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Northern Territory

HYDROGEOLOGY OF THE ORD RIVER IRRIGATION AREA

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Hydrogeology of the Ord River Irrigation Area

by

C. A. O'Boy, S. J. Tickell*, C. Yesertener, D. P. Commander,
P. Jolly* and A. T. Laws

Science and Evaluation Division
Water and Rivers Commission
Western Australia

and

Natural Resources Division*
Department of Lands, Planning and Environment
Northern Territory

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Copies available from:

Science and Evaluation Division
Water and Rivers Commission
3 Plain Street EAST PERTH
WESTERN AUSTRALIA 6004
Telephone: (08) 9278 0300 Facsimile (08) 9278 0586
http://www.wrc.gov.au

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Cover photograph: Irrigation of sugar cane on the Ivanhoe Plain, Ord River Irrigation Area.

Foreword

Since the Ord River Irrigation Area was developed in the 1960s a number of groundwater studies have been carried out, initially to monitor the effects of irrigation, and later to assess the feasibility of additional irrigation areas. In common with most irrigation areas, the watertable has risen substantially in the 30 years since the start of irrigation, and in some areas is close to the surface and requiring consideration of remedial measures. The feasibility of groundwater pumping on the Ivanhoe Plain has been trialed and appears to be a viable option.

In assessing the prospects for additional irrigation areas, government agencies carried out extensive programs of exploratory drilling between 1969 and 1996. The aim of this Report is to provide a comprehensive picture of the hydrogeology of the existing and potential irrigation areas, and to reference and summarise all previous relevant work.

The Western Australian State agencies responsible for the investigations over the 30 years period include Agriculture WA, the Geological Survey, Public Works Department, Water Authority, Water Corporation, and Water and Rivers Commission, supported by the Department of Resources Development. In the Northern Territory, the group responsible for groundwater investigations moved from the Water Resources Division of the Power and Water Authority to the Natural Resources Division of the Department of Lands, Planning, and Environment.

Information contained in this Report provides the regional framework to plan management strategies to control rising groundwater levels. Additional monitoring and investigation work will be required to design detailed groundwater control measures.

Acknowledgments

The work undertaken during this study has been carried out by agencies of both the Western Australian and Northern Territory Governments, and by a number of private consultant companies. At all times ideas, concepts, and information were freely exchanged and, where appropriate, field programs undertaken in close cooperation.

Many people assisted in the successful completion of this study. All were guided by the wisdom of *Peter McCosker* from the Ord Development Council. His knowledge of the region and its people was greatly valued by everyone who participated in this study.

Dr Joe Sherrard and Chris Robinson–from Agriculture Western Australia, Kununurra, provided assistance and unpublished data on groundwater in the Stage 1 area.

Following is a list of people who provided assistance to the authors of this Report while they were undertaking the work. For those we have neglected to acknowledge, we apologize, but have greatly appreciated your input.

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G. Humphreys–for his oversight and interpretation of geophysical work undertaken during this study.

G. Hoxley–for his detailed modelling of the groundwater resources of the ORIA.

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WATER AND RIVERS COMMISSION
Hyatt Centre
3 Plain Street
East Perth
Western Australia 6004
Telephone (08) 9278 0300
Facsimile (08) 9278 0301
Website http://www.wrc.wa.gov.au

DEPARTMENT OF LANDS, PLANNING AND ENVIRONMENT
Goyder Centre
Palmerston
Northern Territory 0831
Telephone (08) 8999 3662
Facsimile (08) 8999 3667
Website http://www.lpe.nt.gov.au

1 Introduction

1.1 Purpose and scope

The Government of Western Australia has investigated groundwater conditions in the Stage 1 areas of the Ivanhoe and Packsaddle Plains from the 1960s. Since 1994, jointly with the Northern Territory Government, it has investigated and promoted the Stage 2 extension of the Ord River Irrigation Area (ORIA) to accommodate an increased demand for irrigable land (Fig.1). This Report synthesises the available hydrogeological information from a number of previous studies, and in particular the 1994 to 1996 Stage 2 investigations, to give a comprehensive account of the groundwater conditions over the entire area of potential irrigation. This will provide an invaluable document for the management of groundwater within both the current and future irrigation areas.

1.2 Location

The ORIA straddles the border between the WA and NT portions of the Kimberley Region, and is situated on black soil plains associated with the Ord and Keep Rivers. The Ord River Dam impounds Lake Argyle, which supplies the water for the irrigation area. The town of Kununurra is the commercial and administrative centre for the area.

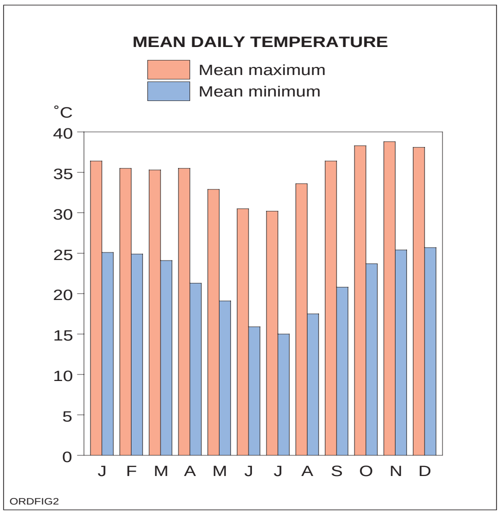
Access to the west and south is by the all-weather Victoria and Great Northern Highways, and to the east by the Victoria Highway. Airlines serve the Ord River Irrigation Area through Kununurra and the nearest seaport is Wyndham, 100 km by road from Kununurra. During the wet season, graded clay roads can become impassible, in particular across the Weaber Plain, Knox Creek Plain, and Keep River Plain.

1.3 Economic and social environment

At the time of the first settlement of European pastoralists in the 1880s, the Miriuwung, Gajerrong and Dulbung peoples occupied the Kununurra–Wyndham area and the Baimbarr and Djangada peoples occupied areas west of Cambridge Gulf. Since the 1880s, pastoral, mining, pearling, irrigated agriculture, and tourism industries have developed. In 1995, the estimated population of the Wyndham/East Kimberley Shire, in which the WA portion of the Ord River Irrigation Area is located, was 6275 (Kimberley Development Commission, 1997). The expansion of the irrigation industry will influence the projected population growth of 2.4% per year from 2001 to 2011.

1.4 Climate

The climate is tropical monsoonal with two dominant seasons separated by short transitional periods (Bureau of Meteorology, 1996). A ‘wet’ monsoonal season occurs from November to April and a ‘dry’ season for the rest of the year. The mean January temperatures range from a minimum of about 26°C to a maximum of 36°C. The mean July temperatures range from a minimum of about 15°C to a maximum of 30°C (Fig. 2).



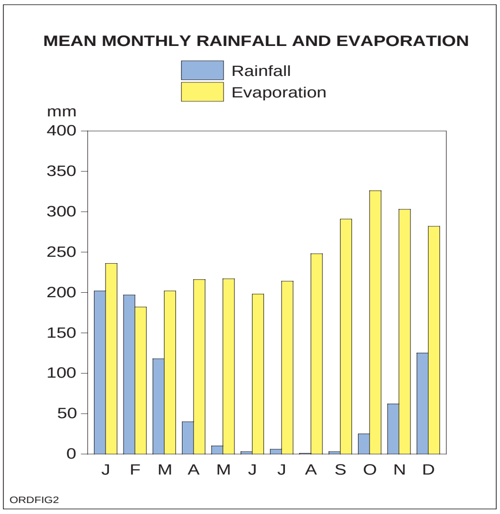


Figure 2. Climate data for Kimberley Research Station (Frank Wise Institute)

The monsoonal weather is hot and uncomfortably humid with mainly northwest winds and frequent thunderstorms causing heavy rainfall. Tropical cyclones and low-pressure systems often mark the 'wet' season, and can produce heavy rain, causing floods in the Ord River catchment which feeds Lake Argyle. The ORIA receives about 90 % of its rainfall during the wet season. Annual rainfall ranges from around 500 to 1400 mm and averages about 800 mm (Fig. 3). Dry sunny days and cooler nights typify the 'dry' season, as trade winds blow from central Australia northwest towards the equator.

1.5 Physiography

The Ord River and its tributaries drain an area approaching 50 000 km^2, and in its lower reaches the Ord River drains the western ORIA. After leaving the gorge country of the Carr Boyd Range the Ord River flows into Lake Kununurra, located east of Packsaddle Plain, impounded by the Diversion Dam, which is constructed on Proterozoic bedrock at Bandicoot Bar. Packsaddle Creek, in the west of Packsaddle Plain, runs northwards and joins the Dunham River close to the confluence with the Ord River downstream of the Diversion Dam (Fig. 1).

The Ivanhoe Plain is uniformly flat, widening in the north, and reaching its maximum width of about 12 km between Buttons Gap and Martins Location. The plain ends in Martins Location and Green Location, two areas subject to seasonal flooding. The Ivanhoe Plain is at a higher elevation than the recent natural levee and has not apparently been flooded since the 1880s. Small gullies now drain the western edges of the plain. West of the Ord River the Dunham River, Valentine Creek, and smaller creeks drain the area.

The Ord River has incised the west of the broad, flat valley of the Ivanhoe Plain and runs northwards before entering Buttons Gap. Here the river turns west around Deception Range and runs for about 10 km through sandstone hills and ranges with associated sandy soils, with practically no alluvial flats. West of Mantinea Creek and False House Roof Hill are plains of varying width and the Ord River follows a winding course to its tidal estuary about 30 km away in the east arm of the Cambridge Gulf.

South of the Ord River, the Mantinea Flats and other plains, which are up to 8 km wide, extend 23 km from Mantinea Creek to the prominent landmark of Goose Hill, which is only about 55 m high. It is 6 km from the present course of the Ord River but at the foot of the hill, very high tides inundate old river meanders where the flats are less than 3 m above high-tide level. These meanders and low stony hills running away south from Goose Hill form a natural division between the flats proposed for the ORIA on the east and tidal flats to the west.

Watercourses emanate from the rocky hills south of the Mantinea Flats and Goose Hill area. Drainage is away from the Ord River via a broad channel into Saltwater

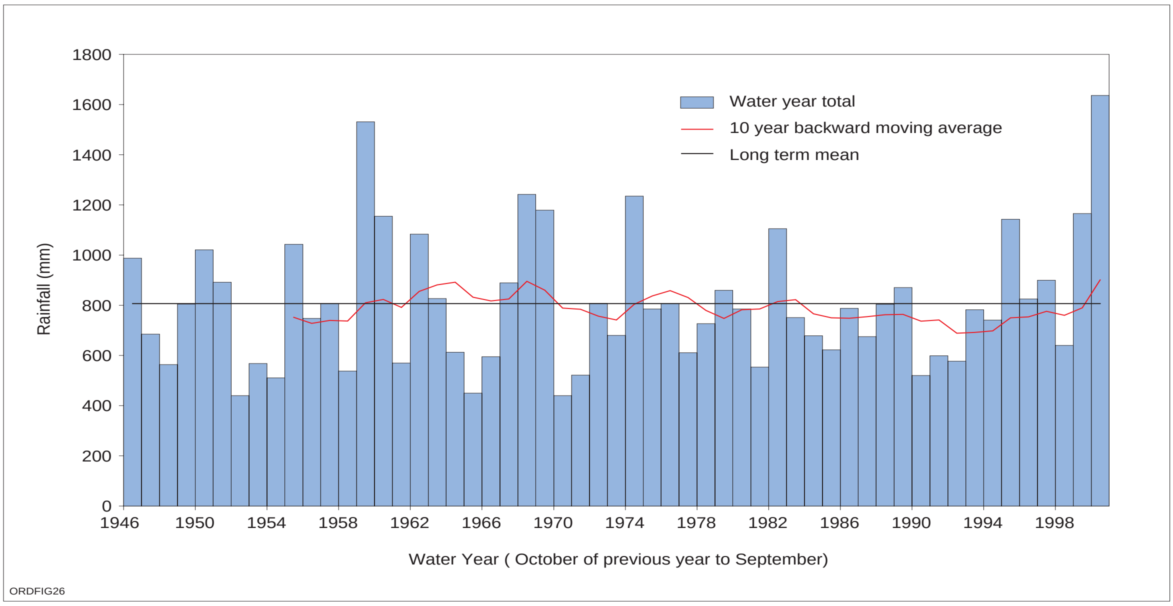


Figure 3. Kimberley Research Station (Frank Wise Institute) rainfall 1960 to 1998

Creek and Goose Hill Creek, which flow into old river meanders and thence to the Ord Estuary. Before construction of the Ord River Dam, overflow from the Ord, especially at the Bend of the Ord, sometimes accentuated the extensive seasonal flooding.

West of False House Roof Hill, the Ord River takes a large northward loop bringing it close to the foot of House Roof Hill. House Roof Hill and False House Roof Hill are over 300 m high and have very similar profiles from certain aspects. Surrounding House Roof Hill are alluvial flats that end farther north at the Proterozoic sandstone hills near Carlton Station Homestead. These alluvial flats extend westward, eventually merging west of Reedy Creek with the tidal flats of the Ord River estuary. Tides influence the Ord River inland as far as the Bend of the Ord, south of House Roof Hill, where the Ord River is about 200 m wide and up to 2 m deep, when not in flood. Before construction of the Ord River Dam, the river overflowed its banks and flooded large areas of flats on average about once in eight years, according to Kim Durack (Burvill, 1991).

The black clay soils of the Ivanhoe Plain are continuous through the Cave Spring Gap and widen out onto similar clay plains of the Weaber Plain. These continue in an easterly direction between the Weaber Range and the north end of the Pincombe Range to the Keep River. Similar clay plains also extend southward for about 25 km on the western side of the Keep River. Border Creek, at the foot of the Weaber Range, drains a large area into Keep River. Many watercourses from the sandstone hills to the north of the Weaber Plain spread their waters onto these clay flats. Water emanates from the Pincombe Range and other sandstone hills in the south of the Weaber Plain causing extensive seasonal flooding.

Bounding the Knox Creek Plain to the north is the Weaber Plain and to the east the Keep River. North of Milligans Hill, Eight Mile Creek and the Pincombe Range form the western boundary of the plain. In the Northern Territory, bounding the plain to the west, is the Milligans Hill sandstone outcrop and to the south, the Burt Range sandstone and limestone hills of Mounts Septimus and Zimmerman. South of Milligans Lagoon, remnant levees with associated sandy soils are abundant across the plain. Sandy colluvium slopes of the surrounding hills fringe the black, cracking clay soils that cover most of the plains.

The Keep River Plain lies between the Keep River in the east and Sandy Creek to the west. Rugged ridges and scarps, formed from faulted and jointed sandstone and siltstone up to 250 m above sea level, lie to the east of the plain. The plain gradually rises from sea level to about 15 m. Erosional remnants of flat-lying Palaeozoic rocks west of the Keep River form hills that rise up to 150 m above the Keep River Plain. Cainozoic alluvium and soil generally underlie the plain. The Keep River incises the Permo-Carboniferous bedrock.

1.6 Vegetation

Field surveys in the ORIA have recorded 682 taxa from eighty-seven families (Wesfarmers *et al.*, 2000). The most numerous families are grasses (Poaceae), eucalypts and paperbarks (Myrtaceae), sedges and rushes (Cyperaceae), wattles (Mimosaceae), daisies (Asteraceae), peas (Fabaceae), and Combretacea (*Terminalia* spp). Gardner (1941) described the natural vegetation of the area, noted for the Indo-Melanesian elements of the flora, and remarked on the mixture of eucalypts with deciduous trees, such as *Gyrocarpus americanus* and the baobab (*Adonsonia gregorii*).

On the sandy alluvial levee soils along the Ord River trees and mostly tussocky grasses form a savannah woodland. The predominant tree species, ranging in height from 3 to 10 m, include bloodwood (*Eucalyptus dichromophiloia*), cabbage gum (*E. clavigera*) and box (*E. spenceriana*), silver-leaved box (*E. pruinosa*), and carbeen (*E. tessellaris*). Apart from the eucalypts, other common trees are *Gyrocarpus americanus*, baobab (*Adonsonia gregorii*), native apple (*Owenia reticulata*), mangaloo (*Careya australis*), kurrajong (*Brachychiton diversifolium*), sandpaper fig (*Ficu orbicularis*), and beefwood (*Hakea arboresceus*). A range of perennial grasses forms the understorey. Though most of the grass species are perennials, many may be mistaken for annuals because they appear dry during the winter. Common perennial grasses of the tussocky habit are kangaroo grass (*Themeda australis*), blue grass (*Dichanthium fecundum*), and white grass (*Sehima pervosum*). Low growing perennial grasses include water couch (*Brachyachne convergens*).

Gardner (1941) described the main elements of vegetation of the black soil plains as tussocky and tall grasses, with trees almost entirely absent on some of the plains of the Mantinea Flats—Goose Hill area.

Beard (1990) described the Western Australian portion of the Project Area as 'grassland with sparse bauhinia (*Bauhinia cunninghami*) and coolibah (*Eucalyptus microtheca*) on cracking clay soil'. The clay plains generally support open savannah vegetation with the main trees being the flooded box (*E. microtheca*) and the gutta percha (*Excoecaria parvifolia*). The small-flowered bloodwood (*E. polycarpa*), the bauhinia (*Lysiphylum cunninghamii*) and the conkerberry (*Carissa lauceolata*) are the other main species. Native sorghum, known locally as cane grass, (*Sorghum stripoideum* and *S. plomosum*) predominates in uncultivated parts of the Ord River Irrigation Area. Grasses vary and cattle grazing has altered the proportions especially near watercourses. Common perennial grasses, reaching two metres or more in height, include blue grass (*Dichanthium teniculm* and *D. fecundum*), plume sorghum (*S. plumosum*), silky brown top (*Eulalia fulva*), canegrass (*Ophiuros exaltatus*), blue mitchell grass (*Astrebla squarrosa*), and golden beard grass (*Chrysopogon fallax*).

Areas subject to regular seasonal flooding, such as billabongs and swamps, commonly include coolibah, gutta percha (*E. parvifolia)*, and chestnut tress (*Terminalia platyphylla*). On the sandy soils adjoining the sandstone hills can be found sorghum grasses, spinifex, and monsoon woodland, where Pandanus palms or screw palms (*Pandanus odoratissimus*) are indicators of groundwater seepage. On the stony hills, stunted gums, *Teminalia* spp, cotton tree, and spinifex are the main elements of the vegetation.

1.7 Stygofauna

Researchers have recently discovered stygofauna, obligate subterranean fauna living within aquifers, in the alluvium although they are probably best developed in the karst-fissured aquifers of the ORIA. The few samples collected to date are unlikely to represent the diversity of stygofauna present (Humphreys, 1999). In the alluvial aquifers, individual species are likely to have patchy distributions because of variations in groundwater characteristics. The alluvial aquifers contain undescribed species in two families of bathynellid syncarid Crustacea on the Ivanhoe and Weaber Plains, and a significant stygofauna is associated with the karstic landforms in the Devonian limestone.

1.8 Surface water hydrology

During the wet season, streams rapidly respond to local thunderstorm events of high rainfall intensity, which produce local flooding but only small flows in the larger tributaries of the Ord. Major flood events are the result of broad-scale monsoonal low-pressure systems, the number of which governs the amount of streamflow discharge. In some years, only thunderstorms occur and streamflow is low. In others years many monsoonal depressions occur, some of which build into intense cyclones, and major flooding results in large volumes of annual streamflow. During the remainder of the year, falls are light and sporadic and most rivers dry up by mid-June. The long-term (1905–1990) average annual Ord discharge is 3980 gigalitres (GL) (Ruprecht and Rogers, 1999).

Before the construction of the Ord River Dam in 1972, large floods occurred down the Ord River during the wet season causing flooding over the Carlton Plain and Mantinea Flats. Dry season flows in the Ord River were negligible, and water in the Ord River channel across the western portion of the Carlton Plain and Mantinea Flats was largely of estuarine origin.

With the construction of the Ord River Dam and the Kununurra Diversion Dam, since 1972 there has been a lessening in the seasonal variability of Ord River. There are now significantly decreased peak flows in the wet season and maintenance of flow in the dry season. The commissioning of the hydro-power station in 1996 has further decreased the seasonal variability by steady releases. Since the construction of the Ord River Dam, about 30% of the inflow is lost by evaporation from Lake Argyle (Ruprecht and Rogers, 1999). The annual water balance of Lake Argyle, in gigalitres, is as follows:

$$\text{Inflow (3940) + Rainfall (650) = Evaporation (1750) + Overflow (890) + Releases (1950)}$$

1.9 Irrigation

In 1963, the completion of the Diversion Dam impounded the Ord River to create Lake Kununurra from which channelled water has supplied irrigated agriculture on the Ivanhoe Plain. In 1972, the formation of Lake Argyle made possible the release for irrigation of up to 13 000 ha of land on the Ivanhoe Plain and 2500 ha on the Packsaddle Plain.

The Governments of Western Australia and the Northern Territory are currently promoting the development of irrigation over large areas of open-range cattle grazing land. These Stage 2 areas include the West Bank of Ord (1000 ha), Carlton Plain (9000 ha), and Mantinea Flats (4200 ha), and areas to be supplied from the proposed M2 channel. These are the Weaber Plain (14 500 ha), Keep River Plain (10 600 ha), and the Knox Creek Plain (7000 ha). The Ord River Irrigation Area will eventually contain about 62 000 ha of irrigable land (Fig. 1).

The Department of Resources Development (1996) produced a conceptual report concerning the Ord Irrigation Scheme Stage 2 containing discussions concerning the subsurface drainage requirements and accessions to groundwater. A detailed assessment of the groundwater system under irrigation followed in a draft Public Environmental Review for the Stage 2 M2 development area and a draft Consultative Environmental Review for the Riverside Development Area (Department of Resources Development, 1997a,b). More recently, a consortium lead by Wesfarmers Pty Ltd has presented an Environmental Review and Management Programme (ERMP) and Draft Environmental Impact Statement for the Stage 2 M2 area (Wesfarmers *et al.,* 2000).

1.9.1 Existing irrigation

The largest area of irrigation in Stage 1 is the Ivanhoe Plain, which covers an area of almost 12 000 ha, and consists of blocks ranging in size from 80 to 350 ha irrigated from the M1 Channel. The area stretches from Kununurra in the south to the Pincombe Range in the north, and is predominantly east of the Ord River. The irrigation area on Packsaddle Plain covers an area of about 2400 ha and extends south of the Diversion Dam and west of the Ord River.

Cotton was the primary commercial crop from the 1960s until 1974 when production ceased because of chemical-resistant insect pests, and the removal of Government subsidies, which made cotton uneconomical. Commercial agriculture was sustained from the mid 1970s until the early 1980s by crops such as sorghum, sunflower, soybean, maize and rice, along with hybrid seed crops, peanuts and mung beans. Returns from finishing beef based on intensively producing leucaena, a legume forage crop, are comparable with field cropping. From the early 1980s, the introduction of high value horticultural and hybrid seed crops has quickly made these lower value crops less relevant. The main horticultural products are cucurbits (especially melons), bananas, and mangoes. A mill constructed in the mid-1990s has permitted the establishment of sugar cane as a major field crop, replacing lower value crops (Agriculture Western Australia, 1997; Government of Western Australia, 1996).

1.9.2 Proposed irrigation

The six main areas promoted for the Stage 2 development of irrigation cover about 46 500 ha. The sustainability of irrigation depends considerably on the hydrogeological conditions present beneath each area, which determines the ability to control the rate at which groundwater levels will rise. The irrigation regimes and groundwater-level control methods under consideration will lessen the risk of crop-yield reduction from soil salinity and waterlogging.

Further irrigable land exists in the western part of the Packsaddle Plain and investigations have identified an additional 1650 ha on the West Bank of Ord. Agencies are also studying the expansion of the existing Ivanhoe Plain irrigation area into the Green Location area.

The Weaber Plain, connected to the Ivanhoe Plain through Cave Spring Gap, consists of 14 000 ha of irrigable soils. The Knox Creek Plain, consisting of nearly 5500 ha of irrigable soil, is south of the eastern end of the Weaber Plain, and east of the Pincombe Range extending to the Keep River. The Keep River Plain, nearly 10 600 ha of irrigable soil, is entirely in the Northern Territory and consists of an alluvial plain bounded in the west by the Keep River and in the east by Sandy Creek. The proposed M2 Channel would supply these areas, with water pumped to the head of the Knox Creek Plain. The Wesfarmers–Marubeni–Water Corporation joint venture (Wesfarmers, 2000) is carrying out a detailed feasibility study for establishing a major sugar cane industry on the black soil plains of the Weaber, Knox Creek, and Keep River Plains.

The Carlton Plain and Mantinea Flats are about 20 km west of the northern end of the Ivanhoe Plain. About 9000 ha of irrigable soils exist on the Carlton Plain, and while surface grades are satisfactory for irrigation, water supplies would need to be obtained direct from the Ord River (Agriculture Western Australia, 1997).

The Mantinea Flats area is south of the Ord River and has about 4200 ha of variable soil suitable for intensive horticulture. The areas where intensive horticulture is planned are located adjacent to the banks of the Ord River at the West Bank of Ord (Ivanhoe Plain), Mantinea Flats, Mantinea Loop, and the Carlton Plain. In addition, about 1800 ha of broad-acre irrigation is proposed for the Carlton Plain.

When the Stage 1 Ord River Irrigation Area was constructed, there was not a rigorous environmental assessment. The development of Stage 2 is taking place in a different context in which the principles of ecological sustainable development increasingly form the basis for land and water management. Siewert (1998) proposed that the principles should include a precautionary approach with recognition of the biophysical limits on natural resource use.

One of the main concerns, with respect the extension of the irrigation scheme is rising groundwater levels, which has already occurred on the Ivanhoe and Packsaddle Plains. Rising groundwater levels could lead to increased groundwater discharge to the rivers as well as land degradation and could alter groundwater ecosystems within the subsurface environment. Investigations, that are the basis of this Report, enable an assessment to be made of the environmental consequences of changes in the groundwater system.

2 Previous investigations and studies

2.1 Groundwater drilling investigations

Since the 1960s, Government agencies from WA and the NT have conducted a series of groundwater drilling investigations, installed piezometers, and constructed test production bores for pumping tests in the ORIA (Table 1). The agencies recognised that an understanding of the geology, groundwater level fluctuations, chemistry, and aquifer hydraulics is required to define the hydrogeology in sufficient detail to plan management for sustainable agriculture. Knowledge of the sub-surface conditions has permitted the modelling of the groundwater regime response to irrigation and has provided the basis to objectively plan and manage irrigation, and assess groundwater management options.

Early investigations included the construction of piezometers to monitor groundwater levels and salinity on the Ivanhoe Plain and Carlton Plain in 1964–65. There was some re-drilling on the Ivanhoe Plain in 1968 and Carlton Plain in 1978. The Weaber Plain saw an extensive piezometer construction program in 1968 with some redrilling in 1970. In 1983, the GSWA supervised a large piezometer installation program on the Ivanhoe Plain and Weaber Plain including Cave Spring Gap (Laws, 1983a,b; McGowan, 1983). The Keep River Plain had a modest spread of piezometers installed in 1966 and 1972. Little documentation is available for early drilling on the Mantinea Flats.

From 1994 to 1996, the government agencies of WA and the NT undertook a drilling program across the entire ORIA. It included expanding the monitoring network, constructing production bores with monitoring bores and undertaking pumping tests. The GSWA and the Power and Water Authority (PAWA) of the Northern Territory started the program in 1994. The Water and Rivers Commission (WRC) of Western Australia and Department of Lands Planning and Environment (DLPE) of the Northern Territory completed the program in 1996. Details of borehole completions for the 1994–96 program are presented in Humphreys *et al.,* 1995; Nixon (1997a,b,c,d,e,f,g,h), and O'Boy (1997, 1998).

Agriculture Western Australia (AgWA) has also undertaken extensive shallow drilling for irrigation infiltration studies. These studies are at irrigation-bay scale, and piezometers are monitored with continuous data loggers.

Bores drilled in WA have generally been numbered with a prefix letter, which in latter years has denoted location (e.g. PS – Packsaddle, KC – Knox Creek). The year of drilling and a sequential number identify piezometers installed by AgWA (e.g. 91/1 is the first bore drilled in 1991). Bores in the NT are identified by a Registered Number (RN) which is sequential in order of drilling (Table 1).

2.2 Mineral exploration

Mineral exploration has also provided much subsurface information. Companies have carried out exploration for diamonds across the Ord River Irrigation Area, in particular on the Ivanhoe, Packsaddle, and Weaber Plains. In addition, mining companies have carried out drilling around the lead–zinc deposits of Sorby Hills in the northeastern Weaber Plain and the Knox Creek Plain. There has been some limited drilling on the Carlton Plain and Mantinea Flats.

The WA Department of Minerals and Energy holds exploration data in company annual reports and on Open File through the WAMEX database. Laws (1993) reviewed and evaluated 175 company reports that outlined mineral exploration in the Ord River Irrigation Area, and while few provided specific hydrogeological data, most contained some geological data. The review provided recommendations that formed the basis of the 1994 to 1996 drilling program to thoroughly establish background hydrogeological data to assess the suitability of the area for irrigation.

2.3 Geophysical investigations

In 1994, the WA and NT government agencies jointly undertook an airborne geophysical survey (World Geoscience Corporation Ltd, 1994). The Weaber Plain, Knox Creek Plain, and Keep River Plain were flown with QUESTEM electromagnetics to provide

Table 1. Summary of groundwater investigation bores drilled to 1996

Location	*Date*	*Agency*	*Bores*	*Bore identification*
Packsaddle Plain	1971	PWD	22	P1 to P22
	1978	PWD	2	PS1 to PS2
	1994	DRD, GSWA, WAWA	7	PS1*, PS3, PS5, PS12, PS14, PS15
	1996	DRD, WRC	5	PSPB1, PSPB1M1, PSPB1M2, PSPB1M3, PSPB1M4
Ivanhoe Plain	1964	PWD	51	1A to 1G, 2A to 2I, 3A to 3K, 4A to 4E, 5A to 5F, 6A, 6B, 9A, 10A to 10D, 11A to 11C, G1, CS3, CS6
	1965	PWD	4	6C, 6D, 9A, G6
	1968	PWD	9	2F*, 2G*, 3B*, 3E*, 4E*, 5D*, 6A*, 10A*, 10B*
	1983	GSWA, PWD	29	PN1S, PN2S, PN2D, PN3S, PN3D, PN4S, PN5S, PN5D, PN6S, PN6D, PN7S, PN8S, PN8SD,PN6S, PN6D, PN7S, PN8S, PN8SD, PN9S, PN9D, PN10S, PN10D, PN11S, PN12S, PN12D, PN13S, PN13D, PN14S, PN15S, PB1, PB1M1 to PB1M4, PB2, PB2M1 to PB2MM4, PB3, PB3M1 to PB3M3S
	1991	AgWA	12	91/1 to 91/12
	1994	AgWA, DRD, GSWA, WAWA	52	94/1 to 94/39, GS1 to GS3, ML1 to ML3, ML6, CG1 to CG6
	1996	AgWA, DRD, WRC	9	PB4, PB4M1 to PB4M4, 96/1 to 96/6
Weaber Plain	1964	PWD	16	CS8, CS10, CS12, CS12E1, CS12E5, W2, W3S1, W5S1, W5S2, W7, W16B, NB4, B3, 14, B6, B4W1
	1968	PWD	4	B4W1, B4W1N,B4W1S,W5
	1970	PWD, PAWA	30	CS14, CS15, CS16, CS17, W1, W1S1, W2S1, W3, W4, W6, W8, W9, W10, B2, B4, B5, B7, 8 to 12 CS12E2, CS12E2.5, CS12E3, CS12E4, RN7412 to RN 7415
	1980	Aquitaine Minerals	2	7024 (α-β Pod), 7034 (I Pod)
	1983	GSWA, PWD	7	W6S1, W5S2*, W5S1.5, CS12E2.5, CS12E1*, W2*, CS13
	1994	DRD, GSWA, PAWA, WAWA	5	WP9, WP15, WP19, WP21, WP29
	1996	DRD, DLPE, WRC	25	WP1 to WP7, WP6PB, WP10 to WP14, WP16, WP17, WP24,WP25, RN29655, RN29656, RN29658 to RN29662
Knox Creek Plain	1994	DRD, GSWA, PAWA, WAWA	8	KCF1, KCF2, KCF4, KC3, KC3A, KC6, KC8, KC10
	1996	DRD, DLPE, WRC	16	KC2, KC3PB, KC4, KC5, KC9, KC11, KC12, KC13, KC14, RN29667, RN30825, RN30829(J28PB), RN30827(J28), RN30828, J35, WBS1155M
Keep River Plain	1966	PAWA	2	RN5181, RN5669
	1972	PAWA	7	RN7859 to RN7865
	1994	PAWA, DRD, GSWA	13	RN29516 to RN29519, RN29650 to RN29654, RN29657, RN29663 to RN29666
Carlton Plain	1964	PWD	17	Y1 to Y17
	1978	PWD	17	Y1* to Y17*
	1994	DRD, GSWA, WAWA	6	CP1, Y1A*, Y3A*, Y10A*, Y16A*, Y17A*
Mantinea Flats	1994	DRD,GSWA, WAWA	3	MP1, MP4, MP6
	1996	DRD, WRC	6	MP2, MP3, MP5, MP7, MP8, MP10

Notes: PWD – Public Works Department of WA
GSWA – Geological Survey of WA
DLPE – Department of Lands Panning and Environment of NT
DRD – Department of Resources Development of WA
PAWA – Power and Water Authority of NT
WAWA – Water Authority of WA
AgWA – Agriculture WA
* denotes a re-drill

information on electrical conductivity of rocks, soils and water quality, and total-field magnetics for basement structure and basement depth. Preliminary maps at 1:250,000 and 1:100,000 scale were presented to allow siting of ground geophysics and drilling locations for the 1994 investigation program.

