Geoinformatics vulnerability predictions of coastal ecosystems to sea-level rise in southeastern Australia

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ABSTRACT
Coastlines are dynamic environments, with their Eco-geomorphology controlled by a complex range of natural and anthropic processes. Estuarine environments and associated wetland ecosystems are a critical shoreline types with regards to biodiversity, and are particularly susceptible to the influence of sea-level rise. This project applied future sea-level rise of Intergovernmental Panel on Climate Change (IPCC) hydro-scenarios to assess its impact on the eco-geomorphic aspects of coastal ecosystems in terms of risk assessment and sustainability. Comerong Island is used as a case study and is compared with other surrounding ocean-influenced and lagoonal deltas to assess the regional effects of sea-level rise. Applying the IPCC scenarios to the chosen geomorphic coastal data-sets resulted in a hydro-geomorphic model that shows the study site was already under pressure in 2015, with significant land area projected to be lost by 2050 and 2100. These findings are also expected to occur across the remaining estuaries in southeastern Australia. Applying this broad-scale, multi-strand application of geoinformatics simulation (GIS & RS), together with the various IPCC sea-level rise scenarios, will be necessary to assess future ecosystem sustainability management plans for coastal zones worldwide.

KEYWORDS
Ecosystems vulnerability; climate changes; remote sensing (RS); GIS modelling; coastal conservation

1. Introduction
The earth as a planet has had balanced and sustainable Holocene ecosystems (eco-sustainability) for thousands of years (Tilman et al. 1996; Michener et al. 1997; Siddall et al. 2003). Although it has faced fluctuating Quaternary weather conditions (Fairbanks 1989), like glaciations followed by warm periods (Siddall et al. 2003), its coastal ecosystems have become balanced and stabilized during the Holocene, especially within last 4000 years in Australia (Michener et al. 1997; Watson 1999; Troedson et al. 2004; Steffen et al. 2009). However, during the last century, the increased population and rural, urban and industrial pollution have stressed these coastal ecosystems, and even overloaded them, threatening the ecosystem’s balance and even its loss (Parmesan and Yohe 2003; Neumann et al. 2015; Al-Nasrawi, Jones, Alyazichi, et al. 2016; Al-Nasrawi, Jones, and Hamylton 2016). For example, temperature increases during the twenty-first century as a result of CO₂ emissions are causing climate change and mean sea-level rise (IPCC 2014), significantly threatening many ecosystems, especially coastal environments such as wetlands (Michener et al. 1997; IPCC 2014).
Mean sea level started to rise globally in the nineteenth century, but significant rises have occurred since the 1950s and it has been estimated that the sea level will continue to rise throughout the twenty-first century (Nicholls et al. 1999; Hughes 2003; Meyssignac and Cazenave 2012; IPCC 2013, 2014; Deconto and Pollard 2016). Based on a range of CO₂ emission scenarios, the sea level is expected to rise by 26–55 cm by 2100 AD under low emission estimates, whereas high estimates suggest a rise of 52–82 cm according to IPCC (2013). Moreover, under the most popular projections, it is probable that the rate of sea-level increase will exceed the records from 1971–2010 based on the current global warming rates and gas emissions that will lead to increased ice-sheet melting. In fact, the post-1990 rate of sea-level rise is already faster than in the preceding 20 years (Michener et al. 1997; Church et al. 2013; IPCC 2013, 2014).

Within the last few decades, scientists and the United Nations Intergovernmental Panel on Climate Change (IPCC) have outlined a range of future emission scenarios to explain the existing and forecast future geomorphological responses to sea-level rise. Many of these methods depend on digitizing and analysing remote-sensing (RS) data. Several methods have been developed to simulate geomorphological surfaces to create digital elevation models (DEMs; Arun 2013). Examples of models include elevation changes within coastal ecosystems that have led to the invention of several methods and devices, such as Sediment Erosion Tables (SETs) designed by Boumans and Day (1993), and its subsequent modification to Surface Elevation Tables allowing very accurate surface dynamic measurements (Boumans and Day 1993; Cahoon et al. 2002; Whelan et al. 2005). However, SETs are generally costly, have a limited areal coverage and take a long time to obtain accurate trend results. SETs may need up to 20 years on average to get accurate results (McIvor et al. 2013; Cahoon 2015). Thus, since higher resolution and more accurate RS data have become available to represent geomorphological surface patterns (Patel et al. 2016), like Light Detection and Ranging (LiDAR) cloudsed data-sets (Gillin et al. 2015), environmental scientists have been using the DEM as a surface dynamic analyser. It is accurate enough, cheaper and faster than using SETs and can be based on several modelling methods (White and Wang 2003; Gillin et al. 2015). DEM analyses may be utilized as ecosystem management, modelling and decision-support tools (NPWS 1998; Haq et al. 2012; Arun 2013).

