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STORMWATER & DRAINAGE
RISING GROUNDWATER LEVELS ASSOCIATED WITH CLIMATE CHANGE

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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.

Meanwhile, the climate of the Swan Coastal Plain is drying. Rainfall since the mid-1970's has reduced significantly all along the coast between Perth and Busselton, and projections for the future indicate that rainfall will continue to decrease. This will result in decreased recharge to the superficial aquifer and place further pressure on groundwater systems and necessitate further restrictions on groundwater abstraction.

The reduced groundwater throughflow, together with sea level rise, will result in migration inland of the salt water interface along the coast.

2. FUTURE CLIMATE PROJECTIONS FOR WESTERN AUSTRALIA

DoW (2015) describes the importance of standardising future climate scenarios used for modelling water resources in WA noting that since 1970's south west Western Australia has experienced declining rainfalls and general circulation models (GCMS) suggest that this trend will continue into the 21st Century.

In 2013 the Department of Water developed standard climate scenarios for 5 broad climatic regions across WA to enable consistent application of climate projections.

The climate scenarios are reported using anomalies – the average change in climatic variable for a future period compared to the baseline period. The period 1961 to 1990 has been adopted as the baseline period for WA.

DoW (2015) analysed 12 GCMS with 4 emissions scenarios resulting in 48 scenarios.

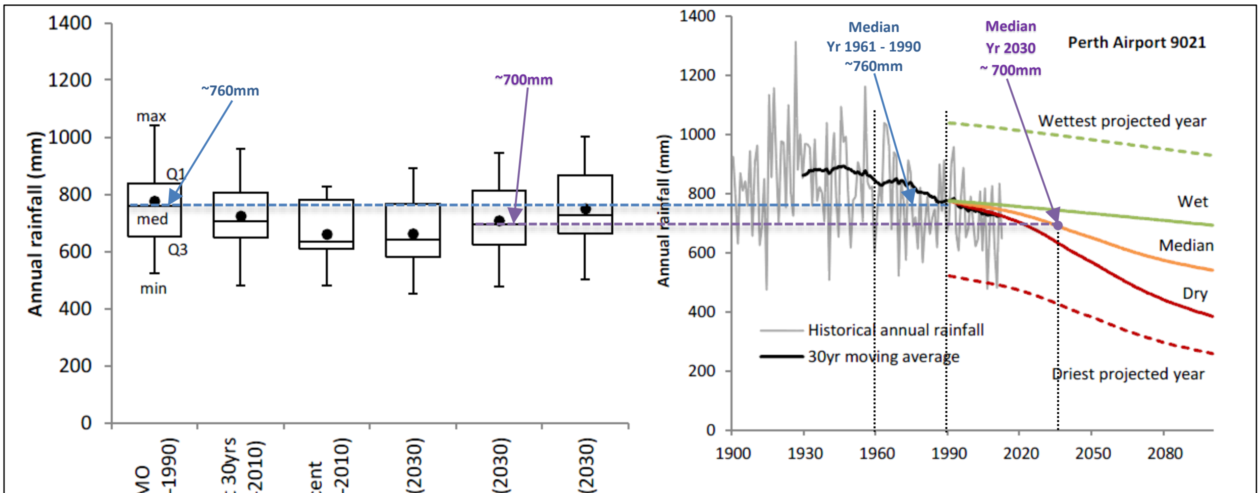
These were ranked in terms of percentage change to rainfall from the baseline period (1961 to 90) through to 2100. All 48 scenarios indicated a reduction in rainfall to 2100 from the baseline period in south west WA.

The regional average change in annual rainfall for the south west to 2030 relative to baseline period is -14%, -5% and -2% for the dry, median and wet scenarios respectively. For the south west to 2100 relative to the baseline period the average change in annual rainfall is -47%, -17% and -7% for the dry, median and wet scenarios respectively.

The dry, median and wet scenarios are approximately the 10th, 50th and 90th percentiles of the 48 scenarios modelled to 2100.

