RISING GROUNDWATER LEVELS ASSOCIATED WITH SEA LEVEL RISE

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1.   Introduction

Global sea-levels are rising. As Shakespeare put it: "…. I have seen the hungry Ocean gain advantage on the kingdom of the shore".

State Planning Policy 2.6 State Coastal Planning incorporates the report: "Sea Level Change in Western Australia: Application to Coastal Planning". This report, dated February 2010, gives a comprehensive summary of historical sea-level change and its causes, and recommends that: "a vertical sea level rise of 0.9m be adopted when considering the setback difference and elevation to allow for the impact of coastal processes over a 100 year planning timeframe (2010 to 2110)".

One of the consequences of sea-level rise will be a corresponding rise in groundwater levels near the coast, as groundwater discharge adjusts to the higher base level of the ocean and rivers.

This will happen in many coastal areas around the world. Perth and the Swan Coastal Plain in general (particularly between Perth and Busselton) will be adversely affected, having a highly permeable aquifer adjacent to the coast, and a shallow water-table.

In terms of the Conference theme "Solutions Beyond Boundaries" this paper addresses the need for all levels of government to address the inevitable groundwater rise associated with sea-level rise, hence "moving the boundary" of community concerns from the ocean side of the coast (sea-level rise) to the landward side (groundwater rise).

2.   Sea-Level Trends

Sea-levels have fluctuated widely throughout geological time. In the last 140,000 years they have risen and fallen many times as polar icecaps have advanced and retreated. If you had stood on the Darling Scarp 20,000 years ago, and looked to the west, the ocean would have been out of sight, well beyond the horizon. Since that time, not a long time geologically speaking, sea-levels have risen by about 140m. In the last 5000 years levels have been quite stable, but in the 15,000 years before that they rose so rapidly that aborigines living on the coastal plain would have noticed the ocean advancing during a lifetime.

About 110,000 years ago, in the last interglacial, sea-levels are thought to have been 5 to 8m higher than the present day.

Over shorter time-periods, it can be difficult to distinguish between variations in sea level and longer-term trends in Mean Sea Level, particularly as many of the variations are of much greater amplitude than any underlying trend.

Mean Sea Level (MSL) is defined as the height of the sea relative to a local land benchmark, averaged over a period of time, such as a month or a year, so that fluctuations caused by waves or tides are largely removed (UNESCO, 2002).

As measured by coastal tide gauges, MSL is therefore relative to any movement of the land that affects the benchmark, and any trend may be caused either by movement of the land or by actual change in the adjacent sea surface. Measured changes in sea-level must therefore be corrected for land movements to determine any absolute change in MSL. Such land movements include isostatic changes caused by long-term adjustment of continental plates to large-scale deposition and erosion of sediment, to advance and retreat of icecaps, groundwater abstraction, or indeed to large changes in sea-level. Major earthquakes are another potential influence.

Many other factors also affect sea-level, including storm surges, tsunamis, changes in water density as a result of temperature changes, and ocean currents. Barometric pressure also affects sea-levels, low pressure causing a rise, high pressure a fall.

The El Nino Southern Oscillation (ENSO) affects both climate and sea-levels around

Australia. ENSO alternates between El Nino and La Nina conditions in a three to eight year cycle (BoM, 2005). El Nino is characterised by warmer temperatures in the central to eastern Pacific Ocean and lower than normal sea-levels (Haigh et al, 2011), and may cause drought, particularly in eastern Australia. La Nina has the opposite effect, causing cooler than normal ocean temperatures in the eastern Pacific, higher than normal sea-levels and higher than average rainfall in the north and east of Australia.

The main control on global sea-level over the longer term is the net loss or gain of ice in the polar regions.

In Antarctica, conditions are not uniform, but there appears to be a general net loss, with decrease of ice mass on land exceeding an increase of sea ice (Hambrey et al, 2010). The East Antarctic ice-sheet is approximately stable, with ice loss balanced by increased snowfall. This is just as well, as melting of this ice sheet would cause a rise in global sea-level of about 60m! West Antarctica shows a net loss of ice, contributing an estimated 0.3mm/year rise in sea-level, with potential total loss of 3.3m. The Antarctic Peninsula is also losing ice, but not at a rate which is likely to noticeably affect sea-levels.

In the Arctic, as we have seen on the news over the past few years, the ocean is losing more and more of its ice cover in summer, and may be completely ice- free in summer within 40 years if current trends continue. The North West Passage opened for the first time in human memory in 2007 and did so again in 2012. The melting of floating ice, however, although spectacular in recent years, does not contribute to sea-level rise. The Greenland icesheet is a different matter, where net ice loss is estimated to be adding about 1.3mm/year to global sea-levels, with an increasing trend and potential total rise of 7m.

Glaciologists in general forecast an aggregate contribution of about 1m to sea-level rise by 2100, with some predicting up to 2m.

Recent studies have suggested that worldwide abstraction of groundwater may be contributing about 0.4mm/year to sea-level rise (Konikow, 2011), and may be contributing 0.8mm/year by 2050 (Wada et al, 2012). This would be due to increased evaporation and consequent increased rainfall, and to runoff into canals and rivers.

Sea-levels have been measured precisely in Australia since the early 1990's by the Australian Baseline Sea-Level Monitoring Project. This uses an array of 16 tidal gauges, termed S E A F R A M E stations (UNESCO, 2002). SEAFRAME stands for Sea-level Fine Resolution Acoustic Measuring Equipment. One of these is at Hillarys. These stations have been supplemented by satellite imagery since the 1990's, TOPEX/Poseidon (launched 1992), Jason-1 (launched 2001) and Jason-2 (launched 2008). The SEAFRAME and satellite measurements show good agreement.

