Hawkesbury River Coastal Inundation Study

Synopsis Paper

Hornsby Shire Council

RR-01-1601-00

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Cover image: Refuge Bay, Cowan Creek, 3 December 2018.

Table of Contents

Tables

Figures

1 Introduction

1.1 Hawkesbury-Nepean River Estuary Coastal Management Program

In accordance with the NSW Coastal Management Framework, management of the Hawkesbury-Nepean River estuary system and its tributaries will be guided by a Coastal Management Program (CMP) prepared in accordance with the *Coastal Management Guidelines* (OEH, 2018a). The six councils that are located along the tidal waterways of the Hawkesbury River system are working together to prepare an integrated, whole-of-system CMP. These six Council, along with the NSW Department of Planning and Environment (DPE), form the Hawkesbury-Nepean Steering Committee:

- Central Coast Council (CCC).
- Northern Beaches Council (NBC).
- Hornsby Shire Council (HSC).
- Ku-ring-gai Council.
- Hawkesbury City Council (HCC); and
- The Hills Shire Council (THSC).

The Steering Committee has completed the first stage of the CMP process (as shown in **Figure 1-1**) through the preparation of the *Hawkesbury-Nepean River System Coastal Management Program Stage 1 Scoping Study* (Water Technology, 2020).

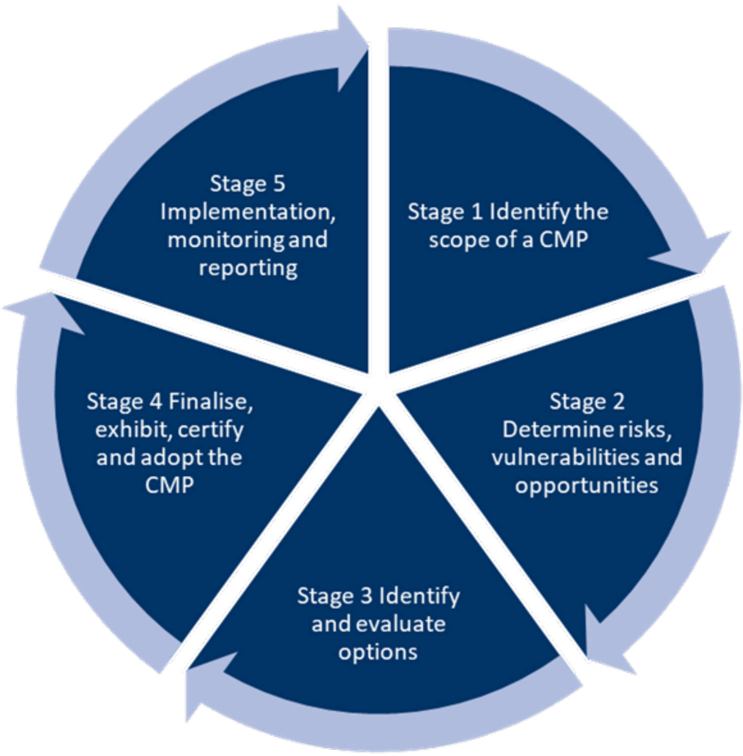

Figure 1-1 The CMP Process (adapted from OEH, 2018a)

Stage 2 of the CMP process involves undertaking additional studies where the scoping study identified knowledge gaps that need to be addressed. This Hawkesbury River Coastal Inundation Study is one of several Stage 2 studies currently in progress for the Hawkesbury-Nepean River System CMP.

Hornsby Shire Council engaged Rhelm and Baird Australia on behalf of the Hawkesbury-Nepean Steering Committee to undertake a coastal inundation study for the Hawkesbury River. The coastal inundation study adopts a staged approach as follows:

- Phase 1 – Synopsis of existing information.
- Phase 2 – Coastal inundation knowledge gaps and data collation, including –
    - Expansion of the existing coastal modelling,
    - Additional data compilation (if required),
    - Delineation of foreshore zones,
    - Hydrodynamic modelling,
    - Mapping of coastal inundation, and
    - Creation of a foreshore planning level database.

This Synopsis Paper has been prepared in fulfilment of Phase 1 of the coastal inundation study.

The purpose of this paper is to summarise the existing information on tidal and oceanic inundation in the study area, to include a review of the relevant studies and modelling outputs for Brisbane Water, Pittwater and Cowan Creek (noting the Pittwater model outputs in GIS have not yet been received at the time of issuing this draft report). It includes an assessment of the adequacy of the available information for purposes of undertaking risk assessments and defining coastal inundation hazards for the Hawkesbury River CMP, and potentially definition of a Coastal Vulnerability Area under the State Environmental Planning Policy (Resilience and Hazards) 2021. This Synopsis Paper recommends where additional coastal inundation modelling is required for consistency throughout the study area as part of Phase 2 tasks for this study.

1.2 Study Area

The Study Area consists of the estuarine section of the Hawkesbury River that is affected by coastal inundation. The specific extent of coastal inundation may be further defined through the investigation process in Phase 2 of this project, however at this stage the study area is assumed to incorporate:

- Brisbane Water.
- Pittwater.
- Cowan Creek; and
- The area upstream of Juno point through to approximately Spencer on the Hawkesbury River, and up to Berowra Waters on Berowra Creek.

The study area is shown in **Figure 1-2**.

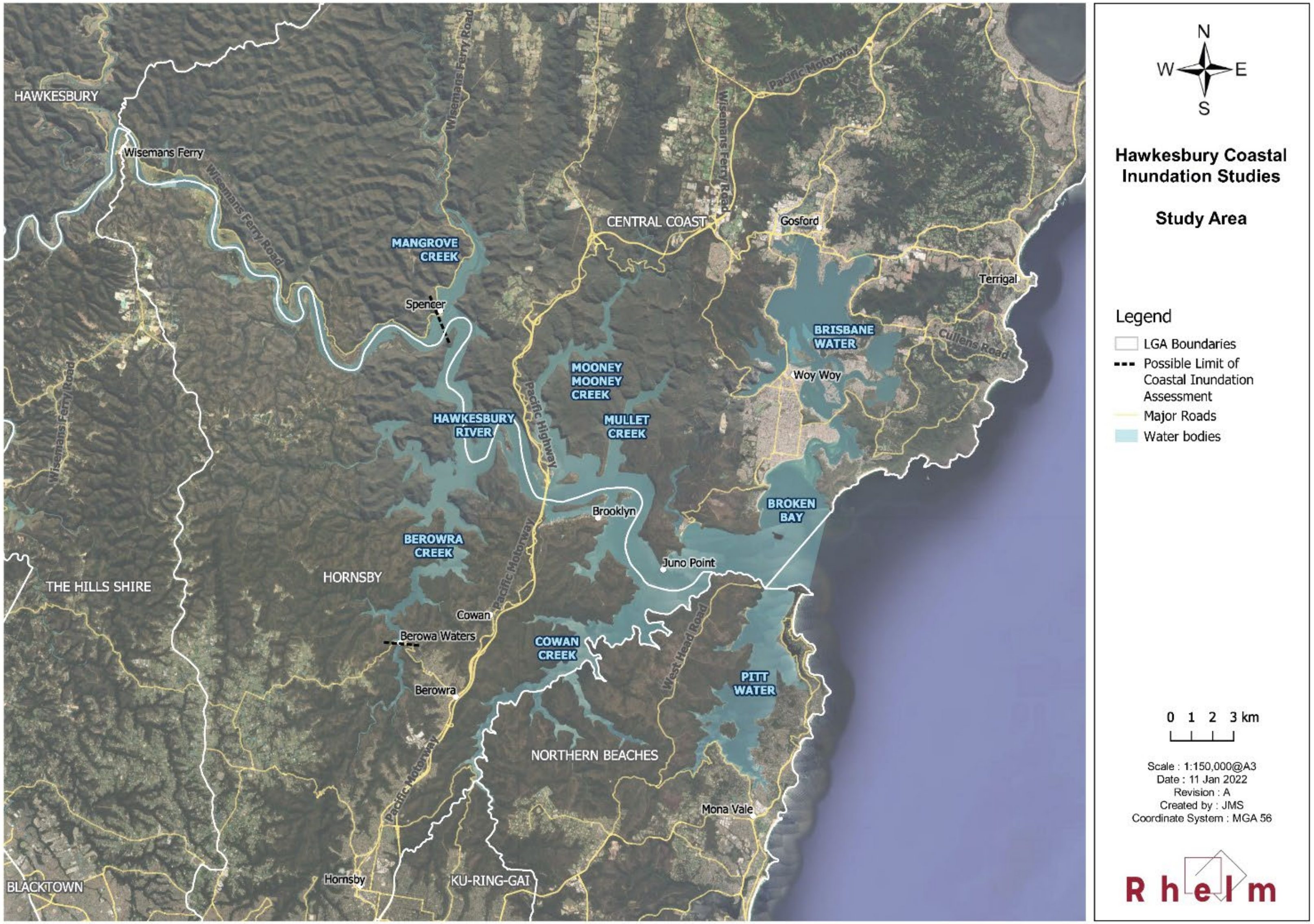

Figure 1-2 Study area

1.3 Scope and Purpose of the Synopsis Paper

As described in the NSW Coastal Management Manual (OEH, 2018a), coastal inundation is typically associated with storms that result in elevated still water levels (storm surge), wave set-up, wave run-up and wave overtopping. Coastal inundation extents and levels are calculated to reflect the likely extreme water levels along the foreshore that generally occur during an intense ocean storm (that may occur, on average, once in a lifetime or longer).

Coastal inundation is one of the eight coastal hazards identified in the NSW Coastal Management Manual (OEH, 2018a) and can impact open space, property and infrastructure contributing to coastal vulnerability. The management of coastal inundation hazard is required through the preparation of coastal emergency action plans as an element of a CMP.

The foreshores of the Hawkesbury River and its related waterways, Pittwater, Brisbane Water, Broken Bay and Cowan Creek, are subject to periodic coastal inundation. Detailed evaluations of coastal inundation have been undertaken for Pittwater by NBC and for Cowan Creek and Brisbane Water by CCC. These form the basis of planning levels for foreshore infrastructure based on a range of oceanic and estuarine processes (including ocean tide, wind set-up, wave height, wave run-up), plus a freeboard and allowance for climate change. However, no such evaluations have been undertaken for the rest of the Hawkesbury River system.