The QUESTEM system is a time-domain electromagnetic (TEM) system developed by Questor in Canada and refined for Australian conditions by World Geoscience Corporation (Street and Anderson, 1994). World Geoscience Corporation presented the QUESTEM survey results as coloured images of the conductance in channels: -2, 0, 3, 8, and 12. To establish areas of consistency of data, World Geoscience based the study of the channel responses on the colour images. These were used to define hydrogeological environments with similar characteristics, and were ground truthed by PAWA with a variety of methods. The geophysical targets were generally in areas of high electrical conductivity, where conductivity could relate to salt storage, to shallow groundwater, or to basement rock-type changes. The geophysics comprised ground-penetrating radar (GPR), joint resistivity/transient electromagnetics (TEM), and ground EM traversing and bore logging with both passive gamma and EM probes. Later, they aimed ground reconnaissance at differentiating geophysical regions to indicate variations in the hydrogeological environments defined by the airborne work (Humphreys *et al.,* 1995). The investigation consisted of twelve joint DC resistivity and Sirotem soundings on the Weaber and Keep River Plains. The intention was for the soundings to provide information on electrical layering in the earth at certain sites, and to relate the soil and geological structure to the airborne geophysical maps. The DC soundings were more useful because the Sirotem II TEM soundings gave little information on the first ten metres below ground surface. Where possible, PAWA drilled at the sounding locations and validated the airborne EM map.

Drilling and revision of geological mapping was necessary to evaluate the geophysical results in terms of hydrogeology. PAWA and the GSWA selected drilling targets to investigate the palaeochannel of the Ord River and Keep River. The drilling would also define basement hydrogeological characteristics, varying soil types, and locations where alluvium depth might be crucial to the irrigation potential. The GSWA was able to log the boreholes with gamma and inductive EM using a Century Geophysics logger. The borehole logging provided correlation of units in several places where drill returns were poor, and the comparison of inductive resistivity with soil conductivities provided further insight into the assessment of soundings and the QUESTEM data.

2.4 Hydrogeological studies

Although piezometers were installed following the commencement of irrigation, the hydrogeology had not been described until 1982 when Laws and George (1982) undertook the first review of the hydrogeology and groundwater conditions beneath the Ivanhoe Plains (Table 2). They highlighted the rapidly rising groundwater levels and variable salinities. From the review, a drilling and hydraulic testing program was proposed (Laws, 1983a).

The GSWA supervised a program of drilling, piezometer installation, and hydraulic testing on Ivanhoe Plain and Weaber Plain, which was analysed and reported on by McGowan (1983) and Laws (1983b), respectively. At the same time, Banyard (1983) studied infiltration from irrigation channels on the Ivanhoe Plain. McGowan (1984) next reported on the hydrogeological aspects of proposed rice growing on the Ivanhoe Plain. Reviews of the ORIA monitoring data for the period to 1986 (McGowan, 1987) and from 1986 to 1990 (Laws, 1991a) also included an outline of the hydrogeology. Laws (1991b) presented a paper summarising the hydrogeology.

Laws (1993a) reviewed all the available drilling and hydrogeological information and proposed investigations, which was followed up by a drilling-program proposal (Laws, 1993b). This led to the drilling programs undertaken throughout the ORIA in 1994 and 1996. Nixon (1995) reported on the preliminary results of the hydrogeological investigations, except for the Mantinea Flats where the preliminary results were reported later (Nixon, 1996). Humphreys *et al.* (1995) reported on the sub-surface hydrology of the Keep River Plains and Chin *et al.* (1997) produced a draft executive summary for the sub-surface hydrology of the Knox Creek Plains.

The most recent review of groundwater monitoring data for the Packsaddle and Ivanhoe Plains highlighted the rising groundwater levels and made predictions of

Table 2. Summary of hydrogeological reporting

Topic	*Reference*
Sorby Hills pumping tests	Dudgeon and Cox (1981)
Groundwater conditions in the ORIA	Laws and George (1982)
Drilling and hydraulic testing program	Laws (1983a)
Analysis and interpretation of drilling and hydraulic testing—Ivanhoe Plains	McGowan (1983)
Ivanhoe Plain waterway infiltration	Banyard (1983)
Groundwater conditions in the ORIA—Weaber Plains area	Laws (1983b)
Hydrogeologic aspects of rice growing—Ivanhoe Plains	McGowan (1984)
A review of ORIA monitoring data to 1986	McGowan (1987)
A review of ORIA monitoring data 1986–1990	Laws (1991a)
The geology and hydrogeology of the ORIA	Laws (1991b)
ORIA review of information and investigation proposals	Laws (1993a)
Proposed drilling program	Laws (1993b)
Preliminary results of hydrogeological investigations	Nixon (1995)
Sub-surface hydrology of the Keep River Plains	Humphreys *et al.* (1995)
Preliminary results of hydrogeological investigations—Mantinea Plain	Nixon (1996)
Sub-surface hydrology of the Knox Creek Plains	Chin *et al.* (1997)
Review of monitoring data in ORIA 1996—Ivanhoe and Packsaddle Plains	Yesertener (1997)
ORIA test pumping	O'Boy (1997)
ORIA Stage 1 water and nutrient balance study	Water Corporation of WA (1997)
ORIA Stage 2 and Riverside Development—environmental reviews	Dept of Resources Development (1997a,b)
ORIA long-term test pumping	O'Boy (1998)
ORIA Stage 1 control of rising groundwater level—draft	Water Corporation of WA (1998)
ORIA Stage 2 ERMP and draft environmental impact statement	Wesfarmers (2000)

future rates of rise (Yesertener, 1997). The Water Corporation of Western Australia (WAWA) (1997) commissioned a water and nutrient balance study for the Ivanhoe Plain, which was followed with a draft report on the control of rising groundwater levels (Water Corporation of Western Australia, 1998). O'Boy (1997, 1998) reported on the long-term test pumping of large-diameter bores, which included an assessment of their use to control groundwater levels on the Packsaddle and Ivanhoe Plains.

The WA Department of Resources Development (1997) commissioned Sinclair Knight Merz to produce a draft Public Environmental Review (PER) for the M2 Development Area, and a Consultative Environmental Review (CER) for the Riverside Development Area, which contained significant groundwater components. A consortium consisting of Wesfarmers, Marubeni, and the Water Corporation of Western Australia (2000) appointed Kinhill to produce an Environmental Review and Management Programme (ERMP) and Draft Environmental Impact Statement for the proposed development of the M2 area.

2.5 Detailed investigations

2.5.1 Packsaddle Plain

The Western Australian Public Works Department (PWD) drilled and constructed 22 piezometers, P1 to P22, in 1972 and a further two, PS1 and PS2, in 1978 to measure groundwater levels and salinity. The boreholes were drilled without geological supervision and, consequently, data on the unconsolidated materials that overlie bedrock are limited to abbreviated drillers' logs. Some of the logs indicate that the full succession of unconsolidated sediments was not penetrated, and, because of the type of drilling rig used, there may be some doubt concerning reported bedrock in some boreholes.

The value of the early piezometers is limited because of the lack of geological control, which hindered a clear understanding of the surficial geology of the irrigation area. The loss of 50% of the piezometers resulted in a reduced monitoring program. The levelling of only three piezometers to Australian Height Datum (AHD) limited the understanding of the watertable configuration.

As part of the 1994 drilling program, seven piezometers (PS1, PS3, PS5, PS12, PS12A, PS14, and PS15) were drilled to depths not exceeding 15 m (Nixon 1995, 1997e). The reverse-circulation rig that drilled the bores encountered problems penetrating the collapsing basal sands and gravels. In 1996, a test production bore (PSPB1) and four associated observation bores with piezometer nests (PSPB1M1 to PSPB1M4) were drilled (O'Boy, 1997). AgWA then ran a long-term pumping test program from late 1997 through most of 1998 (O'Boy, 1998).

Gem Exploration and Minerals Ltd and Striker Resources NL explored for diamonds on Packsaddle Plain commencing in 1988, with the main drilling program in 1989 (Hissink, 1990), and further drilling in 1990 (Hissink, 1991). Most of the drilling straddled Packsaddle Creek in the area between the irrigation bays and the Carr Boyd Ranges in the west. A few sites were along irrigation channels in the northern part of the plain.

The 1989 program consisted of 102 exploration holes using a Barber rig for 50 holes, a small-diameter auger rig for 41 holes, and air-core methods for 11 holes. A further 20 air-core boreholes were drilled in 1990. The deepest borehole penetrated surficial sediments and bedrock to 100 m and the thickest sand and gravel sequence intersected was 18.5 m. However, the geological logs provided are brief with no geophysical logs to aid interpretation, and groundwater levels were recorded only for two boreholes, in the 1990 program.

2.5.2 Ivanhoe Plain

Following the commencement of irrigation, the Western Australia Public Works Department (PWD) undertook drilling and construction of piezometers in 1964, 1965, and 1968. These formed the basis of a monitoring program to 1983, although there were many gaps in the monitoring data, and several piezometers became unusable. The PWD drilled the boreholes to a maximum depth of 22 m but did not fully penetrate the unconsolidated sediments because of the type of drilling rig used.

In 1983, following the reports of Laws and George (1982) and Laws (1983a), the PWD drilled 29 additional holes to depths of 61 m into bedrock but had problems fully penetrating loose sand and gravel. The GSWA logged the holes and the PWD installed piezometers PN1 to PN15 to monitor the effects of irrigation on groundwater (McGowan, 1983). Three test production bores, PB1 to PB3, with associated observation bores, were constructed and test pumped.

In 1991, AgWA installed 12 piezometers, 91/1 to 91/12, at six sites to closely monitor water levels around irrigation bays.

As part of the 1994 reverse-circulation drilling program, ten piezometers (94/19, 94/20, 94/21, GS1, GS2, GS4, ML1, ML2, ML4 and ML6) were installed on the Ivanhoe Plain. The program also included six piezometers in Cave Spring Gap, CG1 to CG6, and AgWA installed a further 36 piezometers, 94/1 to 94/18, and 94/22 to 94/39. The bores were up to 22 m deep on the Ivanhoe Plain and up to 38 m deep in Cave Spring Gap but again problems were encountered penetrating loose sand and gravel. The program continued using mud rotary techniques in 1996 with a further six piezometers (96/1, 96/2, 96/3, 96/4, 96/5 and 96/6) installed for AgWA (Nixon, 1995, 1997e). In 1996, the test production bore PB4 and four associated observation bores with piezometer nests were drilled with mud rotary and completed (O'Boy, 1997). AgWA and farmers then ran a long-term pumping test program from late 1997 through most of 1998 (O'Boy, 1998). The WRC also undertook a five-yearly monitoring review of water levels, which is incorporated into this Report (Yesertener, 1997).

Initially Gem Exploration and Minerals Ltd and Striker Resources NL explored for diamonds. All drilling was carried out along irrigation channels and in other accessible reserves (Hissink, 1989). They drilled and surveyed to AHD about 123 mineral exploration holes, of which 95 were 100 mm in diameter and the remainder, a diameter of 170 mm. The deepest hole reached 46.5 m, and the thickest gravel sequence intersected was 23 m. The geological logs provided are rudimentary; with no geophysical logs to aid interpretation and no groundwater levels or salinity data reported. Since 1994, AuDAX Resources NL and Carnegie Minerals NL have undertaken detailed drilling investigations for diamonds on the West Bank of Ord.

2.5.3 Weaber Plain

The Weaber Plain has remained undeveloped to date, although there have been several episodes of drilling. The PWD drilled and constructed 16 piezometers in 1964 and a further four in 1968 (Table 1). Twelve had been destroyed and six were dry by 1970 when

30 piezometers were constructed, 26 by the PWD including five redrills and four constructed by PAWA.

The PWD carried out the 1968 and 1970 drilling programs without trained geological supervision or logging. The general inadequacies of the drillers' logs place doubt on the recorded succession, especially in the eastern part of the plain with the material described as bedrock. Here, subsequent mineral exploration drilling has indicated substantial thicknesses of sand and gravel.

In 1983, a further three boreholes were redrilled to a maximum depth of 22 m, and four new holes constructed (Laws, 1983b) (Table 1). From 1984 to 1990 the PWD monitored 11 piezometers from the 15 available. In addition, they also monitored an Australian Aquitaine cased exploratory hole, WBS1155.

The value of the groundwater level and conductivity data collected from the pre-1983 piezometers is limited by the lack of geological control, particularly in the eastern half of the Plain. The loss of about 50% of piezometers, and reduction in the number of piezometers, placed a severe restriction on the interpretation of the data and evaluation of the groundwater flow patterns and salinity trends. The 1994 and 1996 drilling program took into account the recommendations of McGowan (1987) and Laws (1991a) for redrilling of some 'lost' sites and the drilling of new sites.

In the 1994 reverse-circulation (RC) drilling program, five piezometers were completed (WP9, WP15, WP19, WP21, and WP29) (Nixon 1997b). In the 1996 mud rotary drilling program, one test production bore was completed (WP6PB) and 24 piezometers (WP1 to WP7, WP10 to WP 14, WP17, WP17, WP24, WP25, RN29655, RN29656, RN29658, and RN29662) placed to a maximum depth of 38 m. An additional ten bores from the WBS lead–zinc exploration drilling series were logged geophysically (Nixon, 1997b,h).

Several mining companies, either singly or within joint ventures, have carried out extensive mineral exploration for lead–zinc and diamonds over parts of the Weaber Plain and adjacent areas. Alcoa of Australia WA Ltd has carried out lead–zinc exploration in the northern part of the plain. A joint venture of Amax Exploration Australia Inc., Australian Selection Pty Ltd, CRA Exploration Pty Ltd, Tenneco Oils and Minerals Aust., and Seltrust Mining Corp. Pty Ltd also undertook lead–zinc exploration in this area.

From 1972 to 1992 in the Sorby Hills area exploration companies drilled several hundred holes using a variety of techniques and reported on these in numerous annual and technical reports. In general, there is limited information on the unconsolidated overburden material and, apart from thickness, fewer than 50% of these holes have any information. The overburden isopach maps (Noakes, 1976b; Heuillon and Uttley, 1977; Rowley and Lee, 1982) cover a small area and do not indicate the relative thicknesses of sands and gravels.

A consortium has undertaken a major exploration for lead–zinc in the Sorby Hills area. The consortium consisted initially of Aquitaine Australia Minerals Pty Ltd, Placer Prospecting Pty Ltd, and St Joe Bonaparte Pty Ltd and subsequently of Elf-Aquitaine-Triako Mines Ltd, BHP Minerals Ltd, and BHP Utah Minerals International.

An Amax joint venture (Gellatly, 1972; Uren, 1978; Scott, 1979; Anon., 1980; Franzen, 1981; Woodhouse, 1981; Bannister, 1983) has drilled percussion and diamond-cored holes around Point Springs for lead–zinc. The geological logs are sketchy for the overburden and detailed for the underlying bedrock. In general, they describe the overburden as clay and silt but provide no details of groundwater. Woodhouse (1981) refers to four percussion holes drilled in the Weaber Range to the north of the Weaber Plain that were all abandoned at 100 m because of water problems. Supplies of more than 1000 m^3/d were intersected in the Point Spring Sandstone, which could be considered a possible target for water supplies.

In 1989, Lancaster Resources NL drilled a series of nine holes north of Border Creek to locate diamonds in the meandering Ord River palaeochannel (O'Hara, 1989). The holes intersected between 7 and 16 m of silt and clay, overlying from 20 to 38 m of sand, gravels and cobbles. Although there was no mention of groundwater in these holes, a water bore drilled nearby obtained a supply of 240 kL/d, presumably from the gravels.

In 1975, a joint venture of St Joe–Aquitaine–Mimets undertook lead–zinc exploration in the Jeremiah Hills area and drilled ten (4000 Series) percussion holes in the Gum Creek area (Uttley, 1975). These holes intersected between 8 and 32 m of sand, with the thickest sequence close to Gum Creek. Further drilling in 1983 of three holes (1001, 5001, and 5003) intersected between 25 and 31 m of alluvium but no detailed logs are available (Ingebritsen *et al.,* 1984).

2.5.4 Knox Creek Plain

The Knox Creek Plain area has remained undeveloped, and until the 1994–1996 drilling program, agencies had not carried out drilling specifically to establish the groundwater conditions beneath the plain. Mineral exploration provided most of the information for interpretation of the hydrogeology.

In the 1994 drilling program using reverse circulation, eight piezometers (KCF1, KCF2, KC3, KC3A, KCF4, KC6, KC8 and KC10) were completed (Nixon 1997a,b). In the 1996 mud rotary drilling program, two test production bores were completed; RN30829 (J28PB) and KC3PB. In addition, bores were drilled to depths reaching 56 m and 14 piezometers (KC2, KC3, KC4, KC5, KC9, KC11, KC12, KC13, KC14, RN29667, RN30825, RN30827 (J28), RN30828, J35, and WBS1155M) were completed (Nixon, 1997a,b).

At least two joint ventures have carried out mineral exploration for lead and zinc over parts of the Knox Creek Plain. As part of the Sorby Hills group of mineral claims, a consortium undertook most of the exploration in the western part of the Knox Creek Plain, close to the Pincombe Range. The consortium consisted initially of Aquitaine Australia Minerals Pty Ltd, Placer Prospecting Pty Ltd, and St Joe Bonaparte Pty Ltd and subsequently of Elf-Aquitaine-Triako Mines Ltd, BHP Minerals Ltd, and BHP Utah Minerals International. In addition, a joint venture carried out limited exploration on claims over Milligan Hills in the southeast of the Plain. The joint venture consisted of Amax Exploration Australia Inc., Australian Selection Pty Ltd, CRA Exploration Pty Ltd, Tenneco Oils and Minerals Aust., and Seltrust Mining Corp. Pty Ltd.

Most of the lead–zinc exploration drilling was undertaken by the Aquitaine consortium, and reported on in Noakes (1976a,b), Heuillon and Uttley (1977), Uttley (1978), d'Auvergne (1980), Ingebritsen *et al.* (1982), and Ingebritsen and Shelley (1984). The drilling techniques include percussion, rotary air, and diamond coring. Like the Weaber Plains, there are very few drilling logs for the overburden section of the holes, and although many holes are shown on company plans, they have reported on very few.

The limited data from the above programs indicate that close to the Pincombe Range and extending up to 3 km east of Knox Creek, the overburden is mostly clay with a maximum thickness of 18 m. Eastwards towards the WA/NT border and the Keep River, sand and gravel increase in thickness to the east with drilling intersecting up to 40 m in the northern half of the plain.

In the southern part of the plain a line of percussion holes was drilled in 1980 (Franzen, 1981). Overburden details are again very limited. However, all holes intersected sand and gravel sediments that increase in thickness towards the Keep River. The most eastern hole, drilled to 100 m, failed to fully penetrate a sequence of sands, gravels, and pebbles, which are probably part of the Keep Inlet Formation. The company reports do not refer to the occurrence of groundwater or its quality.

2.5.5 Keep River Plain

Before the 1994 investigation program, the nine investigation bores drilled for water resources were RN5181, RN5669, and RN7859 to RN7865. In addition, petroleum exploration companies had completed three bores. PAWA conducted Ground Penetrating Radar (GPR) on several test lines, following the QUESTEM aerial survey. The method used reflects a high-frequency wave (25Mhz) from the subsurface at varying strength depending on layering, but the conductive nature of the black soils covering most of the area limited penetration to about 5 m. This precluded mapping of watertables and hydrogeological structures. There were no definite conclusions about the ability of the method to define thickness of black soil. PAWA undertook 12 joint DC resistivity and Sirotem soundings on the Weaber and Keep River Plains (section 2.2.4).

Along two of the GPR traverses, profiles were run with EM31 (depth of investigation about 5 m) and EM34 (about 20 to 30 m for vertical coils and 30–40 metres for horizontal coils). Unfortunately, airborne data were not available for the EM traversing, which consequently was not concentrated on the best targets. The EM31 showed a conductive response on black soils and resistive response on the red and sandy soils and proved an effective soil-mapping tool (Humphreys *et al.*, 1995).

The results from the EM34 reflected variations in soil type, soil thickness, and groundwater depth and quality. Although the EM34 horizontal-coil geometry was noisy, the profiles did show good correlation with the airborne EM data. The vertical-coil geometry is a shallower focussed configuration, and has closer correlation with the EM31 data. Overall, the EM34 did not provide additional information (Humphreys *et al.,* 1995).

In the 1994 program, PAWA in conjunction with the Western Australia Department of Resources Development and GSWA drilled 13 investigation holes to depths of 55.5 m using rotary air and mud methods (Humphreys *et al.,* 1995). These were RN29516 to RN29519, RN29650 to RN29654, RN29657, and RN29663 to RN29666. The initial drilling was concentrated along the QUESTEM geophysical profiles and at joint DC resistivity and Sirotem sounding locations. Bores were air-drilled for quick and basic information to obtain some stratigraphic control in the study area. The latter part of the drilling phase aimed to delineate the palaeochannel aquifer and to establish sampling points for water levels and quality.

2.5.6 Carlton Plain

In 1964, the PWD established 17 piezometers, Y1 to Y17, which they subsequently redrilled to a maximum depth of 17 m and completed with PVC casing in 1978. The auger rig had difficulty penetrating the large gravels, consequently, the material described as bedrock may be coarse gravel. The monitoring does appear to provide reasonable groundwater level and salinity data. Monitoring of water levels and electrical conductivity has been carried out since 1983, although by 1986 only 14 of the piezometers were serviceable (McGowan, 1987). In 1994, six bores were drilled using reverse circulation techniques to a maximum depth of 24.5 m, including five redrills, and piezometers installed at CP1, Y1A, Y3A, Y10A, Y16A, and Y17A (Nixon, 1997c).

During the 1980s, the Broken Hill Pty Co Ltd and Carr Boyd Minerals Ltd held temporary exploration reserves over the Carlton Plain and adjoining areas for diamonds and other minerals. They carried out the main exploration drilling programs in 1981 and 1982 with the main alluvial testing program in the southeast, between House Roof Hill and the Ord River, and to the west-northwest of House Roof Hill. A component of the program was drilling to test magnetic anomalies and the Ord River alluvial gravels. They drilled additional holes on the southern side of the Ord River to the southeast of False House Roof Hill, and a series of holes to test various magnetic anomalies mostly outside the Carlton Plain.

In 1981, the drilling of 40 narrow diameter test holes investigated the alluvium in the southwest and western part of the plain, and 32 test holes investigated the southeastern area (Paterson, 1982a). The deepest hole in the western area penetrated alluvial sediments and bedrock to 24 m with the thickest sand and gravel sequence being 15 m. Many holes did not reach the target bedrock because of caving gravels. In the southeast, the drilling did not intersect alluvium and generally penetrated bedrock described as shale at shallow depths.

The magnetic anomaly drilling generally intersected bedrock, usually basalt, at depths of 2 to 11 m with little or no minor alluvium being penetrated (Paterson, 1982b). They provided extremely brief geological logs with no geophysical logs to assist interpretation, and no water levels.

2.5.7 Mantinea Flats

Only limited data on some pastoral water bores drilled pre-1960 are available for the period up to 1994. Apart from drillers' logs referring to eleven metres of overburden (as 'levee soil') in the Bend of the Ord Bore, it is understood that the Western Australian Public Works Department bores drilled in the 1960s were abandoned with positions unknown. In 1994, three piezometers were drilled and completed (MP1, MP4, and MP6) with a further six (MP2, MP3, MP5, MP7, MP8 and MP10) in 1996 (Nixon, 1997d). The bores were drilled to a maximum depth of 28 m using reverse circulation in 1994, and mud rotary techniques in 1996.

Mining companies have carried out only limited exploration. During the 1980s, Broken Hill Pty Co Ltd and Carr Boyd Minerals Ltd held temporary exploration reserves, for diamonds and other minerals, which extended onto the Mantinea Flats. The reserves lay between the Bend of the Ord Bore in the east and Wild Goose Lagoon in the west and extended beyond the plain to the south. Mineral exploration south of the Ord River and to the east of the plain provides no relevant information.

BHP and Carr Boyd carried out drilling programs to test magnetic anomalies and sample the Ord River alluvial gravels. Drilling on the Mantinea Flats was limited to four rotary air blast (RAB) holes around a magnetic anomaly. The drilling intersected bedrock, described as shale, at depths ranging from 5 to 8.5 m (Paterson 1982a,b), but there is no description of the overlying overburden.

3 Geology

3.1 Introduction

Cainozoic surficial sediments, mainly alluvium derived from the Ord and Keep Rivers, and consisting of river gravel, sand, weakly cemented sandstone, silty clay, and clay, rest on a palaeo-topographic surface of Proterozoic and Palaeozoic sedimentary and volcanic rocks beneath the main irrigation areas. Proterozoic and Palaeozoic rocks crop out in adjoining ranges, as inliers within the irrigation areas, and within the bed of the Ord River. They consist of massive quartz and feldspathic sandstone and conglomerate, siltstone, and shale of Proterozoic age, and basalt, sandstone, conglomerate, limestone, and shale of Palaeozoic age.

Hardman (1885), who accurately outlined the geology of the East Kimberley, first described the bedrock geology. The first stratigraphic study of consequence in the Ord and Bonaparte Basins was by Matheson and Teichert (1946), and this was extended by Traves (1955). Guppy *et al.* (1958) subdivided the Kimberley Basin sediments and Harms (1959) extended their work. Veevers and Roberts (1968) wrote a detailed report on the Upper Palaeozoic rocks in the Bonaparte Gulf Basin.

The Ord River Irrigation Area falls on two 1:250 000 geological sheets with explanatory notes. These are the WA sheet CAMBRIDGE GULF, SD/52-14 (Plumb and McGovern, 1968) with explanatory notes (Plumb and Veevers, 1971), and the NT sheet AUVERGNE, SD/52-15 (Pontifex *et al.*, 1968) with explanatory notes (Pontifex and Sweet, 1972).

Whitehead and Fahey (1985) reported on the geology of the Keep River National Park, and the geology of the Onshore Bonaparte and Ord Basins in Western Australia has been comprehensively revised (Mory and Beere, 1988). The GSWA Memoir 3 includes summaries for the Bonaparte Basin (Mory, 1990a), Ord Basin (Mory, 1990b), Kimberley Basin (Griffin and Grey, 1990a) and the King Leopold and Halls Creek Orogens (Griffin and Grey, 1990b).

The map of the bedrock geology (Plate 1) has been complied from these sources with modifications based on the results of the recent drilling programs and an earlier geophysical survey (World Geoscience Corporation Ltd, 1994). The stratigraphic nomenclature and rock descriptions are summarised in Table 3.

3.2 Proterozoic and Palaeozoic bedrock

3.2.1 Stratigraphy

The oldest rocks in the region are the Proterozoic rocks of the Kimberley Basin (Fig. 4). These are located to the west of the northern Ivanhoe Plain and underlie the Carlton Plain and Mantinea Flats. Parts of the southern Ivanhoe Plain and the Packsaddle Plain overlie Early to Middle Proterozoic rocks of the Victoria Basin. Most of the Ord River Irrigation Area overlies bedrock within the Palaeozoic Bonaparte Basin, which plunges to the

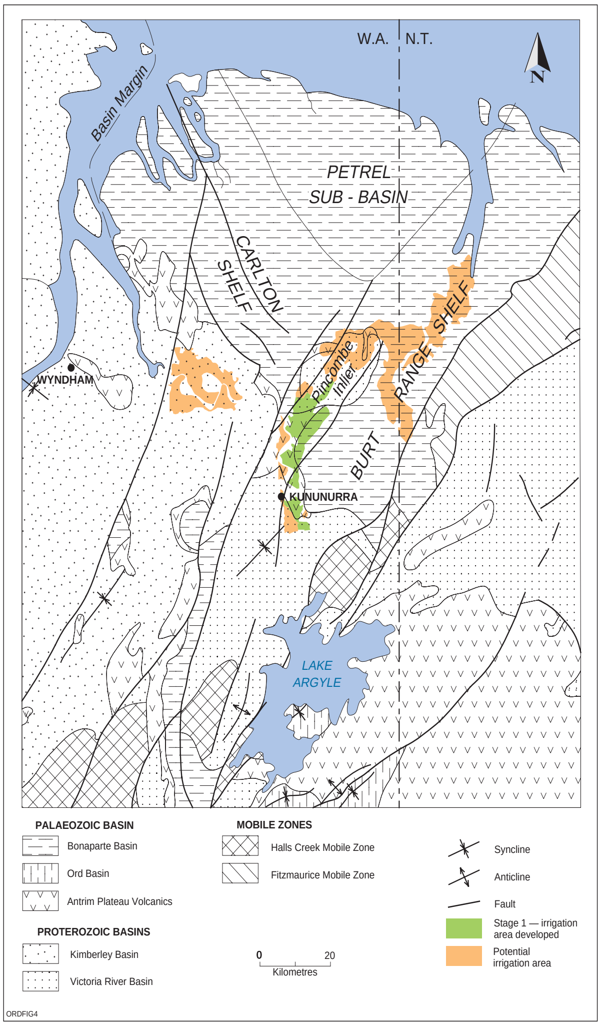


Figure 4. Tectonic units and basin subdivisions (after Mory and Beere, 1998)

Table 3. Summary of bedrock stratigraphy

Era	*Period*	*Stage*	*Group*	*Formation/Member*
Palaeozoic	Permian			Keep Inlet Formation (WA) / Kulshill Formation (NT)
	Carboniferous	Late Carboniferous Visean	Weaber	Border Creek Member Point Spring Sandstone Burvill Formation Milligans Formation
		Tournaisian	Langfield	Septimus Limestone Enga Sandstone Burt Range Formation
	Late Devonian	Fammenian	Ningbing	Buttons Formation
		Frasnian	Cockatoo	Hargreaves Formation Cecil Sandstone Abney Sandstone Kununurra Formation Kellys Knob Sandstone Steeple Peak Sandstone Ragged Range Conglomerate
	Cambrian	Late Cambrian	Carlton	Clark Sandstone Pretlove Sandstone Skewthorpe Formation
		Middle Cambrian		Hart Spring Sandstone Tarrara Formation
		Early Cambrian	Goose Hole	Antrim Plateau Volcanics
Proterozoic	Early to Middle Proterozoic		Carr-Boyd	Bandicoot Range Beds Pincombe Formation Stonewall Sandstone
	Early Proterozoic		Bastion	Cockburn Sandstone Wyndham Shale Mendena Formation
			Kimberley	Pentecost Sandstone Elgee Siltstone Warton Sandstone Carson Volcanics King Leopold Sandstone

Note: \`\`\`\`\`\`\`\`\`\`\`\`\`\`\`\` unconformity north and forms a broad downwarp containing the main belt of Phanerozoic outcrop. At the base of the succession are the Antrim Plateau Volcanics, continental tholeiitic basalt of Early Cambrian age.

The Early Proterozoic Kimberley Group occurs to the west of the northern Ivanhoe Plain, and to the north of the Carlton Plain, and consists of quartz sandstones and red siltstone. The Bastion Group underlies the Carlton Plain and Mantinea Flats alluvium and consists of alternating shale and quartz siltstone of the Mandena Formation, shale and siltstone of the Wyndham Shale, and massive quartz sandstone forming the Cockburn Sandstone.

The younger Victoria Basin rocks are Early to Middle Proterozoic age. These rocks are located to the west of the Packsaddle Plain, in the southern Ivanhoe Plain, and between the Ivanhoe Plain and Weaber Plain, and form the Pincombe Inlier, which comprises the Pincombe Range and Cave Range. They include the Carr Boyd Group, which generally consists of quartz siltstone and sandstone. The oldest formation in the Group is the Stonewall Sandstone, a quartz and feldspathic sandstone, which is overlain by siliceous siltstone of the Pincombe Formation. The youngest rocks are Bandicoot Range Beds consisting of quartz sandstone and a clayey sandstone conglomerate with massive, highly ferruginous sandstone interbeds.

At the base of the Palaeozoic Bonaparte Basin sequence is the Cambrian Antrim Plateau Volcanics, which underlies the alluvium beneath most of the Ivanhoe Plain and the southern Weaber Plain. This unit consists of predominantly massive, vesicular, amygdaloidal and porphyritic basalt with minor agglomerate, siltstone, sandstone, tuff and chert. The basalt crops out at Dumas Lookout on the Ivanhoe Plain.

The predominantly silty sandstone Cambrian Carlton Group is found to the northwest of the Ivanhoe Plain and west of the Weaber Plain. It conformably overlies the Antrim Plateau Volcanics. The Carlton Group consists, in ascending order, of the Tarrara Formation Siltstone, Hart Spring Sandstone, the sandstone of the Skewthorpe Formation, Pretlove Sandstone, and Clark Sandstone.

The predominantly quartz sandstones of the Late Devonian Cockatoo Group unconformably overlie the Cambrian rocks. The Cockatoo Group is present in the south of Packsaddle Plain, then trends northwards in the east of the Ivanhoe Plain and northwest across to Knox Creek. The group also outcrops in the southwest of the Knox Creek Plain. The Cockatoo Group consists, in ascending order, of the Ragged Range Conglomerate, Steeple Creek Sandstone, Kellys Knob Sandstone, Kununurra Formation, Abney Sandstone, Cecil Sandstone, and the Hargreaves Formation.

The Late Devonian Ningbing Group is a limestone reef complex that outcrops in a narrow north-northwesterley trending belt from Eight Mile Creek to Sorby Hills and also east of the Weaber Plain around Sandy Creek. Local disconformities and rapid lateral changes in facies cause variations in thickness. Five formations make up the group with only the Buttons Formation differentiated from Eight Mile Creek to Sorby Hills.

