8

The peninsula containing the suburbs of Cottesloe, Claremont, Peppermint Grove, Mosman Park and North Fremantle is an area of high risk from saltwater intrusion.

This peninsula is completely underlain by salt water. The thickness of the lens of fresh water above the salt water is dependent on local recharge rather than on lateral inflow of groundwater from the Gnangara Mound.

The water table is less than 0.5 m above sea level throughout the peninsula and, as a result, saltwater occurs at a shallow depth below the water table, and there is a risk that it will be drawn into bores if appropriate bore construction and pumping techniques are not used.

CONCLUSION 9

The response of the groundwater system to above-average or below-average rainfall varies across the region according to aquifer permeability and thickness.

This is particularly significant in areas which overlie lower permeability or thinner parts of the aquifer, such as the suburbs between Bayswater and Marangaroo and parts of the Eastern Perth Area which are subject to wide variations in water level. The difference in water levels between above-average and below-average rainfall periods, with current urban development, could be up to 4.0 m, even allowing for the effect of the existing drainage system. Decreased bore yields may be experienced in below-average rainfall periods and flooding may occur in above-average rainfall periods.

Appropriate design and construction of bores are necessary to ensure yields are maintained, even with low water table elevations. An adequate drainage system is necessary to guard against flooding when water table elevations are high. Nevertheless, the system should be designed, where possible, to maximise groundwater recharge.

CONCLUSION 10

Regionally, water quality is not a cause for concern for current users of groundwater. However, elevated nutrient concentrations within parts of the urban area are a risk to wetlands and to the use of groundwater for drinking.

Groundwater contamination is closely associated with land use, particularly in market garden areas, industrial areas or in urban areas where septic tanks are in use or where large amounts of fertiliser are applied.

Land planning procedures are available which, if implemented, would ensure that land use remains compatible with maintaining good groundwater quality. Control measures are also available to prevent point-source discharge of polluting materials and non-point-source contamination of the groundwater resource.

Regional landuse planning and public water supply planning should include thorough consideration of the effects of urban development on groundwater quality. In areas where groundwater quality is adversely affecting the environment, Environmental Protection Policies should be considered to control non-point-source pollution of the groundwater resource in urban areas.

9.3 MANAGEMENT STRATEGIES

CONCLUSION 11

A number of management strategies can be applied to secure the groundwater resource and protect the environment of the Perth region, in general, and of specific risk areas, in particular.

About two hundred different combinations of management strategies and climatic and urban development scenarios were evaluated. The scenarios included above-average, average and below-average rainfall periods for both current and full urban development in accordance with the Corridor Plan for Perth.

To demonstrate the evaluation process and to indicate the sensitivity of the groundwater system to variations in climate and land use and to different management strategies, the results of nine possible management strategies are included in the Study report.

Effective management of the resource will include elements of many of the strategies presented in the Study report. On-going reviews of the effectiveness of management will enable the adopted strategies to be modified and additional strategies to be implemented, if necessary.

CONCLUSION 12

Assessment of social, political and economic factors, together with assessment of the technical factors considered in the Study, is essential in the selection of the optimum management strategy.

Although it is concluded that immediate implementation of an active regional management program is essential, based upon the outcome of the Study, it is recognised that strategies implemented immediately may need to be refined after assessment of social, political and economic factors. However, expertise and experience exists to enable the immediate implementation of acceptable management strategies.

CONCLUSION 13

Effective on-going management of the resource requires comprehensive groundwater monitoring, criteria for environment management and, because of the complexity of the groundwater system, a calibrated computer model.

To ensure that management strategies are effective and to provide better estimates of the use of groundwater and of the distribution of groundwater users, a comprehensive monitoring program is required. The program should provide regionally synoptic and locally detailed water level, water quality, abstraction and saltwater intrusion data which are relevant for assessing management strategies.

Because of the close link between groundwater and the environment of the Swan Coastal Plain, environment management criteria should be developed. In particular, a better understanding of wetland ecosystems is needed so that accurate predictions of the impacts of water level variations can be made and appropriate wetland management strategies can be formulated. From these strategies, criteria for desirable water levels and water level variations and for desirable water quality can be determined so that appropriate groundwater management strategies may be developed.

During the Study, it was demonstrated that the computer model can be used effectively to predict regional water table movements for various climatic and landuse scenarios and with possible future management strategies. Furthermore, it is a valuable facility for the regular review and possible amendment of implemented strategies.

