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SIMPLE ANALYTIC METHODS FOR ESTIMATING CHANNEL SEEPAGE FROM CONSTRUCTED CHANNELS IN THE UPPER SOUTH EAST OF SOUTH AUSTRALIA

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INTRODUCTION

This document outlines a methodology for estimation of seepage losses from proposed channels as part of the Coorong South Lagoon Flow Restoration Project (CSLFRP). The CSLFRP has investigated options for diverting significant volumes of water from the drainage network of the South East northwards to the Coorong using a combination of purpose-built floodways and existing flow paths. The methods outlined in this document form part of the Hydrological Modelling component of the CSLFRP project, in which simple methods suitable for use within GIS were required to estimate transmission losses from proposed channels as part of a broader assessment of volumes that could be delivered to the Coorong South Lagoon.

The methods are simple analytic mathematical models for one dimensional flow under steady state conditions and assume homogeneity and isotropy in the aquifer, the underlying aquitard and the overlying soil layer. They are suitable for use in the low lying sections of the study area (Figure 4), where the extant conditions are a shallow water table within an unconfined Tertiary Limestone Aquifer (TLA) overlain by a relatively low conductivity soil layer of variable thickness. The TLA is composed of a fine to coarse calcarenite sandstone with abundant shell fragments (Cobb and Brown, 2000). It is underlain at significant depth by an aquitard of low permeability Tertiary marls and black carbonaceous clays (Brown, 2000).

The methods have been divided into three cases, based on the variety of physical conditions in the field. The applicability of each case is dependent on the location of the channel and regional watertable in relation to the lower conductivity soil layer which overlies the aquifer.

Worked examples are provided for each of the three methods presented. These examples, using low and high range parameters values, demonstrate the large range of seepage loss estimates that are possible with the plausible range of field parameter values. It is important when these methods are applied, that the sensitivity of the derived results to the parameter values is examined and that the range of uncertainty in channel seepage estimates is acknowledged.

This is an initial assessment and the methodology may alter as more data about soil and aquifer characteristics in the study area become available.

METHODS

Case 1. Saturated flow: The channel intersects the aquifer and the watertable is shallow

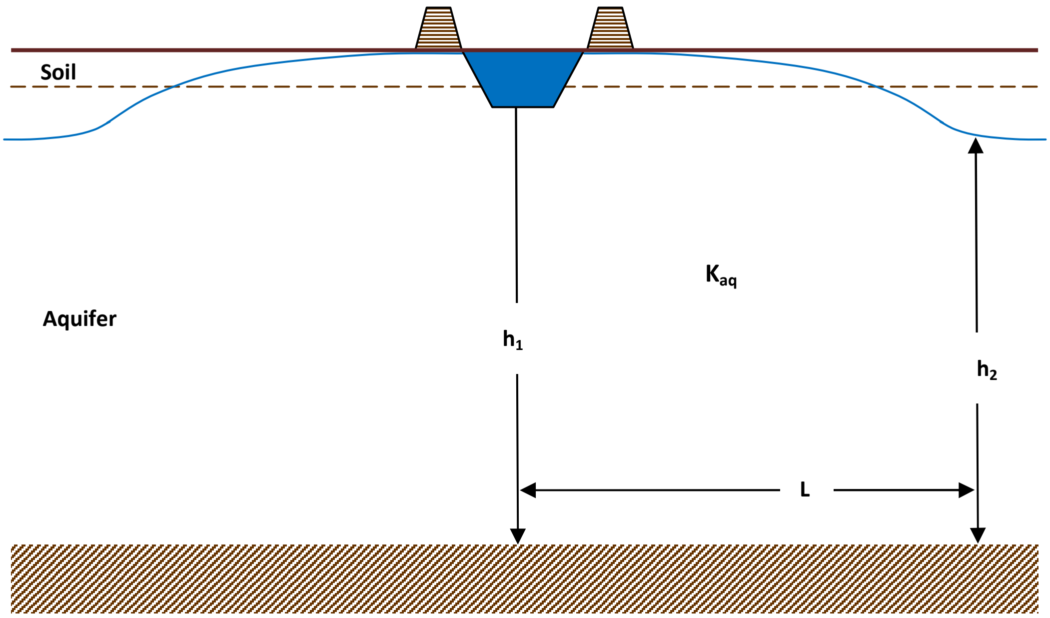

Figure 1. Channel seepage where the channel intersects the aquifer and the watertable is shallow (Case 1). Note, the watertable is depicted as forming a convex parabola away from the channel, in accordance with the boundary conditions of the Dupuit equation and neglecting evaporation from the watertable.

