Gamay (Botany Bay, Australia): What we know and still need to know about this highly modified coastal waterway?

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Abstract

Gamay is a coastal waterway of immense social, cultural and ecological value. Since European settlement it has become a hub for industrialisation and human modification. There is growing desire for ecosystem-level management of urban waterways, but management efforts are often challenged by a lack of integrated knowledge. We systematically reviewed published literature, Traditional Ecological Knowledge (TEK) and consulted scientists to produce a review of Gamay that synthesises all published knowledge of Gamay's aquatic ecosystem to identify key knowledge gaps and future research opportunities. We found 577 published resources on Gamay, of which over 70% focused on ecology. Intertidal rocky shores were the most studied habitat, with research focusing on invertebrate communities. Few studies considered more than one habitat or multiple taxa. There is a lack of studies investigating long-term trends and habitat connectivity, and the role of artificial substrate as habitat in Gamay is poorly understood. TEK of Gamay remains a significant knowledge gap, both in its documentation and its inclusion in research. Habitat restoration in Gamay has seen positive results highlighting significant opportunities for expansion. This review highlights the extensive amount of knowledge that exists for Gamay, but also highlights key gaps that need to be filled for effective management.

Lay summary

Ecosystem management efforts are often challenged by a lack of integrated knowledge. Gamay (Botany Bay) is no exception to this, despite being the focus of much research. We reviewed published literature on the aquatic ecosystem of Gamay to produce a synthesis of all published knowledge, identify key knowledge gaps and highlight future research opportunities for the bay.

Keywords

Australia, Botany Bay, Cooks River, estuary, First Nations people, Georges River, Kamay, Traditional Ecological Knowledge, urbanisation.

Introduction

Botany Bay, or Gamay (also pronounced *Kamay*) as it is called by First Nations People of Australia has a long history with humans and holds great cultural significance to both First Nations People of Gamay as well as to those that migrated or were transported to Australia from abroad. Gamay's main bay is fed by two major freshwater tributaries, the Georges River and the Cooks River (Figure 1). The waters of Gamay and its tributaries provided food and other resources for First Nations people of Gamay for thousands of years prior to European settlement, with the harvest and use of its resources being deeply entwined with their identity, culture and traditions (ALS 1977, National Oceans Office 2002). More recently, Gamay was the landing place of British explorers when they first arrived in Australia in 1770. The British first called Gamay, Stingray Bay due to the large number of stingrays they saw in its shallow waters, but soon after changed it to Botanist Bay (later shortened to Botany Bay) due to the diversity of botanical specimens they were able to collect from along the bay's shoreline on that first visit (Adam 1997).

In the years since British colonisation, Gamay has become an epicentre for industrialisation in Australia which has led to extensive modification of the bay (ALS 1977). Urbanisation and land-use changes have exacerbated these modifications, resulting in the waterway being largely unrecognisable from the one First Nations people of Gamay would have interacted with prior to European settlement (see Reid 2020 for an in-depth review of land-use changes in Gamay). Gamay's long and complex history with humans means that successful and sustainable management requires consideration of the often competing interests of many different stakeholders including; government, industry, national and international transport, recreational users, residents, local Indigenous communities and the environment. Management efforts will also be challenged by a lack of integrated knowledge of how the physical, geochemical and biological processes of Gamay as a whole interact to ultimately drive its functioning (Christensen et al. 1996). An important first step in the sustainable management of Gamay is therefore a thorough understanding of its current biophysical state.

To this day, the most comprehensive study of Gamay and its tributaries is the Environmental Control Study undertaken by the State Pollution Control Commission in conjunction with the Maritime Services Board of NSW and the Port Authority of Botany Bay which produced a series of technical reports on the processes, communities and habitats of Gamay and its tributaries published between 1978 and 1981. Whilst extensive in scope, this series of reports predates many of the recent human modifications to Gamay and as a result, many of the processes, communities and habitats originally assessed in these reports either no longer exist or no longer occur as they once did. A recent review summarised published literature of some of the habitats within Gamay (Reid 2021), yet a detailed synthesis of the complete body of biophysical studies on Gamay has not been completed. Such a synthesis is key to determining knowledge gaps and prioritising future research efforts in order to develop an integrated management strategy for Gamay. The present review therefore looks to build on previous reviews of Gamay by synthesising all published knowledge on Gamay, including its physico-chemical characteristics and all its habitats (natural and human-made), to identify critical knowledge gaps and highlighting research opportunities which current work has generated to ensure a sustainable future for Gamay.

First Nations people have actively managed and modified natural landscapes for tens of thousands of years (Rowland 2004). This includes the lands and water of the Gamay catchment, which First Nations People of Gamay subsistence fished and farmed for tens of thousands of years before European settlement. The local ecological knowledge held by First Nations people (hereafter Traditional Ecological Knowledge, TEK) encompasses their experiences with the environment over time (Berkes 1993). Historically TEK from First Nations people of Australia has been overlooked by scientists and managers, however, recent shifts in perspectives have meant that TEK is becoming increasingly recognised as an important and valuable source of ecological information (Fischer et al. 2022). In recognition of the importance of TEK in understanding ecological systems, we have included this knowledge, where available, in addition to scientific literature identified in our literature review process, to produce the most comprehensive review of Gamay to date.

This review of Gamay is the second in a series of reviews which summarise the current state of knowledge on the aquatic ecosystem and highlight key knowledge gaps for urban waterways in the Sydney region (see Johnston et al. 2015 for a review of Sydney Harbour). These reviews can assist in planning research and management actions for the waterways upon which they focus and inform similar practices for urban waterways around the world. In this review, we collated information regarding the geology, hydrology, chemistry and ecology of Gamay. Historical literature was also included as these early accounts contain some of the only written accounts of First Nations people of Gamay, Gamay's aquatic ecosystem and their interactions prior to European settlement. We used three search methods: a systematic online literature search, a questionnaire and a workshop with scientists. The information we uncovered was then analysed and synthesised into a review of Gamay, summarised by habitat type, which quantified areas of high and low research effort, discussing what we do and don't know about this urban waterway and highlighting future opportunities for science and management in the bay. On occasions where up-to-date syntheses on a habitat and/or an ecological community in Gamay already exist in the published literature (e.g., those reviewed in Reid 2021) we give only a brief summary and refer to that source.

Systematic literature review

Our review used three search methods: (1) a systematic literature search of databases, using the keywords: 'Botany Bay' and 'Kamay' and 'Gamay' and 'Georges River' and 'Cooks River'; (2) a questionnaire, distributed to around 60 scientists and managers affiliated with the Sydney Institute of Marine Science and (3) a two-day workshop and discussion with an interdisciplinary panel of marine scientists that have undertaken research in Gamay. Workshop participants examined literature relating to their fields of expertise and highlighted works missing from our initial search. This allowed relatively obscure yet important texts to be included, as well as highlighting many unpublished works and datasets not available on searchable databases. This was a key component of our search methods, as many important texts failed to include 'Botany Bay' or similar search terms in either the article title or keywords.

The titles, abstracts (and occasionally methods) of each article and report were examined, and the study was included in our review if it discussed or assessed any physical, chemical or biological aspect of Gamay. Articles and reports were included in the review if they presented data wholly or partially collected from Gamay. Gamay was defined to include the main bay and the lower, estuarine regions of the Georges River and the Cooks River. This included a distance of 200 km extending seaward from the mouth of the bay and the coastal waters off the headlands, Cape Banks and Cape Solander. It also included terrestrial areas associated with the Towra Point Aquatic Reserve (e.g., mudflats, mangroves and saltmarsh habitat), as this area is an important region for wading birds. Each publication was assigned to a field of study (e.g., Ecology, Oceanography etc.) and a habitat type (e.g., rocky intertidal shores, seagrass etc.). Some publications considered multiple habitat types. In these instances, each habitat type was considered an individual study and so was counted separately. Individual publications may therefore occur in multiple habitat type categories (see 'multiple', Figure 2). To identify areas where research was lacking, where appropriate, publications were also classified according to the major taxon they considered (e.g., fish, invertebrates etc.). If multiple taxa and/or multiple habitats were considered that publication was classified as 'multiple' (Figure 7).

Results of literature review

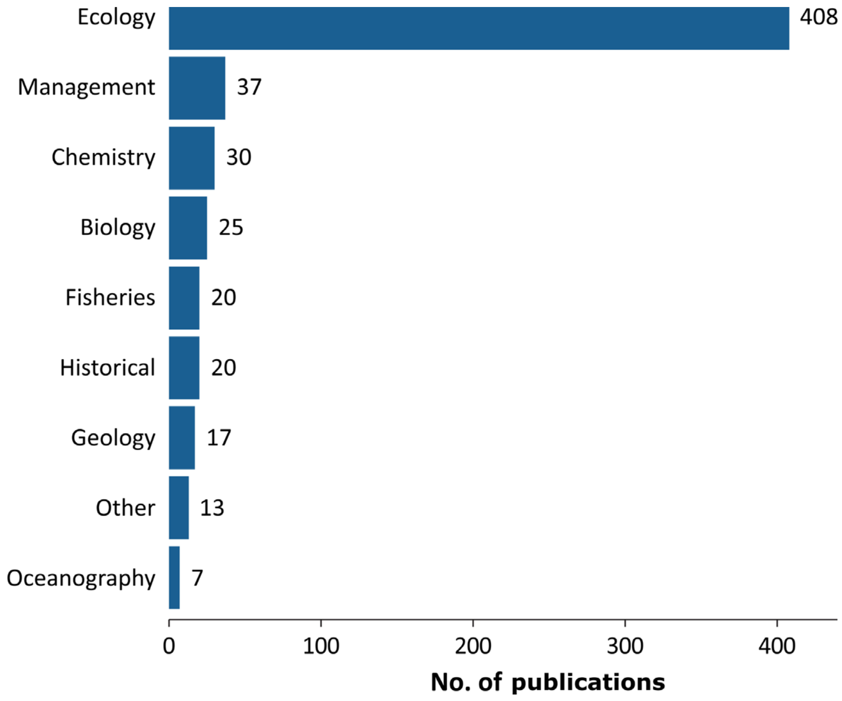

Figure 1. Number of publications describing studies done in Gamay, catagorised by discipline. 'Other' represents categories with <7 publications (inc. taxonomic based papers and studies detailing industrial developments).