It is noted that some properties that will be affected by coastal inundation may also be affected by catchment flooding processes from the Hawkesbury River. Flood inundation (from catchment flooding) is currently being evaluated under a separate project commissioned by Infrastructure NSW (INSW) and is not considered as part of the coastal inundation study.

The height of wave run-up is dependent on the height and type of the foreshore edge (e.g., vertical seawall or natural rocky edge). Without a detailed inventory of foreshore conditions (noting these can change), coastal inundation will necessarily need to be the worst case for each foreshore type and crest height.

If the data is later used for the purposes of development control, property owners or developers would then have the opportunity to select the appropriate foreshore type for their property when calculating a planning level.

Phase 2 of this project, the coastal inundation study, consider following components of inundation:

- 100-year Average Recurrence Interval (ARI) design still water level (or an appropriate design still water level for a more severe event); and
- Wave run-up and wave overtopping.

The proposed approach would be to model and map the following inundation extents:

- The Local Water Level Extent, which is the 100-year Average Recurrence Interval (ARI) ocean water level event plus local wind set-up (or a greater event, such as the 500-year ARI or 1,000-year ARI design event).
- These extents will be modelled for three sea level scenarios: the present day, 2050 and 2100.

It is assumed that the maximum inundation extent would be within 40 m of the foreshore.

Hence, the required data inputs for the coastal inundation study and risk assessment include:

- Aerial photography.
- LiDAR for the foreshore area.

- Bathymetric data.
- Water level data.
- Wind data.
- Cadastral data and land use; and
- Mapping of foreshore types:
  - 1 in 10 natural slope (representing grassed and sandy gently sloping foreshores),
  - 1 in 5 rocky shoreline (representing natural rocky foreshore or sloped rip rap),
  - Vertical sea wall (e.g., block work or other retaining walls), and
  - Mangroves.

This Synopsis Paper reviews the existing data, studies and hydrodynamic models with respect to its adequacy and coverage of the study area for purposes of the coastal inundation study.

2 Existing Studies, Models and Data

2.1 Existing Inundation Studies

There are several existing studies for parts of the study area that consider coastal inundation, summarised in **Table 2-1**. **Table 2-2** summarises which existing hazard studies apply to each general location within the study area and highlights where relevant study currently exists.

Table 2-1 Existing studies

Reference	Summary
Modelling and Mapping of Coastal Inundation under Future Sea Level (CSIRO, 2011)*	This study focuses on the evaluation of coastal inundation using dynamic numerical modelling methods for the Sydney coastal and estuarine regions spanned by the Sydney Coastal Councils Group. The focus of the study was the development of maps showing the inundation that arises from contribution of storm surges and astronomical tides to extreme sea levels, referred to as storm tides. Wave run-up was not included (although a flexible framework for assessing coastal inundation has been adopted so that information on wave set-up could be incorporated in the future). **Study area:** Sydney region coastal zone and estuaries. **DEM data sources:** • LiDAR covering Pittwater and Hornsby LGAs, Geoscience Australia LiDAR for other parts of the study area, • 1984 hydrosurvey from NSW Public Works. **Design still water levels:** 1-year and 100-year ARI design still water levels for Fort Denison, including wave set-up. **Sea level rise scenarios:** 0.4 m by 2050 and 0.9 m by 2100. **Foreshore types:** Not considered. **Adopts freeboard:** No. **GIS sourced:** Water level contours, provided by HSC for their LGA only.
Brisbane Water Foreshore Flood Study (Cardno, 2013)*	Simulated both catchment flood and ocean storm events with selected approximate return periods, wind and wave parameters. Based on the outcomes of the study, flood planning levels were developed along the Brisbane Water foreshore. **Study area:** Brisbane Water upstream of Half Tide Rocks (refer **Figure 2-1**). **DEM data sources:** • 2m and 5 m topographic contours for urban areas and the entire LGA respectively, • Bathymetry compiled for the Brisbane Water Estuary Processes Study. **Design still water levels:** 5, 10, 20, 50, 100, 200-years ARI and a 10,000-years ARI ocean water level event including wave set-up, plus wave run-up and overtopping. **Sea level rise scenarios:** • 0.18 m, 0.3 m, 0.55 m and 0.91 m for 2009 version, • 0.4 m by 2050 and 0.9 m by 2100 for 2013 version. **Foreshore types:** 1 in 20 natural slope, 1 in 10 beach face, 1 in 5 embankment, 1 in 2 seawall, and vertical wall. **Adopts freeboard:** Yes. **GIS sourced:** 2010 flood extent and flood planning areas.

<table>
<tr><th>Reference</th><th>Summary</th></tr>
<tr><td>Open Coast and Broken Bay Beaches Coastal Processes and Hazard Definition Study (Worley-Parsons, 2014)*</td><td>The study examines the hazards that impact the coastline between Patonga and Forresters Beach and assesses these hazards to determine the immediate, 2050 and 2100 hazard lines. The relevant hazards examined include coastal inundation and climate change.
Study area: Broken Bay beaches of Ocean Beach, Umina Beach, Pearl Beach and Patonga Beach (refer Figure 2-1).
DEM data sources:
• OEH photogrammetric data,
• 2007 LiDAR at 0.5 m interval.
Design still water levels: 100-year ocean ARI water level including wave set-up, plus wave-run up.
Sea level rise scenarios: 0.4 m by 2050 and 0.9 m by 2100.
Foreshore types: N/A.
Adopts freeboard: N/A.
GIS sourced: building lines/cadastral lots impacted by the current inundation hazard.</td></tr>
<tr><td>Brisbane Water Foreshore Floodplain Risk Management Study (Cardno, 2015a)</td><td>This study builds on the findings of the Brisbane Water Foreshore Flood Study (Cardno, 2013) with additional tidal mapping of future sea level rise scenarios of 0.4 m by 2050 and 0.9 m by 2100.</td></tr>
<tr><td>Pittwater Estuary Mapping of Sea Level Rise Impacts (Cardno, 2015b)*</td><td>This study includes an assessment of coastal inundation across the Pittwater Estuary and the derivation of Estuary Planning Levels (EPLs). Inundation modelling and mapping was undertaken for tidal inundation, and coastal storm-based inundation corresponding to a 100 Year ARI event.
Study area: Pittwater
DEM data sources:
• LiDAR data plus local survey data, where available,
• Available hydrosurvey.
Design still water levels: 100-year ARI ocean water level including wave set-up, plus wave run-up and overtopping.
Sea level rise scenarios: 0.4 m by 2050 and 0.9 m by 2100.
Foreshore types: 1 in 10 natural slope (e.g., grassed or sandy gently sloping foreshores), 1 in 5 rocky shoreline (e.g., natural rocky foreshore or sloped rip rap), Vertical seawall, and mangroves. Three crest heights for all categories except mangroves.
Adopts freeboard: Yes.
GIS sourced: Not provided.</td></tr>
<tr><td>NSW Estuary Tidal Inundation Exposure Assessment (OEH, 2018b)*</td><td>The study was undertaken by DPE (formerly OEH) in 2018 (OEH, 2018b), including mapping of tidal inundation extents, to assess the impact of inundation in estuaries associated with projected sea level rise on the NSW coast. The aim of the study was to refine estimates of the extent of current exposure of properties and infrastructure to potential sea level rise to help assess the need for, and prioritisation of, adaptation planning and action (OEH, 2018b). The exposure assessment is limited to broadscale quantification inundation to property and infrastructure – and DPE notes that it does not replace the need to undertake flood or inundation studies for individual estuaries and results should not be used to assess risk to individual properties and assets.</td></tr>
</table>

Reference	Summary
	Nonetheless, the study provides a high-level indication of exposure to tidal inundation. As such, model files were not reviewed as part of this project. **Study area:** NSW. **DEM data sources:** LiDAR data. **Design still water levels:** High High Water Solstice Springs water level, and a 0.5 m water level offset (note: uses interpolated tidal planes). **Sea level rise scenarios:** 0.5 m, 1.0 m and 1.5 m. **Foreshore types:** not considered. **Adopts freeboard:** N/A.
Climate Change Policy 2018 (CCC, 2019)	The Policy is a whole of Council commitment that guides the ongoing planning and sustainable development of the Central Coast Region as well as support community initiatives to respond to climate change. The Policy commitment statements provide direction for the development of strategies on climate actions, to respond, to adapt and build resilience to changing risks to the community, council assets, infrastructure and the environment. The Policy points to a Climate Change Action Plan and subsequent documents including a Sea Level Rise Policy and Disaster Resilience Strategy that come under the framework.
Hawkesbury-Nepean Valley Regional Flood Study (WMA Water, 2019)* **Hawkesbury-Nepean Valley Regional Flood Study July 2019 Overview (INSW, 2019)**	This is a technical document and corresponding overview document, describing the existing flood behaviour of the main Hawkesbury-Nepean River from Bents Basin near Wallacia downstream to Brooklyn Bridge, and the backwater flooding associated with river flooding. The draft Regional Flood Study was peer reviewed by Rhelm, prior to being finalised in 2019. Further work is underway to increase understanding of flood behaviour using latest information including the February 2020 and March 2021 flood events. **Study area:** Hawkesbury-Nepean River Valley between Bents Basin near Wallacia and Brooklyn Bridge. **DEM data sources:** • Primarily 2017 LiDAR data, plus 2011 LiDAR for the Hawkesbury River downstream of Wisemans Ferry, • Combination of surveyed cross-sections and hydrosurvey. **Sea level rise scenarios:** 0.4 m by 2050 and 0.9 m by 2100. **Foreshore types:** N/A.
Cowan Creek Estuarine Planning Levels Study (Rhelm, 2021)	This study includes an assessment of coastal inundation across the Cowan Creek estuary and the derivation of EPLs. Inundation modelling and mapping was undertaken for tidal inundation and coastal storm-based inundation. The coastal modelling adopted methods to generate coastal flood parameters consistent with the Pittwater Estuary Mapping of Sea Level Rise Impacts (Cardno, 2015b), which provided the flood data to inform coastal planning. **Study area:** Cowan Creek (refer **Figure 2-1**). **DEM data sources:** • LiDAR data, • Available hydrosurvey. **Design still water levels:** 100-year ocean ARI water level including wave set-up, plus wave-run up and overtopping.

