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# Geographic Information System Planning for Future Sea-Level Rise Using Evidence and Response Mechanisms from the Past: A Case Study from the Lower Hunter Valley, New South Wales

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## ABSTRACT

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One of the greatest challenges of coastal land-use policy is predicting future rates of sea-level rise from different proposed climate change scenarios. This study uses evidence from past higher Holocene and Pleistocene shorelines in southern Australia to develop possible response functions for future sea level modelling. A rule-of-thumb is determined by comparing rising sea levels of the past from relic intertidal biological markers with Antarctic temperature fluctuations during the mid-Holocene. The result is that for every 1°C increase in Southern Hemisphere relative temperatures, there would be, on average, a 0.9-m positive response in mean relative sea levels. Spectral analysis, comparing mean sea-level records from Sydney, Australia; the Southern Hemisphere temperature anomaly data (1850 to 2011); and Antarctic temperature fluctuations from the last 7000 years suggest that there are significantly longer (~20 y and ~50 y) periodicities that must be accounted for in any accurate determination of projections for 2100. For southern Australia, past sea-level rise appears to be in phase with Antarctic temperature changes and possible meltwater surges, suggesting that the use of linear sea-level rates *per* year, whilst convenient for planning, may be physically misleading. The policy response from the past should be a precautionary principle, based on centennial envelopes, capturing possible intermittent rapid surges that can be punctuated by decadinal stillstands. Three past–present–future (PPF) sea-level scenarios are applied to a case study of an area surrounding the Hexham Swamp, Newcastle, Australia. An impact infrastructure audit is undertaken, using a light detection and ranging geographic information system relative to multiple PPF centennial sea-level rise envelopes, to plan in this context for future sea-level rise.

**ADDITIONAL INDEX WORDS:** *Coastal planning, decelerating sea-level rise, climate change, geographic information systems, past marine environments, future modelling.*

## INTRODUCTION

'Warming of the climate system is unequivocal, which is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising average global sea level' (Intergovernmental Panel on Climate Change [IPCC], 2007, p. 2). As observed by the IPCC, climate may be changing, and it is expected to result in many changes to the Earth's system. Of particular importance is sea-level rise, where one of the greatest challenges lies in predicting the rate of global-averaged and regional sea-level rise (Antarctic Climate and Ecosystems Cooperative Research Centre [ACE CRC], 2008, p. 9). Planning for sea-level rise is therefore an important issue for coastal communities, which need to ensure that they are adequately prepared for future changes (Walsh *et al.,* 2004, p. 586).

The aim of this paper is to use evidence of past possible sea level behaviour during the Holocene (10,000 y to present) and Pleistocene (10,000 y to 2.6 million y) to construct potential inundation scenarios relative to projected sea-level rise from anthropogenic global warming. These higher shorelines of the past could be related to episodes of warming accompanying previous retreats of glaciers and ice sheet melting in Greenland and Antarctica. This hypothesis is controversial; in any likelihood analysis, such possibilities are a relevant consideration, since there are possible correlations to be made between past sea-level heights and ice sheet temperatures. This is much more difficult for the Holocene than the Pleistocene warming periods, since over the past 10,000 years the centennial warming events on both ice sheets have not been synchronous (Fig. 1). This approach using past observed evidence, however, is an alternative to the current IPCC modelling position using computer simulations based on the last century of fluctuating records. The height projections from past shorelines are applied to topographical modelling of the Lower Hunter Valley

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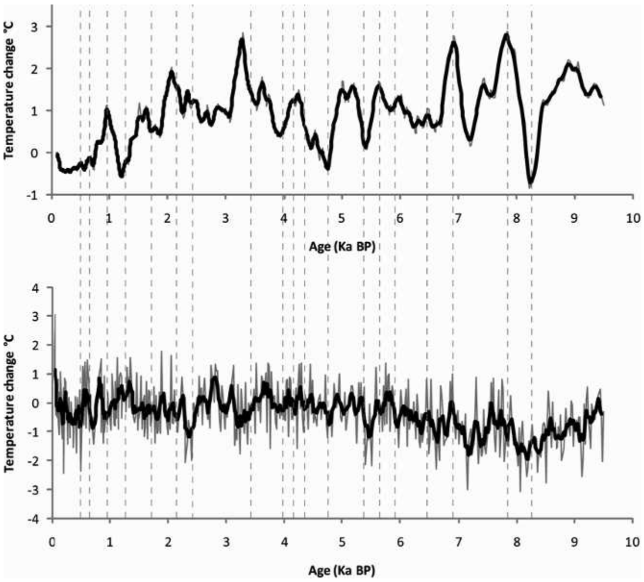

Figure 1. (top) The temperature anomaly for the past 7000 y from present for the GISP2 ice core, Greenland. (bottom) The temperature anomaly for the past 7000 y from present for the EPICA C ice core, Antarctica. This was a period when some evidence suggests that sea levels rose during the Holocene and glaciers retreated to higher than present. Notice that the most sustained period of warmer temperatures in Antarctica around 2700 cal YBP are not matched in the Greenland record (between dashed lines), suggesting significant hemispheric differences to warming responses between the poles.

(Hexham Swamp), and potential infrastructure and land-use impacts, identified for any strategic planning, are presented as an example of the developing methodology.

## SEA-LEVEL RISE AND COASTAL SYSTEMS

Sea-level rise is caused by the thermal expansion of the oceans and the melting of glaciers, ice caps, and polar ice sheets in response to global warming (IPCC, 2007; Pittock, 2009). Changes to surface and groundwater storage levels also contribute to sea-level rise (Walsh *et al.,* 2004). The global average sea-level rise since 1961 has been estimated at 1.8 (1.3 to 2.3) mm/y, and since 1993, it has been estimated at 3.1 (2.4 to 3.8) mm/y (ACE CRC, 2009). Variations in sea-level rise may occur, in the short term, at different locations globally because of regional variations in atmospheric patterns, because of lag effects within oceanographic circulation patterns (DECCW, 2009b), and because of local responses to geophysical adjustments from the preceding glaciations (Clark and Huybers, 2009). However, if there is a causal connection between global warming, glacial and ice sheet retreat, and sea-level rise in the present IPCC scenarios, observed past fluctuations should provide an alternate scientific basis to estimate future temperature/ocean level responses. One goal should be to understand why there were variations in past climates (such as shown in Fig. 1), since any anthropogenic change that may occur in the future will overlay and interact with any natural climate variability (Bradley, 2000, 2008). This has resulted in considerable debate about what future sea levels may be, with predictions for sea levels in 2100 ranging from 0.18 m to 5 m above present. The absence and uncertainty of scientific data on sea-level rise at a regional or local scale further increases the difficulty of predicting future sea levels and developing adequate coastal management plans (Walsh *et al.,* 2004).

## THE EVIDENCE OF PAST SEA LEVELS

The understanding of how sea levels have responded to higher temperatures in the past will assist in predicting how sea levels will respond to potential future temperature increases (Kennedy, 2008). Palaeo-data (evidence of past sea levels) can be used in a number of ways to predict future rates of sea-level rise. It can be used to test the validity of models that predict the response of tide-dominated estuaries to changes in sea levels (Bouma *et al.,* 1996). The effects of past episodes of sea-level rise on other coastal landforms can also be used to predict possible future impacts (Bouma *et al.,* 1996). The palaeo-record also illustrates how the climate system has responded to changes in greenhouse gases in the past and can be used to test the validity of climate models for the future (Bradley, 2000; Pittock, 2009). Climate variations of the Holocene are viewed as being useful in assessing the validity of models predicting future changes, since insolation forcing then was similar to modern values (Paleo Sea Level Working Group [PALSEA], 2010).

However, noticeably absent from many models predicting future rates of sea-level rise is the recognition of past episodes of sea-level rise, which could then be used as a proxy for determining how sea levels will respond to any future changes in climate. As outlined by Nunn (1998, p. 23), ‘only by successfully linking the distant to the recent past can we properly hope to understand how sea levels might change in the future’. The nature of previous sea-level rise can therefore provide a proxy for predicting the response of coastal areas to future climate change (Kennedy, 2008). The absence of changes of this magnitude in sea level in the recent past makes it necessary to use the geological record to accurately predict future sea levels (Kopp *et al.,* 2009). Past episodes of global warming in the Holocene and Pleistocene could be used to allow us to better comprehend how sea levels respond to climate changes (Bradley, 2000, 2008).

