DWLBC REPORT

Groundwater Salinisation in the Naracoorte Ranges Portion of the Padthaway Prescribed Wells Area

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Government of South Australia
Department of Water, Land and Biodiversity Conservation

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Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

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FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Rob Freeman
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

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1. INTRODUCTION

This report has been written in collaboration with CSIRO Land and Water, Adelaide, and in conjunction with a series of four reports (Volumes 1–4) for the *Padthaway Salt Accession Investigations and Determination of Sustainable Extraction Limits (PAV) Study.* The Padthaway Prescribed Wells Area (PWA) is a long established and important irrigation area in the South East of South Australia. Here, groundwater for irrigation is extracted from the high yielding unconfined limestone aquifer. Annual groundwater salinity trends indicate a rise of between 5 mg/L/yr and 18 mg/L/yr and there is concern for the long-term viability of the irrigation industry should the increasing salinity trends continue.

The key mechanisms that are believed to be responsible for the salinity increases in the aquifer are:

- Pumping at rates that exceed vertical recharge, and recycling of irrigation water result in accession of salt back to the unconfined aquifer (Padthaway Formation) in the main irrigation area.
- Mobilisation of salt in the unsaturated zone (Bridgewater Formation) of the adjacent Naracoorte Ranges. This is due to the clearance of native vegetation and high water use perennial pastures, and the resulting increase in groundwater recharge.

The current study focuses on the latter of the two mechanisms, and attempts to quantify groundwater recharge and salt fluxes as a result of native vegetation clearance in the Naracoorte Ranges portion of the Padthaway PWA. The objective of this report is to provide a description of the theoretical background and modelling approach used to derive results presented in Van den Akker et al. (2005).

The initial aim of this work was to quantify the historic salt store in the unsaturated zone, determine recharge rates under various land-uses and the time lag associated with groundwater salinisation at selected sites. The scope of the project was then expanded to provide a spatial interpretation of increased groundwater recharge and salt flux to the aquifer across the entire Naracoorte Ranges portion of the Padthaway PWA.

2. BACKGROUND

2.1 INCREASING RECHARGE AND GROUNDWATER SALINISATION FOLLOWING LAND CLEARANCE: THE CHLORIDE FRONT DISPLACEMENT TECHNIQUE

Numerous studies have discussed the potential for increased groundwater recharge and salinisation following the clearance of native vegetation in semi-arid regions of southern Australia (e.g. Allison et al., 1990; Walker et al., 1991; Cook, 1992; Kennett-Smith et al., 1994; Leaney et al., 1999; Leaney and Herczeg 1999; Leaney, 2000; Cook et al., 2004; Leaney et al., 2004).

Clearance of native vegetation and subsequent replacement with low water use, shallow rooted crops and pastures causes an increase in drainage past the root zone. The increase in drainage establishes a pressure front that moves through the soil profile towards the water table (Jolly et al., 1989). This results in the flushing or downward displacement of saline soil water as the pressure front moves downward through the unsaturated zone. When the pressure front reaches the water table, an increase in aquifer recharge occurs. Hence, there is a lag-time between the increase in drainage and the increase in recharge. Therefore the term drainage refers to water movement in the unsaturated zone whilst recharge refers to water movement to the saturated zone. If post clearance drainage rates are adequately high, a new steady state may be quickly attained (Allison et al., 1990).

However, the re-establishment of steady state conditions can take considerable time. Walker et al., (1991) developed a transient method that estimates drainage below the root zone under non-steady state conditions. This is known as the chloride front displacement technique:

$$D = \int_{z_{cf}^{o}}^{z_{cf}^{n}} \theta dz + \int_{z_r}^{z_{cf}^{o}} \delta\theta dz + \left[\int_0^{z_r} \delta\theta dz \right] \left(c_n / c_d \right) \qquad (1)$$

Where D is the drainage rate; z^n_{cf} and z^o_{cf} are the depths (m) of the chloride fronts under new and old land uses respectively; c_n and c_d are the chloride concentrations under new and original steady state condtions and $\delta\theta$ is the difference between volumetric water content under old and new land uses (see Walker et al. (1990) for the full derivation). Chloride is an anion found commonly dissolved in natural waters, and whose concentration is generally unaffected by geochemical reactions. Its conservative nature and simple analysis procedure make it a commonly used indicator of salinity in models such as that described above.

2.2 REGIONAL ESTIMATES OF DRAINAGE, RECHARGE AND GROUNDWATER SALINISATION FOLLOWING LAND CLEARANCE

2.2.1 DRAINAGE VS. % CLAY RELATIONSHIP: PREDICTION OF POST-CLEARING DRAINAGE RATES

Application of the chloride front displacement method for estimating drainage and recharge following land clearing over a large area, such as the Naracoorte Ranges, is not practical because of the coring and analysis costs involved. Hence, it is necessary to use a measurement that is more readily available as a proxy measurement for drainage. Kennett-Smith et al. (1994) identified a relationship between post-clearing drainage rates and the clay content of the soil in the top two metres of the soil profile. Since then, a number of studies have used this empirical relationship as a tool for scaling up point estimates of drainage (e.g. Leaney and Herczeg, 1999; Cook et al., 2004, Leaney et al., 2004).

Figure 1 shows the relationship between drainage rates under dryland agriculture and the clay content of the soil in the top two metres for 270, 300–399 and 470 mm/yr mean annual rainfall zones. Although there is considerable scatter in the data, a negative log-linear relationship is observed between post-clearing drainage rate and clay content. The graph also shows higher rates of drainage for wetter areas. The exception to this is where estimates of drainage are considerably less than those for a similar rainfall area in a similar environment (closed triangles). In this case, it is difficult to determine whether this is a real difference or a result of the limited availability of data. Leaney et al., (2004) assumed the latter and hence used a correlation for all data from the 470 mm/yr rainfall zones to determine a relationship between % clay content in the top 2 m of the soil profile and drainage for their site at Tintinara.

The relationship between clay content (C) and post-clearing drainage rate used by Leaney et al. (2004) for the Tintinara area was (Fig. 1):

$$\text{Drainage (D)} = 10^{(-0.035*C+1.9)}\ \text{(mm/yr)} \qquad (2)$$

2.2.2 A 1-DIMENSIONAL MODEL FOR THE ESTIMATION OF RECHARGE RATES FOLLOWING AN INCREASE IN DRAINAGE

The first step when estimating temporal changes in the salinity of the groundwater is to provide temporal estimates of recharge rate to the groundwater. An approach similar to that used recently by Cook et al. (2004) and Leaney et al. (2004) for studies in the Riverland and Tintinara areas of South Australia respectively, was applied to Padthaway. The equations used by them to model temporal changes in recharge rate assume a log normal distribution of recharge around a mean recharge rate (as originally developed by Cook et al. (1993)). The log normal distribution is defined by two parameters, μ and σ that are related to the variation coefficient.

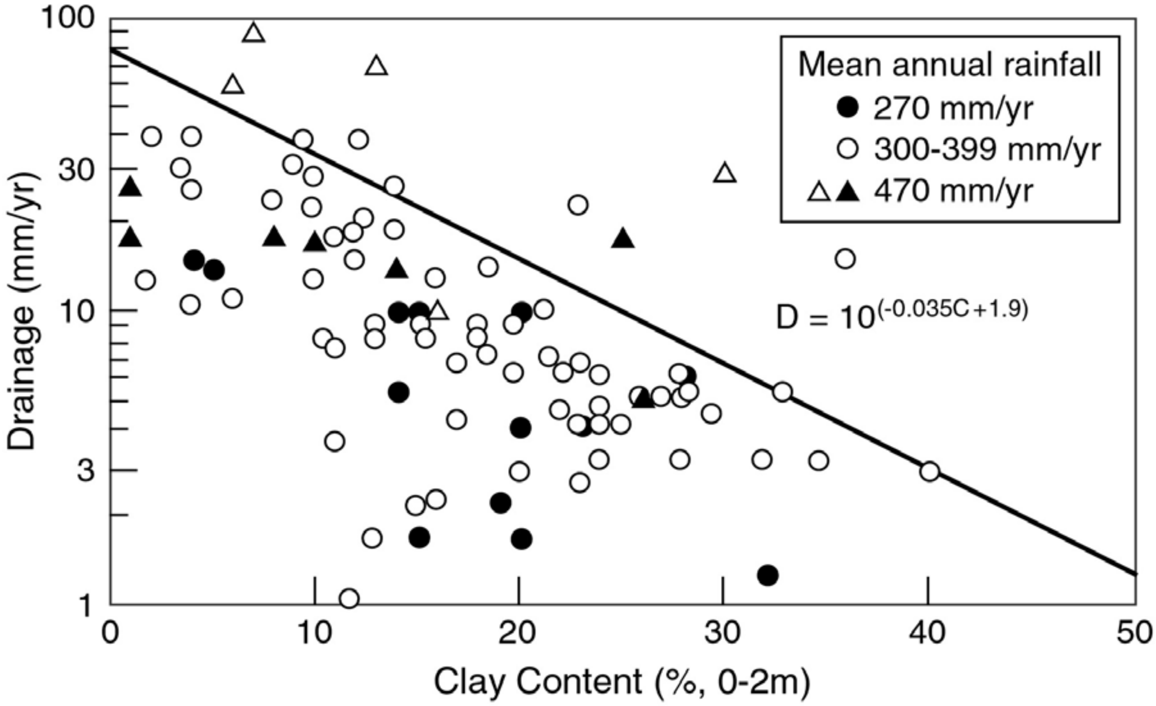

Figure 1. Relationship between soil texture and drainage under dryland agriculture in the 270 (closed circles), 300–400 (open circles), and 470 (diamond) mm yr^{-1} mean annual rainfall zones (Cook et al., 2004). The line of best fit was determined for data from the 470 mm/yr rainfall sites.

The present study uses the method developed by Cook et al. (2004) to calculate the water content (θ_w) as a function of the mean final drainage rate and the maximum hydraulic conductivity, K_{max} for different soil types. This is a more generic approach than that originally used by Cook et al., (1993) as it allows estimates of θ_w through a full range of drainage rates and soil types and can be applied to values for drainage expected under irrigated conditions.

The model of Cook et al. (2004) allows the inclusion of two soil layers, and the movement of water in the unsaturated zone can be modelled under conditions of varying thickness of a heavier clay layer overlying lighter textured soils. The different soils are characterized by the parameters (θ_m^a, θ_0^a, θ_m^b, θ_0^b, K_m) where θ_0^a, *and* θ_0^b are the residual water content for zero recharge (equilibrium water content under native vegetation) for the soil layers 'a' and 'b' respectively, and K_m is the reference value of hydraulic conductivity at a water content of θ_m^a, and θ_m^b. K_m should be greater than the drainage rates that are to be simulated. Recharge (*R(t)*) is then given by:

$$R(t) = 0.5e^{\mu+\sigma^2/2}\left(1 - erf\left(\frac{\ln\left(L/t^2\right) - \mu - \sigma^2}{\sigma\sqrt{2}}\right)\right) \qquad (3)$$

A full description of the method and nomenclature is given in Appendix 1 of Cook et al. (2004).

2.2.3 SOIL SALINITY VS. % CLAY RELATIONSHIP: PREDICTION OF SALT LOADS TO THE AQUIFER

The salinity of soil water in the unsaturated zone is an important parameter when determining rates of groundwater salinisation because it is directly proportional to the salt load to the aquifer. However, as is the case with estimates of drainage, soil water salinity is difficult to measure on a large scale and a surrogate measurement is required.

For example, in the recent study by Leaney et al., (2004), a relationship between the mean soil water chloride of the unsaturated zone under the 'pre-clearing' native vegetation scenario and the clay content of the top 2 m of the soil profile was given:

Soil water salinity (S_{sw}) = 408 x % clay (0–2 m) + 14 580 (mg/L) (4)

2.2.4 ESTIMATION OF RATES OF GROUNDWATER SALINISATION FOLLOWING CLEARING

Following the characterization of the 'pre-clearing' salt store and estimation of 'post-clearing' drainage and recharge rates, fluxes of salt to the aquifer over time since clearing can be estimated. As discussed previously, clearing of native vegetation causes an increase in drainage resulting in the establishment of a pressure front. The pressure front moves through the unsaturated zone towards the water table, subsequently displacing previously stationary saline soil water downwards. When the pressure front reaches the water table, recharge to the aquifer occurs. Therefore a lag time exists between a change in the drainage rate of the unsaturated zone and a change in the recharge rate to the aquifer. Hence, initial recharge to the aquifer will consist predominantly of saline soil water displaced from the unsaturated zone. As time progresses, there will be an increasing component of freshwater (start of the freshwater front) in the recharging water. This is because drainage for any soil landscape unit (SLU) is considered to have a log-normal distribution about a mean value and is not considered to be constant within the SLU. Hence the salt flux will reach a maximum value and then decrease as the pre-existing salt in the unsaturated zone is flushed into the groundwater. The salt flux will not reach zero because of the small amount of salt present in the post-clearing drainage. The equation for estimating the salt flux, $F(t)$, is given below:

$$F(t) = [R(t) - R_f(t)]\, S_{SW} + R_f(t)\, S_{SW} \qquad (5)$$

Where $R_f(t)$ equals the rate of movement of the freshwater front; and S_{SW} equals the salinity of the saline soil water (from Leaney et al., 2004).

3. METHODOLOGY

3.1 GENERAL

Clearing of native vegetation in the Naracoorte Ranges occurred approximately 45 years ago and, in addition, the unsaturated zone is in excess of 40 m thick in places. This means that unless the post clearing drainage rates are very high, the chloride front probably has not reached the water table throughout most of the Naracoorte Ranges and the chloride front displacement technique described above could be applied for point estimates of groundwater recharge.

Core samples from the unsaturated zone beneath differing land use and soil types were used to locate the position of the chloride front. The analytical model (given above) was then applied to the data to predict point estimates of unsaturated zone soil water movement (i.e. drainage). Point estimates of drainage and salt flux to the water table were then extrapolated spatially via a GIS interpretation of SLU maps to produce potential recharge and groundwater salinisation maps.

3.2 FIELD METHODS

In March and June 2003 a series of investigation holes were cored then completed as monitoring wells in the Naracoorte Ranges with the aim of sampling a range of land use types that are common to the area. Land uses chosen include; native vegetation, cleared dryland agriculture and irrigated Lucerne. Sites were also chosen to follow two transects, Transects A and B, along groundwater flow paths from the Naracoorte Ranges towards the main Padthaway Irrigation Area. Each site number includes a prefix, PA for dry land sites located along Padthaway transect A, PB for Padthaway transect B, NV for native vegetation sites and IRR for an irrigated Lucerne site (Fig. 2).

Unsaturated zone soil cores were taken from each of the investigation holes using hollow flight augers and split-tube wire line recovery technique on an Investigator drill rig. The hollow flight auger and split tube wire line recovery method enables no additional air, water or drilling fluids to be used therefore minimising the affect on pore water chloride and water contents of the core samples. Core samples were taken at 0.5 metre intervals to a depth of approximately ten metres, and then at one metre intervals thereafter. At each interval, cores were split with half being placed in airtight 500 mL glass jars for soil physical properties and pore water chloride analysis and the remaining part sample retained as a continuous core sample. Core samples were taken through the unsaturated zone to one to two metres below the water table with the exception at a few sites where sampling stopped at approximately 26 m, the limit for coring with hollow flight augers, despite the water table not being reached. Drilling then continued with air rods for completion of investigation holes as monitoring wells.

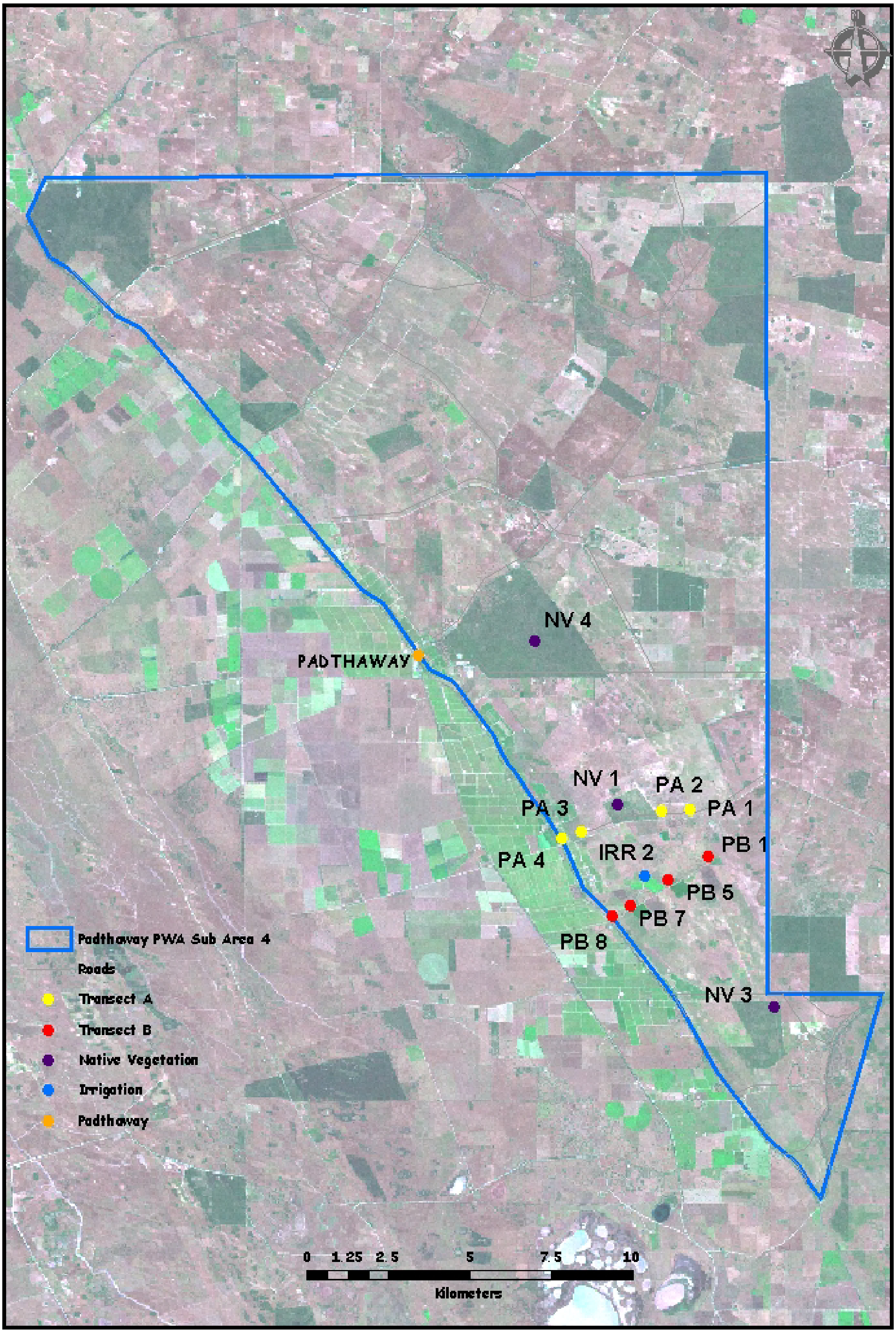

Figure 2. Cored investigation holes - site map

3.3 ANALYTICAL METHODS

The unsaturated zone core samples were analysed at CSIRO Water and Land – Adelaide for water content, matric potential, particle size and pore water chloride.

The water contents of the samples were obtained gravimetrically by oven drying the samples overnight at 105°C and measuring the wet and dry weights.