A total of 577 different resources were included in this systematic review, including 477 journal articles, 75 reports, 13 books as well as 12 additional resources of other types (see Supplementary Material for full list of references included in this review). The earliest study included was published in 1876. There were 10 times the number of publications on the ecology of Gamay (70.7% of publications, 408 publications in total, Figure 1) compared to those describing any other field of study. Despite First Nations people having inhabited Gamay for tens of thousands of years, and Gamay being the location that European colonists first made contact with First Nations people of Gamay, there was little in the way of published information on First Nations people of Gamay or TEK from First Nations people of Gamay ('historical', 3.5% of publications, 20 publications in total, Figure 1). Similarly, there has been little scientific examination of Gamay's fisheries, despite the bay's long history of commercial fishing (until it was banned in 2002) and the continued use of the bay by recreational fishers ('fisheries', 3.5% of publications, 20 publications in total, Figure 1).

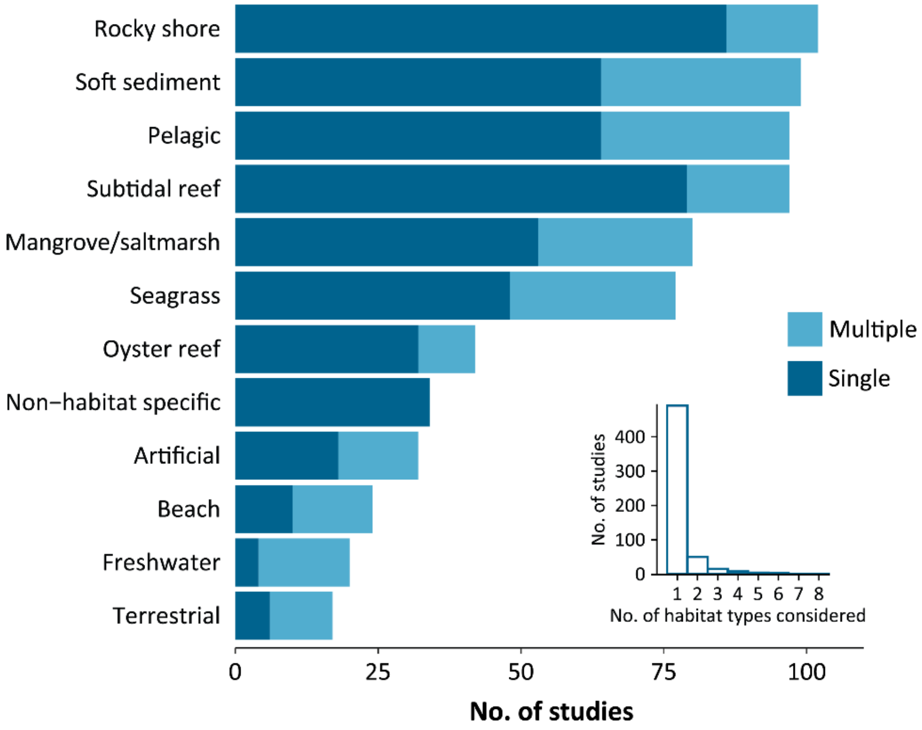

Figure 2. Studies were separated by habitat type. The number of studies that considered individual habitat types in isolation are shown in dark blue ('single'). The number of studies that featured a given habitat type in addition to one or more other habitat types is shown in light blue ('multiple'). Individual publications may therefore appear in multiple columns and thus the sum of all bars will be greater than the total number of publications included in the literature review. 'Terrestrial' represents habitats dominated by littoral vegetation. Inset plot in the lower right corner is a histogram of the number of different habitat types considered in studies.

Rocky intertidal shores were the most common habitat featured in single habitat studies (19.9% of publications, 86 publications in total , Figure 2), with much of this research being undertaken at the Cape Banks Aquatic Reserve on the bay's northern headland (Figure 3). In comparison, freshwater habitats in Gamay represent the most poorly studied habitats in single habitat studies (0.7% of publications, 4 publications in total, Figure 2), whilst terrestrial habitats (which represent habitats dominated by littoral vegetation such as Tuckeroo (*Cupaniopsis anacardioides)* and the threatened species Magenta Lilly Pilly (*Syzygium paniculatum*)) were the most poorly studied habitat overall (inc. both single and multi-habitat studies, 17 studies in total, Figure 2). Single habitat studies were by far most common (Figure 2 insert plot). Oyster reef habitats featured least often in multi-habitat studies (Figure 2). The habitat types most commonly studied in combination were soft sediment and beach habitats (6 studies, Figure 2), followed by soft sediment and rocky shore habitats (4 studies, Figure 2), and subtidal reef habitat and artificial substrates (4 studies, Figure 2).

In the following pages we present a synopsis of current knowledge of the Gamay ecosystem that arose from our literature search. All literature cited in this review is listed under References (this includes studies from outside Gamay), whereas the full list of all references uncovered during our systematic literature review is included separately in Supplementary Material (contains only studies directly relating to Gamay).

Physico-chemical characteristics of Gamay

The Gamay environment

Gamay is a semi-enclosed, low inflow embayment centred at ~34°S, 151°12'E. It lies ~13 km south of the CBD of Sydney, Australia (Figure 3). The Gamay catchment is fed by two major freshwater tributaries, the Georges and Cooks Rivers (Figure 3), with a total catchment area of approximately 1165 km^2 (SPCC 1977). The Georges River sub-catchment which includes the Georges and Woronora Rivers drains nearly 90% of the bay, with the Cooks River and other minor tributaries draining the rest (SPCC 1977). Depths of the bay itself are shallow, less than 5 m across much of the bay, although the average depth is 11 m. The entrance is up to 25 m deep, where dredging occurred in order to expand Port Botany, and for sediment to reclaim land for two runways at Sydney Airport (Kinhill Engineers 1990) and Port Botany.

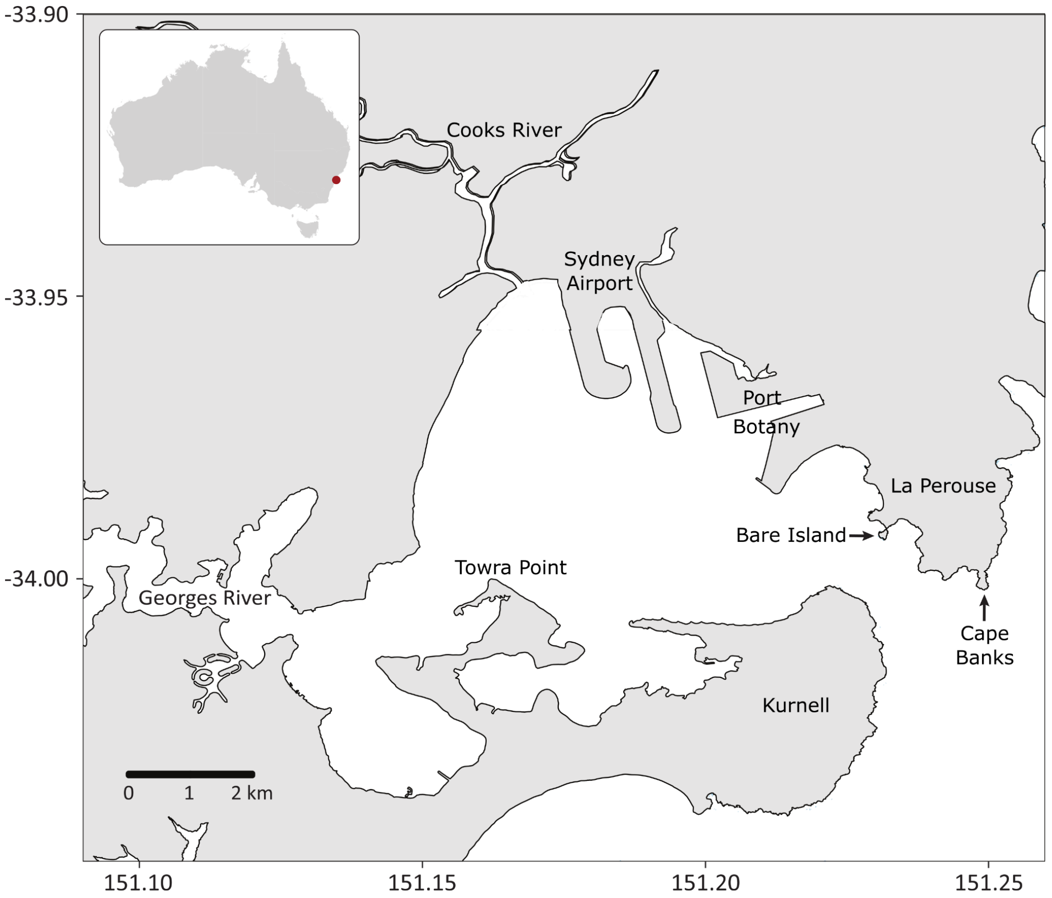

Figure 3. Map of Gamay showing the lower sections of its two major freshwater tributaries, Georges and Cooks River, and other significant locations around the bay that are discussed in this review.

Geological history

Gamay is part of the greater Botany Basin (Roy and Crawford 1981), originally carved out of Hawkesbury sandstone by three ancient river systems; the Cooks River, Georges River and a third, smaller ancient (unnamed) river (Albani et al. 1976). At 9,000 yBP, sea-level rose and the combined Cooks and George paleo-rivers joined the ancient Port Hacking channel and exited to the ocean from Bate Bay. Gamay's geological history has been strongly influenced by climatic events of the Quaternary Period (2.58 million yBP to the present), where oscillations between low and high sea level conditions caused the respective deposition and mobilasation of sediments in the Botany Basin (Albani 1981).

Our review found geology was one of the fields of study with the lowest number of published studies (2.9% of publications, 17 publications in total, Figure 1), with roughly an equal number of publications discussing the geology and geological history of Gamay as did focus on sedimentology in the bay.