Reference	Summary
	Sea level rise scenarios: 0.4 m by 2050 and 0.9 m by 2100. **Foreshore types:** 1 in 10 natural slope (e.g., grassed or sandy gently sloping foreshores), 1 in 5 rocky shoreline (e.g., natural rocky foreshore or sloped rip rap), vertical seawall, and mangroves. Five crest heights for all categories except mangroves. **Adopts freeboard:** Yes. **GIS sourced:** EPL database of cadastral lots impacted by coastal inundation hazard and reporting locations.
Hawkesbury-Nepean River March 2021 Flood Review – Hawkesbury-Nepean Valley Flood Risk Management Strategy (INSW, 2021)	Severe flooding impacted many parts of NSW in March 2021, including the Hawkesbury-Nepean Valley. This report describes the causes, nature and impacts of the flood, and the response to and recovery from flooding. The focus is on flooding of the main river between Bents Basin near Wallacia and Brooklyn, plus backwater flooding. The detailed new 2D flood model developed for the Flood Strategy's Hawkesbury-Nepean River Flood Study was used to model a March 2021 flood level surface. This was then compared to buildings in INSW's Hawkesbury-Nepean 2018 spatial assets database.
Your Vision. Your Future. Climate Wise Hornsby Plan (HSC, 2021)	This Climate Wise Hornsby Plan sets out the future direction for Council to operate as a low carbon organisation and community that is resilient to climate impacts. This plan outlines immediate actions to be taken as well as a monitoring pathway, between now and 2050, to enable adaptation to evolving data and projections. Section 12.6 contains the risk assessment for sea level rise and coastal inundation. Several Future Adaptation actions in the risk assessment include ensure sea level rise and coastal inundation are included in the CMP.

*Summary text has been largely extracted from Table 5-1 of the Stage 1 Scoping Study report (Water Technology, 2021).

Table 2-2 Applicability of existing hazard mapping within the study area*

<table>
<tr><th>CVA Hazard Type</th><th>Lower Hawkesbury River</th><th>Pittwater Estuary</th><th>Brisbane Water Estuary</th><th>Broken Bay</th><th>Cowan Creek</th></tr>
<tr><td>Tidal inundation (sunny day flooding) - including SLR</td><td rowspan="2">Modelling and Mapping of Coastal Inundation under Future Sea Level (CSIRO, 2011) – southern foreshore only from Cowan Creek to Spencer</td><td rowspan="3">Pittwater Estuary Mapping of Sea Level Rise Impacts (Cardno, 2015b)</td><td>Does not exist</td><td rowspan="2">Open Coast and Broken Bay Beaches Coastal Processes and Hazard Definition Study (Worley-Parsons, 2014)</td><td rowspan="2">Cowan Creek Estuarine Planning Levels Study (Rhelm, 2021)</td></tr>
<tr><td>Coastal inundation (storm tide and wave run-up)</td><td rowspan="2">Brisbane Water Foreshore Flood Study (Cardno, 2013)</td></tr>
<tr><td>Estuary foreshore inundation from combined coastal and catchment flooding</td><td>Hawkesbury-Nepean Valley Regional Flood Study (WMA, 2019) – upstream of Brooklyn</td><td>N/A</td><td>Does not exist</td></tr>
</table>

* This table has been adapted from Table 5-2 of the Stage 1 Scoping Study report (Water Technology, 2021).

The coverage of existing inundation models is shown in **Figure 2-1**, with the exception of the Pittwater model as this GIS is currently pending from NBC.

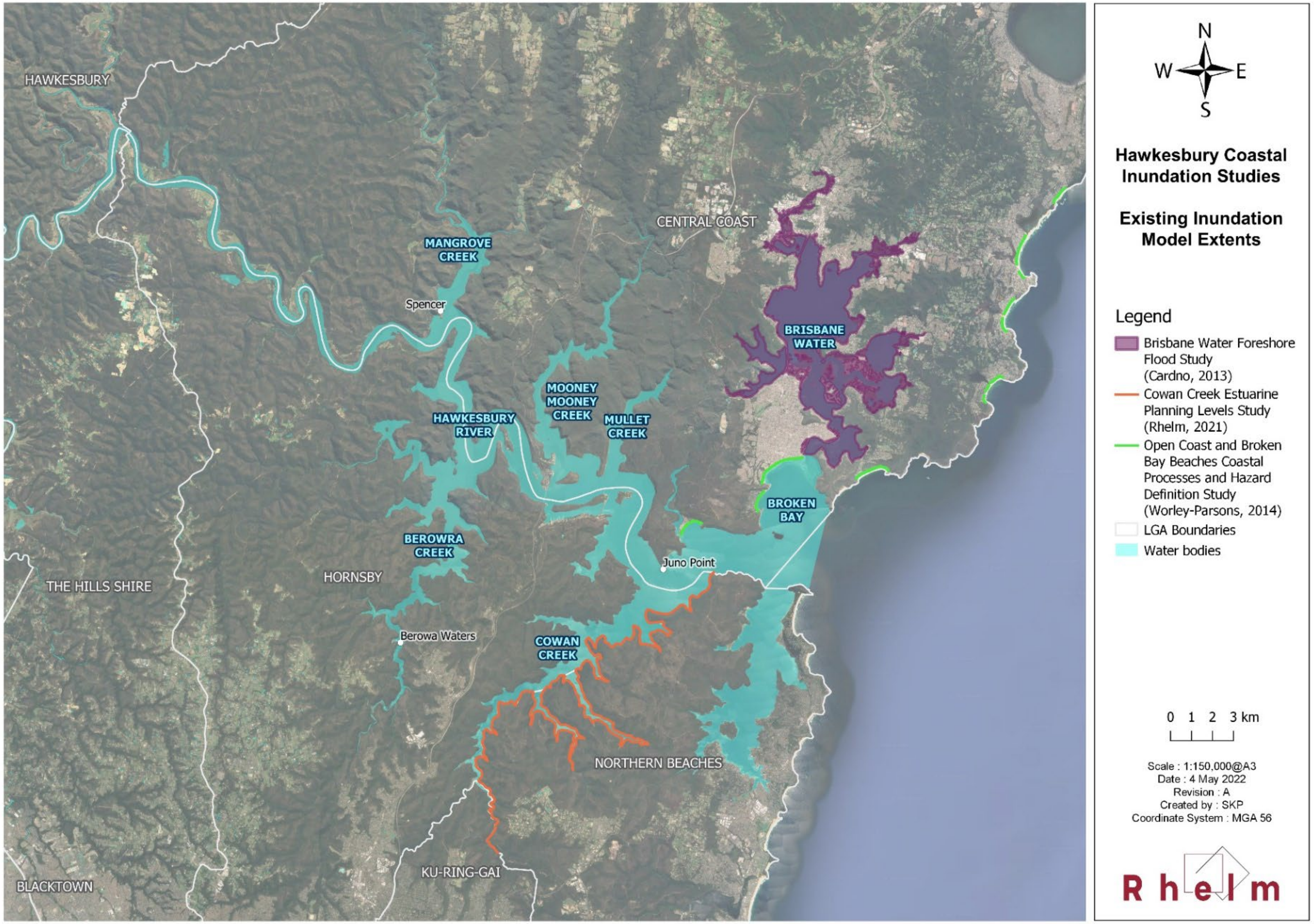

Figure 2-1 Existing inundation model extents

The key studies for which model files could be sourced include:

- Brisbane Water Foreshore Flood Study (Cardno, 2013); and
- Cowan Creek Estuarine Planning Levels Study (Rhelm, 2021).

The Cowan Creek tidal inundation model is the most recent of the three models, being completed in 2021. The coastal modelling for Cowan Creek adopted methods to generate coastal flood parameters consistent with the Pittwater Estuary Mapping of Sea Level Rise Impacts (Cardno, 2015b).

The Brisbane Water model is the earliest of the three models for the area, originally completed in 2009 with minor revisions in 2013 as part of the Brisbane Water Foreshore Flood Study (Cardno, 2013).

The Pittwater model was unable to be obtained by NBC from Cardno for review for this project as the model files were no longer held due to the time elapsed since the model was established.

The report and GIS files produced for the Sydney Coastal Councils (CSIRO, 2011) and the Open Coast and Broken Bay Beaches (Worley-Parsons, 2014) studies were reviewed; however, the model files themselves were not provided for this project.

2.2 Available Data Sets

In addition to the existing studies and model files as discussed in previous sections, HSC, CCC and NBC provided other relevant data for this study, generally for the portion of the study area within their Local Government Area (LGA). This included bathymetric and Light Detection and Ranging (LiDAR) data, along with high-resolution aerial imagery and GIS data (cadastre, land use, coastal hazards lines, inundation extents, etc).

This section provides a review of the various types of data.

2.2.1 Bathymetric and Topographic Data

Bathymetric data was sourced from:

- The Australian Ocean Data Network (AODN), which contains bathymetry collected by the former OEH (now DPE); and
- 2019 bathymetric data captured by DPIE for INSW for the Hawkesbury-Nepean Flood Study.

The bathymetric data coverage for the study area is shown in **Figure 2-2** (with the exception of the HSC compiled bathymetric data in BIL format).

As part of the recovery and clean-up after the major flood events over 2021 and 2022, the Environment Protection Agency (EPA) has been undertaking Sonar survey of the Hawkesbury to identify submerged debris that is a risk to navigational and water safety. Rhelm contacted the EPA on 8 July 2022 regarding the survey extent, however the downstream limit of their current survey area is Spencer, which coincides with the upstream limit of the coastal inundation study. Due to the very limited potential overlap around Spencer, no effort was made to obtain and review the EPA data.

The available topographic data for the study area is mapped in **Figure 2-3** and includes:

- LiDAR data from Elvis – Elevation and Depth – Foundation Spatial Data (mapped as the grey area).
- NSW Marine 5 m TopoBathy Digital Elevation Model (DEM) sourced from Elvis (mapped in blue).
- DEM prepared from LiDAR data, provided by HSC (mapped in green); and
- DEM prepared from LiDAR data, provided by NBC (mapped in red).