For the period to 2030 the reductions in mean annual rainfall relative to the baseline period of 14, 5 and 2% (dry, median and wet respectively) are spatial averages over the south west, which typically increase from near 0% inland to a maximum (>than the average) in the south west corner of the state.

Figure 1 shows box and whisker plots from DoW (2015) for the wet, median and dry scenarios through to 2100 for Perth Airport.



$$\frac{760 - 700}{760} = 8\% \text{ reduction "anomoly"}$$

Figure 1: Box and whisker plots of annual rainfall for historical periods and climate scenarios for 2030 (mean showed by dot); and scenarios at Perth Airport, projected mean annual rainfall to 2100 for the wet, median and dry scenarios (DoW, 2015)

Figure 1 shows median rainfall at Perth Airport from 1961 to 1990 is approximately 760 mm/yr declining to 700 mm/yr by 2030 (8% reduction) relative to baseline, and declining to 550 mm by 2100 (28% reduction).

For Perth (City), the baseline median rainfall is 780 mm/yr, declining to 711 mm/yr by 2030, then 655 mm/yr by 2050, 600 mm/yr by 2070 and 545 mm/yr by 2100.

Time series of 30 year projections of rainfall can be obtained from DoW based on baseline data 1961 to 90 by incorporating monthly anomalies (DoW, 2015).

DoW (2015) recommends which climate scenario to use for water resource applications based on uncertainty and risk management.

Figure 2 shows that for south west WA if the range in climate projections is unlikely to be significant to the outcome of the planning, then use of the median climate projections should underpin the modelling.

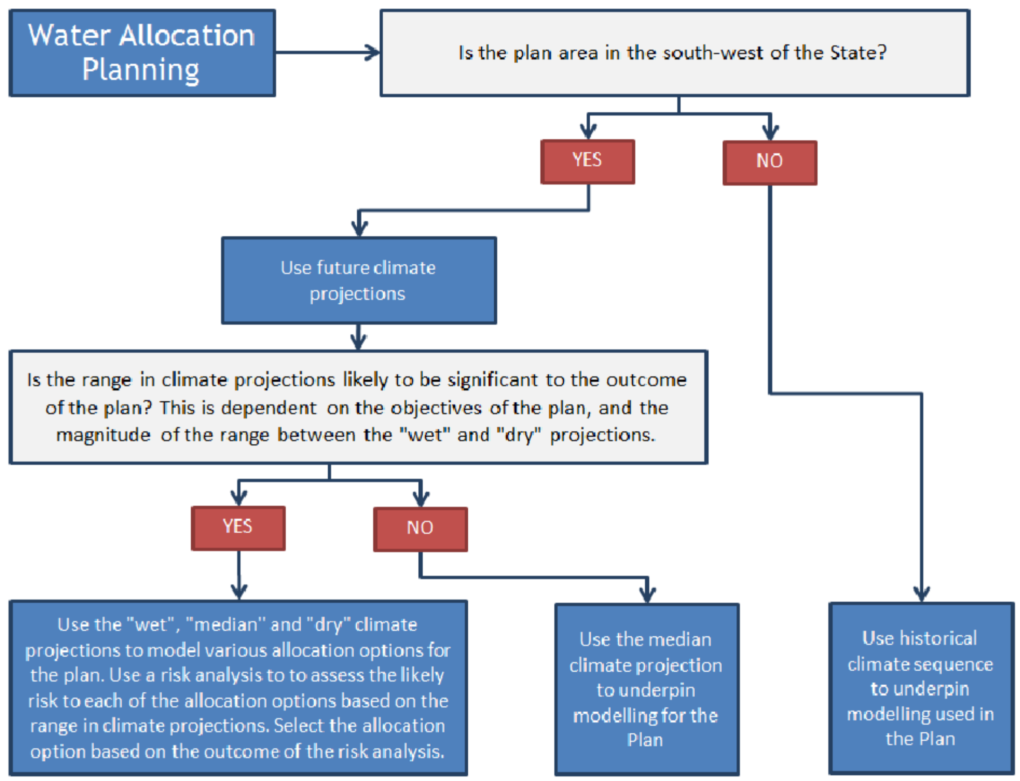


Figure 2: Department framework used to select an approach to incorporate climate in water allocation planning (DoW, 2015)

3. 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 SEAFRAME 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 3). 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.

