



Sea level rise and the increasing frequency of inundation in Australia's most exposed estuary

David J. Hanslow¹ · Martin G. Fitzhenry¹ · Michael G. Hughes² · Michael A. Kinsela³ · Hannah E. Power³

Received: 12 May 2023 / Accepted: 4 October 2023 / Published online: 1 November 2023
© The Author(s) 2023

Abstract

The large tidal lake systems along the Southeast Australian coast are amongst the most vulnerable estuaries in Australia to the effects of sea level rise. In these lakes, reduced tide ranges compared with the ocean, in combination with modest flood extremes, have allowed development to occur in close vertical proximity to the current mean sea level. In this study, we examine water levels within Lake Macquarie, Australia's most exposed estuary to sea level rise. We analyse water level data from the entrance channel and the lake to investigate recent changes to the frequency and duration of inundation or flooding of low-lying streets and examine the potential impacts of future rises in sea level. Our analysis shows that the numbers of days each year when water levels exceed those of low-lying streets, while subject to some variability, have increased significantly over recent decades. The increasing frequency of inundation is attributed to both mean sea level rise and an increase in tide range over the period of available data, which is thought to be associated with scour processes related to ongoing morphological adjustment to entrance training works undertaken over a century ago. Comparison of the projected behaviour of lake and open coast water levels under sea level rise shows the lake has significantly greater sensitivity to sea level rise. Projected inundation frequency for a given amount of sea level rise within the lake is double that of open coast sites, exposing infrastructure in the estuary to increasing risk of damage.

Keywords Sea level rise · Tidal inundation · Coastal inundation · Coastal lake · Coastal flooding

Communicated by Wolfgang Cramer

✉ David J. Hanslow
david.hanslow@environment.nsw.gov.au

Martin G. Fitzhenry
martin.fitzhenry@environment.nsw.gov.au

Michael G. Hughes
michael.hughes@environment.nsw.gov.au

Michael A. Kinsela
michael.kinsela@newcastle.edu.au

Hannah E. Power
hannah.power@newcastle.edu.au

¹ Coast and Marine Unit, Science Division, NSW Department of Planning and Environment, Locked Bag 1002, Dangar, Sydney, NSW 2309, Australia

² Department of Planning and Environment, University of Wollongong, Sydney, Australia

³ University of Newcastle, Newcastle, Australia

Introduction

Global sea levels are rising and impacts on coastal communities are expected to grow over the coming decades through higher, more extensive and more frequent inundation events with eventual permanent inundation of low-lying areas. Over the present century, sea level rise is projected to accelerate (Church et al. 2013) potentially resulting in rapidly increasing exposure of property and infrastructure to inundation. Estuaries in particular are highly vulnerable to sea level rise owing to the absence of natural defences like the beach-dune systems that often buffer open coast settlements and the presence of low-lying foreshore land (Hanslow et al. 2016, 2018; McInnes et al. 2016; Short 1988). In some of these settings, the effects of sea level rise are becoming apparent through increasing frequency of inundation or coastal flooding, otherwise known as 'nuisance inundation' or 'sunny day flooding' (Sweet and Park 2014, Sweet et al. 2016, Moftakhari et al. 2015, 2018, Hanslow et al. 2019, Hague et al. 2020, 2022).

Sea level rise is not uniformly distributed and most coastlines around the world are projected to experience sea level

change within about 20% of the global average (Fox-Kemper et al. 2021). For Southeast Australia, model predictions suggest mean sea level rise slightly above the global average (Fox-Kemper et al. 2021). Along this coast mean model predictions for sea level rise extracted using the NASA AR6 sea level rise projection tool (Fox-Kemper et al. 2021; Garner et al. 2022), indicate a likely increase of 0.24–0.57 m (SSP1-1.9); 0.28–0.62 m (SSP2-2.6); 0.41–0.79 m (SPP2-4.5); 0.54–0.96 m (SSP3-7.0) and 0.63–1.1 m (SSP5-8.5) by 2100 relative to 1995–2014. Equivalent ranges by 2150 are 0.33–0.88 m (SSP1-1.9); 0.41–0.1.02 m (SSP2-2.6); 0.64–1.38 m (SPP2-4.5); 0.89–1.74 m (SSP3-7.0) and 0.99–2.01 m (SSP5-8.5). The upper limit of potential MSL rise under SSP5-8.5 indicated by the 95% exceedance of the low confidence AR6 modelling incorporating ice sheet processes approaches 2.37 m by 2100 and 5.58 m by 2150.

As highlighted by Sweet and Park (2014), many studies examining the impact of sea level rise focus on the tail or extreme component of the sea level distribution (e.g. Church et al. 2006; Hunter 2012; Wahl et al. 2017) and fewer have focused on the effects of transitioning between the tail and the central portion of sea level distribution that captures tidal oscillations. But it is this transition that exhibits a highly nonlinear pattern characterised by increasing rates of inundation. Sweet and Park (2014) describe these transition levels as tipping points for coastal inundation impacts as sea levels rise. The elevation of coastal infrastructure relative to these tipping points becomes critical to assessing the impact of future sea level rise. Initially, ocean inundation or flooding may be infrequent, largely associated with extreme events or surges; however, as sea levels rise and the elevation of coastal infrastructure relative to the tide level (freeboard) decreases, inundation frequency will rapidly increase. Such thresholds may trigger a marked shift in coastal management strategy within adaptive policy pathways (e.g. Haasnoot et al. 2013, Stephens et al. 2018).

In this study, we investigate the present and future occurrence of inundation impacting low-lying settlements around Australia's most exposed estuary to sea level rise, Lake Macquarie. The Australian National Coastal Risk Assessment (Cechet et al. 2011; DCC 2009) ranked Lake Macquarie as the most exposed local government area in Australia, and a more recent and detailed state assessment confirmed Lake Macquarie to be the most exposed estuary in New South Wales (NSW) (Hanslow et al. 2018). Its vulnerability to sea level rise has also been explored using probabilistic modelling carried out by Callaghan et al. (2020), who applied an efficient hydrodynamic model within a statistical modelling framework to investigate the impacts of future uncertainty in sea level rise on the estuary. The high exposure of Lake Macquarie's settlements to sea level rise has been attributed to an attenuated lake tidal range (compared with the adjacent ocean range) and relatively low-lying foreshore terrain that

has enabled development to occur in close proximity to sea level (Hanslow et al. 2018). Future vulnerability to sea level rise is also amplified by increasing tide range (Palmer et al. 2021) thought to be associated with ongoing channel scour (Nielsen and Gordon 2008, 2015).

Our aim is to analyse recent rates of inundation within the lake and to examine the impacts from rising sea levels on surrounding communities. We focus particularly on the frequency of inundation exceedance of the levels of streets within the suburbs of Swansea and Marks Point, which offer informative case studies for exploring the need for and design of adaptive management pathways and associated thresholds and triggers (e.g. Kool et al. 2020). Both localities presently experience inundation during higher water level events (Hanslow et al. 2019) (Fig. 1). We also explore insights on the potential implications of future sea level rise using the current daily water level cumulative exceedance distribution.

Regional setting and study site

Lake Macquarie is a large estuarine barrier lake located on the central New South Wales (NSW) coast near the city of Newcastle (Fig. 1). Tides along this coast are microtidal and semi-diurnal with a significant diurnal inequality. Highest astronomical tide at Fort Denison, 94 km to the south of Lake Macquarie, is 2.1 m above the lowest astronomical tide while the mean spring range is 1.2 m and the mean neap range is 0.8 m (AHO 2023). Tide range varies along the NSW coast with an increase of around 0.2 m from south to north (MHL 2012). The magnitude of the lunar nodal cycle (18.61 years) on the NSW coast is relatively small (Haigh et al. 2011).