There is overlap between the NSW Marine 5 m TopoBathy DEM and the Northern Beaches LGA DEM around Pittwater, which is visible as a slightly darker blue area in **Figure 2-3.**

The NSW Marine LiDAR data sourced from Elvis provides updated bathymetric coverage for the shallow/mobile areas in Broken Bay, including the entrance to Brisbane Water, Patonga and Pittwater, but it did not penetrate the deeper areas.

HSC also provided combined bathymetric and topographic data in BIL format, compiled from a number of datasets by Wilson et al. (2018), as summarised in **Appendix A**. Notably, this dataset includes bathymetric data coverage for Pittwater.

In addition, CCC provided 0.5 m, 1 m and 2 m contour data derived from 2011-2014 LiDAR.

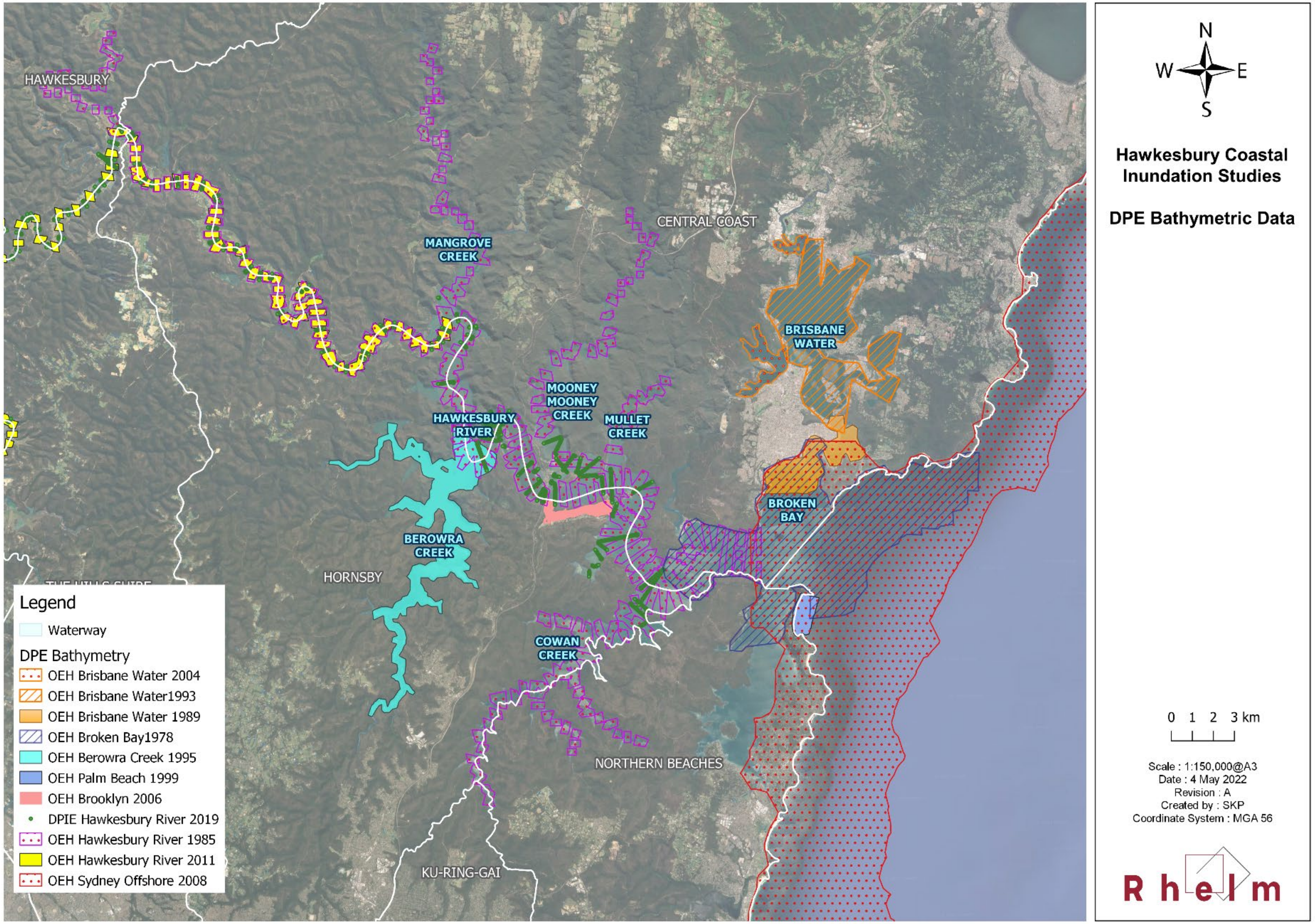

Figure 2-2 DPE bathymetric data

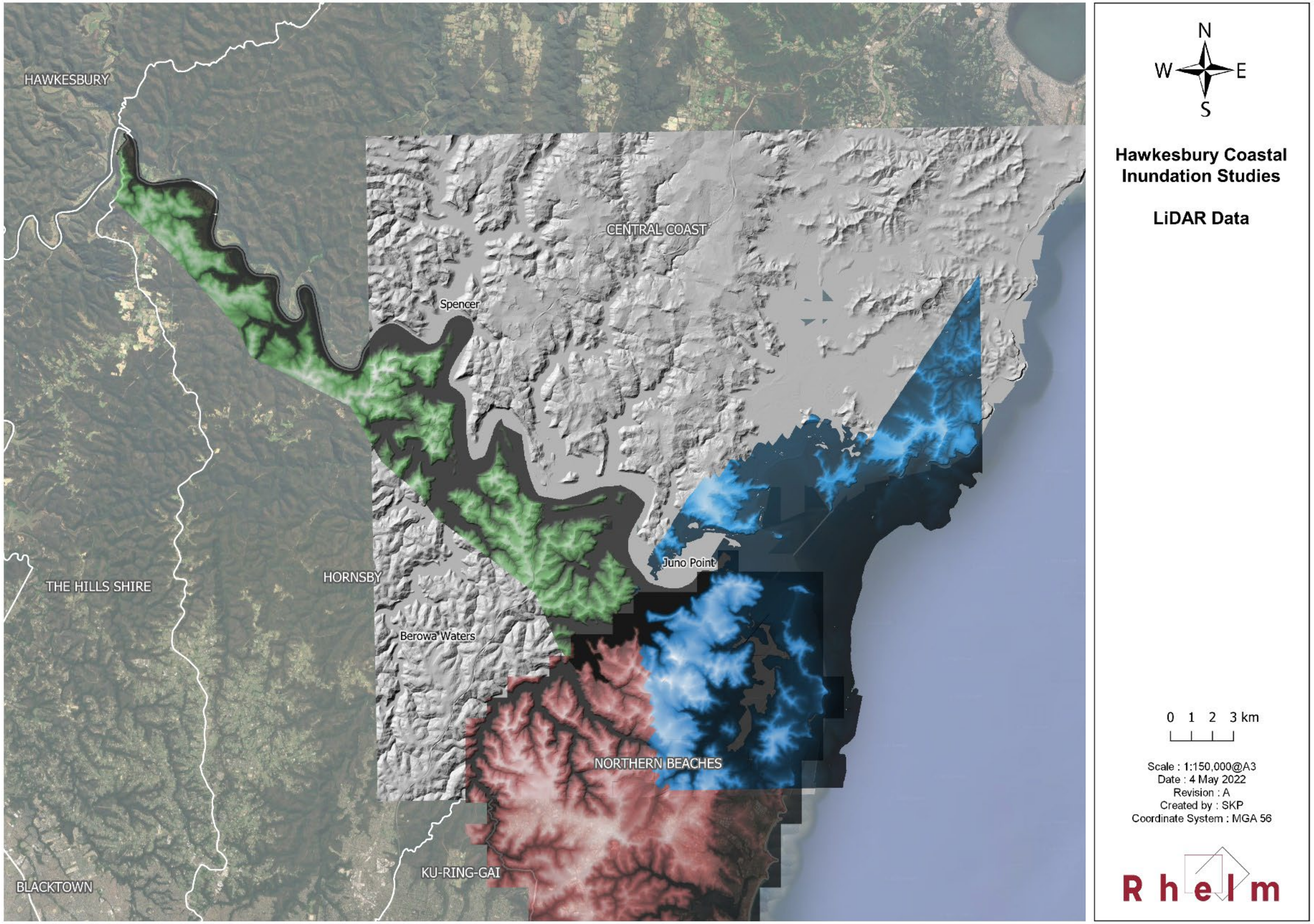

Figure 2-3 LiDAR data

2.2.2 Wind Data

The key available wind data sets for purposes of the Hawkesbury River coastal hazard study include:

- Long-term measured directional wind speeds from Sydney Airport, which cover the period 1948-2016.
- 23 years of wind measurements from Fort Denison, which cover the period 1990-2019; and
- A synthetic East Coast Low wind dataset comprised of a 1,000 year independently derived Monte Carlo model (Taylor et al., 2017).

2.2.3 Water Level Data

The Sydney Harbour (Fort Denison) tide gauge provides a reliable, long-term data set over the period 1886-1993. In addition, present day design still water levels have been derived for Fort Denison by Watsons and Lord (2008), enabling comparison with the Patonga tide gauge.

The Patonga tide gauge is located in the study area but has a shorter time series of data, having been operational since 1992.

2.2.4 Current Sea Level Rise Projections

The majority of the studies / models discussed in **Section 2.1** use the same sea level rise (SLR) projections of 0.4 m by 2050 and 0.9 m by 2100.

SLR projections were updated by the IPCC in 2019 and have recently been revised again by the IPCC in 2021, as summarised in **Table 2-3**.