DEM analyses are used to measure characteristic geomorphological aspects of the surface (Wood 1996). Several software tools can be used to create DEMs (Omran 2016). However, a geographic information system (GIS) provides the most advanced and accurate results that can be achieved at present (White and Wang 2003). A number of data-sets, like Shuttle Radar Topographic Mission (SRTM) and LiDAR data-sets, can be used to suit the purpose of making the DEMs (White and Wang 2003). A GIS format can be developed to characterize three specific objectives, namely, to identify spatial patterns, to identify scale dependency in form and to allow visualization of results (Wood 1996).

Approximately one-third to half of the major coastal environments on earth have been degraded, including eastern Australian coastal wetlands, during the past decades (Valiela and Fox 2008; Saintilan and Williams 2010; Al-Nasrawi, Jones, and Hamilton 2016). An additional 6%–22% of sensitive coastal ecosystems (such as coastal wetlands) are expected to be lost by 2080, with little anthropogenic contribution, by applying different natural climate change scenarios (Nicholls et al. 1999). However, human activities are likely to have more impact than the magnitude of sea-level rise on the future of wetlands during the twenty-first century (IPCC 2013, 2014). Losses of 36%–70% by 2080 are expected by considering combined natural and human change scenarios (Michener et al. 1997; Wall 1998; Nicholls et al. 1999; Morris et al. 2002; Nicholls 2004).

### 1.1. Case study and setting

Comerong Island, 120 km south of Sydney in southeastern NSW, Australia (Figure 1(a)), is used as a main case study to show the influence of mean sea-level changes on changing the island’s elevation and ecosystems. Comerong Island is located at the end of the Shoalhaven and Crookhaven Rivers,
and represents an example of large-scale biodiversity habitats like saltmarsh and mangrove (and their associated oysters, fish, animals and birds) where the shorelines and vegetation extent are being influenced by climate change (Kingsford 1990; Thompson 2012; Al-Nasrawi, Jones, and Hamylton 2016; Al-Nasrawi, Hamylton, Jones, and Kadhim 2018). Comparative study sites with different geographic settings include Wandandian Creek delta (Figure 1(b)), Towamba estuary near Eden (Figure 1(c)) and the Macquarie Rivulet and Mullet/Hooka Creek deltas in Lake Illawarra (Figure 1(d)).

Comerong Island is mostly made of sand, and it has important coastal wetlands that have existed for thousands of years. Situated east of the Southern Highlands, the riverine and coastal area is now degraded in its ability to adjust ecologically and geomorphologically as a result of human settlement, landscape modification and sea-level rise. This has culminated in a series of changes in the coastal wetlands and the distribution of habitats like saltmarshes and mangroves (Thompson 2012; Al-Nasrawi, Jones, and Hamylton 2016).

The major natural processes affecting coastal wetlands into the future are likely to be Global Mean Sea-Level Rise (GMSLR), erosion, sedimentation and altered rainfall patterns. These processes will initiate changes to the long-term average wetlands distribution and drive habitat changes in the future. Other factors such as salinity, rainfall and flooding are also likely to have an impact on the distribution of coastal environments. The processes currently affecting Comerong Island, and the level of influence that each process has on the coastal wetland growth/persistence, need to be understood. Previous studies on Comerong Island have shown clear shoreline erosion and wetland losses on the western side, adjacent to Berry Canal (southwestern), and the southern and middle portions of the island (Figure 2; Thompson 2012; Al-Nasrawi, Jones, and Hamylton 2016; Al-Nasrawi, Hamylton, Jones, and Kadhim 2018).

This paper has focused on southeastern NSW to investigate the possible future responses to environmental changes caused by GMSLR. Several parameters of the coastal ecosystems need to be addressed in order to estimate and apply a suitable modelling approach. Such parameters include historical shoreline responses, grain-size distributions and their vulnerability to tidal dynamic stressors. Meanwhile, it should be understood that tidal planes (levels) up an estuary will change depending on the estuarine type and shape. The study site is recognized as having a significant ecological value and the island is mostly classified as a conservation area under NSW biodiversity legislation/State Environmental Planning Policy (SEPP-14), which aims to ensure preservation and protection of the wetlands both environmentally and economically. For these reasons, future sustainability of the coastal ecosystems needs to build on the previous investigation by Al-Nasrawi et al. (2016b) that assessed the existing situation on Comerong Island and its past temporal and spatial changes.