In addition to the astronomic tide, numerous other processes contribute to variations in water level along the NSW coast. These tidal anomalies are typically less than 1 m but vary greatly in duration (e.g. Modra and Hesse 2011, Viola et al. 2021). They include background variations in mean sea level associated with long-period ocean seiches (Folland et al. 1999) and/or incoming Rossby waves (Holbrook et al. 2011) that modulate the East Australian Current at periods related to El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO). Short-lived phenomena also influence sea level, the largest of which are typically associated with combinations of wind setup and barometric influences, and/or coastal trapped waves (e.g. Modra and Hesse 2011; Callaghan et al. 2017). Storm surge, while smaller than on many coasts elsewhere, can still raise water levels above normal tide levels by over 0.5 m (e.g. NSW Government 1990; You et al. 2012; Callaghan et al. 2017; MHL 2018) and can be short lived or last for more prolonged periods

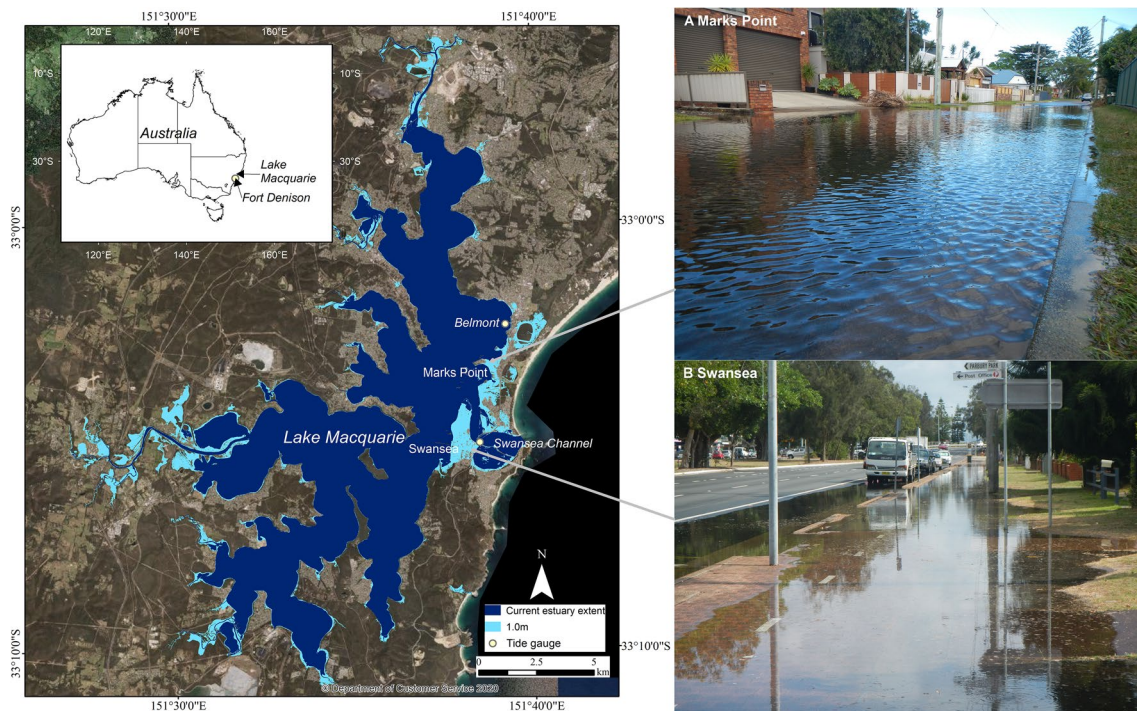


Fig. 1 Lake Macquarie, located on the central NSW coast including the locations of the Swansea Channel and Belmont tide gauges, Marks Point and Swansea, as well as the current mapped estuary extent and a 1-m sea level rise scenario mapped above HHWS

following Hanslow et al. (2018). The figure also shows examples of street inundation during high water levels (without rainfall) in Marks Point (A) at 10:10 on 05/05/2018 and Swansea (B) at 8:25 on 02/12/2017 Photos: D. Hanslow

(days) depending on storm characteristics and propagation. Coastal trapped waves are a regular contributor to tidal anomalies (Maiwa et al. 2010, Woodham et al. 2013) on the NSW coast and typically have a height of 0.2 to 0.3 m but have been measured up to 0.5 m (MHL 2015) generally with a period of between 7 and 10 days. These longer events are known to fully propagate into larger coastal lakes (McPherson et al. 2013) and can raise lake water levels to an extent that even low tide levels are higher than normal high tide levels (MHL 2015). Other potential contributors to water level variability include steric effects associated with the East Australian Current (MHL 2018).

White et al. (2014) reviewed ocean tide gauge records from around Australia and noted that most of the differences in sea level trends observed between locations around Australia were closely related to the El Niño Southern Oscillation (ENSO), with the strongest influence on Australia's northern and western coasts. After the influence of ENSO, glacial isostatic adjustment and air pressure are removed, Australian mean sea level trends are close to global-mean trends from 1966 to 2009, including an increase in the rate of rise in the early 1990s. White et al. found the Australian average rate of relative sea level rise between 1966 and 2009 was 2.1 ± 0.2 mm per year. From 1993 to 2009, the rate was 3.1 ± 0.6 mm per year. Off the New South Wales

coast, there is a maximum in the rate of sea level rise at a latitude of about 35°S in the Tasman Sea, which is consistent with the spin-up of the South Pacific subtropical gyre by increased wind stress curl (Roemmich et al. 2007, Church et al. 2012). Along the coast of NSW, tide gauge data over the corresponding time frame indicate a lower rate of rise suggesting a gradient in sea level trends between the Tasman Sea and the coast, which is explained by increased strength and southward flow of the east Australian current (Hill et al. 2008, 2011, Church et al. 2012, Deng et al. 2010) and contributions from glacial isostatic adjustment (Zhang et al. 2017).

Lake Macquarie has a surface area of around 114 km² and a catchment area of approximately 604 km² (OEH 2018). The lake is separated from the ocean by Nine Mile Beach, a barrier system which extends north from the lake entrance and the Wallarah Peninsula which extends south of the entrance (Fig. 1). The lake is connected to the ocean by a channel which is around 0.4 km wide and 5.8 km long, bordered by a mixture of rock revetments and sandy foreshore. The entrance channel reduces the tide range in the lake significantly when compared with the adjacent ocean, with the spring tidal range estimated to be 0.1 m at the western end of the entrance channel (MHL 2023). As a result, high tide levels in the lake are significantly lower than those in the ocean and low tide levels are higher (e.g. MHL 2023).

Despite this reduced tidal exchange, the lake is marine dominated because of minimal freshwater dilution from the two main fluvial inputs. The lake is subject to occasional floods associated with heavy rainfall. The highest recorded flood level is 1.25 m AHD which occurred in 1949 with more recent events reaching 1.05 m AHD in June 2007 and 1.00 m AHD in February 1990 (LMC 2012). Much of the area around the lake has been subject to underground coal mining and is thus potentially undergoing subsidence although the mapped subsidence districts identified by the Mine Subsidence Advisory Board are to the north, south and west of Swansea and Marks Point (DFSI 2017).

The estuary entrance was trained in the late 1800s to improve navigation. Most development of the area occurred after entrance training and thus proceeded in a manner acclimatised to the reduced tide regime which would have developed post entrance training. The training works are thought to be contributing to ongoing entrance and channel scour at a multi-centennial scale resulting in changes in the tidal regime over time including an increase in the lake-to-ocean tide ratio (Nielsen and Gordon 2008, 2015; Hart et al. 2017; Palmer et al. 2021). This includes ongoing increases in the main tidal constituents, particularly the principal lunar semi-diurnal constituent (M₂) which are contributing to an increase in tide range within the lake (Palmer et al. 2021) which adds to the effects of sea level rise. Watterson et al. (2010) used a hydrodynamic model to predict tidal ranges and the tidal prism of Lake Macquarie under a sea level rise scenario of 0.91 m by 2100. Their results show a potential doubling of the spring tidal range at Belmont in 2100 as a result of both sea level rise and channel scour.

The area around the City of Lake Macquarie has a population of 213,967 (as of 2021), which is expected to grow significantly over coming decades. An additional 36,000 dwellings are proposed in Lake Macquarie local government area, 15,000 in the new land release areas, and the balance within the existing urban areas (NSW Govt 2006). Hanslow et al. (2018) showed significant numbers of properties around the lake are exposed to potential sea level rise. This included some 2470 properties at least in part, located within 0.5 m of the Higher High Water Solstice Springs (HHWSS) tidal plane, 5803 within 1 m and 7848 within 1.5 m.

Methods and data

To determine recent rates of inundation within Lake Macquarie, we combined analysis of available water level gauges with ground survey data. We analysed the frequency of inundation and sea level trends using data from two water level gauges, one located in the entrance channel (Swansea Channel) and one in the body of the lake

(Belmont). The locations of these gauges can be seen in Fig. 1. For comparison, we also analysed data from Fort Denison located in Sydney Harbour to the south. The Fort Denison gauge is generally thought to be representative of regional ocean water levels on the central NSW coast (e.g. Modra and Hesse 2011, Callaghan et al. 2017). The water level data were sourced from Manly Hydraulics Laboratory (MHL see www.mhl.nsw.gov.au) and the Bureau of Meteorology (BOM see <http://www.bom.gov.au/oceanography/projects/ntc/monthly/>). Our approach involves analysis of observed water levels (i.e. water levels comprising both astronomic and non-astronomic factors) as this is what is impacting the lake Macquarie communities and do not separately analyse astronomic tide. The raw data included water level measurements recorded at 15-min intervals at Swansea Channel and Belmont and 1 h at Fort Denison referenced to Australian Height Datum (AHD) which approximates mean sea level on the open coast. The Swansea Channel data have been corrected by MHL for a minor instrument drift in the early part of the record identified by NTC (2013). To compare results from each site, we examine trends over two periods. The first corresponding to the period of the shortest record (Swansea Channel), which began in April 1996 through to the end of 2021. The second from June 1986 to the end of 2021 corresponding with the start of the Belmont record.

