The effects of total suspended sediment associated with dredging on fishes: a review and management strategies

Theme: Fisheries and Aquatic Resources

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ABOUT THE MARINE SCIENCE PROGRAM

The WAMSI Westport Marine Science Program (WWMSP) is a $13.5 million body of marine research funded by the WA Government. The aims of the WWMSP are to increase knowledge of Cockburn Sound in areas that will inform the environmental impact assessment of the proposed Westport development and help to manage this important and heavily used marine area into the future. Westport is the State Government's program to move container trade from Fremantle to Kwinana, and includes a new container port and associated freight, road and rail, and logistics. The WWMSP comprises more than 30 research projects in the biological, physical and social sciences that are focused on the Cockburn Sound area. They are being delivered by more than 100 scientists from the WAMSI partnership and other organisations.

FUNDING SOURCES
The $13.5 million WAMSI Westport Marine Science Program was funded by the Western Australian Government, Department of Transport. WAMSI partners provided significant in-kind funding to the program to increase the value to >$22 million.

DATA
Finalised datasets will be released as open data, and data and/or metadata will be discoverable through Data WA and the Shared Land Information Platform (SLIP).

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FRONT COVER IMAGE
Theme: Fisheries and aquatic resources
Front cover image: A school of Pink snapper in Cockburn Sound (DPIRD).

Contents

The WAMSI Westport Marine Science Program is a $13.5 million body of research that is designed to fill knowledge gaps relating to the Cockburn Sound region. It was developed with the objectives of improving the capacity to avoid, mitigate and offset environmental impacts of the proposed Westport container port development and increase the WA Government's ability to manage other pressures acting on Cockburn Sound into the future. Funding for the program has been provided by Westport (through the Department of Transport) and the science projects are being delivered by the Western Australian Marine Science Institution.

1 The effects of total suspended sediment associated with dredging on fishes: a review and management strategies

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Project
Project 4.4 Effects of TSS on key fish species

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Executive Summary

The Western Australian Government is planning to develop a new container port in Cockburn Sound, along the coast of the Kwinana Industrial area. The Sound supports a diverse range of marine life and serves as a significant spawning and nursery ground for many commercial and recreational species. The proposed development will likely create added environmental pressures to the Sound, including increased suspended sediment from dredging operations. Knowledge on dredging related pressures to marine life, particularly fish, is still largely unknown. This literature review identified the potential impacts from elevated suspended sediment on fish from dredging, with focus on Cockburn Sound. Both behavioural and physiological processes are likely to be impacted during elevated levels of sediment. Behaviourally, fish are likely to avoid dredging areas, or elevated levels of sediment may cause visual impairments for foraging and predation, impacting feeding success. Elevated levels of suspended sediment may cause physiological changes to fish gills, including gill irritation and damage, in addition to increased susceptibility to pathogenic bacteria. Increased suspended sediment may also effect egg and larval development of fishes, reducing hatching success and larval development which may reduce successful recruitment to the embayment. The effects of elevated suspended sediment, however, are likely to be species and site specific, with the severity of impact depending on the concentration, duration of exposure, type of sediment, and the life stage of the species exposed to the sediment. Consultation of stakeholders identified 65 species of most concern during the proposed port development, with the top 10 ranking being:

1. Pink Snapper (*Chrysophrys auratus*)
2. Blue Swimmer Crab (*Portunus armatus*)
3. Southern Calamari (*Sepioteuthis australis*)
4. Western Australian Salmon (*Arripis truttaceus*)
5. King George Whiting (*Sillaginodes punctatus*)
6. Australian Herring (*Arripis georgianus*)
7. West Australian Seahorse (*Hippocampus subelongatus*)
8. Southern Garfish (*Hyporhamphus melanochir*)
9. Sandy Sprat (*Hyperlophus vittatus*)
10. Australian Sardine (*Sardinops sagax*)

Most of these species have high recreational and/or commercial value, with most spawning in the warmer months. The Sound also constitutes as an important spawning and nursery area for many of the species. Of these species, only one, *C. auratus*, has been studied for effects of suspended sediment (i.e., trigger values), highlighting the need to evaluate more species that are present in Cockburn Sound. This review reveals site and species specific knowledge gaps about the impact of increased total suspended sediment (TSS) from dredging on fish in Cockburn Sound. Due to this lack of knowledge, we recommend that a precautionary approach is taken following Wenger et al. (2018), which advises maintaining suspended sediment concentrations below 44 mg/L and for less than 24 hours to protect 95% of fish from dredging-induced mortality.