Chloride analyses of the sediment pore water samples were carried out on solutions of 10 g of sediment in 50 g of deionised water. These were analysed by a first-derivative potentiometric endpoint titration with $AgNO_3$ using an ORION Model 960 Autotitrator. The $AgNO_3$ titrant was standardised with a 1000-ppm chloride standard solution and the sample volume used was 1 ml. Uncertainty for this method determined by replicating standards is ± 3%. Chloride measurements were then corrected for the dilution factor and water content.

Estimates of particle size were carried out using the time settling method (Lewis, 1983). Sand is considered to be coarser then 0.02 mm, silt between 0.02–0.002 mm and clay finer than 0.002 mm.

4. RESULTS

Results for gravimetric water content (θ_g), soil water chloride $[Cl]_{sw}$ and particle size distribution for each site are tabled in Appendix A. The large range in θ_g values, from 0.008 to ~0.27 through the unsaturated zone, are due mainly to site and depth variations in soil texture and soil water suction. Soil water suction measurements were carried out on samples collected during this study as they are useful in determining areas where perching may occur and in determining the position of the pressure front, however they are not essential when estimating rates of drainage. From observations made during the drilling program, perching of water did not occur at any site.

Soil water chloride concentrations at the field sites range from ~25 to ~7800 mg/L (Figs 3–5). Typical native vegetation that occurs in the Mallee region of South Australia is very water efficient and consequently the amount of drainage below the root zone is extremely small (Cook et al., 2004). Due to the processes of evapotranspiration, the low concentrations of salts in rainfall become concentrated giving high soil water salinity levels. The soil water chloride profile from site NV4 appears to be the best representation of a typical natural salt store under native vegetation. The profile at this site is similar to those observed by Cook et al., (2004) in the northeast Mallee region of South Australia. Matric suction data also supports the typical native vegetation soil water chloride profile at site NV4. As shown in Figure 6, the matric suction data at NV4 does not show a downward displacement of the pressure front. In contrast, site NV1 appears to have been influenced by vegetation clearance and re-growth, as the chloride profile seems to have been displaced downward. Site NV3 has soil water chloride data that ranges between ~1000 and ~2000 mg/L over the entire profile and it is thought that this may be due to vegetation evolving in an environment where it does not need to be as water efficient (because more water is available).

Soil water chloride vs. depth profiles from sites PA1 and PA4 are comparable with those that have been observed under native vegetation, including site NV4 in this study. At these two sites, there is no evidence of the displacement of salt in the unsaturated zone and therefore little or no increase in drainage following the regional clearance of native vegetation. It is suspected that nearby trees may be influencing drainage and hence the observed chloride profiles at these sites.

At sites PB7 and PA2, the soil water chloride vs. depth profiles show a displacement of the salt downward in the profile. The soil water chloride concentrations in the top few metres of the profile at PA2 are between 100–300 mg/L, while between the depths of six and nine metres the soil water chloride concentration reaches a maximum of 3000–3400 mg/L. A similar pattern is found at PB7 where the top 6 m of the profile displays soil water concentrations of less than 900 mg/L and has a maximum chloride concentration at ~22 m of ~5400 mg/L. As described above, although originally chosen as a native vegetation site, site NV1 also shows a displacement of salt downward in the profile. Much of the top 10–12 m of the profile has soil water chloride concentrations less than 500 mg/L, while from 14–22 m the maximum concentration ranges from ~4500–5500 mg/L. A possible explanation of why site NV1 displays a soil water chloride profile similar to PB7 is that NV1 was located in an area of native vegetation re-growth, having been cleared at one time.

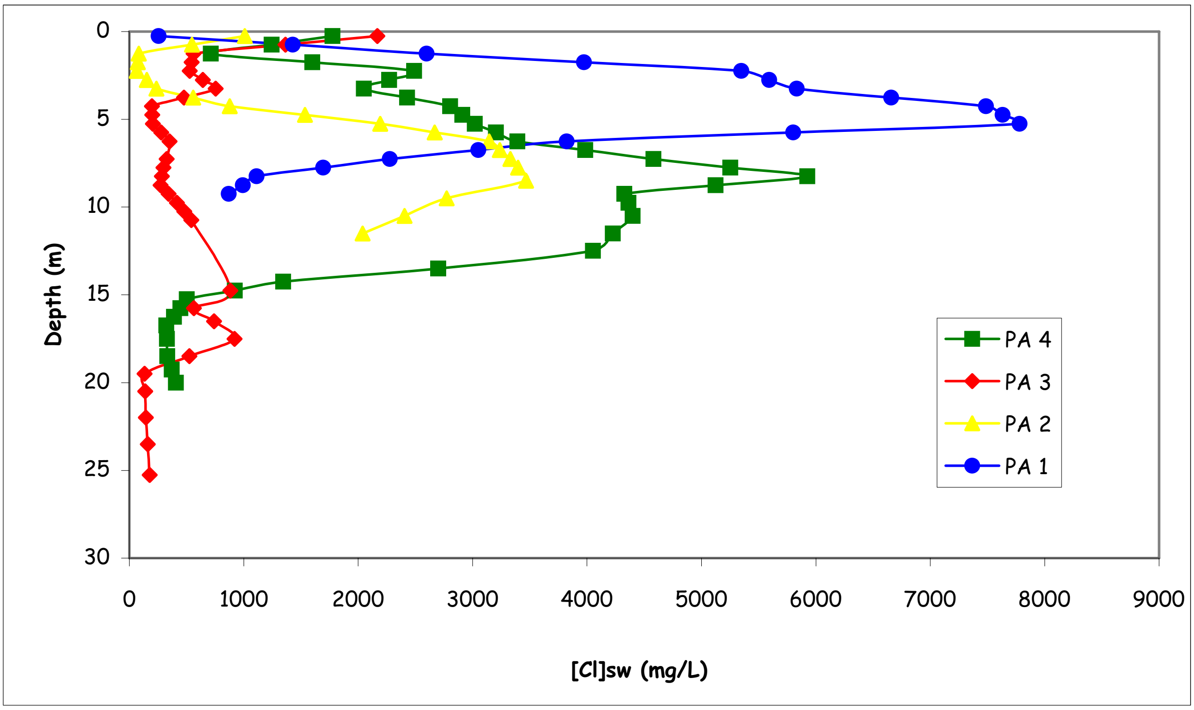

Figure 3. Soil water chloride vs. depth profiles for the PA series study sites.

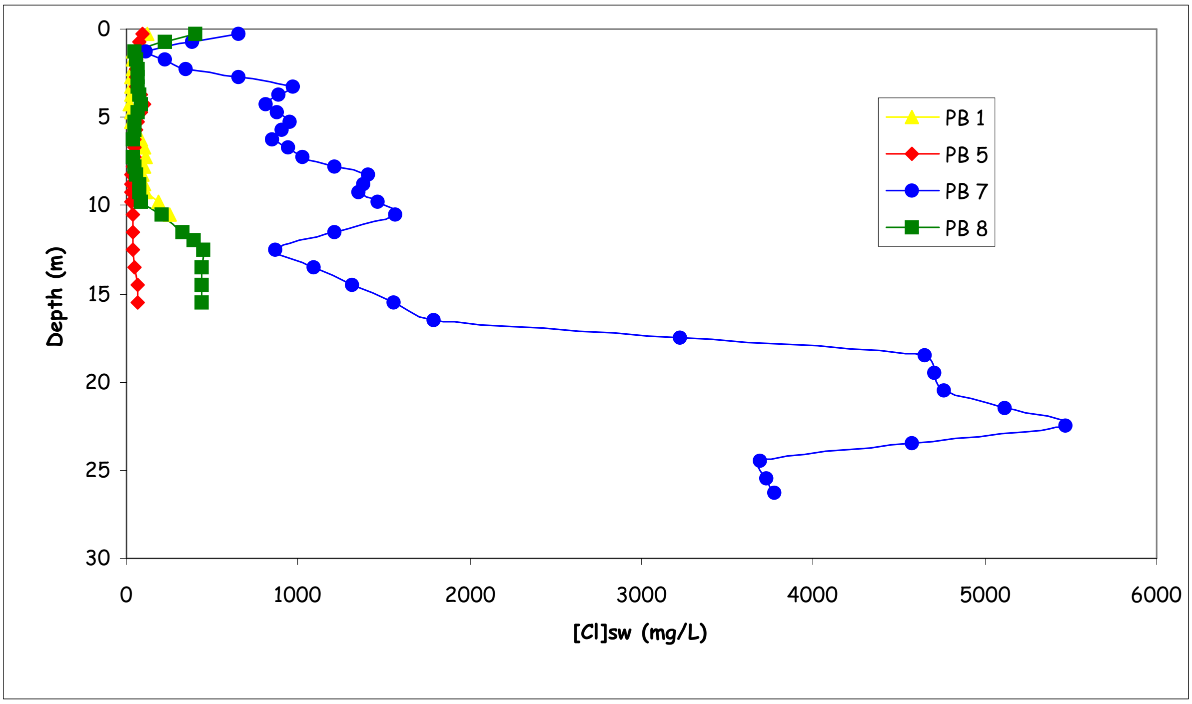

Figure 4. Soil water chloride vs. depth profiles for the PB series study sites.

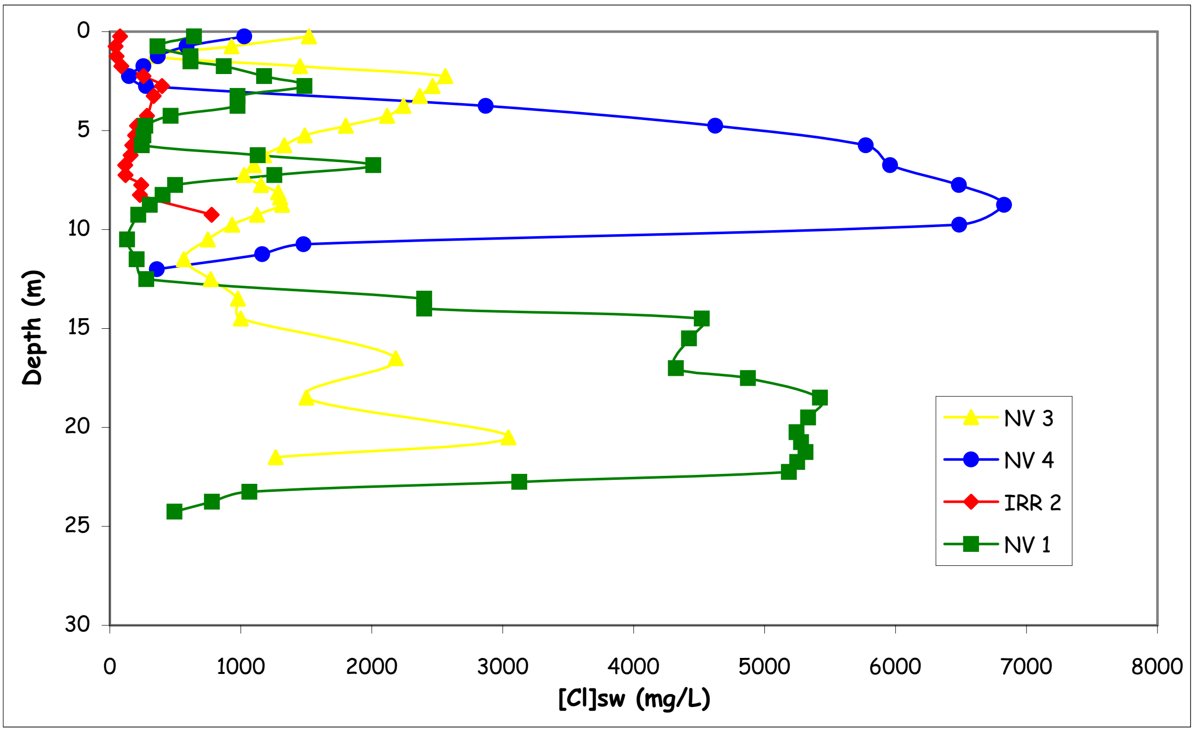

Figure 5. Soil water chlorides vs. depth profiles for the NV and IRR study sites

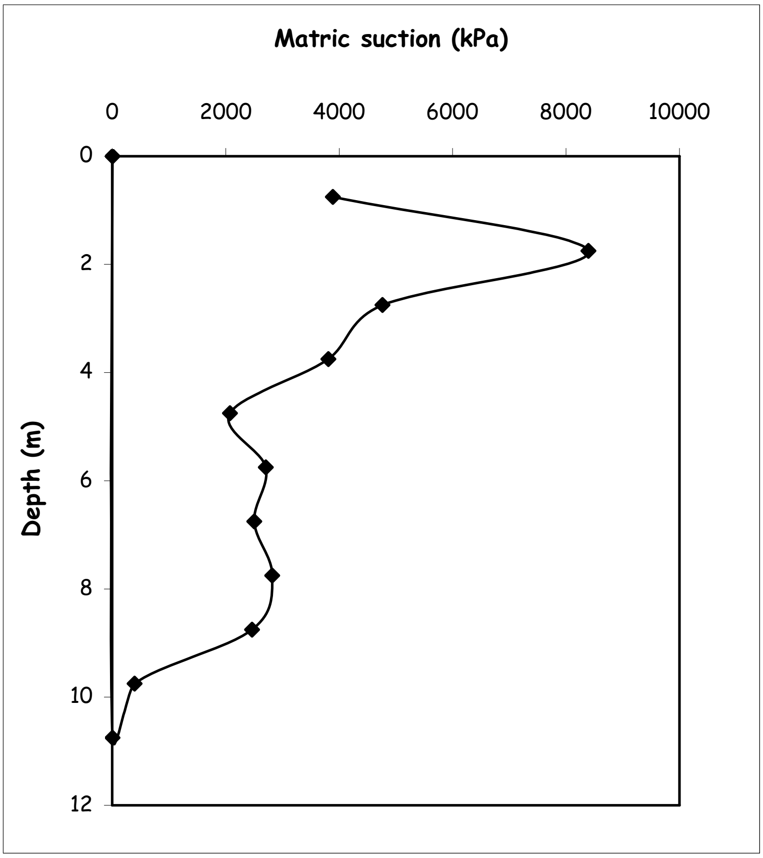

Figure 6. Matric suction profile for NV4

Soil water chloride data for sites PB1, PB5 and PB8 indicates that the historical salt store has been completely flushed from the profile. Concentrations of soil water chloride in the unsaturated zone at these sites range between approximately 25 mg/L and 100 mg/L. High sand content in the top 1–2 m of the profile and shallower depths to groundwater would have contributed to the flushing of salt from these sites.

Site IRR2 is located on a Lucerne stand irrigated by a traveling irrigator. As shown by the soil water chloride profile, salt has been flushed out of the profile, with chloride values ranging between ~50 and 400 mg/L.

The results of the particle size analyses showed that there are no significant clay layers present in the profile to inhibit drainage, with predominantly sand to loamy sand profiles (App. A).

5. DISCUSSION

5.1 POINT ESTIMATES OF RECHARGE USING THE CHLORIDE FRONT DISPLACEMENT TECHNIQUE

Estimates of recharge, shown in Table 1, were carried out for all sites using the chloride front displacement method described above (Walker et al., 1991). For the calculations, it was assumed that all sites were cleared of native vegetation 45 years ago (in 1960) and the plateau chloride concentration under native vegetation was estimated to be 5000 mg/L.

For several sites, a minimum recharge rate was estimated because the center of mass of the historical salt store had been flushed to the water table. At these sites, the average clay percentage in the top two metres is generally less than 10%. This, combined with a shallower water table, contributes to the estimate of recharge being expressed as a minimum value (estimates are >13 mm/yr to >49 mm/yr) (Table 1). Recharge rates are estimated to range between 2.5 mm/yr and 35 mm/yr at the remaining three sites where the center of mass of the salt store has not been flushed to the water table. These estimates are in line with estimates of recharge given in Cook et al. (2004) for the Riverland area and in Leaney et al. (2004) for the Tintinara area.

Table 1. Estimated recharge rates at study sites (chloride front displacement method)

Site	Average clay % (0–2 m)	Plateau [Cl]sw (mg/L)	z_{cf}^{o} (m)	z_{cf}^{n} (m)	Recharge rate (mm/yr) *
PA 1	17	7500	0.27	2.5	2.5
PA 2	1	3300	3.6	>10.5	>21
PA 3	2	200	3.45	>26	>17
PA 4	16	4300	0.41	8	13
PB 1	9	50	2	>5.5	>13
PB 5	0.5	50	3.75	>15	>36
PB 7	22	4800	0	18	35
PB 8	19	50	0	>11.5	>49

* Assuming that clearing took place 45 years ago (1960)

5.2 REGIONAL ESTIMATES OF RECHARGE AND GROUNDWATER SALINISATION FOR PADTHAWAY

5.2.1 THE DRAINAGE VS. % CLAY CONTENT RELATIONSHIP

The majority of data collected from Padthaway during this study provides estimates of minimum drainage only using the chloride peak displacement method, as the historical salt store has already been flushed at many sites. Therefore, only a few points can be plotted on the drainage vs % clay content (0–2 m) graph for the Naracoorte Ranges at Padthaway.

Estimates using the chloride mass balance method, which assumes steady state conditions, (Allison et al., 1990) may also represent minimum drainage rates, as the profiles may not yet have reached a new steady state. Complicating this further is that the drainage vs. % clay content (0-2 m) was intended for dryland agriculture data. At a couple sites, data for this study was gathered from roadside sites where factors such as excess run-off may give rise to higher than expected drainage values.

The limited unsaturated zone data available for the Padthaway area, and a qualitative analysis of observation well salinity and water level records, were used to adjust the parameters of the drainage rate vs. % clay content relationship of Leaney et al. (2004) (Equation 2) to account for the higher rainfall (510 mm/yr) and slightly different geology at Padthaway compared with Tintinara (470 mm/yr). Hence, the correlation between drainage rate and % clay content in the top two metres of the soil profile (C) was adjusted to:

$$\text{Drainage (D)} = 10^{(-0.035*C+2.3)}\ \text{(mm/yr)} \qquad (6)$$

This relationship could be improved through the collection of additional unsaturated zone field data, with the drilling program guided by the model results.

5.2.2 THE 1-DIMENSIONAL MODEL FOR INCREASING RECHARGE FOLLOWING AN INCREASE IN DRAINAGE

Drilling in the Naracoorte Ranges, carried out as part of this study, showed that the properties of the unsaturated zone (Bridgewater Formation) are more uniform than those encountered in the Murray Basin, where the Blanchetown Clay aquitard has a significant effect on drainage. The Bridgewater Formation observed during the drilling at Padthaway generally consisted of sand and unconsolidated sandstone with very few clay layers. Hence, in the model of the onset of recharge following an increase in drainage, it was not necessary to consider the effects of a second layer of different hydraulic properties, and the thickness of the 'clay layer' was set to zero in the model. The soil parameters for the 'non-clay layer' were selected based on observations from the soil cores collected during the drilling, and are defined as: θ_m^a = 0.27 and θ_0^a = 0.06 (see App. A for range of θ values). K_m was adjusted from the value of 0.45 m/yr used by Cook et al. (2004) and Leaney et al. (2004) to 0.9 m/yr during the reconciliation of the model results with soil core and observation well data, and to account for the sandier nature of the study area. Following Cook et al. (2004), the thickness of the clay in the unsaturated zone is denoted z_b. The thickness of the non-clay layer, z_a, is the difference between the water table depth, z_{WT}, and the thickness of the clay layer (i.e. $z_a = z_{WT} - z_b$.)

To be consistent with the work in the Riverland and Tintinara studies, and due to a lack of data on the statistical variability of soil properties in the Naracoorte Ranges at Padthaway, a value of 0.28 was used for σ and μ varied accordingly (as described in Cook et al., 2004) based on the mean drainage rate (as given in App. B).