Thresholds for street inundation in the most low-lying areas of Swansea and Marks Point (Fig. 1) were obtained using both high-resolution Light Detecting and Ranging (LiDAR) and Real Time Kinematic (RTK) GPS survey data. Initially, we used a digital elevation model created from LIDAR data along with available ground photographs of inundation to identify the most low-lying sites where inundation first becomes apparent, consistent with the methods of Hanslow et al. (2019). We then refined the thresholds for inundation by undertaking site surveys in Swansea and Marks Point using RTK surveying to find the lowest point in the area. These were generally in street gutters with the lowest points coinciding with stormwater drains. Owing to the water level gradient through Swansea channel, we limited the Swansea sites to streets in reasonable proximity to the Swansea Channel Gauge (< 1 km) while the Belmont data, which is representative of the lake (where water level gradients are expected to be insignificant), is used to examine inundation at Marks Point. The lowest point at which inundation occurs was identified for each site. These were generally restricted to one or two locations in each suburb, although as both localities are reasonably flat, inundation becomes more widespread with relatively small increases (0.1 to 0.2 m) above these thresholds. Thresholds for inundation were set to 0.1 m above the minimum levels to provide a more realistic count of days when inundation which is likely to be apparent to the casual observer.

To examine past changes in yearly threshold exceedance, daily maximum water level time series from the gauges were first checked and then tallied into annual counts of days above thresholds for inundation of low-lying areas. Any gaps in annual counts were addressed using pro rata adjustment, i.e. annual counts were increased proportionally to account for any gaps in the record. Depth of inundation was also examined using counts at 0.1-m increments above this threshold. For duration of inundation, we tallied total hours each year above the threshold, again adjusted for gaps in the record.

We also calculate linear trends in mean sea level from each water level gauge set using monthly means. Monthly maximums and minimums were also examined to investigate changes in water level excursion. The seasonal component of each time series was separated using the Seasonal and Trend decomposition using Loess (SLT) function in R (Cleveland et al. 1990). This function decomposes time series into trend, seasonal and error components using locally weighted polynomial regression. The seasonal component, once separated, was subtracted from the original time series to produce a deseasonalised time series. These were then checked for autocorrelation using the Durbin Watson test (Durbin and Watson 1950) and the analysis of each time series was adjusted for autocorrelation using an autoregressive AR(1) model in R. The statistical significance of each trend was checked along with the significance of the differences between trends. This was undertaken by calculating the z statistic as the difference between the two slopes divided by the standard error of the difference between the slopes.

The potential implications of near-term sea level rise on the frequency of inundation were examined by first plotting the cumulative frequency of daily maximum water levels and then examining the implications of projected sea level rise. To do this, we used daily maximum water level data, detrended and then binned into 1-cm increments. Detrending is undertaken by adjusting the early part of the time series upwards to account for sea level rise and increasing water level range over the period of observation, and thus make the overall exceedance plot representative of the 2021 mean sea level. Bin counts were then summed to produce cumulative exceedance plots which show the frequency (in terms of days per year) of different levels reached based on the overall daily maximum water level time series.

Implications of sea level rise on the potential future frequency of inundation are examined by adding the latest sea level rise projections from Newcastle (extracted from the NASA AR6 sea level rise projection tool Fox-Kemper et al. 2021, Garner et al. 2022) to the cumulative exceedance plots assuming a continuation in the current (1996–2021) differential in trend of the daily maximum above the mean (i.e. we assume the water level range will continue to increase at the current rate, and thus, our results are conservative

given the potential for acceleration as rates of sea level rise accelerate). For each site, we examine the implications of sea level rise on street flooding via storm water ingress using the street height threshold and via overland flooding based on the estimated lowest point for over land inundation. Additionally, to explore the spatial implications of sea level rise for each site, we map the frequency inundation using under current conditions and in 2050 and 2100 for 3 scenarios: low (SSP1-2.6 17% exceedance), medium (SSP3-7.0 50% exceedance) and high (SSP5-8.5 83% exceedance) in 2050 and 2100 again assuming the water level range will continue to increase at the current rate. To do this, we generate high-resolution digital elevation models (30 cm) from LiDAR point cloud data downloaded from the Geoscience Australia Elvis (Elevation and Depth) data portal (<https://elevation.fsdf.org.au>) and then overlay the projected changes in the frequency of inundation. For Swansea, the extent of this mapping is restricted to the area near the Swansea Channel gauge and adjacent to the bay which extends southwards of the gauge to avoid errors associated with the relatively steep water level gradients in Swansea Channel. An overview of the methods used is also provided in the supplementary information (Supplementary Table 1).

Results

Water level time series for each gauge from June 1986 through to December 2021 along with the monthly means are shown in Fig. 2. The reduction in water level ranges from the ocean (represented by Fort Denison) through Swansea Channel and into the lake (represented by Belmont) is clearly apparent in Fig. 2A. Also evident is a trend of rising water levels. To make this more apparent, we plot the monthly and annual means at each site without the 15-min water level data in Fig. 2B.

Annual time series of days exceeding the thresholds for street inundation at Swansea (0.8 m AHD) and Marks Point (0.34 m AHD) are shown in Fig. 2C and D respectively along with the total annual duration of inundation. Also shown in these plots are days where inundation exceeds depth thresholds in 0.1-m increments. While displaying some variability, the number of days with inundation of low-lying streets in Swansea has doubled over the period of available data (5-year average). In Marks Point, the number of days which exceed the inundation threshold has increased by over 3 times (5-year average). Total annual duration of inundation at each site also increases significantly but is subject to greater variability.

Calculated annual rates of sea level rise are provide in Supplementary Table 2. Mean sea levels at both the Swansea Channel and Belmont gauges in Lake Macquarie are rising as are sea levels at Fort Denison to the south. Rates of mean