Table 2-3 Sea level rise projection comparison

Planning Period (year)	SLR* (m) as per IPCC (2019)	SLR (m) as per IPCC (2021)#
2050	• 0.24 (0.17–0.32, *likely* range) under RCP2.6 • 0.32 (0.23–0.40, *likely* range) under RCP8.5	• 0.16 ±0.07 under SSP1-1.9 (lowest emissions scenario) • 0.23 (±0.08) under SSP5-8.5 (highest emissions scenario)
2100	• 0.43 (0.29–0.59, *likely* range) under RCP2.6 • 0.84 (0.61–1.10, *likely* range) under RCP8.5	• 0.34 (±0.18) under SSP1-1.9 (lowest emissions scenario) • 0.78 (±0.28) under SSP5-8.5 (highest emissions scenario)

* Increase above 1986-2005 Global Mean Sea Level.
# Projections are relative to a 1995-2014 baseline and are based on the Sydney, Fort Denison location using the online IPCC 6th Assessment Report Sea Level Projections – Sea Level Projection Tool at https://sealevel.nasa.gov/data_tools/17.
Note: Representative Concentration Pathways (RCPs) are prescribed pathways for greenhouse gas and aerosol concentrations, together with land use change, that are consistent with a set of broad climate outcomes used by the climate modelling community. In IPCC (2019) there are four RCPs, with RCP2.6 being the lowest emissions scenario and RCP8.5 being the highest emissions scenario. More recently these have been replaced with the term Shared Socio-economic Pathways (SSPs) by IPCC (2021). In IPCC (2021) there are five SSPs, with SSP1-1.9 being the lowest emissions scenario and SSP5-8.5 being the highest emissions scenario.

2.2.5 Other GIS Data and Aerial Imagery

HSC, CCC and NBC provided relevant GIS data for the portion of the study area within their respective LGAs, as listed in **Table 2-4**. Selected GIS layers related to coastal inundation are shown on **Figure 2-5**.

Central Coast Council also provided high-resolution aerial imagery for several years, but most recently 2019.

Table 2-4 Summary of GIS layers provided

Council	GIS Layer Name	Comments
Central Coast	Cadastre	-
	Contour_05m *(Pending from Central Coast Council as at August, 2022)*	Derived from 2011_2014 LiDAR.
	Contour_1m	
	Contour_2m	
	Drainage_Estuary_Catchments	-
	Drainage_Subcatchments	-
	Gosford_Coastal_Building_Lines___Current_Inundation_Impact	-
	Gosford_Coastal_Hazard_2014___Inundated_Cadastre_Analysis*	Cadastral lots impacted by coastal inundation as determined by the Open Coast and Broken Bay Beaches Coastal Processes and Hazard Definition Study (Worley-Parsons, 2014).
	Gosford_Coastal_Hazard_Lines_Pre_2014*	Outputs from the Open Coast and Broken Bay Beaches Coastal Processes and Hazard Definition Study (Worley-Parsons, 2014).
	LEP_2013_Wyong___Land_Zoning	-
	LEP_2014_Gosford___Land_Zoning	-
	Brisbane_Water_Foreshore_FS_2010*	This is the 100yr flood extent for the Brisbane Water Foreshore Flood Study (Cardno, 2013).
	Flood_Planning_Areas_2021	-
	PMF_2021	-
	100yr Flood Extents: • Davistown Catchment FS 2010 • Empire Bay Catchment FS 2010 • Erina Ck FS Review 2013 • Gosford Coastal Lagoons OFS 2020 • Gosford OFFS Gosford CBD 2012 • Gosford OFFS Pt Frederick 2012 • Gosford OFFS West Gosford 2012 • Green Pt Sun Valley TDS 1991 • Hawkesbury River Lower FS 1997 • Kahibah Creek FS 1991 • Killcare Mudflat Creek FRMP 2008 • Kincumber OFS 2014 • Koolewong Dge Study 2001 • Narara Ck FS Review 2012 • Pearl Beach Green Pt Ck FRMP 1992 • Pearl Beach Lagoon Fldg Dge Investigation 1992 • Pearl Beach Middle Ck FRMP 2008 • Pretty Beach Turo Ck 2007	-

Council	GIS Layer Name	Comments
	• Somersby Dge Study Piles Ck 1996 • Tascott Basin FMS 1990-1992 • Woy Woy Peninsula FS 2010 • Yattalunga TDSS 1994	
Hornsby Shire	Water_Lvl_Contours_1pct*	These water level contours are based on former Department of Land Water Conservation and 2011 CSIRO coastal studies. This is the bath-tub flood mapping provided for the HSC Planning branch to use for DA assessments (N.B. Inundation was included but in a simplified way).
	Water_Lvl_Contours_40cm*	
	Water_Lvl_Contours_90cm*	
Northern Beaches	20210209_EPL_Database*	This layer shows the cadastral lots affected by estuary planning levels as part of the Cowan Creek Estuarine Planning Levels Study (Rhelm, 2021). There are only two populated locations along the Cowan Creek foreshore within the Northern Beaches LGA – Cottage Point and Akuna Bay.
	J1389_EPL_Reporting_Locations_0mSLR	These are model output points for EPL Reporting Locations.
	J1389_EPL_Reporting_Locations_0_4mSLR	
	J1389_EPL_Reporting_Locations_0_9mSLR	
	Pittwater GIS TBC	*TBC – GIS outputs from the Pittwater Estuary Mapping of Sea Level Rise Impacts (Cardno, 2015b) study have been requested from NBC*
NSW Fisheries	Estuarine macrophytes	Maps distribution of estuarine macrophytes, including mangroves and mangrove/saltmarsh complex within the entire study area.

* Indicates GIS layers shown on **Figure 2-5**.

3 Data Collation and Review Summary

The key outcome of this synopsis paper is identification of data gaps that of relevance to the delivery of the Hawkesbury River Coastal Inundation Study. A summary is provided below on the available data and key data gaps that would need to be filled in Phase 2.

Table 3-1 outlines the required data inputs to the Hawkesbury River coastal inundation study and identifies gaps in coverage or availability of data for the study area.

Table 3-1 Identified data gaps

Required data input	Status
Aerial photography	Aerial photography of adequate resolution could be sourced for the project from the participant Councils or other sources (e.g., Nearmap). No data gap.
LiDAR for the foreshore area	LiDAR data sufficient to cover the foreshores of the study area (i.e., up to the possible limits of the study area at Spencer and Berowra Waters). No data gap.
Bathymetric data	Available bathymetric data is mapped in **Figure 2-2**. ***Data gap:*** *Recent hydrosurvey data for Pittwater.*
Water level data	Sufficient water level data available from the Fort Denison and Patonga tide gauges to derive extreme ocean water levels, including for return periods of 200-year ARI and greater. No data gap.
Wind data	Sufficient wind speed data is available from Sydney Airport, Fort Denison and the synthetic data set derived by Taylor et al. (2017). No data gap.
Mapping of foreshore types, to include: • **1 in 10 natural slope** • **1 in 5 rocky shoreline** • **Vertical seawall** • **Mangroves.**	All four foreshore types currently mapped for: • Pittwater • Cowan Creek – Northern Beaches LGA only (south-eastern shoreline). Other foreshore types currently mapped: • Vertical seawall – Brisbane Water. Mangrove extent mapping available for entire study area. ***Data gaps:*** • *Foreshore type mapping for Hornsby Shire, Central Coast, Ku-ring-gai, Northern Beaches (excl. Cowan Creek and Pittwater) LGAs.* • *Note: GIS data of foreshore type mapping still to be obtained for Pittwater and Brisbane Water. If not available, would need to re-mapped.*
Cadastral and land use data	Cadastre available from each Council or NSW Digital Cadastral Database. Land use zoning mapping available from each Council. Crown land, National Park Estate mapping available from Sharing and Enabling Environmental Data portal. No data gap.
Numerical model files	The numerical models prepared for the following projects could be used to support preparation of an updated numerical model for the study area: • Brisbane Water Flood Study (Cardno, 2013), • Open Coast and Broken Bay Beaches Coastal Hazard Definition Study (Worley Parsons, 2014); and

<table>
<tr><th>Required data input</th><th>Status</th></tr>
<tr><td></td><td>Cowan Creek Estuary Planning Levels Study (Rhelm, 2021).
The Pittwater model appears to have been corrupted and would not be available.
Data gaps:
Pittwater hydrodynamic model not available
No model available for the remainder of the Hawkesbury River and Berowra Creek.</td></tr>
<tr><td>Coastal inundation studies</td><td>The following studies adopt the same SLR projections and have sufficient information up to the 100-year ARI event:
Brisbane Water (pending provision of the associated database of planning levels)
Pittwater (pending provision of the associated database of planning levels and GIS files)
Cowan Creek.
However, these studies did not consider the larger events (i.e., >100-years ARI) that may be required for a CMP.
Data gaps:
Coastal inundation study for larger events may be required for Brisbane Water, Pittwater and Cowan Creek
Coastal inundation planning levels database and mapping for the rest of the study area.</td></tr>
</table>

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Appendix A

Wilson et al. (2018) bathymetric and topographic datasets

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SCIENTIFIC DATA

OPEN

Data Descriptor: Seamless bathymetry and topography datasets for New South Wales, Australia

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Kaya M. Wilson[1] & Hannah E. Power[1]

This paper describes three datasets of seamless bathymetry and coastal topography for Sydney Harbour (Port Jackson), Botany and Bate Bays, and the Hawkesbury River. The datasets used to form these compilations were the most recent and highest quality available to the authors and were originally collated using the software ESRI ArcGIS. The original compilation of this data was undertaken to support tsunami modelling research by the authors of this paper. Before processing, all data were adjusted and/or reprojected to conform to the vertical datum Australian Height Datum (AHD) and horizontal projection WGS84 UTM zone 56. Data resolution and density was highly variable and grid resolutions of the final datasets were selected as the highest resolutions possible using the most sparse data in the compilation in question. For areas where no data were available, the ESRI ArcGIS interpolation tool, *Topo to Raster*, was used to provide a best estimate. These dastasets of three important Australian waterways provide a useful tool for coastal research and scientific interest.