Australian sea levels of the past 6000 years have been subject to much debate. There are three main views in Australia. The first is that sea levels have been relatively stable over the past 6000 years and not higher than present, subject to a small zone of uncertainty of ±1 m (Belperio, 1979; Thom and Roy, 1985). The second view is that during the mid-Holocene sea levels were not much higher than 1 m above present (Chappell, 1987). This view has evolved from the first, but has taken into account hydro-isostasy (that is, the weight of glacial meltwater on the continental shoreline elevating or depressing shorelines) to explain the presence of subfossil coral microatolls in North Queensland that are 1 m above present levels (Chappell, 1983).

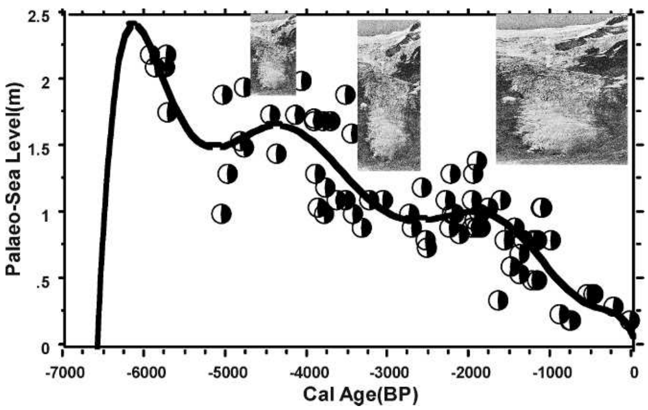

Figure 2. The nonlinear line of best fit for time-elevation samples ($N = 66$) of the tightly constrained intertidal tubeworm *Galeolaria caespitosa* showing oscillations of sea levels of up to 2 m over the past 6000 y. The troughs of these oscillations, when sea levels fell, correspond to a period of global glacial advances from 5000 to 4200, 3500 to 2800, and after 1500 cal YBP into the Little Ice Age (pictured). There is also a period from 4200 to 3700 YBP when sea levels rose on average from 1.0 m to 1.8 m above present. This was coincident with the evidence of invasion southward of some subtropical species along the NSW coastline. This evidence is used to calculate a Holocene response function.

The final view is that sea levels in Australia reached a highstand of 1.7 m at 6000 years before present (YBP) and that there have been up to at least two $\sim$1-m oscillations before reaching the present level (Baker and Haworth, 2000; Baker, Haworth, and Flood, 2001; Lewis *et al.,* 2008; Fig. 2).

There is growing evidence that at least one peak (3600 to 4200 calibrated [cal] YBP) was associated with warmer sea surface temperatures of at least 1°C along the New South Wales (NSW) coast (Baker, Haworth, and Flood, 2001; Vale, 2004). This warmer period between 3600 cal YBP and 4200 cal YBP was also a time of greater solar insolation than present (Steinhilber, Beer, and Fröhlich, 2009). There was a rapid fall of $\sim$0.7 m after 3600 cal YBP and a substantial decrease in sea surface temperatures and disruption to coral reefs after 3600 cal YBP (Baker, Haworth, and Flood, 2001; Donders, Wagner-Cremer, and Visscher, 2008; Lybolt *et al.,* 2010). This rapid fall in sea level preceded widespread glacial advances in New Zealand from 3200 to 3650 cal YBP (Gellatly, Chinn, and Röthlisberger, 1988; Schaefer *et al.,* 2009); Mount Kenya, 3300 to 3500 cal YBP (Karlén *et al.,* 1999); and in Tibet, 1400 to 3500 cal YBP (Yi *et al.,* 2008). This is what should be expected from the postulated relationship of global temperatures, the cryosphere, and sea levels.

There has been much less debate concerning Pleistocene sea levels. However, relative sea-level heights are much more uncertain from the exposure of the evidence to 100,000 years of weathering. It is generally agreed that sea levels in Australia during the Last Interglacial were recorded between 4 and 6 m above present (IPCC, 2007; Murray-Wallace and Belperio, 1991; Thom, Bowman, and Roy, 1981).

## ESTIMATING SEA-LEVEL RESPONSES FROM PAST ATMOSPHERIC TEMPERATURE INCREASES

### Introduction

Calculating the exchange mechanism between atmospheric temperatures and sea-level responses in a complex climate system is difficult. The results could simply be dependent on what ice core is used and from which hemisphere the core is taken. For example, Antarctic data from the Vostok ice core suggests that temperatures reached a maximum of 3.23°C above present 128,357 years ago (Petit *et al.,* 2001), whilst the European Project for Ice Coring in Antarctica (EPICA) C core shows a maximum temperature of +5.46°C four hundred years later (Jouzel *et al.,* 2007). Second, the temperature correspondence between Greenland (such as the Greenland Ice Sheet Project 2 [GISP2] core) and Antarctica (such as EPICA C) can also show opposite trends of warming and cooling within their histories (Fig. 1). This 'seesaw' means that there are millennial and centennial lags that should be directly relevant to current sea-level modelling (Blunier *et al.,* 1998). Greenland warms rapidly, contrasting with a gradual warming from Antarctica, and the latter appears to lag behind the former in an antiphase relationship by 400–800 years (Steig and Alley, 2002). This makes accurate response estimations even more difficult in an already complex system.

### A Pleistocene Response Function

Nevertheless, with these provisos, if there is an exchange mechanism based on global and hemispheric averages, then some scientific basis can be established between estimated rates of sea-level rise in the past compared with recent increases over the past 50 years. Within the EPICA C ice core, for the 1000-year period surrounding the temperature maximum of +5.46°C at 128,600 cal YBP, the mean temperature was 3.92°C with a standard deviation of 0.72°C. Therefore, if mean temperature plus one positive standard (4.64°C) is assumed to be the aggregate temperature envelope for centennial sea-level response, then the exchange rate for the lower 4-m Pleistocene level is 1°C = 0.86-m rise in sea level, whereas for the upper boundary, it is 1°C = 1.29 m. Between 1961 and 2011, the average rise in the temperature anomaly for the Northern Hemisphere was 0.164°C, whilst for the Southern Hemisphere, it was approximately half at 0.078°C (see Climatic Research Unit, University of East Anglia [CRU-UEA], 2012). So if we assume that the relative average global warming for this period is 0.12°C for an equal weighting between Antarctica and Greenland, then the predicted rise in sea level using this crude Pleistocene response function would be between 2.0 mm/y and 3.0 mm/y (for example, 0.86 multiplied by 0.11 divided by the 50-year period between 1962 and 2011 = 2.02 mm/y), which is within the IPCC rate range (1.8 to 3.1 mm/y).

### A Holocene Response Function

The Holocene sea-level curve from the relic intertidal *Galeolaria* tubeworm found in southern Australia (Fig. 1) can give an accurate response measurement for periods of rising sea levels in the past. The tightly constrained present *Galeolaria* zone has been used to measure recent relative sea-

Table 1. *The average relative centennial sea-level rise from 5100 to 5001 cal YBP to 3800 to 3701 cal YBP from the* Galeolaria *curve (Fig. 2) compared with same period temperature fluctuations from the EPICA C Antarctic and GISP2 Greenland temperature anomaly. The standardised Antarctic temperature from 3700 to 5100 cal YBP in column 5 allows for a comparison to the relative sea level averages in column 2.*

| Time Period (YBP) [1] | Palaeo Sea Level Change (m/100 y) [2] | Average Antarctic Temperature Anomaly (EPICA C) (°C/100 yr) [3] | Average Greenland Temperature Anomaly (GISP2) (°C/100 yr) [4] | Antarctic Temperature Anomaly Standard (°C/100 y) [5] |
|---|---|---|---|---|
| 3701–3800 | 0.700 | 0.370 | 1.240 | 0.660 |
| 3801–3900 | 0.450 | −0.110 | 0.580 | 0.180 |
| 3901–4000 | 0.570 | −0.230 | 0.450 | 0.060 |
| 4101–4200 | 0.750 | 0.070 | 1.210 | 0.360 |
| 4201–4300 | 0.550 | 0.310 | 1.320 | 0.600 |
| 4301–4400 | 0.450 | −0.240 | 0.680 | 0.050 |
| 4401–4500 | 0.600 | 0.010 | 0.210 | 0.300 |
| 4801–4900 | 0.500 | −0.190 | 0.400 | 0.100 |
| 4901–5000 | 0.300 | 0.000 | 1.160 | 0.290 |
| 5001–5100 | 0.000 | −0.290 | 1.420 | 0.000 |

level rise in Victoria, Australia, since 1988 (Bird, 2008). In the relic *Galeolaria* curve from the mid-Holocene, there was a period between 3700 and 5100 cal YBP when sea levels rose by approximately 0.8 m and a warming occurred in sea surface temperatures of at least 1°C (Fig. 1). This previous response to hemispheric warming in southern Australia could provide a benchmark to determine a possible response function between atmospheric temperature, the cryosphere, and sea-level change that could be relevant to future sea-level modelling.

