DETERMINING RECHARGE VALUES FOR LAND MANAGEMENT UNITS IN THE WIMMERA RIVER CATCHMENT, VICTORIA.

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DETERMINING RECHARGE VALUES FOR LAND MANAGEMENT UNITS IN THE WIMMERA RIVER CATCHMENT, VICTORIA

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ABSTRACT

An estimation of groundwater recharge occurring under each of the twenty one Land Management Units of the Wimmera River Catchment has been determined by drawing together various sources and methods of recharge calculation. Approximately 150 00 – 400 00 ML of water recharge the watertables of the Wimmera Catchment annually. The upper catchment (19.5% of the total catchment area.) contributes about 40% of the total recharge. Average estimated recharge for the combined land Management Units of the upper catchment is 15 to 43 mm/yr, while across the lower catchment (plains, dunes, lunettes) it is 6 – 19 mm/yr. Priority Land Management Units for recharge control were determined by their contribution to saltloads in the Wimmera River and Wimmera Stock and Domestic Water Supply System, as well as the practicality of treating the high recharge areas within those units. The Flat Grey Plain, Upland Alluvial Plain, Grampians Alluvial Plain, Granite Terrain, Sedimentary Rises and Metamorphic Ridges Land Management Units are deemed to be priority areas for recharge control in the Wimmera River Catchment.

INTRODUCTION

This paper has been undertaken as a requirement of the Wimmera River Sub-Regional Salinity Management Plan, and draws together presently known information and theories for discussion. The aim of the plan is to improve the water quality of the Wimmera River and the Stock and Domestic Supply System. Groundwater recharge affects water quality in many areas of catchment as it promotes saline groundwater discharge directly into watercourses and onto land where surface runoff washes salt into streams.

Groundwater recharge may be defined in a general sense as the downward flow of surface water reaching the watertable, forming an addition to the groundwater reservoir (Lerner *et al.* 1990). Despite this simplistic definition, many external environmental factors such as flow through the unsaturated zone, local variations in aquifer porosity, the effect of atmospheric pressure on bore levels etc., complicate its calculation.

Intensive groundwater recharge estimation, which involves many years work, has taken place in several areas of Victoria, with very little work undertaken specifically within the Wimmera. Where possible, those methods of estimation and/or recharge values have been extrapolated for Land Management Units (LMU's) within the Wimmera River Catchment. LMU's were drawn up for the Wimmera River Salinity Management Plan to coordinate salinity control. They are area of similar landform, soils, geology, groundwater processes and land use which therefore have common salinity control measures. They also allow priority areas for salinity control to be targeted. A 1:750,000 scale map of Land Management Units is attached (Appendix 1).

Methods used for the Wimmera draw on the following:

- salt and water balances
- natural isotope (chloride) mass balance and flux analyses
- saturated hydraulic conductivity (infiltration)texture and depth of soils
- bore hydrograph fluctuations
- piezometeric contours.

All of these require a varying degree of estimation and may include significant error. Recharge estimations for nine LMU's rely mainly on bore hydrograph fluctuations, and therefore the methodology is outlined separately.

The most important problem with assigning a recharge value to a large area is spatial variation. Groundwater recharge for Land Management Units (LMU's) has been calculated using only a few data points, and large variation away from the given values should be expected. To partially compensate for error and spatial variation, a recharge range is given for each unit which is considered to be an average for the whole unit area.

Recharge estimations for the LMU's of the Wimmera Catchment are summarised in Table 1 (column 4). Also estimated in the table are:

(a) Proportion of High Recharge (Column 6): the percentage of area within the LMU which is thought to contribute higher than average groundwater recharge. The category includes both, landform areas which are mappable (eg. Rocky ridges) and those which vary from year to year, such as paddocks under fallow and inundated sites.

(b) High Recharge Contribution (Column 7): the percentage of the total recharge for a particular LMU that it's high recharge area contributes.

RECHARGE ESTIMATIONS

Sedimentary Hills

Estimated recharge for the Sedimentary Hills LMU has been calculated using a salt and water balance model developed for the Axe Creek catchment in the Ordovician Bedrock east of Bendigo (Dyson, ms). As with all salt and water balances, it assumes total hydrological equilibrium (i.e recharge equals discharge). This assumption itself introduces varying degrees of error. The intermediate groundwater systems under the steep, hilly country of Axe Creek (similar to Sedimentary Hills LMU) are considered to be nearing equilibrium. However, equilibrium of slower moving regional groundwater systems, such as under the Sedimentary Rises LMU, may be distant. The log associations were derived using a regression analysis of log recharge and rainfall values. This model is considered the most appropriate to this and the Metamorphic ridges LMU as it accounts for similar geology, landform, soils, clearing regimes and rainfall.

LOG (RECHARGE) = 2.77 LOG (RAINFALL) – 6.4

Average annual rainfall Sedimentary Hills LMU 450 – 650 mm.

LOG (RECHARGE) = LOG (0.95 to 1.39)
= 8.9 to 24.65 mm.

RECHARGE ESTIMATE 10 – 25 mm.

The estimate of 10 – 25 mm annual recharge is an average across the Sedimentary Hills LMU. Obviously some areas within the Sedimentary Hills unit will have a much higher value. Estimates of recharge on rocky outcrops range from 50 to 100 mm/year (Dyson, P., pers. comm.) depending upon the extent of soil cover. Shallow gradational soils on the upper slopes of this unit are also thought to have a higher than average groundwater recharge value. This is because they are shallow, have lower water storage capacity, and higher permeability than the relatively deep duplex soils which occur on the lower slopes. These high recharge areas (usually lass than 30% of the total area) are capable of applying in the order of 50 – 90 % of recharge occurring throughout the LMU within a 550 – 650 mm/year rainfall zone, however this depends very much on their size (Dyson, P., pers. comm.).

Metamorphic Ridges

The method used below was formulated to calculate approximate recharge across a catchment area where rocky ridge (high recharge) country is <30% of the total area. The Metamorphic Ridges LMU consists of >80% rocky ridges with little or no soil, and therefore the recharges value gained using this method will be an under-

estimate of actual recharge. The recharge estimate has been calculated in the absence of a more appropriate method.

LOG (RECHARGE) = 2.77 LOG (RAINFALL) – 6.4

Annual average rainfall Metamorphic Ridges LMU 550 – 750 mm.

LOG (RECHARGE) = LOG (1.19 to 1.56)
= 15.51 to 36.64

RECHARGE ESTIMATE 15 – 35 mm.

The estimated average recharge in this LMU ranges from about 15 mm – 35 mm (see Table 1). Within this unit, areas with little to no soil overlying fractured rock in the high rainfall zones (>80% of LMU) will recharge the most.

Sedimentary Rises

The recharge estimate for the Sedimentary Rises LMU is 10 – 25 mm/year. This was assumed from work completed at Burkes Flat in the Avoca Catchment (Day 1985) using a simple water balance model (Recharge x Recharge area = discharge x discharge area, Jenkin and Dyson 1983). At the Burkes Flat Study Catchment, an average of 10 mm recharge was calculated for sedimentary rise country in a 435 mm rainfall zone. In the Wimmera Catchment, although the rises have similar large areas of deep duplex soils which restrict infiltration, the given recharge range is relatively high. This is due to an assumed direct relationship between recharge and rainfall, which in the Moyston/Pomonal area is 650 – 750 mm. Recharge in the Sedimentary Rises unit may be about 20 – 40 mm/year on the tops of the rises (about 10% of the total area) where the duplex soils are shallowest. The limiting factor to recharge in these weathered Ordovician systems is the top of the B horizon in the duplex soils which rarely has a saturated vertical hydraulic conductivity (infiltration) of greater than 5 mm/day (Jenkin and Dyson 1983).