Design Type(s)	data integration objective • source-based data analysis objective
Measurement Type(s)	elevation
Technology Type(s)	lidar
Factor Type(s)	data acquisition system • temporal_interval • geographic location
Sample Characteristic(s)	estuary • Sydney Harbour • Botany Bay • Bate Bay • Hawkesbury River

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Background & Summary

Seamless elevation datasets comprising nearshore bathymetry and coastal elevation are extremely useful for coastal process research, including morphological studies[1] and coastal modelling[2]. Producing quality datasets requires some hydrographic expertise and, typically, licensed software to align multiple datasets from numerous sources into consistent datums and projections. Data quality and density may also be highly variable and there may be a lack of metadata. The datasets published as a compilation in this study have been collated from multiple sources and thoroughly assessed for data accuracy and quality. The authors have made these datasets publicly available to avoid replication of effort and to further research efforts in the region.

Geoscience Australia (GA) is the official Australian national repository for bathymetric data, however, the collection is not comprehensive. Data for the regions examined in this study are also held by several local and state authorities, including the New South Wales (NSW) Office of Environment and Heritage (OEH), the Port Authority of NSW, and NSW Roads and Maritime Services (RMS). The majority of data are held under creative commons licensing (CC BY) and are usually obtained by contacting the relevant authority with a request.

The standard method of handling Digital Elevation Models (DEMs) by Geographic Information Systems (GIS) and modelling software suites is to use a single resolution for the whole DEM as opposed to a variable resolution. This means that the most appropriate resolution selected for a single DEM is that of the more sparse datasets being compiled. Some data can be interpolated, however, interpolation reduces accuracy and should only be used if there is no measured data available.

If interpolation is necessary across areas with no data coverage, various techniques can be used. These techniques tend to take into account the surrounding datasets and suggest an estimate of missing data using different mathematical interpolations. The *Topo to Raster* tool in ESRI ArcGIS provides an efficient method of interpolation that is specifically designed for the creation of hydrologically correct DEMs. It is based on the ANUDEM program developed by Hutchinson[3,4] and has been used for several continent wide DEM productions including Australia's national 250 m resolution elevation grid[5]. *Topo to Raster* can be described as a discretised thin plate spline technique[6] with adaptations made to the roughness penalty in order to provide continuity of terrain.

DEMs compiled from multiple sources can be updated with new datasets sampled to the same resolution, however, DEMs do not have the flexibility of raw data as some information is lost when the data is transposed, resampled, and/or compiled. Date of compilation and/or publication is therefore always relevant and should be referenced alongside DEM usage.

Data coverage was deemed to be sufficiently extensive to warrant the creation of a DEM for the geographical areas in this study but areas of interpolation must be viewed as estimation only and treated with the knowledge that major features may not be visible. In addition, the DEMs created in this study are for use in research and are not held to the standards and specifications of nautical charts published by hydrographic authorities. These DEMs are therefore not suitable to be used for navigational purposes.

In this paper, we present three study sites selected for the compilation of seamless, gridded elevation datasets originally compiled to support a larger tsunami modelling project[2]. The study sites selected were Sydney Harbour, Botany and Bate Bay, and the Hawkesbury River (Fig. 1). These major Australian waterways were selected based on their proximity to low lying development and bathymetric data availability. Topographic data were available in high resolutions for all locations. The seamless datasets are presented in Figs. 2–4. These datasets provide an additional tool for further research in these areas and aim to reduce replication of work and effort in the production of DEMs.

Methods

The data used to compile the seamless elevation datasets in this paper were the most recent and highest quality available to the authors in 2016.

Data Acquisition

Data were obtained from multiple sources and methods of acquisition (see Tables 1–3). In general, data were provided as a series of individual surveys. These surveys were derived from variable sources: singlebeam, multibeam, bathymetric lidar, and topographic lidar. Topographic datasets were collected to standards consistent with Australian Intergovernmental Committee on Surveying and Mapping (ICSM) LiDAR Acquisition Specifications and covered the entirety of each location, so did not require compilation or interpolation. Where bathymetric surveys overlapped, multibeam data and lidar data were preferenced over singlebeam data, which were often very sparse. If an overlapping dataset appeared anomalous and showed significant deviation from all other datasets, it was not included in the compilation. In general, metadata specifying the make and model of instrumentation used in data collection was not provided. Similarly, survey specifications were generally not provided. Therefore, we infer that the survey data and subsequent compilations do not meet minimum standards of any International Hydrographic Organisation (IHO) Order specifications for a hydrographic survey[7].

Data Processing

Bathymetry data were imported into the software ESRI ArcGIS 10.1™. The majority of data obtained was in point form and imported as x,y,z files. The vertical datum and horizontal projection were provided

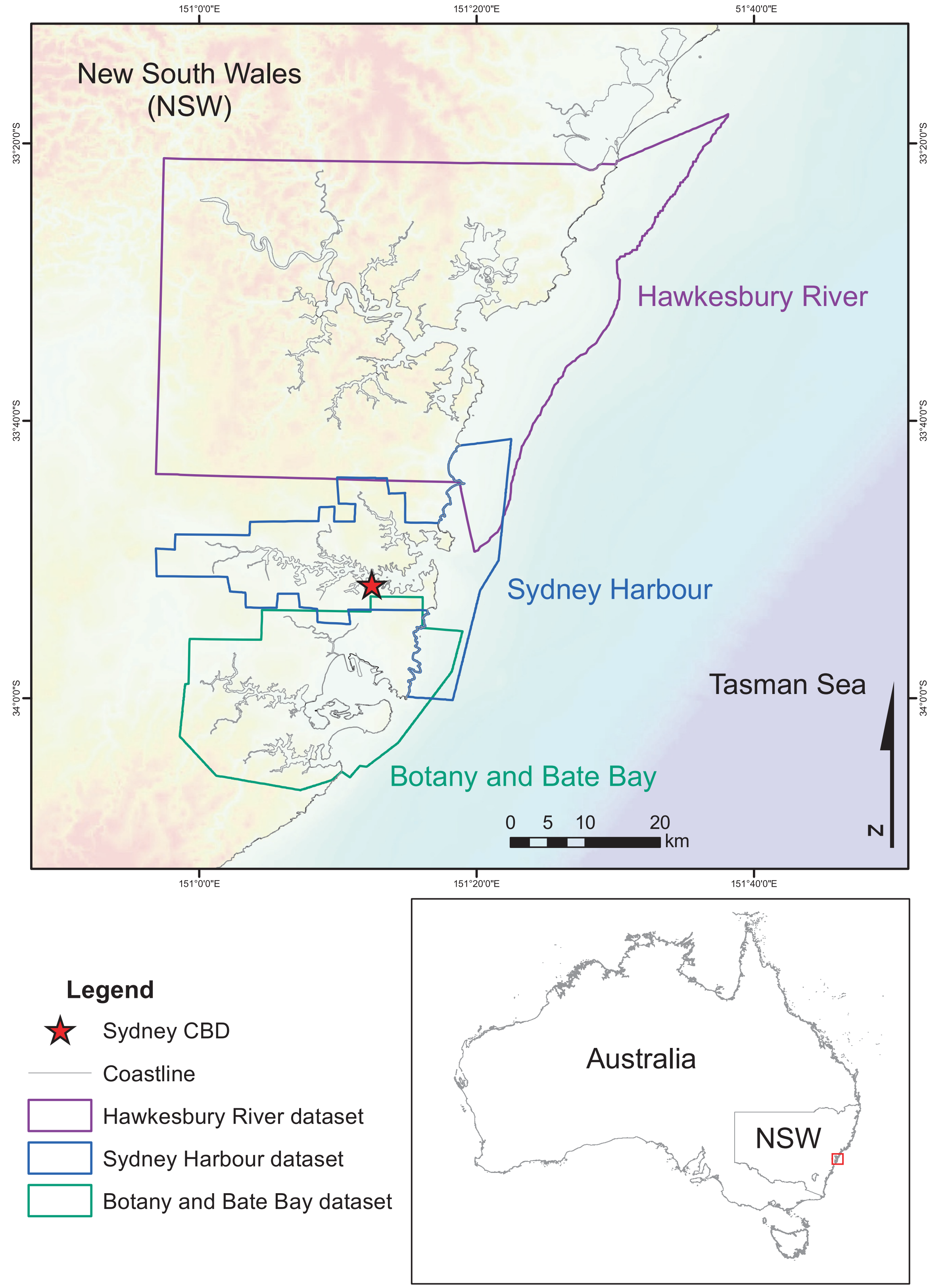

Figure 1. Dataset location map. Image created by KMW using ESRI ArcMap 10.3.1 (http://www.esri.com/arcgis/about-arcgis) with background elevation[5] and coastline data[8] from © Commonwealth of Australia (Geoscience Australia).