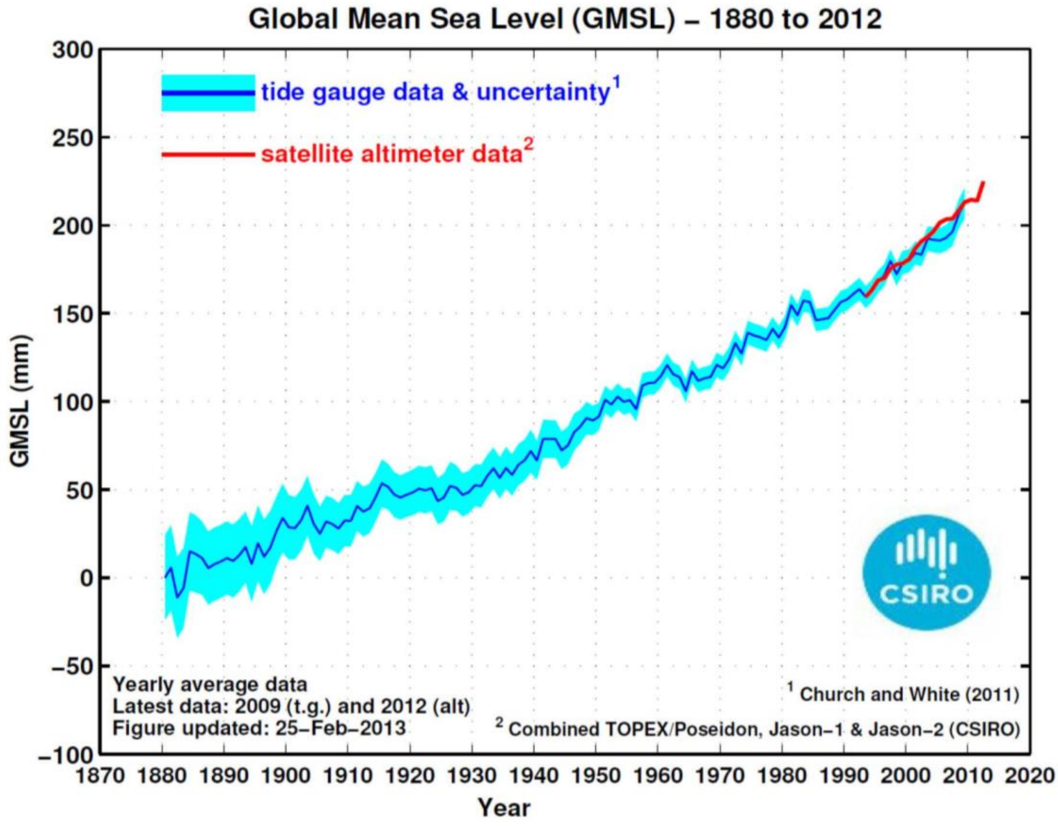


Figure 3: Average Absolute Sea Level Time Series

4. UNSW – WATER RESEARCH LABORATORY STUDY

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 1 km further inland in response to a 1 m 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 100 m.

5. GROUNDWATER MODEL

JDA has developed a groundwater model using MODFLOW to simulate the likely effects of climate change – decreasing rainfall and a 0.9 m sea-level rise – on the water table by 2115 on a cross-section across the Gnangara Mound (Figure 4). 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 5). 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 6). The Tamala Limestone consists of limestone and sand, the former containing cavities and solution channels. It is highly permeable, with hydraulic conductivity ranging from 100-10,000 m/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 10-15 m/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 30 km inland, incorporating values of hydraulic conductivity for the superficial aquifer from Davidson (1995). Recharge is applied uniformly at 25 percent of an initial average annual rainfall of 780 mm. The model does not include any interaction with surface watercourses, nor any change in land use. The assumed recharge rate takes into account groundwater abstraction by bores and wells.