The time-elevation estimates of *Galeolaria* boundaries for the selected range (3700 to 5100 cal YBP; Fig. 1) are partitioned and averaged for centennial periods with the corresponding mean temperature anomalies determined for ice cores EPICA C in Antarctica and GISP2 in Greenland (Table 1). The GISP2 temperature anomaly was positive and averaged 0.9°C warmer than present for the 1400-year period, whereas Antarctic temperatures fluctuated between –0.29°C and 0.37°C. Regression analysis, using both a linear and a nonlinear (fifth-order polynomial) plot, were undertaken for relative temperature and sea-level response variables (Fig. 2). The fifth-order polynomial (rather than lower orders) was employed because it was better at capturing any oscillations in the data. Both models were relevant to the understanding of the nature of sea-level rise, since the linear model assumes a constant rate of increase in sea level, whereas the nonlinear model assumes that rates can accelerate or decelerate (see Baart, van Koningsveld, and Stive, 2012).

There was a positive correlation with an $r^2$ value of 0.322 for the linear plot of the EPICA C data (Fig. 2), but there was little association with Greenland, which was out of phase (Table 1). The linear plot, however, had autocorrelation problems in the residuals with a Durban-Watson (DW) statistic of 1.037. Statistically, the fifth-order polynomial plot was more robust, with an $r^2$ value of 0.877 and a DW statistic of 1.909, meaning there was no autocorrelation in the residuals. The nonlinear model suggested that rather than creeping rises, Antarctica, over the 3700 to 5100 period, responded with rising temperatures in two pulses of $\sim$100-year and $\sim$500-year duration in meltwater. The model had periods of acceleration and deceleration in sea-level rise with intervening stillstands. The relevance to the recent debate of decelerating sea levels in Australia is obvious (Baart, van Koningsveld, and Stive, 2012; Church and White, 2006; Watson, 2011). This model suggests that the period of sea-level deceleration at the end of the 20th century is not unusual when compared with 3700–5100 cal YBP warming, despite increasing Southern Hemispheric temperatures (0.2386°C since 1991; see CRU-UEA, 2012).

The model has been standardised to zero, and change is measured *per* 100 years. The Greenland component is assumed constant at 1.0 m above present in the standardisation, and this is equivalent to the average 0.9°C warming for the period (that is, $1°C = 1.1$ m). The linear regression model for southern Australia for an Antarctic response to rising atmospheric temperatures is then

$$SL = 0.349 + 0.531T \tag{1}$$

For a 1.0°C *per* 100-year rise in temperature, there will be on average a 0.88 m *per* 100-year rise in sea level according to the model, which is similar to the lower boundary response rate for the Pleistocene. The average with variance correction in the Southern Hemisphere temperature anomaly from 1961 to 1990 from the Hadley Centre, UK (CRU-UEA, 2012), was –0.0422°C, but from 1991 to 2011 the average increased to 0.251°C. The reference point for the current temperature anomaly for the whole global record (1850–2011) is the 1960–1991 average. If previous sea-level rise (including the 1961–1990 period) is assumed from the model to be 0.327 m (by substituting an average temperature anomaly –0.0422°C in Eq. [1]), then, since 1991, the model predicts a rise of 0.155 m/100 year or a rate of 1.55 mm/y ($[0.349 + 0.251 \times 0.531] - [0.349 - 0.0422 \times 0.531]$) for southern Australia. This is close to the Church and White (2006) conclusion that mean sea-level rise around the Australian coastline between 1920 and 2000 was $\sim$1.2 mm/y. The difference between 1.55 mm/y and 1.2 mm/y may represent the average hydro-isostatic rebound of the southern Australian shoreline during the Holocene ($\sim$0.35 mm/y or 0.35 m/1000 y), and this may be a palaeo-correction to the initial response function.

The nonlinear model is a better statistical fit of the data and gives points of inflexion between two major pulses of meltwater for the period. This rate of change for the fifth-order polynomial (quintic) response models can be defined by calculus as

$$\frac{\partial SL}{\partial T} = 17.394 - 359.278T + 2168.673T^2 - 4817.336T^3 + 3521.285T^4 \quad (2)$$

For the 1961–2011 average of 0.078°C for the Southern Hemisphere, the rate of sea-level rise for the fifth-order model is computed as 3.63 mm/y (or 3.28 mm/y from the hydrostatic correction). This is within the upper limits of global IPCC projections but not for the Australian coastline for the 20th century (Church and White, 2006). The acceleration/deceleration rate is then

$$\frac{\partial^2 SL}{\partial T^2} = -359.28 + 4337.35T - 14452.0T^2 + 14085.1T^3 \quad (3)$$

For 0.078°C (1961–1991), the rate is decelerating ($\partial^2 SL/\partial T^2$ is negative), which is a similar conclusion of Watson (2011) using 20th century data. The argument would be that we have passed the first peak of the model at the end of the 20th century (Fig. 2), and therefore this deceleration could be part of a longer term natural cycle of sea levels. However, by just looking at the period 1991–2011 of 0.251°C of relative warming, the average predicted rate of rising sea level from Eq. 2 is 16.1 mm/y (or 12.6 mm/y with a hydro-isostatic correction) and accelerating with $\partial^2 SL/\partial T^2$ positive. By 2091, the equivalent of 1.19°C warming will yield a relative sea-level rise of 1.10 m. As in the case of the linear model, a 1°C nonlinear rise in relative Antarctic warming yields a ~0.9 m in sea-level rise for southern Australia (the IPCC estimate for 2100), but the polynomial suggests there are a number of variables, not just one variable, that are contributing to the increase.

Why are we not observing such rates at present? Are there decadinal and centennial periodicities that are implied statistically from the fifth-order model, discernible from the mean sea level (MSL), temperature, and Antarctic data, and if so, are we currently trending toward a centennial 'stillstand' despite the warming? The answers to these questions are very important to sea-level management and what underpins a 'precautionary principle'. Implicit in a linear model is the idea of 'creeping centennial inundations', where policy action can be deferred from short-term management priorities, whereas the nonlinear model suggests a 'decadinal surge' of meltwater after a stillstand is likely, which would warrant more immediate action. What is also relevant is that the greatest average centennial response in the relic *Galeolaria* record for the above period (Table 1) was a ~30-cm rise from ~0.4°C of atmospheric warming over the Antarctic Ice Sheet. The assumption still remains that an anthropogenic affect is accelerating this centennial change nearly three times the previous average natural response from Antarctica. There is still, however, evidence of extreme ~50-year warm periods in the Antarctic temperatures concurrent with anomalous heights in the *Galeolaria* record.