The Langfield Group and overlying Weaber Group represent the Carboniferous Period. The Langfield Group is present from the southern Knox Creek Plain northwards to Sorby Hills. Three units are present, which, in ascending order, are the Burt Range Formation limestone, Enga Sandstone, and Septimus Limestone. The Weaber Group is present across the Weaber Plain, Knox Creek Plain, and the eastern Keep River Plain. The group is about 2500 m thick with the shale-dominated Milligans Formation at the base coarsening upwards into the sandstone dominated Burvill Formation, and the Point Spring Sandstone, which includes the Border Creek Member.

The Late Carboniferous to Early Permian sequence is referred to as the Keep Inlet Formation in WA and the Kulshill Formation in the NT. The sequence consists of sandstone, shale, and minor conglomerate.

3.2.2 Structure

The area includes parts of four major tectonic divisions. Part of the Victoria River Basin, the Sturt Block and the Fitzmaurice Mobile Zone flank the Bonaparte Basin in the east. To the south of the Bonaparte Basin lies Halls Creek Mobile Zone, a fault-bounded belt of relatively highly deformed rocks, and to the west, lies the Kimberley Block (Fig. 4).

The structure of the region is dominated by an anastomosing set of left-lateral wrench faults that trend north-east, such as the Ivanhoe Fault, and secondary folds and reverse faults of similar trend. Plumb and Veevers (1971) have postulated large horizontal displacements of up to 80 km and large vertical displacements. Superimposed on these are northwest-trending normal faults and folds largely related to vertical block movements on the margins of the Bonaparte Basin. Intermittent movements, particularly on wrench faults (Plate 1), have occurred over a long period.

3.2.3 Pre-Cainozoic geological history

The geological history of the area in which the Ord River Irrigation Area lies is complex (Fig. 4). Folding of the Early Proterozoic sediments of the of the Halls Creek Group into a zone of intense metamorphism formed the Halls Creek Mobile Zone, part of which is located southwest of Packsaddle Plain. Considerable igneous activity in and around this zone preceded uplift and erosion followed by subsidence of the Kimberley Basin in which about 5000 m of sediments were laid down (Plumb and Veevers, 1971). Further intense movements in and near the Halls Creek Mobile Zone preceded subsidence between marginal faults and the deposition of about 9000 m of sediments of the Carr Boyd Group in the Early to Middle Proterozoic. At about the same time, thick arenaceous deposits accumulated in a basin and were subsequently folded and faulted to form the Fitzmaurice Mobile Zone to the east of the project area (Pontifex and Sweet, 1972).

The evolution of the onshore Bonaparte Basin is tectonically linked to rifting events of the northwest Australian continental margin and periodic reactivation of the Halls Creek Mobile Zone faults, which influenced Phanerozoic sedimentation (Mory and Beere, 1988). Cambro-Ordivician deposition occurred in the resulting intracratonic basin with extensional tectonics permitting the extrusion of about 1000 m of tholeiitic basalts, the Antrim Plateau Volcanics, which flowed over much of the terrain in the Lower Cambrian. Some 1000 m of sediment, the Carlton Group, was deposited in the Upper Cambrian and Lower Ordovician in continental and shallow-marine environments, with the basin probably being uplifted at the same rate as global sea level rise. An erosion or non-deposition hiatus then intervened until the Middle Devonian during pre-rift arching (Mory and Beere, 1988).

A complex pattern of subsidence and uplift occurred during the Late Devonian to Late Carboniferous. Frasnian to Westphalian deposition took place adjacent to the Halls Creek Mobile Zone (Mory and Beere, 1988). The development of the Bonaparte Basin includes deposition of about 1600 m of continental to shallow-marine clastics of the Cockatoo Group and 2000 m of marine carbonate and clastics of the Ningbing and Langfield Groups. There followed localised uplift associated with the Halls Creek Mobile Zone. Then rapid subsidence and deposition of 2500 m of deltaic basin fill formed the Weaber Group. A subsequent period of uplift erosion and faulting may represent pre-rift arching. This was followed by the deposition in episodes of at least 250 m of shallow-marine and continental sediments in a graben sub-parallel to the Halls Creek fault system to form the Keep Inlet Formation.

3.3 Cainozoic superficial deposits

The results from investigations over the Ord River Irrigation Area have proved the presence of substantial deposits of unconsolidated sediments (Plate 2). Across the black soil plains, sediments fill valleys that have been cut into the bedrock. The sediments generally fine upward with basal sands and gravels overlain by sand, red silty sand, silt and, finally, black soil. The sediments generally range up to 30 or 40 m in thickness except on the Carlton Plain and Mantinea Flats, where the valley fill is shallower (up to 20 m), but laterally more extensive.

In order to simplify the information derived from the geological borehole logs, this Report uses four major units to classify the fining upward sequence of sediments (Table 4). The geological sections (Plate 2) show these units, together with calcrete. This is an interpretation based on geological borehole logs logged at different times and for different reasons, and is necessarily generalised. Grain size is the basis of classification, and hence the 1:125 000 map (Plate 2) depicts hydrogeological characteristics and the most permeable sediments preferentially, irrespective of depth.

The source of most of the sediments is the Ord River catchment, which sits astride the Western Australia–Northern Territory border. Geological logging of the drillholes has provided firm evidence that erosion of Proterozoic and Palaeozoic rocks in the Ord River catchment has supplied most of the alluvial material underlying the ORIA plains. The Knox Creek Plain alluvium is derived from the Keep River. A suggestion

Table 4. Classification of unconsolidated sediments

Section	*Map*
Clay, silt, clay soil	This groups soil, clay sediments and at some locations minor silt.
Silt, sandy silt, silty sand, in places altered to calcrete	Dominated by silt, but containing lenses of silty sand and sandy silt.
Sand	Typified by lenses of sand and minor gravel, this may be less extensive or continuous than the sand and gravel unit and have a higher silt content.
Sand and gravel	Sand and gravel consisting of at least 2 m of non-clayey sand and gravel, somewhere within the alluvial sequence

by Carroll (1947) that Eight Mile Creek was a former course of the Ord River is unlikely because of the elevated nature of the watershed.

Layered alluvial sequences deposited by former courses of the Ord River dominate the sediments of the Ord River Irrigation Area. The thickest of the sediments are palaeochannel deposits, which have a maximum identified thickness of 42 m in WP 12 under the Weaber Plain. The deepest deposits at the base of the palaeochannel are typically coarse, well-rounded sands and gravels with cobbles up to 70 mm in diameter. Sand and gravel deposits higher in the sequence are also associated with former courses of the Ord River. The sources of the clay and silt deposits that lie away from the main Ord River channel result from periods of flooding and inundation. The lithology of all these sediments is consistent with exposed bedrock in the modern Ord catchment.

At the top of the sequence are swelling clays, which are typically dark grey, brown or bluish black, ranging in thickness to 5 m, and known colloquially as ‘black soil plains’. The clays form two main soil types; Cununurra Clay, which is moderately swelling, and Aquitaine Clay, which is a highly swelling clay. When these clays dry out, large cracks form that can extend to several metres in depth. Clays which lie directly over bedrock are either alluvium, colluvium or derived from the weathering of the bedrock profile. Clay derived from the local weathering of bedrock is generally found close to outcrops, and where the bedrock is shallow.

The thickness and position of the sequences vary greatly, with sands and gravels commonly present to within metres of the surface; lenses of silt within sand and gravel are common. Where bedrock is shallower, coarser sediment may be entirely absent.

The Weaber Plain has no major surface drainage that is active to account for the substantial thickness of unconsolidated sediments. The drilling evidence supports the suggestion of Gunn (1969) that the Ord River flowed through Cave Spring Gap out across the Weaber Plain to the Keep River Plain before discharging into the sea. A westward-flowing stream then captured the Ord River and it now follows along its present course to Cambridge Gulf. The former course of the Ord River is a meandering palaeochannel, masked by the Weaber Plain (Plate 2), the base of which is shown by the bedrock contours on Plate 1.

3.3.1 Depositional models

3.3.1.1 General model

The deposits along the courses of the Ord River, Knox Creek, and Keep River are consistent with deposition in a fluvial environment, and many of the features of meandering rivers can be recognised (Fig.5).

In this model, floodplain rivers are active streams that flow in a definite channel. Natural levees border the meandering channels on each side and consists of low, rounded ridges of very fine sand and coarse silt. The channel and its flanking natural levees form the meander belt, and flood plains extend from the meander belts to the lateral margins of the valley floor. During flooding, water covers the low, flat floodplain valley bottom. Flood basins or backswamps are closed depressions within the floodplain that may be under water for long periods.

Floodplain deposits consist of the contrasting suites of channel deposits, channel margin deposits, and overbank deposits. The channel deposits grow chiefly by lateral sedimentation, whereas overbank deposits accumulate by vertical sedimentation.

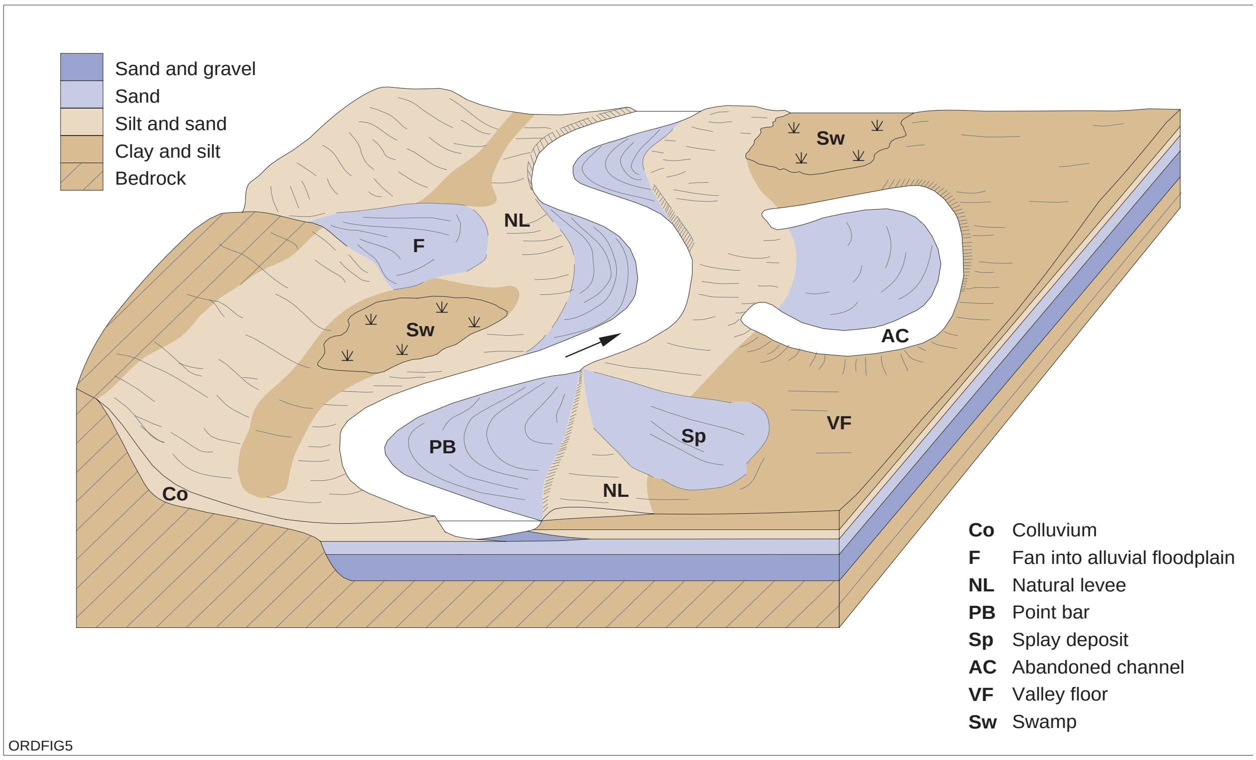


Figure 5. Depositional model for alluvium (after Friedman and Sanders, 1978)

Point-bar deposits and channel-floor lag are further subdivisions of the channel deposits. Point-bar deposits are crescent-shaped deposits built out from the convex bank of a meandering stream channel. The slip-off slope is the gently sloping side of the channel next to the point bar. The channel-floor lag forms at the very bottom of the channel and consists chiefly of pebbles and coarse debris, which spread as the meanders migrate down valley.

Natural levees and crevasse splays form at the margins of the channel. Natural levees build upwards uniformly as broad, shallow laminated sheets of silt and sand where flood water spills out of the channel. Sheet flows can easily become concentrated into channels and thus easily erode sediment, leaving gaps in the levee known as crevasses. Splays are lobate bodies of sediment deposited as a fan, which extends away from the crevasse.

Overbank deposits form when water flowing through crevasses or over natural levees or from tributary drainage combine to inundate the floodplain. The floodwaters, commonly containing much suspended sediment, may flow slowly down-valley or may become fully ponded, and deposit sheets of silt. After the flood, much of the water will disappear from the floodplain leaving only small lakes and swamps. Clays accumulate in the swamps and, if vegetation is abundant, the clays may contain much organic matter. The swamp deposits form thin pockets or lenses within the overbank silts. Abandoned meander channels (billabongs) are similarly filled.

3.3.1.2 Packsaddle Plain and Ivanhoe Plain depositional model

The deposition of sediments beneath the Packsaddle and Ivanhoe Plains results from the Ord River meandering across the plain and heading out through the Cave Spring Gap, eroding and forming the bedrock topographic surface (Plate 1, see back pocket). The channel contains preferentially eroded basalt and shale bedrock units. The Ord River deposited the coarse-grained sediments that generally exist lower in the sequence in high-energy channels meandering over the western portion of the plains. Deposition of the finer grained sediments has occurred in lower energy environments, such as the inside of channel bends. There have been many generations of channels with the base of the channel deposits occurring at various heights. The level of the modern Ord River is generally consistent with the top of the coarse gravels but lower than several sandy sequences. Above the height of the modern Ord River, sediments are dominated by overbank levee deposits, with minor drainage reworking the levees and depositing lenses of sand and fine gravel. Drainage outside the modern Ord River channel before irrigation was generally low energy, with local inundation of the plain forming a series of interconnected swamps in the wet season.

Sand and gravel, considered to be associated with high-energy channels, dominate sediments west of the M1 irrigation channel down to the Ord River. From the Stock Route road south to the Diversion Dam, there is a connection between these sediments and gravels in the bed of the modern Ord River. In places, bedrock underlies the modern Ord River channel, such as at Ivanhoe Crossing and Bandicoot Bar. In the north of the Ivanhoe Plain, the main channel diverges from the modern Ord River and heads out through the Cave Spring Gap and forms the Ord Palaeochannel.

There are also sandy sediments associated with a paleo-tributary flowing from the present day Martins Location area along the southeastern side of the Cave Spring Range to the Ord palaeochannel. These finer sandy sediments are consistent with a lower energy environment. East of the M1 supply channel sediments are dominated by overbank type levee soils, and farther east still, shallow weathering profiles are composed of clay. Clayey profiles over shallow bedrock dominate the Green Location area, although there is a transition area of levee type deposits between the clays in the north and the channel deposits from the Cave Spring Gap to Drovers Rest.

A small area of shallow levee sediments, within the main channel, surrounds outcropping basalt at Dumas Lookout and smaller outcrops to the west. On the West Bank of Ord, coarse channel deposits occur close to the river in association with levee deposits and clays. Bedrock outcrops to the north in the riverbed, and in the south close to the river.

Following diversion of the Ord River through Buttons Gap to the west, the river would have ceased to meander across the northern Ivanhoe Plain sooner than the southern Ivanhoe Plain. Consequently, exposure of the northern soils to weathering and pedogenesis for a longer period would have led to them being maturer than soils in the south (Aldrick *et al.,* 1990).

As the Ord River incised into its own meanders, there was a reduction in wet-season flooding across the Ivanhoe Plain, through Cave Spring Gap and onto the Weaber Plain. Terraces cut into the alluvium appear to have formed along the Ord River. In addition, it is likely that the sediments contained in the floodwater that overtopped the riverbanks would have become progressively finer. The diverted river would have deposited most of the coarser gravel and sand onto the Carlton Plain and Mantinea Flats where the younger depositional history is probably similar to that of the Ivanhoe Plain before the diversion of the Ord River.

Local opinion and geomorphic evidence indicate that even before the construction of the Ord dams flooding no longer occurred across the Ivanhoe Plain (Aldrick *et al.,* 1990). Burvill (1991) reached a similar conclusion, that the Ord River is entrenched in its own alluvium, and that the Ivanhoe Plain is a relict. However, it is possible that flooding of the Ivanhoe Plain still occurred, although much less frequently because of the river diversion and incision.

3.3.1.3 Weaber Plain and Keep River Plain depositional models

The depositional model proposed for the transport and deposition of sediments is a restricted high-energy palaeochannel flowing through the Cave Spring Gap out onto the Weaber Plain. The palaeochannel runs through the gap on less-resistive shale bedrock into which the Ord River has preferentially eroded and shaped the bedrock topographic surface between resistive sandstone units. Sediments within the Cave Spring Gap are coarser, which is consistent with an environment high in energy. The sandstone units dip to the southeast, resulting in the superficial sediments on the southeastern side of the Gap being deeper where the palaeochannel has preferentially eroded the shale. Silt, sand, and minor clay levee deposits are present on the northwestern side of the gap overlying the shallow sandstone bedrock. On the southeastern side coarser alluvial deposits are present with typically around 10 m of clean, coarse sand and gravel at the base of the sequence

As the Ord palaeochannel emerges from the Cave Spring Gap beneath the modern Weaber Plain, the channel widens creating a lower energy environment. This facilitated the deposition of finer sediments containing higher percentages of silt and clay, such as intersected in bores WP2, WP3, and WP4. The main course of the Ord palaeochannel then proceeds south of Brown Ridge (Folly Rock); however, it is possible that channel sediments may also be present around the western and northern sides.

Just west of Brown Ridge, along the access road to Point Springs, an accumulation of fine sediments dominates in bores to a depth of 20 m. These were probably deposited as levees in a low-energy valley environment between Brown Ridge and the bedrock ridge expressed as two unnamed outcrops 500 m to the east of the access road. The valley is a tributary of the main channel, which is present to the east of the bedrock ridge.

A tributary of the main Ord palaeochannel exists north of Folly Rock, draining a catchment bounded by bedrock of the Pretlove Hills, Hargreaves Hills, and the south Ningbing Range to the north and west. Further drilling is required to refute the possibility that a channel running west of Folly Rock was originally the main course of the Ord palaeochannel. From the confluence of the Sandy Creek tributary, the main Ord palaeochannel has cut a broader channel south of the Weaber Range into the shale bedrock, which is less resistive to erosion than the surrounding bedrock units. Here, the meandering Ord River deposited alluvium, with basal sandy gravel, across a broader front.

Where the channel is deepest in the northeast of the Weaber Plain, the base of the channel is 25 m below Australian Height Datum (AHD), indicating a lower sea level during erosion and sediment deposition. As sea levels rose, channel gradients reduced causing a gradual reduction in the energy of the depositional environment and a fining of the deposited sediments. The palaeoriver valleys gradually filled with overbank levee deposits with minor drainage reworking the levees, depositing lenses of sand and gravel. It is probable that, later, the Ord River overflowed from the Ivanhoe Plain at Drovers Gap, creating a new outlet through the Carlton Plain and Mantinea Flats and consequently incising the Ivanhoe Plain.

The modern Weaber drainage is mostly a very low energy environment. Inundation of the plain from rainfall and local streamflow runoff during the wet season feeds a series of interconnecting swamps. The low energy system has lead to the formation of the black soils — the Aquitaine Clays. These are essentially swamp mud deposits located in the lowest areas of the plain with a height variation of only several metres in tens of kilometres. The occurrence of weathered clays above shallow bedrock is largely from weathering in situ and local transport of these materials. The largest area mapped as clay on the Weaber Plains is to the west of Brown Ridge where the area is dominated by shallow bedrock, clayey weathering profiles and alluvial clays.

East of Sorby Hills, weathered Milligans Shale, that flanks the Permo-Carboniferous sandstone straddling the State border, forms an area of shallow clay. Similarly, east of the Pincombe Range and Sorby Hills, carbonate-rich clay about 6 m thick is derived from the weathering of Devonian and Carboniferous dolomitic limestone.

On the Keep River Plain, drilling has delineated a valley incised into the bedrock and filled with alluvium beneath the black soil plains. The main trunk valley runs from west to east from the Weaber Plain in Western Australia and is a continuation of the former course of the Ord River, the Ord palaeochannel. Where it crosses the border, it is about 3.5 km wide and may reach 35 m in depth. The valley then passes beneath the present-day Keep River and runs in a general northeasterly direction parallel to and east of the Keep River. It widens to a maximum of about 7 km and is about 40 m below ground level at its deepest point at the northern end of the plains. West of the Keep River, erosion has cut the valley predominantly into shale of the Milligans Formation, whereas to the east, the valley is in Permo-Carboniferous sandstone. The valley-fill sediments comprise two main units: an upper clay sequence underlain by sand and gravel. Every borehole drilled intersected these units in the deeper sections of the valley.

The sands and gravels which form the bulk of the fill are channel deposits of high-energy streams, whereas the overlying clays and sandy clays represent overbank environments such as levee and floodplain. Remnants of broad abandoned channels with long-wavelength meanders and meander scrolls is evidence for past tidal influence because their geometry is similar to the tidal section of the present day Keep River. These are visible on aerial photographs and satellites images of the floodplain but are generally not obvious on the ground. The abandoned channels can be traced some 5 to 10 km upstream of the present-day tidal limit and probably extend across the border into Western Australia (Humphreys *et al.,* 1995).

The Keep River Plain lie between 10 and 20 m above mean sea level, even in those areas known to have formed under tidal influence. An explanation for this relatively high elevation is that the area has undergone regional tectonic uplift in recent geological times (Humphreys *et al.,* 1995). This may also have provided a mechanism for the dramatic shifting of the course of the Ord River from the Keep River outlet to its present outlet in the Cambridge Gulf. Alternatively, a decrease in tidal amplitude may have caused progressive infilling of the estuary by sediments (Wright *et al.,* 1972), although this mechanism is less likely than tectonic uplift because the magnitude of the emergence seems too great.

3.3.1.4 Knox Creek Plain depositional model

The geological model proposed for the deposition of the sediments on the Knox Creek Plain is that of a low-energy fluvial environment largely coincident with the modern Keep River. Initially, the former main channel preferentially eroded the least resistant bedrock units and deposited coarse-grained sediments along the main channel. Overlying the coarse sediments of the main channel are finer grained natural levee deposits with lenses of fine sand formed from minor reworking of the levee material. Wet-season deposition of silty overbank sediments occurs in the low-energy environment outside the main channel of the modern Keep River. This low-energy system has led to formation of the black soils, the Cununurra Clays. The derivation of clays above shallow bedrock is largely from bedrock weathering in situ and local transport of weathered bedrock material. The Knox Creek Plain differs from the other areas described in this Report, because the Keep River catchment is the predominant source of the alluvium, although the Keep River catchment contains a suite of rocks similar to those in the Ord River catchment.

3.3.1.5 Carlton Plain and Mantinea Flats depositional model

Burvill (1991) noted that on the Mantinea Flats the river levee is the highest level from the Ord River to the southern foothills, and that during the wet season at least ten large southern hills watercourses flood the Mantinea Flats. The flood waters find their way into the old river meanders and swamps via Salt Creek and Goose Hill Creek and finally to the river estuary or the tidal flats. Pre-1972, the Ord River sometimes over-topped the levees at the Bend in the Ord and flowed along the flood channel system. When this occurs, areas of black soil are flooded. On these occasions, Mantinea Creek also changed direction and fed into the flood channel area.

Seasonal flooding is quite extensive, which probably accounts for the alluvial deposits east and north of Goose Hill having an irregular surface. The plains are about 10 m above mean sea level and within about 3 m above high tide level. If there had been regional tectonic uplift, the Ord River would have incised into the alluvial plain. Moreover, there is some evidence that the river has transported coarser material farther downstream before deposition over tidal flats. Evidence from drilling investigations suggests that there was later fluviatile deposition of finer material over this gravel.

The sediments increase in thickness westwards and range up to about 25 m in thickness. Dominating the sediments are upward-fining fluviatile depositional sequences. Gravels lie directly on bedrock over much of the plains. In addition, coarse sand and gravel colluvium is probably present at the base of slopes, such as House Roof Hill. Above the gravels, river sands grade into fine sands associated with natural levees. The upper part of the sequence is dominated by overbank silts. Swamp mud clays and clayey soils are present on the northern and southern extremities of the plain.

Before the diversion of the Ord River, the small catchment serving the present Carlton Plain and Mantinea Flats would have accounted for only minor fluviatile deposition. However, there is no clear evidence that other depositional environments are present. Much of the sediment, therefore, probably postdates diversion of the Ord River from its previous course through Cave Spring Gap.

3.4 Soils

Burvill (1991) undertook the first soil survey, and since then a further seven major surveys have been carried out (Aldrick and Moody, 1977; Aldrick *et al.,* 1990; Dixon, 1996; Schoknecht and Grose, 1996a,b,c; Schoknecht, 1996). The surveys have shown that cracking clays belonging to the Cununurra and Aquitaine families are the dominant soils within the project area. The main irrigated soil is the Cununurra family, consisting generally of a black cracking clay in which the dominant mineral is montmorillonite. The Aquitaine family, a blue to grey cracking clay is also widespread and occurs in areas of prolonged wet-season inundation. The black soils are generally thin and overlie older red brown alluvium and most basement rock types. Minor associated soils are better drained, medium-textured loamy soils occupying river levees, ideally suited for intensive horticultural development, and the Cockatoo Sands, which are formed on colluvial deposits flanking the sandstone ridges and used for horticultural crops under spray irrigation.

Burvill (1991) suggested a lacustrine origin for the plains because of the uniformity of the clay soils. However, the overall fall of the plains is probably too great, soil textures too coarse and subsoil colours too reddish (Aldrick and Moody, 1977). In addition, recognition of old meanders, remnant channels, levees, and river gravels on the plains confirm fluviatile sedimentation. An inspection of the reddish material underlying the soils shows the substrate is generally suitable for the formation of cracking clay soils. Aldrick *et al*. (1990) postulates that the soils are uniformly 1.2 to 1.5 m deep because that represents

Table 5. Classification of soils (after Aldrick *et al.*, 1990)

Family	*Phase*	*Colour*	*Drainage*	*Parent material*	*Location*
Cununurra (cracking clays)	Normal	Dark	Poor	River alluvia	Plain
	Darker	Darker	Very poor	River alluvia	Seasonal inundations
	Eroded	Browner	Better drained	River alluvia	Erosion gullies
	Alkaline	Brown	Imperfect to poor	Recent river alluvia	Plain
	Leached	Grey	Poor to very poor	Old river alluvia	Plain
	Wetter	Grey	Very poor	River alluvia	Around swamps and flat interfluves
Aquitaine (cracking clay swamp soils)	Bluish	Blue	Very poor	Old river alluvia	Swamps, inundation prone plain margins
	Greyish	Grey	Very poor	River alluvia	As above, but lesser inundation
	Olive-yellow	Dark greyish -brown	Very poor	River alluvia	As above, but adjoin sandier country
Keep (cracking soils)	Normal	Dark brownish	Very poor	River alluvia	Inundated gilgai depressions.
	Flooded	Brown	Very poor	River alluvia	Small locally depressed swamps
Weaber (reddish soils, non-cracking)	Normal	Dark reddish -brown	Moderately to well-drained	Coarser river alluvia	Small areas of coarser alluvium
	Heavier	Dark reddish -brown	Moderately to well-drained	As above, finer more clayey	As above
Walyara (reddish soils, non-cracking)		Dark brown	Imperfect to poor	River alluvia	Levee remnants
Milligan (non cracking)				Fine textured with inclusions of ferruginous gravel and sand	Adjacent to sandy country
Mottled (cracking clays)		Dark, mottled			Seasonally inundated depressions between Milligan soils

the depth to which incident rainfall normally percolates, thus allowing pedogenesis to occur. The basic subdivision (Aldrick, *et al.*, 1990) of the soils is into cracking clay soils, seasonal swamp soils, and reddish soils (Table 5).

Cracking clay black soil belongs to a distinctive group present in all five continents in the tropics (Dudal, 1965). It is common in Australia, although not in WA where it is restricted to isolated areas in the northern part of the State (Hubble *et al.*, 1983). Complex pedological processes are involved in their formation over 5000 to 10 000 years, and particular conditions of climate are necessary for their development. The climate over northern Australia has been stable for the last 8000 years (Stocker, 1971) and the 740 mm of annual rainfall and a mean temperature of between 20 and 35°C satisfy conditions for the formation of cracking clay soils. The ORIA alluvium has fine texture and is rich in carbonates of magnesium and calcium, which allows ready release of these elements with weathering to maintain a high pH. These chemical conditions are ideal for the formation of montmorillonitic clays (Dudal, 1965; Buringh, 1968). The low permeability of the upper alluvium over the Ord River Irrigation Area restricts the removal of alkaline earths by leaching. In addition, the topography is relatively flat and natural rates of erosion low, so an extended period was available for the pedogenesis of cracking clays.

On the edges of the plains, seasonal swamps occupy broad land-locked areas and 'junction complexes'. The swamps receive material from runoff, including clays and sandy material depending on their situation, which produces minor variations in their pedological character. Although clay content is high (~70%) and permeability very low, the leaching of salts and other dissolved solids is intense (Aldrick *et al.,* 1990).

Reddish soils occur in areas of coarser alluvium on levees, point-bar sequences, sandy land systems, and junction complexes. Their coarseness precluded the formation of cracking clays and led to pedogenesis of a lateritic nature.

4 Hydrogeology

4.1 Introduction

The Ord River Irrigation Area is located within a complex topographical and geological system, which controls groundwater flow. Differences in subsurface stratigraphy and the resulting variations in hydraulic conductivity have a profound effect on local and regional flow systems. Geological heterogeneity affects the interrelationship between local and regional systems, the surficial pattern of recharge and discharge areas, and the quantities of flow that are discharged through the system.

Groundwater exists in the alluvial superficial deposits and in bedrock throughout the region, but the most important groundwater flow systems are in highly transmissive gravels, which directly underlie the irrigation areas. The bedrock in the ORIA varies from low-permeability shale aquitards to highly permeable cavernous limestone. The bedrock aquifers are generally less important, as they underlie either the alluvial aquifers or the elevated areas on the flanks of the irrigation areas.

The groundwater flow system in the Ord Palaeochannel gravels was previously largely controlled by recharge from the Ord and Keep Rivers. On the Packsaddle and Ivanhoe Plains, the raised level of Lake Kununurra, and leakage from irrigation channels, drains, and bays regime have substantially modified the groundwater system. On the northern Ivanhoe Plain, irrigation has created a groundwater divide; where once groundwater flowed from the Ord River through Cave Spring Gap, it now flows from the Ivanhoe Plain into the Ord River.

Hilly areas surround the black soil plains of the Ord River Irrigation Area. Groundwater recharges the hilly areas and moves towards the low-lying plains, where it discharges into rivers. Few data are available concerning the permeability of the bedrock flanking and underlying the alluvium of the black soil plains. Therefore, the study has used experience gained from the drilling and testing of similar rocks in the Kimberley to estimate hydrogeological characteristics of the ORIA bedrock.

The Permo-Carboniferous sandstone bedrock has moderate to high permeability and is probably in good hydraulic connection with the coarse alluvium on the eastern Knox Creek Plain and Keep River Plain. On the Weaber Plain and Knox Creek Plain the solution of Carboniferous and Devonian dolomitic limestone has produced moderate to high secondary permeability and low to high storage. The hydraulic connection with the overlying alluvium is unmapped, but is probably highly variable. The remaining Palaeozoic and Proterozoic bedrock generally has low permeability and storage, and poor hydraulic connection with the alluvium.

The presence of low-permeability bedrock underlying the alluvium limits groundwater throughflow from highland areas into the lowland alluvium, and the low-permeability soil in the upper alluvium also significantly limits recharge potential from rainfall. Therefore, pre-irrigation groundwater gradients are low and groundwater heads are at an elevation similar to the riverine groundwater recharge and discharge zones.