Current CSIRO estimates indicate that, after several thousand years of relative stability, sea-levels apparently started rising slowly from about 1870, with increasing rates from about 1940 and again in the early 1990's (Figure 1). The rate of rise has averaged about 1.7mm/year since 1870, and 3.2mm/year since the early 1990's (CSIRO/ACERC, 2014).

The Intergovernmental Panel on Climate Change (IPCC) predicts a total rise of between 0.5m and 0.95m by 2100, with a mean value estimate of 0.73 (IPCC, 2014).

The Western Australian Planning Guideline of 0.9m is therefore a prudently conservative value, according to the current knowledge of sea-level controls and trends.

3.   <u>UNSW – Water Research Laboratory Study</u>

A UNSW – Water Research Laboratory Study (2013) concluded that water-table response to sea- level rise was most significant in coastal aquifers with high transmissivity and low hydraulic gradient.

Their modelling confirmed that the water-table rise would match sea-level rise near the coast, and diminish further inland. The Study noted that such a rise in water-table near the coast may affect sewers and the basements of buildings, and may affect the stability of swimming pools and underground tanks.

The UNSW-WRL Study also indicated that the seawater interface in a coastal aquifer

may intrude up to 1km further inland in response to a 1m sea-level rise. This might cause shallow bores near the coast to become brackish or saline.

A rise in sea-level may also cause landward advance of the shoreline. Depending on topography, a sea-level rise of lm may be expected to cause a shoreline advance in the range 50 to 100m.

4.   Groundwater Model

JDA has developed a groundwater model using MODFLOW to simulate the likely effect of a hypothetical 1m sea-level rise on the water table by 2113 on a cross-section across the Gnangara Mound (Figure 2). Modflow is an industry standard finite difference numerical model for the simulation of groundwater.

The surface geology in this area, across the coastal plain from west to east, consists of the Safety Bay Sand, Tamala Limestone, Bassendean Sand and Guildford Formation (Figure 3). These form a single groundwater flow system, termed the superficial aquifer.

The two main components of this aquifer are the Tamala Limestone and the Bassendean Sand (Figure 4). The Tamala Limestone consists of limestone and sand, the former containing cavities and solution channels. It is highly permeable, with hydraulic conductivity ranging from 100-10,000m/day, generally increasing towards the west. The Bassendean Sand consists mostly of medium-grained moderately sorted sand, with much lower hydraulic conductivity than the Tamala Limestone, about 10-15m/day.

Regional groundwater flow across the northern Gnangara Mound is a simple pattern of flow from east to slightly south of west, to discharge into the Indian Ocean.

MODFLOW was used to create a vertical slice model, representing a cross-section across the northern part of the Gnangara Mound, extending 30km inland, incorporating values of hydraulic conductivity for the superficial aquifer from Davidson (1995). Recharge is applied uniformly at 25 percent of average annual rainfall of 800mm. The model does not include any interaction with surface watercourses, nor groundwater abstraction by bores and wells.

The model was initially run in steady state mode to reproduce the present-day configuration of the water-table across the Gnangara Mound. It was then run in transient mode to simulate an annual rise of 10mm/year for 100 years for a total rise of 1m.

The representative cross-section for the year 2113 shown on Figure 5 shows a rise in water-table at the coast of 1m, corresponding to the total sea-level rise, declining progressively to 0.75m rise at 1km inland, 0.5m at 3.25km and 0.25m at 8.5km inland. At the top of the Gnangara Mound the rise is predicted to be only 0.1m.

The JDA groundwater model thus provides a semi-quantitative estimate of water-table rise in the superficial aquifer, in response to a 1m rise in sea-level by 2113. The model provides a basis for future development which could take account of local variations in hydrogeology and transmissivity.

The predicted groundwater rise across the model domain shows a marked decrease where the water-table passes from the highly transmissive Tamala limestone adjacent to the coast into the much less transmissive Bassendean sand further inland, as shown schematically on Figure 6.

Davidson (1995) includes a map proving transmissivity contours in the superficial aquifer, reproduced here as Figure 7. The water-table predicted by the JDA groundwater model can be extrapolated over the Perth coastal region by correlation with variations in transmissivity (Figures 8a and 8b). Sea level rise will be transferred upstream in the Swan River causing a groundwater rise along the river foreshore. Transmissivity is generally relatively low inland along the river, however, so that the water-table rise will not progress far from the shore.

The extent of water-table rise will therefore vary across different council boundaries, according to local variations in the geology and superficial aquifer transmissivity. In general to the north of the Swan River (Figure 8a) Wanneroo, Joondalup, Stirling and the western suburbs will be the most affected coastlines, and to the south of Perth (Figure

8b) Fremantle, Cockburn, Kwinana, Rockingham and Mandurah. Further south Bunbury and Busselton will experience similar rise.

Where the water table is already shallow, obviously the effect of groundwater rise will be to reduce the separation between ground surface and the water table.

5.   Conclusions

The present Western Australian Planning Guideline of a 0.9m rise in sea-level by 2100 is a prudently conservative value.

Groundwater levels in Perth will rise in response to sea-level rise. A rise of 0.9m in sea-level will cause an equivalent rise in the water-table adjacent to the coastline, diminishing progressively inland. The water-table rise will decrease markedly where it passes from the highly transmissive Tamala Limestone near the coast into the much less transmissive Bassendean Sand further inland.