For the EPICA C ice core record, the greatest prolonged period of Antarctic warming was between 2817 and 2851 cal YBP (Fig. 1), a 50-year period when the temperature anomaly was 1.19°C warmer than present. This was also a period when there was a millennial peak in the rate of increase in solar irradiance (averaging 0.424 watts/m$^2$ more than present; Steinhiber *et al.,* 2009). There was a further ~50-year period of abnormal warmer temperatures (+0.975°C) between 2732 and 2784 cal YBP. This period was in antiphase with Greenland (Fig. 1). Likewise, in the next millennium, there was a period between 1889 and 1922 cal YBP where average temperatures were 0.9°C warmer than present (including a spike of 1.79°C). This also coincided with the rate of increase in solar irradiance, averaging 0.32 watts/m$^2$ more than present (1922 to 1967 cal YBP). These warmer episodes stated above correspond to previously reported anomalously higher sites in the southern Australian *Galeolaria* record (Baker, Haworth, and Flood, 2001), which now suggest meltwater surges and retreats within a 100-year period.

These sites, on the southern coast of NSW, were remeasured and corrected for exposure (~0.72 m) as 2.28 m and 1.98 m above present (G. Smedley pers. comm. 2010). The 2.28-m site at the Wasp Head formation had a $\partial^{18}$O indicating warmer sea surface temperatures (–0.3) than present and dated between 2795 and 3255 cal YBP. Within the same locality, Young *et al.* (1993) found remains of the coral *Goniopora lobata* in beach deposits with U/Th ages of 2930 ± 190 years and 2760 ± 125 years, also indicative of a warmer than present phase. This abnormally high *Galeolaria* formation at Wasp Head represents a relative increase in sea level of 1.28 m from the 3000-year height of ~1.0 m above present (Fig. 2). The equivalent Antarctic response to sea levels for southern Australia from the rule-of-thumb (1°C = 0.88-m rise) for this ~50-year temperature increase of 1.19°C should have been a relative response increase of 1.05 m, leading to an estimated 2.15-m height above present. Likewise, the second site in a sea cave at Clear Point had relic *Galeolaria* 1.98 m above present, dated between 1539 and 1983 cal YBP, and had a $\partial^{18}$O indicating warmer sea surface temperatures (–1.3) than present. The relative sea-level rise of 0.98 m can be compared with the response function prediction of 0.79 m for 0.9°C relative warming, so the results are encouraging for the reliability of the response function. This could be a causal explanation to previously published anomalous time-elevation *Galeolaria* sites in southern Australia.

This idea of periodicity in the polynomial model can be further tested by looking at relevant data sets of mean sea levels for Fort Denison, Sydney (Watson, 2011); the Hadley Centre temperature anomaly data set for the Southern Hemisphere (1850 to 2011); and the EPICA C $\partial^{18}$O ice core data set for the last 7000 cal YBP. Any significant periodicity within the data can be ascertained by sophisticated spectral analysis. Two methods of analysis will be used: first, a single taper Blackman (Harris, 1978) spectral analysis to discern longer cycles in the record, and second, multitaper spectral analysis (Thomson 1982) using initially five tapers ($K = 5$) and a bandwidth ($BW = 4$) to deconstruct any shorter cycles within the data sets. The periodicity can be further checked by using additional tapers ($BW = 5, K = 8$), and this was also undertaken in the analysis. Spectral methods, such as the Lomb-Scargle algorithms, overemphasize data points at the centre and weakly weights extreme values. The Blackman tapers can apply 20% cosine weightings (or tapers) to address this problem and discards only 12.5% of available data variable constraints. This taper may be adequate in many cases but would not be appropriate for dispersive or unusually band-limited signals (Park, Lindberg, and Vernon, 1987). The multitaper spectral

Table 2. *The results from the Blackman (Harris) 4 and Multitaper (*BW = 4 *and* K = 5*) spectral analysis using AutoSignal of Fort Denison, Sydney, Australia, mean sea-level data, 1886–1993 (PSMSL, 2012); Southern Hemisphere variance adjusted temperature anomaly, 1850–2011 (CRU-UEA, 2012; Wood for Trees, 2012); EPICA C ice core temperature anomaly (Jouzel* et al.*, 2007) from 7000 cal YBP to present; and Dome Fiji ice core* $^{10}$Be *record, 700 CE to 1900 (Horiuchi* et al.*, 2008). Higher taper analysis (*BW = 5 *and* K = 8*) shown by (*$^{+}$*) and significant periodicities indicated for 90% and over (* 95%, ** 99%).*

| | Blackman (Harris) 4 | | | Multitaper $BW = 4$, $K = 5$ ($^{+}BW = 5$, $K = 8$) | | | |
|---|---|---|---|---|---|---|---|
| | Frequency | Power | Period (y) | Frequency | Spectral Density (dB) | $F$ | Period (y) |
| Mean sea level (Southern Hemisphere) | | | | | | | |
| Fort Denison | 0.049072 | 13.25 | 20.38* | 0.046296239 | 75.8288 | 3.88 | 21.60 |
| (Australia) | 0.015381 | 45.401 | 65.02* | 0.018518496 | 77.4731 | 3.78 | 54.00 |
| Temperature anomaly (Southern Hemisphere) | | | | | | | |
| Southern H. temperature anomaly (1850–2011) | 0.046874 | 58.6057 | 21.33** | 0.049382 | 28.84077 | 6.67**$^{+}$ | 20.25 |
| (variance adjusted) | 0.017578 | 86.7403 | 56.89** | 0.018518 | 35.96541 | 3.62$^{+}$ | 54.00 |
| Antarctica proxies | | | | | | | |
| EPICA C ice core ($^{18}$O) (0–7000 YBP) | | | | 0.019648 | 21.74644 | 6.52* | 50.90 |
| Fiji dome ($^{10}$Be) (1900–700 CE) | | | | 0.046343 | 7.083 | 3.83* | 21.58 |
| | | | | 0.020222 | 11.924 | 4.81*$^{+}$ | 49.45 |

analysis (MTSA) was developed by Thomson (1982) to overcome the trade-off between the resistance to spectral leakage and the variance of the spectral estimates from single taper algorithms. It discards very little data and weights the data relatively evenly with significance determined by an $F$ ratio and therefore is quite sophisticated (Park, Lindberg, and Vernon, 1987). The data were analysed for both algorithms (Blackman Harris 4 [BH4] and Multi Taper Spectral Analysis [MTSA]) using Autosignal.

The results for the Fort Dension MSL record show that there are significant periodicities using BH4 at 95% of 20.38 years and 65.02 years, and for multitapers (MTSA4/5 or $BW = 4$ and $K = 5$) there were 90% significant periodicities at 21.6 years and 54.0 years (Table 2). These significant harmonics were repeated in the Hadley temperature anomaly data (BH4, 21.33 y and 56.89 y at 99% and MTSA5/8, 20.25 y at 99% and 54.0 y at 95%) and the EPICA C $\partial^{18}$O ice core fluctuations for the last 7000 years (MTSA4/5, 50.9 y at 95%). The fifth-order polynomial model is therefore not solely a statistical artefact; rather there are common significant $\sim$50-year periodicities across the three data sets. Whilst this might be a coincidence, it is possible that sea levels have been accelerating and decelerating as part of these centennial natural cycles not only in the 20th century (Watson, 2011), but since the mid-Holocene. What is striking, on further investigation of Antarctic isotopes, is that a dominant periodicity of the $^{10}$Be production rate is also 21.58 years and 49.45 years at 95% (Table 2). The $^{10}$Be production rate is a function of the relationship between the intensity of high energy galactic cosmic rays and the solar wind, and therefore, one of the independent variables underpinning the polynomial model could be from a solar periodicity and its affect on atmospheric ionisation and cloud cover (see Baker, 2008). With a high likelihood that the next decade will be a centennial minimum in solar activity, it should not be surprising that the sea-level rise is at least decelerating. The relevance to public policy is that whilst the two-variable linear model is attractive and easy for modelling and computer simulation, the natural response mechanism of sea levels in the past with increasing temperatures for Antarctica appears, at least from the *Galeolaria* proxy curve and sophisticated spectral analysis, to occur within a number of longer period harmonics. The resulting centennial increases of the past occur from rapid rises punctuated by stillstands, rather than creeping linear inundations, which is currently inferred by the use of yearly rates.