Hydrology and oceanography

Since British colonisation Gamay has undergone significant development which has influenced the region's hydrology. Extensive urbanisation as well as reclamation and dredging projects have substantially altered the broader catchment and localised hydrology, including rainfall-runoff patterns, hydrodynamics and hydraulics (Figure 4). Increased urbanisation has made large areas of the catchment impervious and has connected these areas directly to waterways via stormwater infrastructure (SMCMA 2011). This means water (including pollutants) regularly runs directly off the land surface and quickly makes its way into the bay, instead of being filtered through the soil and vegetation posing significant problems to the waterways of the Gamay catchment (SMCMA 2011).

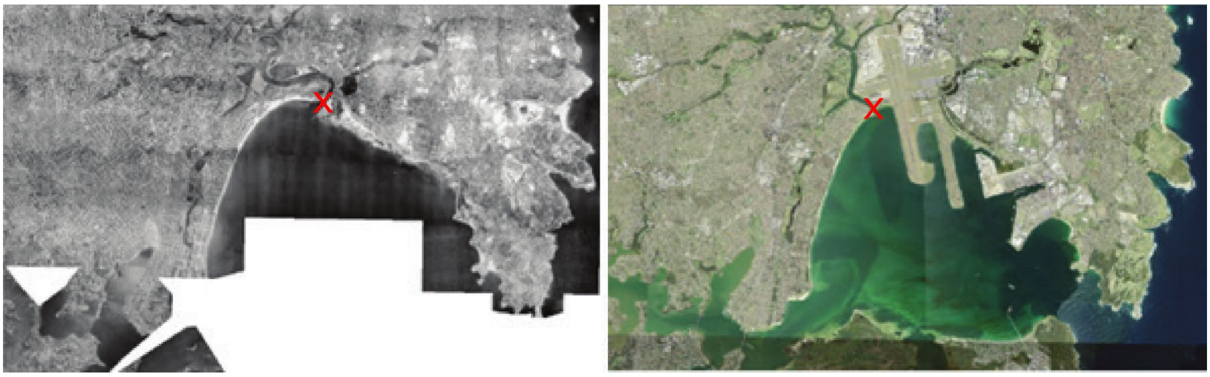

Figure 4. Aerial image of Gamay in 1945 (left) versus 2022 (right), highlighting urbanisation changes and alterations to the coastline which have impacted circulation flow paths. Major changes include the additions of the airport runways, the Port Botany expansion and the realignment of the Cooks River entrance (marked with red 'x'). Image source is SixMaps.com.

Oceanography was the field of study with the least number of publications, comprising just 1.2% of publications, or 7 publications in total (Figure 1). Of those studies that have investigated Gamay's hydrology and oceanography most have focused only on the main bay, with its two major tributaries (Georges River and Cooks River) often excluded from studies due to their low inflow (e.g., Roughan and Hallam 2022) and lack of data. Freshwater input from these rivers into Gamay can, however, be significant during periods of intense rainfall. The inclusion of these freshwater tributaries in future work on Gamay's hydrology will be important as climate change and urbanisation is predicted to alter freshwater inflow into the main bay (Gillanders et al. 2011).

The habitats of Gamay

Soft bottom and beach habitats

Gamay contains a range of soft sediment habitats, including intertidal beaches, sandflats and mudflats as well as extensive subtidal sediment habitats. Soft bottom habitats (not including beach habitats) were among some of the most studied habitats in Gamay (11.1% of studies, 64 studies in total, Figure 2) and were commonly included in multi-habitat studies (35 studies, Figure 2). By comparison, beach habitats were amongst the least studied habitats (1.7% of studies, 10 studies in total, Figure 2).

Intertidal mudflats are prevalent in sheltered coves, estuarine areas, rivers and creeks, as well as filling in the gaps around mangroves and built infrastructure. Gamay sediments and mudflats are productive habitats rich in organic materials, which underpin substantial communities of heterotrophic protists that consume up to 65% of bacterial production daily (Lee and Patterson 2002 , Fenchel 1992) and underpin detritus-based food webs (Bishop and Kelaher 2008, Kelaher et al., 2013). In particular, the mudflats of Gamay support resident and migratory wading bird populations, some of which are in serious decline (ALS 1977, NSW Threatened Species Scientific Committee 1998). Changes in detrital sources to Gamay mudflats influence decomposition rates, primary productivity, nutrient cycling and community metabolism, as well as the structure and function of macrofaunal communities (Bishop and Kelaher 2008, Bishop and Kelaher 2013, Kelaher et al. 2013). Detrital dynamics on mudflats will likely continue to change in the coming decades as ocean warming influences decomposition and nutrient liberation (Kelaher et al. 2018, Litchfield et al. 2020).

Subtidal soft sediments in Gamay have changed significantly with respect to physico-chemical characteristics as a direct and indirect result of European colonisation and land use changes (Reid 2020). Gamay has a predominantly sandy subtidal benthos with muddy areas associated with dredging near the bay's entrance, around port infrastructure and the airport runways. Georges River has predominantly muddy embayments while the channels have muddy sand (Reid 2021). Beaches in Gamay are considered low energy beaches when compared to beaches on the open coast but can still experience significant storm erosion, as seen following notable storms in 1974 (Fellowes et al. 2021) and 2016 (Gallop et al. 2020).

Little is known about sediment transport patterns and magnitudes in Gamay. However, it is thought that the presence/absence of channels or shoals next to beaches controls beach recovery after erosive events in Gamay.

Gamay's soft sediment habitats support a wide range of organisms. The diversity of fish and invertebrate species associated with benthic sediment habitats in Gamay are discussed in detail by Reid (2021) and so are only briefly summarised here. The biodiversity of infauna inhabiting sandy beaches are dominated by peracarid crustaceans, with the number of species being greater at the lower intertidal levels, and in areas with reduced wave action (Dexter 1984, Dexter 1985). Infaunal communities in sand flats in Quibray Bay are more diverse than in sandy beaches, probably due to the lower exposure to waves (Rossi and Underwood 2002, Bugnot et al. 2022). No studies have directly investigated the demersal fish and macrobenthic communities in Gamay, however, by-catch from prawn trawling undertaken in Gamay did find 37 taxa associated with sediment habitats, including, 115 finfish taxa, 11 crustaceans, 10 molluscs and 1 echinoderm (Liggins et al. 1996). Of these, Eastern fortesque (*Centropogon australis*), snapper (*Pagrus auratus*), two spot crab (*Ovalipes australiensis*), blue swimmer crab (*Portunus pelagicus*) and mantis shrimp (*Squillidae* spp.) were found in numbers exceeding a mean of 100 individuals caught per fisher-day.

Gamay's sediment microbial communities have been assessed in a number of comparative studies across NSW estuaries (Lee and Patterson 2002, Sun et al. 2012, Sun et al. 2013, Dafforn et al. 2014). Community composition of microbial communities in soft sediments and phytoplankton was comprehensively sampled throughout as part of surveys for marine pests (see Pollard and Pethebridge 2002). Over 50 species of dinoflagellates, including cysts have been identified in Gamay sediments including Gonyaulacids, Protoperidiniids and Diplopsalids, including multiple species potentially producing harmful toxins (Tan et al. 2018, Murray 2009). Dinocysts have also been found to correlate with organic carbon content in sediments (Tian et al. 2018). Currently little information exists on the biodiversity of sediment bioturbators such as large sediment macrofauna, rays and fish, as most studies to date have focused on small macroinvertebrates that can be captured from surface layers using grabs. These larger macrofauna can, however, significantly affect sediment functioning and as such more information about these communities is essential to understand the functioning of sediments and nutrient cycling in the bay.

Seagrasses

Seagrasses have been a key component of the ecology of Gamay for thousands of years. The primary seagrasses in Gamay are *Posidonia australis*, *Zostera muelleri* ssp. *capricorni*, *Halophila ovalis* and *Halophila minor* (SPCC 1978). *P. australis* in Gamay is one of six NSW populations listed as endangered under state legislation (*Fisheries Management Act* 1994) and was listed as a threatened ecological community under Commonwealth legislation (*Environmental Protection Biodiversity Conservation Act* 1999). Of all the vegetated habitats that occur in Gamay, seagrass habitats were the most poorly studied (8.3% of studies, 48 studies in total, Figure 2). Of those studies that do exist, most were concerned with seagrass physiology or their distribution in Gamay with few considering interactions between seagrasses and other organisms.