This Report bases the classification of the hydrogeological units on potential borehole yield from the alluvial superficial deposits and bedrock (Table 6, Plate 2 see back pocket). The distribution of the data

Table 6. Classification of hydrogeological units

Age	*Lithology*	*Permeability*	*Bore yield (L/s)*	*System*
Cainozoic	sand and gravel	moderate to high	5 to >25	aquifer
—superficial deposits	sand	moderate	>5	aquifer
	silt, silty sand, silty sand, calcrete	low	0.5 to 5	poor aquifer
	clay, silt, clay soil	very low	0.05 to 0.5	aquitard
Proterozoic to Permian	porous sandstone	moderate	>5	aquifer
—bedrock	limestone and dolomite	low to high	1 to >25	poor aquifer to aquifer
	basalt and indurated sandstone	very low to low	< 1	aquitard to poor aquifer

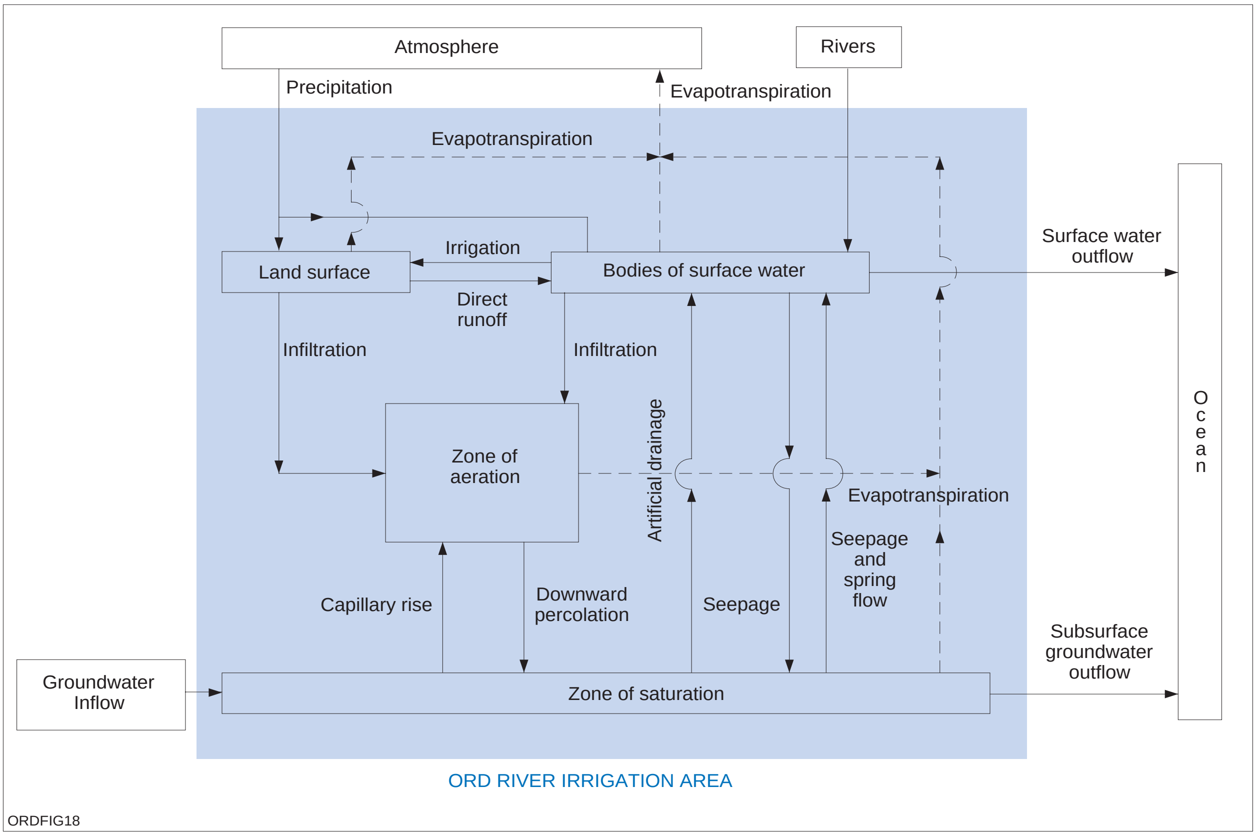


Figure 6. Water balance components (adapted from Todd, 1980)

and information used for the classification is not uniform. Hydrogeological information for the alluvial sediments have been derived from specific groundwater investigations, whereas information for the bedrock has largely come from mineral exploration and mining studies.

Drilling has led to a good appreciation of aquifer geometry, but the drilling coverage, and thus understanding, is far from uniform. Fewer than ten pumping tests have been undertaken to obtain aquifer hydraulic parameters. All the groundwater water balance components are open to interpretation, as there are few meteorological stations, river gauging stations and groundwater observation bores in some areas and groundwater recharge studies are also rudimentary. Figure 6 summarises the water balance components.

The monitoring data have enabled groundwater contours to be drawn for the black soil plains, although in some areas the contours are tenuous because of lack of data (Plate 2). Pumping tests indicate that the overlying fine-grained alluvium, silt and clay has a permeability several orders of magnitude lower than the sand and gravel. Generally, groundwater in the overlying silt and clay aquitard drains slowly downwards into the underlying basal sand and gravel where the groundwater then flows horizontally.

There is a wide variation in groundwater salinity across the Ord River Irrigation Area ranging from fresh, less than 1000 mg/L total dissolved solids (TDS), to saline of up to 35 000 mg/L TDS. Low-salinity groundwater is associated with recharge from the Ord River, channels, drains, and elevated areas of fractured rock. High salinity is associated with areas of low recharge, low permeability, groundwater discharge areas, deep groundwater systems in bedrock (such as Sorby Hills), shale, and proximity to the tidal flats (Fig. 7).

4.2 Packsaddle Plain and Ivanhoe Plain groundwater regime

4.2.1 Groundwater recharge, throughflow and discharge

Recharge from the Ord River largely maintained groundwater levels on the Packsaddle and Ivanhoe Plains before large-scale irrigation commenced in the 1960s. At times of flood, water from the river would flow into the basal sandy gravel aquifer across the northern Ivanhoe Plain, into the Ord Palaeochannel, through Cave Spring Gap, under the Weaber Plain, and out to the Keep River Plain.

The groundwater recharge component from rainfall falling directly onto the black soil plains of the ORIA is probably very limited. During the exceptional wet season of 1996/97, with rainfall of long duration and moderate intensity over large areas, there was an average groundwater level rise of 0.65 m in both the Ivanhoe and Packsaddle Plains (Fig. 8). This contrasts with normal years in which, when irrigation ceases, the groundwater level declines until the start of the next irrigation period, although there is some infiltration from local rainfall affecting groundwater levels during the wet season. In the natural environment, uptake by vegetation would be considerably greater than that from fallow irrigation bays in the wet season.

Pumping tests were carried out on Ivanhoe Plain test production bores PB1, PB2, and PB3 screened in the basal sand and gravel alluvial aquifer (McGowan, 1983). Transmissivity values ranged from 1700 to 7000 m^2/d, and estimates of specific yield ranged from 0.02 to 0.05. However, the specific yield was recognised as probably being too low and reflected the short-term nature of the analysis. Typically, the specific yield for unconsolidated fluvial sediments is between 0.05 and 0.2. The three-day test undertaken at PB1 showed that the cone of depression, although deepening, did not expand beyond the 1300 m measured after 7 hours, although test pumping continued for 72 hours. McGowan (1983) postulated that the cone of depression had intercepted a barrier boundary at 1300 m, probably the basalt bedrock of Dumas Lookout.

O'Boy (1997,1998) reported on pumping test results for test production bores PB4 on the Ivanhoe Plain and PSPB1 on the Packsaddle Plain, which were screened in the sand and gravel alluvium. The phase one Ivanhoe PB4 short-term pumping test indicated that delayed drainage effects from the overlying silt aquitard caused retardation of the expansion of the cone of depression. The calculated mean sand and gravel aquifer

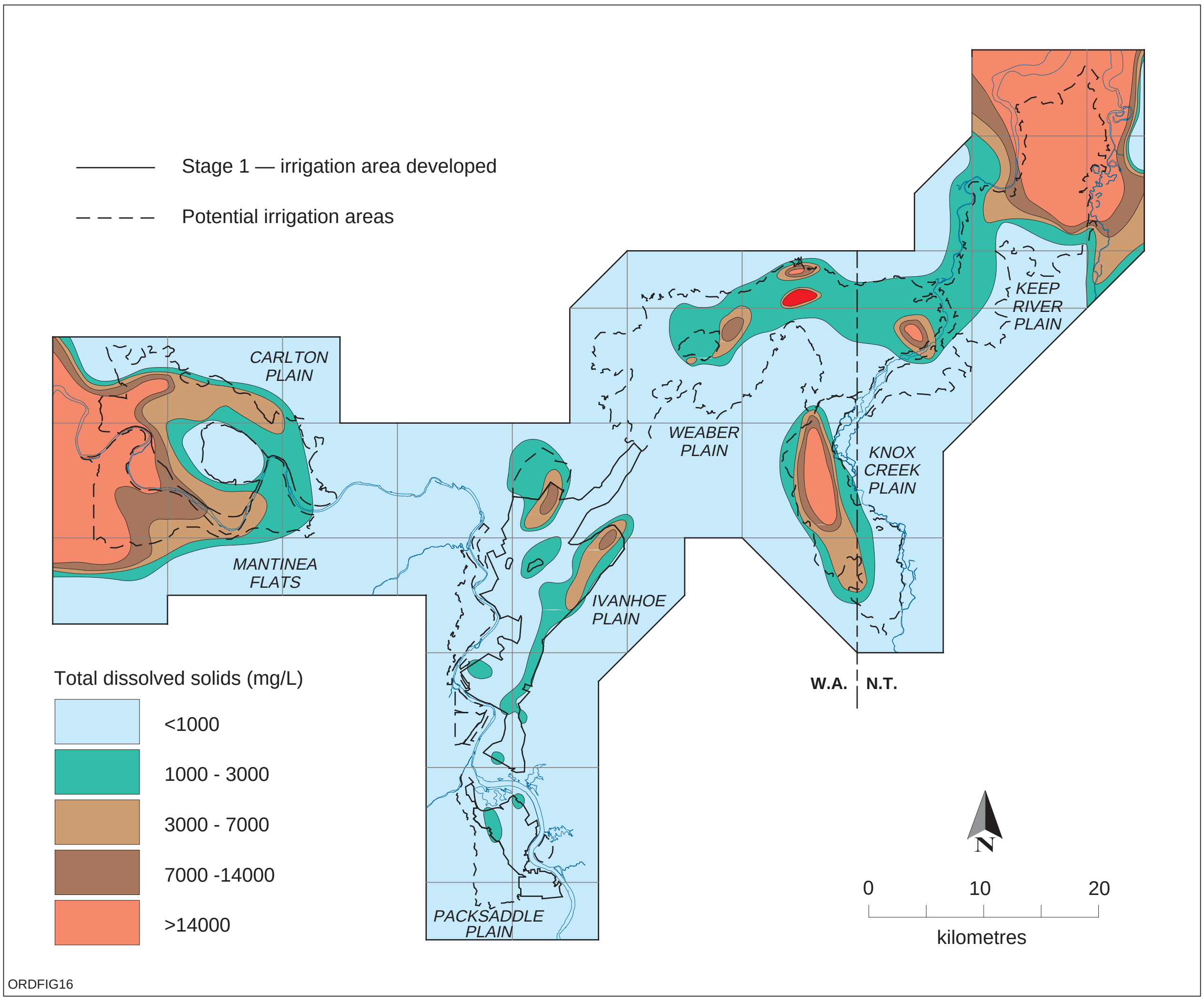


Figure 7. Groundwater salinity

transmissivity of about 2400 m^2/d gives a hydraulic conductivity of 400 m/d, assuming a 6 m-thick aquifer. The mean storativity is about $5x10^{-5}$, and the estimated vertical hydraulic conductivity in the clays, silts, and sands is about 0.01 m/d. Flow net analysis, discussed later, indicated that the contribution from the irrigation canal at the Ivanhoe site appears to have been limited to no more than 10 % of the test bore yield. The phase two long-term test indicated that barrier boundaries, associated with Dumas Lookout, caused additional drawdown.

The mean transmissivity of the deep gravel aquifer at Packsaddle is about 2000 m^2/d, which gives an hydraulic conductivity of 330 m/d assuming a 6 m-thick aquifer (O'Boy, 1997). The mean storativity is about $4x10^{-4}$. The estimate of vertical hydraulic conductivity in the upper clays, silts, and sands is about 0.1 m/d. The transmissivity of the shallow gravel aquifer is about 1000 m^2/d, which gives a hydraulic conductivity of 330 m/d assuming a 3 m-thick aquifer. The estimate of storativity is about $2x10^{-2}$. The long-term pumping test undertaken for 115 days on test production bore PSPB1 indicates that Packsaddle Plain groundwater levels are controlled largely by the water level in Lake Kununurra and associated wetlands, which form recharge boundaries. These recharge boundaries caused quasi-steady state conditions after a few days of pumping.

Since completion of the diversion dam, the water level in Lake Kununurra controls the overall groundwater regime on the Packsaddle Plain and southern Ivanhoe Plain (Plate 2). In the Packsaddle Plain, groundwater flows in the highly permeable basal sands and gravels from Lake Kununurra west towards Packsaddle Creek and then north under Packsaddle Creek towards the low-permeability bedrock of Bandicoot Bar. The bar acts as a barrier to groundwater flow and causes groundwater to flow west of the bar into the Dunham River alluvium, to then merge with the Ord River alluvium groundwater or discharge into the Ord River. The basal sands and gravels also receive groundwater that has leaked vertically through the overlying silt and clay from irrigation, the irrigation channel network, and minor direct rainfall.

Recharge from Lake Kununurra enters the highly permeable basal sands and gravels of the south Ivanhoe Plain. The groundwater then flows in a northwesterly direction and discharges into the Ord River. Seepage from the M1 supply channel in the central and northern Ivanhoe Plain has caused groundwater to flow in a westerly direction towards the Ord River, where it discharges. In addition, on the northern Ivanhoe Plain there is a groundwater mound, due to irrigation, from which groundwater flows in a northeasterly direction into Martins Location. To the north of this mound, the watertable is flat and groundwater drains west towards the Ord River, north into Green Location, and northwest into Cave Spring Gap. Significant basal sands are not present beneath southern Martins Location or Green Location and groundwater is slowly filling the alluvial sequence in these areas because of the low permeability. The basal sands and gravels also receive groundwater vertically from the overlying silt and clay. These fine-grained upper units receive recharge from rainfall, irrigation, and the irrigation channel network (Fig. 9).

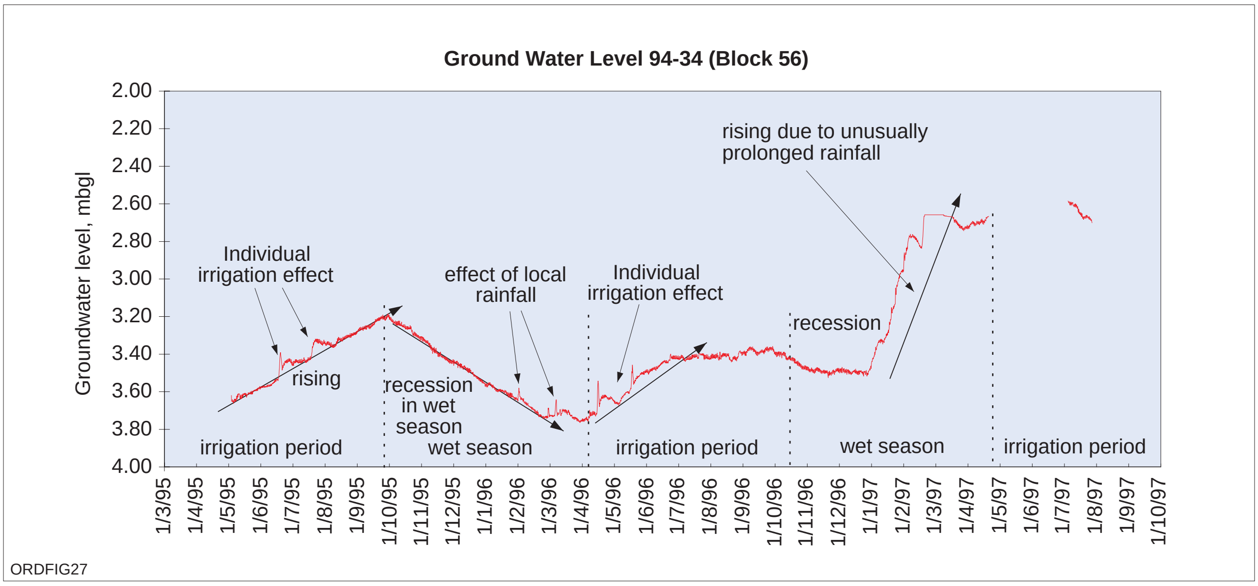


Figure 8. Ivanhoe Plain Piezometer 94/34 (courtesy AgWA)

Flanking and underlying the eastern Packsaddle Plain and Ivanhoe Plain are indurated Devonian sandstones of presumably low permeability from which little groundwater would flow into the alluvium. The low permeability Cambrian Antrim Plateau Volcanics lying beneath parts of the Packsaddle Plain and Ivanhoe Plain will also not readily transmit groundwater from the flanking hills into the alluvium. The low permeability of the Proterozoic bedrock surrounding the western flanks of the Packsaddle Plain and Ivanhoe Plain provide little groundwater flow into the alluvium beneath the black soil plains when compared with the alluvial aquifer throughflow.

4.2.2 Groundwater salinity

Because of the sparsity of the data, the areal distribution of the electrical conductivity (EC) values in Ivanhoe Plain and Packsaddle Plain have been drawn using the average EC values between 1990 and 1996 (Fig. 10). When calculating average values of EC, data that deviated significantly were excluded.

On the Packsaddle Plain, the zone of low EC groundwater existing around PS2/78, PS3, PS12, PS14 and PS15 (Plate 2) is indicative of recharge from the wetlands associated with Lake Kununurra. Particularly high EC groundwater occurs near P13 and P9. The high EC is indicative of slow groundwater flow caused by low hydraulic conductivity and consequently less recharge to aquifer in these areas. Pockets of low EC groundwater exist around piezometers P2 and P14, where rapid leakage from the main supply channel or adjacent irrigation practices may be a contributory factor. There are insufficient data to analyse EC trends over the entire Packsaddle Plain. However, there is a

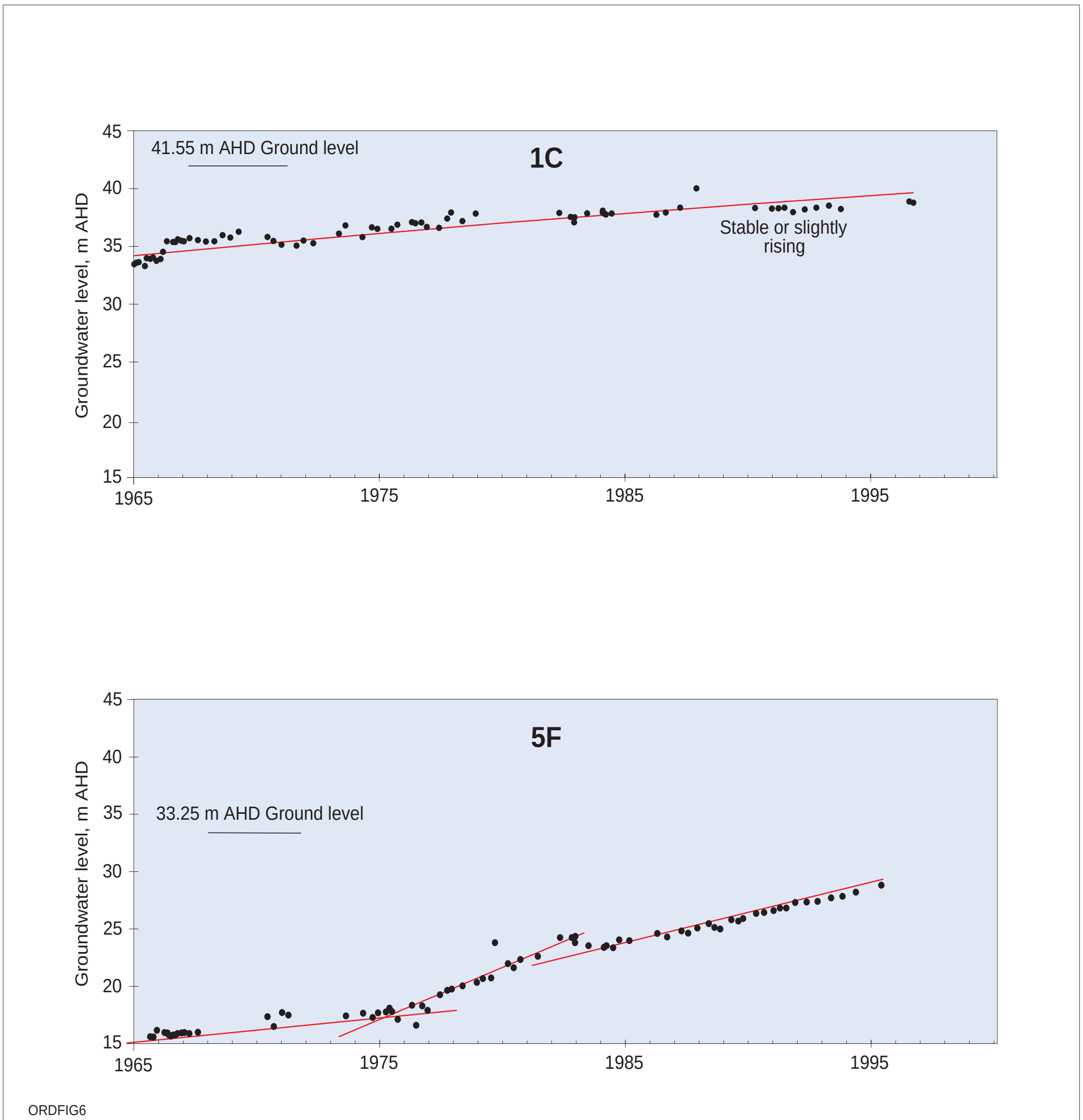


Figure 9. Hydrographs for 1C and 5F, Ivanhoe Plain

falling trend at PS1/78 while the groundwater level is rising slightly, which might indicate leakage from the main supply channel, or adjacent irrigation practices, or both.

The spatial distribution of EC in the shallow and deep bores shows generally low EC groundwater in the southern half of the Ivanhoe Plain. Low EC groundwater of less than 500 mS/cm occurs near the M1 Channel, but increases to over 1000 mS/cm in the direction of groundwater flow towards the Ord River.

In the northern half of the Ivanhoe Plain, the EC values of shallow and deep bores are much higher. Pockets of low EC water exist around PN12S and PN3S, where rapid leakage from D4 Drain may be a contributory factor. In addition, the zone of low EC water in Cave Spring Gap is probably caused by the M1 discharge. High EC water occurs in the Green Location and at Martins Location. The rapid increase in conductivity is indicative of very slow groundwater flow and concentration by leaching associated with the swampy areas.

Changes in groundwater electrical conductivity and groundwater levels in the southern Ivanhoe Plain show that there is an inverse relation between EC and groundwater level. When the water level rises, the EC level decreases. This relationship is also valid for most of the northern Ivanhoe Plain with the exception of bores such as PN2S and PN3S, which show an increase in electrical conductivity with rising groundwater levels. At Martins Location, although there is high EC groundwater present, there has been a significant drop of more than 1000 µS/cm in the EC levels in the period 1990–1996. This may be due to the gradual mixing with fresher groundwater flowing into the area from the groundwater mounds formed under the irrigation area (Yesertener, 1997).

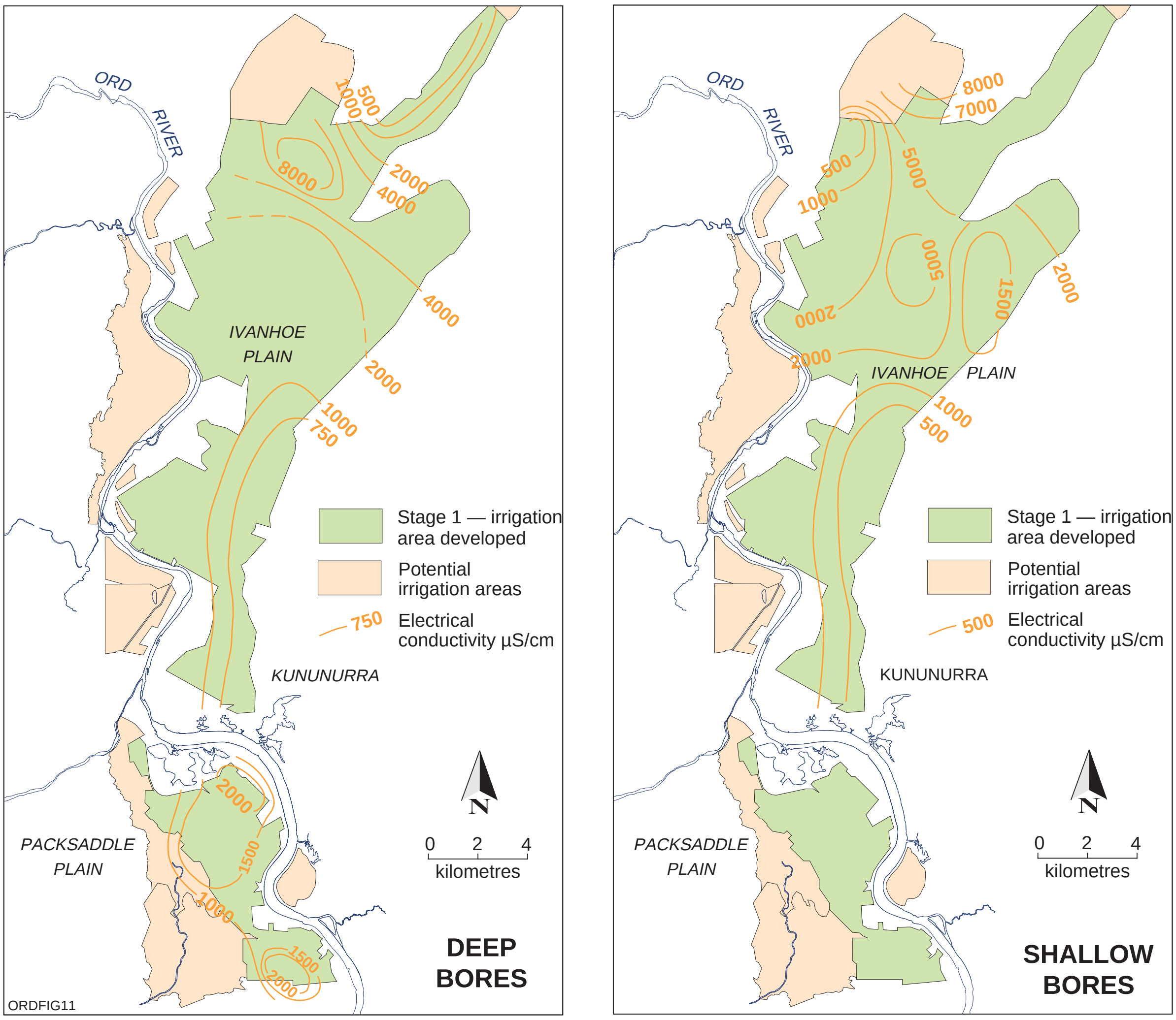


Figure 10. Packsaddle Plain and Ivanhoe Plain groundwater salinity, 1990 to 1996

4.3 Weaber Plain, Knox Creek Plain, and Keep River Plain groundwater regime

4.3.1 Groundwater recharge, throughflow, and discharge in superficial deposits

Groundwater level monitoring data for the Weaber Plain, Knox Creek Plain, and Keep River Plain show little change from 1965 to 1996, for example, in piezometers CS10, W5S1, and WBS1112 (Fig. 11). Present groundwater levels (Plate 2) are, therefore, similar to those in 1965. Groundwater recharge by direct infiltration of rainfall is inferred to be very low because of deep groundwater levels in the alluvium. Thtical seepage beneath the wetland is recharging the sand and gravel aquifer and causing a rise in groundwater level, such as the few metres in CS10.

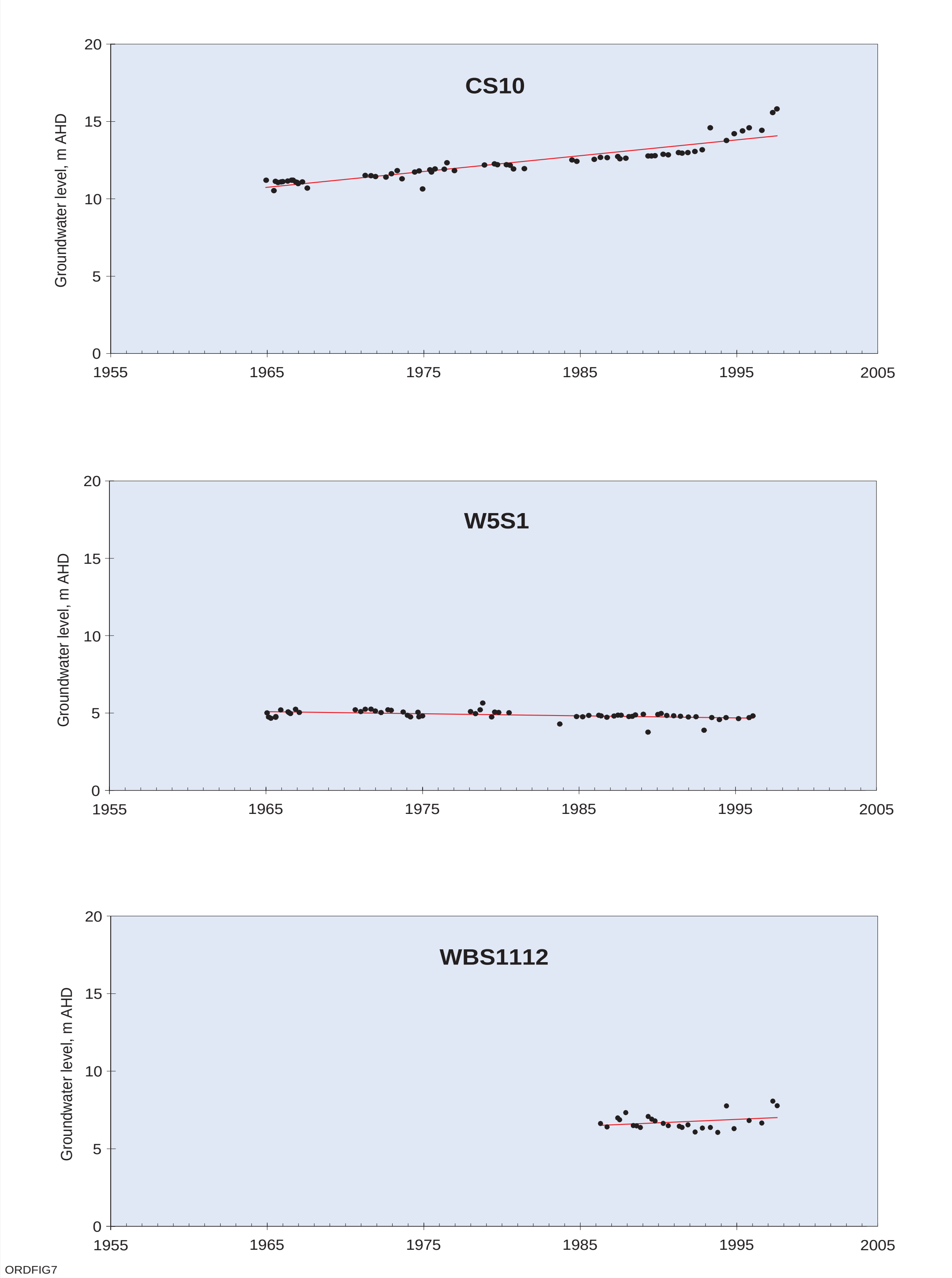


Figure 11. Monitoring bore hydrographs for Weaber Plain, Knox Creek Plain, and Keep River Plain

Humphreys *et al.* (1995) identified direct infiltration as one avenue for recharge to the Keep River Plain groundwater system. They observed that there is little infiltration into the black soil, which overlies most of the region, and has low permeability when saturated. Keep River Plain monthly observation bore measurements during 1972 and 1973 indicated natural annual variations of less that 0.3 m in groundwater levels. They therefore surmised low effective infiltration from rainfall through the sandy and porous soils overlying areas of sub-cropping and outcropping Permo-Carboniferous sandstone adjacent to the black soil plains.

Groundwater flow in the basal sand and gravel generally is in an easterly direction from Cave Spring Gap and theSandy Creek tributary across the Weaber Plain where it discharges into the Keep River. The natural hydraulic gradient is very low.

The construction and test pumping of test bore RN29659 on the western Weaber Plain in 1994 gave performance indicators and hydraulic parameters. Extrapolated test results indicated that sustained yields of more than 2000 m^3/d (>25 L/s) can be expected from properly designed bores screened in the basal sand and gravel aquifer. The transmissivity was determined to be greater than 1500 m^2/d, but without suitable observation bores, a value for specific yield could not be determined (Humphreys *et al.,* 1995).

The Milligans Shale, which underlies the north Weaber Plain, eastern Knox Creek Plain, and southern Keep River Plain, is also expected to have a low permeability and form an aquitard with little groundwater flow. The Cambrian Antrim Plateau Volcanics is of low permeability and will not readily transmit groundwater from the flanking hills into the alluvium. Similarly, groundwater flow into the alluvium from the low permeability Proterozoic rocks flanking the southern Weaber Plain is probably small in comparison with the groundwater throughflow in the alluvial aquifer.

Test production bore RN30826 was test pumped to determine hydraulic characteristics within the Knox Creek Plain and Keep River sandy and clayey alluvium. Based on previous experience the estimated transmissivity was 100 m^2/d with a specific yield of 0.05 to 0.15.

In the Knox Creek Plain, groundwater flow in the basal alluvial sand and gravel is in a northerly direction toward the Weaber Plain. Low-permeability Milligans Formation shale largely underlies the basal sand and gravel. Flanking the alluvium to the east and west is moderately permeable bedrock consisting of Permo-Carboniferous sandstone and Devonian and Carboniferous dolomitic limestone. The very limited piezometric data indicate that groundwater is generally flowing from these moderately permeable bedrock units into the alluvium. Groundwater flows vertically from the low-permeability silts and clays into the moderately permeable basal sand and gravel aquifer, where groundwater is flowing horizontally northwards. There is no groundwater mounding in the silt and clays, where basal sand and gravel underdrainage is present. The main watertable is well below the level of the rivers and creeks, which feed water into the groundwater system through silts and clays. A perched watertable feeds Milligans Lagoon (Wesfarmers *et al.,* 2000).

The southern Keep River Plain groundwater flow direction is from east to west from the higher Permo–Carboniferous sandstones into the basal sands and gravel of the Ord palaeochannel, which probably has a northeastern groundwater flow component. Groundwater also flows into the Permo-Carboniferous sandstones from the palaeochannel sand and gravel, which then discharges into the Keep River. Groundwater flows vertically from the low permeability silt and clay into the basal sand and gravel aquifer, where the groundwater flows horizontally. Groundwater mounding is generally not occurring in the silt and clays, where basal sand and gravel underdrainage is present.

The mean water level in the Keep River and Sandy Creek control the groundwater levels in the basal sand and gravel aquifer underlying the Keep River Plain, eastern Weaber Plain, and northern Knox Creek Plain. Groundwater discharge into these rivers maintains groundwater levels at close to sea level (Fig. 12).