The terminology used within the above conceptual model refers to the following:

- Soil – A low conductivity layer of variable thickness at ground surface
- Aquifer – The unconfined Tertiary Limestone Aquifer (TLA), which is of relatively high hydraulic conductivity compared to the overlying soil
- Aquitard – The Lower Tertiary Confining Bed, assumed in this analysis to be impermeable

Case 1 applies when the channel intersects the aquifer, the watertable is below the water level in the channel and there is saturated flow between the channel and the aquifer (Figure 1). In this case seepage from the channel can be estimated using the Dupuit equation, which describes steady flow through an unconfined aquifer resting on a horizontal impervious surface (Fetter, 2001).

The Dupuit equation assumes horizontal flow. For channel seepage this assumption is valid when the depth to the watertable from the water level in the channel, which here is assumed to be at ground surface, is less than approximately twice the width of the channel (Bouwer, 2002). The proposed channel widths in the study area are between 5m and 35m. Therefore the depth to the watertable needs to be less than 10m from the ground surface for the assumption of horizontal flow to be valid. The average depth to the watertable is generally less than 6m in low lying areas (Figures 5 and 6), which is where the proposed channels will be located (David Way [DWLBC] 2010, pers. comm.). Therefore, the assumption of horizontal flow is reasonable and the Dupuit equation is applicable.

Using the Dupuit equation (Fetter, 2001) and assuming symmetry across the channel, seepage loss from the channel is given by:

$$q = \frac{K_{aq}\left({h_1}^2 - {h_2}^2\right)}{L} \tag{1}$$

Where:

- q is the seepage rate per metre of channel (m^2/d),
- K_{aq} is the hydraulic conductivity of the aquifer (m/d)
- h_1 is the hydraulic head elevation (m) of the water in the channel (see Figure 1) calculated using the base of the TLA as a datum. In this document the value of h_1 is estimated by adding the saturated thickness of the TLA, the depth to watertable and the level of the water in the channel above (or below) the ground surface.
- h_2 is the hydraulic head (m) in the aquifer a distance L from the channel, where the watertable is unaffected by the channel flow (Figure 1). The head is calculated using the base of the TLA as a datum. In the examples below, the value of h_2 is estimated from the saturated thickness of the aquifer.

It is important to note that the value of L can only be determined through field work but has been assumed to be 250m in this document, in line with assumptions made by AWE (2009a). Bouwer (1965) used a distance of ten times the width of the base of the channel for L. While this approach incorporates channel size it is still an arbitrary value and would ideally be refined through field work.

Example calculations

The following calculations illustrate the use of the Dupuit equation for Case 1 using a range of parameter values.

In the area of interest, the average depth to the watertable ranges between 0m and 6m (see Figure 5). The range of saturated thickness (based on drill hole records) is approximately 15 m to 185 m (Figure 6).

The groundwater flow model developed by Keith Brown (2000) for the confined aquifer in South East of South Australia reported hydraulic conductivity values for the unconfined aquifer in the area of interest ranging between 5 m/d and 120 m/d, while reported values derived from pump tests range from 15 m/d to 150 m/d (Fennel and Stadter, 1992).

- Example 1. Low range

  To calculate channel seepage at a location where saturated thickness is 15 m, depth to watertable is 1m and water in the channel is at ground surface (therefore h_1= 15 + 1 + 0 = 16m, h_2 = 10 m), K_{aq} is 5 m/d and L is 250 m. The seepage loss per metre of channel is:

$$q = \frac{K_{aq}({h_1}^2 - {h_2}^2)}{L} = 5\,\frac{(16^2 - 15^2)}{250} = 0.62\ \mathrm{m^2/d} = 0.62\ \mathrm{KL/d/m}$$