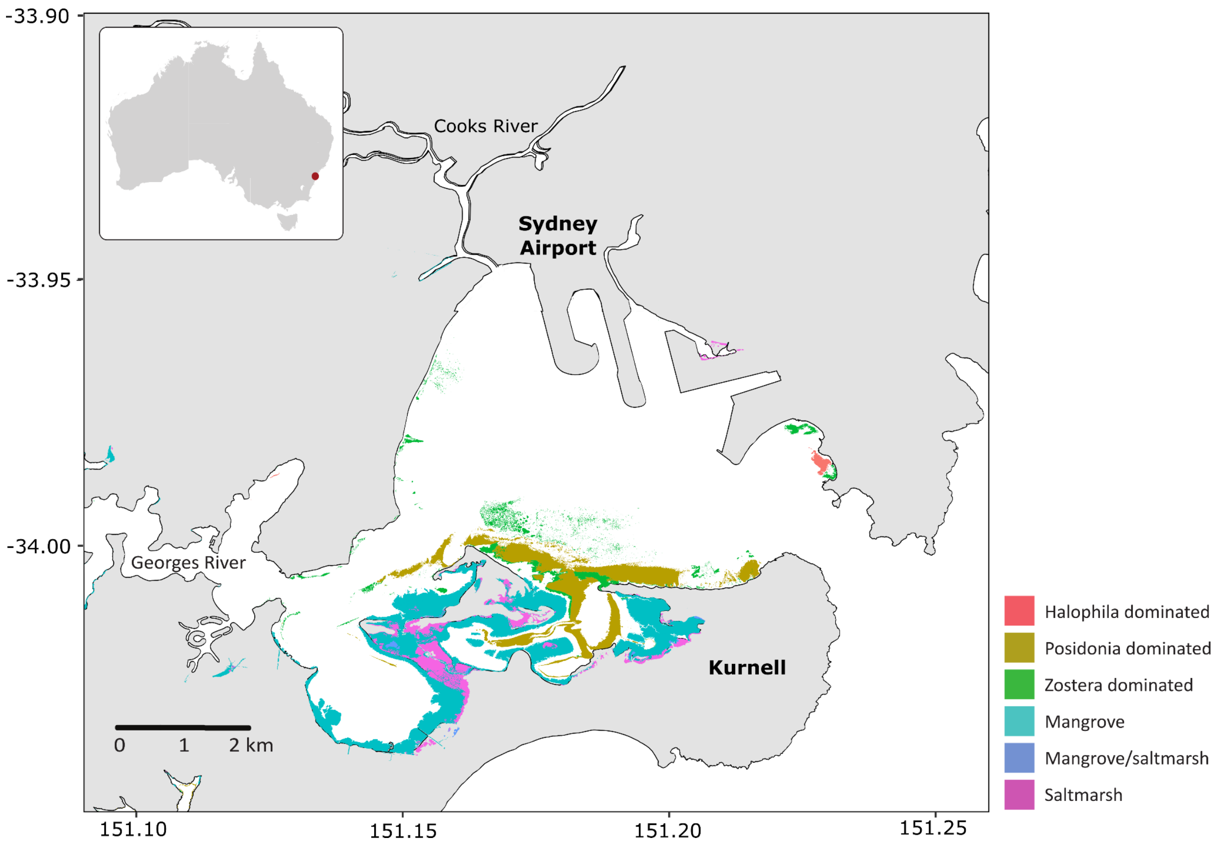

Figure 5. Distribution of estuarine macrophytes (seagrass, mangrove, saltmarsh) in Gamay (excluding upper Georges River) in 2019 (Data source: NSW Department of Primary Industries, 2020).

Today seagrasses cover a little over 300 hectares of Gamay, primarily along the southern shoreline (Figure 5). The current extent is potentially only a fraction of the extent before European colonisation, when *P. australis* probably covered the majority of the bay (Larkum 1976, Reid and Bone 2020). Analyses of aerial photos demonstrate that the area of all seagrasses in Gamay has been steadily declining since the 1940s (NSW Department of Primary Industries 1972, NSW Department of Primary Industries 1986, Larkum and West 1990, NSW Department of Primary Industries 2020, West and Glasby 2021). The largest historical declines of seagrass in Gamay have occurred along the northern shoreline, possibly due to historical contamination in the 1800s and early 1900s (Larkum and West 1990) and more recently due to disruptions associated with the construction of both Port Botany (and its expansion) and the second and third airport runways (Reeds 2018, Blount 2019, Macbeth 2019). The rates of decline of seagrass over the last 80 years has been 0.75% yr^{-1} (total seagrass) and 0.64% yr^{-1} (*P. australis*-dominated meadows) which, although on the lower range of rates recorded globally (Waycott et al. 2009, Dunic et al. 2021) are cause for concern. Once meadows get too small (< 50% of their maximum mapped area), or become fragmented, rates of decline can increase markedly (Larkum 1976, Dunic et al. 2021). Notably, Gamay has some of the most fragmented *Posidonia* meadows in NSW (T.M. Glasby, per. comm).

Seagrass beds provide some of the most ecologically significant habitats within estuaries, being particularly important habitat for many commercially and recreationally important fish species (Bell and Pollard 1989, Smith and Suthers 2000, Smith and Sinerchia 2004, Reid, 2021). Seagrass meadows also provide important nursery habitat for a wide range of fish and invertebrate species (Bell and Pollard 1989). For a more detailed summary of the species associated with seagrass habitats in Gamay see Reid (2021). The importance of symbiotic microorganisms (bacteria, fungi, and archaea) for plant growth is being increasingly recognised, however, remains a relatively new area of research for seagrass ecology (Nguyen et al. 2021). There is growing evidence that seagrasses have intimate relationships with their associated microbial communities, and that these communities may aid in resource acquisition and buffering seagrasses from environmental stress (Brodersen et al. 2014, Gribben et al. 2017, Tarquinio et al. 2019, Martin et al. 2020, Piercey et al. 2021). Additional gaps in Australia's seagrass research, many of which are directly relevant to seagrasses in Gamay, are summarised in York et al. (2017).

Mangroves and saltmarsh

Much of Gamay's coastal wetland habitat lies within the Ramsar-listed Towra Point Aquatic Reserve on the southern shore of Gamay (Figure 5), although other small patches of habitat are found in Penrhyn estuary and further up the Georges and Cooks Rivers. The extensive wetlands at Towra Point equate to ~25% of the area of Gamay. The ecology of the Towra Point Nature Reserve has been reviewed in great detail elsewhere as so is not included in this review (e.g., ALS 1977, DECCW and SMCMA 2010, Reid 2021).

Mangrove and saltmarsh habitats in Gamay support the aquatic ecosystem throughout the broader bay via both provision of hard substrata for sessile and mobile invertebrates (Warren, 1990; McGuinness, 1990; Ross & Underwood, 1997; Ross, 2006) and nursery habitats for fish (Ross et al. 2009; Mazumder et al. 2011). Saltmarsh plants are important habitats for high densities of molluscs (McGuinness 1990; Roach 1998) and are a primary source of dietary carbon for the resident grazing herbivores in the Towra Point wetlands as shown in stable isotope analyses (Mazumder et al. 2011). A restored wetland in inner Gamay, Rockdale wetland, was found to provide an important nursery area, especially for yellowfin bream and mullet which were able to move through a permanently open 700 m long pipe into the modified wetlands (Gibbs et al. 1999). Mangrove and saltmarsh habitats are also known to support the high densities of zooplankton (Ross 2001) which are a major source of food for estuarine fish (Mazumder et al. 2009, Mazumder et al. 2011). Across the bay, however, there has been a steady decrease in the extent of saltmarsh since ground-truthed mapping in Gamay began in 1980 (NSW Department of Primary Industries 2020). At Towra Point, 30% of the saltmarsh habitat has been lost since the 1930s (Saintilan and Williams 1999, Saintilan and Williams 2000). Mangroves have shown the opposite trend, with mangrove cover increasing in the bay (Figure 6). Aerial photographs from the 1930s and maps from as early as 1882 show that this is a long-term trend for the bay (Mitchell and Adam 1989a, Mitchell and Adam 1989b).

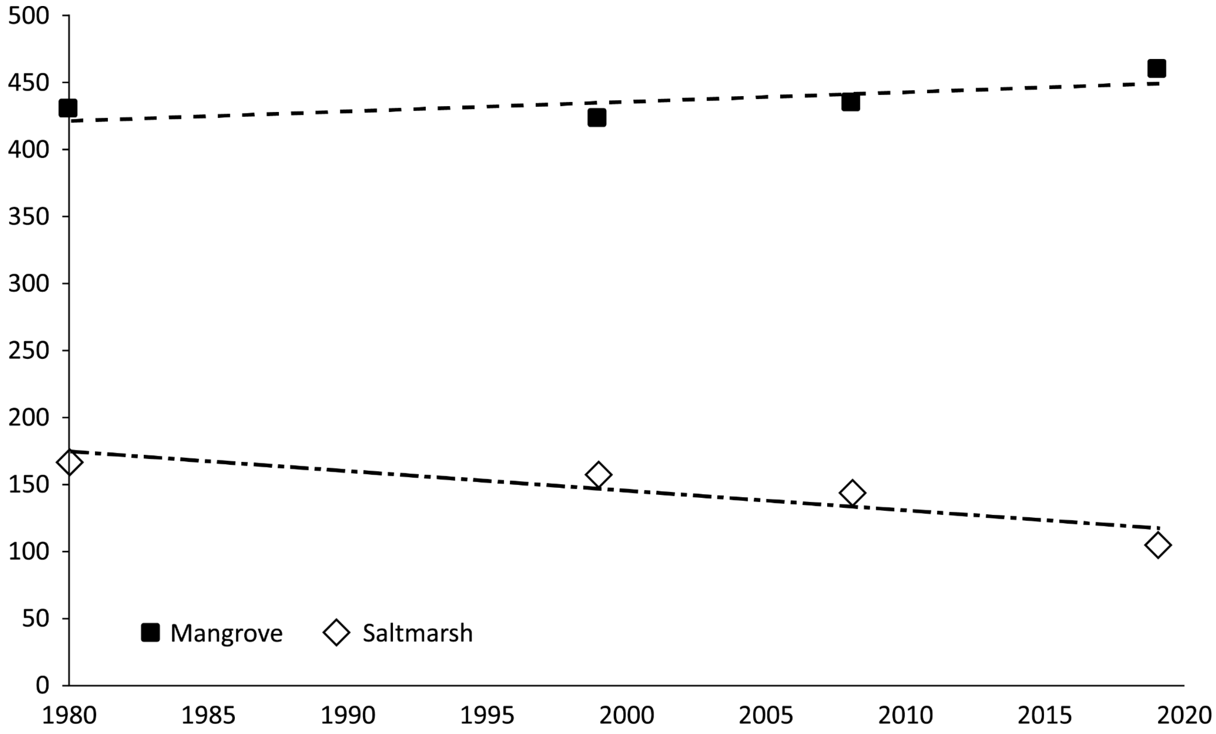

Figure 6. Mapped areas (hectares) of mangrove and saltmarsh in Gamay (excludes Cooks and Georges River) in 2019 (NSW Department of Primary Industries, 2020).

Reports dating back to the first fleet suggest First Nations people of Gamay used coastal wetland habitats for a variety of resources (ALS 1977). Whilst more specific reports of how these resources were used by First Nations people of Gamay are lacking, the use of wetland resources by First Nations people in other places around Australia have been recorded in more detail. The fruit of the mangrove tree *Avicennia marina* (known as *egaie*, Friess 2016) were baked and eaten by First Nations people of Australia (Hegerl 1982, Thozet 1985). The mangroves themselves were also used to make canoes (Wilson 1858, Martin 1865) and to make wood carvings (Hegerl 1982).