5.2.3 THE SOIL SALINITY VS. % CLAY RELATIONSHIP

To calculate the salt loads to the aquifer following an increase in drainage, it was necessary to modify Equation 4 to reflect the different conditions at Padthaway compared with Tintinara, particularly the higher rainfall at the former site. Data was gathered for three native vegetation sites in the Naracoorte Ranges. At each site, soil water salinity has been averaged from the depth at which chloride concentrations plateau to the depth at which coring ceased. This represents the chloride concentration of the soil water under native vegetation (i.e. prior to clearing). This probably represents a slight over-estimate in the amount of salt in the unsaturated zone because soil water salinity close to the water table is likely to be considerably fresher as a result of diffusion processes within the capillary fringe.

As described previously, not all "native vegetation" cores display typical soil water chloride profiles with only NV4 showing a classical semi-arid native vegetation (pre-clearance) chloride profile. At this site, a plateau chloride concentration of 6000 mg/L is observed. Due to the limited data set, plotting a soil water chloride vs. clay content relationship for the Naracoorte Ranges would not be appropriate. However, as with the drainage vs. % clay (0–2 m), a surrogate relationship for soil water salinity is required. If we assume that the salinity of soil water is approximately double the chloride concentration of soil water (i.e. 12 000 mg/L for site NV4), then the relationship between soil water salinity and % clay (0–2 m) is:

$$\text{Soil water salinity } (S_{sw}) = 408 \times \%\text{ clay } (0\text{–}2\text{ m}) + 8000 \text{ (mg/L)} \qquad (7)$$

This gives a reasonable match to the data from site NV4. Equation 7 uses the same slope as given in Leaney et al. (2004) and replaces the constant given in Leaney et al. (2004) to represent the lower salinities found in the Naracoorte Ranges, a result of the higher rainfall at that site. Additional data from native vegetation sites in the Naracoorte Ranges would be required to verify or improve this relationship. A problem encountered during this study was the sparse occurrence of stands of undisturbed remnant native vegetation. It was also discovered that, in order to obtain representative 'pre-clearing' profiles, it is necessary to position drilling equipment well within a dense stand of such vegetation, something that is not easily achieved.

5.3 COMPARISON OF MODEL RESULTS WITH FIELD OBSERVATIONS

The field data collected during this study has been used to refine the parameters and empirical relationships used in the analytical model for recharge rates and salt fluxes in the Naracoorte Ranges. In particular, the modelled recharge rate lag times after clearing are compared with the observed increase in water level in particular monitoring wells. Good agreement between the modelled results and observed water level and salinity trends gives confidence to extrapolate the model across the entire Naracoorte Ranges. For example, comparison of modelled results and observation data for Departmental observation well PAR044 reveal measured water level and salinity trends match reasonably well with the model output (Figs 7–9).

The model predicted groundwater recharge to increase approximately 20 years after clearing and continue to rise for another 20–25 years after which a plateau recharge rate is reached. Observed water level data for PAR044 matches the models predictions, showing a steady rise in water levels from around 1980 until a plateau was apparently reached in the last few years of the record. A delay as shown in Figure 9, in observing the increase in salinity may be expected due to the lag time associated with mixing in the groundwater system.

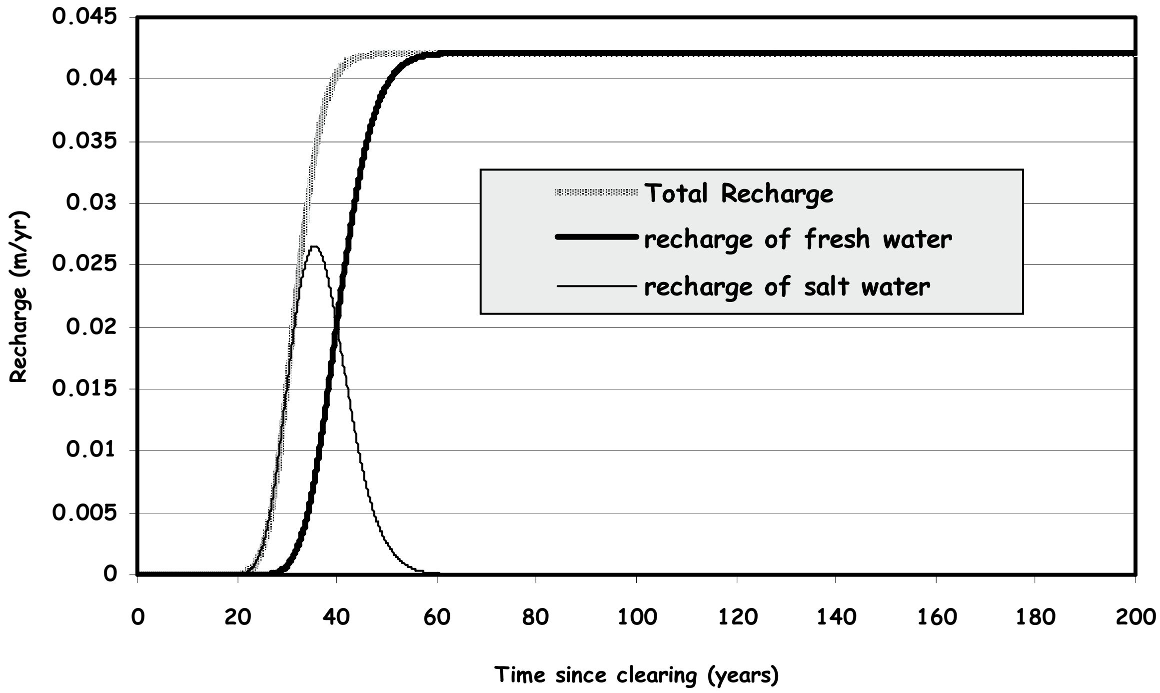

Figure 7. Modelled output for PAR044

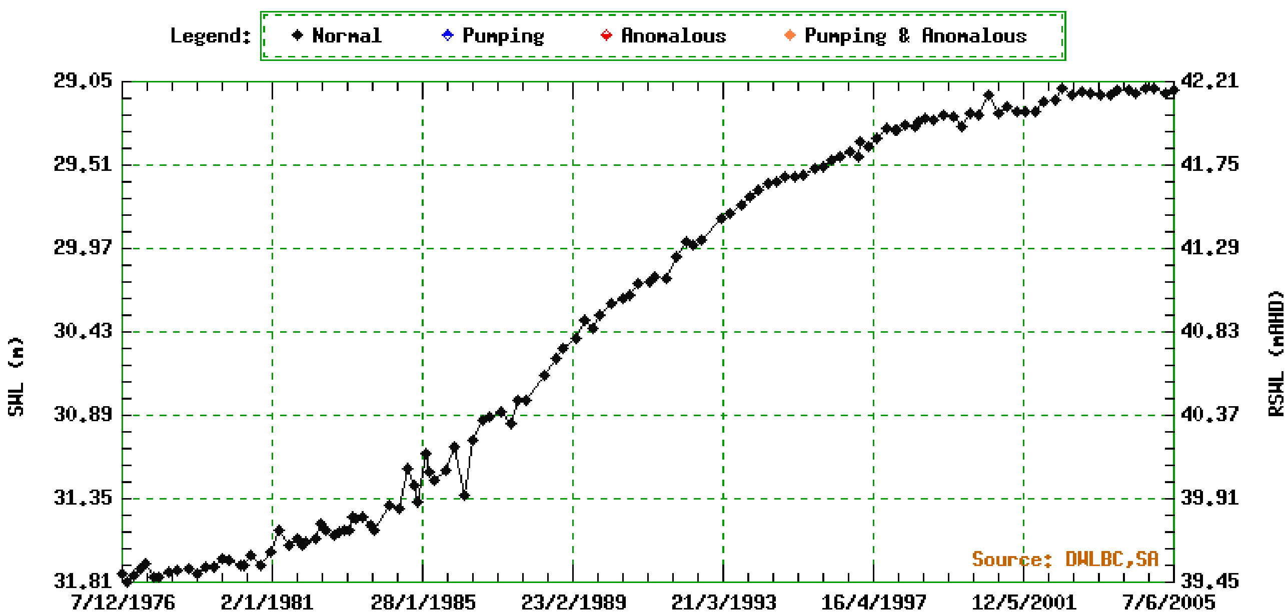

Figure 8. PAR044 historical water level data

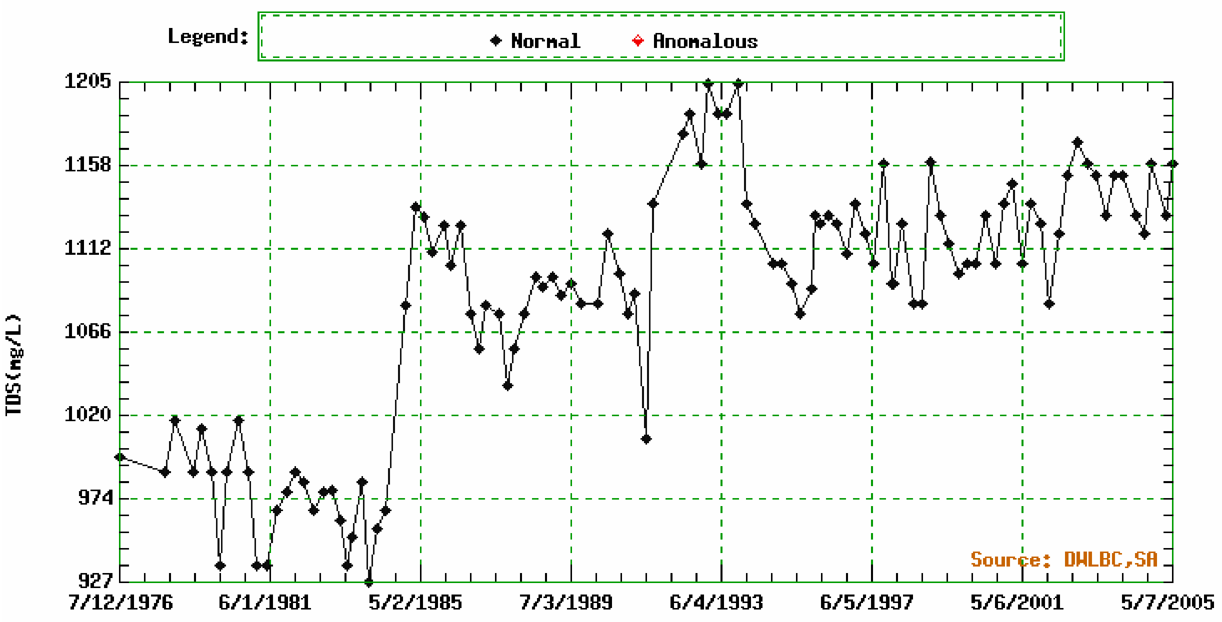

Figure 9. PAR044 historical salinity data

5.4 SPATIAL EXTRAPOLATION OF THE 1-D MODEL BASED ON CLAY CONTENT IN THE ROOT ZONE (0–2 M) AND WATER TABLE DEPTH

5.4.1 RECHARGE

The amount of clay in the top two metres of the profile was used as a proxy for determining drainage rates when spatially modelling the data. For the study area, there are 38 SLUs with one sub-unit (soil type) for each (App. B). Seven of the 38 SLUs had not been mapped at the time modelling was completed for this project. However, the seven SLUs comprise approximately 2% of the total study area (Fig. 10) and are located along the southern boundary of the study area (Fig. 11). The mean clay content of the SLUs for the 0–2 m depth interval ranges from 10–55% (Fig. 11). Greater than 72% of the area has soils with clay content (0–2 m) of 10% (Figs 10–11).

Drainage was estimated for each SLU using Equation 6. Mean drainage estimates for each of the SLUs ranges from 2.4–89 mm/yr (Fig. 12 and App. B).

The shallowest water table area occurs generally on the southern and western boundaries of the Naracoorte Ranges study area (Fig. 13). In a number of areas in the northeastern portion of the study area, greater depths to water coincide with higher clay contents (up to 55%) in the surface soil (Figs 11 and 13).

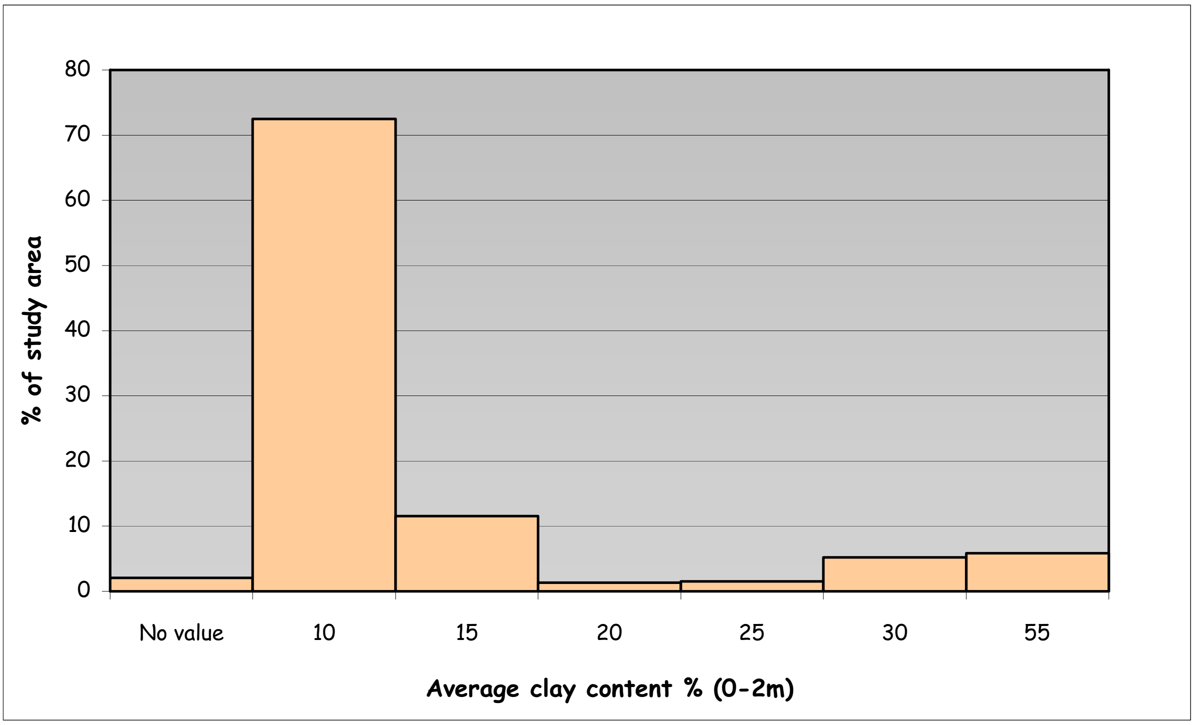

Figure 10. Histogram of the average clay content of the SLUs as a percentage of the study area

Using the above soil physical characteristics for the soil layers, the clay content (Fig. 11), the drainage map (Fig. 12) and the GIS coverage for watertable depth (Fig. 13), spatial distributions of recharge can be calculated as a function of time since clearing. Estimates of recharge rate to the aquifer at 10, 20, 45 and 50 years after clearing are depicted in Figures 14 (a–d) respectively. Figures 15 (a–d) also show predicted cumulative recharge over the study area at various times following clearing. The model suggests that recharge has reached a plateau across most of the study area after approximately 100 years post clearing. However, it is considered unrealistic to make any detailed predictions over such a long time period using an empirical model.