The historical and current situations on the island have been checked and mapped by Al-Nasrawi et al. (2016b) using aerial photographs and RS data for 1949, 1961, 1970, 1981, 1993, 2002 and 2014 (Figure 4 in Al-Nasrawi, Jones, and Hamylton 2016). These analyses have shown significant shoreline changes around Comerong Island; the northern part of the island has expanded by 0.41 km², whereas, the western, southwestern and southern parts have been eroded by 0.73 km² (Figure 2; Thompson 2012; Al-Nasrawi, Jones, and Hamylton 2016). This situation has resulted from interrupting the natural sediment delivery and erosion/deposition cycles (Al-Nasrawi, Jones, Alyazichi, et al. 2016). The eco-geomorphic processes around Comerong Island have been significantly influenced by human infrastructure upstream, such as the Tallowa Dam, and the increased fine sediment runoff from agricultural land. These changes, combined with the rising ocean tidal prism, have caused a reduction in sediment delivery that cannot balance the erosion/deposition around the island caused by natural processes (Thompson 2012; Al-Nasrawi, Jones, Alyazichi, et al. 2016; Al-Nasrawi, Jones, and Hamylton 2016).

Grain-size analysis of 113 sediment samples (Figure 3) has shown the vulnerability of Comerong Island, which mostly consists of sand (96.4%; Al-Nasrawi, Jones, and Hamylton 2016). This sandy non-cohesive sediment means that tidal currents associated with GMSLR will have a greater effect...
Figure 1. New South Wales location in Australia showing: (a) the study site, Comerong Island, in southeastern NSW, with a complicated mostly intertidal eco-geomorphic wetlands system created by tidal and river interactions, and the comparative examples on the southern NSW coast, (b) Wandandian delta, (c) Towamba estuary and (d) Macquarie Rivulet and Mullet/Hooka Creek deltas in Lake Illawarra.
on Comerong Island and its ecosystems than if there was a rocky foreshore. Although, most coastal wetlands in NSW have ecosystems developed on unconsolidated sediments, Comerong Island has an additional sediment delivery problem caused by the construction of Tallowa Dam on the main Shoalhaven River, which has limited the amount of sediment derived from the sixth largest

Figure 2. Study site at Comerong Island in southeastern NSW, Australia, showing the complicated mostly intertidal eco-geomorphic wetlands system created by tidal and river interactions (after Al-Nasrawi, Jones, and Hamylton 2016).

Figure 3. Sand content in sediment samples from grain-size analysis, Comerong Island (after Al-Nasrawi, Jones, and Hamylton 2016).
catchment in NSW (7177 km²). Altogether, these factors are likely to increase erosion rates and decrease the amount of deposition at the same time.

Four other study sites have been investigated to examine the proposed methods, geomorphic settings and to prove the study findings. They are Wandandian delta (Al-Nasrawi et al. 2017), Towamba estuary (Al-Nasrawi, Hamylton, Jones, and Kadhim 2018), Macquarie Rivulet delta and Mullet/Hooka Creek delta (Hopley 2013; see Figure 1).

The delta of Wandandian Creek has actively prograded into western St. Georges Basin, about 155 km south of Sydney (Figure 1(b)). Outcrops of the Permian shallow-marine Snapper Point Formation can be observed along the southwestern shore of the delta while the northwestern shoreline is marked by outcrops of the overlying deeper-marine Wandrawandian Siltstone. Wandandian Creek is about 25 km long with its headwaters located on the Tianjara Range to the west of the delta (Windley 1986; Hopley and Jones 2006).

The Towamba estuary is located on the southeast coast of New South Wales near Victoria ~385 km south of Sydney, Australia (Figure 1(c)). The main coastal ecosystem in the Towamba estuary is located at the end of the Towamba River delta where the active tidal channel has an average depth of 1.14 m. Towamba estuary is mostly surrounded by rock outcrops, resulting in restricted estuarine shape (Figure 1(c)). According to Roy et al.’s (2001) classification, it is a wave-dominated estuary and estuarine barrier in mature stage of ecosystem development.

The Macquarie Rivulet delta and Mullet/Hooka Creek delta are part of Lake Illawarra system. They are river- and wave-dominated deltas, respectively, located ~80 km south of Sydney, Australia (Figure 1(d)). The lake is relatively shallow (~3.5 m maximum) with a total surface area of 35 km². Morphologically, the total catchment area of the lake is approximately 235 km² with 12 waterways draining five sub-catchments, including Macquarie Rivulet (96.4 km²) and Mullet Creek (75.2 km²). The Macquarie Rivulet and Mullet/Hooka Creek deltas are actively prograding from the western margin of Lake Illawarra (Hopley et al. 2007; Hopley 2013).