## SEA-LEVEL RISE AND COASTAL PLANNING

Sea-level rise therefore poses many challenges for the strategic planning and management of the coastal zone and, as a result, is a critical issue for planners and coastal researchers (Kennedy, 2008). Current coastal development has occurred without consideration of changes in the natural system (Rigby, 2005). The uncertainty of the effects of climate change (Hebert and Taplin, 2006) and insufficient information on existing conditions have many policy makers becoming overwhelmed by the complexity of the issues involved and the magnitude of the problem (Rigby, 2005). In particular, the rate of future sea-level rise is problematic for planners (Rigby, 2005; Walsh *et al.,* 2004). Recent research supports the adoption of higher sea-level rise projections when undertaking risk assessments (Department of Climate Change, 2009). The development of policies is also hindered by the large number of stakeholders, conflicting interests, and the multiple levels of government involved.

Until recently, coastal planning for sea-level rise had received little attention, with few studies having been undertaken in Australia or internationally. The primary concern for governments had been the mitigation of climate change, not adaptation to any future sea-level rise. It is therefore essential that adequate planning for sea-level rise is undertaken now while decisions are being made regarding the development of public and private land and infrastructure. The infrastructure put into place in the near future will, if properly constructed, still be in place after sea levels rise (Deyle, Bailey, and Matheny, 2007). It has been estimated that if an improved building code, reflecting future changes in sea levels, is implemented in Australia by 2015, then around 20% of buildings would be in compliance by 2030 (Department of Climate Change, 2009). A major barrier to adaptation is that it is generally perceived that when properties are threatened or damaged, the insurance industry or government will bail out property owners, and as a result people are often ill prepared for long-term consequences (Department of Climate Change, 2009).

The precautionary approach should be taken when developing sea-level rise policy, and uncertainty should not be used as an excuse for delaying policy developments. Although it is necessary for guidance to be received from the commonwealth and state governments, planning strategies need to be developed at a local scale because of the varying nature of the coastline and varying regional and local effects (Walsh *et al.,* 2004). Uncoordinated approaches to policy development between governments can also create a barrier to decision making (Department of Climate Change, 2009). Rates of sea-level rise should also be monitored, and policies should be regularly reassessed in light of new scientific evidence (Walsh *et al.,* 2004).

## EXISTING COASTAL POLICIES AND SEA-LEVEL RISE

Much of the existing coastal policy is based on historical climate and assumes that sea levels have remained static (Department of Climate Change, 2009). As outlined in the Australian Constitution, land-use planning and coastal management are generally the responsibility of the states. The states are then responsible for the development of land-use planning frameworks and benchmarks. The day-to-day administration of these frameworks and benchmarks are then the responsibility of local government. This has resulted in the absence of a coordinated national approach to coastal planning, with policy becoming increasingly fragmented with each successive level of government. For effective adaptation to take place, it is necessary that all levels of government collaborate to ensure a consistent approach to policy development and to reduce the duplication of activities.

The Department of Climate Change in 2009 undertook a first pass national assessment of climate change risks to Australia's coast. It identified that sea-level rise greater than the global average is expected in SE Australia. A sea-level rise of 1.1 m above 1990 levels was adopted for the above report and based on recent scientific findings. From the above calculations, this equates for southern Australia to a relative change in temperature of 1.25°C.

There are a number of pieces of legislation and policies in NSW addressing sea-level rise. These include the NSW Coastline Management Manual, the 1997 Coastal Policy, State Environmental Planning Policy (SEPP) 71, Clause 5.5 of the Standard Instrument–Principal Local Environment Plan, the NSW Sea-Level Rise Policy Statement, the Draft Coastal Risk Management Guide, and the Draft NSW Coastal Planning Guideline: Adapting to Sea-Level Rise. In 1990, the New South Wales Government released the 'NSW Coastline Management Manual', which incorporates the Coastline Hazard Policy. Together they seek to provide guidance for local government decision making in regard to coastline hazards (NSW Government, 1990). They aim to assist users and occupiers of the coastal zone to understand the nature of coastal hazards and possible management strategies (NSW Government, 1990). Climate change and associated sea-level rise are identified as coastal hazards, but the manual provides little guidance on how to address climate change when undertaking coastal management. Suggestions are made in regard to possible adaptation responses to sea-level rise, but these are generally vague and lack sufficient detail.

The 1997 Coastal Policy was developed to build on the 1990 Coastal Policy and provide a new direction for the planning and management of the NSW coastline. With the introduction of the new policy, the coastal zone was extended to include a distance of 1 km around all bays, estuaries, coastal lakes, lagoons, and islands (NSW Government, 1997). It was given statutory effect through SEPP 71 and through a Ministerial Direction to local councils under Section 117 of the Environmental Planning and Assessment Act 1979 (DECCW, 2009a). State Environmental Planning Policy 71 requires that land-use planning and development assessment within the NSW Coastal Zone consider the likely impacts of coastal processes and coastal hazards on developments and any likely impacts of the development on coastal processes and hazards, including sea-level rise.

The NSW Sea-Level Rise Policy Statement (DECCW, 2009a) outlines the objectives and commitments of the NSW government to sea-level rise adaptation. This statement also outlines the support that the NSW government aims to provide for coastal communities and local councils. Sea-level rise planning benchmarks of 40 cm by 2050 and 90 cm by 2100 are also provided. The supporting Technical Note (DECCW, 2009b) outlines how these benchmarks were derived, and here we have derived a similar scenario from past evidence of a 1°C increase in the Southern Hemisphere temperature anomaly equating to an 88-cm increase in relative sea levels.

## CASE STUDY: HEXHAM SWAMP, LOWER HUNTER VALLEY NSW

### Introduction

As an example of the past–present–future methodology, a case study will focus on the potential impacts of sea-level rise on urban planning in Hexham Swamp, 140 km north of Sydney and 20 km west of Newcastle. It is bounded to the NE by the Pacific Highway, to the NW by the now defunct Richmond Pellaw railway line, to the SW by the suburb of Maryland, and to the SE by the suburb of Shortland (Fig. 3). It is dominated by freshwater and estuarine swamp ecosystems, but as a result of the proximity of Hexham Swamp to Newcastle, a significant amount of infrastructure is also located within the study area. Also, historical land-use patterns of Hexham Swamp have resulted in sections of the swamp being filled to reduce the impacts of flooding. The installation of floodgates on Ironbark Creek (the main creek within the study area) in the 1970s restricted the level of tidal inundation within Hexham Swamp (WBM Oceanics Australia, 2005), altering the ecosystem composition. In December 2008, the Ironbark Creek floodgates were reopened to allow tidal flows to return to the swamp (Hunter-Central Rivers CMA, 2011).

### Methodology

As identified above, there are a number of knowledge gaps regarding planning for future sea-level rise. Increased sea levels in estuaries will result in damage of public and private assets, including private dwellings and sewage infrastructure

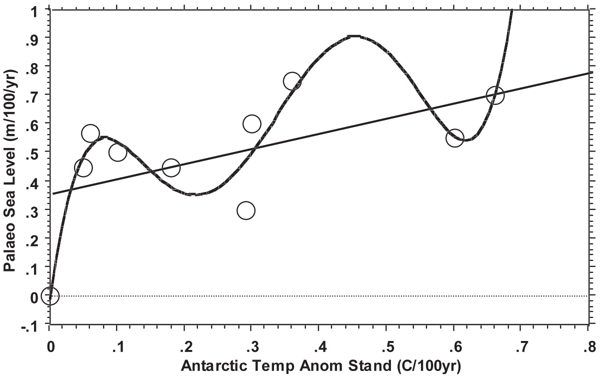

Figure 3. Linear and polynomial (fifth order) regression fit of the data in Table 1 showing a trend over the 1400-y period where in the nonlinear model there are two periods of accelerating sea levels as part of ~50–100 y and ~500–600 y pulses in meltwater from a warming Antarctica, punctuated by periods of relative stillstands. Both regression equations are shown where the fifth-order polynomial is a more robust statistical description of the data distribution.