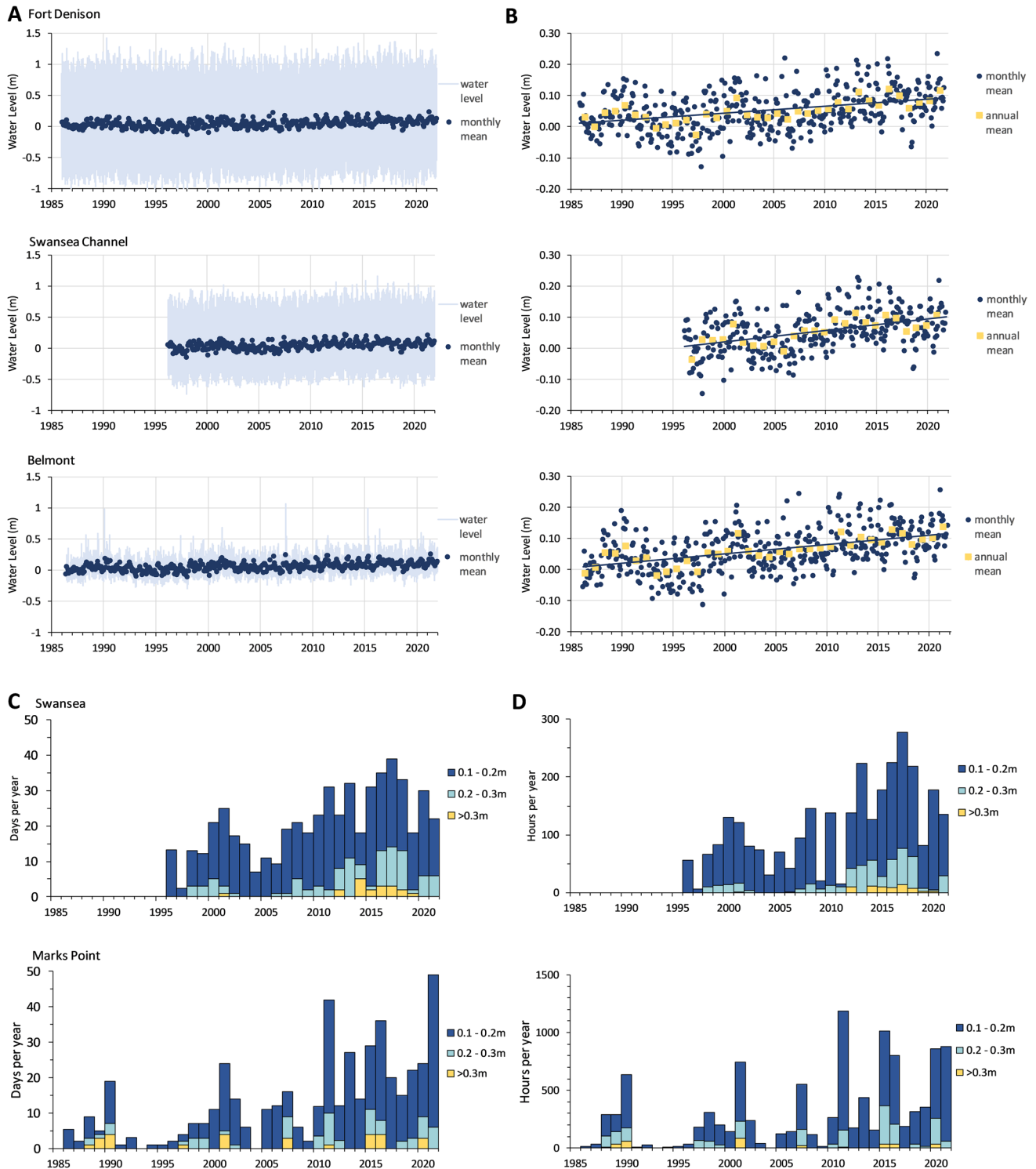


Fig. 2 Water level time series for Fort Denison, Swansea Channel and Belmont from 1986 to 2021 and annual counts of days and duration of inundation at Swansea and Marks Point. **A** shows 15-min water level data plotted in light blue and monthly means in dark blue. **B** shows the monthly and annual mean water level time series and linear

trends with increased vertical scale. **C** shows annual counts of days exceeding thresholds (0.8 m for Swansea and 0.34 m for Marks Point) for street inundation for different depths of inundation. **D** shows total annual duration of inundation in hours for different depths of inundation at Swansea and Marks Point

sea level rise are higher over the period 1996 to 2021 (when the Swansea record starts) as compared with 1986 to 2021 (when the Belmont record starts). Rates over the respective time periods are similar at each location with Swansea Channel slightly higher between 1996 and 2021 and Fort Denison slightly lower than Belmont between 1986 and 2021. Noticeably, the rates of rise of the daily maximum are significantly higher than that of the minimums at both Belmont and Swansea gauges indicating a trend of increasing water level excursion consistent with the findings of Palmer et al. (2021). The difference between the monthly maximums and minimums at Belmont is consistent with an increase in monthly water level excursion within the lake (max-min) of $1.79 \pm .47$ mm/year (p value = 0.000165). Trends at each gauge are statistically significant but the differences between the lake gauges and Fort Denison are not significant.

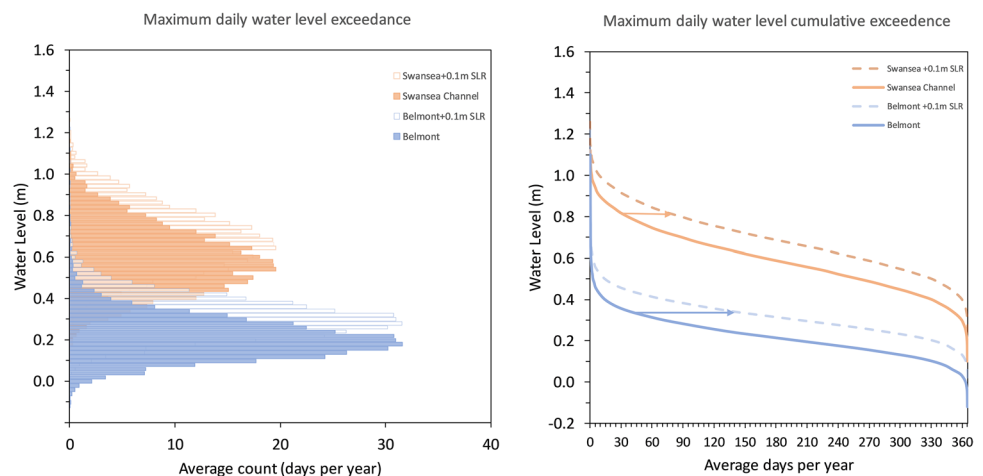
The increase in frequency and duration of inundation is highly correlated with the long-term trend in mean sea level as seen in supplementary Fig. 1, thus suggesting that sea level rise has had a measurable impact on the frequency and duration of inundation events at both sites. At Swansea, the relationship between the frequency and duration of inundation and mean sea level is linear while at Marks Point the relationship is nonlinear shown here with a quadratic fit following Sweet and Park (2014). The difference in the nature of the relationships at each site is explained by the location of the inundation threshold in relation to the shape of the water level distribution at each site (as seen in Fig. 3). The transition from the tail to the central part of the water level distribution is more nonlinear at Marks Point compared with Swansea. The degree of sensitivity of the frequency of inundation to very small changes in sea level varies between the lake (Belmont gauge) and the channel (Swansea channel gauge), with increased sensitivity in the lake associated with the reduced water level range. This is reflected in both the observed increase in threshold exceedances at Marks Point

when compared with Swansea (Fig. 2C) as well as the projected effects of minor sea level rises as seen in Fig. 3.

In Figure 3, we examine the potential implications of small increases in future sea level on the frequency of inundation at Swansea and Marks Point. We use the data from Swansea Channel and Belmont gauges to plot the current distribution of water levels and the cumulative exceedance of water levels (in terms of days per year) at each site using the daily maximum time series. In this plot, we also show the same water level distribution raised by a hypothetical 0.1 m to show the implications of relatively small changes in sea level on the frequency of inundation for the identified threshold levels of 0.34 m and 0.80 m at Marks Point and Swansea, respectively. The length of the arrows in Fig. 3 indicates the projected impact of the 0.1-m SLR on number of inundation days per year. At Swansea, it more than doubles the days exceeding the threshold for street inundation, increasing from the current 36 days per year to 88 days per year. At Marks Point, a 0.1-m increase in sea level results more than a threefold increase in threshold exceedances from 40 days per year to 140 days per year.

Projected changes in the frequency of inundation days at each site are shown in Fig. 4. Here, we examine the implications of sea level rise on street flooding via storm water ingress using the street height threshold and via overland flooding based in the estimated lowest point for over land inundation at both Swansea and Marks Point. The projected rate of increase in inundation days is significantly higher at Marks Point as a result of the smaller water level range and hence flatter water level cumulative exceedance curve (see Fig. 3). Under higher scenarios, inundation occurs every day of the year by 2060 at Marks Point and by 2080 at Swansea. Overland flooding occurs occasionally now at both sites. This type of inundation increases slowly at Swansea become more significant after 2040. At Marks Point overland inundation increases very rapidly after 2050 occurring most days of the year by 2090 under higher scenarios.

Fig. 3 Maximum daily water level exceedance and cumulative exceedance (m AHD) and assuming 0.1 m of sea level rise (dashed lines) at Swansea and Belmont (in terms of days per year) calculated using detrended daily maximum time series (1996–2021). The arrows show the implications of a 0.1-m increase in sea level on the number of days when the daily maximum exceeds the street level in Swansea and Marks Point