The water-table rise will decrease the separation between land surface and groundwater (even in areas with groundwater controls such as subsoil drainage) and may affect sewer systems, basements of buildings, and the stability of swimming pools and underground tanks.

Sea-level rise is also likely to cause the salt water interface in the superficial aquifer to migrate inland, perhaps by as much as 1km, causing some bores near the coast to become brackish.

A 0.9m sea-level rise may also cause landward encroachment by the ocean, by up to 100m, depending on local topography.

Management of the effects of water-table rise will require improved monitoring of water-table levels, and of the saltwater interface in the superficial aquifer, in coastal suburbs.

The effect of this inevitable rise in water table needs to be factored into policy settings at all levels of government and to be integral to future land use planning.

Within our children's lifetimes we will indeed see "the hungry Ocean gain advantage on the kingdom of the shore".

6.   References

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Figures

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Global Mean Sea Level (GMSL) – 1880 to 2012

Legend:
- tide gauge data & uncertainty[1]
- satellite altimeter data[2]

Yearly average data
Latest data: 2009 (t.g.) and 2012 (alt)
Figure updated: 25–Feb–2013

[1] Church and White (2011)
[2] Combined TOPEX/Poseidon, Jason-1 & Jason-2 (CSIRO)
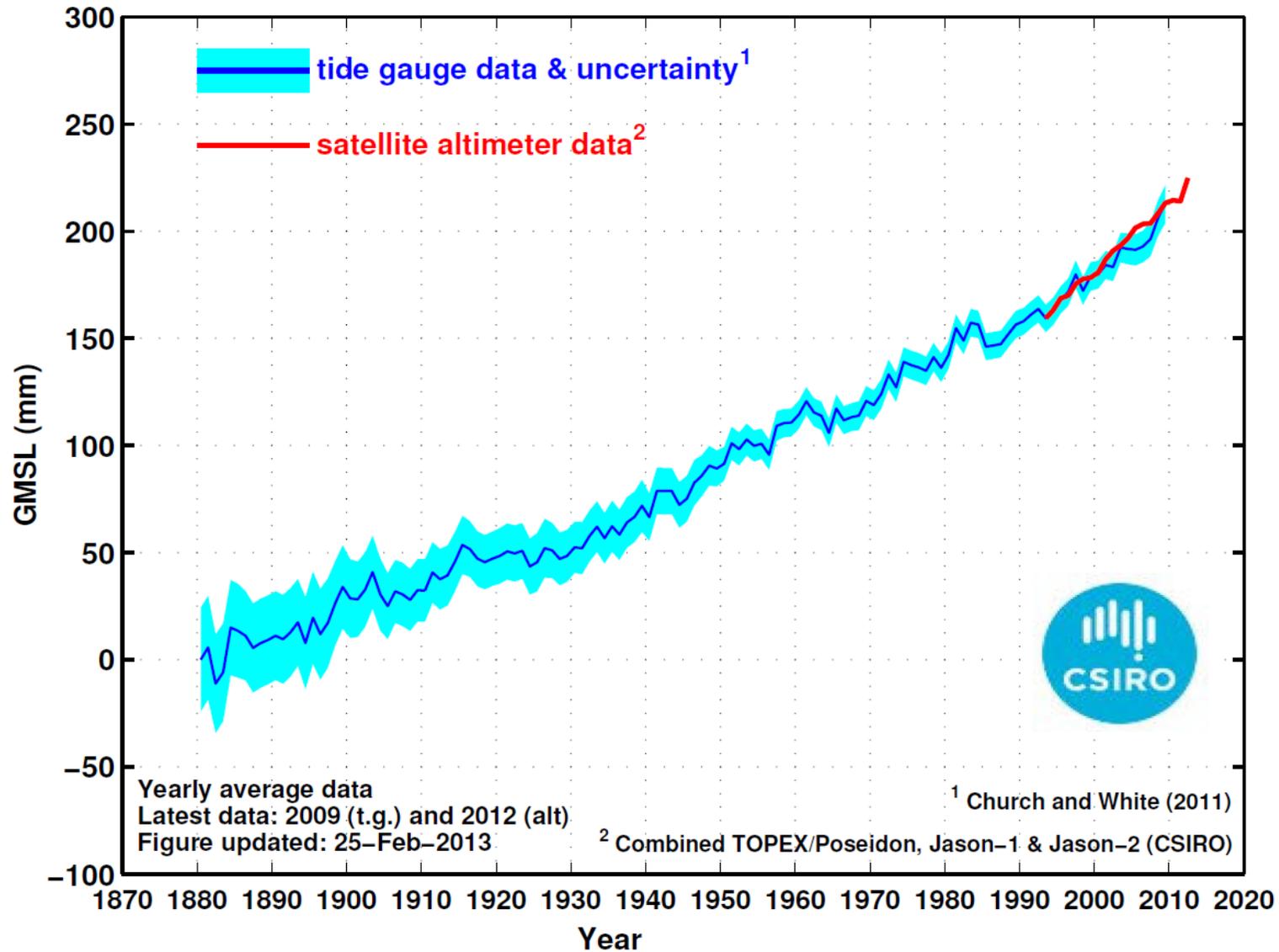
Data Source: (CSIRO & ACECRC)
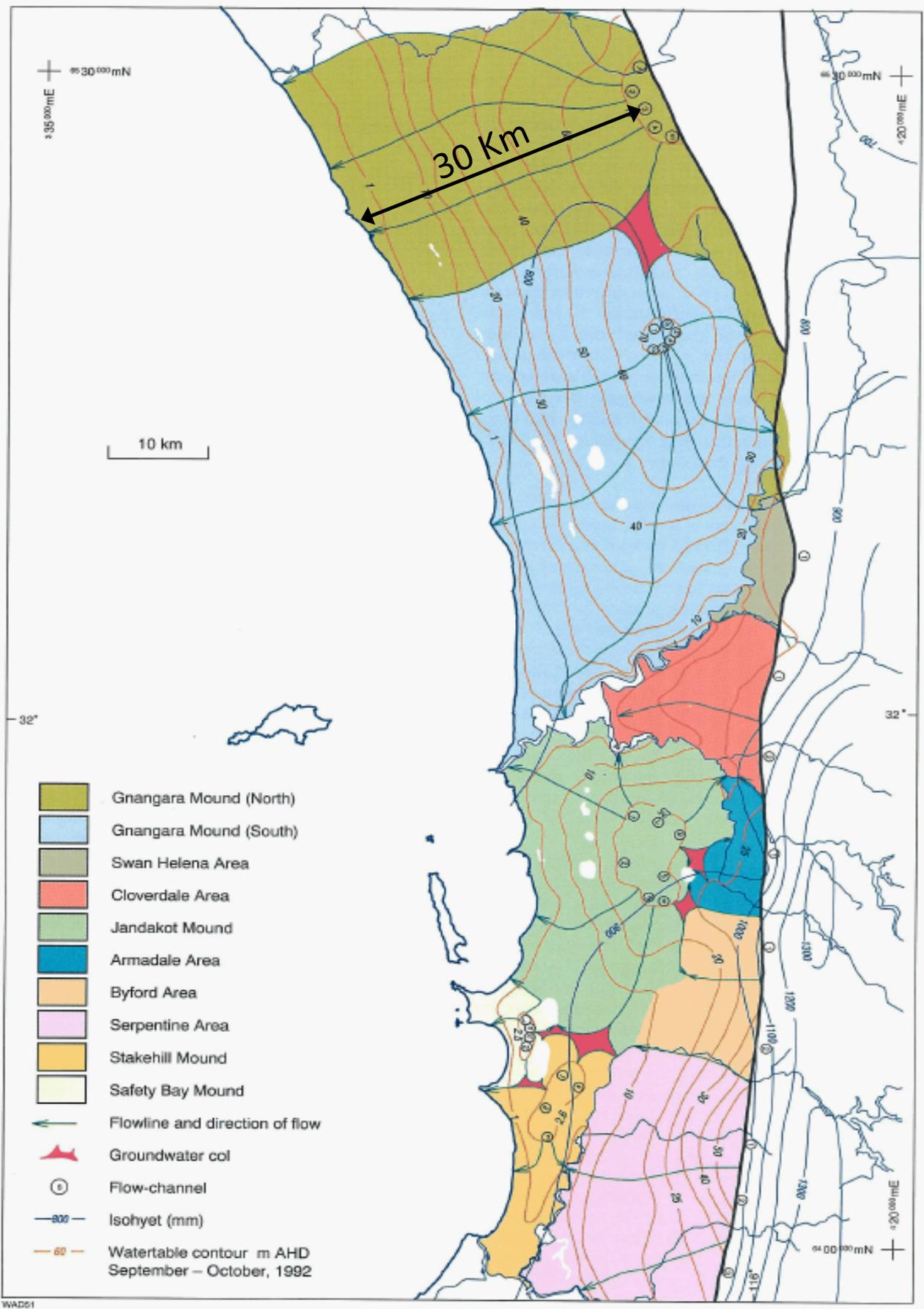
Figure 27. Superficial aquifer groundwater flownet