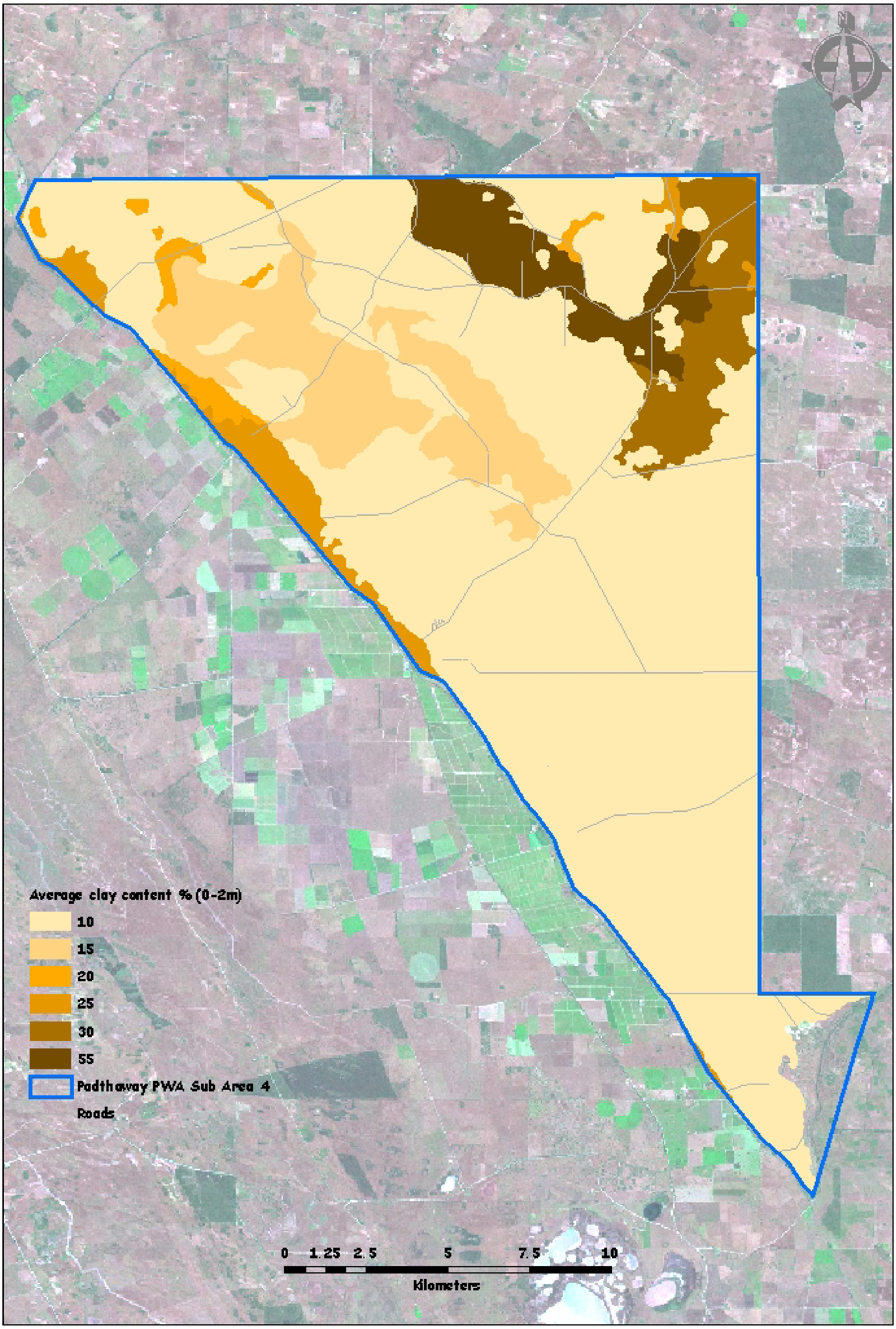

Figure 11. Map of clay content % for soil landscape units in the study area

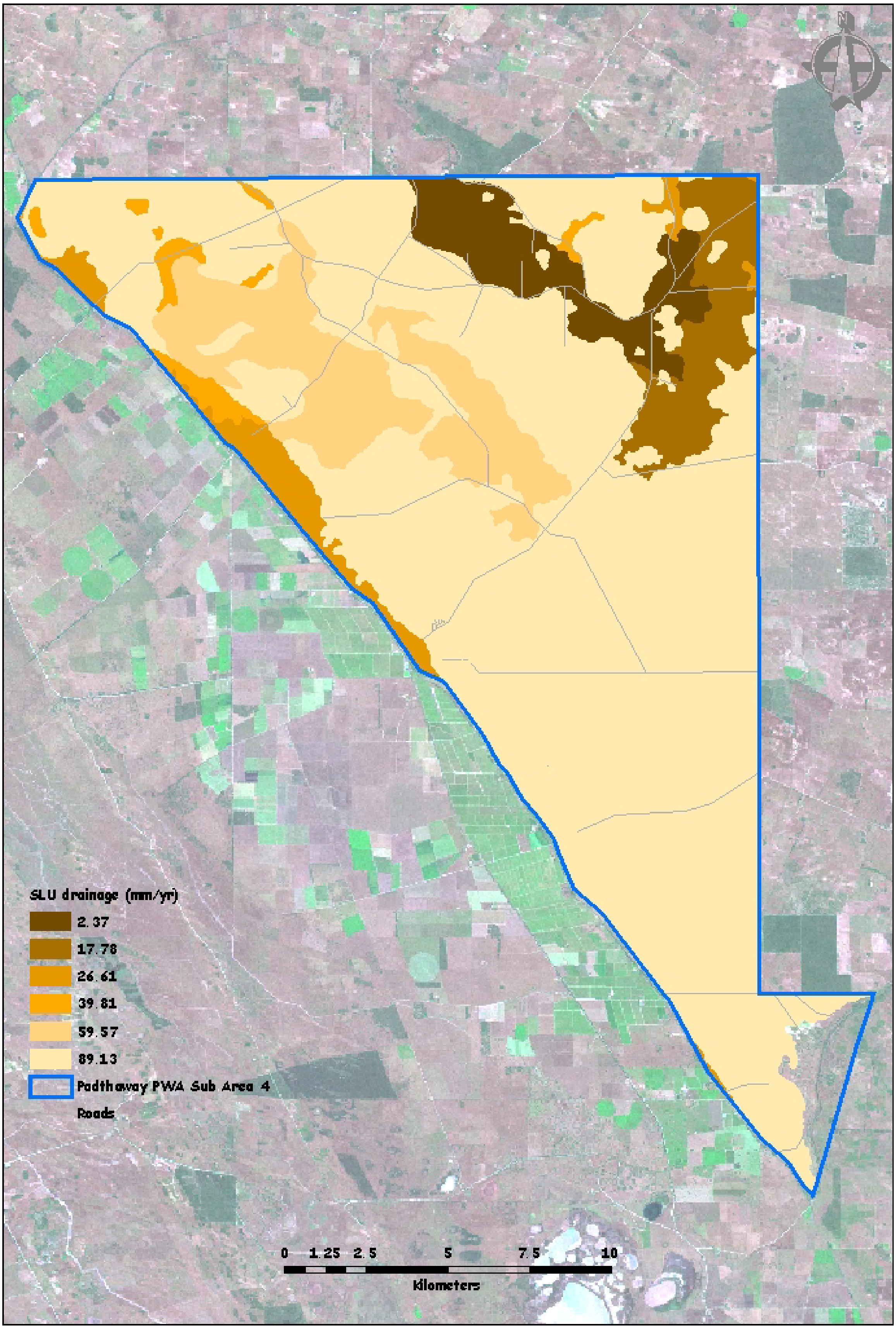

Figure 12. Estimated rates of drainage within the study region based on the % clay content of the SLUs

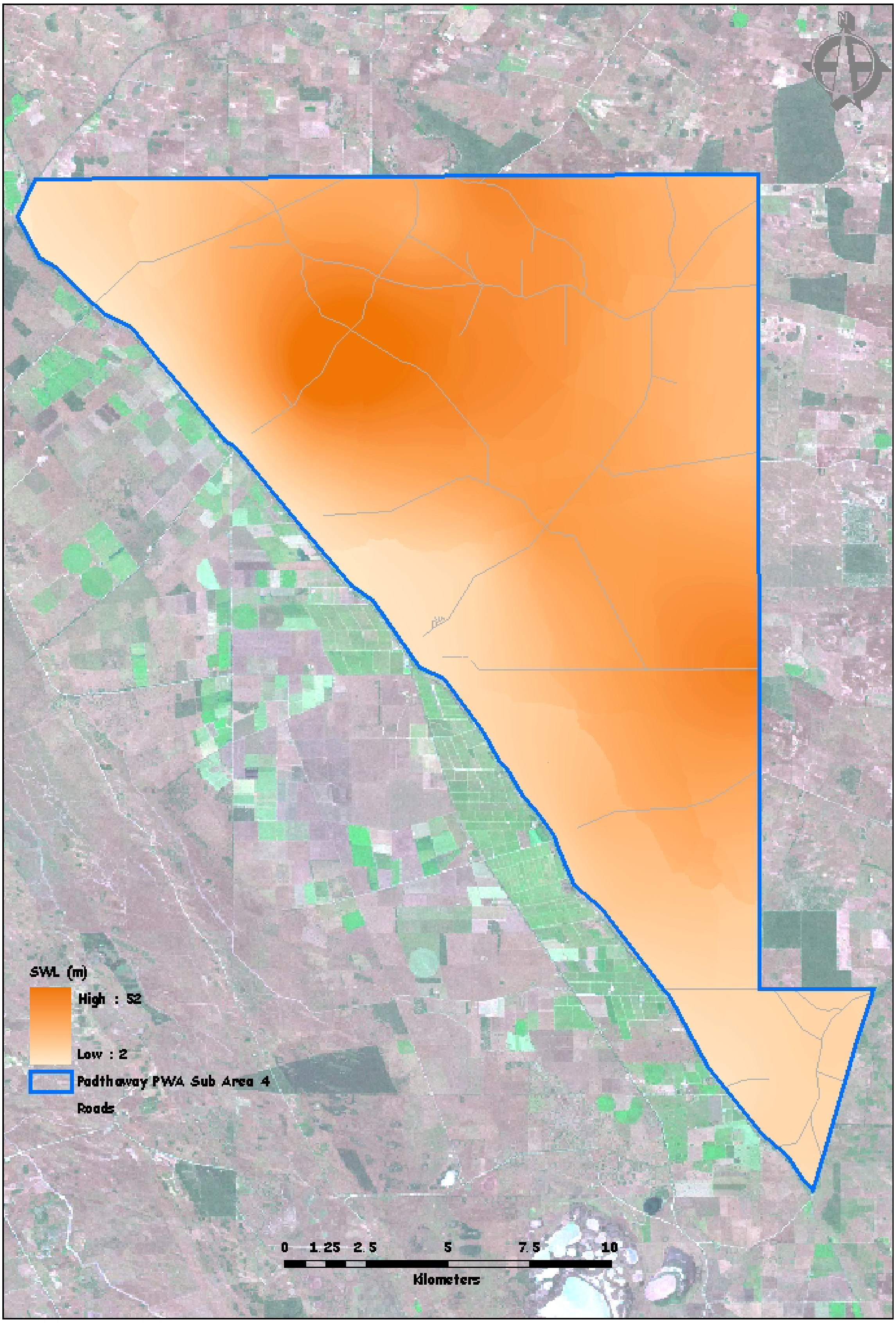

Figure 13. Map of water table depth for the study area

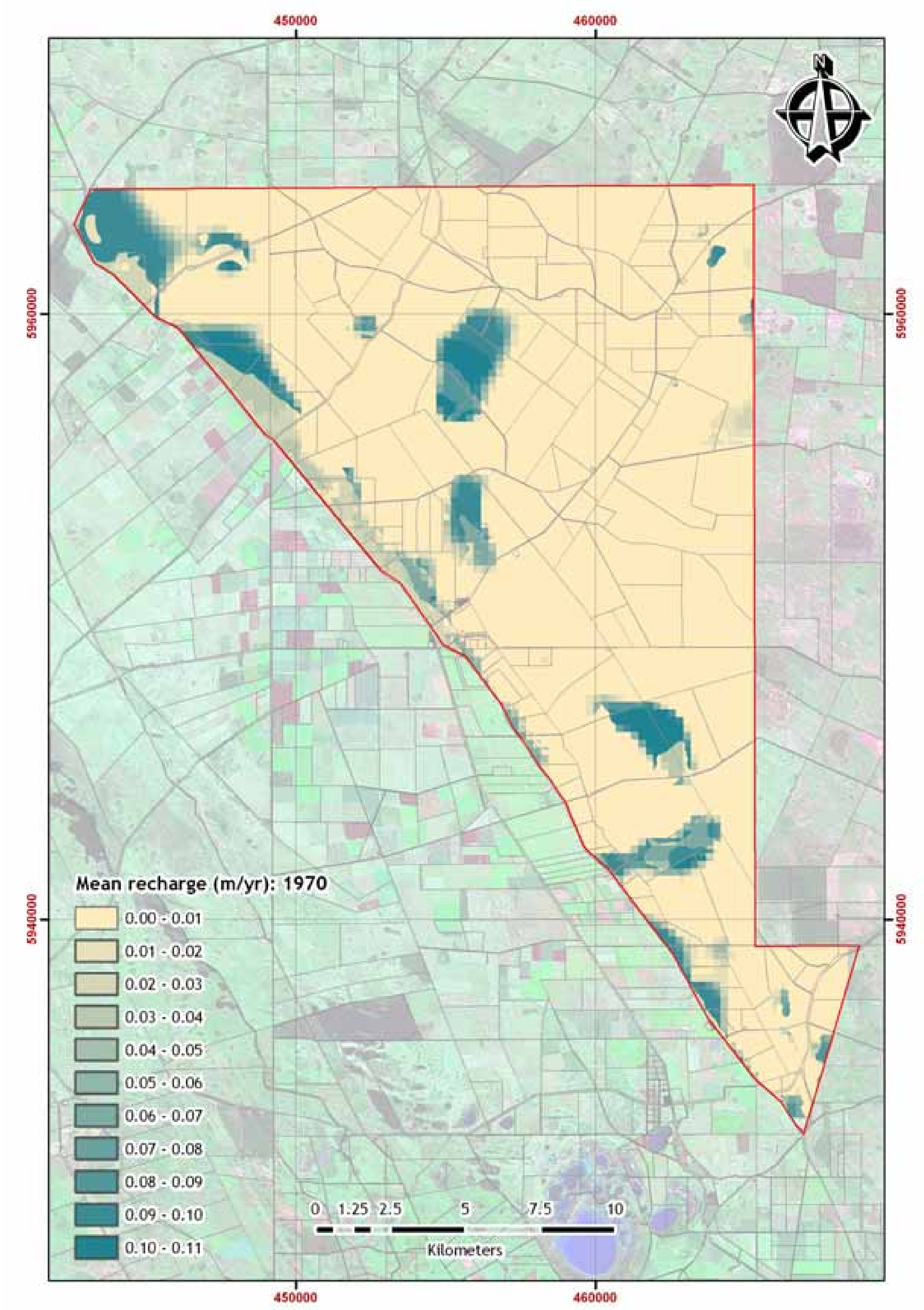

Figure 14a. Predicted mean recharge rates for the study area in year 1970 (10 years after clearing)

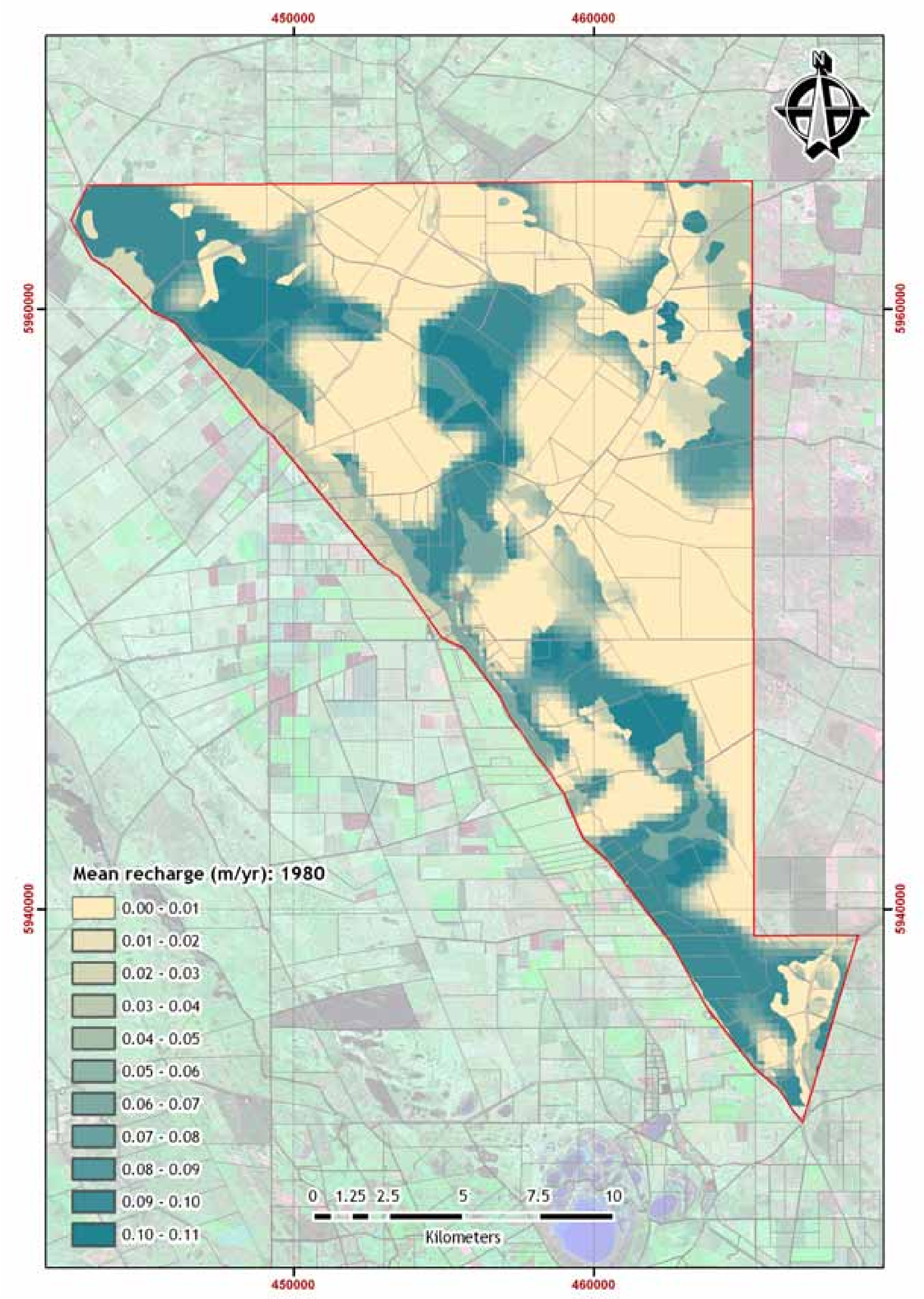

Figure 14b. Predicted mean recharge rates for the study area in year 1980 (20 years after clearing)

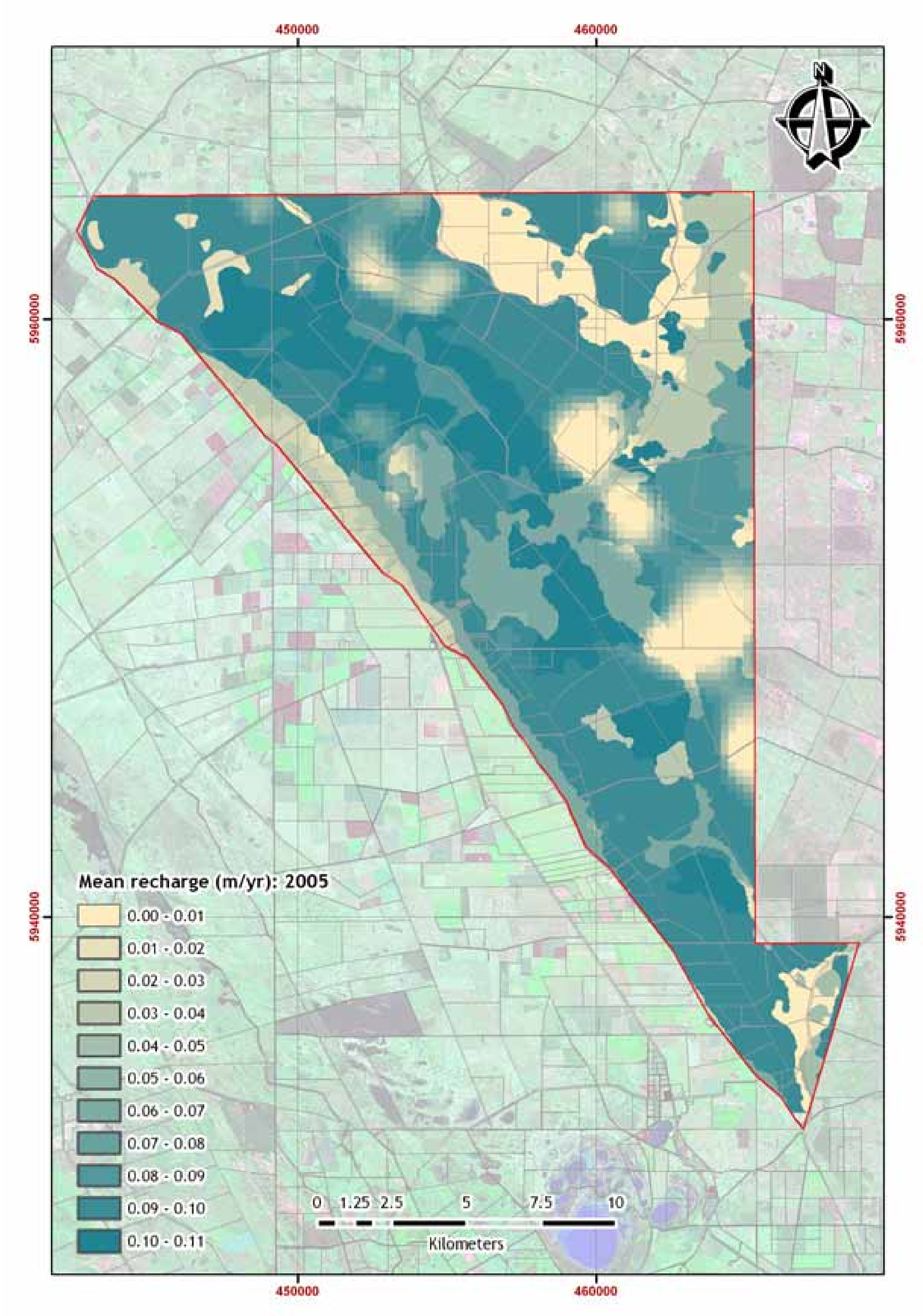

Figure 14c. Predicted mean recharge rates for the study area in year 2005 (45 years after clearing)