Actual recharge in the previously mentioned LMU's will probably vary between 10 and 40 mm/year depending upon rainfall.

Cambrian Greenstone

The recharge estimate for this small section of the Wimmera Catchment is 15 – 25 mm/year. This range, for the whole LMU, was estimated taking into account recharge data from the Mt. Camel Cambrian Greenstone Range in Central Victoria (Kevin, ms). The area of greatest (exposed fractured rock) may allow 50 – 100 mm recharge annually, which could be up to 50 – 90% of the total recharge occurring in this LMU (See Table 1). Actual recharge figures could be slightly higher or lower than those predicted depending upon the degree of fracturing, weathering, and the amount of high recharge area in the Wimmera Greenstone which is presently unknown.

The recharge has resulted in the occurrence of several salt affected gullies within the greenstone unit (McAuley, c., pers. comm.)

Volcanic Plains

The relatively high 550 – 850 mm rainfall range on the volcanic plains accounts for the estimated annual recharge of 20 – 30 mm. These estimates have been extrapolated from values used for the Loddon Catchment which are supported by other authors (Shugg 1984). The soils of the smallest LMU in the catchment mainly vary between medium and heavy clays, indicating low infiltration. Poor surface drainage results in water lying over a significant proportion of this area during winter.

One small volcanic cone (ash, tuff etc.) occupies less than 2% of the LMU. Associated with the cone are isolated areas of deep red gradational soil which directly overlays fractured basalt. These areas, which lack the restricting clay may allow higher annual recharge (>50 mm), depending upon the soil storage capacity which is currently unknown. The small size of the cone reduces its significance to recharge within this LMU.

Most of the information for this LMU was supplied by Clem Stumfel (DCE, Ararat).

Lowan Dunefields

Allison *et al* (1990) used chloride flux analyses and chloride mass balances to calculate recharge for uncleared and cleared areas (respectively) of Lowan Dunefield. Recharge under uncleared areas was found to be 0.06 mm/year while cleared areas allowed 20 40 mm/year (some sites were as low as 10 mm/year).

At Glendooke in the Big Desert country, a preclearing recharge value os 0.5 – 1.2 mm was recorded in the Lowan dunes using chloride analyses (Kennett-Smith *et al.*, ms:a). This is significantly higher than the 0.2 – 0.4 mm recorded in an interdune swale. Post clearing results have not yet been finalised, however the values are expected to be "high" (Thorne, R., pers. comm.).

Major fires in uncleared Lowan Dunefields (as well as Mallee Plains) have significant effect on groundwater recharge. At Nangwarry in south Australia (20 km north of Mt. Gambier), bushfires in 1983 destroyed native vegetation which has resulted in a 4 – 5 m rise in watertable over the past 8 years (Staedter, F., pers. comm.). This equates to 100 – 125 mm/year recharge in a 700 mm rainfall zone (assuming 20% specific yield, see Recharge Estimates from Bore Hydrographs).

Mallee Plains

Allison *et al.* (1990) calculated 0.06 mm/year recharge under uncleared Mallee (7.5 mm in some isolated depressions) and 5 mm/year for cleared Mallee at Walpeup. However, the Walpeup site is not considered to be representative of the Mallee Plains as it s soils are heavier. Allison *et al.* (1990) also assigned an average value of 17 mm/year to the whole of the Mallee. Under fallow this value may increase to 25 –30 mm in some areas (O'Leary, G., pers. comm.).

Bore hydrographs from around Manangatang (north of the Wimmera Catchment) with 10 years record suggest an average annual recharge of 6 – 10 mm under the Mallee. Rather than a gradual rise in regional watertable, recharge under the Mallee is high (50 – 130 mm) in years of above average rainfall and below average potential evaporation, such as 1989 (Bourton, ms). During the most years however, the watertable under the Mallee either remains constant (recharge equals discharge) or gradually lowers from the surface. At Manangatang, recharge occurs under the low E-W fine sandy dunes during most years, while the saltplans between them only recharge during wet years (Bourton, ms). Variations in bore fluctuations in the southern Mallee (Yapeet, Beulah, Birchip, Pullut, see Appendix 1) are low due to the depth to watertable being >10 m.

Soil type (ie. % clay) is the main reason for recharge variations throughout the Mallee with rainfall a secondary factor (Allison *et al.* 1990), as high amounts of clay increases soil water storage capacity in the top 0.5 m where it is available for use by plants/crops.

Granite Terrain

There is no specific method of estimating values within this LMU as no saturated hydraulic conductivity (infiltration) or bore data are available. Therefore, the given values were approximated from the general information below.

Recharge in granites is determined by the degree of fracturing of the crystalline rock and the amount of chemical weathering. At least 75% (Bell, G., pers. comm.) of the granites n the Wimmera Catchment are expected to contribute very low groundwater recharge (<5 mm) as they are presumed to be poorly fractured and the ground surface varies between bare rock and shallow sands. Therefore, a very high proportion of annual rainfall becomes surface and subsurface runoff. Most weathered granite material is carried by runoff and deposited downslope.

Recharge (20 – 40 mm) occurs in the remaining area (the lower slopes) if the LMU where surface runoff infiltrates deeper soils developed on the granite colluvium. In these areas there is a varying degree of

weathered material and therefore soils range between uniform sandy and yellow duplex soils with at least 2 m of sandy clay (Bell, G., pers. comm.). High recharge (50 – 80 mm) probably occurs through the uniform sandy soils to shallow local alluvial aquifers. Groundwater within these aquifers flows on top of the impermeable, unfractured granite, and discharges into creeks at "springs". Salinity is associated with some of these springs in the Upper Wimmera Catchment.

Wimmera Plains

A joint between CSIRO (Division of Soils), Rural Water Commission (RWC), and the Department of Food and Agriculture (VIDA, Horsham) has provided the recharge estimates for the Wimmera Plains LMU. Chloride analyses produced values of < 0.1 mm for an uncleared site at Barret Forest, south west of Warracknabeal and 26 mm for a cleared area nearby (Kennett-Smith *et al.*, ms:b). Only one bore hole was drilled (and samples analysed) at each site and therefore replication is desirable to reduce the likelihood of error. The cleared site value may be slightly overestimated due to the effects of drilling which dries the profile (Walker, G., pers. comm.). As a result of limited data the ranges 10 – 20 mm for cleared, and < 0.2 mm for uncleared Wimmera Plains have been adopted.

Further DFA investigations at Longerenong suggest that in a 450 – 500 mm rainfall zone, bare fallowed land provides 3 – 8 mm/year more recharge than non fallowed land on the Wimmera Plains (O'Leary, G., pers. comm.). These investigations however, are also in preliminary stages and further work is planned to test the consistency of these results. For the purpose of this paper it is presumed that fallowed areas (roughly 17% the Wimmera each year) provide the high recharge (20 – 30 mm, see Table 1) for most of the LMU's in the Lower Wimmera River Catchment. Results from investigations spanning the next 5 years will more accurately determine the long term effect of widespread fallow.

Direct watertable responses to recharge are more obvious where the watertable is relatively shallow, ie. < 10 m. There are several monitoring bores on the Wimmera Plains, however, the depth to watertable is about 30 m and it is possible that any increase in recharge resulting from replacement of natural vegetation with crops may not yet have impacted on the watertable, due to the slow downward movement of water through the profile.