- Example 2. High range

To calculate channel seepage at a location where saturated thickness is 185m, depth to watertable is 6m, water in the channel is at ground surface (therefore h_1=185 + 6 + 0=191m, h_2=100m), K_{aq} is 150 m/d and L is 250m. The seepage loss per metre of channel is:

$$q = \frac{K_{aq}({h_1}^2 - {h_2}^2)}{L} = 150\,\frac{(191^2 - 185^2)}{250} = 1354 \text{ m}^2\text{/d} = 1354 \text{ KL/d/m}$$

Case 2. Saturated flow: The channel sits within the soil layer and the watertable is in the soil layer

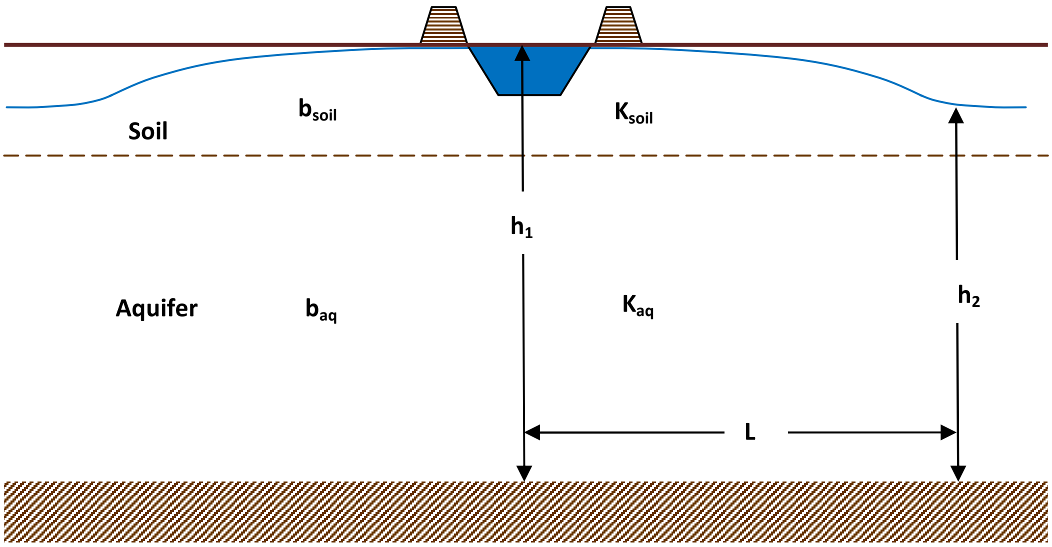

Figure 2. Channel seepage where the channel sits within the soil layer and the water table is in the soil layer (Case 2). Note the watertable is depicted as forming a convex parabola away from the channel, in accordance with the boundary conditions of the Dupuit equation and neglecting evaporation from the watertable.

This case applies when the channel sits within the soil layer, with at least 0.5m of soil below the bottom of the channel, and the watertable is within the soil layer. There is saturated flow below the channel, above a layer of impermeable material (Figure 2).

This is similar to Case 1, and the Dupuit equation (1) applies. However, in this case, an average hydraulic conductivity of the soil and aquifer, K_{av} should be used. A suitable formula for the average hydraulic conductivity of a two-layer soil and aquifer system under saturated conditions is as provided by Bear (1979) (cited in Brunner et al., 2009):

$$K_{av} = \left(\frac{1}{b_{soil} + b_{aq}}\left(\frac{\mathrm{b_{soil}}}{\mathrm{K_{soil}}} + \frac{\mathrm{b_{aq}}}{\mathrm{K_{aq}}}\right)\right)^{-1} \qquad (2)$$

Where,

- K_{aq} is the hydraulic conductivity of the aquifer (m/d)
- K_{soil} is the hydraulic conductivity of the soil (m/d)
- b_{soil} is the thickness of the soil layer (m)
- b_{aq} is the thickness of the aquifer layer (m)

Example calculations

The following calculations illustrate the use of the Dupuit equation for case 2 using a range of parameter values.

In the area of interest, the average depth to the watertable ranges between 0 m and 6 m (see Figure 5). The range of saturated thickness is approximately 15m to 185m (see Figure 6).

A potential range of soil hydraulic conductivities between 0.05 m/d and 2.8 m/d were reported by AWE (2009). A range of aquifer hydraulic conductivities between 5 m/d and 150 m/d were reported by Brown (2000) and Fennell and Stadter (1992).