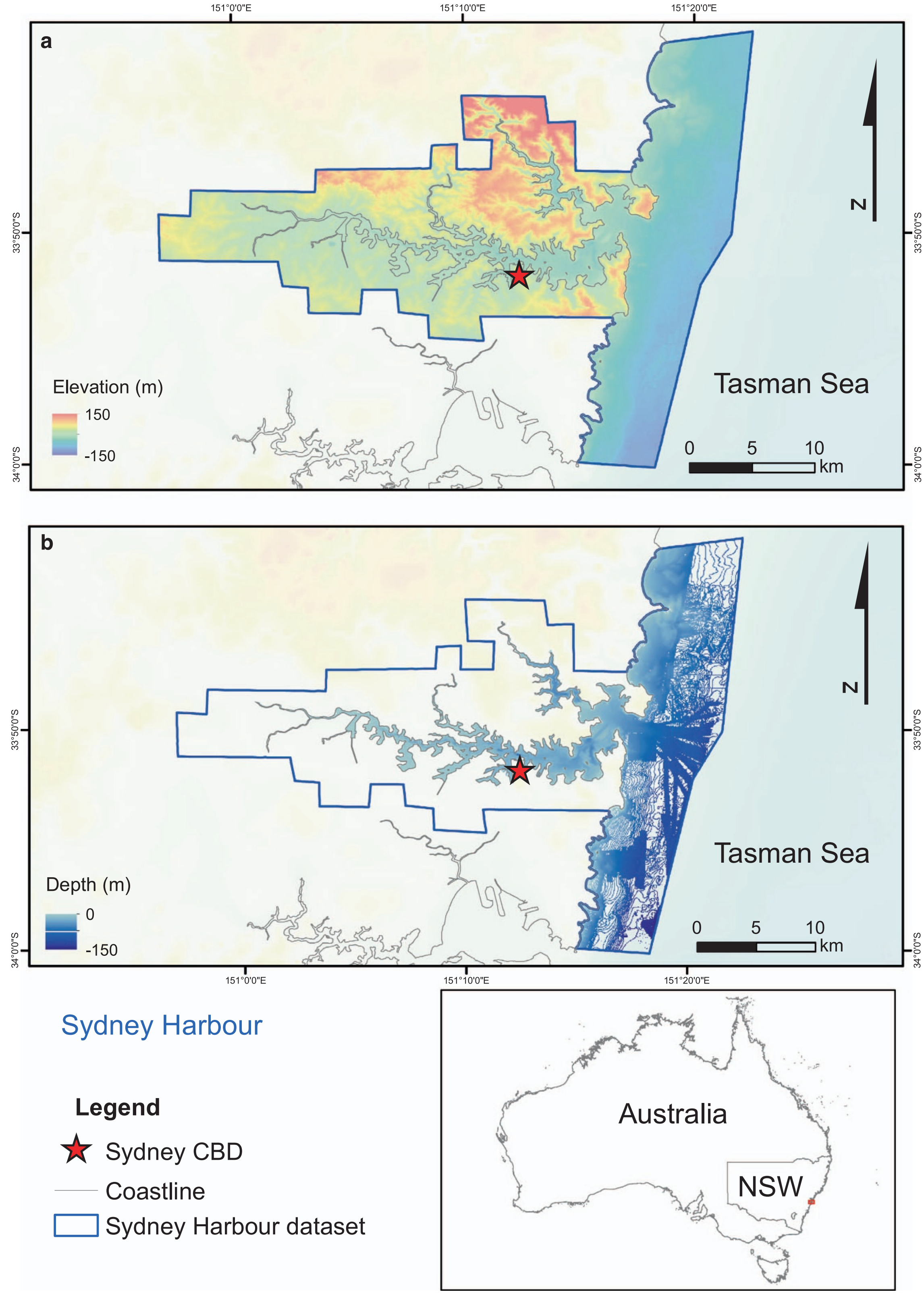

Figure 2. Map of Sydney Harbour (Port Jackson) compilation bathymetric and topographic dataset and the extent of the bathymetry data coverage. (**a**) Bathymetric and topographic dataset for Sydney Harbour. (**b**) Bathymetric data coverage for Sydney Harbour dataset. Image created by KMW using ESRI ArcMap 10.3.1 (http://www.esri.com/arcgis/about-arcgis) with elevation[5] and coastline data[8] from © Commonwealth of Australia (Geoscience Australia).

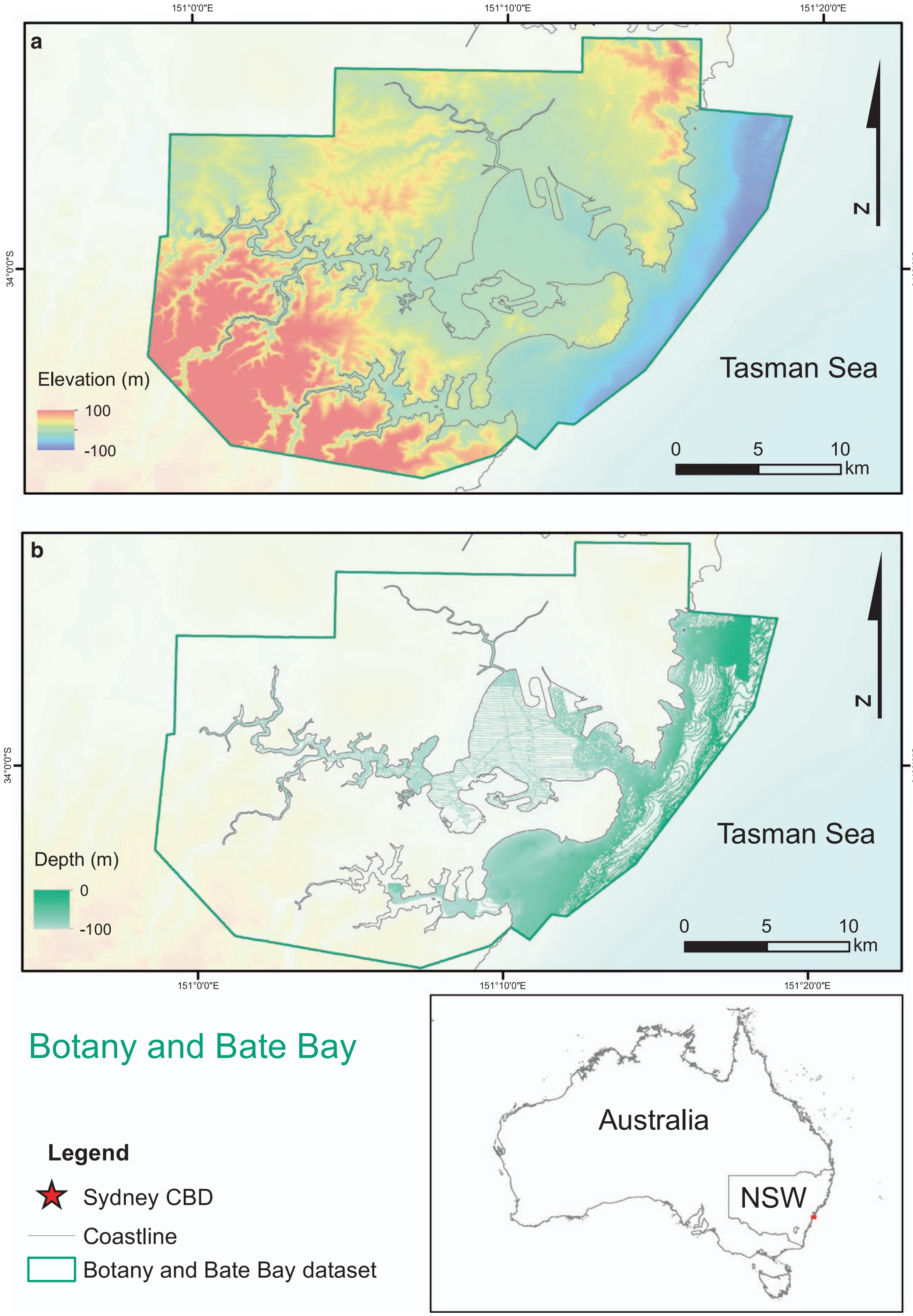

Figure 3. Map of Botany and Bate Bay compilation bathymetric and topographic dataset and the extent of the bathymetry data coverage. (**a**) Bathymetric and topographic dataset for Botany and Bate Bay. (**b**) Bathymetric data coverage for Botany and Bate Bay dataset. Image created by KMW using ESRI ArcMap 10.3.1 (http://www.esri.com/arcgis/about-arcgis) with elevation[5] and coastline data[8] from © Commonwealth of Australia (Geoscience Australia). Elevation data provided are relative to AHD.

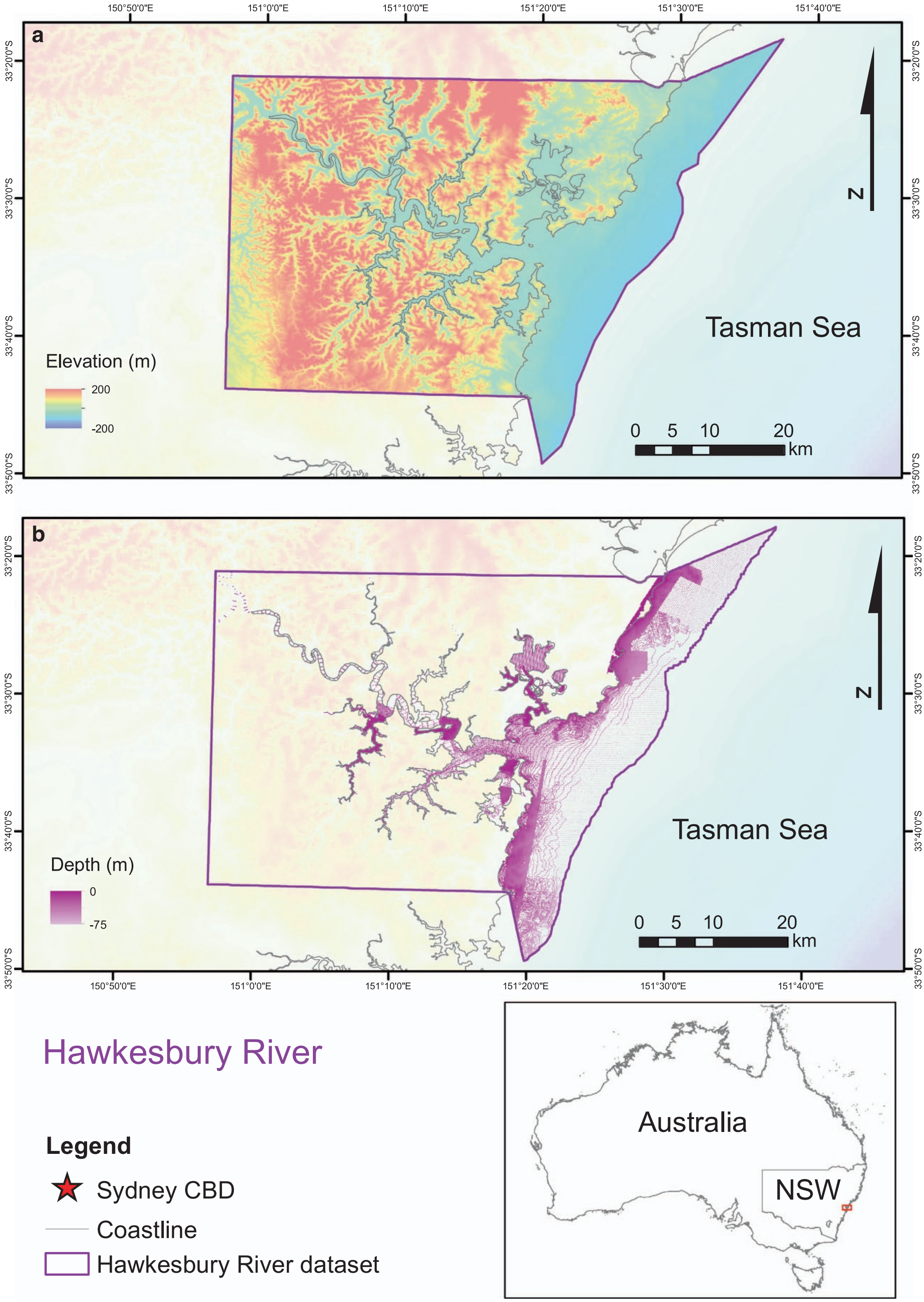

Figure 4. Map of Hawkesbury River compilation bathymetric and topographic dataset and the extent of the bathymetry data coverage. (**a**) Bathymetric and topographic dataset for the Hawkesbury River. (**b**) Bathymetric data coverage for the Hawkesbury River dataset. Image created by KMW using ESRI ArcMap 10.3.1 (http://www.esri.com/arcgis/about-arcgis) with elevation[5] and coastline data[8] from © Commonwealth of Australia (Geoscience Australia). Elevation data provided are relative to AHD.