Subtidal rocky reef

Subtidal reef habitats were the second most studied habitat type (13.7% of studies, 79 studies in total, Figure 1) in Gamay and were most commonly studied in combination with artificial substrate habitats. Subtidal rocky reef is found predominantly around the mouth of Gamay, extending out around both headlands and along the oceanic coastline to the north and south (Figure 7). Within Gamay, most subtidal reef habitat is shallow, extending down to a maximum of 24m. Deeper subtidal reef (20 – 60m) occurs in small, isolated patches at the mouth of Gamay, but dominates subtidal reef habitats outside the bay, on the oceanic side of each headland (Figure 7).

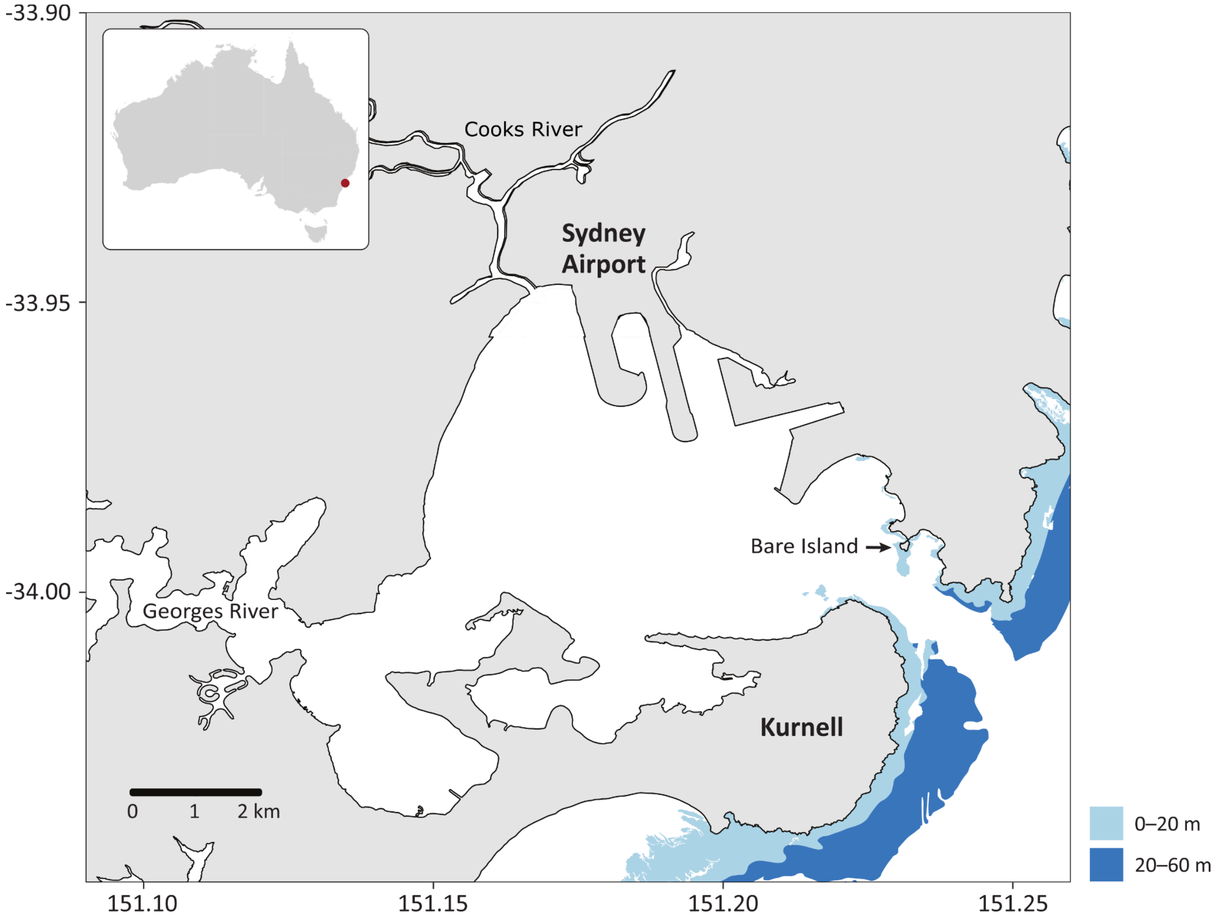

Figure 7. Distribution of mapped subtidal reef in Gamay (Data source: Cardno).

Much of the research on subtidal reefs in Gamay has occurred at Bare Island and Cape Banks, on the bay's northern shore. The macroalgal community at Bare Island is diverse, e.g., 45 species of Rhodophyta, 13 species of Phaeophyta and three species of Chlorophyta have been documented (Van Der Velde and King 1984). The forest-forming fucoid *Phyllospora comosa* was once abundant along shallow reefs on the northern headland but disappeared from the Sydney region in the 1970-80's, likely in response to near-shore sewage outfall discharges (Coleman et al. 2008). Recent restoration efforts for *P. comosa* populations in the Sydney region have had some success in Gamay (e.g., at Kurnell; Mead 2020). Kurnell Reef is another offshore subtidal reef that occurs just off Inscription Point on the bay's southern shoreline. The reef here is deeper (~20m) and diversity is low compared to Bare Island (SPCC 1981d). The area was traditionally dominated by sponges (Davis et al.

1997) but more recently extensive *Ecklonia* beds at ~10m depth have been observed growing in close proximity to the cliffs (Marzinelli et al. 2015).

The subtidal reef at Bare Island is also known to host diverse communities of sessile invertebrates, dominated by sponges, soft corals and bryozoans (SPCC 1981, Underwood et al. 1991, Poore et al. 2000, Knott et al. 2004, Knott et al. 2006). Deeper areas of reef to the east of Bare Island also support colonies of cool-temperate hard coral (SPCC 1981). Together with macroalgal communities, the biogenic habitat provided by these habitat-forming species support abundant and diverse mobile invertebrate communities dominated by crustaceans, polychaetes and molluscs (Van Der Velde and King 1984, Underwood et al. 1991, Poore et al. 2000). The subtidal reefs of Gamay are also home to the blubberabalone (*Haliotis brazeri, Haliotis coccoradiata* and *Haliotis rubra*). Abalone were historically harvested for food and trade purposes around the La Perouse area by First Nations people of Gamay (Cruse et al., 2005), and more recently have become popular with recreational and spear-fishers. There is surprising little in the way of comprehensive assessments of subtidal rocky reef fish assemblages in Gamay (but see Reid 2021). However, hard substrata were one of the three most specious geomorphic zones in the bay for fish (behind seagrass *Zostera capricorni* and deep soft substrate in the western region of the bay) (SPCC 1981c, SPCC 1981b, SPCC 1981d, SPCC 1981a).

Gamay's subtidal rocky reefs have been a focal point of marine microbial research in Australia since the beginning of the new millennium, through a combination of field surveys and *ex situ* experimental manipulations aimed at understanding the ecology of marine free-living and host-associated microbes, and how these interact with benthic macroorganisms (e.g., Huggett et al. 2006, Swanson et al. 2006, Longford et al. 2007, Zozaya-Valdes et al. 2015, Taylor et al. 2022). Temporal sampling of microbial communities associated with kelp, sponges and corals from Bare Island (as well as water, sediments and seagrass from elsewhere in the bay) have generated unprecedented data on microbial diversity (via amplicon sequencing) and function (via metagenomics and metatranscriptomics) which are currently being used to understand environmental drivers of, and connectivity amongst marine microbiomes (Phelps et al. 2021, Taylor et al. 2022). More broadly, microbial samples of kelp-associated microbes at Cape Banks and Kurnell were included in a global effort to characterise microbial diversity and function across Earth's habitats as part of the Earth Microbiome Project (Thompson et al. 2017). This research also revealed the strong association between the health of the kelp host and the structure of its associated microbiota (Marzinelli et al. 2015), with *ex situ* experiments demonstrating how environmental change can disturb host-associated microbes, resulting in strong impacts on host health (Qiu et al. 2019). Most of the research on Gamay's marine microbes has, however, focused on bacteria and archaea, and as such we still have only a limited understanding of the role of other microorganisms such as fungi, microalgae and viruses in these systems (but see Ferrari et al. 2021, McLennan et al. 2021).

Rocky Intertidal Shore

Approximately 30% of Gamay's shoreline is comprised of intertidal rocky substrata (SPCC 1981d). Most of the natural rocky shore area is located around the two headlands of the bay (specifically at Cape Banks and Sutherland Point), with some additional sections being found around La Perouse (Bare Island and La Perouse Point) (SPCC 1981d) and some patchy smaller intertidal shores are found along the Cooks River and Georges River estuary (Courtenay et al. 2005, Gall et al. 2013). Rocky intertidal shore habitats were the most highly studied habitat type within Gamay being considered in 86 single habitat studies (14.9% of studies, Figure 2), with an additional 10 studies that considered rocky shores in addition to other habitat types.

The intertidal communities of the rocky shores found around the Gamay headlands generally display distribution patterns similar to those found on other rocky shores in NSW (SPCC 1981d, Underwood et al. 1983). The rocky shore communities of Gamay are discussed in detail in Reid (2021) and so are only briefly summaried here. At Cape Banks, sea-squirts (*Pyura stolonifera*), various macroalgae and/or tube- dwelling polychaetes cover the low levels of the shore and provide important habitat for associated macro-faunal assemblages (Kelaher et al. 2001, Kelaher 2003a, Kelaher 2003b). The mid-levels in comparison are characterised by encrusting algae, gastropods and barnacles, with periwinkles dominating high levels on the shore (Denley and Underwood 1979, Underwood and Chapman 1996). Overall, the range of species inhabiting the shoreline is higher at the mouth of the estuary than further up the estuary in the channels (Attenbrow 2010a).

First Nations people of Gamay gathered shellfish by collecting them from rocks along the intertidal or from the subtidal by diving (Attenbrow 2010a). Excavated middens in the Gamay area suggest shellfish, namely bivalves and limpets, were a significant part of the diet of the First Nations people of Gamay prior to European settlement (Attenbrow 2010a). The species and relative abundances of shellfish vary among middens and are thought to reflect locational and season variation in availability rather than community structure (Attenbrow 2010a). Molluscan shells were also used by First Nations people of Gamay to make hooks for line fishing, where the robust shells of the turban snail *Turbo torquata* were ground down into a hook shape, with only the pearly nacreous inside surface showing (Attenbrow 2010b).