- Example 3. Low range

To calculate seepage per metre of channel at a location where saturated thickness is 15m, depth to watertable is 1m, water in the channel is at ground surface (therefore h_1 = 15 + 1 + 0 = 11 m, h_2 = 10 m), K_{av} = 0.11 m/d[*] and L = 250 m:

$$q = \frac{K_{av}({h_1}^2 - {h_2}^2)}{L} = 0.11 \times \frac{(16^2 - 15^2)}{250} = 0.014\ \mathrm{m^2/d} = 0.014\ \mathrm{KL/d/m}$$

- Example 4. High range

To calculate seepage per metre of channel at a location where saturated thickness is 185 m, depth to watertable is 4 m, water in the channel is at ground surface (therefore h_1 = 185 + 4 + 0 = 189 m, h_2 = 100 m), K_{av} = 40.1 m/d[**] and L = 250 m:

$$q = \frac{K_{av}({h_1}^2 - {h_2}^2)}{L} = 40.1 \times \frac{(189^2 - 185^2)}{250} = 240\mathrm{m^2/d} = 240\ \mathrm{KL/d/m}$$

[*] Calculated assuming a soil layer thickness (b_{soil}) of 5m and aquifer thickness (b_{aq}) of 6m, with K_{soil} of 0.05m/d and K_{aq} of 5m/d, $K_{av} = (1/(b_{soil} + b_{aq})*(b_{soil}/K_{soil} + b_{aq}/K_{aq}))^{-1}$ = $(1/(5 + 6)x(5/0.05 + 6/5))^{-1}$ = 0.11 m/d

[**] Calculated assuming a soil layer thickness (b_{soil}) of 5m and aquifer thickness (b_{aq}) of 100m, with K_{soil} of 2.8m/d and K_{aq} of 120m/d, $K_{av} = (1/(b_{soil} + b_{aq})*(b_{soil}/K_{soil} + b_{aq}/K_{aq}))^{-1}$ = $(1/(5 + 6)x(5/0.05 + 6/5))^{-1}$ = 40.1 m/d

Case 3. Unsaturated flow: The channel sits within a low conductivity soil layer and is hydraulically disconnected from the watertable

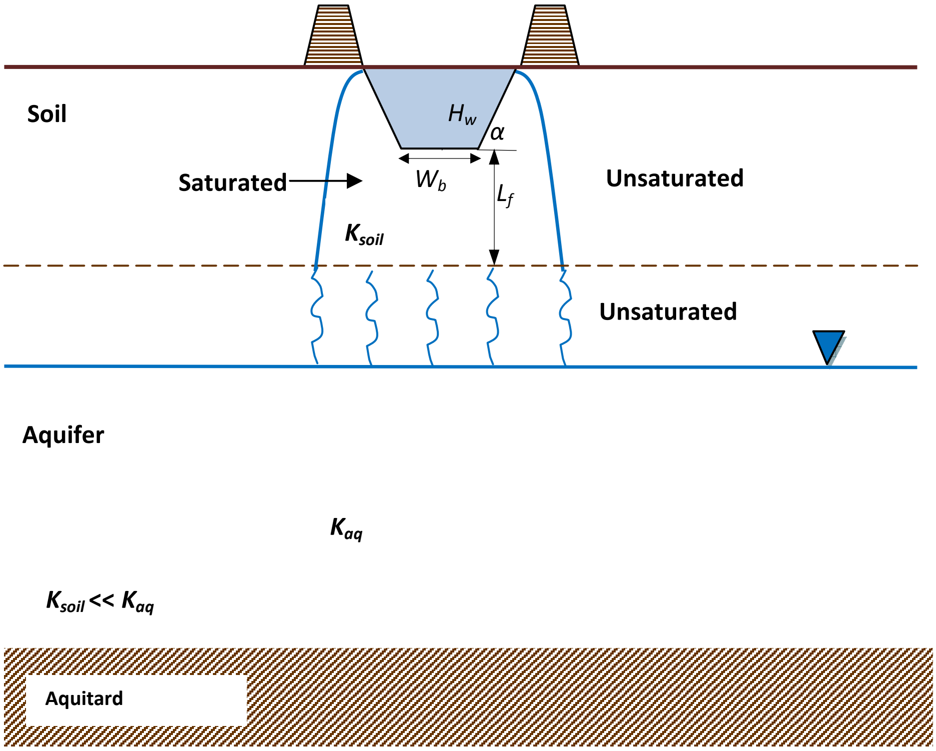

Figure 3. Channel seepage under unsaturated flow (Case 3)