2. Methodology

The geomorphic–hydrodynamic numerical model combines the geomorphological land data-sets with the local sea-level hydrodynamic data. The proposed method is based on LiDAR data point clouds that reflect the island’s surface elevation (ground level as a geomorphological landscape data-set) and incorporate the IPCC (2013, 2014) hydrodynamic variable scenarios that estimate the future position of sea level around the island. According to IPCC (2013, 2014), sea level is estimated to rise by 26–82 cm by 2100 (Figure 4 and Table 1), and this needs to be taken into account when assessing future sustainable approaches to wetland conservation that may be applicable to the eastern Australian coast and similar ecosystems worldwide.

Based on IPCC (2013, 2014) projections, this paper quantifies the local GMSLR (as a hydrological function), the island elevation and erosion rates (as geomorphological variables), and then applies these using GIS analysis tools. A detailed geomorphic assessment of erosion within the coastal zone of the study site has been done (Al-Nasrawi, Jones, and Hamylton 2016). It started by looking at historical mapping and aerial photographs to determine how the local area/shoreline has changed over time to see which areas are eroding and by how much per year, and then applying these rates to future long-term scenarios.

The GIS analysis was accomplished by using ArcScene10.2 and its animation manager tools as follows. First, use the generated DEM (as a raster) and add a simple polygon covering the study site (as the second layer), and then convert the area to ‘ScenLayers’. Second, from the raster properties, choose Display, Cubic Convolution (for continuous data) and then choose Base Heights; floating on a custom surface, change the custom default elevation (to 300 or whatever would make a logical 3D shape). After that, go to the ScenLayers properties and choose Calculate from Extent. Finally, open the Animation manager tool and create an Animation Key frame (for the polygon), then add a
number of these keys and change their ‘Z’ value to the IPCC (2013, 2014) future scenarios, as decided above (24 and 82 cm). Then, simply run and save the scenarios via the Animation control panel.

The available geomorphic data from Comerong Island are sufficiently accurate to model a range of scenarios covering the IPCC (2013, 2014) GMSLR predictions. This paper has tested the extreme projections as well the predicted average GMSLR. Models have been produced to test the current (2015) distribution and the predictions for 2050 and 2100 for sea-level rises of 26 and 82 cm, which is a reasonable approach within the Comerong Island area. Thus, this paper has quantified the range of predictions for mean estimated levels for the twenty-first century. Furthermore, the geomorphological data-sets for the island and the hydrological dynamic factors affecting the shoreline changes and erosion rates have been applied independently to the existing wetland mapped for another study based on the historical and existing situations at the same study site (Al-Nasrawi, Jones, and Hamylton 2016; Al-Nasrawi et al. 2017; Al-Nasrawi, Hamylton, and Jones 2018). Sedimentation rates are an important component that depends on a number of external factors including catchment contributions. Therefore, addressing all relevant factors using empirical data is the safest approach to gain results that reflect the existing situation and any future predictions.

Geoinformatic (GIS and RS) techniques (e.g. LiDAR data-cloud; LPI 2010) have contributed important roles in representing and digitizing the geomorphological surface covers to assess the

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Table 1. Projected change of Global Mean Sea-Level Rise (GMSLR) for the mid and late twenty-first century, by simulating the time-series from the 1986–2005 period (IPCC 2014).

| Scenario | 2050   | Likely range a | 2100   | Likely range a |
|----------|--------|----------------|--------|----------------|
| GMSLR (m)b | 0.24   | 0.17–0.32      | 0.40   | 0.26–0.55      |
| RCP2.6   | 0.24   | 0.17–0.32      | 0.40   | 0.26–0.55      |
| RCP4.5   | 0.26   | 0.19–0.33      | 0.47   | 0.32–0.63      |
| RCP6.0   | 0.30   | 0.22–0.38      | 0.63   | 0.45–0.82      |
| RCP8.5   |        |                |        |                |

a Calculated from projections of 5%–95% model ranges. These ranges are then assessed to be likely ranges after accounting for additional uncertainties or different levels of confidence in the models. For projections of GMSLR, confidence is medium for both time-horizons (IPCC 2014).

b Based on 21 CMIP5 models; changes are calculated with respect to the 1986–2005 period. Based on current understanding (from observations, physical understanding and modelling), only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause the global mean sea level to rise substantially above this likely range during the twenty-first century. There is medium confidence that this additional contribution would not exceed several tenths of a metre of sea-level rise during the twenty-first century” (IPCC 2014).