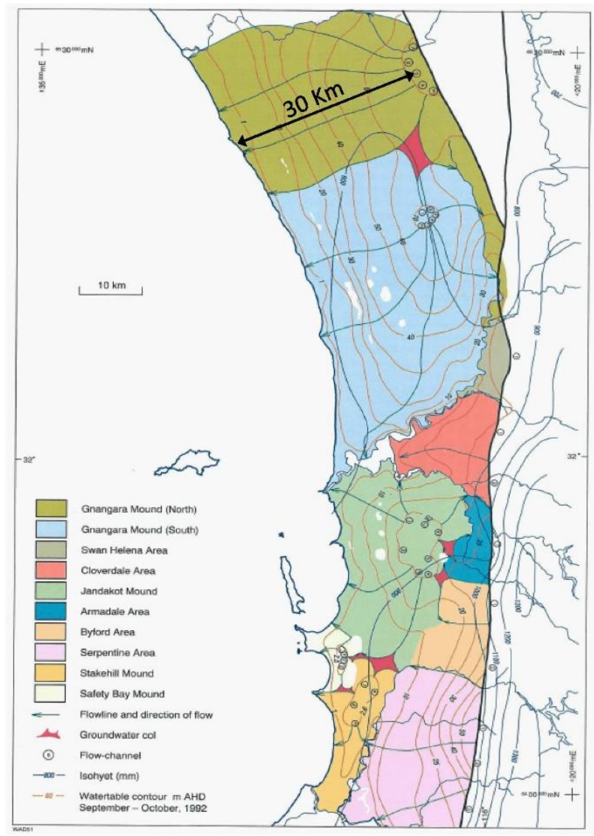


Figure 4: Superficial Aquifer Flownet
(source: Davidson et al., 1995)

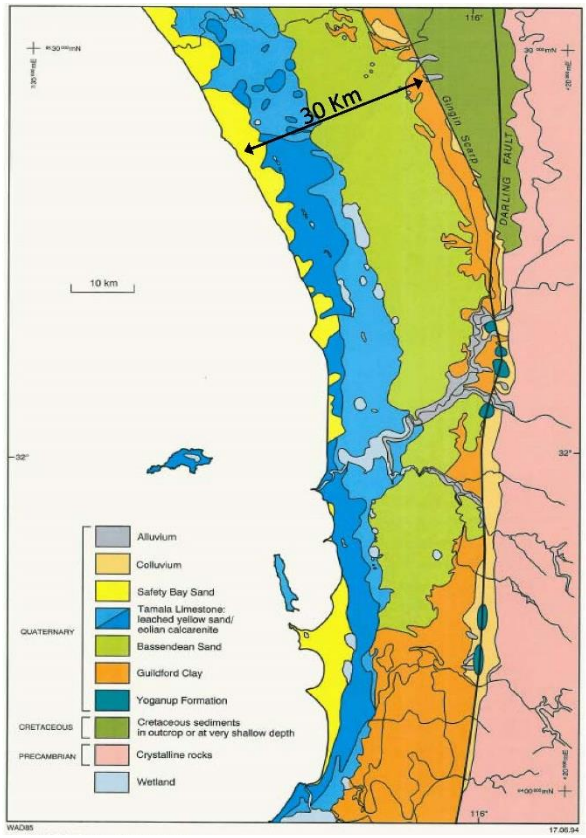


Figure 5: Surface Geology
(source: Davidson et al., 1995)