This case applies when the channel sits within the low conductivity soil layer and there is at least 0.5m of soil below the bottom of the channel. There is saturated flow from the channel through the soil layer. The watertable is below the soil layer and as water will move more quickly in the high conductivity aquifer than through the low conductivity soil layer, unsaturated flow conditions will occur in the aquifer above the watertable. This results in a situation where the flow from the channel is disconnected from the watertable. The seepage rate from the channel is independent of the location of the watertable and can be calculated by applying Darcy's Law to the soil layer and considering the negative pressure head at the base of the soil, as outlined by Bouwer (2002):

$$q = W_p K_{soil} \frac{(H_w + L_f - h_{we})}{L_f} \tag{3}$$

Where:

- q is the seepage rate per metre of channel (m^2/d)
- W_p is the wetted perimeter of the channel (m). This can be calculated using the equation:

$$W_p = W_b + 2H_w / \sin\alpha$$

Where W_b is the width of the channel base,

H_w is the height of water in the channel, and

α is the angle that the channel sides meet the horizontal

- K_{soil} is the vertical saturated hydraulic conductivity of the soil (m/d)
- L_f is the thickness of the soil layer from the base of the channel (m)[1]
- h_{we} is the negative pressure head at the base of the soil layer, typical values can be found in Table 1.

Table 1. Typical values of negative pressure head h_{we} (m) (Bouwer, 2002)

Soil type	Negative pressure head h_{we} (m)
Fine sands	-0.15
Loamy sands –sandy loams	-0.25
Loams	-0.35
Structured clays	-0.35
Dispersed clays	-1.00

Example calculations

The following calculations illustrate the use of this method for case 3 over a range of parameter values. A potential range of soil hydraulic conductivities between 0.05 m/d and 2.8 m/d was reported by AWE (2009b). The proposed channel widths are between 5m and 35m and height of water in the channels is between 1m and 3m (David Way [DWLBC] 2010, pers. comm.).

- Example 5. Low range

  For a channel with α = 45^{o}, W_b = 20 m and H_w = 2 m, the wetted perimeter is W_p = 25.7 m. If the channel sits within a structured clay (with K_{soil} of 0.05 m/d and h_{we} of -0.35 m) that extends for 3 m from the base of the channel (L_f = 3 m), the seepage loss per metre of channel can be calculated as:

$$q = W_p K_{soil} \frac{(H_w + L_f - h_{we})}{L_f} = 25.7 \times .05 \times \frac{(2 + 3 + .35)}{3} = 2.25 \text{ m}^2/\text{d}$$

$$= 2.25 \text{ KL/d/m}$$

- Example 6. High range

For a channel with α = 45^{o}, W_b = 20 m and H_w = 2 m, the wetted perimeter is W_p = 25.7 m. If the channel sits within a loam (with K_{soil} of 1.0 m/d and h_{we} of -0.15 m) that extends for 1 m from the base of the channel (L_f = 1 m), the seepage loss per metre of channel can be calculated as:

$$q = W_p K_{soil} \frac{(H_w + L_f - h_{we})}{L_f} = 25.7 \times 1.0 \times \frac{(2 + 1 + .15)}{1} = 80.9 \text{ m}^2/\text{d}$$

$$= 80.9 \text{ KL/d/m}$$

[1] Within the given equation L_f is used in the denominator to approximate the flow length. It is acknowledged that the flow length from the sides of the channel will be greater than L_f. However, using L_f as an approximation of the flow length will result in a small over estimation of seepage (especially for wide and shallow channels) and is therefore a conservative approach.

It is important to note that following the onset of channel seepage the watertable may form a mound beneath the channel. This may result in the disconnected condition (with unsaturated flow) as represented in Figure 3 changing to a connected condition (with saturated flow) as represented in Figure 2 and then an approach similar to that outlined within Case 2 should be applied.