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Figure 4. Global mean sea-level rise between 2006 and 2100, by simulating and multi-modelling time-series data from 1986 to 2005. The red and blue lines are the mean estimates, and the red and blue bands are the estimated uncertainties of the scenarios that have a likely range of ~±7 cm for 2050 and ~±15 cm for 2100 (IPCC 2014-AR5/SYR/SPM; Table 1).
influences of natural disasters and climate-change patterns like GMSLR (Haq et al. 2012; Arun 2013; Mohamed et al. 2013). This study is based on manipulation of the LiDAR data-set (point-cloud elevations and DEM) and comparison with measured tidal planes at the tidal monitoring station closest to the most affected parts of the island – the Greenwell Point station (Figure 2) located at the middle of Crookhaven River on the southern-side of Comerong Island. A new modelling method based on RS data and GIS has been used for the study site. It used a standard airborne LiDAR survey carried out by the NSW Government in 2010 using a Leica ALS50-II that was integrated with a RCD105 digital camera. The LiDAR data are prepared/pre-processed by the Land and Property Information (LPI) engineers to a minimum density of 1 point-cloud per square metre (representing a minimum 1 m², but averaged 0.8 m²) for spatial resolution, and less than 30 cm for vertical accuracy to create a DEM with 95% confidence to conform with a category 1 DEM as instructed by Intergovernmental Committee on Surveying and Mapping guidelines for specifications of digital elevation data (LPMA 2010). LiDAR data are free of charge for research purposes and a data-licence from LPI can be requested through the scientists’ institution.

This paper focuses on the hydrodynamic and geomorphic processes that will be influenced by sea-level rise and cause considerable modification of the mean levels of the tides. These elevated tidal levels were then applied as the model boundaries and were related to the Comerong Island surface elevations. Such models are commonly used for modelling rivers, estuaries, coasts and flooding, using various aspects of the ArcGIS toolbox. They create contours and a triangulated irregular network (TIN) and then a DEM, as shown in Figure 5, using an example applied from the southern-part of the study site.

3. Results

The Department of LPI in NSW provided LiDAR survey data that covered most of the eastern and southeastern NSW coasts (LPI 2010). These data record the surface elevation as heights (Z-values) relative to a local zero-level datum. The data also incorporate the actual local mean sea level at the time of the survey according to the local ground base-stations for tidal/time dynamics, including the Crookhaven Heads, Shoalhaven Heads and Greenwell Point stations. The recorded surface elevations at Comerong Island ranged from −0.17 to 9.75 m and a DEM was generated using a TIN and the contour spatial analyst tools in ArcGIS.

After creating the DEM, a hydrodynamic numerical model has been used to simulate future GMSLR influences. So, by increasing the water level by 26 cm (as 2050 scenario) and 82 cm (as 2100 scenario), the island will show its new boundaries and shape. In other words, Z-value manipulation of the LiDAR data-set has defined the increasing areas of inundation affected by a continuously rising sea level up to the maximum 0.82 m according to the IPCC (2013, 2014) scenarios.

The geomorphic–hydrodynamic numerical model, which combines the geomorphological land data-sets with the local sea-level hydrodynamic data, has simulated future GMSLR scenarios technically to estimate and detect the areas that will be inundated during the twenty-first century. Such assessments can be used to determine the sustainability of ecosystems and for risk management studies.

Applying this methodology has resulted in the production of clear and significant future vulnerability maps that delineate the changes expected to affect Comerong Island starting with the current stage based on 2010 LiDAR data, and subsequent changes within the next 50 and 100 years. Results show that Comerong Island was under pressure in 2015 (as shown in red in Figure 6(b)) compared with the LiDAR data obtained in 2010 (Figure 6(a)), and about 18% of the island will be covered by sea water by 2050 (Figure 6(c)). Greater influences become apparent at the study site in 2100 when approximately 43% of the island will be lost if the 82 cm maximum average sea-level rise scenario is used (Figure 6(d)). Ground losses will occur particularly within the low elevations of the island surface, which are currently covered by sensitive mangrove and saltmarsh habitats.
Figure 6(d) presents the IPCC-2100 scenario on Comerong Island but because of the ongoing hydraulic activity, especially wave action and tidal currents, this whole area will be more open to erosion and the entire southern portion (sandy substrates; see Figure 3) would be reworked and rounded with most of the remaining beach ridges and sandspits, also being reworked and truncated. The mapped changes in Figure 6(d) also illustrate that the only remaining areas are elevated beach ridges that may support Casuarina, but not saltmarsh or mangroves, resulting in an almost total loss of the coastal wetland habitat on the island.