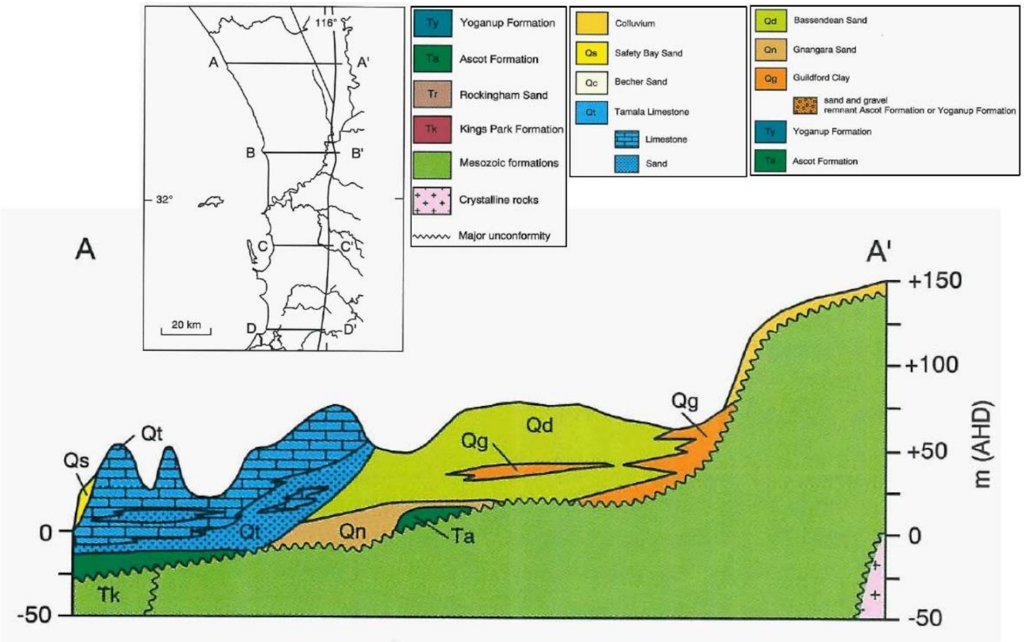


Figure 6: Gnangara Mound Geological Profile
(source: Davidson et al., 1995)

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 9 mm/year for 100 years for a total rise of 0.9 m.

For the declining rainfall, the median estimates for the 2030, 2050, 2070 and 2100 annual rainfalls were used to interpolate rainfall to 2100 and extrapolate to 2115. A recharge rate of 25% was applied over the 100 year simulation period. This assumes no significant changes in land use or abstraction over that period.

As well as the baseline "no change" scenario, 3 options were simulated:

- Scenario 1: No change, i.e. no change in sea level and constant rainfall;
- Scenario 2: Sea level rise of 0.9 m, with no change in rainfall;
- Scenario 3: Decline in rainfall, with no change in sea level; and
- Scenario 4: Decline in rainfall with 0.9 m sea level rise.

The results of the modelling are discussed below.

6. RESULTS OF MODELLING

The representative cross-section for the year 2115 shown on Figures 7 and 8 shows the estimated groundwater levels for the four scenarios. It can be seen that Scenarios 3 and 4 have lower groundwater levels than Scenarios 1 and 2, with the largest difference occurring at the upstream extent of the cross section (top of groundwater mound). The impact of the change in soil type (and corresponding hydraulic conductivity) can also be seen at the 3 km distance from the coast, with the change from Tamala Limestone / Safety Bay Sand to Bassendean Sand.

Figure 9 shows the groundwater levels for Scenario 2 minus those for Scenario 1 for 2115 – this is the impact of sea level rise on groundwater levels. This shows a rise in water-table at the coast of 0.9 m, corresponding to the total sea-level rise, declining progressively to 0.75m rise at 600 m inland, 0.5 m at 2.9 km and 0.25 m at 7.3 km inland. At the top of the Gnangara Mound the rise is predicted to be less than 0.1m.