The model developed during the Study has already been used effectively by the Water Authority for detailed evaluations of the water balance of the Gnangara Mound, the Jandakot area and in the vicinity of wetlands in the Wanneroo area.

CONCLUSION 14

The fundamental aim of any adopted regional management strategy should be to achieve a balance between the availability of and the demand for groundwater, by:

- **ensuring that land use is compatible with the local availability of groundwater in developing areas;**
- **managing the per-capita growth in demand;**
- **ensuring that groundwater is used efficiently; and**
- **increasing recharge of surface drainage, where appropriate, particularly drainage from roads and roofs.**

Liaison between all government organisations and local government authorities involved in landuse development is essential to ensure that all developments are located in areas where the groundwater resource is adequate to meet local requirements, without risk to existing users or to the environment.

Direct control of major public and private users of groundwater would allow for the control of 60% of groundwater abstraction. Public education could be a cost-effective means of reducing the use of groundwater by domestic users. If not effective, public education could then be reinforced with more direct control measures, perhaps involving the licensing of all bores.

On-going education programs should be designed to advise people of methods of maintaining their gardens with minimum use of water and to encourage people to be concerned for the general welfare of the community and the environment.

Stormwater drainage systems provided by the Water Authority and local authorities should be designed, where appropriate, with an aim of maximising recharge to the aquifer. This aim should apply to all new systems and to existing systems as they are upgraded. In areas where there is a risk of detrimental lowering of groundwater levels, existing systems should be modified to maximise recharge.

CONCLUSION 15

In addition to regional management strategies, specific local management strategies are needed for risk areas.

The strategies appropriate for different areas may vary depending upon local hydrogeological, environmental and landuse factors, and should be flexible because of the dynamic nature of the groundwater system. Strategies may include any of the following components:

- groundwater recharge may be increased by modifying existing local drainage systems,
- abstraction may be controlled by increasing restrictions on major users of groundwater or by direct control of domestic users,
- treated sewage or drainage water may be transported and/or recharged, where the expense is warranted, to increase water levels or to limit saltwater intrusion,
- Recreation areas and public open space may be irrigated with treated sewage or by programmed pumping from stormwater drains as alternatives to using groundwater, and
- Intense local education programs may be used advise residents of the impact of their use of groundwater on their own local environment.

CONCLUSION 16

Specific management strategies are required for immediate implementation in the following areas which were identified during the Study as risk areas:

- **the peninsula where the suburbs between Cottesloe and North Fremantle are located;**
- **the peninsula where the suburbs of Applecross, Mount Pleasant and Ardross are located;**
- **the inner western suburbs around Wembley and Floreat; and**
- **the locality of Kardinya.**
  Specific management strategies may also be needed in other areas which have yet to be assessed in detail.

The thin layer of fresh water occurring within the peninsula extending from Cottesloe to North Fremantle is completely underlain by salt water. The fresh water is recharged directly from local rainfall with minimal contribution from lateral groundwater flow. Management strategies to reduce local abstraction and to maximise local recharge are essential.

Increasing intrusion of the saltwater wedge along the northern shore of Applecross has been detected. Strategies are required to reduce local abstraction of groundwater and to increase local recharge in the suburbs of Applecross, Mount Pleasant and Ardross to limit the extent of saltwater intrusion.

Reduced groundwater levels in the suburbs of Wembley and Floreat over the last few years have resulted in significant reductions in the water levels in Perry Lakes during summer months, reducing the recreational and natural amenity of the area. Strategies are required to increase local groundwater levels by reducing local abstraction and increasing local recharge. Some control in this area is necessary to even maintain 1986 levels during extended periods of below-average rainfall.

Following the clearing of vegetation for urban development at Kardinya and Winthrop, rising groundwater levels have placed some of the older homes at risk of flooding. Immediate steps are needed to protect those homes.

Although problems were only identified in some areas, there are likely to be many other areas with similar problems, for example, Maylands, Dalkeith and Fremantle may have similar problems to Applecross. It is therefore essential that the groundwater system in such areas be assessed as a matter of priority to enable appropriate management strategies to be developed. Locally intensive education programs may be all that are necessary initially, however if groundwater utility deteriorates or the environment is adversely affected in those areas, more stringent controls may then be needed.