Dataset	Data Provider	Data Acquisition Method	Date of Acquisition (if known)
5 m Digital Elevation Model (Sydney)	Geoscience Australia (GA), National Elevation Data Frame-work (NEDF)	Topographic lidar	2001–2015
CentralNSW_0_50_4	GA	Compilation	Up to 2012
CentralNSW_50_10000_1	GA	Compilation	Up to 2012
coo02by_v1	OEH	Multibeam	2002
syd5m	OEH	Multibeam	Before 2015
snb_2mby	OEH	Multibeam	Before 2015
snbs_2mby	OEH	Multibeam	Before 2015
BilgolaBeach2014Apr	OEH	Singlebeam	April, 2014
BilgolaBeach2014May	OEH	Singlebeam	May, 2014
BilgolaBeachAug	OEH	Singlebeam	August, 2014
BonginBay2014Apr	OEH	Singlebeam	April, 2014
BonginBay2014Aug	OEH	Singlebeam	August, 2014
BonginBay2014Feb	OEH	Singlebeam	February, 2014
DeeWhyLagoon2012	OEH	Singlebeam	2012
DeeWhyBeach2014Apr	OEH	Singlebeam	April, 2014
DeeWhyBeach2014Aug	OEH	Singlebeam	August, 2014
DeeWhyBeach2014Feb	OEH	Singlebeam	February, 2014
DeeWhyBeach2014May	OEH	Singlebeam	May, 2014
Manly2012	OEH	Singlebeam	2012
Narrabeen2011_jetski	OEH	Singlebeam	2011
Narrabeen2011_quad	OEH	Singlebeam	2011
Narrabeen2011_seascan	OEH	Singlebeam	2011
Sydney Harbour	RMS	Multiple	Up to 2015

Table 1. Sydney Harbour compilation datasets. All datasets were compiled or resampled to a grid size of 10 m.

Dataset	Data Provider	Data Acquisition Method	Date of Acquisition (if known)
1 second SRTM Derived Smoothed Digital Elevation Model (DEM-S) version 1.0	GA, NEDF	Satellite derived topography	2001–2015
jibb_littl	OEH	Multibeam	Before 2015
phent_by	OEH	Multibeam	Before 2015
ph_bb13	OEH	Multibeam	2013
merries_by	OEH	Multibeam	Before 2015
batebay75_by	OEH	Multibeam	Before 2015
Botany_20m	RMS	Multibeam	Up to 2015
BateBay_2011	OEH	Singlebeam	2011
CronullaOffshore2012	OEH	Singlebeam	2012
PortHacking2006	OEH	Singlebeam	2006
PortHacking2001	OEH	Singlebeam	2001
GeorgesRiver1993	OEH	Singlebeam	1993
CooksRiver1989	OEH	Singlebeam	1989
SydWat	OEH	Singlebeam	Before 2015

Table 2. Botany and Bate Bay compilation datasets. All datasets were compiled or resampled to a grid size of 10 m.

with the metadata and were assigned to the ESRI ArcGIS 10.1™ working files. The optimum gridded resolution for each individual dataset was then determined based on the density of the data. The point files were then converted to raster format and gridded at the chosen resolution.

Bathymetry raster datasets were converted to AHD vertical datum with depths below AHD described with a negative number and heights above AHD described with a positive number. Rasters were also

Dataset	Data Provider	Data Acquisition Method	Date of Acquisition (if known)
5 m digital elevation model (Hawkesbury)	GA	Topographic Lidar	2011
WyongOffshore1986	OEH	Singlebeam	1986
snb_2mby	OEH	Multibeam	Before 2015
snbs_2mby	OEH	Multibeam	Before 2015
BrokenBay1978	OEH	Singlebeam	1978
CC_LADS	OEH	Bathymetric Lidar	2011
avoca_5m	OEH	Bathymetric Lidar	Before 2015
Sydney Offshore 2008	OEH	Singlebeam	2008
Broken_Bay_1977_1978	OEH	Singlebeam	1978
Hawkesbury_1987_1988	OEH	Singlebeam	1988
Hawkesbury_1983_1985	OEH	Singlebeam	Before 2015
Hawkesbury_1978_1980	OEH	Singlebeam	1980
Brooklyn_2006	OEH	Singlebeam	2006
Berowra_1995	OEH	Singlebeam	1995
HawkesburyRiver_2011	OEH	Singlebeam	2011
HawkesburyRiver_1985	OEH	Singlebeam	1985
BrisbaneWater1989	OEH	Singlebeam	1989
BrisbaneWater2004	OEH	Singlebeam	2004
BrisbaneWater1993	OEH	Singlebeam	1993
HI341_HSDB_T0001_SD_100035103	OEH	Singlebeam	Before 2015
100004058_m	OEH	Singlebeam	Before 2015
SCHOOL_11_99_HSDB_T0001_SD_1000031002_WGS84z56	OEH	Singlebeam	Before 2015

Table 3. Hawkesbury River compilation datasets. All datasets were compiled or resampled to a grid size of 50 m.

projected using WGS84 UTM56S. Once all raster datasets for each area had been obtained, the rasters were mosaiced together using the *Mosaic to new Raster* tool. Rasters were prioritised based on data acquisition technique and the grid size chosen for the new raster was the largest grid size amongst the component rasters; therefore, the final grid size was the largest of all the component raster grid sizes.

Topography datasets were downloaded from the Geoscience Australia National Elevation Data Framework (http://www.ga.gov.au/elvis/). These datasets were reprojected into WGS84 UTM56S. The coastline dataset shapefile was also downloaded from Geoscience Australia[8] and reprojected into WGS84 UTM56S.

Both the bathymetry and topography rasters were converted to point files. These point files were then input into the *Topo to Raster* tool as ‘Point Elevation’ data. The coastline shapefile was defined as a contour of elevation at 0 m AHD. Since *Topo to Raster* assumes a rectagonal coverage, the output raster was then clipped to coincide with the shape of the original data.

Datasets were also converted into WGS84 Geographic Coordinate System (GCS) to facilitate wider use and both GCS and UTM projected datasets were submitted to GeoMapApp (http://www.geomapapp.org/) and GMRT (https://www.gmrt.org/) databases. Users wishing to use this data on a more regional scale are recommended to explore these databases.

Data Outputs

All three datasets are available in ESRI ASCII Raster format in both WGS84 GCS and projected in WGS84 UTM56S. Data points are provided to a precision of ≤0.001 m. Note that this is not a reflection of data accuracy.

Due to imperfect interpolation, some evidence of the original bathymetric survey data points may be visible in the datasets.

Code availability

The version of ESRI used to create these datasets was ESRI ArcGIS 10.1™. The datasets were exported using newer versions of the software up to ESRI ArcGIS 10.5™. Using the same tools and methods described in this paper, identical datasets would be attainable using different versions of this software.

Data Records

The dataset for Sydney Harbour is available in ESRI ASCII Raster format in both WGS84 GCS and projected in WGS84 UTM56S for download (Data Citation 1).

The dataset for Botany and Bate Bay is available in ESRI ASCII Raster format in both WGS84 GCS and projected in WGS84 UTM56S for download (Data Citation 2).

The dataset for the Hawkesbury River is available in ESRI ASCII Raster format in both WGS84 GCS and projected in WGS84 UTM56S for download at (Data Citation 3).

Technical Validation

The topographic data used in these datasets were captured to standards that are generally consistent with the Australian ICSM LiDAR Acquisition Specifications, which require a fundamental vertical accuracy of at least 0.3 m (95% confidence) and horizontal accuracy of at least 0.8 m (95% confidence) as specified in the topography metadata (http://www.ga.gov.au/elvis). No additional validation was considered necessary.

Numerous bathymetric surveys collected with different specifications contributed to this dataset and the details of those specifications were generally not provided. Therefore, the standard methods of validating bathymetric data, such as calculation of Total Propagated Uncertainty (TPU) or considering IHO Order specifications, were not possible. The data were also gridded which, in places, reduces the resolution of the data. Locations where data overlapped provided some validation. Depth differences between datasets in shallower waters (< 30 m) were within 1–2 m. Fewer datasets overlapped in deeper waters and depth differences in these regions were typically greater (1–5 m). Given the inability to assess the bathymetric data using standard methods of validation, the bathymetric data in these datasets should be considered unsuitable for navigation.

The proportion of the dataset that is comprised of original data and that which is interpolated should be taken into consideration when using these datasets. Original data was available for the full extent of the topographic regions of the dataset, meaning that data points were available for every grid cell in the dataset. The bathymetric datasets, however, varied in their degrees of coverage. Within the bathymetric domain of the datasets provided, for each grid cell the Sydney Harbour dataset had at least one data point in 77% of grid cells, Botany and Bate Bay, 70%, and the Hawkesbury River, 40%. The distribution of this data coverage can be viewed in Figs. 2b, 3b and 4b for each site respectively.

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Author Contributions

K.M.W. and H.E.P. designed the study. K.M.W. carried out the research and wrote the manuscript with substantial contributions from H.E.P.

Additional information

Competing interests: The authors declare no competing interests.

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