Similar losses of wetland habitat would also occur on most other southeastern Australian lagoons and inlets as the sediment supply and lateral migration of wetlands are unlikely to be able to keep pace with the predicted GMSLR. To establish the degree of applicability of these modelling approach examples, different locations along the southeastern Australian coast have been investigated using appropriate data-sets/tools to yield similar results of future inundation estimates.

Wandandian Creek delta is located on the NSW south coast, about 30 km southwest of Comerong Island (Hopley and Jones 2006; Figure 1(b)). It drains a moderately altered catchment and extends out into the western portion of St. Georges Basin, a large lagoon that is subjected to moderate wave action during strong south-easterly winds (Al-Nasrawi et al. 2017). Using equivalent LiDAR data-sets from Wandandian Creek delta modelled with Arc Hydro 10.2 tools (an ESRI extension tool), the majority of the subaerial portions of the delta will be inundated by 2100.
Figure 7. Again, wave-reworking of the thin levee sequences would occur as inundation proceeds removing still more of the protruding delta. Figure 7(d), again, shows significant losses of the low-lying landforms at Wandandian delta, which would result in almost total loss of these coastal wetlands by the end of 2100 AD.

The Towamba estuary is located on the far south coast of NSW ~255 km south of Comerong Island (Figure 1(c)), draining a predominantly forested catchment. This bedrock-enclosed estuary lies within Twofold Bay and is open to northeastern wave and wind activity. Like Comerong Island, this estuary is protected by a coastal sandspit which, in this case, is much narrower than the equivalent geomorphic units at Comerong Island. The analysis used an equivalent LiDAR data-set but with ‘Hydrologic Engineering Centre–River Analysis System tools’ (HEC-RAS v5.0.3) including the steady flow analysis and sediment analysis tools (HEC 2017), which represent totally different forecasting analysis tools. After modifying and presenting the results in the ArcGIS 10.2 format, it resulted in similar future predictions of inundation in the Towamba estuary (Figure 8). Figure 8(d) shows clear losses of the low-lying geomorphological features in the Towamba estuary. However, in contrast to Wandandian Creek delta, the coastal spit at Towamba estuary remains intact with only a small estuary entrance even in 2100 AD. Therefore, the flooded estuary would not be subjected to wave action but increased tidal flows may scour some of the partially flooded sandbanks.
The net effect is the Towamba coastal wetlands may be lost in totality by the end of the twenty-first century.

Hopley (2013) has predicted the potential inundation extent, attributable to sea-level rise, for the Macquarie Rivulet and Mullet Creek deltas, Lake Illawarra (35 km north of Comerong Island; see Figure 1(d)). The predicted inundation extents were determined using a high resolution LiDAR data-set overlain with the NSW sea-level rise policy statement of 2050 (+0.4 m) and 2100 (+0.9 m) projected sea-level rise scenarios and current water elevations relative to mean sea level. To illustrate the inundation extent, Hopley (2013) adopted a simple approach where the DEM scales and colour ramps were modified to align with the nominated scenarios. Despite this simpler approach, Hopley’s results show future estimates of inundation and wetland loss at the Macquarie Rivulet delta (Figure 9 (a)) and Mullet/Hooka Creek delta (Figure 9(b)) similar to those identified in this study. GMSLR has a greater effect on the Macquarie Rivulet delta than Mullet/Hooka Creek delta due to the rapid progradation of Macquarie Rivulet delta, limiting vertical accretion as mapped by Hopley et al. (2007). Irrespective, the models indicate that the existing coastal wetlands are likely to be lost by the end of 2100 AD. This is also supported by Hopley (2013) who noted that subsidence of the Macquarie Rivulet delta is already resulting in the loss of wetlands.