LIMITATIONS

The simple analytic methods provided here are suitable for use in estimating seepage volumes from constructed channels in the study area, which is in the Upper South East of South Australia. In view of the range of values for several variables used in the example calculations, the large variation in the seepage rates calculated in these examples is not unexpected. The implication of these large variations in derived seepage rates is that errors in channel loss estimates can potentially be very large if the values of key variables are not constrained. The range of values of these variables can be constrained by careful selection of values from existing data sets for the locations where the methods are being applied, or by in-field measurement of these variables.

It is also important to note that seepage losses are transient by nature, especially under shallow watertable conditions. A more detailed analysis that incorporates transient effects is also recommended.

ADDITIONAL FIGURES

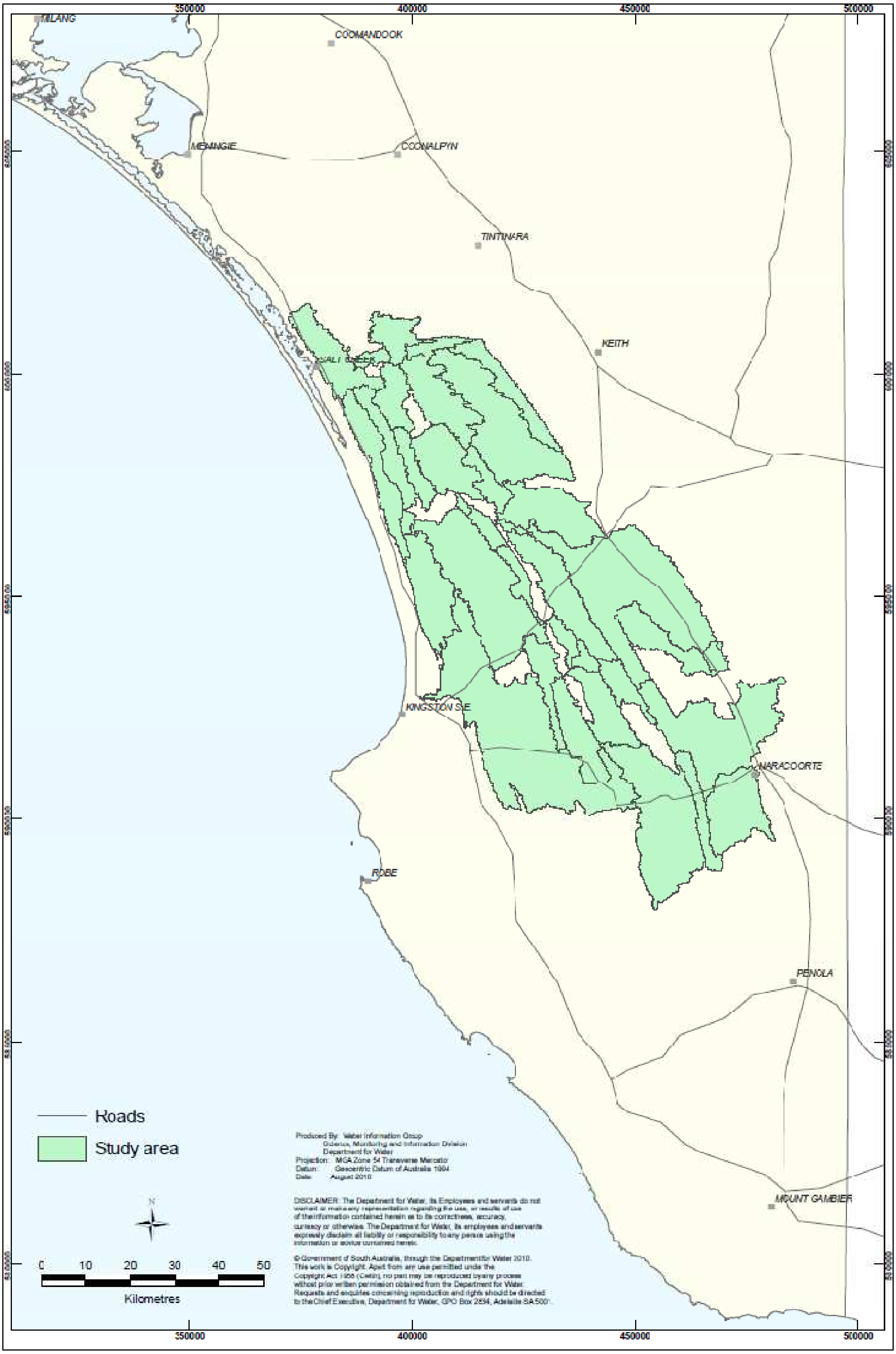

Figure 4. Study area location

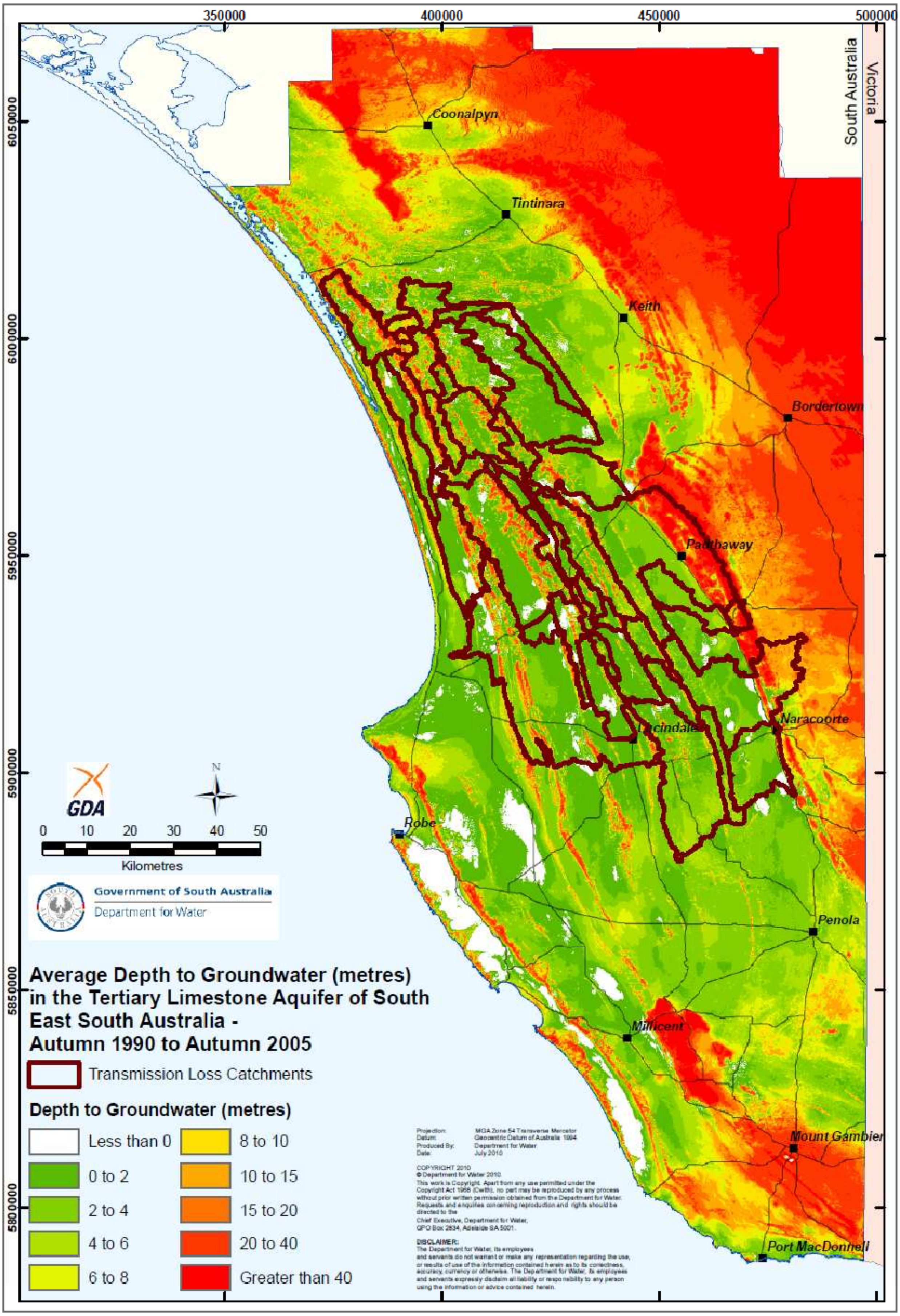

Figure 5. Average depth to watertable - Autumn 15 year average, modified from SKM (2009)