Despite this, a regional watertable rise of 14 mm/year has been recorded at Kewell Est (15 years record), indicating possible contributions from elsewhere in the basin or a pre-clearing disequilibria (McAuley, C., pers. comm.).

East Wimmera Plains

The recharge estimate of 10 – 20 mm is an extrapolation from the Wimmera Plains LMU. Although rainfall for the East Wimmera Plains id lower (see Table 1), soils are generally lighter (more sandy), and are red duplex soils rather than grey cracking clays. The estimated range is consistent with preliminary results in the adjoining Avon-Richardson Catchment (Ryan, ms.). High recharge is expected under fallow.

West Wimmera Plains

The recharge estimate of 10 – 20 mm is an extrapolation from the Wimmera Plains LMU. Soils vary from shallow grey clays (as in the Wimmera Plains LMU) on the flatter country to lighter red duplex and sands/sandy loams on aeolian dunes at the crests of several prominent NNW trending ridges. The sandy ridges may contribute significantly more recharges than the grey clay flats which, in some areas, are prone to waterlogging. As for other LMU's, fallowing is expected to produce high recharge.

Tertiary Gravels

No recharge data is available for the Tertiary Gravels LMU. The gravels occur as small (< 100 ha) isolated patches of deep (2 – 3 m) gravels grading towards sands down the catchment. The gravels are often cemented, laterized and quite hard near the surface (eg. Around Stawell), suggesting high runoff and low recharge. In some areas however, where deep gravels and sandy soils occur, infiltration is greater than the Ordovician Sedimentary Rises LMU (Milton, via Bell, G., pers. comm.).

On a total catchment basis, the Tertiary Gravels have little significance, however, locally they may be preferential recharge areas to the sands under the Uplands Alluvial Plains LMU. The value of < 5 – 30 mm has been assigned simply as an extrapolation of the Sedimentary Rises LMU, (with allowances for differences In soil texture), which mostly bounds the gravels on the upslope side.

South-west Undulating Plains

Gloe (1974) stated that this area is part of "the most" important intake (recharge) area of the entire Murray Artesian Basin, supplying good quality water to a large area of north-west Victoria and south-east South Australia.

The South-West Undulating Plains LMU consists of strings of lakes (mostly fresh) in low swales between prominent NNW-SSE trending ridges of Parilla Sand. Historically it has been thought that the freshwater lakes are the major source of recharge, particularly where Murray Group limestone occurs close to the surface. Recent work in the Goroke area (Kennett-Smith *et al*., ms:c) however, suggests that recharge under the lakes is very low, (< 1 mm), due to thick clays of the Shepparton Formation restricting downward movement.

A recharge value of 1 mm was obtained for an uncleared Parilla Sand ridge which has a thin covering of aeolian clay. It is suspected that high recharge occurs under these ridges where they have been cleared and the aeolian clay is absent (Kennett-Smith, *et al*., ms:c). The report of this work is currently in preparation and involves alternative calculation methodologies which may produce significant variation in recharge estimation (Thorne, R., pers comm.) Therefore, a nominal "high" value of 30 mm has been included for use until the project report is released.

The significance of recharge under this LMU to salinity in the Wimmera Catchment is negligible as the watertable is generally > 5 m below the surface and regional groundwater flow is to the west (Lawrence 1975) and therefore, away from the river.

Note: Gloe (1947) gave a recharge estimate or "catchment efficiency" of 0.2 inches (5mm) for the Goroke-Edenhope area by comparing chloride content of local rainfall and chlorides in bore water samples.

RECHARGE ESTIMATOINS FROM BORE HYDROGRAPHS

The estimations of recharge for the following LMU's have been calculated using a relationship between the annual watertable fluctuation shown on bore hydrographs, and the specific yield (ratio of volume of water that, after saturation, can be drained by gravity to its own volume) of the interval monitored by the bore (Todd 1980).

$$h = Pi/Sy \text{ OR } Pi = h \times Sy$$

where, Pi = the portion of precipitation that percolates to the watertable (Recharge)

h = the net annual fluctuation (rise in wet season) in the bore hydrograph (see Figure 1)

Sy = the specific yield.

This method of recharge estimation is extremely rough, and in most LMU's has been used in the absence of any other. It assumes that all groundwater fluctuations measured in bores are a result of recharge or discharge. Many other factors such as atmospheric (barometric) pressure, wind, evapotranspiration and changes in soil air pressure soon after rain (Todd 1980) affect the water level recorded in bores. Barometric pressure alone is known to produce a diurnal (daily) water table fluctuation of about 100 mm in the Mallee and 160 mm in the highlands (Dyson, P., pers. comm.).

This method is not valid for confined aquifers.