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Figure 2: Superficial Aquifer Flownet
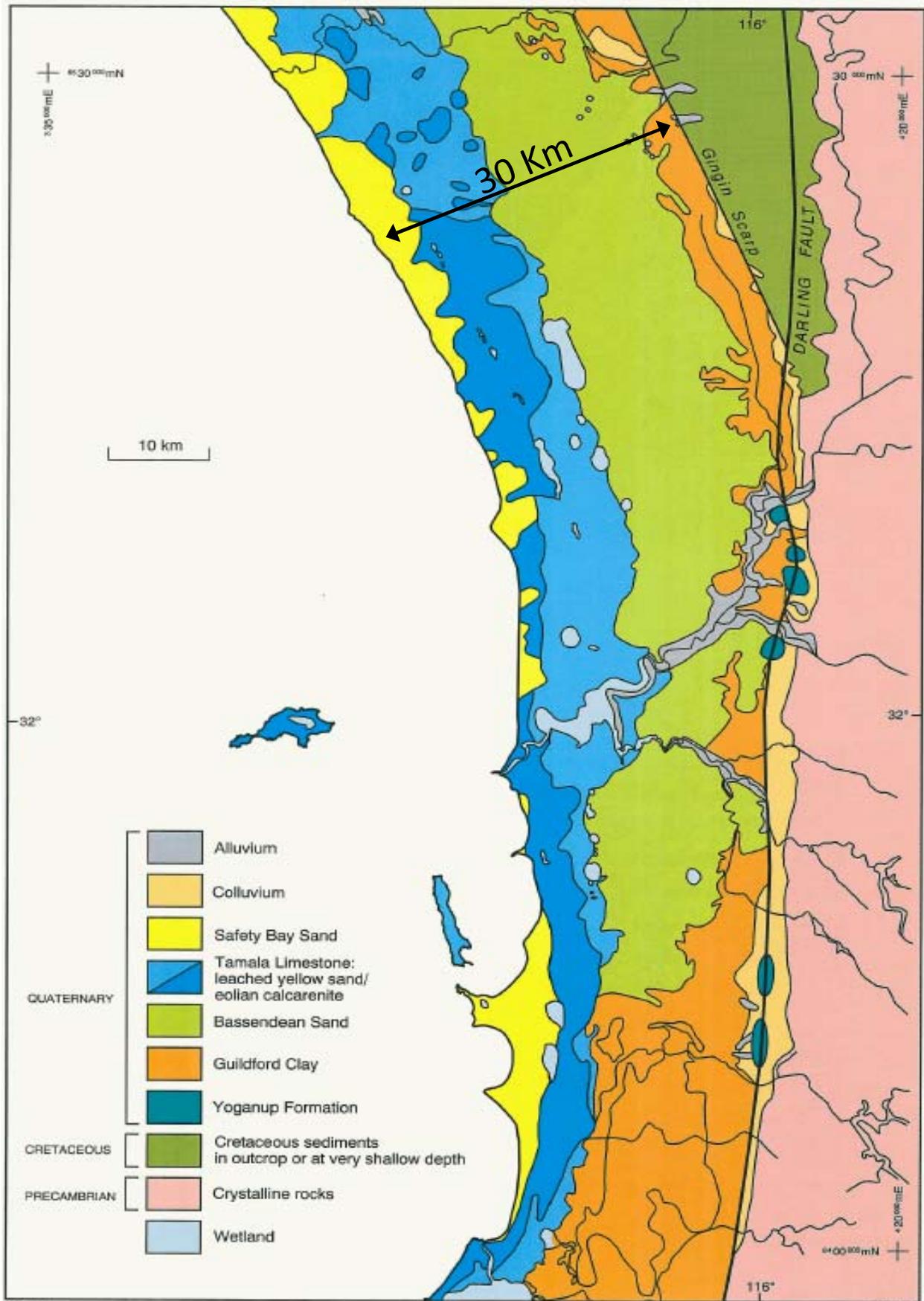
PLATE 50. Surface geology; generalized