2 Introduction

2.1 Cockburn Sound

Cockburn Sound is a temperate embayment which covers an area of 124 km^2, located approximately 20 km south of Perth, Western Australia (WA) (Skene et al., 2005). This semi-enclosed system is bounded by Garden Island to the west, and shallow sand banks to the north (Parmelia Bank) and south (Southern Flats). The south entrance of the Sound is further bounded by the rock-filled causeway which connects the mainland to Garden Island (Hillman and Gersbach, 2002). The central basin of the Sound reaches a maximum depth of 22 metres, with the outer banks ranging from 0-10 metres (Australian Hydrographic Service, 2001). Extensive areas of soft sediment (mainly biogenic carbonate, with muddy sand occurring at greater depths (Skene et al., 2005)) and seagrass meadows (predominantly *Posidonia sinuosa* and *Posidonia australis* (Cambridge and McComb, 1984; Hovey and Fraser, 2018)) dominate the embayment (Figure 1). Small patches of limestone reef also occur along the Eastern Shoal of the Sound, covered with macroalgae (e.g., *Ecklonia radiata* and *Sargassum* spp.), coralline and filamentous algae, and sessile invertebrates such as soft corals and sponges (Ong et al., 1998; Wakefield and Johnston, 2009; Figure 1).

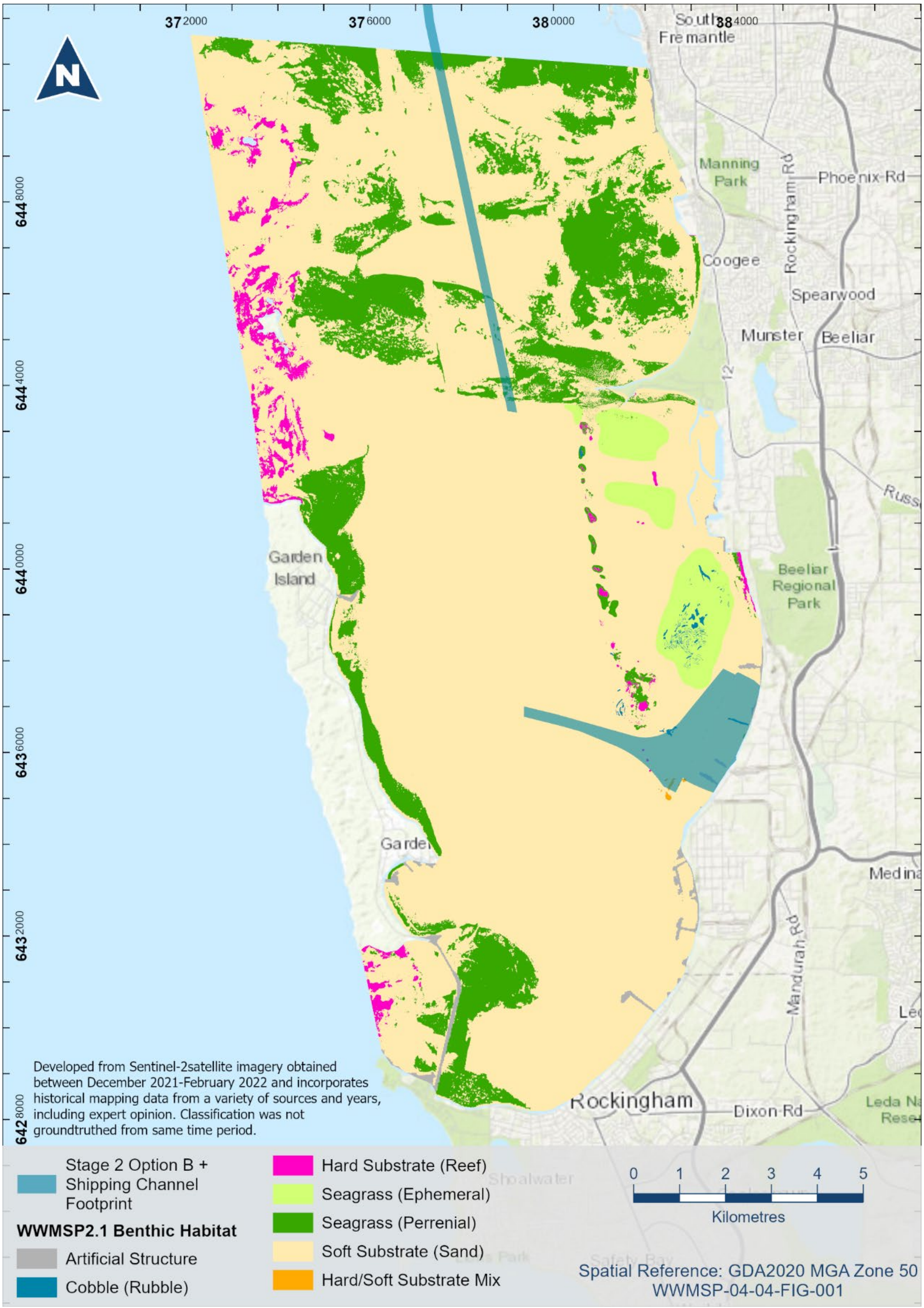

Figure 1. Map of Cockburn Sound with habitat overlays of sand and seagrass from 2017 mapped surveys (Hovey and Fraser, 2018), limestone reef (Oceanica Consulting Pty Ltd as cited in Wakefield et al., 2013), and proposed Westport development (From Westport Program Strategy - Stage 3).

2.1.1 Anthropogenic pressures of the Sound