Figure 1 – Bore Hydrograph, Lake Hindmarsh – Lunette

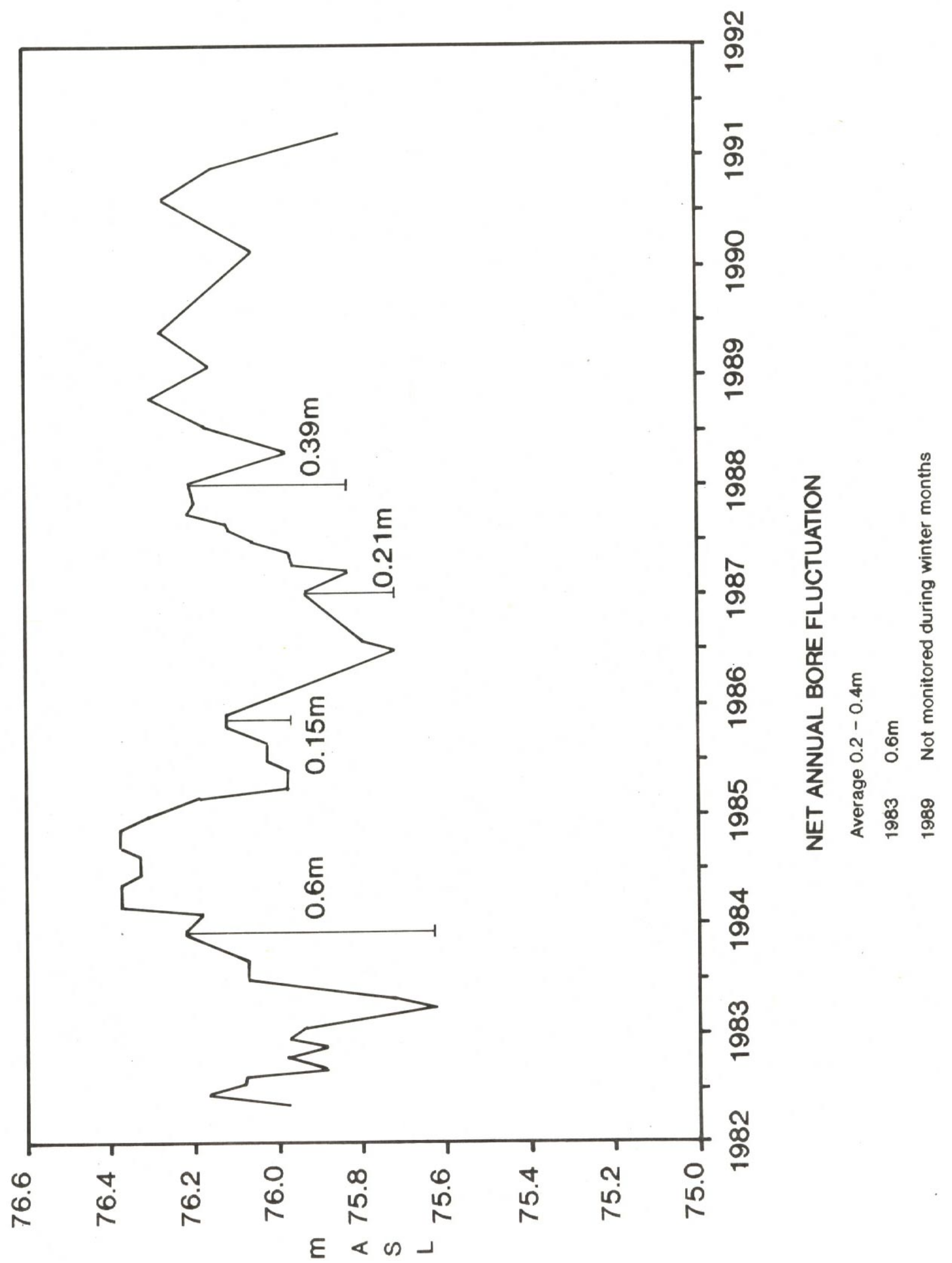


Table 1 - Recharge Estimations - Summary

LAND MANAGEMENT UNIT	RAINFALL RANGE (mm/year)	AREA (ha)	AVERAGE RECHARGE (mm/year)	HIGH RECHARGE (mm/year)	PROPORTION OF HIGH RECHARGE	HIGH RECHARGE CONTRIBUTION	SOURCE/ CALCULATION METHODS
Upland Alluvial Plain	450 – 750	110,646	10 – 30	>50	<10 %	30 – 40 %	Bore Hydrographs
Grampians Alluvial Plain	500 – 100	31,899	30 – 70	>70	<30 %	>50 %	Bore hydrographs
Volcanic Plain	550 – 850	1,562	20 – 30	>50	<2 %	<10 %	Shugg (1984)
Tertiary Gravels	450 – 650	31,290	<5 – 30	20 – 30	30 %	60 – 75%	Estimate only
Granite Terrain	500 – 750	28,870	<15 – 15	50 – 80	15 %	>75 %	Estimate only
Metamorphic Ridges	550 – 750	20,571	15 – 35	50 – 100	>80 %	>90%	Dyson (ms)
Sedimentary Rises	450 – 750	70,872	15 – 25	50 – 100	10 %	50 %	Dyson in Day (1985)
Sedimentary Hills	450 – 650	3,495	10 – 25	50 – 100	<30 %	50 – 90 %	Dyson (ms)
Cambrian Greenstone	550 – 700	2,279	15 – 25	50 – 100	<20 %	Up to 90 %	Kevin (ms)
Grampians Colluvium	400 – 1000	29,160	10 – 100	>100	20 %	>50 %	Bore Hydrographs Riha (1973), Smart (1991a)
Wimmera Plains	375 – 500	268,593	uncleared <0.2 cleared 10 – 20	20 – 30	20 % (fallow)*	Approx. 35 – 40 %	Kennett-Smith *et al.* (ms:b)
West Wimmera Plains	350 – 450	126,483	See Wimmera Plains	20 – 30	20 % (fallow)*	Approx. 35 – 40%	Estimate only
East Wimmera Plains	350 – 450	53,483	See Wimmera Plains	20 – 30	20 % (fallow)*	Approx. 35 – 40 %	Estimate only
Mallee Plains	325 – 450	626,217	uncleared < 1.0 cleared 5 – 20	>25	20 % (fallow)*	35 – 40 %	Allison *et al.* (1990) Bourton (ms)
Undulating Plains	400 – 850	189,534	5 – 30	30 – 40	10 – 30 % hydrographs	60 – 70 %	Bore Hydrographs Smart (1991a)

LAND MANAGEMENT UNIT	RAINFALL RANGE (mm/year)	AREA (ha)	AVERAGE RECHARGE (mm/year)	HIGH RECHARGE (mm/year)	PROPORTION OF HIGH RECHARGE	HIGH RECHARGE CONTRIBUTION	SOURCE/ CALCULATION METHODS
Flat Grey Plain	325 – 550	119,148	5 – 30	>50	<10 %	30 –60 % (inundation) (irrigation)	Bore Hydrographs Smart (1991b)
Lowan Dunefield	320 – 420	165,434	uncleared 0.6 – 1.2 cleared 20 – 40	30 – 40	<20 % cleared	>80 %	Allison *et al.* (1990) Kennett-Smith *et al.* (ms:a)
Lake Floodplain	325 – 400	51,321	5 – 30	>50	50 %	> 80% (inundation)	Bore Hrydrographs
Lunettes	325 – 400	7,374	<10	15	30 % (L. Hindmarsh)	30 %	Bore Hydrographs Todd (1980)
Siluro-Devonian Sandstone	400 – 1000	51,136	30 – 100	>100	30 %	50 – 70 %	Bore Hydrographs Riha (1973), Gloe (1947)
S.W. Undulating Plains	400 – 450	36,975	< 1 – 30?	>100?	15 – 30 %	>90 %	Kennett-smith *et al.* (ms:c), Gloe (1947)

* % fallow from 1988-9, Department of Agriculture Land-Use Summary

Rainfall data and area (ha) for each LMU were provided by Bob Wilson, Geographic Information System Unit (GIS), DCE, Kew.

Errors are introduced into this method by:

- h values are determined from monthly bore readings which represent an average and miss most of the extreme fluctuations (eg. Figure 1, 1989 data).

- Sy values (Todd 1980) are representative values for varying rocks and soils. They assume textual consistency throughout the materials which clearly does not occur in the real world.

- The scarcity of bores with LMU's does not adequately account for actual spatial variation of watertable fluctuation.

It is important to note that this method will underestimate actual recharge as it does not account for discharge away from the bore which occurs concurrently with recharge (Jenkin and Dyson 1983).

A range of estimated recharge is given for each LMU to compensate for the error (see Table 1).

Lunettes

Annual recharge estimation for the Lunettes LMU is < 10 mm. It has been calculated using bores in the sandy lunette at Lake Hindmarsh with 9 years record, which show average bore fluctuations of 0.2 – 0.4 m (see Figure 1). The specific yield value of 20% for fine sand (Todd 1980) was used to give a recharge value of 4 – 8 mm/yr for that site. Although quite porous, the low recharge is due to a low rainfall combined with high evapotranspiration which become more extreme in this LMU generally decrease from south to north.

The given values are for average years. In wetter years such as 1989, recharge may be as high as 15 mm (12 mm calculated for the break of the drought in 1983, see Figure 1). Recharge is significant enough to form a 'mound' of slightly fresher water in the regional watertable under the lunette at Lake Hindmarsh.

A complicating factor is texture of lunettes which varies from one to another (sand to sandy clay to clay). Therefore, a sandy lunette will recharge more than a clay lunette in a similar rainfall and evaporation conditions, due to it's higher subsurface infiltration and lower water holding capacity. Also, even within individual lunettes, there is an irregular presence of finer layers (clayey sand – sand clay) which causes perching of water above the regional watertable. The finer layers effect recharge because:

- they have a lower real specific yield (and therefore recharge). This resulted in the Sy value for dune sand of 38% (Todd 1980) being considered inappropriate for recharge estimation under the Lunettes LMU.

- perching prevents a proportion of water which enters the lunette from reaching the regional watertable, and therefore being measured by bore fluctuation. The perched water may be discharged at 'springs' above the regional watertable. There are many such springs along the eastern edge of the lunette at Lake Hindmarsh.

Perched watertables also occur in the sandy clay lunettes at Lake Albacutya and possibly in the sandy lunette at Lake Coorong (Hopetoun – see Appendix 1). At Lake Albacutya, high evaporation results in salinity where a perched watertable discharges on the lakes' eastern edge.