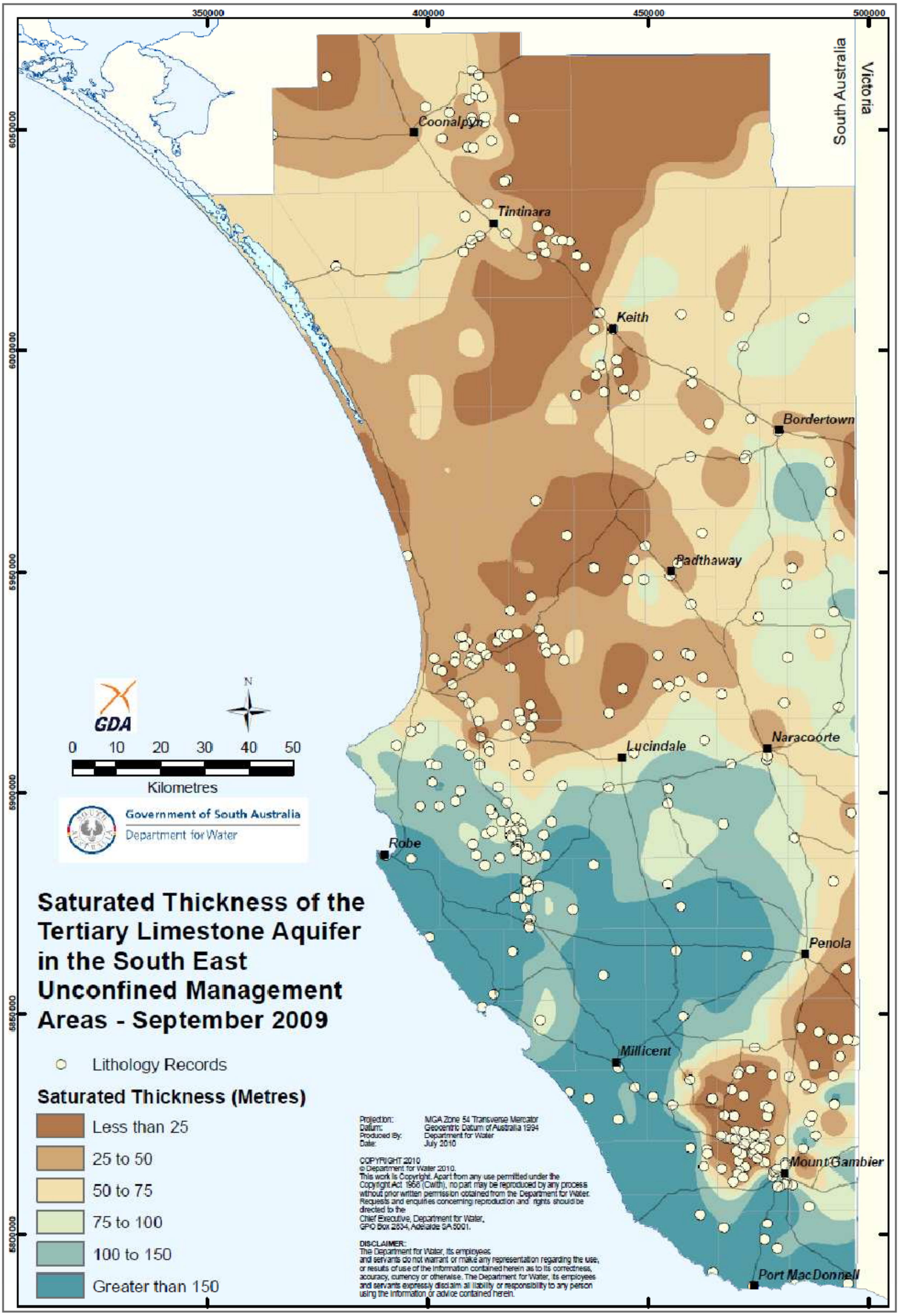

Figure 6. Saturated thickness of the unconfined aquifer (SKM, 2009)

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