(Harty, 2008). Of greatest concern is the uncertainty of the height of future sea levels. There is also the possibility that rather than creeping rises of sea levels in the future, there will be pulses of sea-level rise followed by periods of stillstands (see the section titled 'A Holocene Response Function'). In order to emphasise this uncertainty, a range of shoreline scenarios were developed. These represented a number of possible future sea levels that could occur based on the modelling of past sea-level change. By using a number of shoreline possibilities, the importance of planning for a worst case scenario was also emphasised.

Hexham Swamp was included within the scoping study, undertaken by the New South Wales State Government, in the Lower Hunter and Central Coast, in the use of light detection and ranging (LIDAR) technology for sea-level rise vulnerability assessments. LIDAR involved the use of airborne laser scanning technology to collect elevation data to a very high resolution (*i.e.,* 0.15 m vertical and 0.6 m horizontal) (Department of Planning, 2008). The availability of LIDAR was important, since a digital elevation model derived from LIDAR data is more accurate than one derived from photogrammetry. This study accessed this information and ensured that the mapping undertaken in the study accurately represented each of the sea-level rise scenarios.

### Shoreline 1 Scenario

The first potential future shoreline is at a height of 0.9 m above 1990 sea levels. This shoreline represents the height of sea-level rise as adopted by the NSW Department of Environment, Climate Change, and Water (DECCW) in the 'NSW Sea-Level Rise Policy Statement'. This height was used by DECCW since it is considered to be a best estimate projection of sea level for 2100 (DECCW, 2009a). It was developed using both national and international predictions of sea-level rise (DECCW, 2009a). It is also the conclusion in the section titled 'A Holocene Response Function' that a 1°C increase in Antarctic temperatures will see a 0.88-m centennial response in sea levels.

### Shoreline 2 Scenario

The second potential shoreline would represent a 2.6-m rise in sea level from 1990 levels. It could result from natural climate change and anthropogenic climate change occurring simultaneously. The height for this potential shoreline would be a combination of the warmer Holocene level (including Antarctic and Greenland contributions) 1.7 m above present, based on work by Baker, Haworth, and Flood (2001) (Fig. 2) plus the 0.9-m sea-level rise height adopted by DECCW for anthropocentric climate change. This shoreline represents an estimated 2.89°C in warming, and such a scenario is not hypothetical, since three times during the Holocene, Greenland temperatures increased rapidly up to 2.9°C warmer than present and there have been ~50-year surges of ~1.0 m after 1.1°C increases in Antarctic temperatures at ~2800 cal YBP and 1800 cal YBP (Fig. 1).

### Shoreline 3 Scenario

Hansen (2007) has suggested that sea levels may reach up to 5 m above present by 2100, based on evidence from past episodes of sea-level rise. During the last Pleistocene interglacial, sea levels were approximately 4 m to 6 m above present levels (IPCC, 2007; Murray-Wallace and Belperio, 1991; Thom, Bowman, and Roy, 1981), and temperatures were up to 5.4°C above present (Jouzel *et al.,* 2007). This 5-m level would be estimated to be associated with a 5.68°C increase in warming. This would be at the extreme in any likelihood analysis and represents sea levels at the peak of the last interglacial 128,000 years ago. This shoreline has been identified in the Lower Hunter with the Pleistocene age inference of *in situ* marine shellfish at Largs, 15 km upstream from Hexham Swamp (Murray-Wallace, Leary, and Kimber, 1996; Thom and Murray-Wallace, 1988). Based on IPCC (2007) projections for temperature by 2100, under the A1F1 scenario, there is a 4°C warmer prediction than 1980–1999 temperatures. This extreme scenario is still possible, and therefore a 5-m shoreline needs to be considered under a precautionary principle–based approach.

## RESULTS

The amount of land to be inundated significantly increased between Scenarios 1 and 2 (0.9 m and 2.6 m; Figures 5 and 6). There is only a small increase in the amount of land affected from Scenario 2 (2.6 m) to Scenario 3 (5 m) sea-level rise. The amount of infrastructure and zonings affected increased with each successive sea-level rise scenario (Table 3). This is because they incorporated the results of the lower sea-level rise scenarios.

Impacted infrastructure was generally located around the boundaries of the swamp, with roads being the most common infrastructure impacted. A significant increase in the amount of infrastructure to be inundated was experienced with each

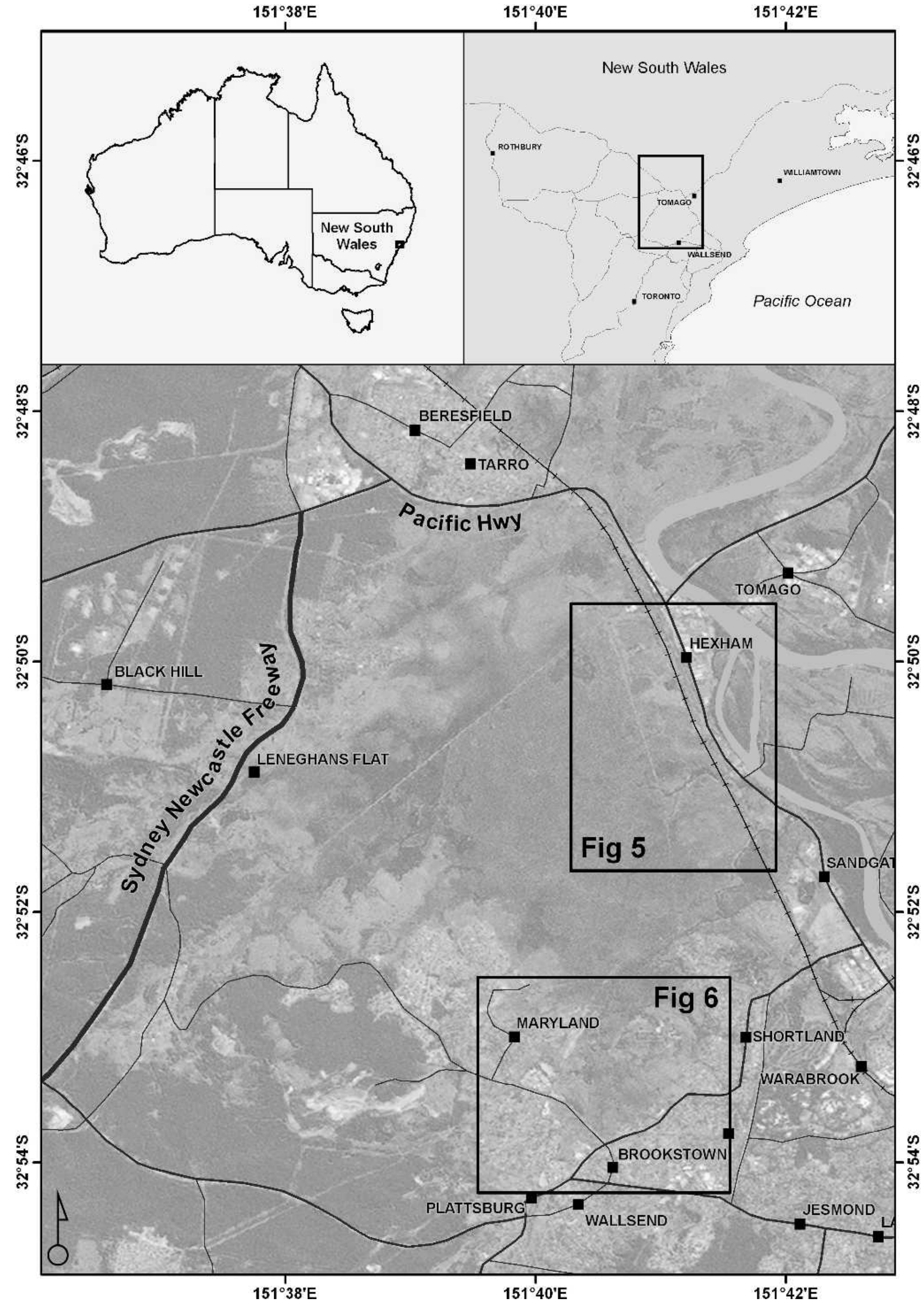

Figure 4. The location map of the study area showing the insets of Figs. 5 and 6.