Figure 7. Applying future GMSLR scenarios (IPCC-AR5/RCP8.5) to the Wandandian Creek delta site: (a) current Wandandian delta (LiDAR data 2016), (b) the existing situation under stressors (2017 with threatened shorelines in red highlighted), (c) Wandandian delta in 2050 and (d) Wandandian delta in 2100.
4. Discussion

NSW intertidal estuarine platforms with their associated ecosystems are located along one of the most globally wave-dominated and vulnerable coasts, exposed to sea-level rise and the increasing frequency of extreme climatic events, saline intrusions and reduced sediment and nutrient loads from their respective catchments (Al-Nasrawi, Jones, and Hamylton 2016; Al-Nasrawi et al. 2017; Al-Nasrawi, Hamylton, and Jones 2018; Al-Nasrawi, Hamylton, Jones, and Kadhim 2018). These combined influences threaten the preservation of coastal assets, which need to be considered and investigated worldwide as an essential conservation imperative. The complexities of modern pressures plus human activities, such as strategies of the institutions to polarize, have created inertia of decision-making for appropriate adaptations (Smajgl et al. 2015). Thus, a greater understanding about all these stressors will help to provide a more comprehensive overview for decision-making. This study has concentrated on climate change and sea-level rise as the primary environmental factors that affect estuarine eco-geomorphology, leaving the other anthropogenic stressors for future studies. Our strategy proposes that an accurate method of representing the IPCC scenarios is by adapting a mix of both GIS analytic tools and modern RS technologies, including LiDAR data-sets, to estimate future sea-level risk and inundation distributions.

Figure 8. Applying future GMSLR scenarios (IPCC-ARS/RCP8.5) to the Towamba estuary site: (a) current Towamba estuary (LiDAR data 2016), (b) the existing situation (2017 with threatened shorelines in red highlighted), (c) Towamba estuary in 2050 and (d) Towamba estuary in 2100.
Ecosystems in estuarine–coastal wetlands may experience declining sediment supply caused by anthropogenic modifications within the catchment region. This will lead to less ecological–geomorphological interactions/responses, which can increase the vulnerability of wetlands’ ecosystem (Lovelock et al. 2015). An accelerating rate of sea-level rise that is higher than the rate of sediment supply will lead to accretion deficits within low-lying wetlands. This is happening within most of these study sites and in most coastal environments worldwide. A few relatively unmodified catchments may be supplied with higher sediment loads from the catchment to maintain the estuaries’ surface elevation (e.g. Al-Nasrawi, Hamylton, and Jones 2018; Al-Nasrawi, Hamylton, Jones, and Kadhim 2018). This is the case in the Towamba estuary, and in similar estuaries globally, where the exposed wetland surface is keeping-up with sea-level rise.

Inundation of wetlands is one of the main influences of sea-level rise on most coastal environments since they lie within tidal zone. This causes many consequential changes within coastal wetland ecosystems, including declining saltmarsh habitat and mangrove retraction. North American scientists (Torio and Chmura 2013; Kirwan et al. 2016) have recently highlighted that coastal vulnerability pressure is causing wetlands, particularly saltmarshes, to migrate landwards (which matches the Comerong Island-estuary and Lake Illawarra case studies), unless this is prevented by man-made structures or surrounding high-sloped terrestrial topographic surfaces (Kirwan et al. 2016), which is the case at the Wandandian and Towamba sites. Wetlands studies in western Europe and the United Kingdom (Van Der Wal and Pye 2004; Van Der Wal et al. 2008; Kirwan et al. 2016) have shown them to become more restricted in size and number within the past few decades caused by continued coastal erosion and inundation together with limited landward ecosystem movement resulting from surrounding human infrastructure (Kirwan et al. 2016). Remarkably, these wetland studies indicated that vertical accretion occurred at a similar rate to sea-level rise, highlighting that evaluation of both the horizontal and vertical distribution of wetlands is an essential component of wetland vulnerability assessments for risk management and environmental planning (Hinkel et al. 2015).

The possible landward movement of coastal wetlands will have a significant influence on wetland survival as sea-level rises, provided there are no boundary limitations to inland movement. The impact of erosion will be concentrated along the open coast to a much greater extent than in estuaries and lagoons. The survival of coastal wetland ecosystems will rely on the possibility of landward movement during a transgression as much as on sediment supply and conservation efforts.

Figure 9. Potential inundation map of (a) Macquarie Rivulet delta (Hopley 2013) and (b) Mullet/Hooka Creek delta (Hopley 2013). Maps show 2050 and 2100 inundation extents plus the 2050 and 2100 inundation extents with an additional 0.25 m overlain to reflect the current elevated water level within the lagoon.
The current study sites are typical of most of the estuarine systems in southeastern Australia, and globally, where sediment supply is graded to current sea level and wetland ecosystems have become well established through the mid to late Holocene. The rate of infilling of these estuarine systems is dependent on the rate of sediment supply from the catchment. Comerong Island lies at the mouth of the extensively infilled Shoalhaven estuary (Umitsu et al. 2001), where abundant sediment was supplied from a very large catchment. In contrast, Wandandian Creek delta has only prograded a short distance into St. Georges Basin since it is fed from a much smaller catchment. Human influence has also affected sediment supply, whereby, essentially natural catchments such as Towamba estuary have seen very little change in sediment supply whereas the Lake Illawarra catchment has experienced moderately significant changes in sediment supply caused by agricultural and urban development (Hopley et al. 2007) and the Shoalhaven catchment initially had both agricultural and urban development but has subsequently had a large reduction in sediment supply caused by the construction of Tallowa dam (Al-Nasrawi, Jones, Alyazichi, et al. 2016).