Map legend:

QUATERNARY
- Alluvium
- Colluvium
- Safety Bay Sand
- Tamala Limestone: leached yellow sand/ eolian calcarenite
- Bassendean Sand
- Guildford Clay
- Yoganup Formation

CRETACEOUS
- Cretaceous sediments in outcrop or at very shallow depth

PRECAMBRIAN
- Crystalline rocks
- Wetland

Map annotations: 30 Km, 10 km scale bar, Gingin Scarp, DARLING FAULT, 116°, 32°, 30 000mN

WAD85   17.06.94

Data Source: (Davidson et al, 1995; Bulletin 142, Page 222)

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	© COPYRIGHT JIM DAVIES & ASSOCIATES PTY. LTD. 2014	IPWEA 2015 **Figure 3: Surface Geology**

Figure 4: Gnangara Mound Geological Profile

Legend:

Ty	Yoganup Formation	
Ta	Ascot Formation	
Tr	Rockingham Sand	
Tk	Kings Park Formation	
	Mesozoic formations	
	Crystalline rocks	
~~	Major unconformity	

	Colluvium
Qs	Safety Bay Sand
Qc	Becher Sand
Qt	Tamala Limestone
	Limestone
	Sand

Qd	Bassendean Sand
Qn	Gnangara Sand
Qg	Guildford Clay
	sand and gravel remnant Ascot Formation or Yoganup Formation
Ty	Yoganup Formation
Ta	Ascot Formation

Data Source: (Davidson et al, 1995; Bulletin 142, Page 48)

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Figure 4: Gnangara Mound Geological Profile

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Figure 5: Rise in Water-Table Along Modelled Transect

LEGEND
- Gnangara Mound
- Streamlines
- Major Roads

ELEVATION (m)
- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 50
- 50 - 60
- 60 - 70
- 70 - 80

0.75 m Rise 1 km from coast

0.50 m Rise 3.25 km from coast

0.25 m Rise 8.5 km from coast

Groundwater Table Rise [±m]

Distance from Coast [km]