Undulating Alluvial Plains

An estimated recharge range of 5 – 30 mm has been assigned to the Undulating Alluvial Plains LMU using bore hydrograph fluctuations (0.04 – 0.14 m) and soil data from Wimmera Industrial Minerals (WIM).

Two bore hydrographs with only three years record gave a range of 6 – 21 mm recharge. A specific yield of 15% was used as locally outcropping Parilla Sand, which underlays most of the shallow alluvial sediments, is relatively coarse in this part of the catchment. (The monitored interval of both bores is within the Parilla Sand).

Recharge is expected to vary considerably within the approximated range due mainly to significant variations in land management, rainfall, thickness of clay and proneness to inundation. Therefore, is expected that more water will infiltrate to the watertable along the southern portion of this LMU bordering the colluvium slopes of the Grampians and Black Range (see Appendix 1) where rainfall is highest, and shallow (< 15 m), well structured clays directly overlay Parilla Sand, Renmark Group sands, or well fractured Grampians Sandstone. Also, semi permanent swamps in this area may have significant effect on recharge during periods of inundation (Smart 1991a).

Investigations undertaken by WIM suggest that very little or no recharge is occurring south of Pine and Taylors Lake. Over 2 – 3.5 m of heavy clays overlay 6 – 10 m of unsaturated Parilla Sand. Samples from the unsaturated zone have soil moistures of < 7% by weight (half that of the saturated zone) and contain an equivalent, and sometimes greater, volume of salt than in the saturated Parilla, indicating very little leaching by downward water movement (Smart 1991a). The Parilla Sand samples are 15% clay and 85% fine sand with a measured specific yield of < 1% (Smart 1991a). The specific yield value is extremely low as 3% is an accepted standard for clays. Further tests are being undertaken to determine their field capacity.

WIM bores in the area show a rising trend of between 0.05 and 0.1 m/year since 1987. This however, is thought to be mainly due to converging groundwater of the northerly regional flow and mounding under the Pine and Taylors Storage Basins.

Lake Floodplain

An annual recharge range of 5 – 30 mm has been estimated for the Lake Floodplain LMU using nine bore hydrographs from Lakes Hindmarsh and Albacutya.

Hydrograph fluctuations ranged from 0.08 – 0.30 m. A specific yield of 8% was used as the Lake Floodplain soils are a mixture of medium/coarse sand (Sy 27%), silt (Sy 8%) and clay (Sy 3%) (Todd 1980).

Recharge within the unit would generally decrease towards the north (downstream) due to lower rainfall, higher evaporation and, most importantly, a lower probability of flooding. When inundated, recharge is probably at least 50 mm/yr, as recharge under irrigation is estimated to be 65 – 100 mm/yr (Tickell and Humphreys 1987). Groundwater recharge from pas natural flood events has produced localised areas of fresher water under the floodplains of the Wyperfield Lakes, Wirrengren Plains and Lake Albacutya. (Some of there were tapped by the first settlers to the area – Gloe 1947). In these areas of the Lower Catchment, recharge from precipitation alone is minimal. Measured fluctuations in DCE (Mildura Region) bores at Lake Albacutya give recharge estimations of 5 – 12 mm for 1991. These bores however, have only one years record and may contain significant error.

The largest single area within this LMU is the floodplain of Lake Hindmarsh (see Appendix 1). It differs from the aforementioned areas as it is mostly under permanent lake and is currently partially a discharge area. The highly saline regional watertable slopes towards the lake from the south and east, discharging in farmland along those margins.

Groundwater monitoring bores in Lake Floodplain fringing the lake show an upward pressure and therefore in most years there is no recharge. During particularly wet years however, (eg. 1956, 1973-5, 1981 and 1989) a shallow sheet of water covers the farmed floodplain for up to 2 – 3 months. This event reverses the hydraulic gradient temporarily, allowing recharge to occur. The permanently high watertable ensures that most infiltrating surface water flows horizontally and discharges prior to the following winter/spring, resulting in very little change in watertable level.

Despite groundwater discharge around the south-eastern lake margins, the lakewater salinity (5,000 – 10,000 µs/cm) suggests that very little groundwater intrudes into the lake itself. Saline groundwater is "held out" by a combination of the lake water level and a confining clay layer under the lake. The relationship between the watertable and lake level alters towards the north-west. Here the groundwater slopes away from the lake and is less saline (Gloe 1947), suggesting that the lake level exerts pressure and recharges the watertable through the confining clay layer. Therefore, the salinity of the lake seems to be due to a combination of salt loads from the Wimmera River, high evaporation from the lake surface, and recharge to the north-west.

Upland Alluvial Plain

The estimated range of 10 – 30 mm recharge has been assigned to the Upland Alluvial Plain using two bore hydrographs (DCE Ararat) and soil descriptions only. A Sy of 10% was adopted as an average for the wide range of alluvial soils (ie. Clays – sandy loams) found within the Upland Alluvial Plain, while hydrograph fluctuations ranged from 0.30 – 0.95 m. Although the bore hydrograph fluctuations suggest a relatively low recharge value (10 mm), most work in other alluvial plains areas have resulted in estimations of up to 30 mm.

e.g. - data leading to recharge estimations for the four other alluvial LMU's in the Wimmera Catchments.

- a groundwater balance gained a result of between 10 and 20 mm/yr to the Loddon deep lead system under the Loddon Plain (Sansom *et al*. Ms) which has a lower rainfall than Upland Alluvial Plain. This recharge volume includes contributions from creek flow into sandy alluvium.

Soils within this LMU vary from grey cracking clays, situated close to the river and streams, to yellow duplex soils which border the sedimentary rises (Morgan, T., pers comm.). Both of these soil types involve heavy clays (B horizon in the yellow duplex) which are expected to limit infiltration of surface water. Bore logs from east of Stawell show about 3.5 m of loam and clay loam overlaying nearly 30 m if wet, fine sand and some gravel, suggesting high storage capacity for further recharge at that site. Amongst these areas are small isolated patches of fine sandy loams which are associated with past stream activity. A significant portion of recharge may occur under these sandier areas as well as locations where the overlying clay is thinnest (< 1m), such as the upper limits of this LMU. Seasonally inundated areas could also provide significant recharge, particularly where surface clay is thin.

Gloe (1947) states that small quantities of reasonably good quality groundwater were present in thin deep leads (beneath this LMU) in the Great Western-Stawell area, suggesting localised recharge.

Flat Grey Plain

The recharge estimates of 5 – 30 mm/yr for the Flat Grey Plain LMU has gained from the hydrograph fluctuations of 37 bores which range from 0.05 – 0.3 m.

Bore logs show that the Shepparton Formation in the Lower Wimmera Catchment consists mainly of fine to coarse sands with some gravels overlain by 1 – 5 m of fine sandy clays and sandy loams. Sediment coarseness, particularly the presence of gravels, decreases downstream of Quantong. A specific yield of 10% was selected for these highly varying alluvial sediments, and is considered to be representative of the Shepparton Formation.

The distributions of recharge under this LMU varies considerably and is determined by land management, soil type/thickness, depth to regional watertable, inundation/river flow regime, irrigation and rainfall. There is however, a general decrease in recharge down catchment due to lower surface water flow and rainfall. Areas of Flat Grey Plain which are not close to watercourses and are not prone to inundation (or irrigation) contribute relatively small volumes of recharge.