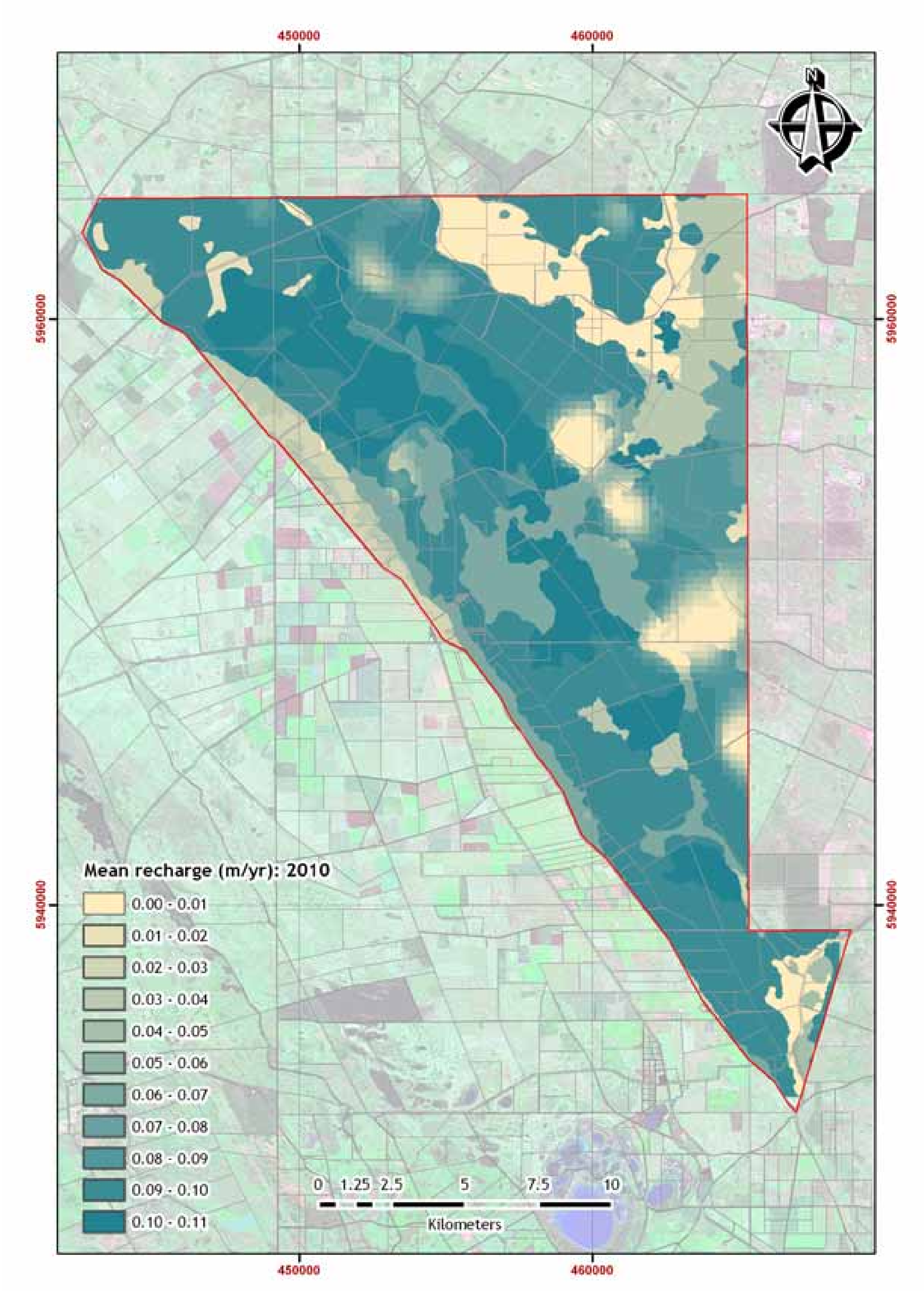

Figure 14d. Predicted mean recharge rates for the study area in year 2010 (50 years after clearing)

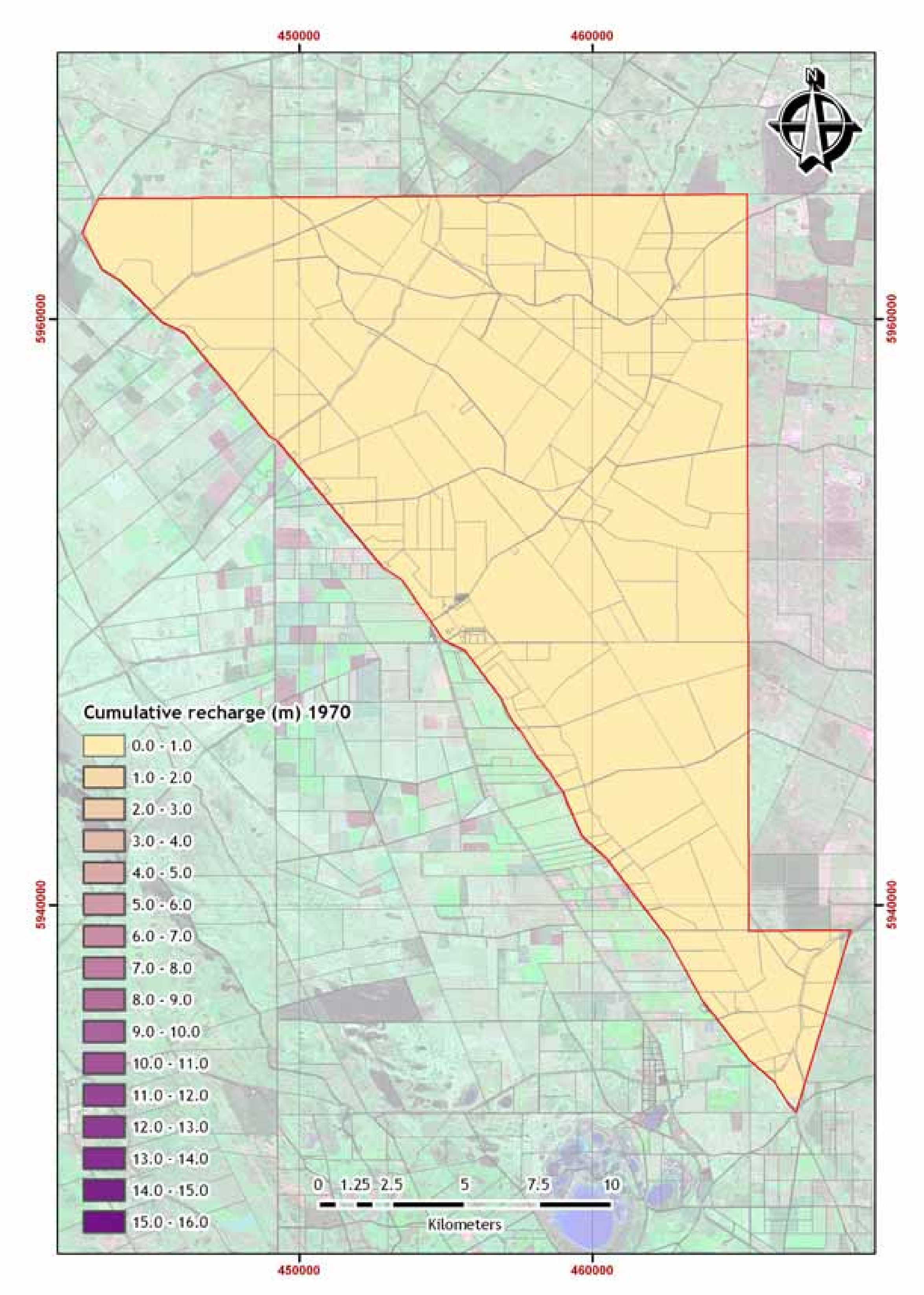

Figure 15a. Predicted cumulative recharge for the study area in years 1970 (10 years after clearing)

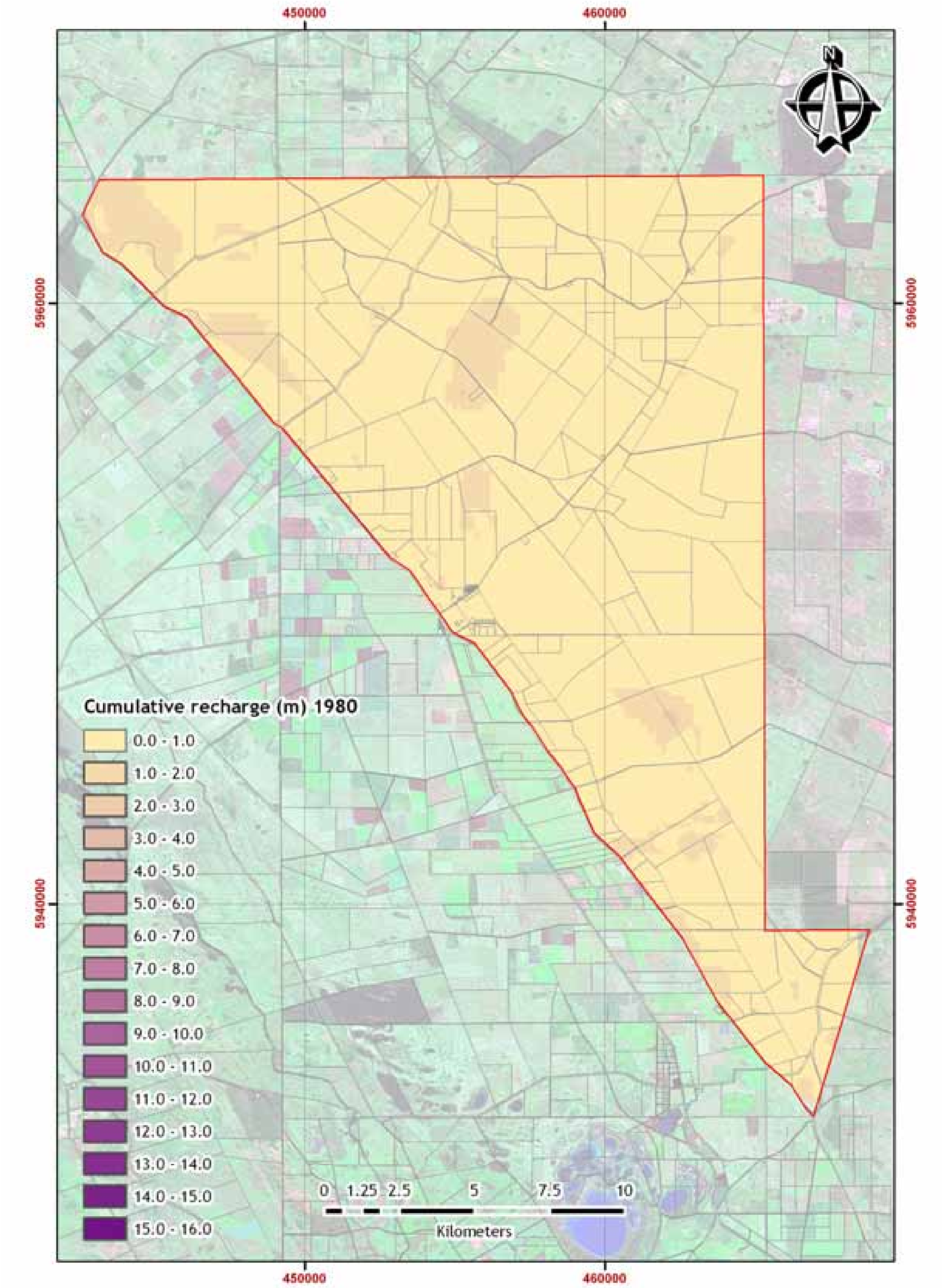

Figure 15b. Predicted cumulative recharge for the study area in years 1980 (20 years after clearing)

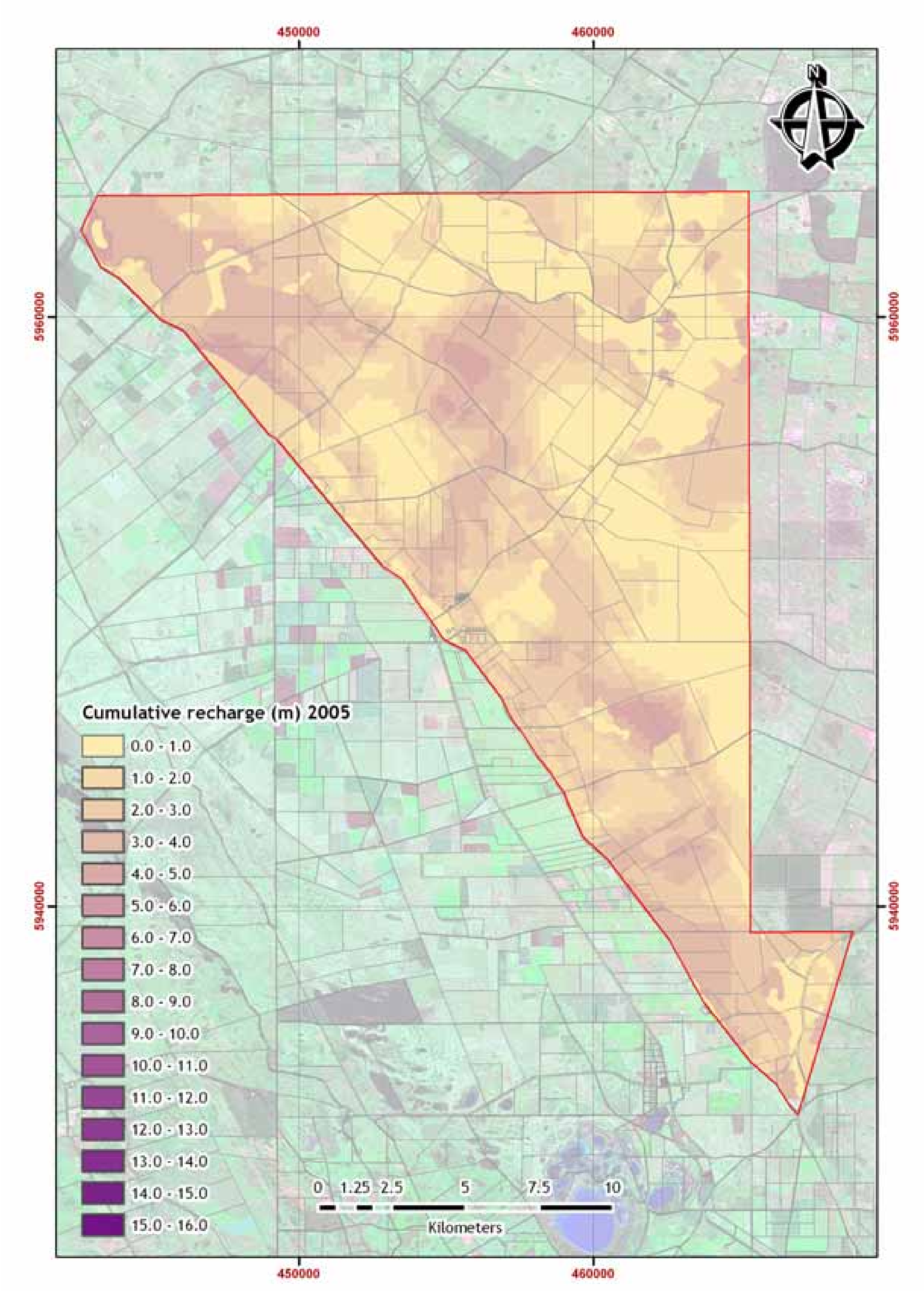

Figure 15c. Predicted cumulative recharge for the study area in years 2005 (45 years after clearing)

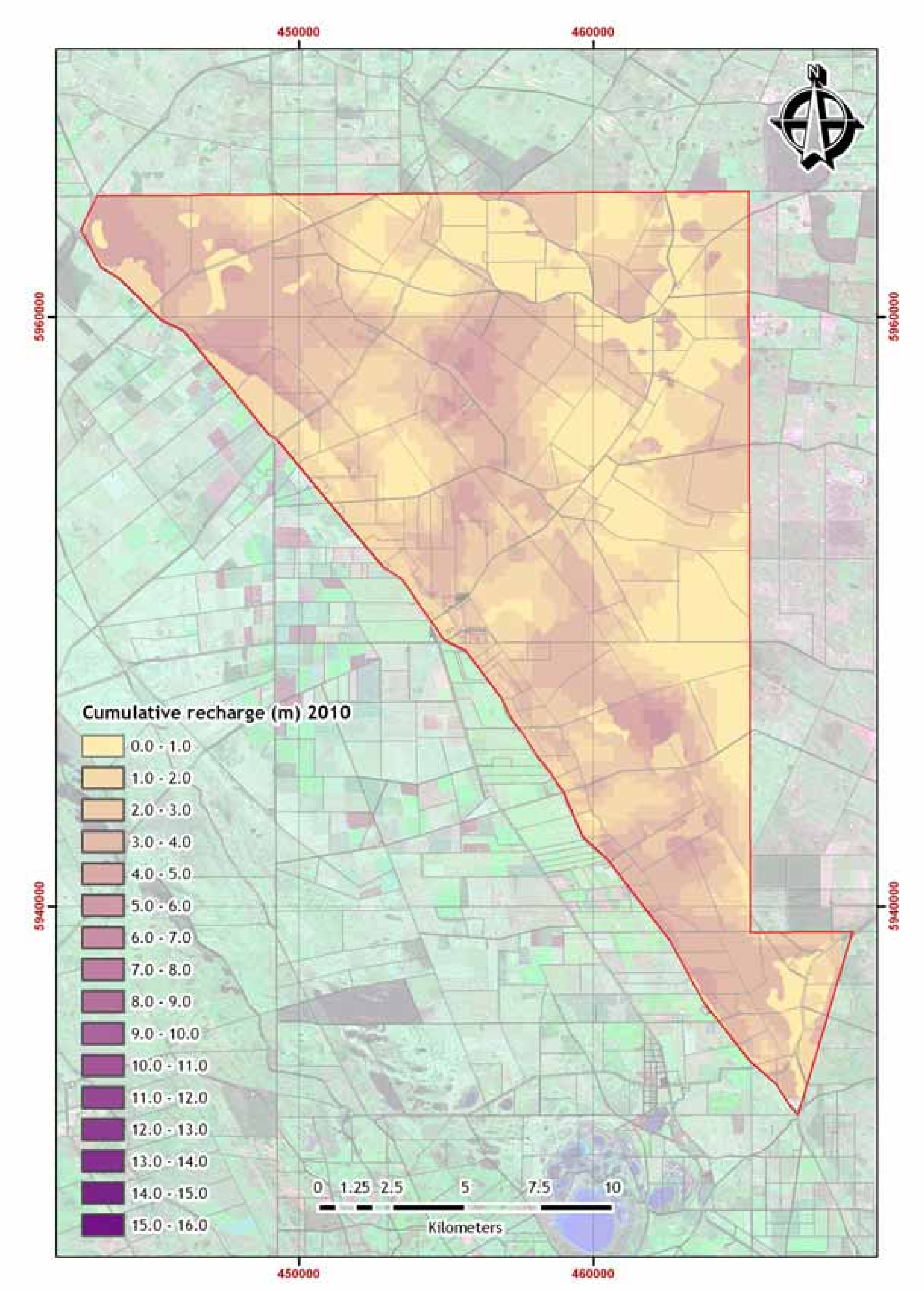

Figure 15d. Predicted cumulative recharge for the study area in years 2010 (50 years after clearing)

5.4.2 SALT FLUX

Salt flux and cumulative salt input to the aquifer can be calculated as a function of time since clearing using Equation 5, the spatial distributions of recharge, salt concentrations of soil water, and 300 mg/L for the soil water concentration of drainage above the freshwater front. Estimates of salt flux to the aquifer at 10, 20, 45 and 50 years after clearing are depicted in Figure 16 (a–d). Again, the model suggests that salt flushing from the unsaturated zone is completed approximately 100 years post clearance, but it is considered unrealistic to make any detailed estimates of salt flux at these time scales based on an empirical model.

Also shown are cumulative salt inputs to the groundwater for nominated times after clearing (Figs 17 (a-d)). This is the amount of salt that has been displaced from the unsaturated zone into the groundwater as a result of increased drainage rates following clearing of native vegetation at a designated time since clearing.