The Sound's proximity to the capital city of WA, coupled with its sheltered waters and diverse marine fauna, has made it an ideal location for recreational use, fishing, shipping, naval operations, and industries that require port facilities (Cockburn Sound Management Council, 2005; Sumner and Lai, 2012; Wakefield and Johnston, 2009). However, industrial development and activity along the eastern coast of the Sound, particularly between 1950s-1970s, resulted in elevated nitrogen and heavy metals in the embayment caused by industrial effluent and wastewater discharge (Cambridge, 1979; Cambridge et al., 1986). This led to metal contamination, and large-scale loss of seagrass coverage within the Sound (~77% reduction, from 1954-1978) due to excessive epiphytic algae growth from high nutrient inputs (Cambridge et al., 1986; Cambridge and McComb, 1984; Kendrick et al., 2002). Physical disturbance from the construction of the Garden Island causeway, scallop dredging, port developments, dredge spoil dumping, and shipping channels also contributed to the disappearance of seagrass within the Sound (Cambridge and McComb, 1984; Kendrick et al., 2002). With improved management and more strict regulations, the water quality of the Sound has been dramatically improved (Hillman, 1986). Localised losses of seagrass continue with slow recovery due to the ongoing development and activity along the coast (Fraser et al., 2016; Mohring and Rule, 2014). The construction of the rock-filled causeway between 1971 and 1973 also initiated another major disturbance to the Sound, which effectively reduced water exchange with the surrounding ocean by 40% and wave energy by 75% (Lord, 2001). It is now estimated that it takes up to 22 days in winter and 44 days in summer to flush ~63% of the water body in the Sound (Hillman and Gersbach, 2002; Lord, 2001). Consequently, Cockburn Sound has become a major sink for fine sediment, nutrients, and other pollutant sources (Van Keulen, 2012).