4.3.2 Bedrock groundwater systems

Uniform recharge is expected over the Permo-Carboniferous sandstone where exposed. Significant, but spatially variable recharge, probably also occurs in the Devonian and Carboniferous dolomitic limestone. The low permeability of the other Palaeozoic and Proterozoic bedrock is indicative that little recharge will occur on a regional scale although locally high recharge could be associated with faulting.

Limited data are available for main bedrock aquifers, the Permo–Carboniferous sandstone and the Devonian and Carboniferous dolomitic limestone. The generally low permeability of the other Palaeozoic and Proterozoic means that little groundwater will be transmitted on a regional scale when compared with groundwater flow in the alluvium.

The Permo–Carboniferous sandstones flank and underlie the eastern Knox Creek Plain and the central and northern Keep River Plain. The anticipated direction of groundwater flow is eastwards onto the Knox Creek Plain. On the central Keep River Plain groundwater flows in a westerly direction into the Keep River. In the northern Keep River Plain groundwater flows east across the plain into Sandy Creek, west toward the Keep River, and north into the Keep River Estuary.

In the Keep River Plain and eastern Knox Creek Plain the intended use for most bores constructed in the Permo-Carboniferous sandstones is for low-yield stock watering supplies. The design of the stock bores therefore limited a maximum pumping test rate to 5 L/s, while testing for greater than 480 minutes was generally not warranted because of the low value of additional information (Humphreys *et al.,* 1995). Further pumping

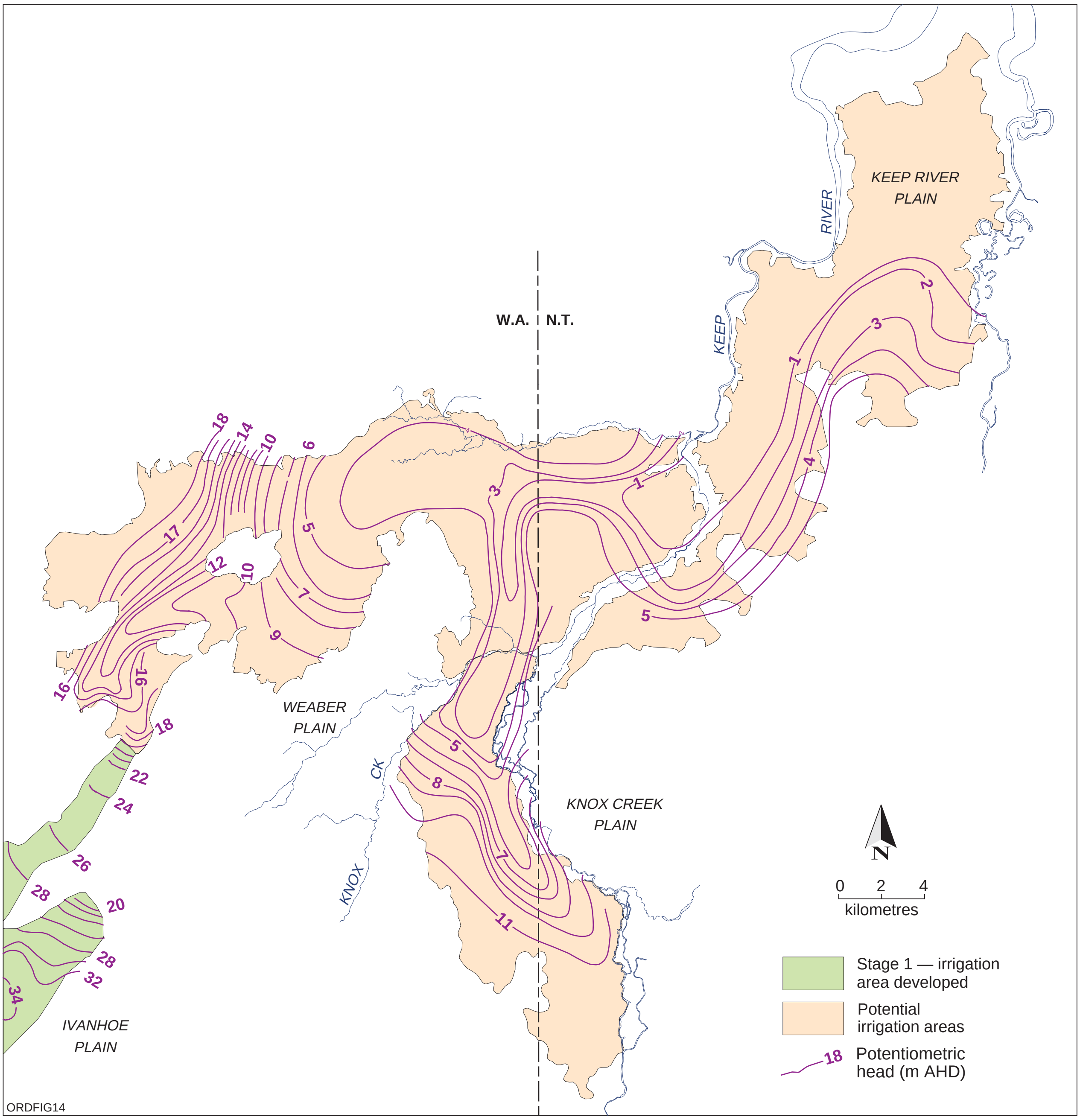


Figure 12. Groundwater contours for Weaber Plain, Knox Creek Plain, and Keep River Plain

tests, however, indicated that the Permo-Carboniferous sandstone is highly permeable. Bore RN29616 indicated increasing airlift yield while drilling and the extrapolated test-pumping yield was in excess of 2000m^3/d (>25 L/s). Regionally, other bores of varying depth produced significant water supplies, indicating that the sandstone is highly permeable. Transmissivity ranges from 150 m^2/d to greater than 2000 m^2/d, but while specific yield values could not be not be calculated, they were estimated to range from 0.05 to 0.1 (Humphreys *et al.,* 1995).

The dolomitic limestone is present on the northwest Ivanhoe Plain, northwest and southern Weaber Plain, and western Knox Creek Plain. Pumping test results at Sorby Hills (Dudgeon and Cox, 1981) have shown that there can be good hydraulic connection between the limestone and gravel alluvium. Drilling has indicated that the limestone has faults, fissures, and cavities enlarged by solution, which act as conduits in which groundwater can flow.

Several mining exploration reports refer to hydrogeological studies at Jeremiah Hills and Sorby Hills (Uttley, 1978; d'Auvergne, 1980; Schlennstedt *et al.*, 1981; Greenway, 1981). Dudgeon and Cox (1981) designed, analysed, and reported on pumping tests at Sorby Hills to determine the need for dewatering the cavernous dolomitic bedrock before lead–zinc mining. Their report did not consider in detail the relationship between the sands and gravels and the bedrock, but the authors highlighted the lack of understanding of recharge–discharge relationships between the unconsolidated sediments and underlying fractured and cavernous dolomitic limestone. Salinities of up to 10 000 mg/L TDS were reported in the dolomitic limestone.

The Sorby Hills pumping tests included step-drawdown and long-term pumping tests. The long-term tests were carried out for six days at 3600 kL/d and at 1150 kL/d for 21 days. The tests were effective in creating significant drawdown more than 1 km from the pumped holes. Analysis of drawdown in more than 20 observation holes yielded average transmissivity and storage values of 4200 to 5500 m^2/d and 1.6 x 10^{-3} to 1.5 x 10^{-3} (Dudgeon and Cox, 1981).

North of Sorby Hills, the dolomite limestone aquifer underlies the shallow palaeochannel alluvial aquifer, which acted as a recharge boundary during the test. This proved that there is a good hydraulic connection between the palaeochannel sand and gravel and the fissure and solution channel system in the dolomitic limestone aquifer. The results also indicated a connection to the gravels in the north via a fault zone of high permeability. Faulting might also assist connection to the gravels in the south but it is more likely that a diffuse connection at the contact between the gravel and dolomitic limestone, particularly in solution channels and sinkholes, is the major influence. The study took the high transmissivity and delayed drawdown as evidence of the effect of the gravel, although there was no indication of recharge from gravels in the overburden in the east (Dudgeon and Cox, 1981).

4.3.3 Groundwater salinity

The interpretation of the shallowest depth penetration channel, Channel-2, shows the correlation of QUESTEM features to geological features and hydrogeological environments (Fig. 13). The electromagnetic interpretation has identified three conductive and four resistive zones. The conductive zones are Permo-Carboniferous with saline groundwater (C1), Milligans Formation shale (C2), and Antrim Plateau Volcanics (C3). The resistive zones are Permo-Carboniferous sandstone with fresh to brackish groundwater (R1), Devonian sandstone (R2), Devonian and Carboniferous dolomitic limestone (R3), and Proterozoic rocks (R4). Over areas of outcrop and laterite, the EM signal from dry rock shows a resistive environment; for example, the Proterozoic rocks. Overall, the control over the response was due to bedrock geology, the salinity of the groundwater in the bedrock, and the depth to watertable. The total-field magnetic data show mainly deep structure and very little information relevant to hydrogeological investigations can be resolved. Seven main groundwater salinity zones are present across the area, and these correspond to the conductive zones C1, C2, and C3, and resistive zones R1, R2, R3, and R4 (Fig. 13).

The C1 zone east of the Keep River and north of the Legune Road has high-salinity groundwater underlying the plains, typically in the range 10 000 to 50 000 mg/L. Salinities increase northwards and adjacent to the Keep River and Sandy Creek. The aquifers include Ord palaeochannel alluvial sands and gravels, and Permo-Carboniferous sandstone. The main avenues of recharge appear to be the tidal sections of the Keep

River and Sandy Creeks. These watercourses cut into Permo-Carboniferous sandstone and contain fresh water during flood flows, and at other times contain seawater or are partly dry. A sample of Keep River water taken downstream of the limit of permanent tidal water contained 52 900 mg/L TDS indicating that evaporative concentration of seawater takes place along those sections of the river.

The C2 zone, associated with sub-cropping low-permeability Milligans Formation shale, has groundwater salinities ranging from brackish to saline. Across the Weaber Plain where the Ord palaeochannel overlies the shale, groundwater throughflow in the basal sand and gravel appears to maintain lower salinities. Areas where low-permeability silt and clay overlie the shale have a higher salinity such as the eastern Knox

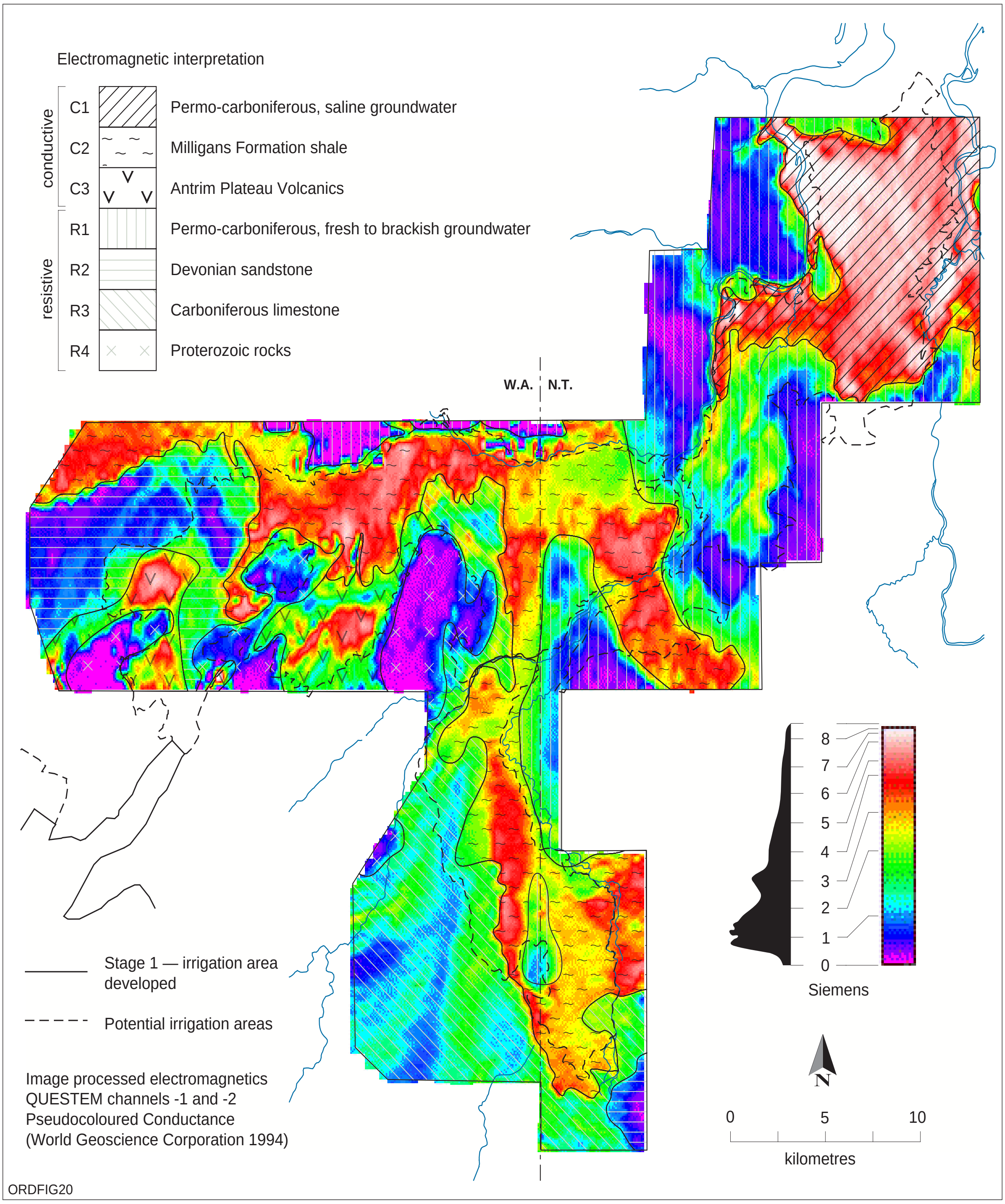


Figure 13. Airborne electromagnetic interpretation

Creek Plain and southern Keep River Plain. The higher salinity is probably due to slow-moving groundwater with long flow paths causing residence times sufficiently long to accumulate salts in the groundwater. Groundwater in the moderately permeable coarser alluvium of the Knox Creek Plain has fresh to brackish groundwater, probably due to shorter residence times.

The C3 zone associated with the Antrim Plateau Volcanics in parts of the western and southern Weaber Plain has low-salinity groundwater. The bedrock does not appear to be contributing significantly to the Ord Palaeochannel salinity.

The R1 zone, underlain by coarse palaeochannel alluvium and Permo-Carboniferous sandstone, has fresh to brackish groundwater of less than 3000 mg/L TDS. The sandstone crops out in the Keep River bed and recharge probably takes place from the flanking sandstone hills during the wet season. Fresh groundwater underlies an area to the southwest of the black soil plains. The aquifers include Permo-Carboniferous sandstone and, in places, alluvial sands and gravels. In areas where Permo-Carboniferous sandstones either outcrop or subcrop, groundwater salinities are low, commonly less than 200 mg/L TDS. These areas are adjacent to the black soil plains and at a slightly higher elevation with relatively high recharge predominantly from direct infiltration of rainfall.

Zones R2, R3, and R4 all have low to moderate groundwater salinity. Low-permeability Devonian sandstone containing low-salinity groundwater underlies the R2 area. Carboniferous limestone units of low to high permeability probably under drain the R3 area, which limits groundwater residence times and thus also limits the build-up of groundwater salinity. Underlying the R4 zone is resistive, mainly Proterozoic rock of low permeability. These resistive rocks are in recharge areas with mineralogy that contributes little salinity.

The Northern Territory Power and Water Authority took samples every metre from holes drilled in the unsaturated zone for EC_{1-5} tests (Humphreys *et al.*, 1995). The upper metre in each hole had relatively low EC values. The peak EC was usually at 1–2 mbgl but could be as deep as 8 mbgl. The salinity is highest east of the Keep River, particularly in the north Keep River Plain where the QUESTEM survey measured peak conductivity. The first 8 m of bore RN29657 intersected clayey colluvium with the highest salt content, in which gypsum crystals were observed, overlying weathered shale of the Milligans Formation. North of Legune Road, the EC in the first eight metres of the unsaturated zone appears to control the QUESTEM results. South of Legune Road the subcropping Milligans Formation shale is the main control on the QUESTEM results and imposes a high EM value, which appears to mask the unsaturated zone conductivity.

Humphreys *et al.* (1995) reasoned that salt from rainfall is the major source of salinity south of Legune Road because similar elevated unsaturated zone salinities have been observed in Northern Territory coastal plains sediments (Tickell, 1994). North of Legune Road, Humphreys *et al.* (1995) considered that the shallow watertable and clayey sediments have led to upward diffusion and capillary rise causing similar salinity above and below the watertable. The relatively high salinities north of Legune Road indicate that only minor downward drainage and thus flushing of salts takes place under natural conditions because the black clay soil and underlying clay layers have very low permeability. The upper metre of black clay has a low salt content because desiccation cracks allow water to penetrate early in the wet season.

4.4 Carlton Plain and Mantinea Flats groundwater regime

4.4.1 Groundwater recharge, throughflow and discharge

The current watertable on the Carlton Plain and Mantinea Flats has a low gradient sloping towards the river. This indicates some degree of recharge from the bedrock on the flanks of the plain, and also outwards from House Roof Hill (Plate 2). There has been little change in the overall trend of groundwater levels from 1979 to 1996 as evidenced, for example, by piezometers Y2, Y6, and Y14 (Fig. 14), although distinct seasonal recharge and regression can be observed. However, it is not clear whether groundwater levels were significantly different before the damming of the Ord River; for instance, whether recharge from the river occurred upstream of House Roof Hill, with groundwater flow around the north of the hill. The mean Ord River water level across the Carlton Plain and Mantinea Flats maintains groundwater between 2 and 4 m AHD.

Groundwater on the Carlton Plain and Mantinea Flats flows in a westerly direction through the basal sand and gravel aquifer and discharges into the Ord River (Fig. 15). Local reversal of flow will occur at high tide level along the Ord River. Minor amounts of groundwater will flow into the alluvium from the low-permeability bedrock flanking and underlying the Carlton Plain and Mantinea Flats.

4.4.2 Groundwater salinity

Groundwater ranges from brackish, 2000 mg/L, in the eastern part of Carlton Plain and Mantinea Flats, and around House Roof Hill, to salinity levels approaching that of sea water, 35 000 mg/L, in the west. The underlying resistive, low-permeability Proterozoic rock contributes little salinity to the alluvium. Along the tidal parts of the Ord River, saline intrusion will locally

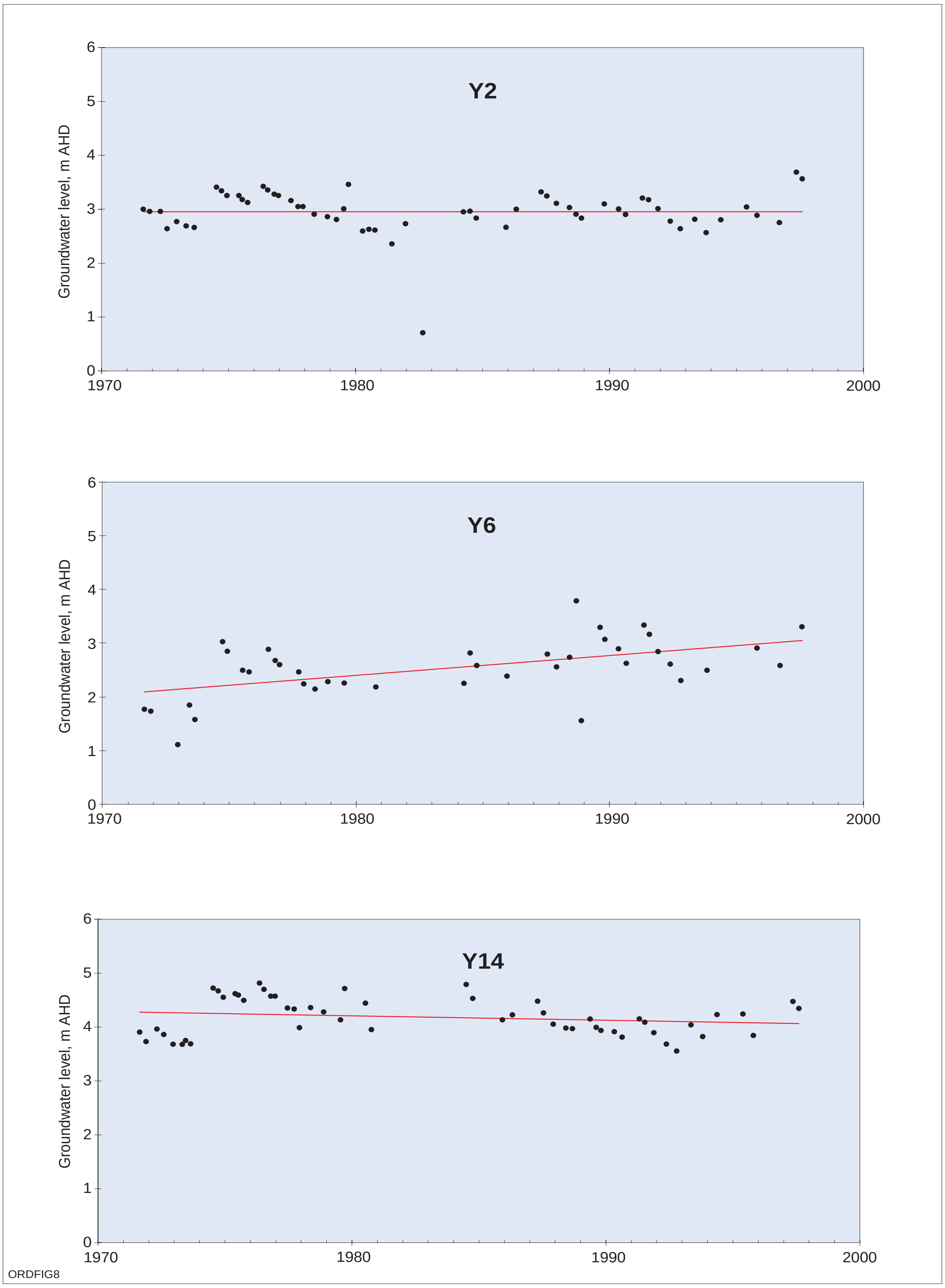


Figure 14. Monitoring bore hydrographs for Carlton Plain and Mantinea Flats

increase salinity. In the west and along extended groundwater flow paths, unflushed seawater probably contributes to salinity.

4.5 Hydrochemistry

A large number of analyses have been carried out since the 1960s, but the various sampling programs have not rigorously applied standard procedures for sampling, preserving, storing, and timely analysis. This was largely due to the logistical difficulties that the Kimberley presents and the lack of justification for the higher costs involved when adopting rigorous standard procedures. Although chemical changes have occurred in the samples, the major ions are probably close enough to the in situ groundwater chemistry to provide the broad hydrochemical variations across the Ord River Irrigation Area. The laboratory pH is included but, due to exposure to the atmosphere resulting in chemical changes, it is probably not representative of the in situ pH. Appendix 1 tabulates selected recent chemical analyses for the major ions.

Figs 16 and 17 are hydrochemical trilinear Piper diagrams of the groundwater chemical analyses (Appendix 1).

The Packsaddle Plain, Ivanhoe Plain, and Cave Spring Gap groundwater cation range is from no dominant type to sodium type. The anion range is from bicarbonate to chloride with some sulphate types associated with the slow draining Martins Location and Green Location. Lake Kununurra water has no dominant cation but the dominant anion is bicarbonate. The analyses indicate that sodium chloride, sodium bicarbonate, and magnesium–calcium bicarbonate waters dominate.

The Weaber Plain groundwater cation range is from no dominant type to chloride type. The anion range is from bicarbonate through no dominant type to marginally chloride. Sodium bicarbonate and sodium chloride water dominates with minor magnesium–calcium bicarbonate water.

The Knox Creek Plain groundwater cation range is from no dominant type to chloride type. The anion range is from bicarbonate through no dominant type to marginally sulphate. The water types are sodium bicarbonate, sodium chloride, sodium sulphate, magnesium–calcium sulphate, and sodium–calcium–magnesium bicarbonate. Bore logs in the Milligans Formation shale refer to gypsum crystals, which might be the source of the sulphate.

The Keep River Plain groundwater cation range is from no dominant type to chloride type. The anion range is from bicarbonate through no dominant type to chloride with some marginally sulphate. The water types are calcium–magnesium bicarbonate through to sodium chloride closer to the estuaries. In the south, minor sulphate is associated with the Milligans Formation shale.

Sodium chloride waters dominate the Carlton Plain and Mantinea Flats groundwater. The groundwater grades from brackish inland to saline towards the Ord Estuary; therefore, the sodium chloride probably has a marine origin.

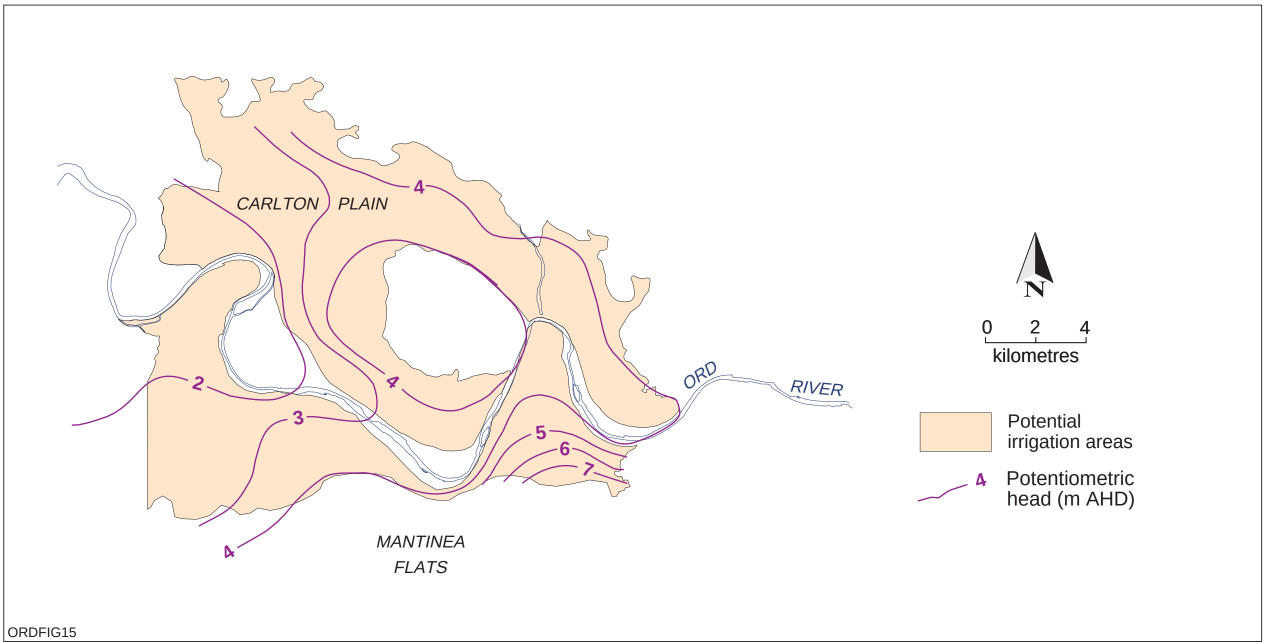


Figure 15. Groundwater contours for Carlton Plain and Mantinea Flats

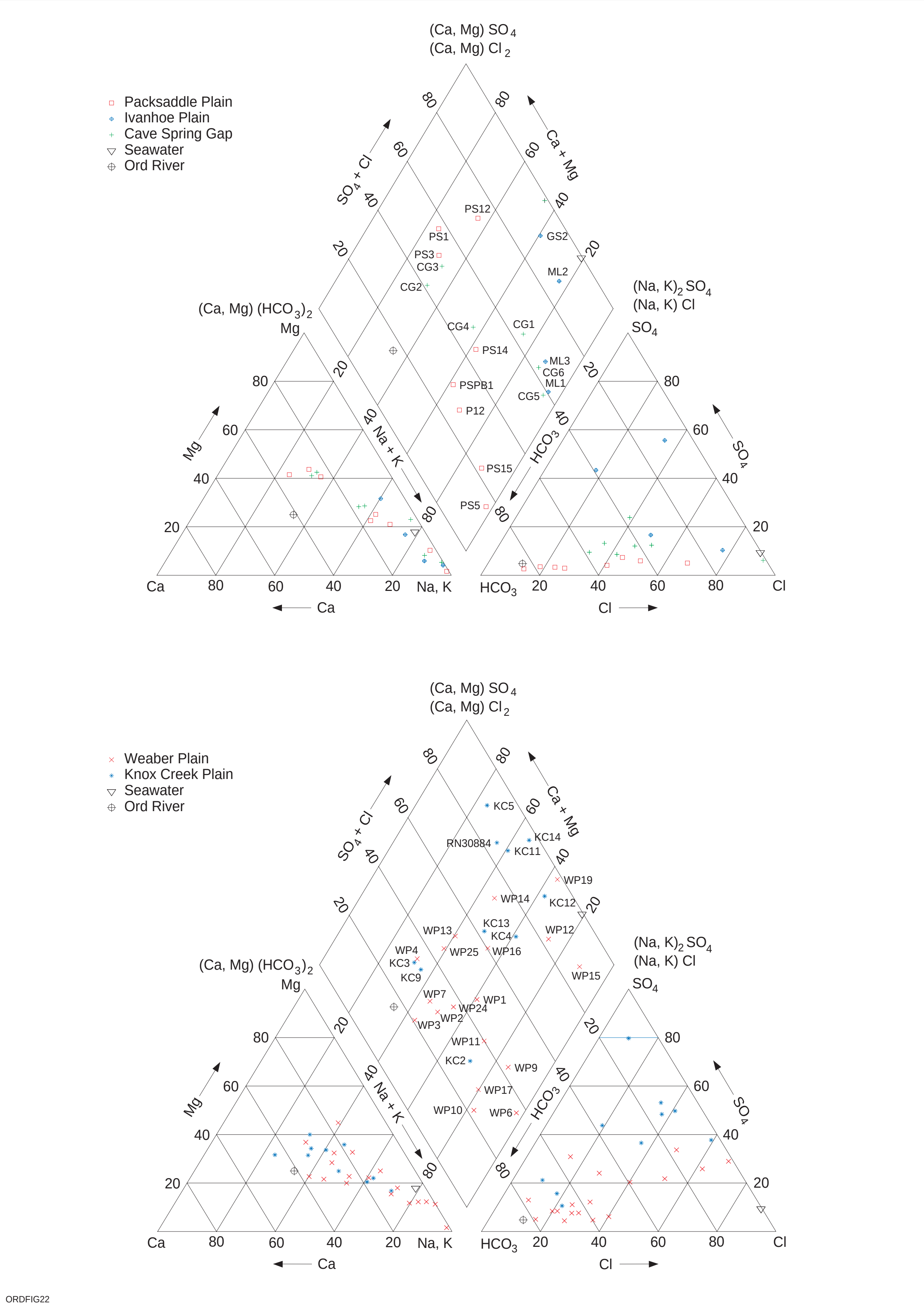


Figure 16. Hydrochemical trilinear diagrams for Packsaddle Plain, Ivanhoe Plain, Weaber Plain, and Knox Creek Plain

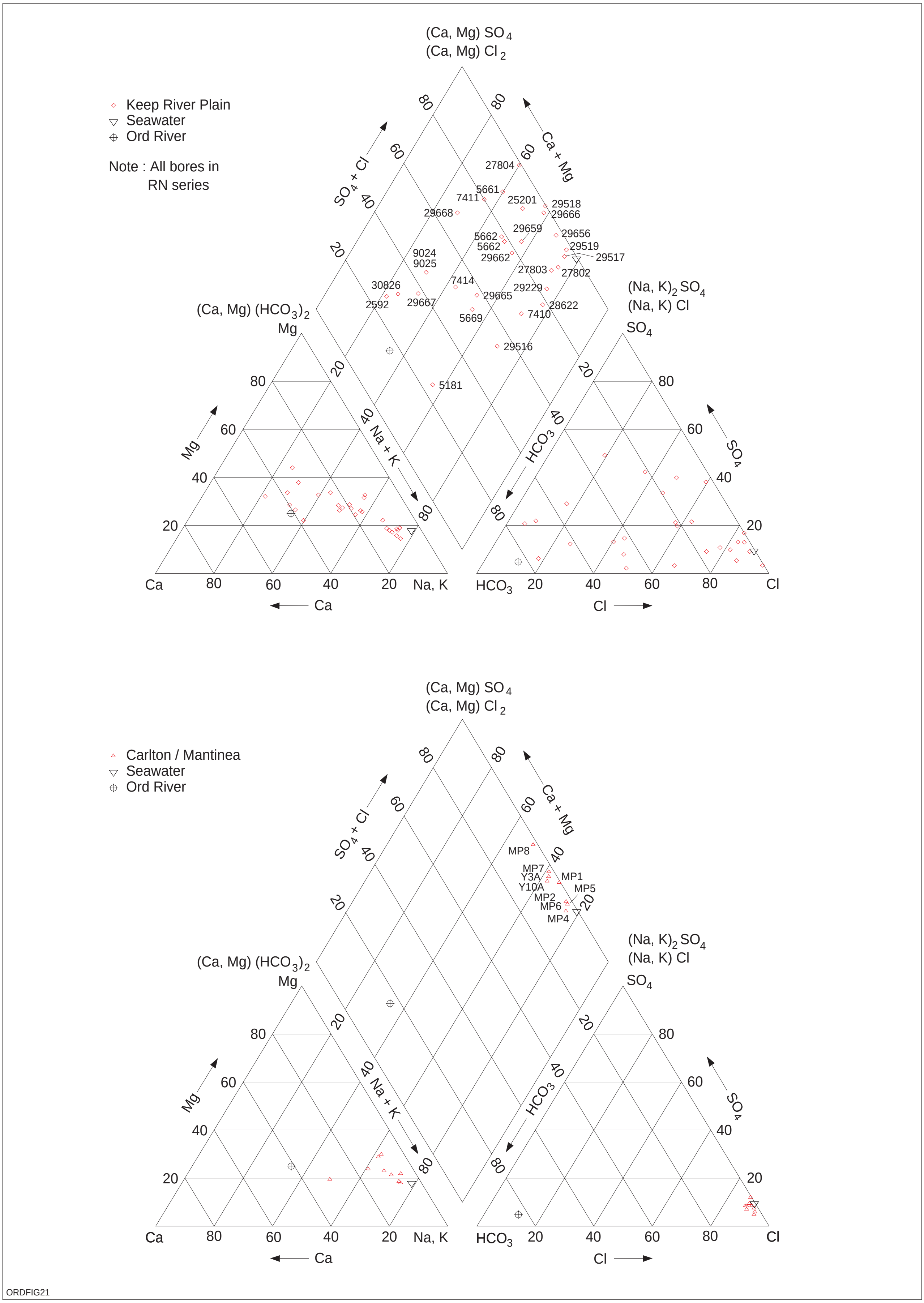


Figure 17. Hydrochemical trilinear diagrams for Keep River Plain, Carlton Plain, and Mantinea Flats

5 Effects of irrigation

5.1 Introduction

In common with other irrigation areas throughout Australia and the rest of the world, groundwater levels have risen owing to increased recharge. Groundwater at or near the surface in irrigation areas can reduce crop yields through waterlogging, salinity in the root zone, and sodicity from high sodium levels in groundwater causing soil-structure problems. A good understanding of the effects of irrigation on the groundwater regime is therefore important for sustainable agriculture in the Ord River Irrigation Area.