■ Δh [m] (+1m Sea Level Rise)
■ Δh [m] (Constant Sea Level @ 0 mAHD)
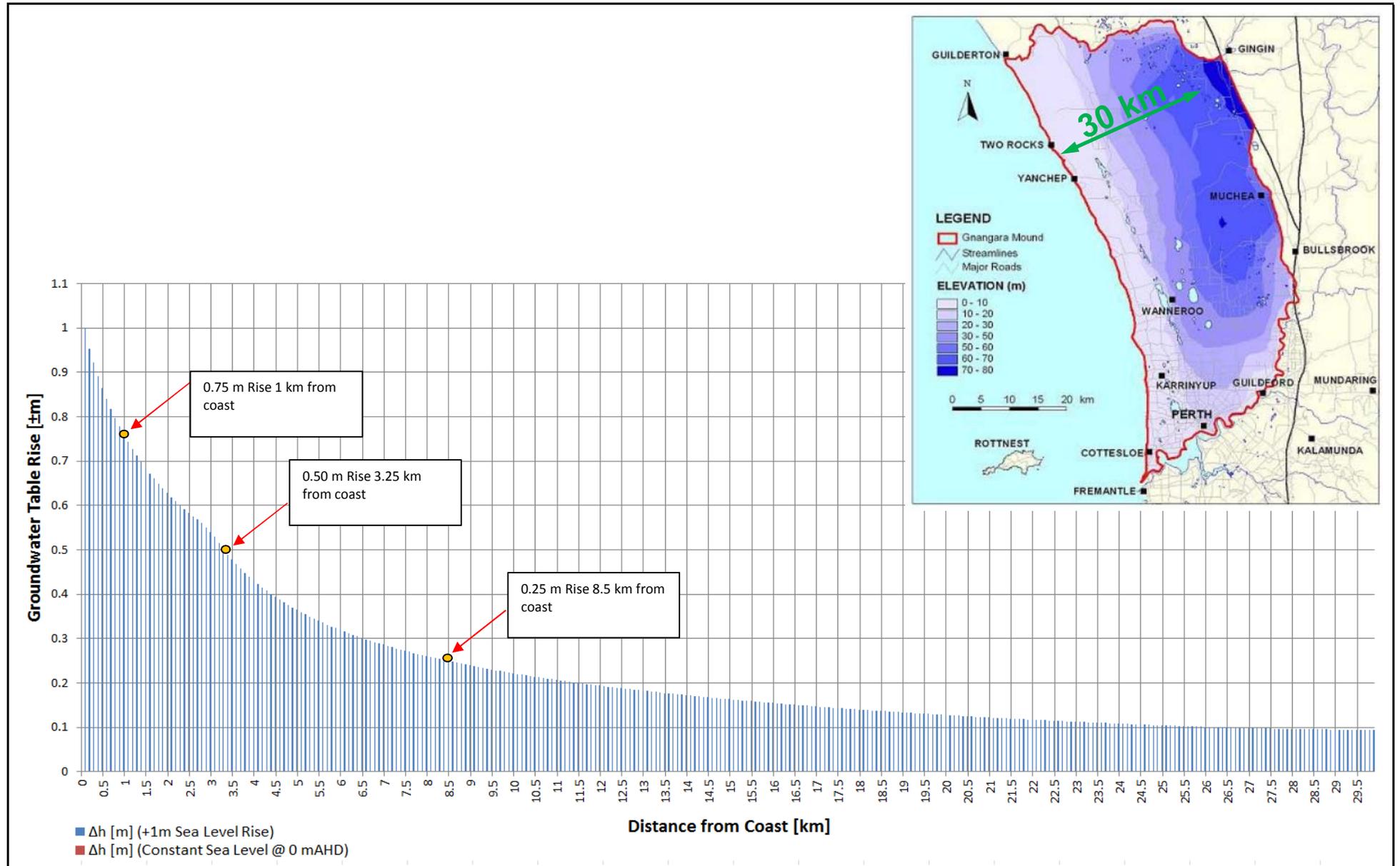
Data Source:

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Figure 5: Rise in Water-Table Along Modelled Transect

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Natural surface

Inland extent of water-table rise

Low transmissivity   Year 2110
Year 2015

Year 2110

Inland extent of water-table rise

Year 2110 Sea level

High transmissivity
Year 2015

0.9m Sea level rise

Year 2015 Sea level

Ocean

Natural Surface ——— High Transmissivity ——— Low Transmissivity

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Figure 6: Conceptual Cross-Section Showing Water-Table Rise in High and Low Transmissivity Aquifers Along Shorelines

PLATE 55. Superficial aquifer contours of transmissivity and chloride concentration
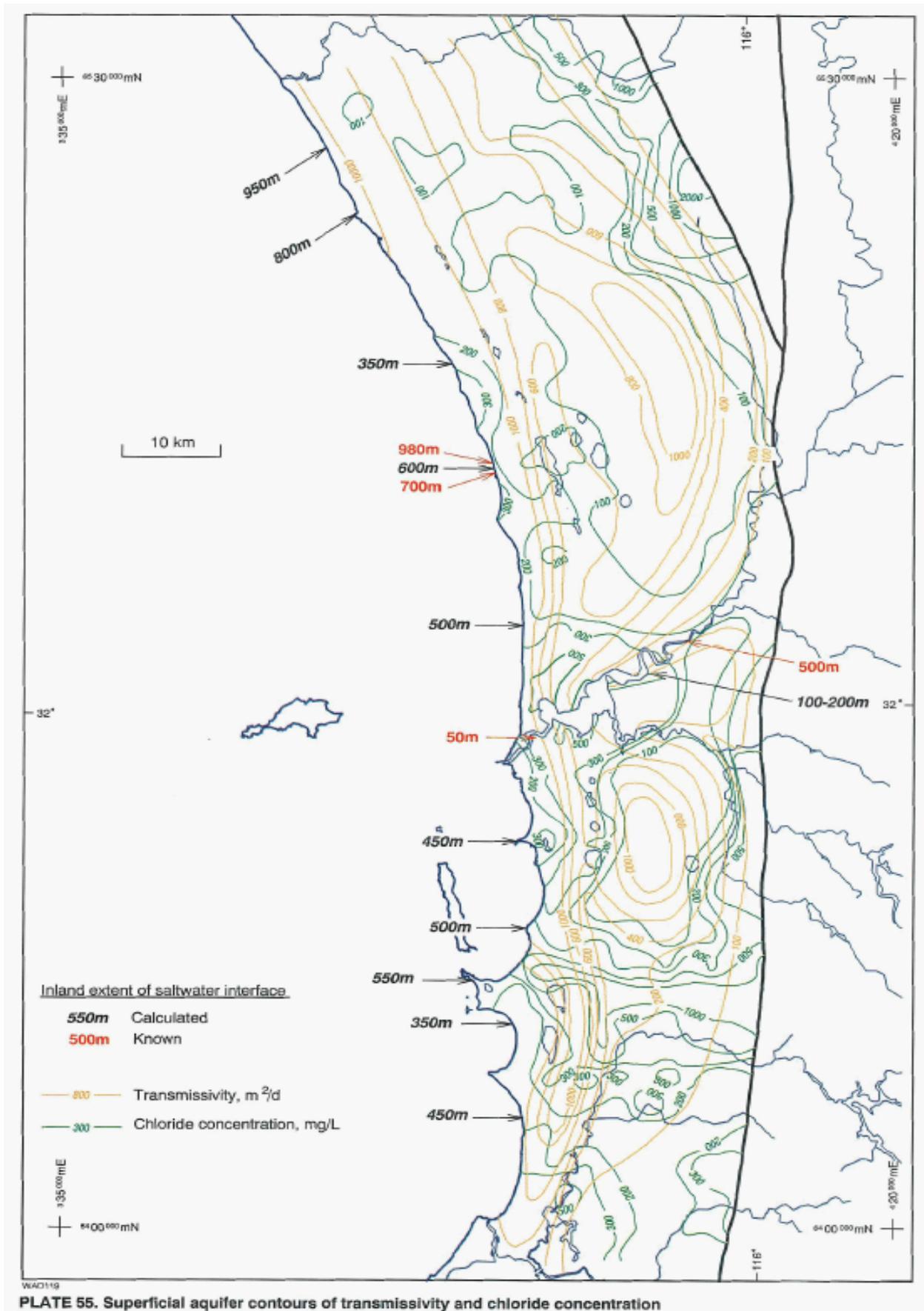
Data Source: (Davidson et al, 1995; Bulletin 142, Plate 55)