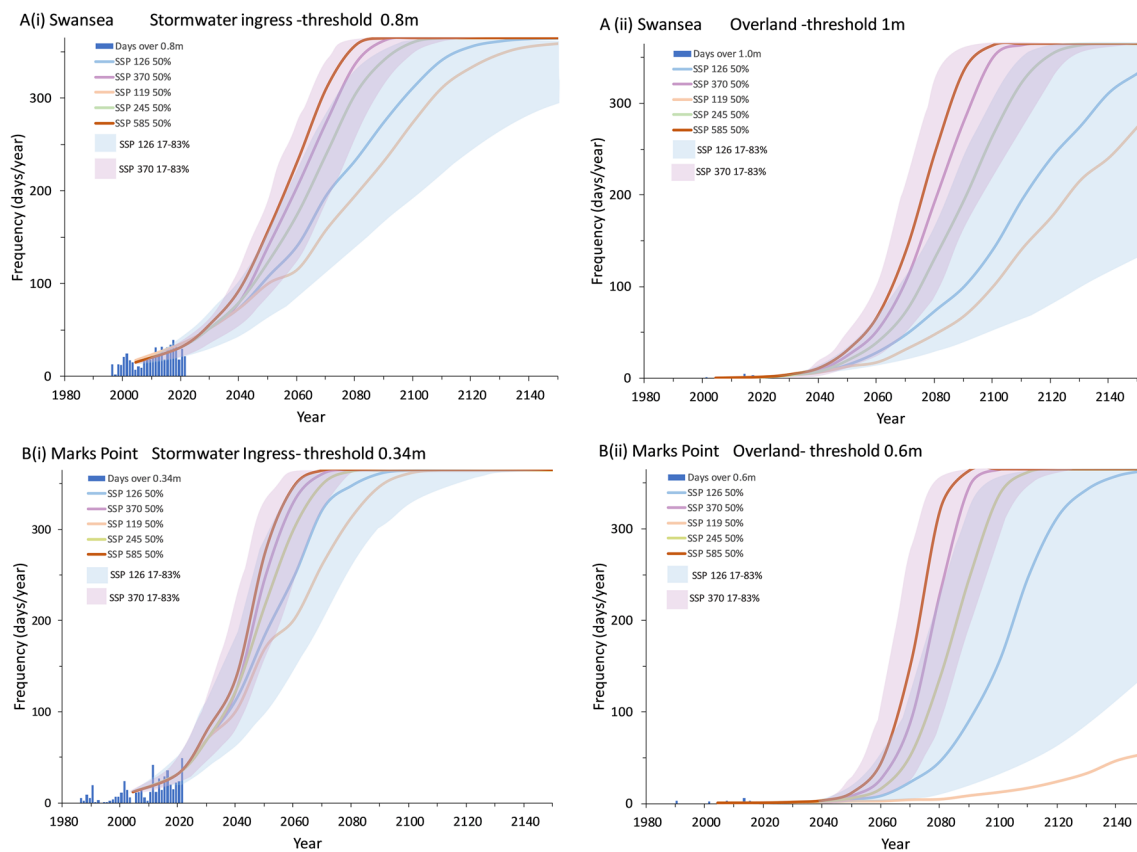


Fig. 4 Projected changes in the frequency of inundation days at Swansea (A) and Marks Point (B) via storm water ingress (i) using the street height threshold and via overland flooding (ii) based in the estimated lowest point for overland inundation at both Swansea and Marks Point

The frequency and extent of current and projected inundation in 2050 and 2100 (under low, medium and high scenarios) at Swansea is shown in Fig. 5 and for Marks Point in Supplementary Fig. 2. In Swansea, current inundation extent is limited to some low-lying streets adjacent to the main highway and the central business district but becomes very widespread under the future SLR scenarios. In Marks Point, frequent inundation is currently limited to 3 low-lying streets, although much of the area is subject to infrequent (<1 day/year) flooding. With future sea level rise, inundation becomes significantly more frequent and widespread. By 2100, both locations see large areas with inundation most days even under the medium scenario.

Discussion

The results presented here show that the frequency and duration when water levels exceeded the level of low-lying streets surrounding Lake Macquarie, while subject to some variability, have been increasing. Similar increases have been reported previously both in the US (e.g. Sweet and Park 2014; Thompson et al. 2021) and Australia (e.g. Hanslow

et al. 2019; Hague et al. 2020, 2022). The impacts of these inundation events to date are generally limited to short lived, nuisance type inundation involving minor flooding of roads, paths and driveways although they foreshadow broader and more frequent impacts ahead as sea levels rise. At the initial threshold level, effects are very localised (generally limited to the gutters adjacent to two stormwater drains at each locality) and short in duration (~ 1 h), although they become more widespread and of longer duration (~ 2–3 h) during higher/deeper inundation events. For events exceeding the threshold by more than 0.2 to 0.3 m, several streets become affected including the main commercial centre of Swansea (see Figs. 1 and 5). At Marks Point, the flood tail of the water level distribution is longer with larger events associated with both rainfall (i.e. catchment driven flooding) and sometimes large tidal anomalies which may be quite long lived. An example being the coastal trapped wave event in early May 2015 which resulted from a number of cold fronts that impacted the southern coast of Australia (MHL 2015). This event resulted in a positive tidal anomaly (surge) of up to 0.5 m lasting 12.5 days. In Lake Macquarie, even low tide levels during this event were higher than normal high tide levels, with some foreshore and local street inundation. This

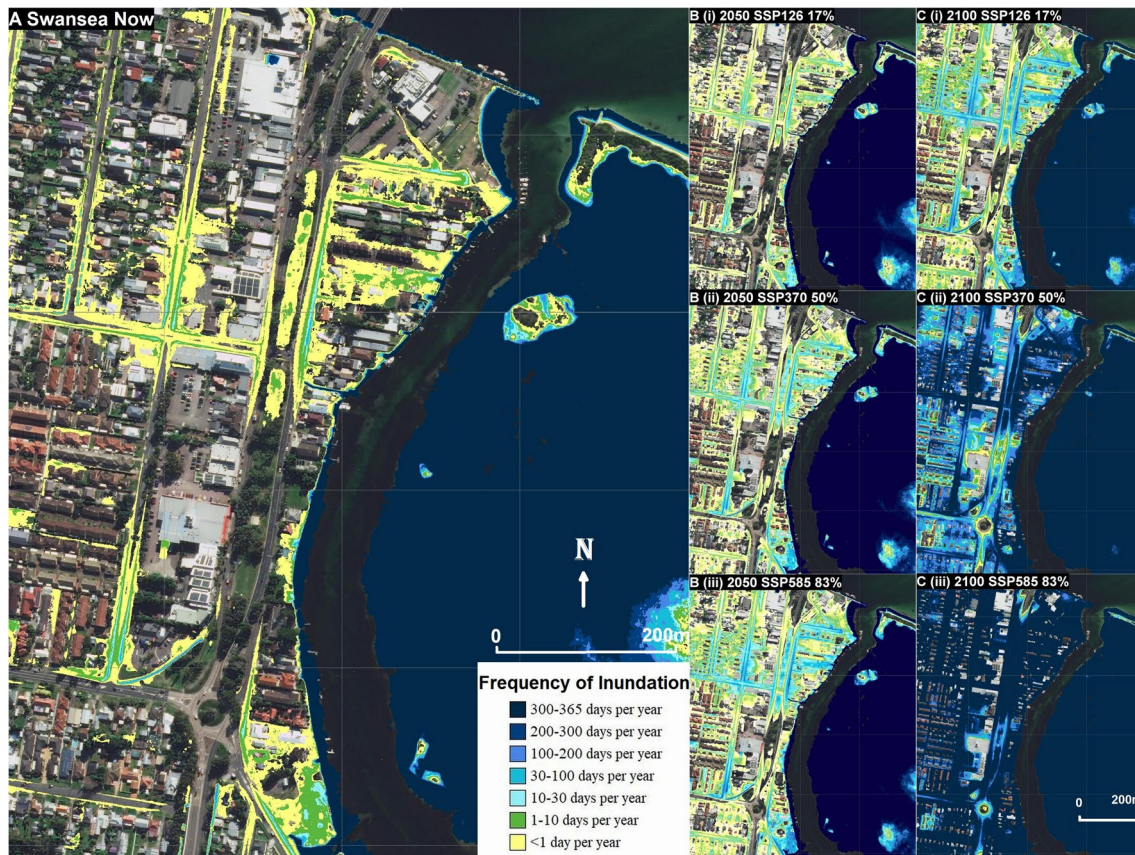


Fig. 5 The frequency and extent of current inundation at Swansea (A) and projected future inundation in 2050 (B) and 2100 (C) under (i) low-SSP1-2.6 17%, (ii), med-SSP3-7.0 50% and (iii) high-SSP5-8.5 83% scenarios

included inundation of street edges in West Swansea where the threshold for inundation is similar to that of Marks Point.

Concerns relating to increasing inundation at both locations have led to trialling of various treatment options for stormwater outlets to limit ingress during higher water level events (Woodhouse 2017). These trials form part of the adaptation strategy for the area (LMC 2016, 2021). At Marks Point, this has had mixed success in preventing inundation. Monitoring of the trial showed the flaps and gates trialled were effective in stopping lake inundation during higher lake water levels; however, there was an increase in nuisance stormwater pooling during frequent, small rain events. These treatments were subsequently removed (Woodhouse 2017). At Swansea, where the tide range is larger, the trial appears more successful with an observed reduction in inundation days.