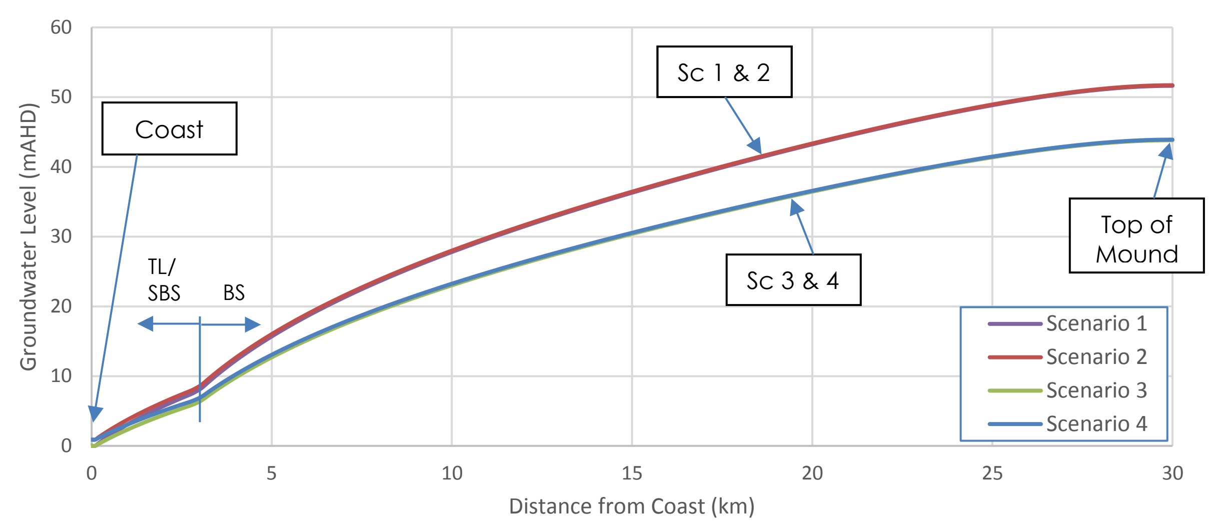


Figure 7: Modelled Cross Section Groundwater Levels for 2115 – All Scenarios 1 to 4

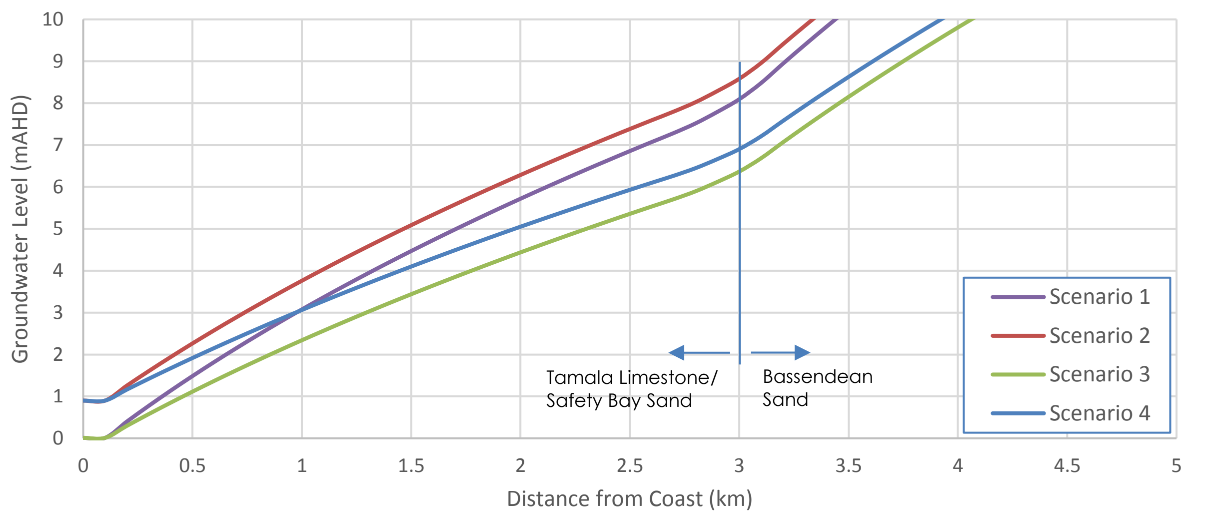


Figure 8: Modelled Cross Section Groundwater Levels for 2115 – Near Coast

Figure 10 shows groundwater levels for Scenario 3 minus those for Scenario 1 for 2115 – this is the impact of decline in rainfall on groundwater levels. It can be seen that this impact is significant. The model provides a semi-quantitative estimate of the impact of a 30% decline in rainfall on groundwater. There is a decline in levels and available capacity. This assumes no change in abstraction over the 100 years to 2115.