5.2 Monitoring reviews

Groundwater monitoring data are available for the whole of the ORIA and the GSWA, and latterly the WRC have regularly reviewed these data for the irrigated areas on the Ivanhoe and Packsaddle Plains. Monitoring data from the piezometers constructed on the Ivanhoe Plain and Packsaddle Plain in 1964, 1965, 1968, 1971, and 1978 formed the basis for the first review of the hydrogeology and groundwater conditions (Laws and George, 1982). The report showed rapidly rising groundwater levels in several areas and variable salinities, and recommended more piezometers, which the GSWA and PWD installed in 1983.

From 1983, monitoring of water levels and electrical conductivity continued in 14 piezometers for the period 1983 to 1985 and ten piezometers from 1985. The Water Authority of Western Australia were monitoring 37 piezometers and bores for groundwater levels when McGowan (1987) reviewed groundwater level data to September 1986. He concluded that the hydrogeological conditions on the Ivanhoe and Packsaddle Irrigation Plains were changing in response to intensive irrigation that had taken place since 1964. He recommended an annual review of the groundwater level data.

Laws (1991a) carried out a review of the Ivanhoe and Packsaddle Plain using data obtained from the drilling investigation bores and piezometers up to August 1990. From 1987 to 1990, monitoring on a regular basis included 27 piezometers and bores, with the occasional monitoring of a further 16. Between 1986 and 1990, over four separate periods, water levels were measured in 15 piezometers and groundwater electrical conductivity at nine to 12 sites. Levelling of the bores enabled groundwater level contours to be drawn. The review concluded that water levels were rising at rates of 20 to 500 mm/year in the Ivanhoe Plain. The minimum depth to the watertable in the Ivanhoe Plain was less than 3 m for only a small area around PN3 and immediately adjacent to the southern section of the M1 main supply channel. In the Packsaddle Plain, the review concluded that the water level in Lake Kununurra controlled groundwater levels by recharge. Groundwater level trends in the monitored piezometers showed a slight increasing trend ranging from 20 to 140 mm/year. Laws (1991a) recommended that a groundwater review occur every five years.

Laws (1993a) maintained that the main limitation of the hydrogeological data existing in the 1993 was the reduction in the number of piezometers monitored during the preceding ten years. In addition, there was an urgent need to undertake the previously recommended drilling in the north at Martins Location and Green Location to understand the hydrogeology in these areas. Agriculture WA installed 12 piezometers at six sites in 1991, and in 1994 several agencies installed a further 52 piezometers (Table 1). By August 1996, the WRC were monitoring 28 piezometers and AgWA were monitoring 24 piezometers. Some of the AgWA piezometers had data loggers provided by the WRC and the Sugar Research and Development Corporation. Yesertener (1997) undertook the most recent groundwater monitoring review for the Ivanhoe Plain and Packsaddle Plain.

5.3 Groundwater levels

5.3.1 Packsaddle Plain

Since 1991, WAWA and latterly the WRC have monitored 16 bores on the Packsaddle Plain. In 1996 groundwater levels in the eastern Packsaddle Plain were above 40.85 m AHD and reflect the water level in Lake Kununurra (Plate 2). Depth to groundwater in the monitored bores ranges from 1.76 (P2) to 8.94 mbgl (PS3). The groundwater-flow system has not changed significantly from the first review in 1982, and groundwater flow remains in the direction of Packsaddle Creek. The appearance of a groundwater mound around P2 and P14 bores is indicative of leakage from the main supply channel and irrigation effects in the adjacent area. For the period from April 1995 to April 1996, regression curve analysis shows the groundwater level rising at rates up to 0.15 m/year (Yesertener, 1997).

5.3.2 Ivanhoe Plain

Groundwater levels have risen steadily over much of the Ivanhoe Plain since commencement of irrigation (Fig. 9). Trends in water levels differ across the area and vary in time and are summarised from Yesertener (1997) in Table 7.

The change in potentiometric level for the period April 1994 to April 1995 has been calculated by Yesertener (1997) from the available information (Table 8). The recent increase in the sugar crop with its high water requirement could cause acceleration in the rate of groundwater rise because of increased groundwater accession.

Figure 18 shows the groundwater level contours for 1965, 1975, 1985, and 1997. The most significant change in the groundwater regime on Ivanhoe Plain concerns the interaction between the Ord River and the gravel and sand aquifer. It is likely that before 1965 the Ord River recharged the aquifer. Conversely, since 1965 groundwater in the sand and gravel aquifer discharges into the Ord River. In the southern half of the Ivanhoe Plain, leakage from the M1 channel largely controls groundwater flow west to the Ord River. Potentiometric levels, which had risen significantly, are now generally stable or slightly rising near the M1 Channel.

Table 7. Potentiometric level changes on the Ivanhoe Plain

Ivanhoe Plain		*Mean potentiometric level changes, (m/year)*		
		1965–75	*1975–85*	*1985–95*
Southern half	M1 Channel area	0.20	0.15	0.20
	South end	0.15	0.12	0.12
	Ivanhoe Crossing	0.20	0.20	0.25
Northern half	Martins Location	1.20	0.45	0.27
	Dumas Lookout	0.30	0.40	0.40
	Block 68, 63-65	0.85	0.55	0.25
	Block 100, 101 and 102	0.15	0.45	0.45
	Cave Spring Gap	0.25	0.40	0.40
	Green Location	0.35	0.40	0.35
	Discharge area	0.10	0.35	0.20

Table 8. Calculated potentiometric level rise on the Ivanhoe Plain

Ivanhoe Plain		*Potentiometric level change (m/year)*
Southern half	M1 Channel area	Stable or slightly rising
	South end	0.1
	Ivanhoe crossing	0.27
Northern half	Martins Location	0.20
	Dumas Lookout	0.35–0.50
	Block 68, 63	0.6
	Block 64, 65	0.45
	Block 100, 101	0.6
	Block 102	0.8
	Cave Spring Gap	0.5
	Green Location	0.3
	Discharge area	0.25

For the period of April 1995 to April 1996, most areas have groundwater levels rising at more than 0.25 m/year and, in some areas, at more than 0.60 m/year. Over most of the agriculturally productive northeastern area, groundwater levels are rising at more at than 0.40 m/year (Fig. 19)

5.3.3 Groundwater accessions

Recharge from reservoirs, irrigation channels, irrigation, and drains are responsible for high groundwater levels on the Packsaddle Plain and Ivanhoe Plain. Monitoring indicates that groundwater levels are rising at between 0.02 and 0.5 m/year over a significant proportion of the area and groundwater is less than 2 m from the surface in some localised areas (Fig. 20) (Yesertener, 1997).

Recharge from Lake Kununurra maintains groundwater levels close to the surface on Packsaddle Plain and the southern Ivanhoe Plain. The contribution of irrigation to groundwater recharge depends on the crop type, irrigation method, irrigation management, and nature of underlying soil. For example, rates of rise of groundwater level under rice crops averaged up to 1.3 m/year (Laws and George, 1982), and McGowan (1984) identified areas where the presence of gravels close to ground surface enhanced groundwater recharge under rice crops. Areas where underlying sand and gravel aquifers are not present to drain overlying silty alluvium are particularly prone to the increasing groundwater levels.

Seepage losses from canals are dependent on the permeability of the underlying soil (Table 9). In the ORIA, drains and channels can cut through the thin

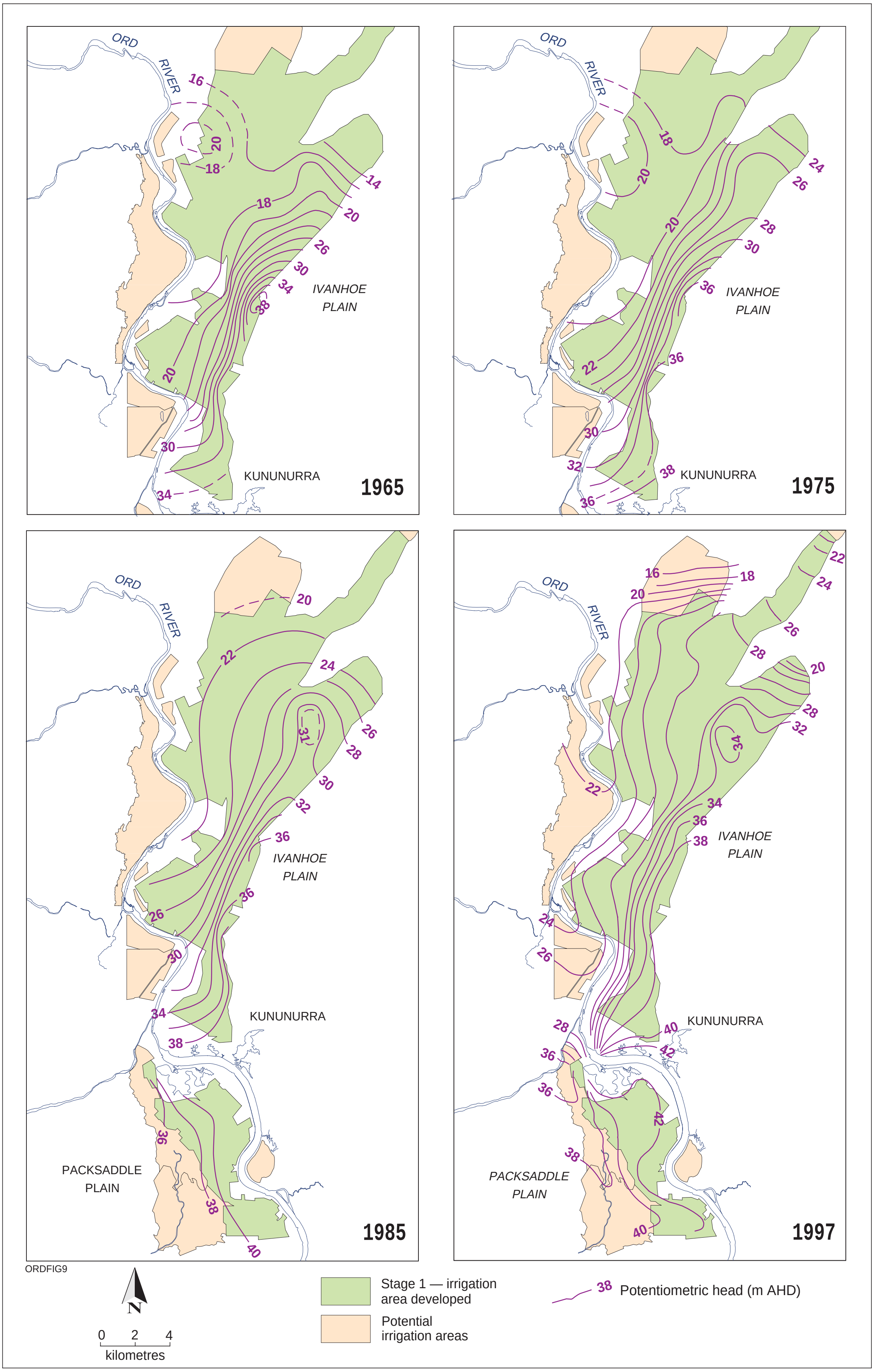


Figure 18. Groundwater contours for the Ivanhoe Plain and Packsaddle Plain, 1965 to 1997

layer of largely impervious black soil over some of their length, exposing the more permeable underlying strata. Banyard (1983) reported that losses from drains on the Ivanhoe Plain drain range from 0.16 to 0.27 m^3/m^2/year of irrigable land. A flow net calculation (O'Boy, 1997) indicates that as groundwater levels rose, recharge from the M1 channel adjacent to PB4 decreased from 1.2 m^3/d/m length in 1965 to 0.4 m^3/d/m length in 1996 (Fig. 21).

Table 9. Seepage losses per square metre of wet canal perimeter (after Poiree *et al.*, 1968)

Surrounding soil	*Loss ($m^3/m^2/day$)*	*Loss per km canal length as % of flow**
Clay	0.09	0.07
Loamy clay	0.18	0.14
Sandy clay	0.20–0.40	0.15–0.31
Sand	0.50	0.38
Sand and gravel	0.75	0.58
gravel	1.00–1.80	0.77–1.39

* Average water depth 1.50 m and stream velocity 1 m/sec

George (1983) gave accessions due to irrigation as 4–55 % of applied irrigation observed in the field. Based on a median application rate of 16 ML/ha/year this amounts to an accession rate of 64–880 mm/year. Sinclair Knight Merz (Department of Resources Development, 1997a,b) calculated irrigation accessions from Ivanhoe Plain bore hydrographs, which have data extending back as far as 1964. A study of the relationship between rainfall, groundwater levels and cumulative residual rainfall concluded that no relationship exists, and it was therefore assumed that irrigation and channel leakage control the entire hydrograph trend. The long-term watertable rise for the monitoring bores ranges from 33 to 534 mm/year and averages about 290 mm/year. They used these watertable rise rates to calculate the recharge for their Ivanhoe groundwater model.

George (1983) suggested that the leaching fraction for Cununurra clay varied from 0.07 for furrow irrigation

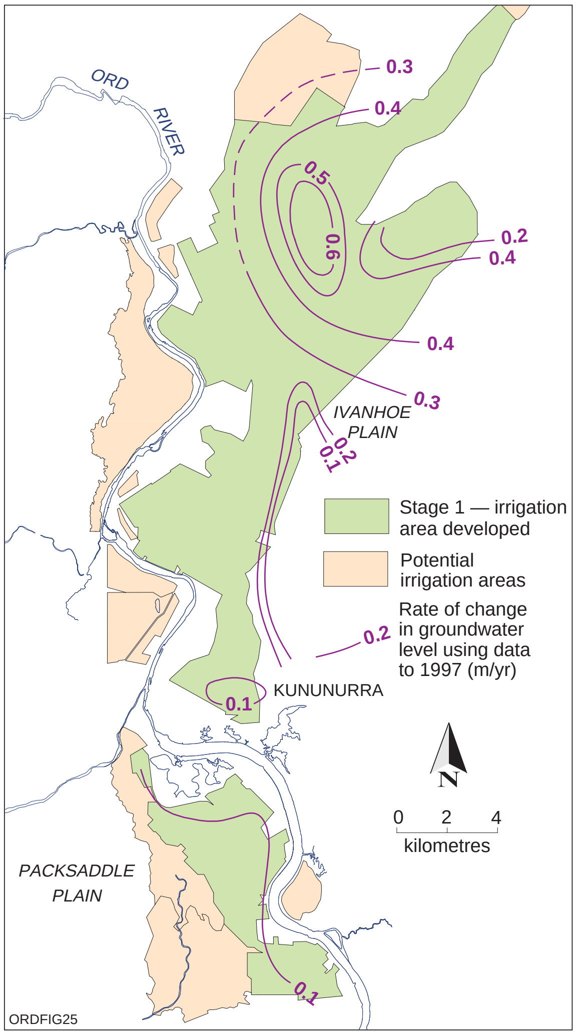


Figure 19. Rate of change of groundwater levels

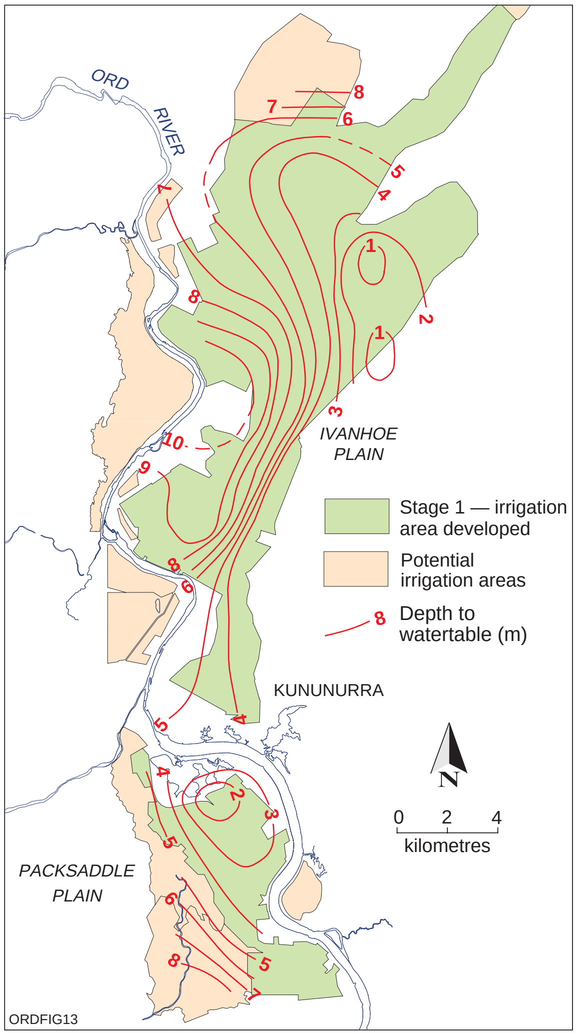


Figure 20. Depth to groundwater for Packsaddle Plain and Ivanhoe Plain, August 1996

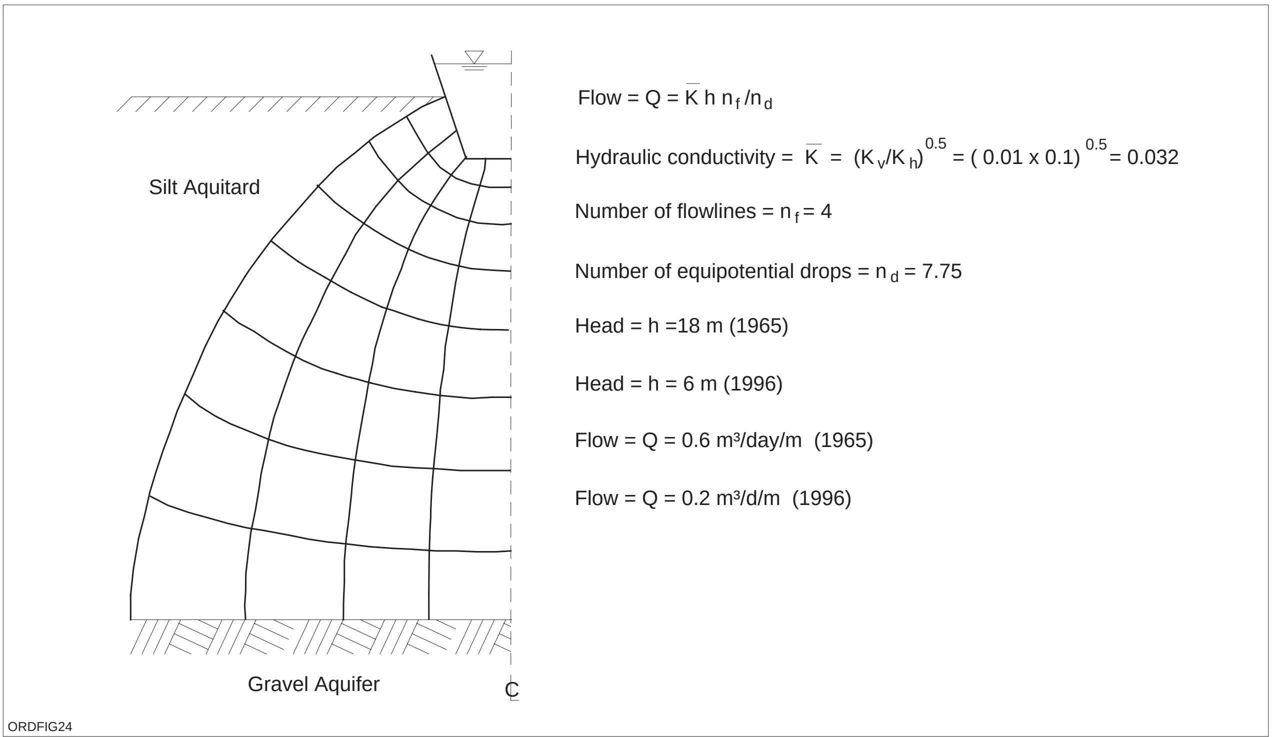


Figure 21. Ivanhoe flow net

to 0.24 for flood irrigation. These approximate rates served as input to the initial simulation exercises for the PAWA modelling of the Weaber and Keep River Plains (Humphreys *et al.,* 1995). The magnitude of recharge was refined from the initial values by trialing various estimates of recharge to replicate the measured groundwater hydrographs. The model calibration indicated recharge rates between 0.1 and 0.2 mm/d.

In order to assess the effect of irrigation in Stage 2, Sinclair Knight Merz (Department of Resources Development, 1997a,b) made assumptions about channel accessions and the type of irrigation. They considered soil type and applied irrigation volume (related to crop type) to be the two critical factors that control groundwater accessions in the Ord River Irrigation Area. Heavier soils would have lower accessions than lighter soils. Their models gave only explicit consideration to accessions from the main irrigation channels. The Soil Properties Model (SALF), developed by the Queensland Department of Natural Resources, was used to determine the likely accessions (Gordon and Gardner, 1997). Estimates of deep drainage ranged from nil to several hundred millimetres per year. Evaluation of Ivanhoe Plain rates of rise yielded accession rates of 10–50 mm/year. Predictions using the SALF model for heavier cracking clay soils under well managed irrigation gave groundwater accessions of 10–70 mm/year. Much of the Carlton Plain, with its lighter soils, could have groundwater accessions at the higher end of the scale. Increasing the salinity (NaCl dominant) increases the maximum accession predicted by SALF to 150 mm/year.

Kinhill (Wesfarmers *et al.,* 2000) used the unsaturated flow-infiltration model LEACHM (Hutson and Wegenet, 1992) to evaluate water movement through soil as well as water uptake by crops. The model predicted that wet-season rainfall causes almost all the accession to the groundwater because the soil profile at the end of the dry season is at field capacity due to irrigation. Stopping irrigation before the onset of the wet season and allowing the soil to dry out could therefore be the most effective strategy in reducing accession rates. The results indicate that the accession to groundwater from cropping areas is in the range 54–119 mm/year with an average of 94 mm/year. They adopted an accession rate of 100 mm/year for planning purposes because groundwater levels would be representative of accession rates over large areas, which would smooth out local variations in soil. The model estimated that 1900 mm of rainfall and irrigation water would infiltrate into the soil. The average accession rate of 94 mm/year therefore represents a leaching factor of 0.05, which is at the lower end of the range estimated by George (1983).

The hydrograph for the Ivanhoe Plain piezometer 94/34 (Fig. 8) shows a rising groundwater level trend under irrigation during the dry season. This indicates an excessive application of irrigation water when compared with the result of the LEACHM modelling, which predicted insignificant groundwater accessions during the dry season under optimised managed irrigation. The wet-season recession shown on the hydrograph for 1995–96 (Fig. 8) indicates that groundwater accessions from rainfall during the wet season are lower than those from irrigation on the Ivanhoe Plain over the dry season. Although in some years where prolonged rainfall occurs in the wet season, such as 1996–97, the groundwater levels continue to rise.

5.4 Groundwater quality

5.4.1 Salinity

Because of the sparsity of the data, the areal distribution of the electrical conductivity values in the Ivanhoe Plain and Packsaddle Plain has been drawn using the average EC values between 1990 and 1996. Appendix 1 tabulates the EC monitoring data since 1990. When calculating average values the method excluded data that deviated significantly. Figure 10 shows the interpretation of the electrical conductivity distribution for the shallow piezometers and deep bores.

High concentrations of soluble salts in groundwater can produce saline soils, which can be toxic, and by increasing the solute suction reduce the availability of soil water to plants. High concentrations of exchangeable sodium in groundwater, if introduced into alkali soils, can produce a soil structure breakdown, which reduces permeability, aeration, infiltration rate, and soil workability. The ability of groundwater to expel calcium and magnesium by sodium can be estimated with the aid of the sodium absorption ratio (SAR) (Richards, 1954). High SAR values indicate a risk of displacement of the alkaline earths.

$$SAR = Na / ((Ca + Mg)/2)^{0.5}$$

The sodium adsorption ratio was 45 in groundwater pumped from test production bore PB4 on the Ivanhoe Plain. When the PB4 SAR and the EC of 2300 mS/cm are plotted (Fig. 22) on a diagram for the classification of irrigation waters (Richards, 1954), the salinity hazard is very high and the sodium (alkali) hazard even higher. As a comparison, the chemical analysis for Lake Kununurra (Rosich and McAuliffe, 1994) has a SAR

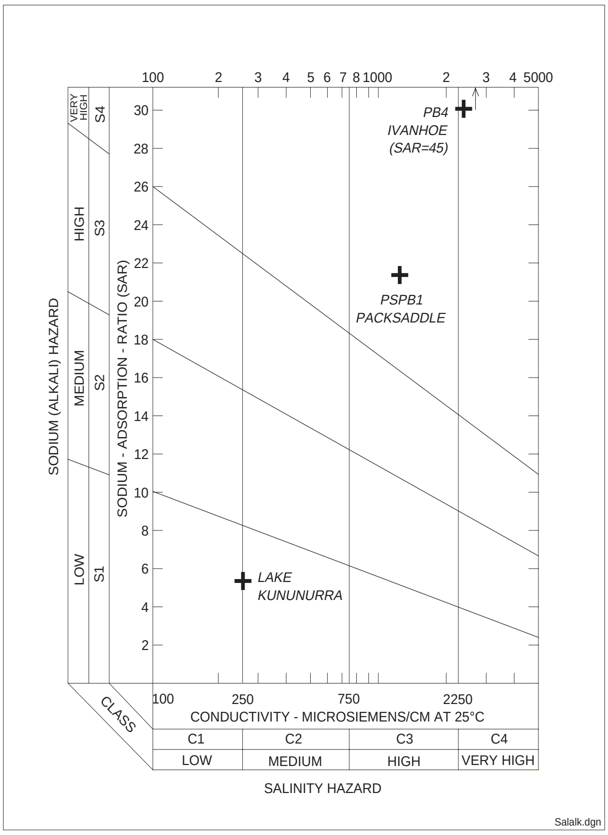


Figure 22. Classification of water for irrigation

of about 5 and electrical conductivity of about 250 mS/cm, which gives a low to medium salinity hazard and low sodium (alkali) hazard. In addition, groundwater rising into the black clay soil (Yesertener, 1997) probably also has the potential to cause a similar hazard over large areas of the Ivanhoe Plain.

Studies indicate that groundwater salinity would change in response to irrigation to become more similar to that of the accessions. Yesertener (1997) shows that the present salinity of groundwater in the basal gravels on the Ivanhoe Plain is similar to the shallow groundwater salinity. However, baseline and temporal data on groundwater salinity is very sparse and it is therefore not possible to chronicle the changes. It is unlikely there are significant quantities of salt in the unsaturated zone that can be mobilised. Other irrigation areas in Australia with cracking soil have the ions in accession water significantly concentrated by the evaporation process. Generally, there is a ten-fold increase in the conservative ions.

Where salts are present in the unsaturated soil profile there is the potential that they might be mobilised by rising groundwater levels. The EC_{1-5} extracts (Humphreys *et al.,* 1995) measured for the Keep River

Plain are less than 1000 mS/cm which indicate that mobilisation of the salts should not increase groundwater salinity dramatically, even over the shale of Milligans Formation.

Areas where the groundwater has a pre-existing high salinity (Fig. 6) could be at highest risk from rising high-salinity groundwater. These areas include the western end of the Carlton Plain and northern Keep River Plain where the source of salinity is seawater, and back-swamp areas of low permeability, such as Martins Location and Green Location on the Ivanhoe Plain.

Salinity does not appear to have affected cracking black soil areas of the Ivanhoe Plain with groundwater levels within two metres of the surface. There seems to be sufficient downward leaching of salts, which has avoided salinity accretion in the shallow soils. Waterlogging problems, exacerbated by sodicity, may prove to be significant. Other non-cracking soils may have more potential to develop high salinity at shallow depth in addition to waterlogging and sodicity. Groundwater accessions under the higher permeability non-cracking soils might also be higher leading to a more rapidly rising groundwater levels.

Land with high groundwater levels adjacent to irrigated areas is likely to respond similarly, regardless of soil type. Salt deposited on the ground by evaporation will show as salt scalding. Sinclair Knight Merz (Department of Resources Development, 1997a,b) estimated that signs of salting will appear within ten years of the watertable reaching within 3 m of the surface.

5.4.2 Agricultural chemicals

Data are not available for nutrients in areas presently under irrigation. The soils have a high Cation Exchange Capacity and in the Ivanhoe Plain require artificial fertilisers. Sinclair Knight Merz (Department of Resources Development, 1997a,b) have therefore predicted nutrient levels of between 0.5 and 3 mg/L and total phosphorus between 0.01 and 0.1 mg/L.

Nearly 100 different chemicals including herbicides, insecticides, fungicides, and growth regulators are used for agriculture in the Ord River Irrigation Area (Siewert, 1998). Amongst these are organochlorides, which are bio-accumulators, residual and highly toxic. Samples taken from PB4 and PSPB1 in 1998 during the long-term test pumping were analysed for organochlorides and organophosphates (O'Boy, 1998), but for all parameters tested, the concentration was below detectable limits for the analytical methods (Appendix 3).

5.5 Groundwater modelling

The primary objective of groundwater modelling in the ORIA has been the prediction of changes in groundwater level under various groundwater accessions from irrigation. PAWA (Humphreys *et al.,* 1995), WRC, Sinclair Knight Merz (Department of Resources Development, 1997a,b), Water Corporation (1997, 1998), and Kinhill (Wesfarmers *et al*., 2000) have all developed digital groundwater models. They all used MODFLOW software (McDonald and Harbaugh, 1984), an internationally recognised code-verified finite difference modelling package. Woodward-Clyde had reviewed available groundwater modelling software and recommended SWAGSIM (Prathapar *et al*., 1994) software, which was specifically designed for application to irrigation areas of less than 4000 ha with shallow watertables (Water Authority of Western Australia, 1995).

Modelling undertaken by PAWA (Humphreys *et al*., 1995) covered the Keep River Plain and eastern Weaber Plain. The modelling provided a first-order prediction of the performance of the Weaber and Keep River Plains under irrigation, and enabled further data needs to be identified. The availability of some monitoring data, though limited, provided a degree of confidence in the model with some indication of the long-term aquifer response to imposed stress.

The Department of Resources Development (1997a,b) commissioned Sinclair Knight Merz to investigate the environmental consequences of the proposed Ord River Irrigation Area Stage 2 development. This included the effect of irrigation on the groundwater regime and the development of numerical models to simulate the groundwater response to present and proposed irrigation. The main objectives of the study are summarised as follows:

- Assess the impact on Stage 2 groundwater levels and likely resulting land salinisation;
- Establish off-site impacts;
- Establish methods for controlling groundwater levels and relate to groundwater management maps;

- Develop guidelines that would enable informed choices for irrigation management that would meet the required groundwater management criteria.

Sinclair Knight Merz collected geological, hydrogeological, and meteorological data from literature sources, the WRC, and the DLPE. They considered some provisional modelling undertaken by the GSWA and PAWA before developing a detailed model for the Ivanhoe Plain. The modellers considered the Ivanhoe Plain and Ord West Bank separately, although in the same model. They developed a further three groundwater models for the Weaber Plain and Knox Creek Plain, Keep River Plain, and Carlton Plain and Mantinea Flats. The Ivanhoe Plain model was the basis for the other three models because of limited information and assumed similar hydrogeological conditions. Detailed calibration of these models was not feasible owing to the lack of water level monitoring data and so they based the calibration on the Ivanhoe Plain model.

The Water Corporation (1997) commissioned Sinclair Knight Merz to study the water balance in the Ord River Irrigation Area, Stage 1. The study objective was to provide a clearer understanding of the hydrological interactions between applied irrigation and rainfall and responses of groundwater levels, drain flows, channel leakage and discharges of nutrients, pesticides and sediments. The Water Corporation of Western Australia (1998) commissioned a further report by Sinclair Knight Merz on control of rising groundwater for Ord River Irrigation Area Stage 1. The main objectives were to define factors contributing to rising groundwater, and to identify potential and preferred control options.