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Figure 7: Transmissivity Contours, Superficial Aquifer
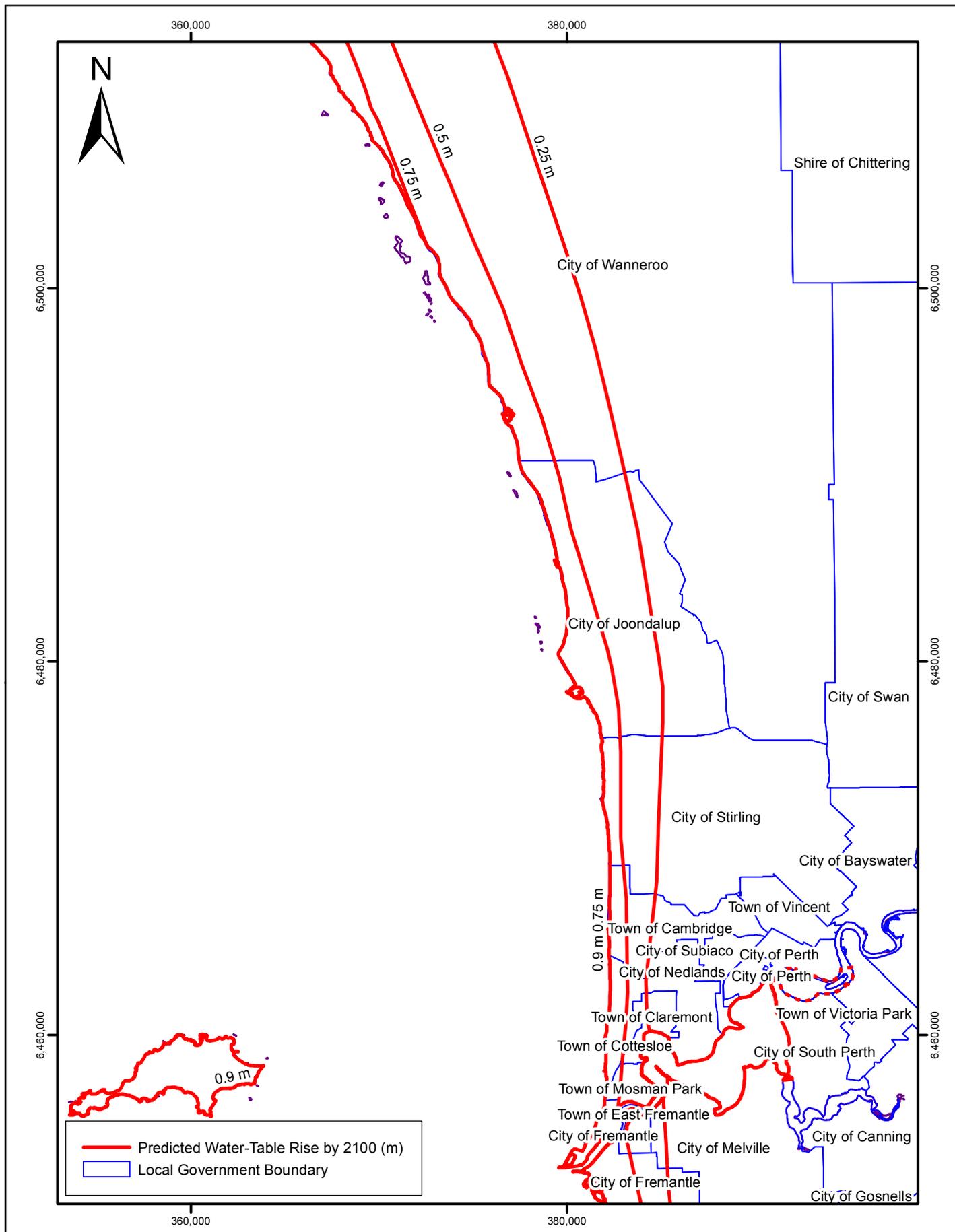
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Figure 8a: Predicted Water-Table Rise by Year 2100
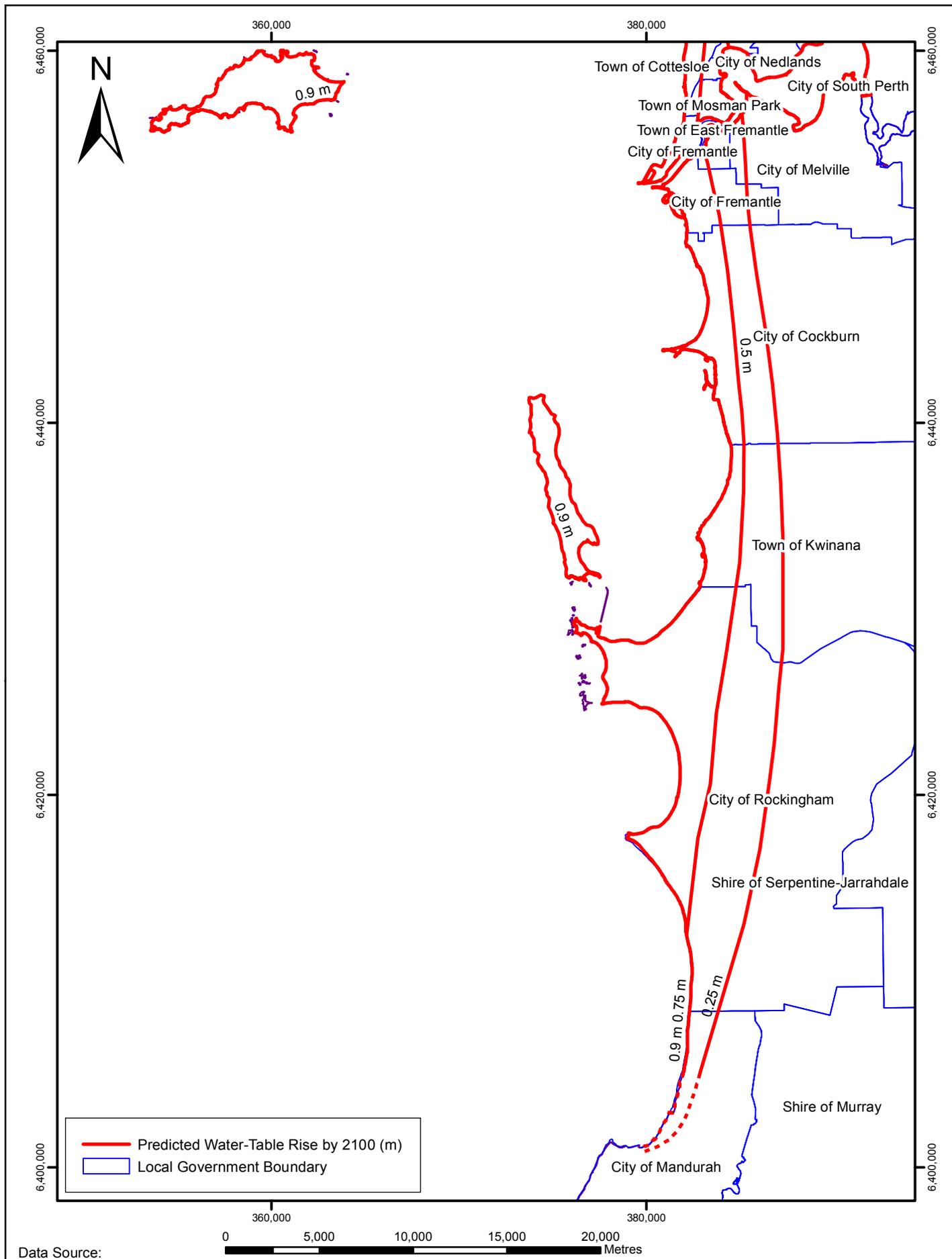
Legend:
- Predicted Water-Table Rise by 2100 (m)
- Local Government Boundary