Cape Banks became a Marine Scientific Research Area in 1975 (McGuinness 1988, Matias 2008), before transitioning to an Aquatic Reserve in 2002. The area is a prominent site for research on key ecological processes, including inter- and intraspecific competition (e.g., Creese and Underwood 1982) and habitat-species interactions (e.g., Creese 1982). In line with this, invertebrate communities on intertidal rocky shores were overwhelmingly the most well studied taxa-habitat interaction (Figure 7), with most of this research occurring at Cape Banks. This has meant, however, that rocky shores in other areas of Gamay have received much less attention. The generality of patterns described for the Cape Banks area has also not been sufficiently explored along neighbouring stretches of rocky shore to the north and south of Gamay.

Oyster Reefs

Oysters were historically a key component of the Gamay ecosystem (Roughley, 1922, Gillies et al. 2020). First Nations people of Gamay have used oysters as an important food source for over 6000 years (Jackson and Forbes 2018). Flat oysters (*Ostrea angasi*) and Sydney rock oysters (*Saccostrea glomerata*) have been found in middens from the Gamay area in large quantities, suggesting that these species were a valuable subsistence resource (Jackson and Forbes 2018). Oysters were also popular with European settlers and were ultimately exploited to near extinction. The demise of wild oyster populations in Gamay and the Georges River then stimulated the emergence of an iconic and valuable Sydney rock oyster aquaculture industry (Reid and Bone 2020). Oyster aquaculture production in the Georges River and Gamay peaked in the 1970's, however, in the following decade disease and pollution caused production to significantly decline (for more details see Reid and Bone 2020). Despite this, however, Gamay is considered to still support some of the best examples of remnant Sydney rock oyster (*Saccostrea glomerata*) reefs along the New South Wales coast.

Today, only 0.098 km^2 of Sydney rock oyster reef remains in Gamay, with oyster reef habitat confined to the intertidal (NSW Department of Primary Industries 2020). Much of this reef is protected by the Towra Point Aquatic Reserve. Despite its small area, this remnant reef has considerable biodiversity and fisheries value. Video sampling at Quibray Bay and Carter's Island in Gamay revealed 44 species of fish associated with oyster reefs – a comparable number to *Posidonia australis* seagrass beds (48 species), and over 60% greater than sedimentary habitat (27 species) and mangrove habitat (29 species) (Martínez-Baena et al. 2022). Censuses of invertebrate populations associated with Gamay oyster reefs have not been conducted due to the destructive sampling methods that are required and the protected status of much of the remnant reef. However, censuses in other NSW estuaries have found a five-fold greater density, biomass and productivity of macroinvertebrates on oyster reefs as compared to adjacent sediments (McLeod et al. 2019), suggesting a similar habitat value may be expected in Gamay. Sampling and experiments in Woolooware and Quibray Bay's mangrove forest indicate the important role oysters also play in enhancing invertebrate abundances and richness in mangroves (Minchinton and Ross 1999, Bishop et al. 2009, Bishop et al. 2012, Hughes et al. 2014).

Since the decline in oyster production in Gamay, selective breeding programs have been implemented to develop disease-resistant oyster lines (Nell and Hand 2003, Nell and Perkins 2006, Dove et al. 2013). Knowledge gaps, however, still surround the transfer of disease and interbreeding between cultured and wild oysters (both *C. gigas* and *S. glomerata*). Increased investment in oyster research in Gamay would not only benefit the oyster aquaculture industry but could provide important information for urban aquaculture generally. The ecosystem service benefits provided by oysters can have far reaching benefits for the entire Gamay ecosystem, however, despite this, compared to most other habitats that occur within Gamay, oyster reefs remain some of the most poorly studied. To maximise the ecosystem benefits of oyster reefs to Gamay more research will be needed into developing and testing different methods of farming and restoration, as well as exploring optimal sites, locations and configurations for oysters to be grown within the bay.

Open Water and Pelagic Systems

Open water or pelagic regions are significant habitats in estuaries and marine embayments providing corridors for the movement and transport of species and resources important for all levels of the estuarine food web. In Gamay, open water and pelagic habitats are amongst the most well studied habitats in Gamay, for both single (11.1% of studies, 64 studies in total, Figure 2) and multi-habitat studies (33 studies, Figure 2).

Gamay is a well-studied system in terms of planktonic processes, generating a highly productive tidal discharge plume and associated tidal front (Kingsford and Suthers, 1994, Kingsford and Suthers, 1996, Reid, 2021) throughout the daily tidal cycle. Jellyfish, *Catostylus mosaicus*, have also been reported to occur in open water habitats in Gamay's main bay and the Georges River (Reid 2021). Significant fish species within the pelagic environment of Gamay include schooling baitfish such as sandy sprat (*Hyperlophus vittatus*) and Australian anchovy (*Engraulis australis*), and the commercially and recreationally important yellowtail scad (*Trachurus novaezelandiae*), silver trevally (*Pseudocaranx georgianus*) and yellowtail kingfish (*Seriola lalandi*). Larger fishes such as whale shark (*Rhincodon typus*) and bump-head sunfish (*Mola alexandrine*) have been sighted within the bay. Mullet *(Mugil cephalus)* is particularly important for First Nations people of Gamay, where harvesting of Mullet around March to June is associated with a time of celebration at Frenchmans Bay and Yarra Bay at La Perouse (Fay and Linkhorn 2021). Little penguins (*Eudyptula minor*) can also be seen foraging for baitfish within Gamay (Carter 2020). Excavated bones of *Dugong* from an indigenous midden near Gamay suggest dugongs occurred in the area historically (Haworth et al. 2004), however, recent sightings along the NSW coast are rare and none have been reported in Gamay (Allen et al. 2004). For further details on the ecology of pelagic fish communities in Gamay see Reid (2021).

While the macrobiota of Gamay's open water is relatively well studied, microbial components are less well documented. Ajani et al. (2013) documented the presence of 33 species of potentially harmful phytoplankton taxa at Woolooware Bay, close to oyster production leases. In Gamay, species producing harmful toxins appear to occur 10-30 times per year at detectable levels (Ajani et al. 2013) and high biomass blooms of other phytoplankton species (Murray and Suthers 1999, McLennan et al. 2021) are also common. Blooms of the paralytic shellfish toxin (PST) producing species *Alexandrium pacificum* (as *A. catenella*) occur regularly in Gamay. Planktonic microbe communities in Gamay are highly dynamic both temporally and spatially (McLennan et al. 2021). Factors impacting this variability include seasonality, which has been shown to play a role in the distribution of the 'red tide' forming microalgal species *Noctiluca scintillans.* These microalgae are highly abundant in Gamay in Spring and late Summer, forming visible water discolouration at times, and present at low levels in Winter (Murray and Suthers 1999). Nutrient inputs due to riverine inflow, land runoff, and other processes influence phytoplankton communities in an episodic manner, as can be seen by the periodic blooms of the dinoflagellate *Prorocentrum minimum*, which was found to be significantly correlated to decreased salinity and water column CO_2 (McLennan et al. 2021).

Within coastal environments like Gamay, planktonic bacteria are both key regulators of important chemical and nutrient cycling processes at the base of the foodweb (Falkowski et al., 2008) and potential indicators of contamination (Newton et al. 2011). However, while bacterial communities associated with macrophytes and sediments have been extensively examined (Burke et al. 2011, Sun et al. 2012, Sun et al. 2013, Phelps et al. 2021), planktonic bacterial communities within Gamay have not been widely characterised to date. One exception is the work by Carney et al. (2019), who performed time-series analysis of bacterial communities at Foreshore Beach. This study revealed 388 bacterial Operational Taxonomic Units (OTUs), spanning 35 different bacterial genera.

Artificial Substrates

Similar to urbanised estuaries globally, a considerable amount of artificial substrate has been added to Gamay and its associated river systems (e.g., breakwalls, groynes, piers, seawalls, pontoons). In 1981, it was estimated that 20% of the shoreline was ‘hardened’ through the addition of infrastructure (SPCC 1981d). A more recent estimate by the authors using satellite images available from Google Earth estimates that around 40% of the shoreline of Gamay, excluding Georges and Cook Rivers, has now been altered through the addition of artificial substrate. Seawalls dominate the shoreline of the main bay (20%), followed by revetments (12%). Recent estimates made by the NSW Department of Primary Industries (NSW Department of Primary Industries 2019) found a total of 33 jetties and pontoons in the main bay, and 39 rock groynes, which occupy an area of 22,513 m^2 and 32,196 m^2, respectively. Three-hundred and eighty artificial reef units have also been added to the main bay (see below for details).

The ecology of artificial substrates in Gamay has not been reviewed before. Of the 18 studies published (3.1% of studies, Figure 2), most have focused on fish assemblages and how artificial reefs and/or breakwaters have influenced those. These have produced mixed results (Burchmore et al. 1985, Fowler and Booth 2013, Porter et al. 2018). On the northern side of the bay, assemblage differences between smaller rock groynes and sandstone reefs of a similar size were driven by sub-adult life stages of numerous species (Fowler and Booth 2013), while mid-water piscivores were found to be more abundant on a large revetment wall relative to nearby rocky reefs (Porter et al. 2018). In contrast to other assemblage parameters, diversity was found to be similar between human-made rock walls and natural reefs in both studies that investigated it (Fowler and Booth 2013, Porter et al. 2018). Only two papers have specifically measured the fouling assemblages on artificial habitats in Gamay (Knott et al. 2004, Mckenzie et al. 2011). This is low compared to the number of studies done at the neighbouring estuary, Sydney Harbour, where > 20 studies have documented these assemblages and associated ecological processes on artificial habitats. Knott et al. (2004) found that many fouling invertebrate taxa showed clear differences regarding their cover between natural rocky reefs and concrete breakwalls in Gamay.