Kinhill developed a model to assess the potential impacts of irrigation activities on the groundwater environment (Wesfarmers *et al*., 2000). The model predicts groundwater levels over time, based on hydrogeological information, infiltration, and groundwater abstraction. They used the model as a design tool and for predicting the groundwater response for the proposed groundwater management strategy.

5.5.1 Ivanhoe Plain and West Bank of Ord

Sinclair Knight Merz (Department of Resources Development, 1997a,b) based the Ivanhoe Plain and Ivanhoe West Bank of Ord model on one developed by the WRC, which assumed interaction between the Ord palaeochannel aquifer and the river system. The model predicted that Ivanhoe Plain groundwater levels would approach within 5 m of the surface within ten years on the eastern side, and within 50 years over most of the plain. Groundwater will drain freely into the incised Ord River from nearby areas and land will remain unaffected. Predictions of groundwater discharge into the Ord River after 50 years ranged from 1380 ML/year for 10 mm/year groundwater accession to 2290 ML/year for 50 mm/year groundwater accession. The part of the model for the West Bank of Ord predicted groundwater levels greater than 5 m below the surface for at least 50 years.

The Sinclair Knight Merz study for the water balance in the ORIA, Stage 1, commissioned by the Water Corporation of Western Australia (1997) concluded that the groundwater model was able to produce the observed long-term response. In addition, irrigation causes groundwater to rise across the plain with the aquifer recharge volume from irrigation and rainfall increasing from 1657 ML/year in 1970 to 11497 ML/year in 1996. The modelled contributions to groundwater accessions from the M1 channel leakage lessened over the years from 3492 ML/year in 1970 to 2777 ML/year in 1996. The modelled total groundwater accession increased from 6192 ML/year in 1980 to 11 070 ML/year in 1996. The modelling showed that three sections of the M1 channel had particularly high leakage and Lake Kununurra contributes to high groundwater recharge in the southern half of the plain. Groundwater accessions average 4 to 5 % of the inputs to the system. System inputs averaged about 140 000 ML/year from 1970 to 1996. Table 10 is a summary of the Water Balance.

The report by Sinclair Knight Merz on the control of rising groundwater for the ORIA Stage 1 identified three main causes of rising groundwater levels (Water Corporation, 1998). These are recharge from Lake Kununurra in the western Packsaddle Plain and southern Ivanhoe Plain, M1 channel leakage in the northern Ivanhoe Plain, and irrigation accessions in the southern Packsaddle Plain and northern Ivanhoe Plain.

5.5.2 Weaber Plain and Knox Creek Plain

The PAWA model (Humphreys *et al.,* 1995) provided a first-order prediction of the performance of the Weaber Plain under a proposed irrigation scheme, and enabled further data needs to be identified. The availability of some monitoring data, though limited, provided a degree of confidence in the model with some indication

Table 10. Summary of water balance

Year	Inputs (ML/year)		Outputs (ML/year)			
	Water delivered to crop	*Rainfall*	*Rainfall runoff*	*Irrigation runoff*	*Groundwater accession*	*Crop water demand ET*
1980	61 189	88 979	50 735	12 638	6 192	82 603
1990	69 023	50 644	23 901	13 805	6 370	75 591
1996	113 492	105 930	62 601	22 698	11 070	123 053
25 year mean	54 880	84 583	47 658	10 975	5 228	75 600

of long-term behavioural patterns and aquifer response to imposed stress. The model assumes that the Keep River intercepts discharge from the Weaber Plain independently from the Keep River Plain discharge and therefore groundwater movement between the plains would be insignificant. This facilitated the development of an independent model for each plain. Short-term test pumping results from the Weaber Plain and Knox Creek Plain and from other parts of the Ord River Irrigation Area provided an indication of the possible variations in hydraulic parameters. The only long-term monitoring data available for model calibration were from the Cave Spring Gap area in the western Weaber Plain; these gave first-order calibration. The paucity of regional data and sketchy understanding of regional groundwater flow regimes resulted in the development of a relatively coarse 2D model.

A sensitivity analysis determined that the parameters to most influence the Weaber Plain model were the specific yield and recharge values. These parameters had inverse and direct proportionality effects on rising groundwater levels respectively. The value for transmissivity had a lesser effect; decreasing the transmissivity by a factor of two resulted in a water level change of less than 10%. Model calibration involved replicating the groundwater levels measured in the Cave Spring Gap monitoring bores. As a first step, the calibration varied transmissivity and storage. The model used a constant specific yield of 0.1, which is typical for alluvium, an alluvial channel bulk transmissivity of 500 m^2/d, and a hydraulic conductivity of 30 m/d. The bulk transmissivity is much less than that obtained from analyses of test pumping results where the screens were set in only the most productive alluvium (Humphreys *et al.,* 1995).

The Weaber Plain modelling predicted no major problems in the first ten years under irrigation. The Ord palaeochannel should cause irrigation developments on the Weaber Plain in Western Australia to have a major influence on water level changes on the Weaber Plain in the Northern Territory. They concluded that before development, investigations are required to better define the location and depth of the Ord palaeochannel, and subcropping Milligans Formation shale (Humphreys *et al.,* 1995).

The LEACHM infiltration modelling indicated that an accession rate of 50 mm/year would be the lowest likely from the irrigated farmland and that the average rate would approach 100 mm/year (Wesfarmers *et al.,* 2000). Kinhill modelled accession rates of 50 mm/year, 100 mm/year and 150 mm/year. The Sinclair Knight Merz modelling considered a maximum recharge rate of 50 mm/year (Department of Resources Development, 1997a, 1997b).

The basis for the Sinclair Knight Merz (Department of Resources Development, 1997a) Weaber Plain and Knox Creek Plain model was one developed by the Water and Rivers Commission. The model showed that following a steady-state condition, 50 years of irrigation would cause the area to experience rising groundwater levels. Six scenarios were tested and in the case of high channel leakage, the model became unstable, indicating that high channel leakage is not sustainable. The model demonstrated sensitivity of shallow bedrock areas to accessions. Large areas have a deep watertable with significant storage for accessions before groundwater reaches a detrimental level. All the models showed areas where groundwater was rising after 50 years. The Weaber and Knox Creek Plain have restricted natural drainage through the palaeochannel system or to the river system. In all conditions modelled, groundwater discharge to rivers increases over time. Predictions of groundwater discharge into the Keep River after 50 years ranged from 110 ML/year for 10 mm/year groundwater accession, to 1050 ML/year for 50 mm/year groundwater accession.

The predictions for the Kinhill modelling (Wesfarmers *et al.,* 2000) for an accession rate of 50 mm/year are very similar to the Sinclair Knight Merz model (Department of Resources Development, 1997a) with a recharge rate of 50 mm/year. The critical area is in the Western Weaber Plain to the east of Brown Rock, where predicted groundwater levels reach within 5 m of the ground surface within 20 years. The modelling also predicts a high groundwater level within 20 years in the area surrounding the Weaber Plain balancing storage dam. Groundwater discharge to the Keep River, including the Keep River Plain, is predicted to increase from 4550 ML/year in year 10 to 6580 ML/year in year 50. This compares with 2350 ML/year at year 50 calculated by Sinclair Knight Merz (Department of Resources Development, 1997a).

Kinhill modelling simulated an accession rate of 100 mm/year without pumping (Wesfarmers *et al.,* 2000). The model predicted that within 20 to 30 years of irrigation starting, the western Weaber Plain would experience problems with rising groundwater levels due to the shallow basement and the absence of a palaeochannel to assist drainage. The model also predicted that in a small area east of Brown Rock, in less than five years groundwater levels would rise to within 5 m of the surface with some waterlogging within 20 years. They predicted that the western Knox Creek Plain, where the bedrock is assumed to have a low permeability, would experience rising water level problems within 20 years and become waterlogged by year 50. Groundwater discharge to the Keep River, including the Keep River Plain, would increase from 7045 ML/year in year 10 to 12 000 ML/year in year 50. The salinity of the accession water is expected to be approximately 1900 mg/L TDS, which is within the range of groundwater salinity beneath the Weaber Plain. Therefore, at an accession rate of 100 mm/year, the modelling indicated the need for active groundwater control. An accession rate of 150 mm/year, even with pumping, would not be sustainable for much over 40 years without the extensive use of field drains.

5.5.3 Keep River Plain

The PAWA model (Humphreys *et al.*, 1995) provided a first-order prediction of the performance of the Keep River Plain under irrigation that enabled further data needs to be identified. Short-term test pumping results from the Keep River Plain and from other parts of the Ord River Irrigation Area provided an indication of the possible variations in hydraulic parameters. The paucity of regional data and sketchy understanding of regional groundwater flow regimes resulted in the development of a relatively coarse 2D model.

As with the Weaber Plain, a sensitivity analysis determined that the parameters most likely to influence the model were the specific yield and recharge values. These parameters had inverse and direct proportionality effects on rising groundwater levels respectively. The value for transmissivity did not have as significant an effect. Generally, decreasing the transmissivity by a factor of two resulted in a water level change of less than 10%. The Keep River Plain model was highly dependent on the presence of the surrounding rivers as drainage paths. The capacity of these to intercept and transmit seepage needs to be confirmed. The parameters used were the same as those in the Weaber Plain, that is, specific yield 0.1, transmissivity 500 m^2/d, and hydraulic conductivity 30 m/d.

The basis for the Sinclair Knight Merz (Department of Resources Development, 1997a) Keep River model was one produced by the PAWA described above (Humphreys *et al.,* 1995). The modellers found river conductance was the major parameter controlling groundwater levels, which by adjustment gave a reasonable calibration. The modelled response to irrigation differed from other areas due to the close proximity of the rivers and the high watertable. The modelling predicted that after 50 years of irrigation, groundwater would be higher in the northern part of the plain and lower in the southwest. For low recharge, only the northern end of the Keep River Plain had groundwater within 5 m of the surface within 50 years. For a recharge rate of 50 mm/year all of the Keep River Plain had a high watertable within 30 years. High M2 channel accessions caused a high watertable within 10 to 20 years. The model predicted a high watertable outside the course of the Ord palaeochannel within 10 to 20 years and considered only limited hydraulic connection between the palaeochannel and the permeable Permo-Carboniferous sandstone. An increase in discharge to the rivers was predicted as groundwater accessions rise. Groundwater discharge predictions into the Keep River after 50 years of irrigation ranged from 230 ML/year for a groundwater accession 10 mm/year to 1300 ML/year for 50 mm/year groundwater accession.

Kinhill predicted that accession rates of 50 mm/year, 100 mm/year, and 150 mm/year would maintain the relatively shallow groundwater level of the Keep River Plain in the natural state. The proximity of the Keep River and Sandy Creek and the highly permeable Ord Palaeochannel beneath the Keep River Plain and the permeable Permo-Carboniferous sandstone bedrock will all serve to regulate the water levels and prevent waterlogging.

5.5.4 Carlton Plain and Mantinea Flats

Sinclair Knight Merz (Department of Resources Development, 1997b) based the development of the Carlton Plain and Mantinea Flats model on limited borehole data and assumed that hydrogeological conditions were similar to those of the Ivanhoe Plain. The model treated the Ord River as a river boundary and the eastern and western ends of the Ord River as constant-head boundaries. The model calibration assumed watertable conditions were constant from 1965 to 1995. The modellers obtained the best model response by adjusting river conductance and head to achieve a reasonable calibration. The model predicted that rising groundwater will first affect the western end of the plain. In all cases, rising groundwater will not affect the eastern end of the plain within 50 years and groundwater discharge to the rivers will increase. Predictions of groundwater discharge into the Ord River after 50 years of irrigation ranged from 320 ML/year for a groundwater accession of 10 mm/year to 1700 ML/year for 50 mm/year groundwater accession. The model predicts that within ten years at a recharge rate of 50 mm/year large areas of the plain in the west will have groundwater levels within 5 m of ground level.

6 Implications for groundwater management

6.1 Introduction

Irrigation in the Ord River Irrigation Area relies on the supply of surface water from Lake Argyle. The Kununurra town water supply borefield is currently the only user of groundwater, although this draws Ord River water through the basal sand and gravel aquifer directly from Lake Kununurra. Groundwater for water supply is therefore of only minor importance in the Ord River Irrigation Area.

The main objective of groundwater management is to maintain the watertable below the crop root zone, to ensure that there are no reductions in crop yields (Sherrard, 1998). In some areas groundwater levels are already approaching the ground surface, and therefore groundwater control measures are required.

Waterlogging and salinity can affect crop yields. Plant roots require air as well as water, and if waterlogging of plant root zones occurs over extended periods, loss of crop yield or even crop failure are likely to follow. High salinity is also a factor, depending on the plant species. Sugar cane is better adapted to waterlogging than other crops, owing to its origin being in the wet tropics. Depending on the species, waterlogging causes crops to use increased carbohydrate reserves to fuel the root system. Nitrogen deficiency is not usually a problem because of the ability to use ammonia formed under waterlogged conditions, but other nutrient imbalances can occur. In Queensland, where groundwater is within 0.5 m of the ground surface, estimated yield losses are 0.5 tonne of cane per hectare. Moderate salinity leads to reduced sugar recovery and quality. High sodicity has also led to total crop failure (Sherrard, 1998).

Cotton is particularly susceptible to waterlogging because it evolved in dry climatic conditions, but is relatively tolerant to salinity. Sodicity causes difficulty in replacing soil moisture. Bananas, maize, and sweet corn are also sensitive to waterlogging. Tomatoes and other crops are susceptible to diseases encouraged by waterlogging. Bananas, citrus, pawpaw, cucumber, beans, maize, sunflower and sweet corn have a low to very low salinity tolerance, whereas tomato and watermelon are moderately tolerant to salinity.

6.2 Groundwater management options

Local conditions largely determine the selection of methods for controlling groundwater levels. Preventative measures might include the lining of water supply channels and the optimisation of irrigation water application with surface drainage. Remedial measures might encompass controlling groundwater levels using phreatophytic plants, subsurface field drains and, where ground conditions permit, pumping from water bores (Robinson, 1998).

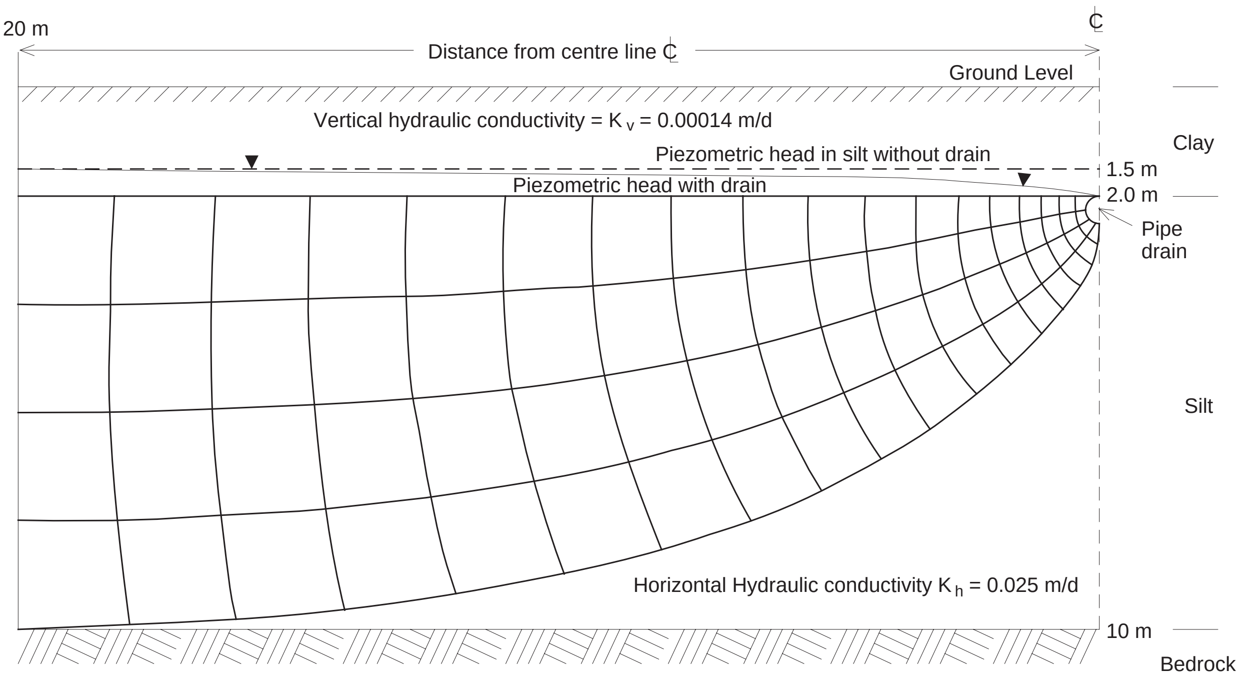
For water bores to be economically feasible in soil drainage, a highly transmissive aquifer must underlie a drainable soil profile, so that pumping can result in a reduction in hydraulic head in the aquifer over a large area. This induces vertical drainage from the overlying less permeable formations, which enables groundwater levels in these upper formations to be controlled.

The results from the short-term pumping test on the Packsaddle and Ivanhoe Plains (O'Boy, 1997) indicated that pumping the underlying gravel aquifer could vertically drain the overlying silt. The long-term pumping tests (O'Boy, 1998) confirmed the short-term results when significant drawdown was measured on the Ivanhoe Plain at distances of up to 630 m from the production bore and with measurable effects projected beyond 1000 m. On Packsaddle Plain steady state was reached after a few days of pumping, probably because the groundwater cone of depression reached Lake Kununurra 1500 m away, which then acted as a constant-head recharge boundary.

Areas not underlain by basal sands and gravels are more difficult to drain. One solution could be the installation of deep field drains, which might need drainage collection sumps with pumps. The initial development of this method was as an alternative to vertical pumped wells (Cavelaars, 1980). A continuous plastic pipe, with no plates to protect the trench from collapsing during pipe installation, can be laid with a continuous excavator ('deep drainer'), beneath the clay soil in the silty alluvium, about 2 m below ground level. Figure 23 is a flow net that shows that for a 10 m deep profile a drain spacing of 40 m is required. The flow net indicates that the main function of the method is to drain groundwater from the underlying silt, which prevents groundwater moving into the overlying clay. Directly draining the overlying clay would be significantly more difficult because of its lower permeability and maintenance of the integrity of the black soil clay would reduce groundwater accessions. Drains in a thinner alluvial profile might need to be spaced at closer intervals.

Sinclair Knight Merz (Water Corporation, 1998) considered eight options for controlling rising groundwater levels on the Ivanhoe Plain (Table 11). In terms of cost and effectiveness, deep pumping from the Ord Palaeochannel sandy gravel was the most viable option. Lining of the M1 main supply channel, would help reduce groundwater level rise near the channel and decrease pumping costs from any control option. A combination of deep pumping and lining the M1 channel was potentially the most effective management option.

The investigations on the Ivanhoe Plain concerned methods to control rising groundwater levels that are relevant for the proposed Stage 2 Ord River Irrigation Area expansion. The Stage 2 drilling investigations indicated that similar conditions exist along the present and previous courses of the Ord River. The exception is the Knox Plain, where limited pumping tests indicate that the permeability of the Keep River alluvium is lower than that of the Ord River alluvium.



Flow to pipe drain

Number of flow lines	$= n_f = 4$
Number of equipotential drops	$= n_d = 18$
Head	$= h = 0.5$ m
Flow to pipe drain per metre width, m_w	$= Q = 2K_h h \frac{n_f}{n_d}$
	$= 2 \times 0.025 \times 0.5 \times \frac{4}{18}$
	$= 0.0056$ m³/d/m_w
	$= 2$ m³/yr/m_w

Drain spacing

Groundwater accession	= 50 mm/yr
Groundwater accession to 1 m²	= 0.05 m³/yr/m²
Flow to pipe drain per m_w	= 2 m³/yr/m_w
Area drained by pipe drain per m_w	= 2 / 0.05
Drain spacing to maintain Groundwater level at 1.5 m below ground level	= 40 m

ORDFIG23

Figure 23. Field drain flow net

Table 11. Options for controlling rising groundwater levels (after Water Corporation, 1998)

Options	*Physical efficacy %*	*Probability of success %*	*Adoptability*	*Flexibility*	*Management*	*Rank*	*Comments*
Do nothing	0	0	Very good	Very good	Very Good	7	Areas affected by waterlogging will increase
Deep pumping	90	80	Good	Good	Good	1	Hydrogeological properties determines drawdown
Shallow pumping	80	70	Poor	Poor	Very poor	5	Spatial variation of hydraulic properties not known
Tile drains	90	70	Very poor	Poor	Moderate	6	As above
Lining M1	<10	50	Moderate	Good	Good	2	Used in conjunction channel with other options
Surface drainage	<5	10	Good	Good		3	Will only reduce rate improvement of groundwater level rise
Irrigation efficiency improvement	<5	10	Good	Good	Poor	4	As above
Stop irrigation	100	100	Very poor	Very poor	Very good	8	Large loss of income

The Sinclair Knight Merz (SKM) groundwater modelling (Department of Resources Development, 1997a,b) identified four management categories ranging from low to intensive management effort. Kinhill (Wesfarmers *et al.*, 2000) provided a similar classification based on modelling. Table 12 compares the classification systems.

Table 12. Groundwater management classifications

Description	*Management action required*	*SKM Category*	*Kinhill Zone*
Passive groundwater management—Groundwater drains naturally and reaches steady state at a deep level.	None		1
Minor groundwater management—Groundwater levels rise slowly under irrigation and there is enough storage for about 50 years of irrigation.	Monitoring groundwater level and quality.	A	2
Moderate groundwater management—Insufficient natural groundwater drainage leads to groundwater levels rising moderately fast under irrigation but this can be controlled by bores pumping from moderately to highly permeable basal sandy gravels.	Monitoring groundwater level and quality for waterlogging and salinity; dewatering bores.	B	3
Significant groundwater management—Restricted natural groundwater drainage leads to groundwater levels rising at moderate to high rates under irrigation. This can be controlled either by a higher density of bores pumping from moderately permeable basal gravelly sands or by field drains or equivalent.	Monitoring groundwater level and quality for waterlogging and salinity; dewatering bores; field drains or equivalent.	C	4
Intensive groundwater management—Poor natural drainage due to low permeability or shallow bedrock leading to groundwater rising rapidly under irrigation, which can be controlled by field drains or equivalent.	Monitoring groundwater level and quality for waterlogging and salinity; field drains or equivalent.	D	4
Unsuitable for long-term irrigation—Extremely restricted groundwater drainage leads to groundwater levels rising at high rates from shallow depths. Field drains or equivalent not viable.	Long-term irrigation avoided.		5

Table 13. Modelling predictions (after Department of Resources Development, 1997a,b)

Area	*Model*	*Case* 1 *10 mm/year accession*	2 *25 mm/year accession*	3 *50 mm/y accession*	4 *5 mm/year accession in categories A, B only*	5 *25 mm/year accession and 20 mm/d channel leakage*	6 *25 mm/year accession and and pumping*
					ML/year		
Ivanhoe Plain	Increased discharge		3 110				
	Pumping in model						
	Required pumping		4 735				
Ivanhoe Plain West bank of Ord	Increased discharge	1 380	1 710	2 290	1 530		1 537
	Pumping in model						200
	Required pumping	810	860	950	830		1 035
Weaber Plain and Knox Creek Plain	Increased discharge	110	430	1 050	155	unstable	245
	Pumping in model						4 100
	Required pumping	3 500	8 750	17 500	4 700	unstable	8 750
Keep River Plain	Increased discharge	230	750	1 300	670	820	225
	Pumping in model						2 300
	Required pumping	1 800	4 400	8 800	9 400	4 400	4 400
Carlton Plain and Mantinea Flats	Increased discharge	320	920	1 700	780		590
	Pumping in model						3 190
	Required pumping	2 570	6 300	12 830	4 490		6 300

Some areas defined by Sinclair Knight Merz (Department of Resources Development, 1997a) as Category D, lie over permeable Permo-Carboniferous sandstones and Carboniferous limestone bedrock (Plate 2). Further studies of the bedrock in the western Knox Creek Plain, eastern Weaber Plain, and southern Keep River Plain might show that pumping from the bedrock or natural groundwater drainage into the bedrock would make irrigation easier to manage.

The results from the modelling undertaken by Sinclair Knight Merz (Department of Resources Development, 1997a,b) indicate the range of pumping required in the long term for different accession rates to achieve a water balance (Table 13).

The results from the modelling undertaken by Kinhill (Wesfarmers *et al.*, 2000) indicate the range of pumping required in the long term for different accession rates to achieve a water balance (Table 14). At 150 mm/year accession with pumping, the modelling indicates that extensive use of field drains would be required after about 40 years.

Seepage losses from channels can be minimised by lining where required and the design criteria for field layouts can include the requirement to minimise groundwater accessions. The development will need to progressively install groundwater control facilities as irrigation proceeds and choose crop types that permit the control of groundwater levels to avoid land degradation. Minimising accession rates is the primary way of lengthening the time before mitigation options, such as deep pumping, are required. The project area includes no land classified as Zone 5 (Wesfarmers *et al.*, 2000), where it is unlikely that irrigation would be able to proceed without the risk of adverse effects, even with the best management.

Based on the available hydrogeological information (Plates 1 and 2) and the work described above the ORIA has been subdivided into three areas where different groundwater control measures are likely to be required (Fig. 24). These are areas

- that naturally drain;
- suitable for deep pumps because of the presence of basal sands and gravels or proven permeable bedrock;
- unlikely to be suitable for dewatering bores but might be suitable for deep field drains or equivalent.

Table 14. Modelling predictions (after Wesfarmers *et al.*, 2000)

Watercourse	*50 mm/year accesssion*	*50 mm/year with pumping at 12 045 ML/year*	*100 mm/year accession*	*100 mm/year accession with 12 045 ML/year*	*150 mm/year accession with 20 440 ML/year*
	Predicted groundwater discharge to watercourse (ML/year)				
Knox Creek					
Year 10	0	0	0	0	0
Year 20	0	0	39	0	0
Year 30	0	0	226	25	0
Year 40	73	0	430	61	63
Year 50	174	0	689	96	265
Keep River					
Year 10	4 550	4 550	7 044	7 044	6 814
Year 20	5 072	4 675	8 515	8 116	7 864
Year 30	5 628	4 741	9 689	8 847	8 693
Year 40	6 148	4 784	10 749	9 361	9 342
Year 50	6 479	4 813	11 977	9 768	9 849
Sandy Creek					
Year 10	375	375	1 118	1 118	1 508
Year 20	347	255	1 288	1 134	1 665
Year 30	361	204	1 427	1 168	1 780
Year 40	382	184	1 535	1 205	1 863
Year 50	402	177	1 615	1 236	1 923

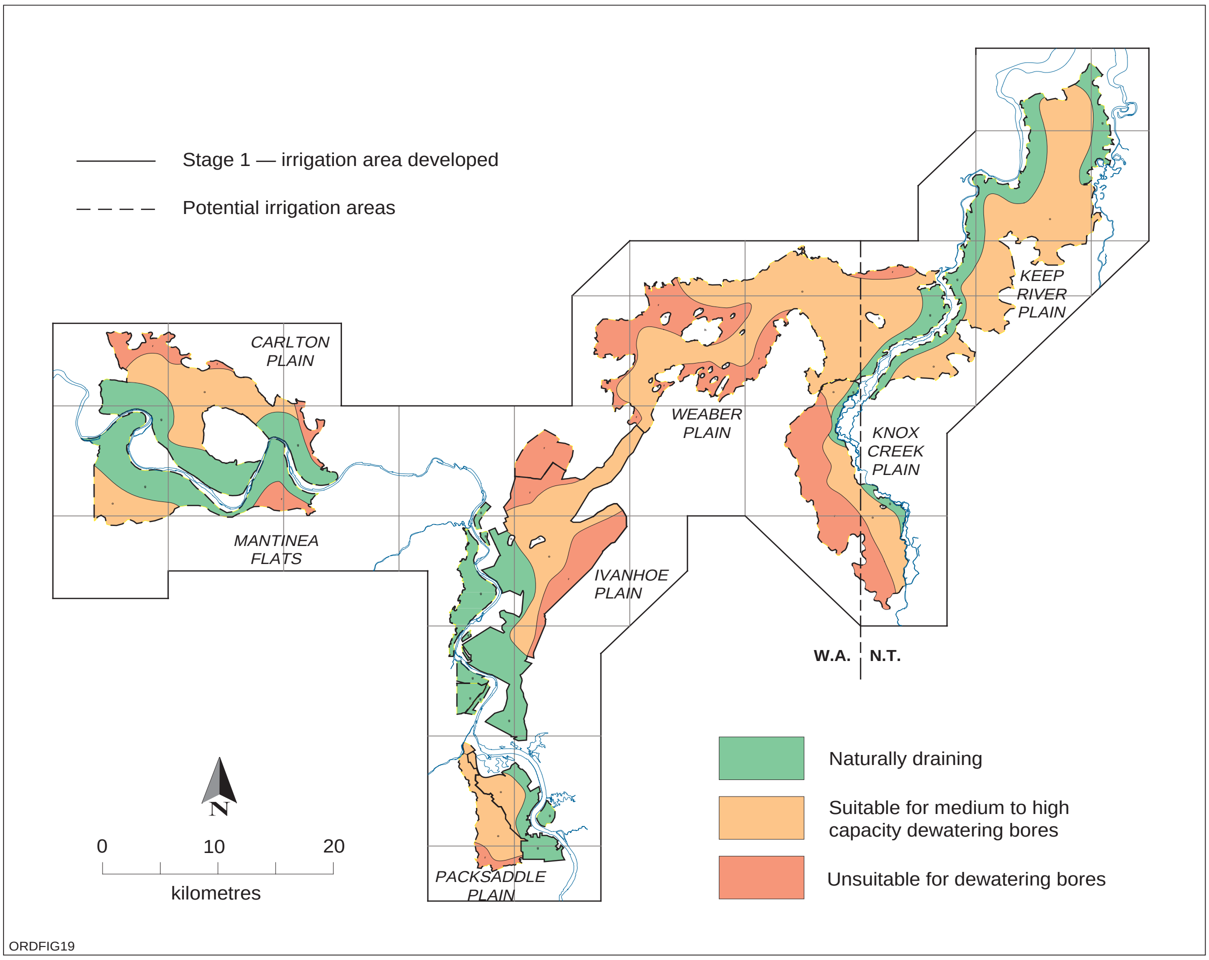


Figure 24. Applicable groundwater control measures

6.3 Local strategies for managing groundwater

6.3.1 Packsaddle Plain and Ivanhoe Plain

This Report has already considered the options for controlling groundwater levels on the Packsaddle Plain and Ivanhoe Plain. Groundwater discharge to the Ord River is significantly smaller than the current channel outfalls from the existing Ivanhoe Plain drainage. Sinclair Knight Merz predicted that if the present situation on the Ivanhoe Plain continues, then discharge will increase by 9810 ML/year and the actual pumping required will be 1930 ML/year (Department of Resources Development, 1997a).

Irrigation on the West Bank of Ord will result in rising groundwater levels, which will increase discharge to the Ord River. Sinclair Knight Merz considered that areas closest to the Ord are least likely to be degraded by rising groundwater levels and that overall there is only a low to moderate risk. They predicted that pumping from the underlying palaeochannel basal sands and gravels would be able to control groundwater levels and reduce discharge to the Ord. Enhanced discharge from the West Bank of Ord could maintain the overall salt balance and preserve a groundwater system of low-salinity groundwater (Department of Resources Development, 1997a).

6.3.2 Weaber Plain, Knox Creek Plain, and Keep River Plain

Underlying the Weaber Plain from the WA/NT border to the Keep River is the Ord palaeochannel. Hydrological modelling (Humphreys *et al.,* 1995) has shown that long-term sustainability is dependent on dewatering of the irrigation areas to limit rising watertables. Groundwater is generally brackish, with significant variations in soil salinity in the unsaturated zone. At the edges of the Ord palaeochannel, impermeable shales may occur at shallow depths, and will significantly limit the natural drainage beneath irrigation areas adjacent to hills. The modelling predicted that no major problems would be expected in the first ten years under irrigation, so there is sufficient time to evaluate performance and devise a water management scheme based on the evaluation. In addition, irrigation developments on the plains in Western Australia will have a major influence on water level changes and will control the rate of rise. They concluded that before developing this sub-area, work is required to better define the location and depth of the palaeochannel, and of any patches of subcropping shale. The report recommended that appropriate ground geophysics, focussed at soil-conductivity measurements, would provide this information.

Where shallow Milligans Formation shale subcrops beneath Knox Creek Plain developers can expect problems with waterlogging (Humphreys *et al.,* 1995). The Keep River sand and gravel alluvial channel covers less than 30% of the Knox Creek Plain, so it would not provide the extensive drainage needed for irrigation. They considered that, based on modelling and investigations in other areas, groundwater dewatering using large capacity bores is not viable because high permeability alluvium is lacking over much of the area. Developers would need to consider alternative drainage measures. Medium-capacity bores might be feasible in the Keep River alluvium, and in areas where Devonian and Carboniferous dolomitic limestone subcrops.

Sinclair Knight Merz modelling predicted that irrigation would cause groundwater levels to rise continuously under all the modelled scenarios. The modelling showed that without groundwater control measures, the Weaber, and Knox Creeks would become permanent drainage features fed by groundwater discharge, rather than intermittent streams. They estimated that groundwater abstraction of 8750 ML/year would likely be required to control watertable rises on the Weaber and Knox Creek Plains. The thickness of the unsaturated zone gives time to plan before a shallow groundwater regime is established. The area of wetland around Milligans Lagoon deserves special protection to preserve the natural habitat. The geology suggests that because of poor hydraulic connection, the groundwater conditions in the alluvium will not affect Point Springs, which have a source in the Permo-Carboniferous sandstone bedrock (Department of Resources Development, 1997a).