sea-level rise scenario. Under a Scenario 1 (0.9 m) sea-level rise, infrastructure that would be affected included power lines, a radio tower, a landing strip, the Chichester Gravitational Trunk Main, and the railway line. Additional infrastructure affected under a Scenario 2 (2.6 m) sea-level rise include a number of local roads, the Pacific Highway, further power lines, sporting fields, a disused air field, industrial areas, the sewage treatment works, the Greyhound facility, and housing. Under a Scenario 3 (5 m) sea-level rise, additional infrastructure affected include further local roads, power lines, sporting

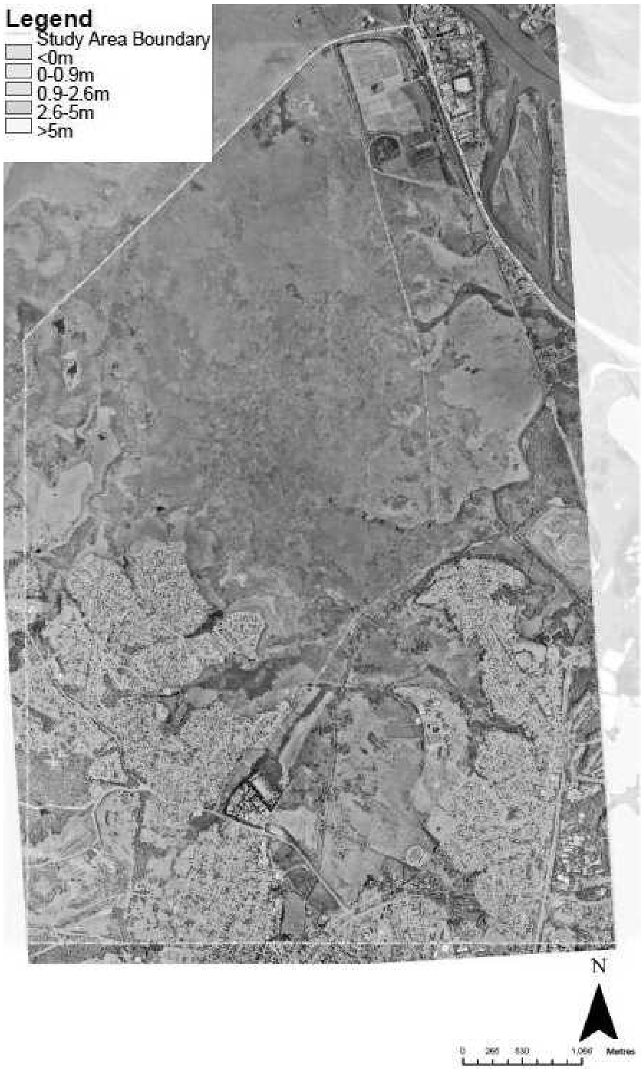

Figure 5. The LIDAR plot of three possible higher shorelines based on evidence from the past for the region surrounding the Hexham Swamp, Newcastle.

fields, industrial areas, and housing, as well as Wallsend Cemetery.

## POLICY RESPONSES TO RISING SEA LEVELS

The options available are retreat, adaptation, or protection. Retreat involves the planned abandonment of land buildings and infrastructure in areas vulnerable to sea-level rise. One strategy that could be used to implement this option is a setback zone. This prevents further development and relocates existing development within vulnerable areas seaward of the setback line (Titus, 2000). Any building constructed subsequently in the setback zone must be capable of relocation or be sacrificed at the time of inundation (Rigby, 2005). With the possibility of sudden pulses in sea-level rise occurring in the future, this policy option is necessary, since rises may occur rapidly with little warning, inundating areas in relatively short periods of time.

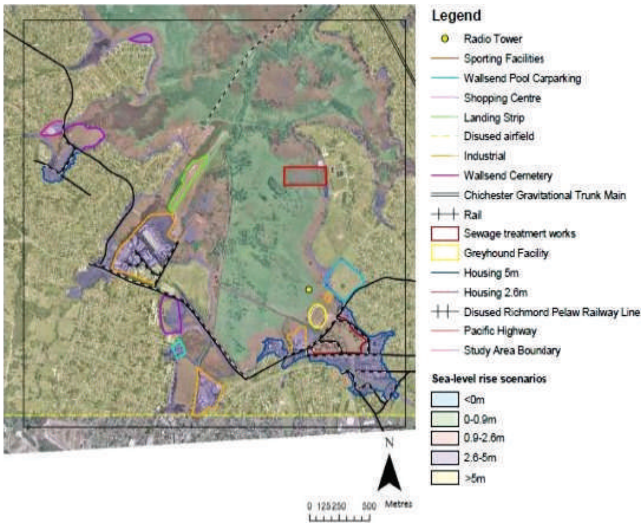

Figure 6. The LIDAR plot of three possible shorelines in the southern region of the study area. Note the potential residential areas that could be affected by a base 5-m rise in sea levels, without the impact of flood events.

Other strategies that can support retreat include the acquisition of land by public authorities or the provision of economic incentives to encourage abandonment (Bray, Hooke, and Carter, 1997). Rolling easements can also be implemented that allow for a gradual abandonment of land as it becomes affected by rising sea levels (Titus, 2000). All of these options require the development of new government policies and planning regulations (Bray, Hooke, and Carter, 1997). Retreat generally reduces risks and minimizes protection costs, but it can potentially have high financial costs if landowners are compensated for their properties (Bray, Hooke, and Carter, 1997).

Adaptation seeks to conserve ecosystems and allow them to respond naturally to climate change (Nicholls, 2003). It also allows for the continued occupancy and use of areas vulnerable to sea-level rise by humans through an adaptation of human activities within the coastal zone (Engineers Australia, 2004; Nicholls, 2003). Although adaptation is less desirable than retreat, it may be necessary in areas where retreat is not possible (McDonald, 2007). A number of methods can be used to support such a policy. Buildings may be adjusted to accommodate rising sea levels, and changes in land use may allow for the continued, but altered, use of affected lands (Bell, Hume, and Hicks, 2001; Bray, Hooke, and Carter, 1997). Infrastructure may also be raised or modified to allow on-going use (Bell, Hume, and Hicks, 2001). Underground infrastructure will generally have to be extensively modified or abandoned, since it is not possible to move it to higher ground (Deyle, Bailey, and Matheny, 2007). Rolling easements may also be implemented. These easements allow the shoreline to recede naturally in response to climate change, with human activities gradually

Table 3. *Infrastructure to be affected under each sea-level rise scenario.*

| Feature | Suburb | 0.9 m | 2. 6m | 5 m |
|---|---|---|---|---|
| Grange Avenue | Maryland | | | X |
| John T Bell Drive | Maryland | | | X |
| Maryland Drive | Maryland | | X | X |
| Rogilla Circle | Maryland | | | X |
| Carbine Circle | Maryland | | | X |
| Ironbark Creek Road | Maryland | | | X |
| Minmi Road | Wallsend | | X | X |
| Sandgate Road | Birmingham Gardens | | X | X |
| Cunningham Street | Birmingham Gardens | | X | X |
| Fraser Street | Birmingham Gardens | | | X |
| Mordue Parade | Birmingham Gardens | | | X |
| Mayo Street | Birmingham Gardens | | | X |
| Cameron Street | Birmingham Gardens | | | X |
| England Street | Birmingham Gardens | | X | X |
| Wilkinson Avenue | Birmingham Gardens | | | X |
| Sparke Street | Hexham | | X | X |
| Fenwick Street | Hexham | | X | X |
| Merchant Street | Hexham | | X | X |
| Shamrock Street | Hexham | | X | X |
| Pacific Highway | Hexham | | X | X |
| Power lines | Hexham Swamp | X | X | X |
| Power lines | Adjacent to Minmi Road | | X | X |
| Power lines | Birmingham Gardens | | X | X |
| Power lines | Maryland | | X | X |
| Power lines | Maryland Industrial Estate | | | X |
| Radio tower | Birmingham Gardens | X | X | X |
| Children's playground | Maryland | | | X |
| Bill Elliott sporting fields | Maryland | | X | X |
| Wallsend High School sporting fields | Wallsend | | | X |
| Wallsend Pool carpark | Wallsend | | | X |
| Maryland Shopping Centre | Maryland | | | X |
| Landing strip | Maryland | X | X | X |
| Disused airfield | Hexham | | X | X |
| Industrial estate | Maryland | | | X |
| Industrial | Wallsend | | | X |
| Industrial | Birmingham Gardens | | X | X |
| One steel metal recycling facility | Hexham | | X | X |
| Wallsend Cemetery | Birmingham Gardens | | | X |
| Chichester Gravitational Trunk Main | Hexham Swamp | X | X | X |
| Railway line | Hexham | X | X | X |
| Sewage treatment works | Shortland | | X | X |
| Greyhound facility | Birmingham Gardens | | X | X |
| Housing | Birmingham Gardens | | X | X |
| Housing | Sandgate | | | X |
| Housing | Hexham | | X | X |

retreating inland in response to the recession of the shoreline (Titus, 2000). Rolling easements prevent the construction of 'hard' or 'soft' engineering methods, which inhibit the ability of wetlands to move inland (Titus, 2000). A rolling easement could be a serious option to consider within a wetland, such as Hexham Swamp.