Thus, sea-level rise will have a significant influence on the coastal eco-geomorphic systems throughout southeastern Australia and equivalent systems overseas by the end of the twenty-first century. This would particularly affect the coastal wetlands as they are the most sensitive and responsive coastal ecosystems as clearly seen by the results from Comerong Island and other southeast Australian examples. These examples show predicted extensive to total losses of coastal wetlands locally, which can be extrapolated regionally and globally, unless they have a high-enough sediment supply to maintain shallow subaqueous platforms suitable for wetland development. However, wetlands’ movement toward inland might also have the opportunity to grow and develop as the rising sea level may inundate low-lying coastal plains. That could occur where suitable low-sloped estuaries and catchments occur, such as west of Comerong Island where the Shoalhaven alluvial plain is not far above the current sea level. To a lesser extent, the floodplains behind the Macquarie Rivulet and Mullet/Hooka Creek deltas could be partly inundated to form wetlands. However, this would not be the case for higher sloped estuaries, including the Towamba estuary catchment, where low-lying floodplains are not present.

5. Conclusions

This paper provides significant results from case studies about future vulnerability of eastern Australian coastal ecosystems, in a geomorphological context, to IPCC (2013, 2014) GMSLR scenarios.

Assessing eco-geomorphic coastal systems for future GMSLR predictions, using IPCC (2013, 2014) hydro-scenarios and the chosen geomorphological coastal data-sets, has provided significant results that show the Comerong Island study site will lose about 18% of its wetlands and associated habitats by 2050, and approximately 43% of the island will lost by 2100, which represent an almost total wetland loss by the end of the twenty-first century. This study approach has resulted in similar outcomes for the other four chosen study sites on the southeastern coast of Australia, indicating that similar effects would accrue on the whole east Australian coastline and worldwide.

Global climate change resulting from greenhouse gas emissions, which is likely to increase in the near future or even if it stays the same, will have a very negative affect on the earth’s ecosystems. It is clear that Comerong Island has already been affected by GMSLR leading to: (i) its low-lying wetlands becoming inundated by the rising sea level; (ii) increased erosion rates caused by higher sea level impacting on the vulnerable sandy sediments around the island; and (iii) a decrease in sediment delivery following catchment modifications and dam construction. The vulnerability of coastal ecosystems has also been affected by increased human settlement and modification of the landscape that controls sediment resources in the catchment area. This has interrupted the balance between natural processes of erosion and deposition over thousands of years that established the equilibrium between sea-level change and the coastal environments. The loss of coastal eco-geomorphic systems, especially wetlands, has been confirmed by other examples on the NSW south coast in a variety of geomorphic settings. To assess the problems associated with rising sea level, the use of advanced
and suitable data and modern software in conjunction with recognized climate-change scenarios is highly recommended. This will lead to a better understanding of the influences of GMSLR on coastal ecosystems.

GMSLR is virtually certain to continue after 2100 for hundreds of years according to the current and likely future gas emissions. Highly confident scenarios produced by IPCC (2013) have estimated that the sea level will rise by up to ~82 cm by the end of this century (at the upper-end maximum scenario) in about 70% of the world, including southeastern Australia (Church et al. 2013). However, based on the findings of AR5, the sea-level rise may be less than 82 cm by 2100.

The southeastern Australian coastal zone will face strong challenges from ecosystem stressors during the twenty-first century. Most of the earth’s oceans will be very likely to rise, which means that we will have new shorelines leading to changes in the shape of the exposed continents as well. Moreover, depending on the future amount of gas emissions, the coming centuries could have continued sea-level rise after 2100 AD.

LiDAR and other similar modern RS data incorporated with GIS software analysis will prove to be very effective tools to obtain accurate predictions that could be available to help manage the environmental conservation targets for ecosystem sustainability. This approach was shown to be very suitable for the Comerong Island study site. In addition, ecological responses to temperature, radiation and so on could be assessed using GIS to classify any vegetation changes indicated by the normalized difference vegetation index and CLIMAX software, and their effect on ecological successions.

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