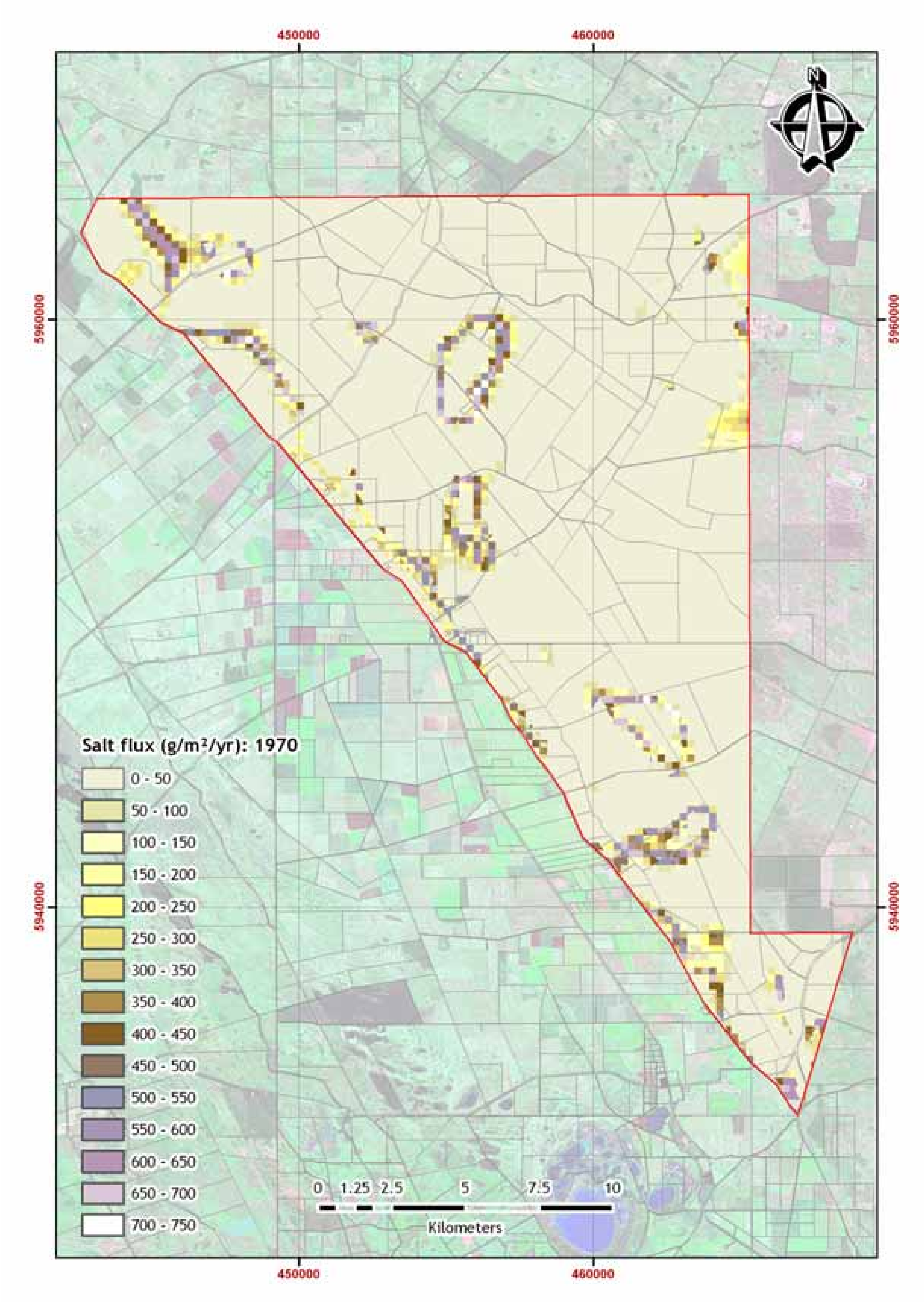

Figure 16a. Predicted salt flux for the study area in year 1970 (10 years after clearing)

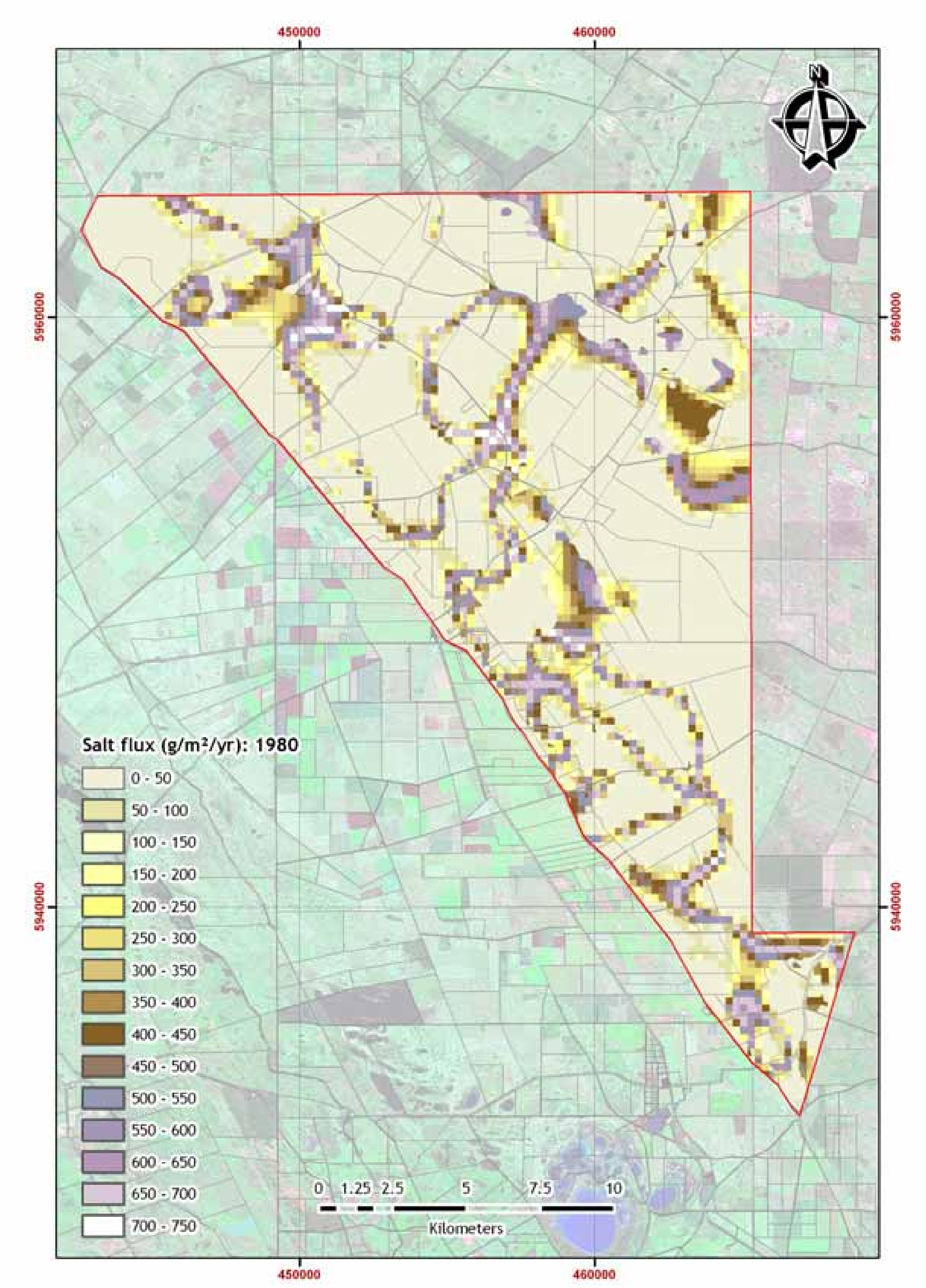

Figure 16b. Predicted salt flux for the study area in year 1980 (20 years after clearing)

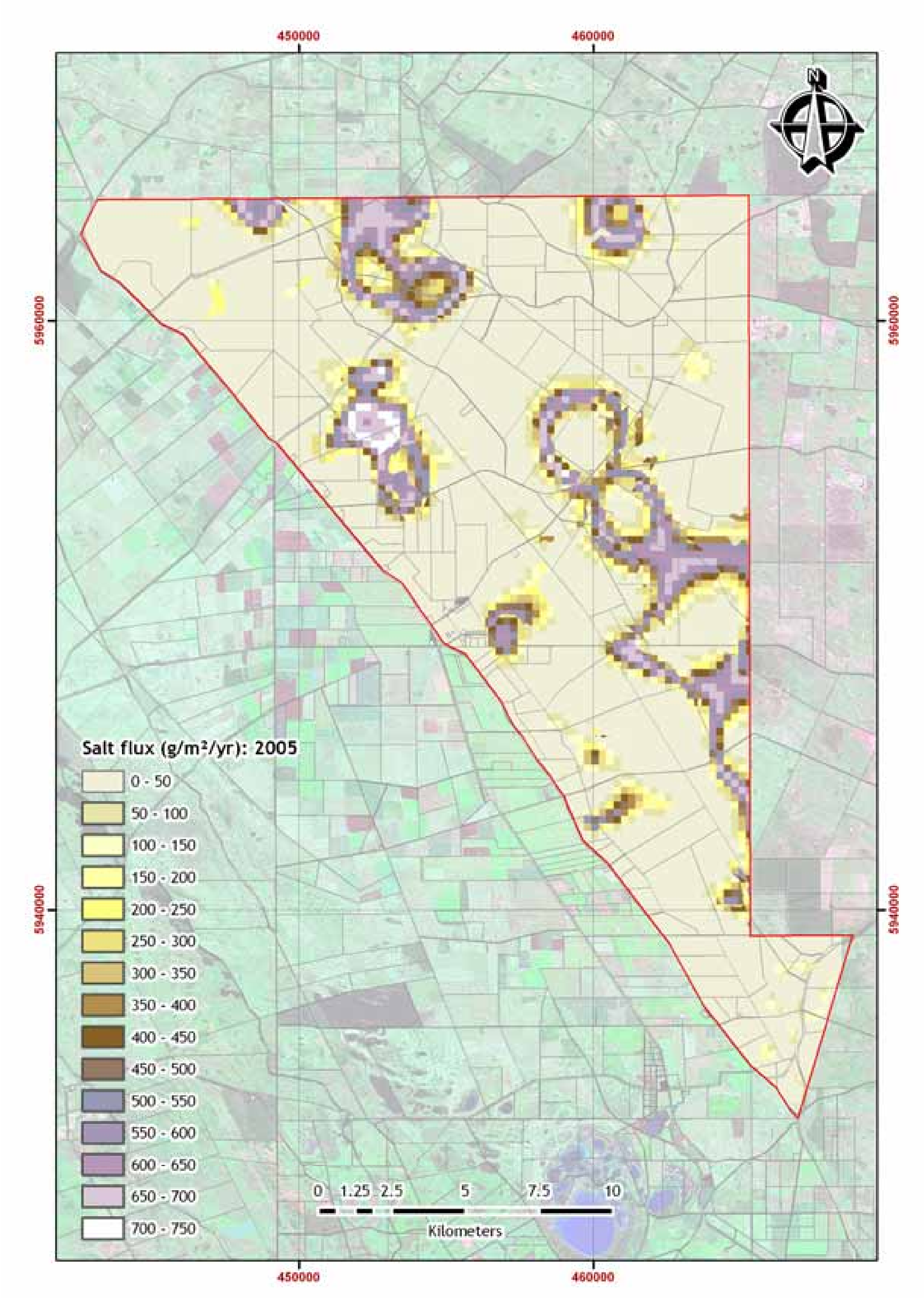

Figure 16c. Predicted salt flux for the study area in year 2005 (45 years after clearing)

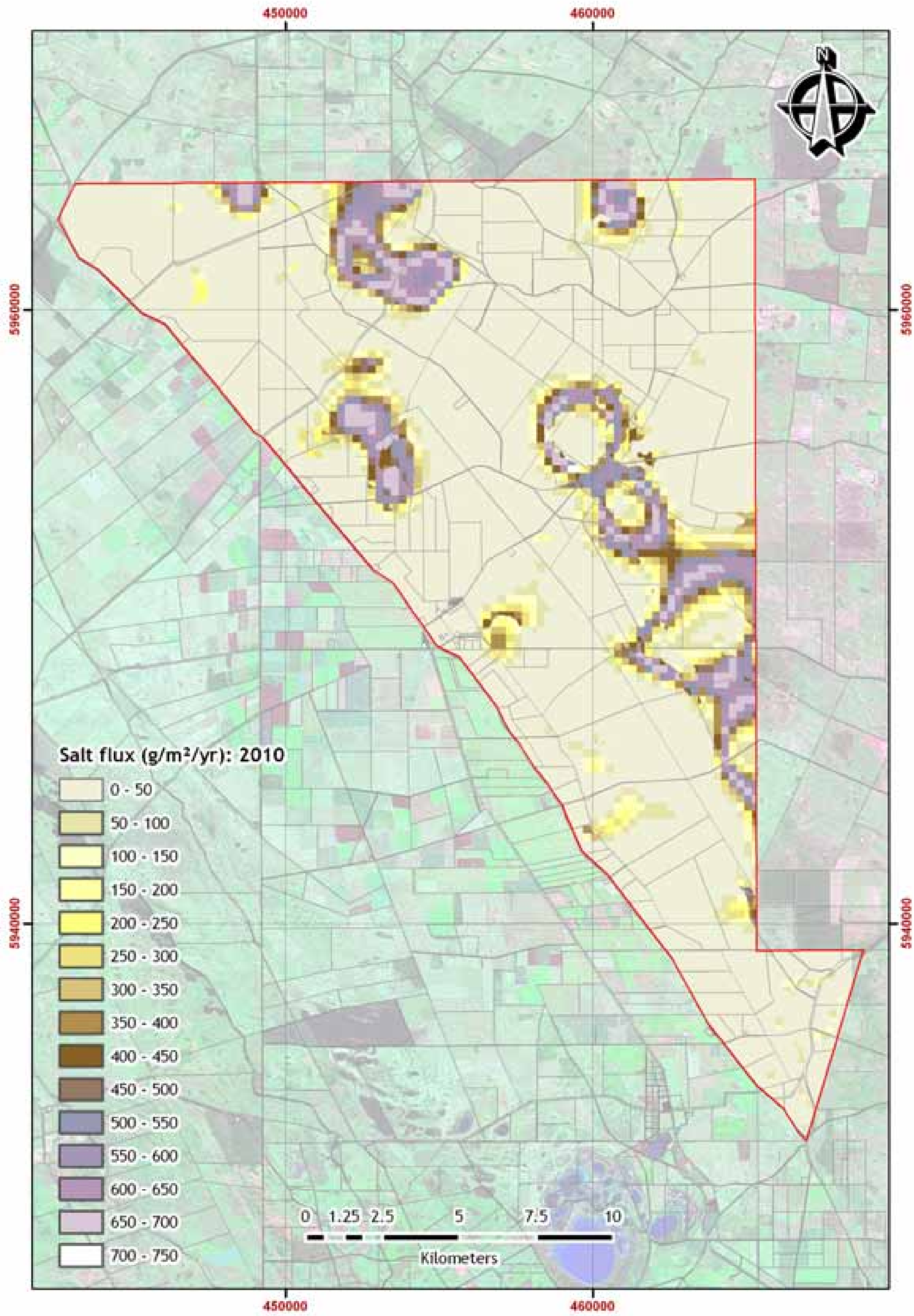

Figure 16d. Predicted salt flux for the study area in year 2010 (50 years after clearing)

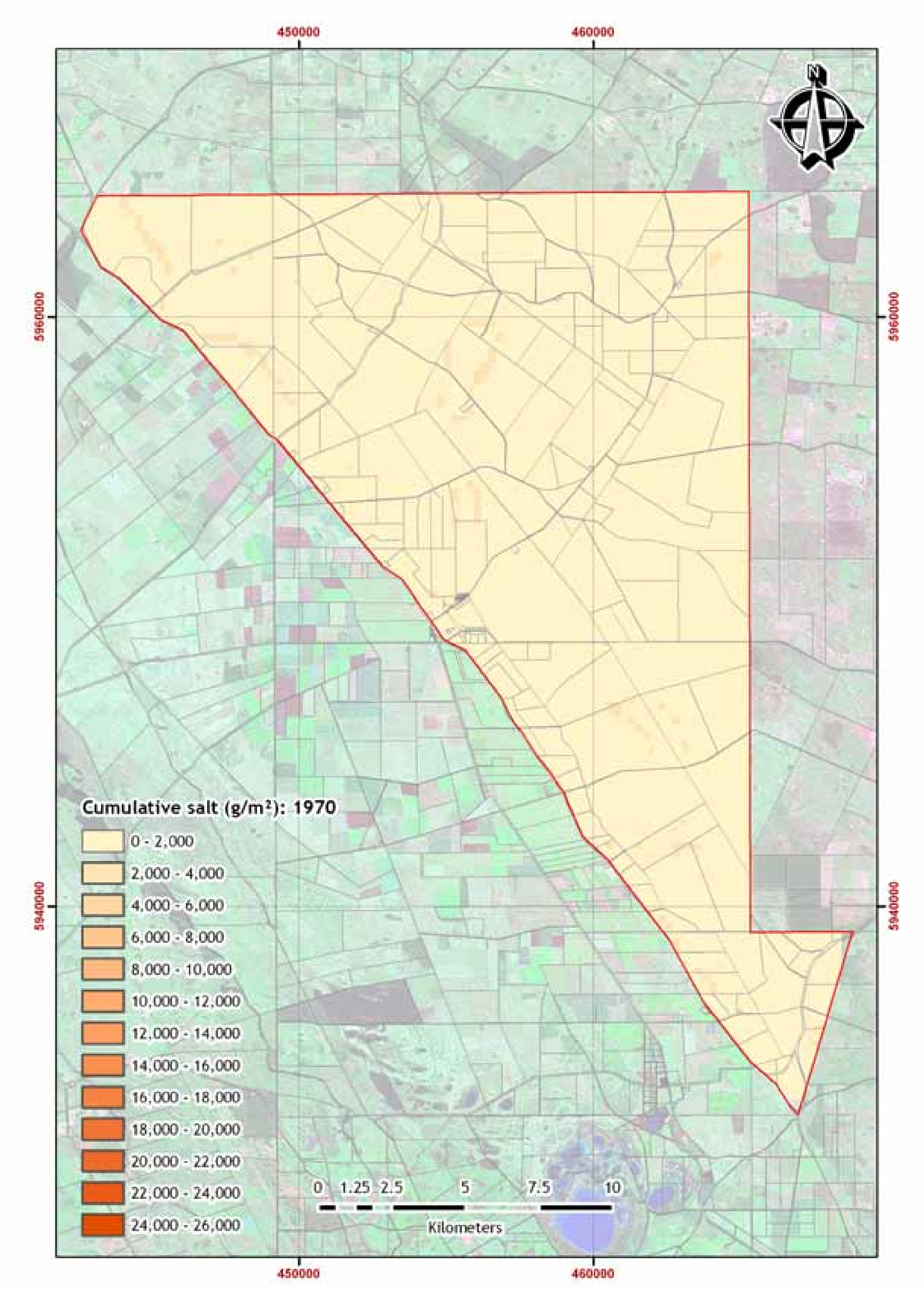

Figure 17a. Predicted cumulative salt input for the study area in years, 1970 (10 years after clearing)