Protection involves the defence of land, infrastructure, and buildings vulnerable to sea-level rise (Engineers Australia, 2004). Generally, protection occurs in areas where building retrofits are not possible or property or infrastructure is not expendable (McDonald, 2007). Protection is likely to be necessary in densely populated urban areas or economically significant sites (McDonald, 2007). Both 'hard' and 'soft' engineering approaches can be adopted. 'Hard' approaches include the construction of structures such as sea walls, groynes, and embankments (Bray, Hooke, and Carter, 1997). 'Soft' approaches generally include beach nourishment and allow for a more natural approach to protection (Bray, Hooke, and Carter, 1997). However, protection can also result in an increase of impacts on adjoining unprotected areas (Rigby, 2005). Over time it may not be economically viable to continue to protect assets, since these structures will have to be continuously modified or relocated as sea levels continue to rise (Deyle, Bailey, and Matheny, 2007; McDonald, 2007). Protection also encourages further development in vulnerable areas, committing authorities to continued protection of these areas (Bell, Hume, and Hicks, 2001). These measures also become increasingly ineffective as sea levels continue to rise (Bell, Hume, and Hicks, 2001).

Under natural conditions, the study area would be subject to tidal inundations and would be periodically inundated by large flood events. As a result, much of the current infrastructure has already been raised to reduce the risk of flooding during high rainfall events. The elevated Pacific Highway and railway line along the edge of the Hunter River act like a levee and have resulted in the swamp being 'cut-off' from the river (Fig. 4). The construction of the flood gates on Iron Bark Creek in the early 1970s further isolated the swamp from the Hunter River and resulted in a significant reduction in the extent of tidal inundation within the swamp (WBM Oceanics Australia, 2005). As a result, much of the swamp, until recently, has been used for grazing purposes. The Hexham Swamp Rehabilitation Project seeks to allow a significant portion of the swamp to return to natural conditions through the gradual reopening of the Ironbark Creek Floodgates (WBM Oceanics Australia, 2005). Privately owned properties that would be affected by the opening of the floodgates were purchased and converted into a national park (WBM Oceanics Australia, 2005). These factors need to be considered when developing a planning strategy for sea-level rise in the study area. It should also be noted that this study does not consider flooding conditions.

Under Scenario 1 conditions, sea levels would be expected to rise 0.9 m above current mean sea level by 2100. As illustrated in Fig. 4, there would be a substantial increase in the study area that would be permanently inundated. Fortunately, though, as illustrated in Table 1, there is relatively little infrastructure that would be affected under this scenario. This makes adaptation for this scenario significantly easier. The adaptation options that can be considered for this scenario vary significantly, depending on whether the Ironbark Creek floodgates are opened or closed. Owing to the height of the floodgates, it would be possible to close them and prevent rising sea levels from entering the study area.

Under Scenario 2 conditions, sea levels would be expected to rise 2.6 m above current mean sea level by 2100. There would also be a significant increase from Scenario 1 in the infrastructure affected (Figures 5 and 6). The closure of the Ironbark Creek floodgates is also not an option in this scenario, since they are lower than the predicted sea level. As a result, the adaptation strategies available for this scenario are considerably different to those available for a Scenario 1 sea-level rise. Retreat policies would need to be adopted to prevent further infrastructure from being located within affected areas. The development of a setback zone, as outlined by Titus (2000), would be the most suitable. This would prevent further infrastructure from being located seaward of the setback zone. If new infrastructure were to be located seaward of the setback zone, it should be designed for future relocation or sacrificed at the time of inundation (Rigby, 2005). Ideally, all infrastructure that would be impacted should be abandoned, allowing sea levels to rise without interference. Realistically, this is not possible, since much of the infrastructure is not expendable. Where possible, infrastructure should be relocated to higher ground to reduce management problems in the future. Infrastructure can continue to be used until it is inundated, but if it is to be replaced or upgraded prior to inundation it should be relocated at this time (Titus, 2000).

Under Scenario 3 conditions, sea levels would be expected to rise 5 m above current mean sea level by 2100. Despite the considerable increase in the height of sea-level rise, there would not be a large increase in the area of land that would be affected. This is due to the steep topography of the land surrounding Hexham Swamp. Despite the small increase in the area of land to be affected under this scenario, there would be a significant increase in the amount of infrastructure that would be affected. An assessment would need to be undertaken to determine the economic feasibility of adaptation compared with abandonment. There are a number of items of essential infrastructure that would be difficult to relocate. These include Minmi Road, Sandgate Road, the Pacific Highway, the railway, the Chichester Gravitational Trunk Main, and the sewage treatment works. The Pacific Highway is a major route from Sydney to Brisbane, while the other two roads are important local arterial roads. The railway is an important transport link between the Hunter Valley and the Port of Newcastle, and all trains travelling north of Newcastle pass through this area. The Chichester Gravitational Trunk Main carries the water supply for Newcastle. The sewage treatment works are an important local asset. As a result, these infrastructure assets would have to be adapted to cope with the rising sea levels using a variety of soft and hard engineering techniques.

## CONCLUSION

This study illustrates the need to consider a variety of sea-level rise scenarios when undertaking vulnerability assessments. Furthermore, it outlines the need to consider previous episodes of probable sea-level behaviour when developing models that predict future sea-level rise. The precautionary principle should be adopted when planning for sea-level rise to ensure that adequate planning occurs in the future, even though there could be hemispheric and regional variations in the rates of sea-level rise. It also identified that urban planning policies should be continuously updated in light of new scientific evidence. When developing management strategies, it is important to consider that sea levels are expected to continue to rise past 2100 from lag effects, even if global temperatures stabilise. Further, linear yearly averages disguise the likelihood of ~0.5-m surges in sea level with a ~50-year recurrence interval. What is also relevant is that the greatest centennial increase in the relic *Galeolaria* record for the warming period (Table 1) was a ~30-cm relative sea-level rise from a ~0.4°C increase of atmospheric warming over the Antarctic Ice Sheet. The assumption still remains that an anthropogenic affect is accelerating this centennial change nearly three times the previous natural response from Antarctica.

The debate on whether sea levels are currently accelerating or decelerating misses the point, since during the Holocene they did both and, after the late 20th century sea-level rise, it should not be surprising that it is decelerating, especially with the likely onset of a new centennial solar minimum. The assumption in both linear and nonlinear models of the past when applied to the present is that by the end of the 100-year period, a 1°C rise in the Southern Hemisphere temperature anomaly could be translated to a 0.9-m rise in sea levels. By 2100, there can still be a 1-m rise in present sea levels, even if there is a stillstand for the next 20 years. This assumes that doubling carbon dioxide levels will triple the natural centennial sea-level response function. If this is not the case, then the warming and sea-level response will be half that of the above projection. This averaging, however, disguises that there have been ~50-year warm periods in the Antarctic record where there is evidence that sea levels have reacted similarly to the proposed response function independent of carbon dioxide. This is the lesson from the past, and both scenarios are captured under a precautionary principle by future scenario modelling from past sea levels in Hexham Swamp.

## ACKNOWLEDGMENTS

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