Gamay was declared a recreational fishing haven in 2002, bringing to a halt a commercial fishery that had operated for over a century. At the same time, NSW Department of Primary Industries Fisheries deployed reef balls to enhance rocky substrate and recreational fishing opportunities in the bay (0.5 m tall, 80 kg, footprint of 0.45 m^2). These were mostly deployed at the mouth of Yarra Bay, east of Bare Island at a depth of 5-10 m. The artificial reefs provided ~80 m^2 of artificial substrate (30 m^3 reef volume), representing a ~16% increase in area (Folpp et al. 2020). An additional 200 reef balls have since been deployed west of Bare Island. The fish communities on reef balls are often different between estuaries (Folpp et al. 2020, Goddard et al. 2021), largely due to the proximity of the deployment location to the estuary entrance. Nearly half of the fish biomass on the reef balls in Gamay is based on plankton (the rest on algal or benthic production), which is similar to the adjacent coastal rocky reefs (Truong et al. 2017, Holland et al. 2020). In contrast, the reef balls in Lake Macquarie, had approximately a third of fish community biomass more evenly based on plankton, macrophytes and detritus. The epibenthic assemblages associated with Mini Bay Reef Balls® has also been assessed (Mckenzie et al. 2011). A total of 16 taxa were found on reef balls in Gamay, higher than both Lake Macquarie and Georges Basin.

Freshwater associated habitats

Gamay has two main freshwater tributaries, Georges River and the Cooks River (Figure 1). The Georges River is about 96 km long with a catchment of around 96,000 ha and a discharge of >300 GL per year (Kingsford and Suthers 1996). The Cooks River is small by comparison, just 23 km long, with a catchment size of 10,900 ha. With a discharge of around 200 GL per year (Kingsford and Suthers, 1996). The Cooks River is nearly entirely composed of concrete drainage ditches and much of the flow occurs through pipes (89% is artificial). The Cooks River is mostly estuarine whereas the Georges is estuarine for nearly half its length up to the Liverpool Weir (Reid 2020). The regulation of freshwater in the Gamay catchment has been significant. Water capture and regulation for drinking water, agriculture and industry occurred at several locations in the Georges River Catchment. The freshwater wetlands around Gamay were used as a source of freshwater from 1859 up until 1889, after which these areas dried up due overuse by industry (SMCMA 2011).

Few studies have investigated the flora and faunal communities of Gamay's freshwater associated habitats. However, water quality, benthic diatoms and macroinvertebrates in Gamay's freshwater tributaries are monitored by both the Cooks River Alliance and the Georges River Keeper council groups. The Georges River is also known to be home to the endangered Macquarie Perch (Faulks et al. 2011). Other native freshwater fish species known to occur in the river include several species of gudgeons (Hammer et al. 2019), galaxids, smelt, Australian bass (Harris 1985) and long and short-finned eels. Mullet also migrate upstream but it is unclear how they navigate the weirs and penetrate into freshwater reaches. Multiple fish ways have been installed but fish passage for anadromous and catadromous fishes is of concern. Far more research is needed examining the freshwater fishes of the catchment. In the Georges River, platypus can still be found but they are restricted to an area near Campbeltown (Hawke et al. 2019). Whilst there are no formal records of freshwater mussels occurring in the Georges River, there are reports of First Nations people of Gamay eating them in the area (Attenbrow 2010b). First Nations people of Gamay are also reported to have sourced eels and wood boring worms, which they called *cahbro* from the upper reaches of the river (Attenbrow 2010b).

Research gaps for the habitats and biological communities of Gamay

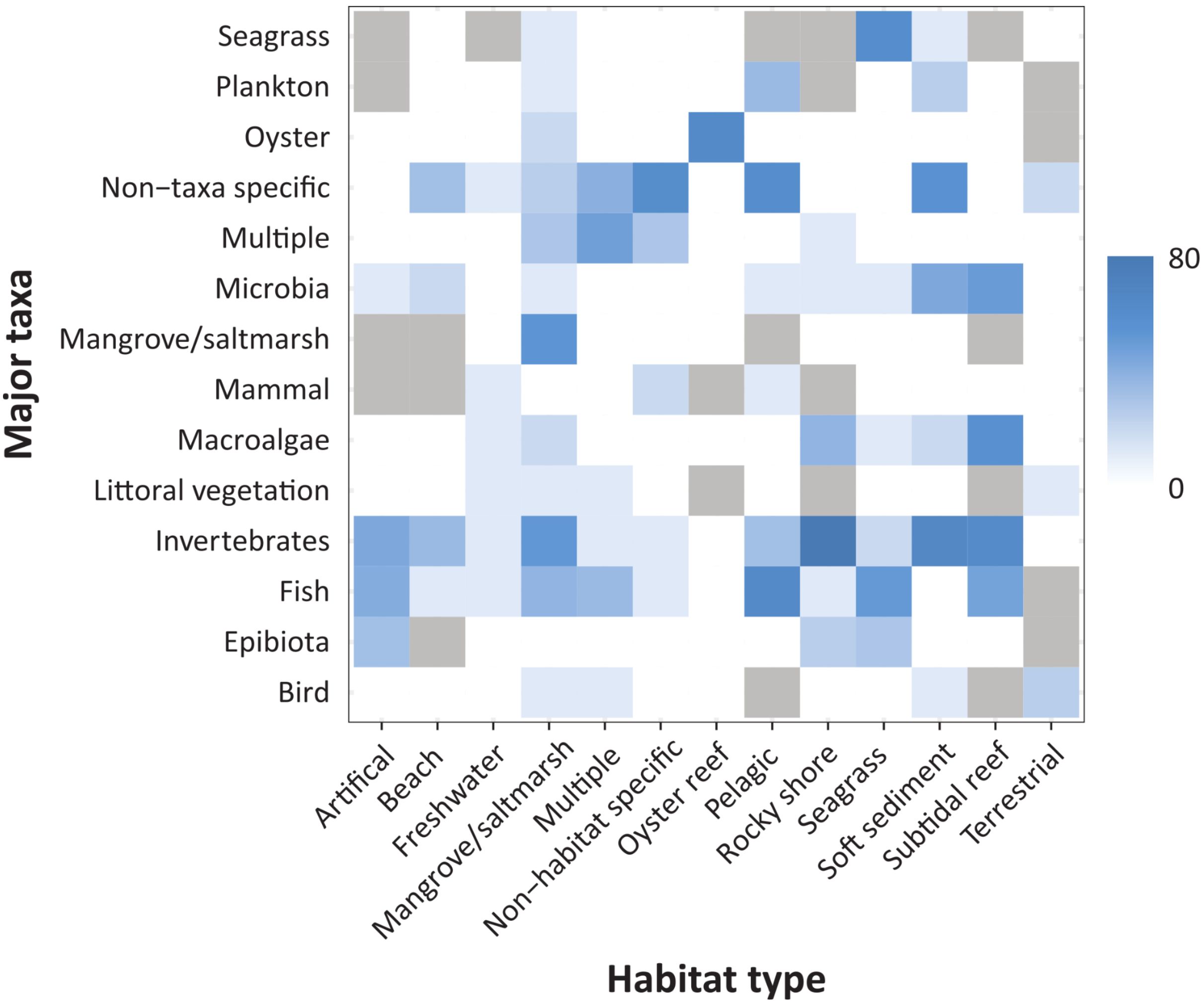

Figure 7. Publications were catagorised by the major taxa and habitat type they considered to identify areas of low and high research effort (quantified as the number of publications). 'Multiple' categories represent publications that considered more than one taxon or more than one habitat. Dark blue grid cells identify taxa-habitat interactions that have been comparatively well studied, whilst white grid cells identify taxa-habitat interactions that have not been studied. Grey grid cells identify taxa-habitat interactions that are not possible/not applicable to Gamay. The number of studies was log transformed for visualisation as invertebrates on intertidal rocky shore habitats has been an area of intense research effort (79 studies) compared to the next most well studied taxa-habitat interaction, invertebrates in soft sediment habitats (36 studies).

In order to identify areas where further fundamental research is lacking, we cross-referenced the number of publications on different taxa within each habitat type (Figure 6). Across most habitat types, invertebrates and fish were the most thoroughly studied taxa (Figure 6), with invertebrates on rocky shore habitats being an area of exceptionally high research effort.

Much of this research was undertaken at the Cape Banks Aquatic Reserve (previously designated as a Scientific Marine Research Area in the 1970s). Mangrove and saltmarsh habitats are the most thoroughly studied habitat across the different taxon categories, with much of this research having been undertaken at the Ramsar listed Towra Point Aquatic Reserve. Whilst oysters on oyster reefs are an area of high research effort, the interaction of oysters with other habitat types remains a major knowledge gap (Figure 7). Similarly, mangrove and saltmarsh vegetation have been well studied in their own habitats, however, how these habitat-formers interact with other habitats in Gamay remains largely unknown (Figure 7). The study of interactions between more than one taxon or more than one habitat type (multiple categories, Figure 7) is also a major knowledge gap for Gamay, with most studies considering individual taxa and habitats in isolation only (Figure 7). Below we discuss knowledge gaps for Gamay as a whole, focusing on those that are most pressing for Gamay's sustainable future. We also highlight significant opportunities that current research has created for research on Gamay into the future.

Discussion, knowledge gaps and opportunities

Long-term trends

Effective management requires a robust knowledge of environmental change over time, including the cause of change and its consequences - both those presently perceived as well as those possible in the future (Lindenmayer et al. 2012). Long-term data sets are invaluable to show changes to the environment in response to short and long-term perturbations. As with research on Sydney Harbour (Johnston et al. 2015), however, few studies published on Gamay have been replicated through extended time periods and thus we identify this as a significant knowledge gap and opportunity to improve our understanding of the bay. An exception to this is temporal variability in the distribution of macrophytes in Gamay. The availability of early maps and aerial photos from as far back as 1942 has motivated several studies on changes in macrophyte cover over time in Gamay, documenting large declines in the cover of seagrass and saltmarsh, whilst the cover of mangroves has increased (NSW Department of Primary Industries 1972, NSW Department of Primary Industries 1986, Mitchell and Adam 1989a, Larkum and West 1990, Saintilan and Williams 1999, Saintilan and Williams 2000, NSW Department of Primary Industries 2020, West and Glasby 2021). Long-term sea urchin monitoring records (1996-2013) have also been used to assess temperature driven increases in the prevalence of sea urchin disease in Gamay (Sweet et al. 2016).