Contour labels: 0.25 m, 0.5 m, 0.75 m, 0.9 m

Local Government Areas labelled: Shire of Chittering, City of Wanneroo, City of Joondalup, City of Swan, City of Stirling, City of Bayswater, Town of Vincent, Town of Cambridge, City of Subiaco, City of Perth, City of Nedlands, Town of Victoria Park, Town of Claremont, City of South Perth, Town of Cottesloe, Town of Mosman Park, Town of East Fremantle, City of Melville, City of Canning, City of Fremantle, City of Gosnells

Coordinate values on axes: 360,000 / 380,000 (horizontal); 6,500,000 / 6,480,000 / 6,460,000 (vertical)

Scale bar: 0 – 5,000 – 10,000 – 15,000 – 20,000 Metres

Figure 8b: Predicted Water-Table Rise by Year 2100

Legend:
- Predicted Water-Table Rise by 2100 (m)
- Local Government Boundary

Labels on map:
- Town of Cottesloe
- City of Nedlands
- City of South Perth
- Town of Mosman Park
- Town of East Fremantle
- City of Fremantle
- City of Melville
- City of Fremantle
- City of Cockburn
- Town of Kwinana
- City of Rockingham
- Shire of Serpentine-Jarrahdale
- Shire of Murray
- City of Mandurah

Contour labels: 0.9 m, 0.5 m, 0.25 m, 0.75 m

N

0   5,000   10,000   15,000   20,000   Metres

360,000   380,000

6,460,000   6,440,000   6,420,000   6,400,000