2.1.2 Biodiversity of the Sound

Despite the anthropogenic pressures experienced within the Sound, it still sustains an important habitat for a diverse range of marine biota. Cockburn Sound is an important spawning and nursery area for a range of species, including some of which are considered recreationally and commercially important (Ryan et al., 2015; Wakefield, 2010). These include the Blue Swimmer Crab (*Portunus armatus*) (Potter et al., 2001), the Western King Prawn (*Melicertus latisulcatus*) (Penn, 1976, 1975), Pink Snapper (*Chrysophrys auratus*) (Lenanton, 1974; Wakefield, 2006), Sandy Sprat (H*yperlophus vittatus*) (Gaughan et al., 1996), and King George Whiting (*Sillaginodes punctatus*) (Hyndes et al., 1998). Cockburn Sound also constitutes an important fishery for herring (*Arripis georgianus*), sardines (*Sardinops sagax*), octopus (e.g., *Octopus djinda*), squid (e.g., *Sepioteuthis australis*), skates and rays (e.g., *Dasyatis brevicaudata*) (Sampey et al., 2011; Smith and Brown, 2014). Bottlenose Dolphins (*Tursiops aduncus*) (Finn, 2005), Australian Sea Lions (*Neophoca cinerea*) (Campbell, 2005), and Fairy Penguins (*Eudyptula minor*, also known as Little Blue Penguins) (Cannell et al., 2016) have also been documented in the Sound, and are highly valued by the community (Westport focus group, 2022 (attached in report)).

2.1.3 Proposed port development

In 2020, the Western Australian Government announced that a future container port could be built in Cockburn Sound, along the coast of the Kwinana Industrial area. The proposed development will likely create environmental pressures to the embayment. These may include increased turbidity, contamination, and physical alteration to the habitat during construction, as well as potential hydrodynamic alterations and increased boat/shipping traffic during port operations (Wakefield and Johnston, 2009; Wenger et al., 2017). Given the ecological, social, and economic importance of the Sound, it is essential that the relationships between port-related pressures and the embayment are understood, so that impacts can be predicted and incorporated into the management strategy. One area of concern is increased suspended sediment from dredging operations during construction. Increases in total suspended sediment (TSS) will not only be associated with dredging, but also with increases in port operations such as ship berthing and exiting of the Sound when fully laden with minimal under keel clearance. Shipping related turbidity due to resuspended sediment is likely to be widespread and continuous, whereas turbidity due to dredging will be limited in its temporal extent, and spatial extent may be limited depending upon the mitigation measures that are adopted.

Knowledge about the extent to which marine life, such as fish, are affected by TSS associated with dredging is limited, with very few studies and reviews covering this topic, particularly for West Australian species (although see Hess et al., 2017; Moustaka et al., 2018; Partridge and Michael, 2010; Wenger et al., 2017, 2018).

2.2 Current knowledge of dredging related pressures on WA fish

In 2013, a WAMSI-funded workshop produced a literature review on the direct effects of dredging on finfish. The workshop included input from stakeholders from relevant sectors of state and federal government institutes, private industry, and academia. The review identified the physiological and ecological implications of suspended sediment, sediment contamination, sedimentation, underwater noise, and hydraulic entrainment on fish across different life stages with a focus on a WA context, using global studies (Harvey et al., 2017; Wenger et al., 2017). Critical Environmental Windows (i.e., periods where species are susceptible to impacts due to life history events) of target species in WA were collated to determine the most appropriate timing for dredging and trigger values for elevated suspended sediment concentrations using comparable studies (i.e., using sediments particle ≤ 4 µm) were identified. Analyses of the collated data for sediment concentrations, involving 20 studies and 17 species, predicted that a trigger value of 2.4 mgL^{-1} would protect 99% of species before observing an impact, while concentrations of 80 mgL^{-1} would protect 50%, and concentrations of 166 mgL^{-1} would protect 25% of species (Figure 2). The collation of a larger dataset that involved a variation of sediment type and size (i.e., 57 studies, 131 records) found that 95% of species would be protected from mortality if exposed to suspended sediment concentrations less than 44 mgL^{-1} and for less than 24 hours (Wenger et al., 2018). Furthermore, concentrations under 1,814 mgL^{-1} would protect 50% of species from lethal impacts (Wenger et al., 2018). While these trigger values provide insights into the potential thresholds of fish with increasing suspended sediment, they may not be applicable for site specific use, as both datasets involve a variety of habitat types, geographic locations, species, life history stages, and sediment types. Consequently, localised research may be required that focuses on site specific species and conditions to determine the true effects of suspended sediment for an area.