The volume of groundwater in storage in the alluvium on the Weaber Plain and Knox Creek Plain is small in comparison to the volume of unsaturated storage available for groundwater accessions from irrigation. The Sinclair Knight Merz modelling predicted that the present groundwater chemistry will change to become more similar to that of the accession water, but that salinity will not change significantly, generally remaining in the range of 1000 to 10 000 mg/L TDS.

They estimated that, without pumping, about 15 000 tonnes/year of salt will accumulate in the ground, but that with pumping this might be recycled in the distribution system, as the salt volume is small in comparison with the irrigation deliveries. Where low-permeability Milligans Formation shale bedrock is present, there may be a limited potential for this rock to contribute salt to the groundwater (Department of Resources Development, 1997a).

The area that lies south of the Keep River over extensive Milligans Formation shale contains saline groundwater, and the salinity of the unsaturated zone, as measured in EC_{1-5} tests, is the highest in the ORIA. Natural drainage is poor, and any irrigation development could result in groundwater rising to the surface and causing soil waterlogging. Groundwater dewatering using large capacity bores is not viable and developers would need to consider alternative drainage measures (Humphreys *et al.,* 1995).

Where the Ord palaeochannel underlies the area to the east of the Keep River, soil salinities are generally moderate, and brackish bore yields of more than 5 L/s are obtainable. Humphreys *et al.* (1995) predicted that developers can expect natural drainage to disperse irrigation recharge, and potential for irrigation development is good and is feasible without dewatering if the recharge is less than 75 mm/year. Ord palaeochannel coarse alluvium underlies the area and dewatering bores are viable. The groundwater conductivity is approximately 3000 µS/cm and may lower with time (Humphreys *et al.,* 1995).

The Ord Palaeochannel and permeable Permo-Carboniferous sandstone underlies the northern Keep River Plain. As this area is adjacent to the tidal Keep River and Sandy Creek, salt contents are very high in both the unsaturated zone and the underlying groundwater. Modelling predicts that the broad palaeochannel will provide natural drainage for irrigation accession rates of up to 75 mm/year (Humphreys *et al.,* 1995). Lateral groundwater drainage is to the adjacent Keep River and Sandy Creek and therefore dewatering and re-use schemes should not be required. The groundwater salinity is approximately 14 000 mg/L TDS and the likely variation in water quality with time is unknown. The upper soil profile salinity as measured in EC_{1-5} tests is high. Humphreys *et al.* (1995) considered that careful management of irrigation application rates would be required as the strata underlying the black soil has higher clay content and is more saline than strata under the other areas.

Groundwater levels will rise in response to irrigation across the bulk of the Keep River Plain. This will increase discharge to the Keep River and Salty Creek. Pumping of groundwater from the Ord palaeochannel will be more effective if there is significant connection with the permeable Permo-Carboniferous sandstone, as this would also dissipate groundwater accessions over a greater area, reducing the rise in groundwater levels. Sinclair Knight Merz estimated that the required pumping of 2300 ML/year is conservative since the model only considered limited hydraulic connection between the Ord Palaeochannel and the permeable Permo-Carboniferous sandstone. An increase in discharge to the rivers was predicted as groundwater accessions rise. The entire irrigation area would require a pumping rate of 4400 ML/year but the Ord palaeochannel was only able to sustain 2300 ML/year (Department of Resources Development, 1997a).

The Sinclair Knight Merz modelling predicted that increasing groundwater discharge would occur as baseflow in the lower reaches of the Border Creek and Keep River and that this could create permanent flows or higher permanent pool salinity during the dry season. The change would take tens of years, which gives time to design specific remedial action and refine groundwater-control designs. The modelling assumes that there is equilibrium on the Keep River Plain between the tidal levels and the groundwater system, with groundwater discharge probably occurring when the tide is low. Increasing groundwater levels due to irrigation will increase groundwater discharge, which could increase salinity in some semi-tidal reaches of the Keep River. Studies have revealed little about the interrelationship between the groundwater system and semi-tidal reaches, so it is difficult to predict the precise impact of rising groundwater levels. Kinhill predicts that evapotranspiration will account for most groundwater seepage in the riverine areas and that the wet season would see most of the salt accumulated on the surface from evaporation flushed out to sea (Wesfarmers *et al.,* 2000).

Indications from the Sinclair Knight Merz modelling are that in the western Keep River Plain, groundwater salinity will remain largely unchanged, with little mobilisation of salt from the unsaturated zone. For the remaining areas, groundwater salinity will remain high if there is significant salt stored in the unsaturated zone. They estimated that there would be little change in the Keep River Plain groundwater salinity, but that pumping will produce considerable volumes of saline water for disposal, perhaps directly to the sea. In addition, approximately 15 000 tonnes/year of salt will be discharged to rivers (Department of Resources Development, 1997a).

Overall, the Sinclair Knight Merz modelling predicted that on the Weaber, Knox Creek, and Keep River Plains, much of the area could remain unaffected for at least 50 years with groundwater pumping increasing this area. The expectation is that land in Management Category D could eventually show signs of salting in the long term (Department of Resources Development, 1997a).

The Kinhill modelling predicted that at 100 mm/year accession and 12 045 ML/year pumping, groundwater levels would remain deeper than 5 m for 50 years across the Keep River Plain, eastern Weaber Plain, and eastern Knox Creek Plain. Where the Ord Palaeochannel and Keep River basal sands and gravels are not present, the modelling predicts higher groundwater levels. The western Weaber Plain and western Knox Creek Plain are predicted to have groundwater levels within 5 m of ground level by five and 30 years respectively. Waterlogging is a possibility in areas of the western Weaber Plain by year 30 and in the western Knox Creek Plain by year 50. The proposed balancing storage dam on the Weaber Plain is shown to have high water levels within 5 m of ground level by year 10 and local waterlogging by year 30. The effect of the Devonian and Carboniferous dolomitic limestone was not modelled owing to the unpredictable nature of basement permeability and uncertainty that pumping would lower groundwater levels (Wesfarmers *et al*., 2000).

6.3.3 Carlton Plain and Mantinea Flats

Modelling predicts that for all scenarios groundwater levels will rise (Department of Resources, 1997b). Over the bulk of the area, groundwater discharge into the Ord River will offset increasing groundwater levels. Least affected will be the eastern end of the area. In all the conditions modelled, groundwater discharge to the rivers will increase but pumping will have significant benefits. The maximum sustainable pumping from the coarser alluvium was 3190 ML/year which, at a recharge rate of 25 mm/year, is only half the required pumping of 6300 ML/year for the entire area. The model predicts that, at a recharge rate of 50 mm/year, within ten years large areas of the plain in the west will have groundwater levels within 5 m of ground level.

According to the Sinclair Knight Merz modelling, there will be a long lead-time to refine groundwater-control designs before groundwater levels become critical. Rising groundwater and higher salinity could affect the freshwater wetlands south of House Roof Hill but groundwater pumping is likely to be very effective in controlling groundwater levels. The southern edge of the Mantinea Flats is at a lower level than the levee area near the Ord River and rising groundwater levels may first affect this area (Department of Resources Development, 1997b).

Groundwater salinity is variable (Fig. 6). The volume of groundwater currently in storage in the alluvium is small when compared with the introduced volume from over 50 years of irrigation. Therefore, groundwater salinity should decrease and approach that of the accession water. Areas close to the Ord River might have a reduction in groundwater salinity as groundwater discharge increases. For the middle and eastern part of the plains, Sinclair Knight Merz predicted that groundwater salinity will remain in the range of 1000 to 10 000 mg/L and, based on the Ivanhoe Plain, assumed that there is no significant salt store in the unsaturated zone. In the west of the plains the groundwater salinity is over 10 000 mg/L and increases westward towards the sea (Department of Resources Development, 1997b).

Under the Sinclair Knight Merz median case 2 (Table 13), the annual input of salt to the groundwater system is 12 610 tonnes/year based on an average accession water salinity of 2000 mg/L. Average discharge of salt to the rivers is 9200 tonnes/year based on an outflow salinity of 10 000 mg/L. In order to maintain a salt balance groundwater pumping is also required. This pumping will also maintain the water balance. They estimate that the volume of salt in pumped groundwater would be small in comparison with the irrigation deliveries and could possibly be recycled in the distribution system. If the groundwater is not pumped, the salt export equilibrium will be reached when the average groundwater salinity is about 12 000 mg/L (Department of Resources Development, 1997b).

After Stage 2 is operational, the proposed flow in the Ord River will still be substantial, and calculations predict that groundwater inflow is not expected to affect river-flow salinity. In the Sinclair Knight Merz case 2, up to 5 kg of nitrate per day may eventually be discharged into the Ord River (Department of Resources Development, 1997b). No data on phosphorus loads are available; however, elevated levels in groundwater are not expected because the black soils are known to be highly effective in binding phosphorus (Wesfarmers *et al.,* 2000).

6.4 Summary

With careful management, salinity problems arising from current and proposed irrigation areas can be minimised. Continued effort will be required in all irrigated areas to minimise accessions to the watertable. This will limit groundwater rises and reduce costs of subsequent groundwater control measures.

Areas of natural drainage, and areas where large capacity production bores are likely to be effective in limiting groundwater rise, have been identified (Fig. 24). In the remaining areas, groundwater management to avoid salinity problems is possible but will require particular attention to minimising accessions and the construction of deep, closely spaced field drains (or equivalent measures) in the medium term. These will be expensive but necessary if irrigation is to continue in the long term.

7 Conclusions and recommendations

The Ord River Irrigation Area (ORIA) is underlain by a sequence of alluvial sediments deposited by the Ord or Keep Rivers. The sediments consist of basal sandy gravels, overlain by a fining-upward sequence. The sandy gravels underlie the greater part of the irrigation area, although only fine-grained sediments are present along the flanks. Bedrock consists mainly of low-permeability basalt and shales in the west of the ORIA; in the east, there is more-permeable limestone and sandstone.

Groundwater salinity ranges from fresh, beneath the Ivanhoe and Packsaddle Plains, to saline beneath the northern Keep River Plain, Carlton Plain, and Mantinea Flats. Irrigation accessions of lower salinity water may lead to lower groundwater salinity.

Natural groundwater recharge to the alluvial aquifer is mainly from the Ord and Keep Rivers with only a minor component of recharge from direct rainfall. The watertable has risen under the existing irrigation area owing to accession from the irrigation bays and irrigation channels and drains. Water levels are now rising at rates up to 0.45 m per year, and are already within 1 m of the surface in the northern Ivanhoe Plain. Water levels may have already stabilised in the Packsaddle Plain. Areas close to the Ord River are free draining, but in the Weaber and Knox Creek Plains, there will be a need to control groundwater accessions from irrigation to ensure that the groundwater does not rise into the soil profile.

Modelling ORIA suggests that groundwater levels in Stage 2 areas will rise close to the surface within several tens of years, and that groundwater-control measures will be needed especially on the Weaber and Knox Creek Plains. The modelling indicated that the Carlton Plain, Mantinea Flats, and west Ivanhoe Plain area at a lower risk from high groundwater levels because the presence of the incised Ord River provides significant natural drainage. The Keep River Plain is also at lower risk because of free flow from the sandy gravels of the Ord Palaeochannel, through permeable sandstone bedrock drainage, to the Keep River and Sandy Creek.

Preliminary studies on the Ivanhoe and Packsaddle Plains have demonstrated the effectiveness of groundwater pumping to reduce water levels where the gravel aquifer is present. However, in areas not underlain by basal sands and gravels, such as Martins Location, Green Location, and parts of Stage 2, further investigation of the use of deep field drains or other methods is required.

The investigations carried out to date are sufficient for regional planning, but a more detailed understanding of groundwater conditions will be required for design of irrigation and groundwater control in the Stage 2 areas in order to ensure sustainable development. Without careful management, inappropriate irrigation practices will result in poor utilisation of surface and groundwater resources, groundwater contamination, land and water salinisation, damage to soil structure and fertility, and detrimental environmental effects. With careful management, the risks of salinity problems arising from irrigation can be minimised.

The Water and Rivers Commission and Agriculture Western Australia are working with Stage 1 irrigators to improve current management. The co-proponents of the Stage 2 Sugar project (Wesfarmers *et al.,* 2000) have made commitments to the implementation of groundwater-control measures for the Stage 2 M2 development area. As this and other Stage 2 developments proceed, further assessment will be necessary to determine the extent and fine tune the groundwater-control measures needed.

Regular monitoring reports are required, which should include groundwater levels, salinity, and water quality. A network is required on the West Bank of Ord, where there are no existing monitoring bores. In the Weaber, Knox Creek, and Keep River Plains, there is a reasonable monitoring bore network coverage with the exception of the southern Knox Creek Plain, Sandy Creek (WA) north of Weaber Plain, and north eastern Weaber Plain.

In Stage 2 areas monitoring bores should be sited in areas that receive the highest accessions and where modelling has predicted the first effects. The irrigation design should include drainage measures for each area in detail with enough flexibility to allow minor modifications based on the monitoring results. The regulatory bodies will need to define trigger levels to ensure management response to high groundwater levels and discharges to the surface.

Although discharge from the test production bores on the Ivanhoe Plain and Packsaddle Plain showed concentrations of organochlorine and organophosphate pesticide to be below detectable limits for the analytical methods, regular monitoring will be required.

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Appendix 1

Packsaddle Plain and Ivanhoe Plain: groundwater electrical conductivity

	PNIS		*PN2S*		*PN2D*		*PN3S*		*PN5S*	
	EC	*WL*	*EC*	*WL*	*EC*	*WL*	*EC*	*WL*	*EC*	*WL*
May-90	1006.0	19.4	444.0	24.8	1097.0	24.6	92.7	32.0	nd	nd
Aug-90	1023.0	19.4	82.2	25.6	1074.0	25.1	90.3	32.2	49.8	24.8
Jan-91	1023.0	19.6	105.5	25.3	1095.0	25.0	90.9	32.5	39.1	25.1
Apr-91	894.0	19.7	268.0	25.6	1142.0	25.2	90.6	32.9	39.3	25.1
Jul-91	708.0	19.7	130.0	26.3	949.0	25.6	76.9	32.8	41.7	25.1
Nov-91	762.0	19.8	105.4	26.4	1154.0	26.0	96.1	32.6	43.0	25.3
May-92	691.0	20.1	175.0	26.3	1098.0	25.9	138.5	32.8	45.2	25.3
May-93	807.0	20.5	475.0	26.3	978.0	26.1	103.9	32.7	nd	25.7
Oct-93	138.1	20.7	960.0	26.9	1039.0	26.7	164.1	32.7	32.8	26.0
Nov-93	690.0	20.6	32.0	nd	nd	nd	nd	nd	nd	nd
May-95	868.0	21.5	350.0	27.7	389.0	27.6	127.9	33.4	28.0	27.1
Jan-96	607.0	21.7	229.0	27.8	88.3	27.8	nd	nd	57.7	27.5

	PN5D		*PN6S*		*PN6D*		*PN7S*		*PN8S*	
	EC	*WL*	*EC*	*WL*	*EC*	*WL*	*EC*	*WL*	*EC*	*WL*
May-90	nd	nd	643.0	27.4	164.0	27.4	215.0	30.4	60.4	26.0
Aug-90	nd	nd	707.0	27.7	153.0	27.7	194.0	30.0	55.8	26.0
Jan-91	138.8	25.4	735.0	28.1	154.7	28.1	580.0	30.5	59.6	25.9
Apr-91	152.4	25.4	752.0	28.0	157.3	28.0	274.0	31.1	60.0	25.9
Jul-91	134.0	25.4	664.0	28.2	474.0	28.3	nd	nd	48.5	26.0
Nov-91	151.8	25.6	794.0	28.4	137.8	28.4	132.5	30.8	58.9	26.0
May-92	138.7	25.6	641.0	28.4	121.3	28.4	125.2	31.3	55.6	26.2
May-93	150.0	26.0	nd	28.8	100.8	28.9	170.0	32.0	56.7	26.2
Oct-93	128.6	26.3	238.0	29.2	204.0	29.3	107.6	32.0	165.3	26.5
Nov-93	nd	nd	475.0	29.2	nd	nd	nd	nd	nd	nd
May-95	120.4	27.4	58.8	30.3	80.8	30.3	667.0	33.3	58.4	27.3
Jan-96	37.5	27.8	187.0	30.3	24.5	30.3	109.8	33.1	52.1	27.3

	PN8D		*PN9S*		*PN9D*		*PN10S*		*PN10D*	
	EC	*WL*	*EC*	*WL*	*EC*	*WL*	*EC*	*WL*	*EC*	*WL*
May-90	85.0	25.9	87.3	26.8	97.9	26.8	97.1	37.5	73.7	37.5
Aug-90	72.0	26.0	43.9	26.8	83.7	26.8	92.8	37.4	79.9	37.4
Jan-91	86.1	26.0	49.1	27.0	99.7	27.0	97.8	37.3	90.6	37.3
Apr-91	88.8	25.9	47.0	27.0	101.4	26.9	101.8	37.5	92.5	37.5
Jul-91	80.2	26.0	62.1	27.1	84.8	27.1	92.0	37.4	80.4	37.4
Nov-91	90.6	26.0	59.6	27.1	103.0	27.1	100.6	37.2	83.6	37.2
May-92	95.9	26.2	52.7	27.3	94.5	27.2	97.8	37.3	74.3	37.3
May-93	82.3	26.1	97.8	27.5	96.2	27.5	74.8	37.8	68.5	37.8
Oct-93	55.0	26.5	156.1	27.7	114.5	27.7	616.0	37.5	93.8	37.5
May-95	32.9	27.2	23.5	28.0	27.9	28.1	78.7	38.7	43.7	38.6
Jan-96	46.9	27.2	100.9	28.4	66.4	28.4	79.5	38.4	44.0	38.4

Appendix 1. Packsaddle Plain and Ivanhoe Plain groundwater electrical conductivity (continued)

	PN12S		*PN13S*		*PN13D*		*PN14S*		*PN15S*	
	EC	*SWL*	*EC*	*SWL*	*EC*	*SWL*	*EC*	*SWL*	*EC*	*SWL*
May-90	35.7	23.4	63.3	36.4	569.0	35.1	6.6	36.8	304.0	25.0
Aug-90	32.8	23.9	58.1	36.3	552.0	34.2	5.1	36.4	257.0	24.9
Jan-91	32.3	23.8	64.9	36.2	572.0	35.1	44.0	36.5	192.0	24.8
Apr-91	32.8	23.6	58.4	36.2	578.0	34.3	9.5	37.0	203.0	25.0
Jul-91	32.3	24.3	71.3	37.0	531.0	32.7	nd	nd	182.0	25.7
Nov-91	34.4	24.4	94.4	35.7	575.0	34.8	nd	nd	261.0	25.4
May-92	32.6	24.4	89.9	35.5	573.0	34.5	nd	nd	179.2	24.7
May-93	28.4	22.3	105.9	35.9	613.0	35.2	nd	37.1	232.0	24.6
Oct-93	30.7	24.8	97.3	35.8	178.5	35.3	nd	nd	145.4	25.0
May-95	23.0	25.3	45.4	36.4	584.0	35.8	46.3	38.4	160.0	25.2
Jan-96	59.4	25.2	49.9	36.3	51.1	36.1	18.8	37.6	203.0	25.4

	PB2		*PB2M1*		*PB3M1*		*PB1*		*PB1M1*	
	EC	*SWL*	*EC*	*SWL*	*EC*	*SWL*	*EC*	*SWL*	*EC*	*SWL*
May-90	nd	nd	nd	nd	271.0	23.8	nd	nd	52.6	27.1
Aug-90	95.8	24.3	84.5	24.2	nd	nd	49.9	27.6	59.5	27.4
Jan-91	98.9	24.5	110.9	24.4	227.0	24.1	nd	nd	49.1	27.8
Apr-91	100.1	24.4	116.4	24.3	229.0	24.2	42.4	27.8	50.0	27.6
Jul-91	94.4	24.9	85.3	24.4	215.0	24.4	44.6	28.0	39.0	27.9
Nov-91	110.0	24.6	119.1	24.5	246.0	24.7	75.9	28.4	47.7	28.2
May-92	126.0	24.6	106.6	24.5	216.0	24.9	43.4	26.4	33.7	28.3
May-93	136.0	24.8	148.0	24.7	245.0	25.3	54.6	28.7	58.9	28.6
Oct-93	117.8	24.9	140.8	24.8	230.0	25.7	55.9	29.4	38.8	29.3
May-95	100.4	25.5	88.7	25.5	82.2	27.0	35.6	29.9	29.4	30.4
Jan-96	98.3	25.5	9.2	25.4	46.3	27.2	55.8	30.0	47.2	30.4

Note: nd – no data

Appendix 2

Selected recent chemical analysis of groundwater

Site	Location	pH	EC (µS/cm)	TDS	Na	K	Mg	Ca	F	Cl	SO_4	NO_3	HCO_3	CO^3	SiO_2
				mg/L											
P12	Packsaddle Plain	8.6	700	440	130	2	21	17	0.4	58	11	0	310	20	62
PS1	Packsaddle Plain	8	700	470	52	2	47	64	0	160	25	5.3	230	nd	71
PS12	Packsaddle Plain	8.2	800	540	66	1	40	39	0	180	18	0	125	nd	58
PS14	Packsaddle Plain	8.4	850	530	135	1	29	25	0.2	125	17	0	290	5	75
PS15	Packsaddle Plain	9.2	600	360	145	1	9	nd	0.5	35	9	0	255	44	51
PS3	Packsaddle Plain	8.4	550	340	31	1	24	24	0.1	67	15	2.1	125	3	75
PS5	Packsaddle Plain	8.55	1 400	1 282	380	4.8	3.3	2.5	1.1	72	19	<0.1	780	20	18
PSPB1	Packsaddle Plain	7.85	1 100	870	170	4	33	39	1.1	110	16	8.5	490	nd	54
GS2	Ivanhoe Plain	7.9	6 350	4 860	1 100	68	305	130	1	925	2 010	0	445	nd	26
ML1	Ivanhoe Plain	8.8	3 950	2 660	1 010	7	23	7	2.2	290	975	0	1 120	47	15
ML2	Ivanhoe Plain	7.8	350	190	60	2	7	5	0.1	88	16	0	25	nd	81
ML3	Ivanhoe Plain	8.2	1 600	890	310	30	11	19	0.6	275	125	0.7	325	nd	30
CG1	Cave Spring Gap	8.5	2 050	1 160	375	4	61	10	0.2	370	120	0	440	10	58
CG2	Cave Spring Gap	8.3	700	440	56	3	38	41	0.1	80	32	0	250	nd	73
CG3	Cave Spring Gap	9.3	300	190	28	6	19	18	0.1	36	10	0.3	73	32	64
CG4	Cave Spring Gap	8.3	1 200	740	175	4	47	41	0.2	160	81	0	400	3	71
CG5	Cave Spring Gap	9.2	1 400	830	335	2	10	2	0.8	210	74	0	325	40	32
CG6	Cave Spring Gap	7.6	100	64	20	1	1	1	0	12	10	8.8	20	nd	39
WP1	Weaber Plain	8.2	610	449	93	4.6	18	23	0.2	87	18	<0.1	200	nd	40
WP10	Weaber Plain	9.15	1 900	1 398	370	4.1	29	21	0.8	54	100	<0.1	760	65	86
WP11	Weaber Plain	7.6	1 500	1 173	280	5.9	32	44	0.6	200	36	<0.1	580	nd	52
WP12	Weaber Plain	7.4	4 100	2 930	740	36	97	85	1.1	780	720	12	460	nd	30
WP13	Weaber Plain	7.9	620	443	57	16	17	46	0.2	61	71	0.2	180	nd	68
WP14	Weaber Plain	7.9	2 000	1 464	240	19	60	150	0.2	400	230	<0.1	360	nd	54
WP15	Weaber Plain	8.8	19 400	13 900	5 000	6	335	4	0.4	4 840	2 730	0	1 620	140	66
WP16	Weaber Plain	7.65	1 300	925	170	6.3	38	65	0.4	190	130	0.3	320	nd	20
WP17	Weaber Plain	8.5	840	701	180	3.2	14	17	0.4	61	35	1.5	380	10	58
WP19	Weaber Plain	7.4	33 500	20 250	5 450	26	1 140	890	0	8 420	4 760	0	335	nd	49
WP2	Weaber Plain	7.1	120	107	17	9.2	5.9	5.2	0.1	13	3	<0.1	60	nd	52

Appendix 2. Selected recent chemical analysis of groundwater (continued)

Site	Location	pH	EC (µS/cm)	TDS	Na	K	Mg	Ca	F (mg/L)	Cl	SO_4	NO_3	HCO_3	CO_3	SiO_2
WP24	Weaber Plain	7.45	570	436	77	6.8	15	32	0.2	59	21	0.2	220	nd	26
WP25	Weaber Plain	7.9	1 100	834	110	6.5	67	40	<0.1	60	170	<0.1	380	nd	18
WP3	Weaber Plain	7.1	110	96	12	3.8	4.7	5.7	0.1	7	3	<0.1	60	nd	60
WP4	Weaber Plain	8.1	520	387	41	7.1	25	35	0.2	50	19	0.2	210	nd	58
WP6	Weaber Plain	9.6	1 300	920	300	14	2.6	2.8	0.7	120	71	<0.1	520	55	38
WP7	Weaber Plain	8.85	270	211	33	4.5	11	17	0.2	17	9	<0.1	95	25	42
WP9	Weaber Plain	8.5	1 800	1 140	420	3	32	11	0.5	215	115	0	685	10	62
KC11	Knox Creek Plain	8.1	2 300	1 690	250	5.2	110	140	0.2	320	670	0.3	200	nd	38
KC12	Knox Creek Plain	7.6	5 500	4 137	910	86	170	200	0.4	910	1 500	0.9	360	nd	28
KC13	Knox Creek Plain	7.5	1 300	1 020	160	19	43	74	0.2	84	260	<0.1	280	nd	22
KC14	Knox Creek Plain	7.4	21 000	12 889	2 400	29	1 000	860	0.7	4 400	3 800	0.3	400	nd	22
KC2	Knox Creek Plain	8.7	530	458	120	5.7	15	18	0.3	18	51	1.1	210	15	40
KC3	Knox Creek Plain	7.7	400	210	27	3	18	21	0.2	20	13	57	105	nd	43
KC3PB	Knox Creek Plain	9.4	70	45	11	3	1.6	3	<0.1	16	<5	0.2	<5	10	48
KC4	Knox Creek Plain	8.1	1 300	856	180	5.9	32	48	1.2	160	220	0.2	210	nd	12
KC5	Knox Creek Plain	7.2	3 100	2 806	230	35	160	370	1.5	150	1 600	1.4	260	nd	12
KC9	Knox Creek Plain	8	1 100	869	98	15	46	80	0.4	73	87	0.3	470	nd	24
RN002592	Keep River Plain	7.5	640	440	33	18	26	62	0.7	15	69	1	309	nd	23
RN005181	Keep River Plain	7.3	460	250	60	8	18	12	0.2	32	15	1	232	nd	3
RN005661	Keep River Plain	7.4	4 850	3 550	496	14	217	305	1.3	936	1 041	1	389	nd	31
RN005662	Keep River Plain	7.7	2 790	1 670	332	5	95	128	0.2	620	279	1	387	nd	0
RN005669	Keep River Plain	7.4	810	520	101	6	27	32	0.3	120	53	1	239	nd	52
RN007410	Keep River Plain	5.6	130	0	12	4	1	2	0.1	31	2	1	4	nd	2
RN007411	Keep River Plain	7.3	2 410	1 560	206	14	83	201	0.2	440	426	1	316	nd	0
RN007414	Keep River Plain	6.3	190	140	17	19	7	8	0.2	33	2	3	54	nd	46
RN009024	Keep River Plain	7	1 350	880	105	14	70	98	0.5	93	224	1	536	nd	20
RN009025	Keep River Plain	7	1 350	880	105	14	70	98	0.5	93	224	1	536	nd	20
RN025201	Keep River Plain	7.8	5 620	3 620	657	20	183	275	0.2	1 750	286	1	305	nd	0
RN027802	Keep River Plain	5.8	273	164	37	4	5	3	1	72	6	1	12	nd	0
RN027803	Keep River Plain	5	64	78	8	1	1	1	0.1	16	3	1	4	nd	0

Appendix 2. Selected recent chemical analysis of groundwater (continued)

Site	Location	pH	EC (µS/cm)	TDS	Na	K	Mg	Ca	F (mg/L)	Cl	SO_4	NO_3	HCO_3	CO_3	SiO_2
RN027804	Keep River Plain	7	14 100	9 290	1 322	123	389	1114	0.3	5 000	241	2	38	nd	9
RN028622	Keep River Plain	5.5	75	57	10	2	1	1	0.1	14	7	1	9	nd	0
RN029229	Keep River Plain	5.9	67	73	9	2	1	1	0.1	18	3	1	7	nd	0
RN029516	Keep River Plain	5.8	84	86	7	9	1	1	0.1	13	3	1	22	nd	0
RN029517	Keep River Plain	7.3	19 300	13 200	3 630	25	465	343	0.3	6 400	1 370	2	536	nd	0
RN029518	Keep River Plain	4	21 400	15 700	3 320	107	805	851	0.1	7 400	2 030	1	1	nd	0
RN029519	Keep River Plain	7.5	20 900	13 600	3 910	67	525	372	0.1	7 200	1 000	1	274	nd	0
RN029656	Keep River Plain	7.3	24 400	19 100	4 870	15	853	705	0.1	6 700	5 820	2	480	nd	0
RN029659	Keep River Plain	7.8	4 100	2 570	547	12	126	164	0.2	970	450	1	416	nd	0
RN029662	Keep River Plain	5.9	120	167	16	4	5	3	0.3	14	22	1	14	nd	0
RN029665	Keep River Plain	7.9	1 520	896	193	5	56	62	0.5	245	113	1	410	nd	0
RN029666	Keep River Plain	7.2	22 000	14 500	3 350	37	786	826	0.2	7 700	1 590	1	303	nd	0
RN029667	Keep River Plain	7.3	280	170	21	9	10	23	0.1	28	18	1	115	nd	0
RN29668	Keep River Plain	7.2	1 200	759	83	28	52	97	0.3	93	323	1	263	nd	0
RN030826	Keep River Plain	7.54	771	495	45	8	42	49	0.3	29	93	1	370	nd	0
RN030884	Keep River Plain	7.1	3 620	2 610	296	6	153	226	0.2	566	1000	<1	383	nd	49
Y10A	Carlton Plain	8.2	6 500	3 980	1 100	12	280	120	0.7	2 230	240	1.2	180	nd	45
CP1	Carlton Plain	7.4	34 500	20 800	4 550	22	1 250	1260	0.1	11 100	995	0	210	nd	32
Y3A	Carlton Plain	7.5	17 800	12 400	3 180	20	785	420	0.4	6840	485	0.7	345	nd	47
MP1	Mantinea Flats	7.8	54 700	32 800	9 350	105	1 710	1260	0.1	17 200	3190	0	110	nd	43
MP2	Mantinea Flats	8.3	19 000	9 460	2 600	50	420	280	0.6	5 00	660	0.3	350	nd	38
MP4	Mantinea Flats	7.8	13 400	8 620	2 710	44	345	225	0.1	4 420	575	0	345	nd	45
MP5	Mantinea Flats	7.7	25 000	12 989	3 900	59	520	340	0.2	6 900	1 000	0.3	270	nd	28
MP6	Mantinea Flats	8	27 600	15 250	4 790	2	760	295	1.7	8 420	735	2.2	300	nd	13
MP7	Mantinea Flats	7.6	31 000	16 714	4 100	74	850	900	<0.1	9 300	1 200	0.3	290	nd	30
MP8	Mantinea Flats	7.6	25 000	13 559	2 800	29	580	1 500	<0.1	7 600	850	0.4	200	nd	38
Ord River	Lake Kununurra	nd	250	200	18	2.3	7	19	nd	12	6.6	nd	143	nd	6
Seawater		nd	nd	34 000	10 760	399	1 290	411	nd	19 350	2 710	0.001	142	nd	nd

Note: nd – no data

Appendix 3

Organochlorine and organophosphate pesticides in groundwater

Borehole	*PB4*	*PSPB1*
Location	*Ivanhoe Plain*	*Packsaddle Plain*
Date sampled	*22/09/98*	*17/11/98*
	μg/L	*μg/L*
Organochlorides		
HCB	<0.01	<0.01
Dichloran	<0.01	<0.01
BHC (a,b,d)	<0.01	<0.01
Lindane (g-BHC)	<0.01	<0.01
Heptachlor	<0.01	<0.01
Heptachlor Epoxide	<0.01	<0.01
Chlordane (total)	<0.01	<0.01
Endosulphan (a)	<0.01	<0.01
Endosulphan (b)	<0.01	<0.01
Endosulphan (S04)	<0.01	<0.01
Endosulphan (total)	<0.03	<0.03
Aldrin	<0.01	<0.01
Dieldrin	<0.01	<0.01
Endrin (total)	<0.01	<0.01
Dicofol	<0.01	<0.01
DDD	<0.01	<0.01
DDE	<0.01	<0.01
DDT	<0.01	<0.01
DDTs (total)	<0.03	<0.03
Methopxychlor	<0.01	<0.01
Total organochlorides	<0.2	<0.2
Organophosphates		
Mevinphos	<0.1	<0.1
Diazinon	<0.1	<0.1
Chlorpyrifos-	<0.1	<0.1
Fenchlorphos	<0.1	<0.1
Parathion-methyl	<0.1	<0.1
Chlorpyrifos	<0.1	<0.1
Malathion	<0.1	<0.1
Fenitrothion	<0.1	<0.1
Parathion	<0.1	<0.1
Chlorfen-vinphos	<0.1	<0.1
Bromophos-ethyl	<0.1	<0.1
Tetrachlor-vinphos	<0.1	<0.1
Ethion	<0.1	<0.1
Total organophosphates	<1.0	<1.0

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