Soils of the Flat Grey Plain consist of cracking clays nearest the drainage lines, deep grey clays and some (10 – 15 % of LMU) red duplex (Dykstra, D., per. Comm.). Some sandy soils occur along watercourses.

Land adjacent to watercourses is recharged by streamflow. Bores in the banks of the Wimmera River indicate that recharge of up to 150 mm occurs during flood flows. Bore responses diminish rapidly from the river and are rarely significant greater than 200 m away. The regional watertable is shallow (< 5 m from the surface) and slopes towards the river under the Flat Grey Plain between Horsham and Lake Hindmarsh (see Appendix 1). These factors, as well as a significant upward hydraulic gradient close to the river, suggest that most (if not all) recharging water stored in the riverbanks during floods, flows back into the river after the flood recedes.

Areas of the Flat Grey Plain which are prone to seasonal inundation are estimated to contribute 30 > 50 mm/yr recharge (see Table 1), depending upon land management and clay thickness. Hydrograph fluctuations from bores near inundated sites suggest recharge of between 50 and 80 mm.

All irrigation area within the catchment (except Murtoa) are located within this LMU. Irrigation is thought to provide up to 75 mm/yr in moderately intensive areas (Tickell and Humphreys 1987).

Inundated and irrigated sites which recharge the shallow (< 5 m) regional watertable pose the most serious and immediate threat to this LMU. This is the case along the river from Polkemmet to the Little Desert, Locheil to Tarranyurk (including Datchack Creek), and all irrigation areas (except Murtoa) where salinity already occurs.

Other areas within this LMU have deeper (> 5 m) watertables, such as Yarriambiack, Dummunkle and Outlet Creeks. They are expected to recharge during periods of flow. Relatively fresh groundwater is located beneath Outlet Creek, possibly due to seepage during past periods of high flow and from beneath Lake Hindmarsh (Gloe 1947).

Smart (1991b) states that significant recharge occurs under the water storages south east of Horsham which are located within this LMU.

Grampians Alluvial Plain

Thirteen groundwater hydrographs have been used to estimate an annual recharge of 30 – 70 mm/yr for the Grampians Alluvial Plain LMU. A specific yield (Sy) value of 10% has been adopted in the calculations, as with other alluvial plain LMU's. Some bores have been monitored for about 13 years with recharge estimates varying between 40 and 180 mm/yr while others have 2.5 years record.

Soils within the Grampians Alluvial Plain are mainly sodic duplex types which includes calcareous areas towards the north. Surface texture is sandy loam suggesting relatively high surface water infiltration. The duplex nature of the soil slows infiltration at the top of B horizon, causing discharge from sub-surface flow and waterlogging to be major land management problems in the lower plain during the wetter months.

Groundwater recharge within this LMU is expected to be highest where there is greater than 750 mm annual rainfall, and less than 1 m of sandy loam overlaying a thin B horizon. These areas occur around the fringes of the Grampians Colluvium. Other significant sites of recharge are these which are inundated or waterlogged during winter/spring and watercourses, particularly the upper reaches of Mt. William Creek. Recharge in these areas causes discharge of saline groundwater which reduces water quality further down Mt. William Creek.

Water storages within this LMU are also likely contribute to recharge, although their significance has not yet been determined (McAuley, C., pers. comm.). ARWC investigation is currently determining the groundwater systems and trends to the Mt. William Creek Catchment.

Grampians Colluvium

A recharge estimate of 10 – 100 mm/yr for the Grampians Colluvium LMU has been gained by hydrographs from only two bores at Bimbadeen, and the written reports of Riha (1973) and Smart (1991a). The individual hydrographs suggested 8 – 14 mm and 86 – 102 mm and although they are highly varied, their range may be valid. A Specific Yield of 20 % was adopted, taking into account variations in the scree deposits which range from boulders and coarse sandstone to sandy clay (Riha 1973). The monitored interval of the two bores consist mainly of fine sand and clayey sand while bore fluctuations ranges from 0.304 to 0.51 m.

The Grampians Colluvium is a significant recharge area however, until recently, recharge has been presumed to be relatively consistent throughout the unit. Riha (1973) described "heavy runoff and percolation of water into the boulder and scree deposits flanking the cliff faces on the eastern edge of Mount William Plateau". He further stated that the scree deposits "are coarse and highly permeable". However, recent WIM investigations in the colluvium along the north eastern margin of the Grampians, suggest low recharge (Smart 1991a). WIM have found that Shepparton Formation clays underlying colluvium sands persist up to the edge of the Grampians and restrict downward flow. They also state that the base of the colluvium and underlying sediments have low moisture contents, and therefore are thought to have little water flowing downward through them.

The two monitoring bores which produced such a wide range in recharge estimation are located in different positions within the colluvium. The bore which produced the high value is situated in coarse sediments near the Grampians Sandstone outcrop, while the low value bore is in finer scree closer to the edge of the Grampians Alluvial Plain.

The above information suggests that high recharge in the Grampians Colluvium occurs in high rainfall areas under its upper slopes adjacent to the outcropping sandstone, as well as along water courses such as the headwaters of the Mt. William and McKenzie Creeks.

Siluro-Devonian Sandstone

The estimate of 30 – 100 mm/yr recharge for the Siluro-Devonian Sandstone LMU has gained from 2 bore hydrographs in conjunction with several reports. The Siluro-Devonian Sandstone contains mainly of medium – coarse quartzose sandstone, interbedded with son siltstone, mudstone and fine sandstone (Douglas and Ferguson Eds. 1988). A Specific Yield value of 8 % is considered to be an average value for fractured sandstone formations (Shugg, ms). The actual Sy value however, is totally reliant on fracture size and density. Bore fluctuations and estimated recharge values will vary considerably (much more than for the unconsolidated aquifers). A third bore produced a recharge value of 120 – 376 mm suggesting its location in a major fracture. Shugg (1989) states that in similar unweathered Siluro-Devonian bedrock at Dargile, more than 90% of water movement occurred through fractures and joints.

Soil throughout this LMU is generally shallow or absent. The sandstone is well known to be extensively fractured and therefore, extremely high (> 150 mm) recharge is expected under the crests of the major ranges where about 1000 mm annual precipitation fall on exposed well fractured sandstone.

High recharge under the Grampians and Mt. Arapiles is not a new concept. Gloe (1947) noted that freshwater was discovered in the fractures and joints of the Grampians in 1884 while tunnelling for the Stawell town water supply. Drought relief bores for the towns of Willaura, Moyston, Glenthompson, Ararat and Hamilton tap the sandstone indicating it to be a substantial resource.

Gloe (1947) proposed that the Grampians are a major “intake” (recharge) area for the Murray Basin. This is supported by WIM investigations which suggest that the Grampians are recharging (sub-surface) the Tertiary Renmark Group and Parilla Sand aquifers (Smart 1991a).

PRIORITY RECHARGE AREAS

According to estimations proposed in this paper, between 150,000 and 400,00 ML of water recharges the watertable of the Wimmera Catchment annually. In terms of total recharge volume, the Lower Catchment (plains, dunes and lunettes) dominates, providing approximately 60 % of recharge (calculated using both high and low values of the estimated ranges). The Mallee Dunefield and Wimmera Plains LMU’s alone contribute about 45 % of recharge for the entire catchment. These figures however, are misleading as the Lower Catchment comprises 80.5 % of the total catchment area. The Upper Catchment (19.5 % of catchment are) contributes approximately 40 % of total recharge. Average recharge across the lower catchment ranges from 6 – 19 mm while in the Upper Catchment it is 15 – 43 mm.