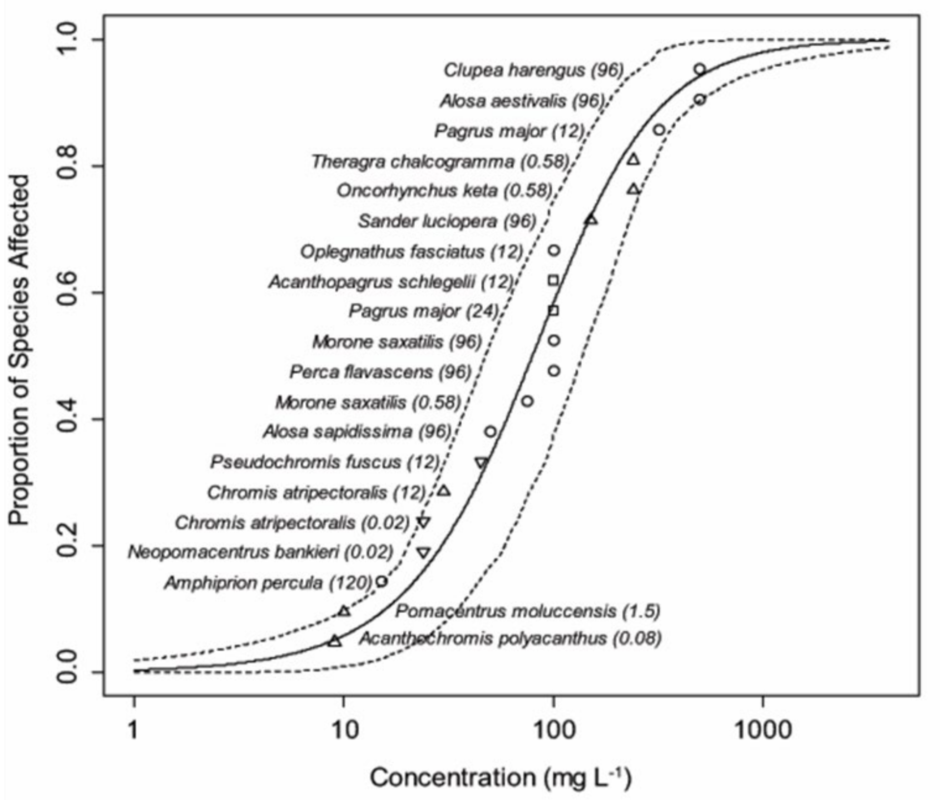

Figure 2. From Harvey et al. 2017 (WAMSI DREDGE) Burr Type III cumulative probability distribution for suspended sediment (<4 µm) concentrations (mgL^{-1}) that impact fish (Appendix 2, Table 5). Numbers in parentheses after species names are exposure times (hours). Dashed lines represent bootstrapped 95% confidence intervals. Fit and confidence intervals estimates were calculated by the Burrlioz 2.0 software (CSIRO 2015).

2.3 Literature review aims

The following literature review will explore the potential effects of suspended sediment on fishes (including invertebrates and other fished species), with a focus on Cockburn Sound. The review will also outline recommended research based on the existing literature to help facilitate new trigger values for management of the proposed port development in Cockburn Sound.