Figure 11 shows groundwater levels for Scenario 4 minus those for Scenario 1 for 2115 – this is the combined impact of decline in rainfall and sea level rise on groundwater levels. At the coast, groundwater levels are primarily influenced by the rise in sea levels, with an increase of 0.9 m immediately adjacent to the coast. This influence rapidly decreases moving away from the coast, with a net "0 m" change occurring at 1 km from the coast. Inland of this, reduced rainfall recharge effects dominate, with an overall net decrease in groundwater levels.

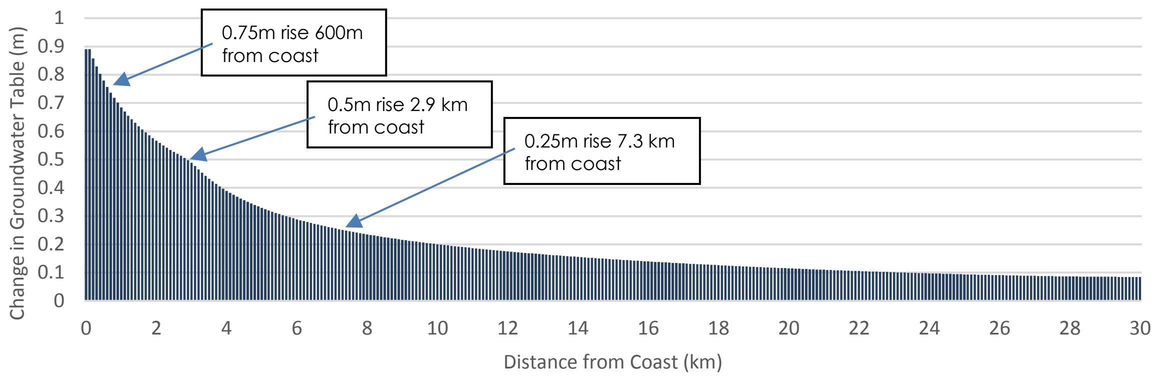


Figure 9: Scenario 2 Groundwater Levels minus Scenario 1 Groundwater Levels – Impact of Sea Level Rise

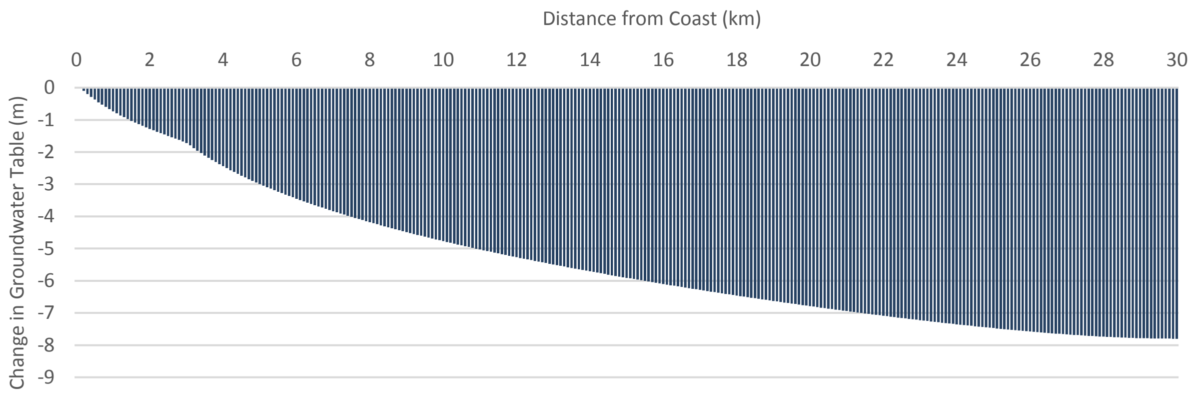


Figure 10: Scenario 3 Groundwater Levels minus Scenario 1 Groundwater – Impact of Decline in Rainfall