The time series analysis in this study identifies rates of mean sea level rise similar to the global average reported from satellite altimeter data collected since 1993 which are around $\sim 3.4 \pm 0.4$ mm/year (Ablain et al. 2017; Nerem et al. 2010). The finding that maximum water levels are increasing within the lake at a higher rate than minimum water levels is consistent with the findings of Nielsen and Gordon (2008, 2015), Hart (2017) and Palmer et al. (2021) who show that

the magnitude of the main tidal constituents and the tide range are increasing. They attribute this to ongoing entrance and channel scour resulting from the entrance training works constructed in the late 1800s. This scour process is expected to potentially add to the effects of sea level rise over coming decades (Hart et al. 2017, Watterson et al. 2010) meaning high water levels in the lake are likely to rise more and at a faster rate than ocean mean sea levels. Comparing rates of monthly maximum increase with those of the monthly means at Belmont suggests that since 1996 around $\frac{1}{4}$ of the observed increase is attributable to increasing water level range, although we do not rule out other contributors. These include effects from floods within the lake as well as the effects of sea level rise itself which may result in increased entrance water depth and thus increased tidal propagation (e.g. Arns et al. 2015, Watterson et al. 2010, Khojasteh et al. 2020a, b).

As sea levels rise and the relative difference between the elevation of coastal infrastructure and sea level decreases, inundation will become increasingly frequent. In this study, the thresholds identified for street inundation have transitioned from the tail of the water level distribution to the tidal portion of the observed water level distribution (Fig. 3) and are likely thus past the tipping point described by Sweet and

Park (2014). Our analysis therefore suggests a more rapid increase in the frequency of inundation in the near future as sea levels rise, albeit with increasing interannual variability related to variations in mean sea level including ENSO (e.g. White et al. 2014, Davies et al. 2017). This variability could involve initial interannual fluctuations in the frequency of inundation days of up to 58 days at Marks Point potentially increasing up to around 158 days, and 48 days at Swansea increasing up to around 96 days based on the variability in annual exceedance distributions to date.

Compared with other open coast sites, the reduced water level range in the lake results in greater increases in the frequency of days exceeding the thresholds for inundation with future sea level rise. The 5–95% range in daily maximum water level derived from the cumulative distribution data at Belmont is approximately half (0.31 m) that seen at Fort Denison (0.6m) inferring a doubling of sensitivity to sea level rise. At Swansea, the 5–95% range is around 80% (0.49 m) of Fort Denison. Inferred rates of increase in the frequency of inundation days with sea level rise are significantly higher at Belmont (1.06 days/mm) and Swansea (0.67 days/mm) compared with Fort Denison (0.55 days/mm). We would expect other tidal lakes in NSW as well as internationally like those in Brazil and South Africa, to exhibit similar increased sensitivity.

Lake Macquarie City Council has been proactive in developing adaptation plans to deal with sea level rise and its impacts on vulnerable communities (LMC 2016). This includes commissioning a probabilistic inundation and damage assessment to inform cost benefit analysis of management options (Wainwright et al. 2018, Callaghan et al. 2020) and having worked with the community over many years to develop adaptation plans for Marks Point, Pelican, Blacksmiths, Swansea, Swansea Heads and Caves Beach (LMC 2016, 2021). These plans include installing of tidal gates on the ends of storm water outlets to limit tidal ingress; construction of revetments to protect the foreshore from erosion; progressive filling to maintain ground levels around 0.5 m above the lake; raising and improving the design of infrastructure such as drains and roads to match the raising of land; constructing new buildings above projected flood levels and raising remaining old homes above projected flood levels (if required) (LMC 2016, 2021). We expect the water level exceedance and projection data provided in this paper will assist in informing the timing of local intervention triggers and sea level rise adaptation thresholds in both communities.

There has been ongoing pressure to dredge the lake entrance channel to improve under keel clearance for navigation (e.g. Morgan et al. 2014, Umwelt 2013). Given the evidence of increasing frequency of inundation within low-lying streets in lakeside communities and the extreme sensitivity of the area to future sea level rise which is projected to accelerate in future decades, great care should be

taken to ensure any future dredging is undertaken in a way which prevents any additional changes to the water level range and daily highs in particular.

Conclusions

Communities living adjacent to Lake Macquarie are subject to inundation of low-lying streets and paths during higher tides, with previous studies showing Lake Macquarie to be extremely vulnerable to sea level rise as a result of high numbers of properties in relatively close vertical proximity to mean sea level. Our analysis shows that water levels in Lake Macquarie have been rising with the impacts of sea level rise in lake side communities both observable and measurable. Furthermore, the frequency of days when water levels exceed the level of low-lying streets, while subject to some variability, has also been increasing such that the numbers of days each year when water levels exceed those of low-lying streets have more than doubled since 1996 at Swansea and tripled at Marks Point since 1986. This increase has resulted from both mean sea level rise and from an increase in water level range that has previously been attributed to entrance scour processes associated with ongoing adjustment to entrance training works but our results are also impacted by the El Niño–Southern Oscillation, ocean/flood process and long-period tidal oscillations. Examination of water level inundation exceedance shows that the levels of streets in both Swansea and Marks Point are now past an inflection or tipping point in the inundation curve. Consequently even very modest future increases in sea level are likely to result in a significant increase in the number of days when lake levels exceed those of low-lying streets. In this study, we further show the reduced water level range is likely to contribute to an increase in future inundation frequency at approximately twice the rate of open coast sites and that the increasing water level range in the lake will increase the frequency of inundation days above that associated with sea level rise alone.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10113-023-02138-8>.

Acknowledgements The authors wish to thank Dr Kathy McInnes (Commonwealth Scientific and Industrial Research Organisation) and Stuart Young (Department of Planning and Environment) for constructive review of the initial draft manuscript. Thanks also to Neale Farmer from Lake Macquarie City Council for his review of the paper.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions

Data availability The water level data used in this study was sourced from Manly Hydraulics Laboratory (www.mhl.nsw.gov.au) who maintain the NSW Coastal Data Network Program funded by the NSW