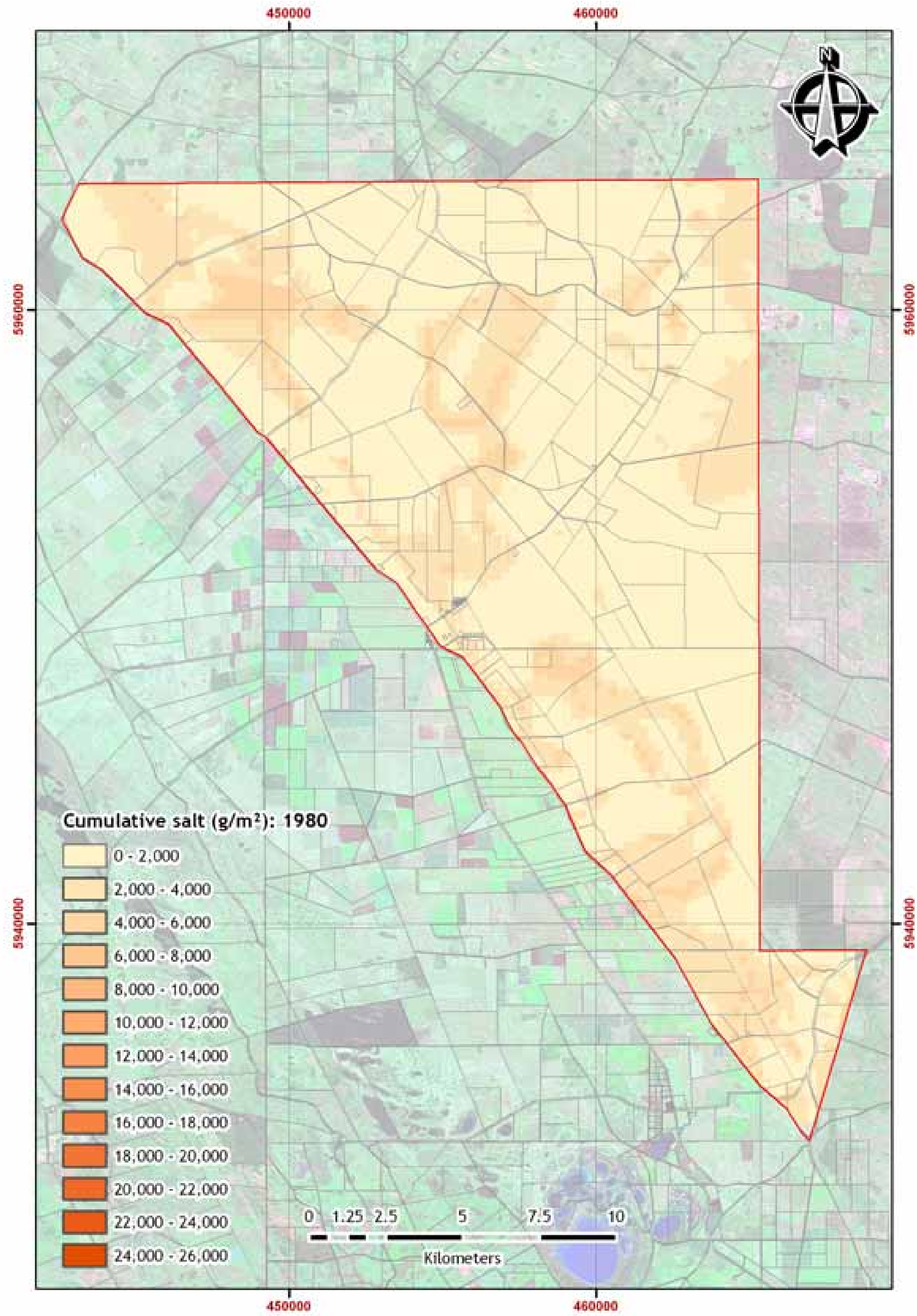

Figure 17b. Predicted cumulative salt input for the study area in years 1980 (20 years after clearing)

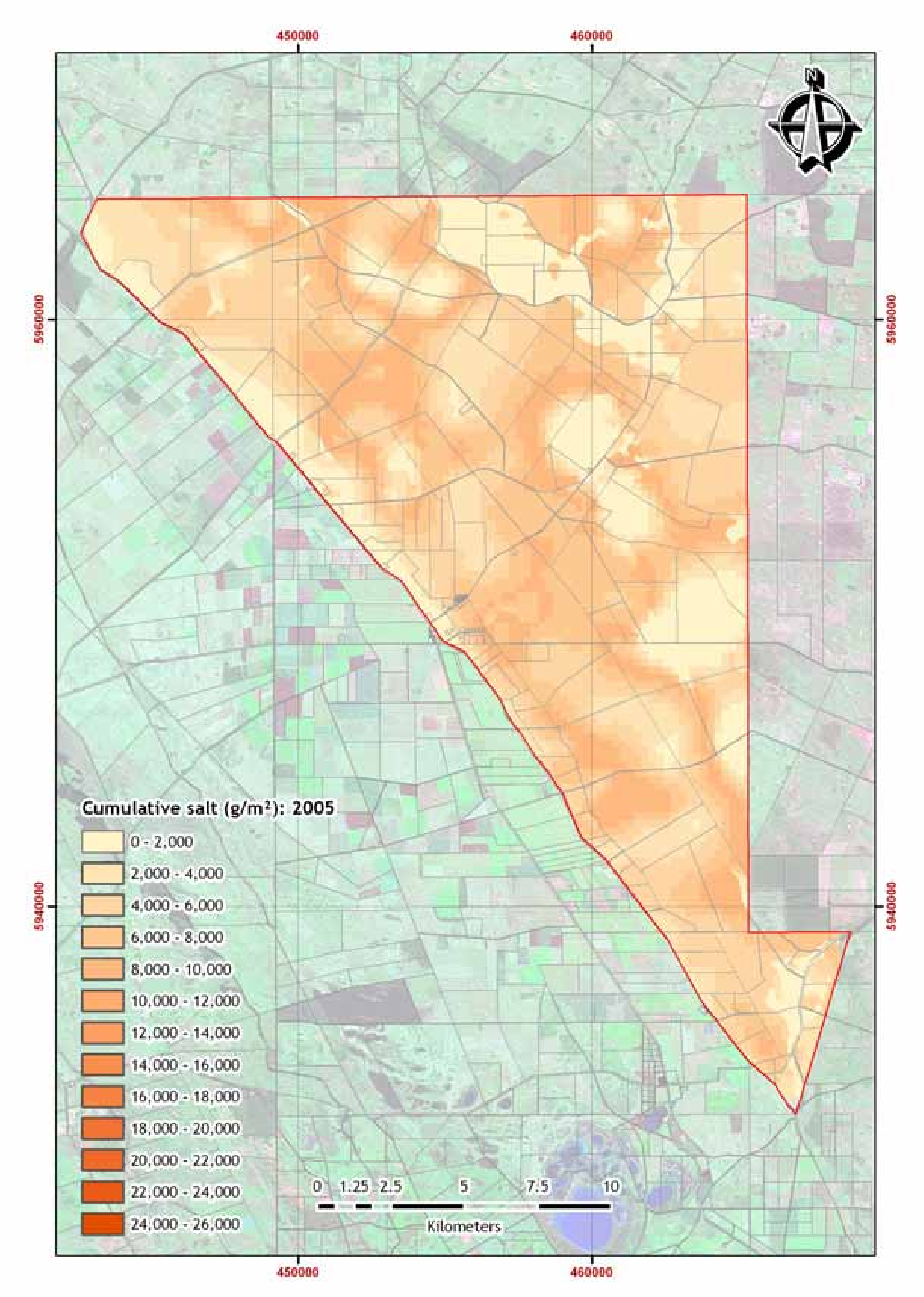

Figure 17c. Predicted cumulative salt input for the study area in years 2005 (45 years after clearing)

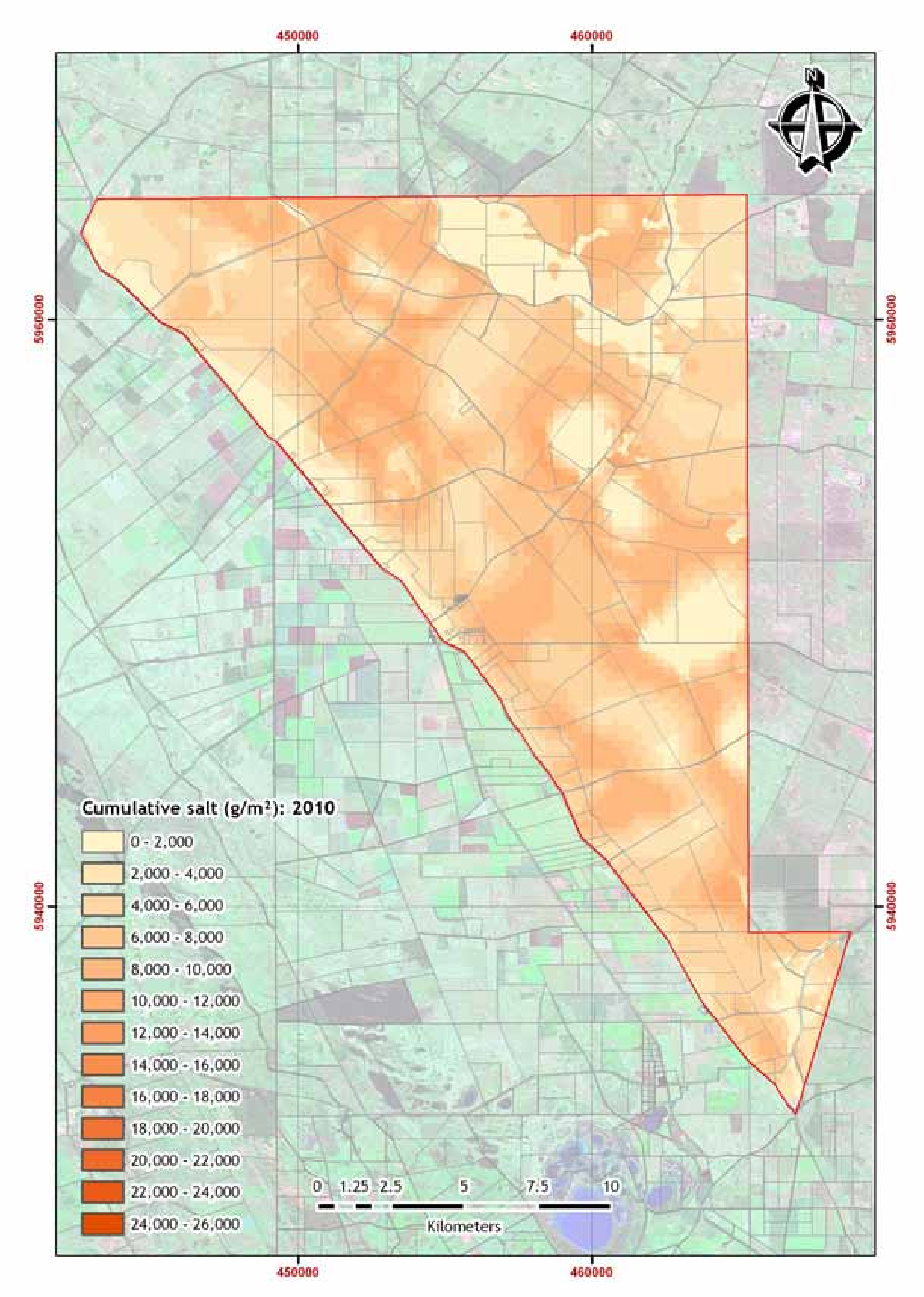

Figure 17d. Predicted cumulative salt input for the study area in years 2010 (50 years after clearing)

6. CONCLUSIONS

Analytical modelling of chloride profiles in the unsaturated zone of the Naracoorte Ranges was carried out. The results suggest that, as a result of clearance of native vegetation, an increase in recharge and salt flux to the unconfined aquifer began occurring in some parts of the Naracoorte Ranges within ten years post clearance, with clearance assumed to be in 1960. This occurs particularly along the western boundary of the study area and coincides with the areas of shallowest depth to water table and low clay percentages in the top two metres of the soil profile. As time progresses, the model predictions indicate larger areas of the aquifer receiving increased recharge and salt fluxes. The areas of actual salt flux to the aquifer then shift as the historic salt store is flushed from the unsaturated zone, with the timing of salt flushing and the commencement of fresher recharge at any point depending upon factors such as the depth to water table and soil clay content.

The modelling carried out in this study demonstrates that the lag time between the commencement of enhanced drainage and recharge is less than a decade in isolated areas, and generally less than 100 years for much of the Naracoorte Ranges. Currently, 45 years after native vegetation clearance, the model suggests that there are zones within the study area where the aquifer has received up to 5 m of cumulative recharge, 10 kg/m^2 of salt, and where current recharge rates are now in excess of 0.08 m/yr. Depending on factors such as the thickness and clay content of the unsaturated zone, the unsaturated zone salt store at any one point may currently be (i) flushing into the unconfined aquifer, (ii) yet to reach the water table or (iii) completely flushed, with recharge of comparatively fresh water occurring behind it.

It is predicted that most of the Naracoorte Ranges may reach a new steady state for recharge within the next 50 years and that much of the historical salt load in the Naracoorte Ranges has the potential to be flushed through to the unconfined aquifer within this time scale. However, it is unrealistic to make any detailed predictions beyond a few decades into the future based on an empirical model.

The modelling carried out in this study illustrates that the mobilization of the historic salt store in the unsaturated zone contributes significantly to the salinity of the unconfined aquifer beneath the Naracoorte Ranges. The considerable input of salt from the Naracoorte Ranges is expected to have a detrimental impact on groundwater salinity in the main Padthaway Irrigation Area located down-gradient on the flats to the west of the Naracoorte Ranges (Van den Akker et al., 2005). However, in areas where the historic salt store has been flushed from the Naracoorte Ranges, recharge will become fresher and in time this is likely to have a beneficial impact to the groundwater condition of the Naracoorte Ranges and Padthaway Flats. Potentially, in the long-term, the flow of fresher recharge to the flats may improve the salinity of groundwater there. However, whether this will fully compensate for the increase in salinity occurring as a result of groundwater pumping and irrigation recycling is currently not known.

Areas of irrigation (generally irrigated pastures) are scattered throughout the Naracoorte Ranges. In these areas, the rate of recharge and therefore salt flux to the unconfined aquifer will have been enhanced over time due to the irrigation practice. The model described in this report has not accounted for these scattered irrigation areas and hence flushing of the historic salt store may be occurring faster in some areas than expected or modelled. The salinity of recharging water post-flushing will not be as fresh under the irrigated areas as under the non-irrigated areas due to the application of groundwater in addition to rainwater.

When looking at the observed monitoring data trends and the observed water level plateaus, the question that needs to be addressed is whether they are due to the system reaching a steady state, or whether the water level trends are more related to the drier than average seasons experienced across the south east of South Australia over the past ten years. This may give the illusion that the system has reached equilibrium.

Some limitations are inherent in the modelling approach applied in this study, meaning that predictions made should be considered as a guide only to the magnitudes and time scales of the processes occurring in the Naracoorte Ranges. The limitations include the sensitivity of the estimated recharge rates and salt fluxes to drainage rates, which are determined based on an empirical relationship between drainage and the clay content in the top two metres of the soil profile. Similarly, the drainage rate is then extrapolated across the study area based on the clay percentage from SLUs. The accuracy of the allocation of SLUs may also be a limiting factor. As discussed in Leaney et al. (2004), factors that are not considered in the drainage-clay content relationship such as surface topography and land use can also influence the drainage rate.

Additional unsaturated zone sampling under native vegetation and cleared dryland agricultural land is recommended to increase the certainty of the model. Critical to the validity of the model are the soil water salinity vs. clay content and the drainage vs. clay content relationships. As discussed previously, these relationships have been approximated for the Naracoorte Ranges based on previous work and assumptions regarding the wetter climate at Padthaway.

Without having to embark on a prohibitively expensive drilling and sampling program, however, the modelling approach used here has provided reasonable estimates of groundwater recharge and salt fluxes following land clearing, that are consistent with field data, given the limitations explained herein.

APPENDICES

A. MEASUREMENTS FROM SOIL CORES

NV 1					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.022	642	92.3	2.3	5.4
0.5-1.0	0.120	364	53.4	2.0	44.6
1.0-1.25	0.148		57.4	1.7	42.6
1.25-1.5	0.021		44.2	0.6	6.8
1.5-2.0	0.014	870	88.5	5.6	5.9
2.0-2.5	0.020				
2.5-3.0	0.014	1487	89.0	6.5	4.5
3.0-3.5	0.014				
3.5-4.0	0.014				
4.0-4.5	0.012	465			
4.5-5.0	0.014	271	93.7	3.9	2.4
5.0-5.5	0.011				
5.5-6.0	0.012	244			
6.0-6.5	0.011				
6.5-7.0	0.011	2013	97.6	1.0	1.4
7.0-7.5	0.036				
7.5-8.0	0.018	500			
8.0-8.5	0.029				
8.5-9.0	0.027	305			
9.0-9.5	0.018		91.1	5.2	3.7
10.0-11.0	0.019	132			
11.0-12.0	0.020				
12.0-13.0	0.015	279			
13.0-13.5	0.014		92.3	5.5	2.2
13.5-14.0	0.032				
14.0-15.0	0.046	4521			
15.0-15.5	0.028				
16.5-17.0	0.023	4323			
17.0-18.0	0.020				
18.0-19.0	0.052	5422	90.8	4.6	4.6
19.0-20.0	0.023				
20.0-20.5	0.193	5244	56.2	5.8	37.9
20.5-21.0	0.123				
21.0-21.5	0.077	5313			
21.5-22.0	0.087		90.3	5.4	4.3
22.0-22.5	0.073	5186			
22.5-23.0	0.086				
23.0-23.5	0.095	1067	91.3	4.4	4.4
23.5-24.0	0.158				
24.0-24.5	0.140	494			
24.5-25.0	0.175				
Depth to water 24m					

NV 3					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.009	1521			
0.5-1.0	0.008		95.1	1.1	3.8
1.0-1.5	0.011	339			
1.5-2.0	0.069		78.5	1.8	19.7
2.0-2.5	0.091	2563			
2.5-3.0	0.051		94.2	1.0	4.7
3.0-3.5	0.037	2368			
3.5-4.0	0.086		82.5	0.9	16.7
4.0-4.5	0.082	2117			
4.5-5.0	0.099		76.3	1.4	22.3
5.0-5.5	0.118	1488			
5.5-6.0	0.151		64.1	0.9	35.0
6.0-6.5	0.105	1178			
6.5-7.0	0.107		75.2	1.7	23.1
7.0-7.5	0.076	1024			
7.5-8.0	0.031		93.8	0.4	5.8
8.0-8.25	0.009	1287			
8.25-8.5	0.027		96.4	0.7	2.9
8.5-9.0	0.010	1316			
9.0-9.5	0.012		97.9	0.3	1.8
9.5-10.0	0.038	933			
10.0-11.0	0.084		80.4	1.4	18.1
11.0-12.0	0.062	565			
12.0-13.0	0.012		97.1	0.9	2.0
13.0-14.0	0.012	978			
14.0-15.0	0.019	1000	97.8	0.2	2.0
16.0-17.0	0.016	2184	96.6	0.7	2.7
18.0-19.0	0.030	1501	98.2	0.4	1.4
20.0-21.0	0.077	3044	98.0	0.4	1.6
21.0-22.0	0.115	1267	95.5	2.7	1.8
Depth to water 22m					