3 The effects of suspended sediment on fishes

Dredging is the extraction and relocation of benthic material, typically used to create or maintain shipping channels, provide material for land reclamation, or to mine benthic resources (Todd et al., 2015). Dredging can directly impact the benthic seafloor by modifying the habitat (i.e., removal and/or dumping), in addition to creating extensive sediment plumes, increasing TSS within the water column (EPA, 2021). The concentration and extent of the sediment plume can vary depending upon the dredging technique (i.e., mechanical or hydraulic), quantity, size and type of the sediment, and the local hydrodynamic conditions (Todd et al., 2015; Wenger et al., 2017). The effects of dredging on fishes are still largely unknown, however, elevated levels of suspended sediment impact behavioural and physiological processes of fish and other marine life. The severity of these impacts can vary depending on factors such as the concentration, duration, and type of sediment, and the life stage of the species exposed to the sediment (Fraser et al., 2017; Magris and Ban, 2019; Todd et al., 2015; Wenger et al., 2018, 2017; Wilber and Clarke, 2001).

3.1 Behavioural changes

3.1.1 Avoidance

One of the primary behavioural responses to elevated suspended sediment is avoidance (Collin and Hart, 2015), which is typically observed in adult fish due to their ability to move away from the source of the sediment (Wenger et al., 2017). This behaviour is common with salmonids (Bash et al., 2001), where sharp increases of suspended sediment have evoked lateral (Servizi and Martens, 1991) and downstream (McLeay et al., 1987) movements away from a disturbed area. Similar preferences for clearer water have been reported with fish in controlled experimental conditions when induced with elevated turbidity (Berg and Northcote, 1985; Sigler et al., 1984). Furthermore, large marine vertebrates have also demonstrated this behaviour, where dredging activities have displaced Common Bottlenose Dolphins (*Tursiops truncatus*) from a foraging ground (Pirotta et al., 2013). For some species, this behaviour can be triggered at very low levels of suspended sediment (e.g., 5 mgL^{-1} for herring (*Clupea harengus*) and cod (*Gadus morhua*) (Westerberg et al., 1996)), while other species (for example White Sturgeon (*Acipenser transmontanus*)) have higher tolerances displaying little or no changes in avoidance behaviour at a dredging site (Parsley et al., 2011). Avoidance behaviours induced by dredging activities, particularly those that run for a long duration, could have long term implications on the abundance and community composition of a fishery, whereby shifts occur in dominant species (i.e., structuring effect) (De Robertis et al., 2003; Freedman et al., 2013; Jonge et al., 1993), or displacement of certain species (Pirotta et al., 2013).

Whether an individual chooses to move away from an area of increased suspended sediment will likely depend upon the perceived benefits of the area (i.e., trade-offs between risk and food and habitat) and ultimately motivation state (Kjelland et al., 2015). Likewise, the return of species back to a disturbed area will be highly dependent on the alternative habitat created, and its suitability for homing (de Groot, 1979). For example, species that are bound to one specific habitat that is vulnerable to dredging, such as seagrass, are less likely to return than those that have a broader habitat range. This was evident with the observed displacement of Brown Tiger Prawn (*Penaeus esculentus*) in Moreton Bay, Queensland following a dredging activity that caused seagrass loss, its preferred habitat. While Greasyback Prawn (*Metapenaeus bennettae*) and Eastern King Prawn (*Penaeus plebejus*) both of which inhabit vegetated and/or unvegetated substrata were documented returning to the disturbed area (Masel and Smallwood in prep., as cited in Hopkins and White, 1998). For some species, avoiding dredging activities may not be possible due to their sessile nature, and/or limited home range, making them more vulnerable to sedimentation and exposure effects of suspended sediment (Fraser et al., 2017; Wenger et al., 2017). For example, the West Australian Seahorse (*Hippocampus subelongatus*) has low mobility and a relatively small home range of between 36.3 ± 40.9 - 93.5 ± 20.4 m^2 (Kvarnemo et al., 2021). These life history characteristics make it potentially vulnerable to the effects of dredging and changes in sedimentation, with the severity depending on proximity to the source of disturbance.