Department of Planning and Environment and the Bureau of Meteorology <http://www.bom.gov.au/oceanography/projects/ntc/monthly/>. The Manly Hydraulics Laboratory data is available by request from datrequest@mhl.nsw.gov.au. The LiDAR data used to create the digital elevation models is available from the Geoscience Australia elevation and depth data portal ELVIS <https://elevation.fsd.fg.org.au>.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ablain M, Legeais JF, Prandi P, Marcos M, Fenoglio-Marc L et al (2017) Satellite altimetry-based sea level at global and regional scales. *Surv Geophys* 38:7–31. <https://doi.org/10.1007/s10712-016-9389-8>
- Arns A, Wahl T, Dangendorf S, Jensen JJ (2015) The impact of sea level rise on storm surge water levels in the northern part of the German Bight. *Coast Eng* 96:118–31. <https://doi.org/10.1016/j.coastaleng.2014.12.002>
- Australian Hydrographic Office (2023) Australian Nation Tide Tables 2023. Australian Government Department of Defence, Australian Hydrographic Service, Australian Hydrographic Publication 11 https://www.hydro.gov.au/prodserv/publications/AHP11_2023.pdf. Accessed 25 Sept 2023
- Callaghan DP, Wainwright DJ, Hanslow DJ (2020) Consideration of uncertainty in sea level rise in Australia's most exposed estuary: a discussion on allowances under different epistemic uncertainties. *Coastal Eng* 159:103718. <https://doi.org/10.1016/j.coastaleng.2020103718>
- Callaghan DP, Couriel E, Hanslow D, Modra B, Fitzhenry M et al (2017) Comparing extreme water levels using different techniques and impact of climate indices. In: *Australasian Coasts & Ports 2017: Working with Nature: Working with Nature 2017 Jan 1* (pp. 282–288). Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, <https://search.informit.org/doi/https://doi.org/10.3316/informit.934236989674825>
- Cechet RP, Taylor P, Griffin C, Hazelwood M (2011) Australia's coastline: adapting to climate change: assessing infrastructure vulnerability to rising sea-levels. *AusGeo News* 101. <https://www.ga.gov.au/ausgeonews/ausgeonews201103/climate.jsp>. Accessed 25 Sept 2023
- Church JA, Hunter JR, McInnes KL, White NJ (2006) Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Aust Met Mag* 5(4):253–260. <https://doi.org/10.1016/j.gloplachs.2006.04.001>
- Church JA, White NJ, Hunter JR, McInnes KL (2012) Sea level. In: Poloczanska, E, Hobday AJ Richardson AJ (eds) *A marine climate change impacts and adaptation report card for Australia*. ISBN: 978-0-643-10928-5
- Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S et al (2013) Sea level change. In: Stocker TF et al (eds) *Climate change (2013): the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ch13 1137–1216 Cambridge University Press
- Cleveland RB, Cleveland WS, Terpenning I (1990) STL: a seasonal-trend decomposition procedure based on loess. *J Off Stats* 6(1):3–73. Retrieved from <https://www.proquest.com/scholarly-journals/stl-seasonal-trend-decomposition-procedure-based/docview/1266805989/se-2>. Accessed 25 Sept 2023
- Davies G, Callaghan DP, Gravois U, Jiang W, Hanslow D et al (2017) Improved treatment of non-stationary conditions and uncertainties in probabilistic models of storm wave climate. *Coastal Eng* 127:1–19. <https://doi.org/10.1016/j.coastaleng.2017.06.005>
- DCC (2009) Climate change risks to Australia's coast: a first Pass National Assessment. Australian Government Department of Climate Change. <https://www.dccew.gov.au/sites/default/files/documents/cc-risks-full-report.pdf>. Accessed 25 Sept 2023
- Deng X, Griffin DA, Ridgway K, Church JA, Featherstone WE et al (2010) Satellite altimetry for geodetic, oceanographic and climate studies in the Australian region. In: Vignudelli S, Kostianoy AG, Cipollini PJ, Benveniste J (eds) *Coastal altimetry*. Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-642-12796-0_18
- DFSI (2017) NSW Mine Subsidence Districts map. NSW Department of Finance, Services and Innovation, Subsidence Advisory <https://www.nsw.gov.au/sites/default/files/2021-12/nsw-mine-subsidence-all-districts-map-PP5228.pdf> Accessed 30 Jun 2017
- Durbin J, Watson GS (1950) Testing for serial correlation in least squares regression. I. *Biometrika* 37(3/4):409–428. <https://doi.org/10.2307/2332391>
- Folland CK, Parker DE, Colman AW, Washington R (1999) Large scale modes of ocean surface temperature since the late nineteenth century. In: Navarra A (ed) *Beyond El Niño: decadal and interdecadal climate variability*. Springer, Berlin Heidelberg, pp 73–102. https://doi.org/10.1007/978-3-642-58369-8_4
- Fox-Kemper B, Hewitt HT, Xiao C, Aðalgeirsdóttir GS, Drijfhout S et al (2021) Ocean, cryosphere and sea level change. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan CS et al (eds) *Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, United Kingdom and New York, 1211–1362. <https://doi.org/10.1017/9781009157896.011>
- Garner G, Hermans TH, Kopp R, Slangen A, Edwards T et al (2022) IPCC AR6 WGI sea level projections. https://doi.org/10.26050/WDC/AR6.IPCC-DDC_AR6_Sup_SLPr
- Haasnoot M, Kwakkel JH, Walker WE, Ter Maat J (2013) Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Glob Env Chang* 23(2):485–498. <https://doi.org/10.1016/j.gloenvcha.2012.12.006>
- Hague BS, McGregor S, Murphy BF, Reef R, Jones DA (2020) Sea level rise driving increasingly predictable coastal inundation in Sydney, Australia. *Earth's Futur* 8(9):e2020EF001607. <https://doi.org/10.1029/2020EF001607>
- Hague BS, Jones DA, Jakob D, McGregor S, Reef R (2022) Australian coastal flooding trends and forcing factors. *Earth's Futur* 10(2):e2021EF002483. <https://doi.org/10.1029/2020EF001607>
- Haigh ID, Eliot M, Pattiaratchi C (2011) Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. *J Geophys Res: Oceans* 116(C6). <https://doi.org/10.1029/2010JC006645>
- Hanslow DJ, Dela-Cruz J, Morris BD, Kinsela MA, Foulsham E et al (2016) Regional scale coastal mapping to underpin strategic land use planning in southeast Australia. *J Coast Res* 75(sp1):987–991. <https://doi.org/10.2112/SI75-198.1>
- Hanslow DJ, Morris BD, Foulsham E, Kinsela MA (2018) A regional scale approach to assessing current and potential future exposure to tidal inundation in different types of estuaries. *Sci Rep* 8(1):7065. <https://doi.org/10.1038/s41598-018-25410-y>

- Hanslow DJ, Fitzhenry MG, Power HE, Kinsela MA, Hughes MG (2019) Rising tides: tidal inundation in southeast Australian estuaries. In: Australasian coasts and ports 2019 conference: future directions from 400 [degrees] S and beyond, Hobart, 10-13 September 2019: future directions from 40 [degrees] S and beyond, Hobart, 520-526 Engineers Australia. <https://search.informit.org/doi/10.3316/informit.798968878931283>
- Hart RM (2017) Tidal dynamics and oscillations within coastal lakes of NSW. BSc (Hons) Thesis, University of Newcastle
- Hart RM, Power HE, Hanslow DJ (2017) Tidal dynamics and oscillations within coastal lakes. In: Australasian Port and Harbour Conference 572-578 Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand. <https://search.informit.org/doi/10.3316/informit.926038482321217>
- Hill KL, Rintoul SR, Coleman R, Ridgway KR (2008) Wind-forced low frequency variability of the East Australian Current. *Geophys Res Lett* 35:L08602. <https://doi.org/10.1029/2007GL032912>
- Hill KL, Rintoul SR, Ridgway KR, Oke PR (2011) Decadal changes in the South Pacific western boundary current system revealed in observations and ocean state estimates. *J Geophys Res* 16:C01009. <https://doi.org/10.1029/2009JC005926>
- Holbrook NJ, Goodwin ID, McGregor S, Molina E, Power SB (2011) ENSO to multi-decadal time scale changes in East Australian Current transports and Fort Denison sea level: oceanic Rossby waves as the connecting mechanism. *Deep Sea Res Part II: Top Stud Oceanogr* 58(5):547–558. <https://doi.org/10.1016/j.dsr2.2010.06.007>
- Hunter J (2012) A simple technique for estimating an allowance for uncertain sea-level rise. *Clim Change* 113(2):239–252. <https://doi.org/10.1007/s10584-011-0332-1>
- Khojasteh D, Hottinger S, Felder S, De Cesare G, Heimhuber V et al (2020) Estuarine tidal response to sea level rise: the significance of entrance restriction. *Est Coast Shelf Sci* 244:106941. <https://doi.org/10.1016/j.ecss.2020.106941>
- Khojasteh D, Hottinger S, Felder S, Cesare GD, Heimhuber V et al (2020b) Impact of sea level rise on hydrodynamics of estuaries with restricted entrances. *Coast Eng Proc* (36v), management.3. <https://doi.org/10.9753/icce.v36v.management.3>
- Kool R, Lawrence J, Drews M, Bell R (2020) Preparing for sea-level rise through adaptive managed retreat of a New Zealand Stormwater and Wastewater Network. *Infrastructures* 5(11):92. <https://doi.org/10.3390/infrastructures5110092>
- LMC (2012) Lake Macquarie Waterway Flood study. Report prepared for Lake Macquarie City Council. <https://floodata.ses.nsw.gov.au/dataset/lake-macquarie-waterway-flood-study-2012-report>. Accessed 25 Sept 2023
- LMC (2016) A plan for Marks Point and Belmont South to adapt to changing lake and flood levels. Volume 1: Summary. Lake Macquarie City Council, March 2016. 36p <https://shape.lakemac.com.au/2116/widgets/4951/documents/207547>. Accessed 25 Sept 2023
- LMC (2021) Local adaptation plan for future flooding and coastal risks pelican, blacksmiths, Swansea, Swansea heads and caves beach October 2021, Lake Macquarie City Council. <https://www.lakemac.com.au/files/assets/public/hptrim/land-use-and-planning-planning-management-plans-adaptation-plans/adaptation-plans-swans-ea-surrounds-adaptation-plan/swansea-phase-d/lap-for-future-flooding-pelican-blacksmiths-swans-ea-volume-1-final-lowres.pdf>. Accessed 25 Sept 2023
- Maiwa K, Masumoto Y, Yamagata T (2010) Characteristics of coastal trapped waves along the southern and eastern coasts of Australia. *J Oceanogr* 66:243–258. <https://doi.org/10.1007/s10872-010-0022-z>
- McInnes KL, White CJ, Haigh ID, Hemer MA, Hoeke RK et al (2016) Natural hazards in Australia: sea level and coastal extremes. *Clim Chang* 139(1):69–83. <https://doi.org/10.1007/s10584-016-1647-8>
- McPherson B, Young S, Modra B, Couriel E, You B et al (2013) Penetration of tides and tidal anomalies in New South Wales estuaries. In: Coasts and Ports 2013: 21st Aust Coastal and Ocean Eng Conf and the 14th Australasian Port and Harbour Conf. <https://search.informit.org/doi/10.3316/informit.828666686315143>
- MHL (2012). OEH NSW tidal planes analysis: 1990-2010 harmonic analysis. Manly Hydraulics Laboratory Report MHL2053. <https://s3-ap-southeast-2.amazonaws.com/www-data.manly.hydraulics.works/www/publications/tide/mhl2053%20OEH%20tidal%20planes%20analysis%20final%20report.pdf>. Accessed 25 Sept 2013
- MHL (2015) NSW ocean and river entrance tidal levels Annual Summary 2014–2015. Manly Hydraulics Laboratory Report MHL2384. <https://s3-ap-southeast-2.amazonaws.com/www-data.manly.hydraulics.works/www/publications/oeh/2015/MHL2384%20ocean%20tides%20annual%20summary%2014-15%20final.pdf>. Accessed 25 Sept 2023
- MHL (2018) NSW extreme ocean water levels. Manly hydraulics laboratory report MHL2236. Prepared for Office of Environment and Heritage. https://s3-ap-southeast-2.amazonaws.com/www-data.manly.hydraulics.works/www/publications/tide/mhl2236_NSW_Extreme_Ocean_Water_Levels.pdf. Accessed 25 Sept 2023
- MHL (2023) NSW tidal planes analysis 2001-2020 harmonic analysis. Manly Hydraulics Laboratory Report MHL2786. <https://s3-ap-southeast-2.amazonaws.com/www-data.manly.hydraulics.works/www/publications/oeh/reports/MHL2786%20NSW%20tidal%20planes%20analysis%202001-2020%20final.pdf>. Accessed 25 Sept 2023
- Modra B, Hesse S (2011) NSW ocean water levels. Proc NSW Coastal Conf, Tweed Heads. <https://www.coastalconference.com/2011/papers2011/Ben%20Modra%20Full%20Paper.pdf>. Accessed 25 Sept 2023
- Moftakhari HR, AghaKouchak A, Sanders BF, Feldman DL, Sweet W et al (2015) Increased nuisance flooding along the coasts of the United States due to sea level rise: past and future. *Geophys Res Lett* 42(22):9846–9852. <https://doi.org/10.1002/2015GL066072>
- Moftakhari HR, AghaKouchak A, Sanders BF, Allaire M, Matthew RA (2018) What is nuisance flooding? Defining and monitoring an emerging challenge. *Water Resour Res* 54:4218–4227. <https://doi.org/10.1029/2018WR022828>
- Morgan B, Blumberg G, Ling A, Nelson H (2014) Swansea channel dredging to improve navigation. NSW Coastal Conf, Ulladulla, NSW. <https://www.coastalconference.com/2014/papers2014/Ben%20Morgan%20full%20paper.pdf>. Accessed 25 Sept 2023
- Nerem RS, Chambers DP, Choe C, Mitchum GT (2010) Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Mar Geod* 33(Suppl 1):435–446. <https://doi.org/10.1080/01490419.2010.491031>
- Nielsen AF, Gordon AD (2008) The hydraulic stability of some large NSW estuaries. *Aust J Civ Eng* 5:1. <https://doi.org/10.1080/14488353.2008.11463937>
- Nielsen AF, Gordon AD (2015) The impact of entrance jetties on the hydraulics and ecologies of large estuaries. *Shore & Beach* 83(3):43–58
- NSW Govt (1990) Coastline management manual. NSW Government Printer
- NSW Govt. (2006) Lower hunter regional plan. NSW Department of Planning, NSW Government. DoP 2006_0034, ISBN 0-7347-5768-9
- NTC (2013) Tidal analyses for three locations in Lake Macquarie, New South Wales. National Tidal Centre, Bureau of Meteorology, April 2013
- OEH (2018) Estuaries of NSW: physical characteristics, tidal surveys and hydrographic surveys, <http://www.environment.nsw.gov.au/estuaries/list.htm>. Accessed 26 Jun 2018
- Palmer K, Harris RM, Watson CS, Hunter JR, Power HE (2021) Coastal lake tidal range amplifies sea-level threat in Lake