Despite the lack of published studies investigating long-term trends in Gamay, some long-term data sets exist. Several sites in Gamay have been monitored on a regular basis over a period of years. For example, as part of the Australian Microbiome coastal project conducted by Bioplatforms Australia and the Integrated Marine Observing System, fortnightly water column plankton and bacterial samples have been collected at a site close to Quibray Bay for the past 5 years (McLennan et al. 2021). In relation to this project, a real time temperature and salinity sensor, with data that is publicly available, has also been deployed close to the sampling site. Similarly, Beachwatch monitors Gamay and Georges River swimming sites every 6 days throughout the summer swimming season (October to April), and monthly during winter (May to September).

Where long-term data sets do not exist Gamay's rich history of field surveys and experiments could provide a unique opportunity to assess long-term impacts through the use of techniques such as modelling and meta-analyses. A proliferation of citizen science programs in the past decade has also increased the availability of datasets that cover large temporal or spatial scales (Devictor et al. 2010). These datasets have immense potential for scientists and managers as they often cover scales difficult to achieve in small research groups (Silvertown 2009). The Cape Solander Whale Migration Study (CSWMS), which operates in Gamay, involves volunteers recording humpback whale numbers from Cape Solander in the Gamay Botany Bay National Park and has been active for the past 20 years. Data collected by the CSWMS has permitted scientists to estimate a 10% per annum increase in the number of humpback whales occurring off Sydney over the last 20 years (Pirotta et al. 2020). Another example is the Australasian Fishes project on the iNaturalist database which involves submission of fish photos by citizens which can then be verified by other users and experts (DiBattista et al. 2021). Over 70,000 images have already been submitted, with a large number from Gamay. Increased use of available citizen science datasets for scientific research in Gamay, as well as the development of more programs represent a significant area of opportunity for Gamay into the future.

Seascape Connectivity

Water-mediated movement of energy, propagules and nutrients is essential for the ecological integrity of estuaries (Pringle 2003). Few studies have investigated Gamay's hydrology despite human modifications significantly altering water flow within the bay. Human-made artificial structures can disrupt the movement of water across seascapes, with the potential to influence connectivity at multiple scales (Bishop et al 2017). These structures can act as physical barriers, preventing movement; but also have the potential to facilitate connectivity by providing channels through which movement can occur (Bishop et al. 2017). Climate change and urbanisation mean artificial structures are being added to coastal habitats at an increasing rate (Firth et al. 2020) and Gamay is no exception to this (see Artificial substrates). This makes it more important than ever to understand connectivity in this coastal waterway and how the addition of artificial substrates might influence it. Additionally, Gamay's connection to the ocean and the influence of adjacent rapid ocean warming (Malan et al. 2020, Li et al. 2022) requires long term datasets and further investigation to understand warming trends within the embayment.

Understanding how habitats and communities are connected is also particularly important in urban estuaries such as Gamay where vegetated habitats are declining and becoming more fragmented. The importance of these vegetated habitats as fish habitat is well documented (Mazumder et al. 2011, Saintilan and Mazumder 2017), however, information on the current fish assemblages within the bay are lacking (Saintilan et al. 2007). This information is necessary to deepen our understanding of the role of fish assemblages in facilitating connectivity amongst different habitats within the bay and the degree to which bay resilience depends upon this. Similarly, little is known about how sediment infauna biodiversity and how their functions are driven by seascape connectivity and habitat configuration patterns such as proximity to habitat-forming species and rocky reefs (but see Bugnot et al. 2022).

The mudflats at Towra Point are important foraging grounds for endangered and migratory shorebirds, yet we know little of how the productivity of these habitats and nearby soft sediment habitats are influenced by adjacent oyster reefs. The contribution of oyster reefs to the present-day fisheries productivity of Gamay is also unknown. Given that Gamay is a designated recreational fishing haven this information will be important to ensure effective fisheries management of the bay. Understanding seascape connectivity is also vital for scientists and managers, assisting them in optimal site selection for habitat restoration efforts, as well as allowing for conservation, restoration and/or fisheries related goals to be reached simultaneously in a more efficient and effective way.

Habitat Restoration and Remediation

A legacy of extensive urbanisation has led to the degradation and loss of many habitats and communities in Gamay. Seagrass restoration is becoming increasingly viable and is seen as a crucial management tool for addressing seagrass losses (Sinclair et al. 2021). There have been recent successful seagrass transplantation projects in Gamay. Restoration by NSW Department of Primary Industries in Gamay found numbers of transplanted *P. australis* shoots doubled over 8.5 years which coupled with extensive vegetative regrowth from the surrounding meadow into the rehabilitated sediments, resulted in the restoration of some 600 m^2 of *P. australis*, albeit at a reduced density compared to natural populations (Glasby 2022). Interestingly, however, they found the success of rhizome transplanting in deeper (3 – 4 m) parts of the meadow was substantially reduced relative to the shallower areas (2 – 3 m), suggesting there are still gaps in our understanding of the mechanisms that regulate the success of restoration efforts. Seagrass and saltmarsh restoration has also been undertaken on Gamay's northern shoreline as part of the Port Botany expansion Penrhyn Estuary habitat enhancement plan (Blount 2019). Positive results here suggest potential opportunities for creating or restoring seagrass or saltmarsh in other areas in Gamay.

The first large scale oyster reef restoration project in Gamay and Georges River was recently established in 2021 by the Nature Conservancy, Greater Sydney Local Land Services and NSW Department of Primary Industries to combat legacy pollution in the water and sediments. Whilst at the time of writing restoration work is yet to begin, the project's long-term aim is to restore up to five hectares of the locally extinct Australian flat Oyster (*O. angasi*) and depleted Sydney rock Oyster (*S. glomerata*) reefs, across four sites: Kurnell, Taren Point, Coronation Bay and Audrey Bay flat (TNC 2022). By recovering oyster habitat, the project hopes to increase biodiversity, improve water quality, and increase production of recreationally and commercially important fish. This oyster reef restoration project will provide an acid test of how well we understand oyster reef ecology in Gamay.

Many of these restoration projects represent pioneering work for habitat restoration, highlighting that there are significant opportunities to trial management strategies in Gamay. These endeavours will, however, have flow-on effects for the fauna and flora of

Gamay and in order for such projects to be successful more needs to be known about species-specific habitat dependencies as well as transfers and linkages between different habitats.

Traditional Ecological Knowledge of First Nations people of Gamay

First Nations people of Gamay have lived off the lands and waters of Gamay and its tribulatries for tens of thousands of years. The extensive knowledge and experience they acquire from their interactions with the environment over this time period is captured as Traditional Ecological Knowledge (TEK). Unfortunately, much of the TEK of First Nations people of Gamay remains largely undocumented in written formats, meaning that much of this knowledge has been lost over the years. In cases where TEK has been documented, it is often recorded as anecdotal observations by early European settlers that lack important detail such as location, dates etc. making it difficult to use such information in scientific research. This means that little is known about Gamay prior to European settlement and in the early years post-European settlement.

The value of TEK for science and management has only recently begun to be realised. Its recognition is, however, paving the way for collaborative efforts between scientists, managers and First Nations people of Australia creating opportunities to advance knowledge and understanding, and share power and responsibilities amongst these different groups (Bohensky et al. 2013). Such collaborations can facilitate the development of novel approaches to environmental management (Houde 2007).

Artificial substrates as habitat

Artificial substrate habitats are one of the few habitat types in Gamay that are increasing in extent, yet despite this, they remain poorly studied. Scientific understanding of the significance of artificial substrates in Gamay is superficial and generally small-scale. For example, all three of the investigations into fish assemblages associated with artificial shoreline structures have been conducted on the northern side of the main bay (Burchmore et al. 1985, Fowler and Booth 2013, Porter et al. 2018). There is a need to examine the bay-wide extent and the influence of artificial substrate on the ecology of Gamay, both to understand the type and magnitude of ecological change that may have already occurred and to predict future change if further substrate is added. To achieve this, comprehensive faunal surveys on all major structure types are required, along with information on the amount and distribution of those substrates within the bay and associated rivers. Knowledge of how biological communities interact and function on artificial substrates is also required to understand the potential effects of differences in community structure observed in numerous studies and the best management practices to mitigate some of these impacts.

Eco-engineering interventions such as Living Seawalls (www.livingseawlls.com.au), offer the opportunity to potentially increase the functioning of artificial substrate habitat by increasing structural complexity for the purpose of enhancing biodiversity. Whilst such interventions are rarely equivalent to natural habitat, at locations where the construction of infrastructure is unavoidable such interventions can act to minimise the negative ecological impacts of such developments (Strain et al. 2018).

Conclusion

Gamay is one of the most well studied coastal waterways in Australia. It is a place of enormous ecological and social complexity and in many ways the extensive amount of research having been undertaken in Gamay represents just the baseline of what's needed to effectively manage the bay. Through this comprehensive review we have synthesised current ecological knowledge from scientific peer-reviewed literature and a wide range of non-scientific sources and have identified major knowledge gaps that should be filled if we are to manage this iconic ecosystem for all its residents, including both the people that live in its catchment and the biota that live in its aquatic habitats.

In addition to highlighting areas where research is lacking, this review has also highlighted the numerous opportunities which current work has generated, creating paths that stakeholders and managers can walk together towards a sustainable future for the bay. The success of many of these opportunities will, however, rely on cooperation and collaboration, not only between scientists and managers, but also between the multitude of other stakeholder groups (e.g., First Nations People of Gamay, government agencies, recreational fishing groups, local councils, community groups, commercial operators, residents etc.) that use and care for the bay. For it is only through cooperation, collaboration and partnerships between stakeholders that a sustainable future for Gamay can truly be ensured.

Conflicts of interest

The authors declare there are no conflicts of interest.

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