It should be noted that the water storage capacities of soil profiles in these LMU’s is largely unknown. An area with a high recharge value may also have a high storage capacity and therefore does not cause discharge and resulting decreased surface water quality. Conversely, an area with a lower recharge value may not store much water and therefore contributes to the saltloads of watercourses.

Obviously it is not possible for the Salinity Management Plan to implement recharge control works over the whole catchment within its planning horizon (ie. 50 years). One of the objectives of this paper is to identify any areas within the catchment which make disproportionately high recharge contribution, and are closely linked to raised saltloads of streams and rivers. Therefore, by prioritising LMU’s and targeting areas within those LMU’s for recharge treatment, the best use I made of limited time and resources.

Two criteria have been employed to identify priority LMU’s. The first, and most important selection criteria involves the major objective of the Wimmera Catchment Salinity Management Plan, which is to improve the surface water quality (increasing saltloads), and on which recharge control works are more likely to provide an improvement in surface water quality within the planning horizon. Secondly, a general rule can be applied using Table 1. Land Management Units which have a low proportion of high recharge area (< 30 % in column 6) and which make a significant high recharge contribution (generally > 50 % in column 7) are priority. Therefore, within the LMU’s identified, there are relatively small, treatable areas which are contributing large volumes of groundwater recharge.

Based on the above criteria six LMU’s have been identified as priorities, within which areas may be effectively targeted for recharge control works.

The Flat Grey Plain, which extends from north of Glenorchy, through Drung Drung and along the floodplains of the Yarriambiack Creek and the Wimmera River to Wirrengren Plains (see Appendix 1), is a priority. The regional watertable under this LMU is generally shallow (< 5 m), and therefore water recharging adjacent to the river contributes to groundwater discharge and the resulting decrease in river water quality. A relatively small part of this LMU requires recharge control (< 10 % high recharge, see Table 1). Improved irrigation management at Drung, Riverside, Haven and Quantong could lower watertable gradients towards the river and resulting discharge. Flat Grey Plain which is prone to inundation, such as flood channels, billabongs etc., also locally recharge the watertable which increases groundwater discharge into the river. Revegetation (including regeneration) could ensure maximum water use occurs before it mixes with the saline regional watertable. The same control method is feasible along the riverbank (within 200 m of the river) to maximise use of bank storage during flood flows, before water of higher salinity returns to the river. Some agricultural land within this LMU also recharges during seasonal inundation. This is often exacerbated by poor surface drainage. Agronomic recharge control options should be applied to these areas with sandy soils or < 1 m of overlying clays. Long term planning within this LMU should also aim at managing water storages to minimise groundwater recharge.

The Upland Alluvial Plain is a priority as recharge under small patches of sandy soils and areas prone to inundation are though to cause saline discharge which impacts on water quality in the Upper Catchment (and therefore effects both the river and the Stock and Domestic Supply). Control options for these areas are similar to those for the Flat Grey Plain.

At least 21,222 tonnes/year of salt flows out of the Mt. William Creek (Hooke 1991) and a significant proportion of this is thought to be due to recharge under the upper portion of the Grampians Alluvial Plain. Improved streamfront management and agricultural water use may lower stream salinities, depending upon the influence of the Sedimentary Rises country in the south east of the catchment which is currently unknown.

Sedimentary Rises comprise the second largest area in the upper catchment and large volumes of recharge occur under it. A regional agronomic change is required to effectively reduce recharge, and current rates of recharge control adoption suggest that this is unrealistic in the short term (ie. < 50 years). Several areas within this unit however, are priority as they discharge into streams. In particular, recharging sedimentary rise country near Moyston and east of Pomanal discharges into Salt Creek while Six Mile, Wattle and a small section of the Upper Concongella Creeks are also affected.

Approximately 4,300 ha os lower slopes of Granite Terrain are though to recharge the local alluvial groundwater systems which discharge and reduce streamwater quality in the headwaters of the Concongella, Port Curtis and Stears Creeks. Identification of high recharging uniform sandy soils is required so they can be targeted for control options.

Recharge control is also a priority for the Metamorphic Ridges. A large portion (about 80 %) of this LMU is high recharge rocky ridge country, however, it is a relatively small area (20500 ha) which is associated with raised saltloads in the Six Mile Creek and the headwaters of the Mt. Cole Creek.

Some LMU’s with high recharge contributions are not considered to be priority. The Siluro-Devonian Sandstone unit is possibly the major recharge area of the upper catchment and is located entirely within the Grampian National Park, At. Arapiles, and Black Ranges State Parks. The upper slopes of Grampians Colluvium are also probably very high recharge contributors. Combined, these two LMU’s provide between 30 – 50 % of the total recharge for the upper catchment. Although this is an extremely high contribution, it has always been so, as part from several olive orchards, land use on these units has not been altered since European settlement. Therefore, the observed changes in catchment hydrology (rising watertables, groundwater discharge at the land surface etc.) are due to altered land management in other parts of the catchment, such as the Grampians Alluvial Plain, Upland Alluvial Plain and Sedimentary Rises.

Despite having small, easily identifiable high recharge areas, the Cambrian Greenstone and Sedimentary Hills LMU’s are so small that their recharge is minor when compared with others. They also do not seem to be directly associated with significant stream degradation.

Sections of the Lowan Dunefield and South-west Undulating plains may allow high recharge, however, it is of low significance as groundwater flow from these units is generally to the north-west and west respectively, and Therefore causes no surface water quality degradation in the Wimmera Catchment. Recharge is required in these areas to maintain the Murray Group Limestone aquifer which is a major groundwater resource.

The Mallee and Wimmera (including East and West Wimmera) Plains LMU’s clearly allow the highest volumes of recharge within the catchment. They comprise nearly 54 % of the catchment area (over 1,000,000 ha) and have no easily identifiable areas for recharge control to be implemented which would result in a reduction in groundwater discharge to the Wimmera River in the forseeable future. Small scale treatment may be appropriate where perched watertables occur. The total elimination of fallow in the Mallee Plains would reduce its recharge by approximately 25 %, however, implementing this over such a large area is not likely in the short term. It is therefore more beneficial to improve the quality of water flowing down the river by recharge control in LMU’s further upstream.

CONCLUSION

Various methods have been used to estimate recharge for the twenty-one Land Management Units of the Wimmera River Catchment. Six units which have a significant effect on surface water quality and have small areas of high recharge are identified as priorities for implementing recharge control options. They are:

Flat Grey Plain

Grampians Alluvial Plain

Upland Alluvial Plain

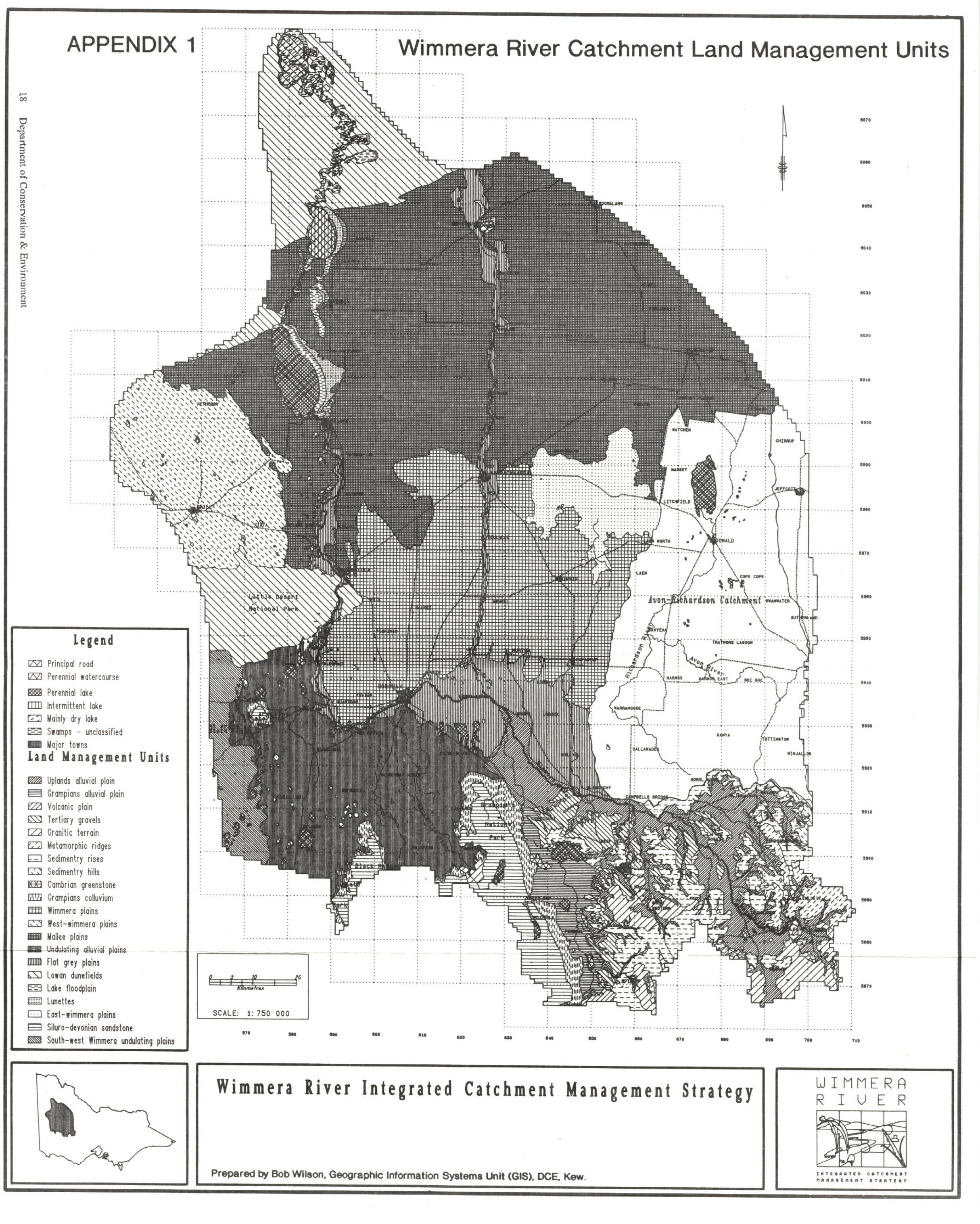
Granite Terrain

Sedimentary Rises

Metamorphic Ridges

There is a further need to identify localised high recharge areas on the Alluvial plains and Granite Terrain to focus recharge minimisation options appropriately.

APPENDIX 1 – WIMMERA RIVER CATCHMENT LAND MANAGEMENT UNITS



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REFERENCES

Allison, G.B., Cook, P.G., Barnett, S.R., Alker, G.R., Jolly, I.D., and Hughes, M.W. (1990) Land clearance and river salinization in the western Murray Basin, Australia. *J. Hydrol.* 119: 1 – 20.

Bourton, S. (ms) Groundwater and salinity research in the Victorian dryland Mallee. Dept. Conservation and Environment, Victoria.

Day, C.A. (1985) The geomorphology and hydrogeology of the Burkes Flat area in relation to salinity. *Land Protection Service Rep*., Dept. Conservation, Forest and Lands, Victoria.

Day, C.A. (ms) Dryland salinity processes at Sheep Pen Creek. Dept. Conservation and Environment, Victoria.

Douglas, J.G. and Ferguson, J.A. Eds (1988) Geology of Victoria. *Victn.Div. Geol. Soc. Aust.* pp. 1 – 664.

Dylan, P.R.D. (ms) Hydrogeology and hydrochemistry of fractured rock aquifers effecting dryland salinity in Central Victoria. Ph.D. Thesis, Geology Dept., La Trobe University, Victoria.

Gloe, C.S. (1947) The underground water resources of Victoria. State Rivers and Water Supply Commission. *Vict., 1.*

Hooke, D (1991) Surface water salinities in the Wimmera Catchment – Preliminary information. Rural Water Commission, Victoria, (unpubl.).

Jenkin, J.J., and Dyson, P.R.D. (1983) Groundwater and soil salinization near Bendigo, Victoria, in Collected Case Studies in Engineering Geology, Hydrogeology and Environmental Geology. *Spec. Publ. Geol. Soc. Aust 11 pp 229 – 257.*

Kennett – Smith, A.K., Cook, P.G. and Thorne, R. (ms:a) A comparison of recharge under native vegetation and dryland agriculture in the Big Desert region of Victoria. Centre for groundwater studies Rep.; CSIRO, Division of Water Resources, Divisional Rep.

Kennett – Smith, A.K., O'Leary, G. and Thorne, R. (ms:b). Estimation of recharge from soil water and chloride profiles under drylands agriculture, eucalypt plantation and natural woodland in the Wimmera district of Victoria. *Centre for groundwater studies Rep. 39; CSIRO, division of Water Resources, Divisional Rep. 92/2.*

Kennett – Smith, A.K., Thorne, R. and Walker, G.R. (ms:c) A comparison of recharge under native vegetation and dryland agriculture near Goroke, Victoria. Centre for groundwater studies Rep.; CSIRO, Division of Water Resources, Divisional Rep.

Kevin, P.M. (ms) Dryland salinity processes at the Mt. Camel Range, Central Victoria. Dept. Conservation and Environment, Victoria.

Lawrence, C.R. (1975) Geology, hydrodynamics, and hrdrochemistry of the southern Murray Basin. *Mem. Geol. Surv. Vict., 30.*

Lerner, D.N., Isaar, A.S. and Simmers, I. (1990) Groundwater Recharge: A guide to understanding and estimating natural recharge. International Contributions to Hydrogeology 8, Internat. Assoc. of Hydrogeologists, Hanover, Heise.

I.L.R.I. (1980) Drainage principles and applications =- surveys and investigations. (2nd. Ed.) *Internat. Inst. For Land Reclamation and Improvement. Pub. 16, vol. 3*

Riha, M. (1973) Groundwater resources – Mount William Creek catchment, Grampian Ranges. Dept. Industry, Technology and Resources (unpubl.)

Ryan, S. (ms) Hydrological characteristics of Avon Richardson catchment. Dept. Conservation and Environment, Victoria.

Shugg, A. (1984) Fractured rock groundwater investigations – Woodend. *Dept. Industry, Technology and Resources Unpubl. Rep. 1984/18.*

Shugg, A. (ms) Hydrogeology of the Wandin Yallock, Dandenong Ranges area. M.App. Sci. Thesis, Dept. Geology University of NSW.

Smart, J. (1991a) Some observations on recharge in the Horsham area. Wimmera Industrial Minerals, Victoria (unpubl.).

Smart, J. (1991b) Watertable changes in the WIM 150 area. Wimmera Industrial Minerals, Victoria (unpubl.).

Tickell, S.J., and Humphreys, W.G. (1987) Groundwater resources and associated salinity problems of the Victorian part of Riverine Plain. *Geol. Sur. Vict., Rep. 1987-84*

Todd, D.K. (1980) *Groundwater Hydrology* (2nd edn) John Wiley and Sons, New York.

Note: (ms) refers to documents in manuscript from previously referred to as (in prep).