NV 4					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.013	1026			
0.5-1.0	0.017		95.6	1.3	3.1
1.0-1.5	0.100				
1.5-2.0	0.069		77.6	3.2	19.2
2.0-2.5	0.097	148			
2.5-3.0	0.085	276	77.2	2.0	20.8
3.5-4.0	0.133	2870	65.8	1.3	32.9
4.5-5.0	0.112	4625	75.1	1.1	23.8
5.5-6.0	0.126	5773	73.9	1.4	24.7
6.5-7.0	0.083	5959	83.7	1.1	15.2
7.5-8.0	0.059	6484	87.0	1.7	11.2
8.5-9.0	0.097	6828	76.7	1.2	22.0
9.5-10.0	0.075	6487	86.5	0.3	13.2
10.5-11.0	0.180	1480	84.0	0.4	15.6
11.0-11.5	0.193	1164	90.2	0.5	9.3
13.0-14.0	0.308	360	78.0	2.9	19.1
Depth to water 10.5m					

PA 1					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.022	255	94.1	1.1	4.8
0.5-1.0	0.114		62.0	0.0	38.0
1.0-1.5	0.043	2599	87.0	2.4	11.3
1.5-2.0	0.051		85.2	2.0	14.3
2.0-2.5	0.086	5350	80.7	1.4	17.9
2.5-3.0	0.055		85.3	1.9	12.8
3.0-3.5	0.068	5833			
3.5-4.0	0.098				
4.0-4.5	0.102	7487	79.8	0.7	19.5
4.5-5.0	0.066		88.6	0.5	10.9
5.0-5.5	0.078	7782			
5.5-6.0	0.101				
6.0-6.5	0.097	3822	88.5	-1.5	13.0
6.5-7.0	0.089				
7.0-7.5	0.107	2277	91.4	-1.2	9.8
7.5-8.0	0.065				
8.0-8.5	0.128	1111	90.9	0.0	9.1
8.5-9.0	0.153				
9.0-9.5	0.177	869			
Depth to water 8.5m					

PA 2					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.024	1007	98.8	0.0	1.2
0.5-1.0	0.029		98.8	0.2	0.9
1.0-1.5	0.036	82	99.3	1.7	1.3
1.5-2.0	0.049		98.5	0.2	1.2
2.0-2.5	0.163	65			
2.5-3.0	0.095		87.0	1.8	11.3
3.0-3.5	0.092	236			
3.5-4.0	0.105				
4.0-4.5	0.086	876			
4.5-5.0	0.116				
5.0-5.5	0.112	2193	79.1	1.7	19.2
5.5-6.0	0.122				
6.0-6.5	0.118	3143			
6.5-7.0	0.107		79.1	-0.2	21.2
7.0-7.5	0.110	3329			
7.5-8.0	0.269				
8.0-9.0	0.247	3465			
9.0-10.0	0.193	2773	77.6	2.7	19.6
10.0-11.0	0.228				
11.0-12.0	0.226	2037	84.8	1.0	14.2
Depth to water 10.6m					

PA 3					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.018	2169	97.0	0.0	3.0
0.5-1.0	0.012		98.0	0.0	2.0
1.0-1.5	0.009	559			1.6
1.5-2.0	0.011		96.8	2.5	0.7
2.0-2.5	0.104	527	65.5	1.2	33.2
2.5-3.0	0.153				
3.0-3.5	0.165	754			
3.5-4.0	0.069		73.2	10.6	16.2
4.0-4.5	0.073	196			
4.5-5.0	0.069				
5.0-5.5	0.029	203			
5.5-6.0	0.024				
6.0-6.5	0.014	351	91.6	5.0	3.4
7.0-7.5	0.013				
7.5-8.0	0.014	296	96.3	1.5	2.2
8.0-8.5	0.013				
8.5-9.0	0.015	271			
9.0-9.5	0.017				
9.5-10.0	0.017	415	96.9	0.7	2.4
10.0-10.5	0.018				
10.5-11.0	0.014	541			
14.5-15.0	0.010	882			
15.5-16.0	0.011	562			
16.0-17.0	0.016				
17.0-18.0	0.013	917			
18.0-19.0	0.016				
19.0-20.0	0.021	130			
20.0-21.5	0.024				
21.5-23.0	0.026	143			
23.0-24.0	0.067		65.8	11.9	22.3
24.5-26.0	0.034	177	90.9	3.8	5.3
Depth to water ~38m					

PA 4					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.018	1774	94.3	3.7	2.0
0.5-1.0	0.024		96.3	3.4	2.6
1.0-1.5	0.142	710	67.4	1.5	31.1
1.5-2.0	0.118		68.9	2.0	30.0
2.0-2.5	0.127	2490	68.4	2.4	29.2
2.5-3.0	0.126				
3.0-3.5	0.164	2051			
3.5-4.0	0.174				
4.0-4.5	0.166	2803			
4.5-5.0	0.222				
5.0-5.5	0.259	3017			
5.5-6.0	0.265				
6.0-6.5	0.101	3391	69.8	8.7	21.5
6.5-7.0	0.049				
7.0-7.5	0.049	4580			
7.5-8.0	0.020				
8.0-8.5	0.026	5925			
8.5-9.0	0.034				
9.0-9.5	0.027	4327			
9.5-10.0	0.033				
10.0-11.0	0.028	4400			
11.0-12.0	0.041				
12.0-13.0	0.055	4053	86.7	7.6	5.7
13.0-14.0	0.081				
14.0-14.5	0.100	1344	89.8	1.2	9.0
14.5-15.0	0.185				
15.0-15.5	0.225	501			
15.5-16.0	0.158				
16.0-16.5	0.160	390			
16.5-17.0	0.236	321			
17.0-18.0	0.229				
18.0-19.0	0.190	332	91.9	3.9	4.2
19.0-19.5	0.166				
19.5-20.5	0.162	405	95.6	2.7	1.7
Depth to water 16.5m					

PB 1					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.033	119	98.5	1.2	0.2
0.5-1.0	0.085		97.5	0.7	1.8
1.0-1.5	0.092	41	89.9	0.2	9.8
1.5-2.0	0.147		71.4	2.9	23.4
2.0-2.5	0.149	34	72.2	0.0	27.8
2.5-3.0	0.119				
3.0-3.5	0.096	31	82.2	0.2	17.5
3.5-4.0	0.091				
4.0-4.5	0.092	21			
4.5-5.0	0.086		88.0	0.0	12.0
5.0-5.5	0.079	32	87.4	0.5	12.1
5.5-6.0	0.113				
6.0-6.5	0.119	83			
6.5-7.0	0.200		87.2	0.5	12.3
7.0-7.5	0.166	116	89.7	0.7	9.6
7.5-8.0	0.200				
8.0-8.5	0.172	91			
8.5-9.0	0.147		89.4	0.7	9.6
9.0-9.5	0.207	115			
9.5-10.0	0.172		96.1	1.7	2.2
10.0-11.0	0.239	255			2.2
Depth to water 5.5m					

PB 5					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.033	90	99.0	0.0	1.0
0.5-1.0	0.047		99.0	1.7	0.0
1.0-1.5	0.046	50	98.2	1.4	1.0
1.5-2.0	0.046		98.5	2.0	0.0
2.0-2.5	0.039	53			
2.5-3.0	0.042		100.0	0.0	0.0
3.0-3.5	0.042	59			
3.5-4.0	0.045		99.5	2.2	0.0
4.0-4.5	0.044	104			
4.5-5.0	0.052				
5.0-5.5	0.069	62	97.0	0.0	3.0
5.5-6.0	0.047				
6.0-6.5	0.082	47	83.1	1.2	15.7
6.5-7.0	0.049				
7.0-7.5	0.068	48			
7.5-8.0	0.090		93.1	1.5	5.4
8.0-8.5	0.086	32			
8.5-9.0	0.095		82.8	0.5	16.7
9.0-9.5	0.111	28			
9.5-10.0	0.187		81.1	0.7	18.2
10.0-11.0	0.125	37	76.3	0.0	23.7
11.0-12.0	0.071		88.9	1.5	9.7
12.0-13.0	0.070	33			
13.0-14.0	0.051		91.8	7.4	0.7
14.0-15.0	0.061	68			
15.0-16.0	0.135				
Depth to water 15m					

PB 7					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.030	649	94.6	3.7	1.7
0.5-1.0	0.071		76.2	1.4	22.9
1.0-1.5	0.096	112	68.6	1.0	30.4
1.5-2.0	0.118		65.4	1.8	34.3
2.0-2.5	0.119	342	67.5	1.5	31.0
2.5-3.0	0.160		55.6	3.2	41.2
3.0-3.5	0.098	966	64.3	10.8	24.9
3.5-4.0	0.103				
4.0-4.5	0.094	808			
4.5-5.0	0.050				
5.0-5.5	0.054	949	72.0	3.6	24.4
5.5-6.0	0.121				
6.0-6.5	0.110	851	74.7	3.2	22.1
6.5-7.0	0.104				
7.0-7.5	0.039	1025	82.1	8.1	9.8
7.5-8.0	0.022				
8.0-8.5	0.013	1406			
8.5-9.0	0.014				
9.0-9.5	0.013	1355			
9.5-10.0	0.010		93.3	7.3	0.0
10.0-11.0	0.012	1566			
11.0-12.0	0.018				
12.0-13.0	0.020	864			
13.0-14.0	0.021				
14.0-15.0	0.089	1316	66.6	17.6	15.8
15.0-16.0	0.040				
16.0-17.0	0.119	1791	71.8	11.1	17.2
17.0-18.0	0.080				
18.0-19.0	0.032	4651			
19.0-20.0	0.030				
20.0-21.0	0.146	4758	83.1	7.1	9.8
21.0-22.0	0.118				9.8
22.0-23.0	0.028	5470			
23.0-24.0	0.036				
24.0-25.0	0.069	3686			
25.0-26.0	0.038				
26.0-26.5	0.030	3774			
Depth to water ~32m					

PB 8					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.056	404	91.0	3.0	6.0
0.5-1.0	0.040		94.9	3.7	3.8
1.0-1.5	0.144	46	67.3	1.5	32.5
1.5-2.0	0.157		65.0	1.2	33.8
2.0-2.5	0.161	68			
2.5-3.0	0.197		58.8	1.4	39.8
3.0-3.5	0.186	64	60.5	3.5	36.0
3.5-4.0	0.181				
4.0-4.5	0.028	80			
4.5-5.0	0.048		78.3	12.1	9.6
5.0-5.5	0.063	48	76.5	10.7	12.7
5.5-6.0	0.046				
6.0-6.5	0.112	40	64.2	29.0	6.8
7.0-7.5	0.089				
7.5-8.0	0.184	43			
8.0-8.5	0.242				
8.5-9.0	0.162	73	74.0	6.0	20.0
9.0-9.5	0.111				
9.5-10.0	0.099	85	87.3	4.9	7.8
10.0-11.0	0.105				
11.0-11.5	0.139	330			
11.5-12.0	0.150		83.0	8.8	8.2
12.0-13.0	0.153	447	82.2	9.8	8.1
13.0-14.0	0.202	435			
14.0-15.0	0.131				
15.0-16.0	0.277	441			
Depth to water 11.4m					

IRR 2					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.090	79	94.6	2.2	3.2
0.5-1.0	0.050	43	98.8	0.5	0.7
1.0-1.5	0.050	52	98.1	1.6	1.5
1.5-2.0	0.060	88	97.9	1.7	1.2
2.0-2.5	0.060	256			
2.5-3.0	0.070	398	85.6	0.7	13.7
3.0-3.5	0.090	336	79.6	0.9	19.5
4.0-4.5	0.120	283	71.7	1.7	26.5
4.5-5.0	0.090	207			
5.0-5.5	0.100	192	79.5	1.2	19.3
5.5-6.0	0.130	172			
6.0-6.5	0.120	158	76.8	-1.0	23.7
6.5-7.0	0.120	118			
7.0-7.5	0.120	120			
7.5-8.0	0.070	240	88.8	-1.0	11.7
8.0-8.5	0.060	230			
9.0-9.5	0.140	778			
Depth to water 9.3m					

NAP 3					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.32	864	56.7	9.1	34.1
0.5-1.0	0.150	1846			
1.0-1.5	0.100	1622			
1.5-2.0	0.140	1733	63.8	19.3	16.9
2.0-2.5	0.170	1821			
2.5-3.0	0.160	1599	61.7	19.7	18.7
3.0-3.5	0.190	1216			
3.5-4.0	0.240	524	60.4	17.1	22.5
4.5-5.0	0.210	566			
Depth to water 3.5m					

NAP 4					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.220	353	74.3	5.5	20.2
0.9-1.0	0.200	869			
1.0-1.5	0.230	1130	70.5	10.5	19.0
1.5-2.0	0.110	972	85.9	3.3	10.8
2.0-2.5	0.200	753	100.0	0.0	0.0
2.5-3.0	0.200	662			
3.0-3.5	0.170	730	73.5	10.7	15.7
3.5-4.0	0.290	718	58.0	12.4	29.6
4.0-4.5	0.260	763			
4.5-5.0	0.230	755	60.3	15.6	24.2
Depth to water 3.5m					

NAP 5					
Depth	θ_g	$[Cl]_{sw}$ (mg/L)	Sand	Silt	Clay
0.0-0.5	0.230	1358	68.1	8.5	23.4
0.9-1.0	0.210	1479	4.7	0.3	8.1
1.0-1.5	0.210	1698	65.1	11.6	23.3
1.5-2.0	0.230	1530	55.7	16.5	27.9
2.0-2.5	0.180	1322			
2.5-3.0	0.260	1291			
3.0-3.5	0.280	1084			
3.5-4.0	0.260	1074			
4.0-4.5	0.190	1074			
4.5-5.0	0.450	1131			
Depth to water 3.5m					

B. ESTIMATED CLAY CONTENT AND DRAINAGE FOR SOIL LANDSCAPE UNITS

SLU	Sub-unit (soil)	Soil propn (of SLU)	Clay %	Drainage (mm) (SLU)
DESNjB	B3	0.1425	20	39.81
KEPMYB				
KEPNFA				
KEPNJA				
KEPNvA				
KEPXaK				
MIMMHC	B2	0.0250	10	89.13
MIMONF	B2	0.0100	10	89.13
MIMPCa	G2	0.0300	10	89.13
MIMPCb	G2	0.3175	10	89.13
NRCMHC				
NRCMYB				
PADMYA	B2	0.2050	25	26.61
SWEMHB	B2	0.0375	10	89.13
SWEMJB	B2	0.0975	10	89.13
SWETTA	E3	0.4550	55	2.37
WEFMHB	B2	0.0050	10	89.13
WEFMHC	B2	0.0250	10	89.13
WEFPRA	G3	0.4275	25	26.61
WEFPYb	B6	0.1200	30	17.78
WLKNAA	B3	0.4500	25	26.61
WNRMcA	B2	0.0600	10	89.13
WNRMcB	B2	0.0250	10	89.13
WNRMcC	B2	0.1150	10	89.13
WNRMHA	G2	0.0100	10	89.13
WNRMHB	B2	0.0050	10	89.13
WNRMHC	B2	0.0050	10	89.13
WNRMHI	B2	0.0050	10	89.13
WNRMNB	B2	0.0250	10	89.13
WNRMNC	B2	0.0250	10	89.13
WNRMRE	B2	0.0500	10	89.13
WNRMYB	B2	0.0150	10	89.13
WNRMYC	B2	0.1049	10	89.13
WNRNFG	B7	0.4000	20	39.81
WNROLe	B3	0.0151	15	59.57
WNROQe	B2	0.0050	10	89.13
YALNAA	B3	0.4275	20	39.81
YALNlB	B2	0.2125	25	26.61

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	μg	10^{-6} g	mass
microlitre	μL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	356 or 366 days	time interval

TDS total dissolved solids (mg/L)

GLOSSARY

Aquifer. An underground layer of rock or sediment which holds water and allows water to percolate through.

Aquifer, unconfined. Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure.

GIS (geographic information system). Computer software allows for the linking of geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis.

Groundwater. *See underground water.*

Hydrogeology. The study of groundwater, which includes its occurrence, recharge and discharge processes and the properties of aquifers. *(See hydrology.)*

Irrigation. Watering land by any means for the purpose of growing plants.

Model. A conceptual or mathematical means of understanding elements of the real world which allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change.

Pasture. Grassland used for the production of grazing animals such as sheep and cattle.

PWA. Prescribed Wells Area.

Recharge area. The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. *(See artificial recharge, natural recharge.)*

Underground water (groundwater). Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground.

Well. (a) an opening in the ground excavated for the purpose of obtaining access to underground water; (b) an opening in the ground excavated for some other purpose but that gives access to underground water; (c) a natural opening in the ground that gives access to underground water.

REFERENCES

Allison G.B., Cook P.G., Barnett S.R., Walker G.R., Jolly I.D. and Hughes M.W. (1990) Land clearance and river salinisation in the western Murray Basin, Australia. Journal of Hydrology, 119:1-20.

Cook P.G. (1992) The Spatial and Temporal Variability of Groundwater Recharge: A Case Study in Semi-Arid Areas of the Western Murray Basin. PhD Thesis, School of Earth Sciences, The Flinders University of South Australia.

Cook P.G., Telfer A.L. and Walker G.R. (1993) Potential for salinisation of the groundwater beneath mallee areas of the Murray Basin. CGS report # 42 Flinders University. EWS (South Australia) Report # 93/6.

Cook P.G., Leaney F.W. and Miles M. (2004) Groundwater Recharge in the North-East Mallee Region, South Australia. CSIRO Land and Water Technical Report 24/04.

Harrington N., van den Akker J., Brown K. and Mackenzie G. (2004) Padthaway Salt Accession Study. Volume One: Methodology, site description and instrumentation. DWLBC Report 2004/61.

Jolly I.D., Cook P.G., Allison G.B., and Hughes M.W. (1989) Simultaneous water and solute movement through an unsaturated soil following an increase in recharge. Journal of Hydrology, 111:391-396.

Kennett-Smith A., Cook P.G. and Walker G.R. (1994) Factors affecting groundwater recharge following clearing in the south western Murray Basin. Journal of Hydrology, 154:85-105.

Leaney F. (2000) Groundwater salinisation in the Tintinara area of South Australia. Results of field investigations. CSIRO Land and Water Technical Report 34/00.

Leaney F., Barnett S., Davies P., Maschmedt D., Munday T., Tan K. (2004) Groundwater Salinisation in the Tintinara Highland Area of SA. Revised estimates using spatial variation for clay content in the unsaturated zone. CSIRO Land and Water Technical Report 24/04.

Leaney F.W. J and Herczeg A.L. (1999) The origin of fresh groundwater in the SW Murray Basin and its potential for salinisation. CSIRO Land and Water Technical Report 7/99.

Leaney F., Walker G., Knight J., Dawes W., Bradford A., Barnett S., Stadter F. (1999) Potential for groundwater salinisation in the Tintinara area of South Australia. CSIRO Land and Water Technical Report 33/99.

Lewis D.W. (1983) Practical Sedimentology. Hutchison Ross, Pennsylvania.

Walker G.R., Jolly I.D. and Cook P.G. (1991) A new chloride leaching approach to the estimation of diffuse recharge following a change in land use. Journal of Hydrology, 128:49-67.

Van den Akker J. (2005) Padthaway Salt Accession Study. Volume Two: Results. DWLBC Report 2005/15.

Van den Akker J., Harrington N. and Brown K. (2005) Padthaway Salt Accession Study. Volume Three: Conceptual Models. DWLBC Draft Report 2005/21.

Zhang L. and Walker G. (1998) Studies in Catchment Hydrology. The Basics of Recharge and Discharge. CSIRO, Australia.