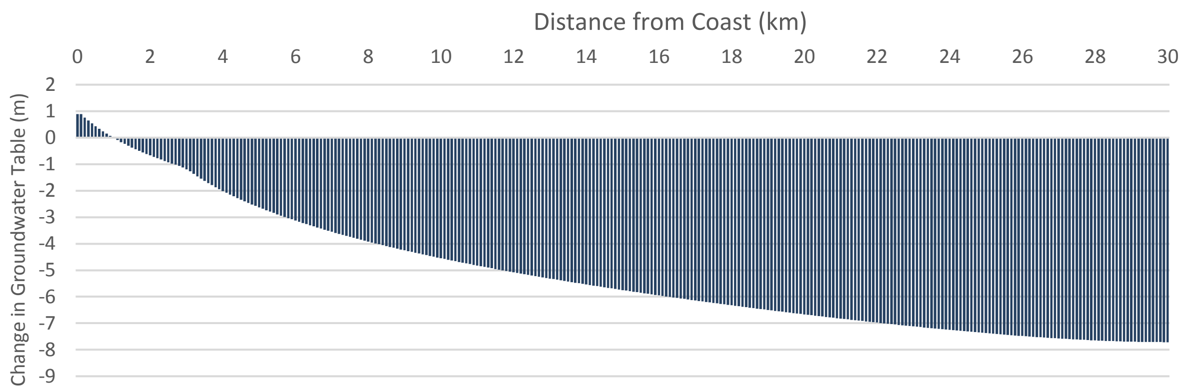


Figure 11: Scenario 4 Groundwater Levels minus Scenario 1 Groundwater Levels – Impact of Sea Level Rise and Decline in Rainfall

There are two significant impacts of the change in groundwater.

The first is the reduced capacity of the groundwater system. Falling groundwater levels will place greater pressure on groundwater dependent systems, and will likely require tightening of groundwater supply systems, including reduction of licenced allocations for irrigation, and reduced use for public drinking water supply. DoW (2015) indicates that the climate change predictions outlined in the report will be used for groundwater modelling to support allocation planning and assess changes to the groundwater system; modelling of supply projections; and modelling of integrated groundwater – surface water systems.

The second significant impact will be on salt water intrusion. On its own, sea level rise would result in an inland migration of the salt water interface. However with decline in rainfall, the groundwater throughflow will also decrease, resulting in further increase in salt water intrusion, as there is less fresh water discharging.

The JDA groundwater model thus provides a semi-quantitative estimate of water-table change in the superficial aquifer, in response to a 0.9 m rise in sea-level by 2115 and decline in rainfall by 30% to 2100. The model provides a basis for future model development which could take account of local variations in hydrogeology and transmissivity.

7. CONCLUSIONS

The present Western Australian Planning Guideline (SPP 2.6) 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.

At the same time as sea levels are rising, the rainfall in Perth (based on the median scenario) is predicted to decline from the 1961-1990 annual average of 780 mm to 545 mm by 2100, a decrease of 30% (DoW, 2015).

The decrease in rainfall will result in a corresponding decrease in recharge to groundwater, and hence groundwater throughflow. This results in falling groundwater levels throughout the system, with the greatest impact at the top of the groundwater mound. This change is estimated to be more significant than the change from sea level rise, except near the coast.

The combined effect of sea level rise and declining rainfall will result in increases in groundwater levels near the coast (within 1 km), while inland groundwater levels fall.

Declining groundwater levels will require reduction in groundwater usage to maintain groundwater dependent systems. DoW has flagged that modelling of groundwater and surface water will be required for allocation planning, integrated water and land use planning, and for water supply planning.

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

A 0.9 m sea-level rise may also cause landward encroachment by the ocean (i.e. inundation), by up to 100 m, 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.

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