- Macquarie, Australia. Aust Coasts & Ports 2021 Conf – Christchurch, 30 November – 3 December 2021. https://www.coastsandports.org/papers/2021/159_palmer_finalpaper.pdf. Accessed 25 Sept 2023
- Roemmich D, Gilson J, Davis R, Sutton P, Wijffels S et al (2007) Decadal spinup of the South Pacific subtropical gyre. *J Phys Oceanography* 37:162–173. <https://doi.org/10.1175/JPO3004.1>
- Short AD (1988) Areas of Australia's coast prone to sea-level inundation. In: Pearman GI (ed) *Greenhouse: planning for climate change*, pp 93–104. CSIRO Publishing, Victoria
- Stephens SA, Bell RG, Lawrence J (2018) Developing signals to trigger adaptation to sea-level rise. *Env Res Let* 13(10):104004. <https://doi.org/10.1088/1748-9326/aadf96>
- Sweet WV, Park J (2014) From the extreme to the mean: acceleration and tipping points of coastal inundation from sea level rise. *Earth's Futur* 2(12):579–600. <https://doi.org/10.1002/2014EF000272>
- Sweet WV, Menendez M, Genz A, Obeysekera J, Park J, Marra JJ (2016) In tide's way: Southeast Florida's September 2015 Sunday Flood. *Bul Am Meteorol Soc* 97(12):S25–S30. <https://www.jstor.org/stable/26265424>. Accessed 25 Sept 2023
- Thompson PR, Widlansky MJ, Hamlington BD, Merrifield MA, Marra JJ et al (2021) Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Clim Change* 11(7):584–590. <https://doi.org/10.1038/s41558-021-01077-8>
- Umwelt (2013) Towards a sustainable framework for navigation in Swansea Channel. Framework Report for NSW Crown Lands Umwelt (Australia) Report No: 3089_RO2 https://www.industry.nsw.gov.au/__data/assets/pdf_file/0010/169552/Sustainable-framework.pdf. Accessed 25 Sept 2023
- Viola CN, Verdon-Kidd DC, Hanslow DJ, Maddox S, Power HE (2021) Long-term dataset of tidal residuals in New South Wales, Australia. *Data* 6(10):101. <https://doi.org/10.3390/data6100101>
- Wahl T, Haigh ID, Nicholls RJ, Arns A, Dangendorf S et al (2017) Understanding extreme sea levels for broad-scale coastal impact and adaptation analysis. *Nature Coms* 8:16075. <https://doi.org/10.1038/ncomms16075>
- Wainwright D, Callaghan D, Howe A, Hanslow D (2018) Probabilistic hazards assessment methodology to support local adaptation planning in Lake Macquarie. NSW Coastal Conf, Bega NSW. <https://www.coastalconference.com/2018/papers2018/David%20Wainwright.pdf>. Accessed 25 Sept 2023
- Watterson EK, Burston JM, Stevens H, Messiter DJ (2010) The hydraulic and morphological response of a large coastal lake to rising sea levels. Proc NSW Coastal Conf. <http://www.coastalconference.com/2010/papers2010/Evan%20Watterson%20full%20paper.pdf>. Accessed 25 Sept 2023
- White NJ, Haigh ID, Church JA, Koen T, Watson CS et al (2014) Australian sea levels-Trends, regional variability and influencing factors. *Earth-Sci Revs* 136:155–174. <https://doi.org/10.1016/j.earscirev.2014.05.011>
- Woodham R, Brassington GB, Robertson R, Alves O (2013) Propagation characteristics of coastally trapped waves on the Australian continental shelf. *J Geophys Res Oceans* 118. <https://doi.org/10.1002/jgrc.20317>
- Woodhouse S (2017) Citizen science and foreshore inundation – tidal valves. Report to Local Government NSW https://lgnsw.org.au/common/Uploaded%20files/Environment/BRCC%20Case%20Studies/7.%20Lake_Macquarie_TidalValves.pdf. Accessed 25 Sept 2023
- You ZJ, Nielsen P, Hanslow DJ, Pritchard T (2012) Elevated water levels at trained river entrances on the east coast of Australia. *Proc Int Coastal Eng Conf, Spain*. <https://doi.org/10.9753/icce.v33.currents.48>
- Zhang X, Church JA, Monselesan D, McInnes KL (2017) High resolution sea level projections for Australian Coasts in the 21st Century. *Geophys Res Let* 44. <https://doi.org/10.1002/2017GL074176>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.