CONCLUSION 17

The effects of using septic tanks in preference to reticulated sewerage, reducing the density of pine plantations and reducing Water Authority pumping were shown to yield insignificant benefits within urban areas.

The volume of water discharged from septic tanks is insignificant in the overall water balance of the region. Water level differences attributable to the use of septic tanks would be negligible.

Reducing Water Authority pumping and reducing the density of pine plantations would result in local rises in groundwater levels which would not have significant impact in urban areas. In non-urban areas, such as rural areas east of Wanneroo, the management of pine forests can result in significant increases in water availability.

CONCLUSION 18

It is imperative that adequate human, technical and financial resources be provided for the development, implementation and regular review of appropriate, on-going management strategies and for the regular monitoring of the groundwater resource of the Perth region.

Because of the community's dependence upon the groundwater resource and because the Water Authority relies on the continued use of groundwater within the community to reduce public demand for reticulated supplies, the careful management of the resource must be regarded as a high priority by the Water Authority. The facilities needed include people in the field and office, advanced computer systems and adequate instrumentation.

Additional staff and financial resources will be required to implement the recommendations of the Study. Experience gained within this Study and from other Water Authority groundwater management activities indicates that, in the initial stages, at least three professional people and two technical assistants will be required within the Water Authority with an additional annual operating budget of $250,000 for computing, investigation and monitoring activities. A hydrogeologist from the Geological Survey and an environmental scientist from the Environmental Protection Authority or the Department of Conservation and Land Management will also be required.

Chapter 10

RECOMMENDATIONS
OF THE PERTH URBAN WATER BALANCE STUDY

The Steering Committee makes the following recommendations.

1. The Water Authority should immediately implement appropriate management strategies to maintain the valuable amenity of the Perth region's unconfined groundwater resource with an appropriate balance between public, private and environmental demands. The behaviour of the resource will need to be monitored and the management strategies will need to be reviewed and amended, as necessary, in the future.

2. The Water Authority should arrange for proclamation of the Perth metropolitan region of the Swan Coastal Plain as a Groundwater Area under the Rights in Water and Irrigation Act, and all non-domestic bores and wells should be licensed with groundwater allocations taking into account current activities and water availability.

3. A regional management strategy should be prepared by the Water Authority in consultation with the Geological Survey, the State Planning Commission, the Environmental Protection Authority, local government authorities and land development agencies. The strategy should aim to maximise recharge to the aquifer, where appropriate, and to reduce the total per-capita growth in demand for groundwater, consistent with the Western Australian Water Resources Council's Demand Management Strategy.

4. When planning for landuse development, the State Planning Commission and local government authorities should aim to develop urban forms to ensure that landuse development is compatible with groundwater availability. This planning should take account of impacts on all components of the water balance.

5. The Environmental Protection Authority should develop criteria for the water level and water quality tolerances of environmental features that rely upon groundwater for their viability. The Water Authority should then take these criteria into account as groundwater management strategies are refined.

6. The Environmental Protection Authority should prepare Environmental Protection Policies for areas where non-point-source pollution may degrade groundwater quality and adversely affect the environment.

7. The Water Authority should immediately develop and implement specific management strategies to reduce abstraction and increase recharge in the peninsula containing the suburbs of Cottesloe, Claremont, Peppermint Grove, Mosman Park and North Fremantle; the peninsula containing the suburbs of Applecross, Mount Pleasant and Ardross; and the inner western suburbs around Wembley and Floreat.

8. Further investigation should be undertaken by the Water Authority, in conjunction with the Geological Survey, the Department of Conservation and Land Management, the Environmental Protection Authority and relevant local government authorities, to determine the need for local management strategies in risk areas not specifically investigated during this Study.

9. The Water Authority should continue to support the Western Australian Water Resources Council's detailed assessment of social, political and economic factors relating to groundwater management. This will provide valuable information to the Water Authority to enable refinement of management strategies.

10. The Water Authority, the Geological Survey and the Environmental Protection Authority should ensure that adequate human, technical and financial resources are provided for the implementation of appropriate regional and local management strategies. These resources are, in the initial stages, at least three professional people and two technical assistants within the Water Authority with an additional annual operating budget of $250,000 for computing, investigation and monitoring activities, a hydrogeologist from the Geological Survey and an environmental scientist from the Environmental Protection Authority or the Department of Conservation and Land Management.

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