3.1.2 Visual impairments

3.1.2.1 Foraging and predation

Elevated levels of suspended sediment can impair specialist processes and behaviours that involve vision (Utne-Palm, 2002). The effects of increased turbidity on feeding behaviour are well documented, and have been linked to reduced visual acuity and reactive distance (Asaeda, 2002; Barrett et al., 1992; Sweka and Hartman, 2003; Zamor and Grossman, 2007). Typically, high levels of suspended sediment have led to a decrease in feeding efficiency due to the inability to discriminate prey from the water column with increasing distance, which can reduce prey encounters and capture (Blaxter, 1969, 1968; Chapman et al., 2014; De Robertis et al., 2003; Johansen and Jones, 2013; Ward et al., 2016). However, there are inconsistencies in the literature, with some species showing no effect on feeding success (Gregory and Levings, 1996), while others show non-linear relationships when exposed to suspended sediment (Wenger et al., 2013). The tolerances to the level and longevity of suspended sediment are likely to be species-specific. The physical presence of sediment particles can also increase light attenuation (i.e., light scattering), further reducing visibility, and in some cases can cause an additive effect on visual impairments for species seeking food (De Robertis et al., 2003; Miner and Stein, 1993; Vogel and Beauchamp, 1999), but not for all species (Granqvist and Mattila, 2004; Utne, 1997).

The effects of reduced visibility are likely to vary between trophic guilds due to prey size and feeding strategy (Wenger et al., 2017). For example, piscivores are likely to be more sensitive to reduced visibility due to their feeding strategy of hunting prey from a distance (Ranåker et al., 2014). Planktivorous fish are more likely to detect their prey at a shorter distance and experience less interference from suspended sediment or low light conditions (Utne-Palm, 2002). In some instances, mild turbidity favours the feeding success of planktivores with suspended sediment aiding in the discrimination of plankton from the background (Ohata et al., 2014; Wenger et al., 2014). Increased turbidity may be favourable for predator avoidance (Miner and Stein, 1996), although increased turbidity can also increase predation due to prey not recognising predators (Ferrari et al., 2010) and not initiating a flight response (Kimbell and Morrell, 2015). For benthic and herbivorous species, the effect of dredging on foraging success is less likely to come from the direct effect of suspended sediment in the water column, and instead from sedimentation which acts as a physical barrier to feeding and reduces organic content of feed. For example, herbivorous scrapers (*Scarus* spp.) showed a significant increase in feeding rates (i.e., more bites) when sediment loads were removed from the epilithic algal matrix compared to those with elevated sediment loads (Bellwood and Fulton, 2008; Goatley and Bellwood, 2012). The effects of elevated suspended sediment, including sedimentation, are likely to result in greater energetic costs to compensate for reduced feeding efficiencies caused by increased foraging and predation. Ultimately, this could lead to a reduction in growth and overall body condition, as observed with juvenile Brook Trout (*Salvelinus fontinalis*) (Sweka and Hartman, 2001) and Spiny Chromis (*Acanthochromis polyacanthus*) (Wenger et al., 2012). To overcome energy costs in search of preferred food, some fish have shown to switch diets with increasing turbidity (i.e., shifting to slow moving prey or larger prey) (Hecht, 1992; Johansen and Jones, 2013; Reid et al., 1999). However, this is likely species specific and not applicable to specialist feeders.

3.1.2.2 Habitat settlement

The ability of pelagic larvae to locate optimal habitats during settlement is crucial for development and survival (Coker et al., 2009; Feary et al., 2007; Wenger et al., 2011). Larval fish rely on a variety of sensory cues for settlement, including visual stimuli to detect suitable habitats (Lecchini et al., 2005; McCormick, 2009; Sweatman, 1988, 1983). Interference with one of these cues could lead to impaired habitat choices (Munday et al., 2009), and therefore reduce recruitment success. Studies on damselfish larvae (Ambon Damsel (*Pomacentrus amboinensis*) and Lemon Damsel (*Pomacentrus moluccensis*)) showed that suspended sediment can impair preferred habitat choice during settlement through disrupted visual and chemical cues (Wenger et al., 2011). Both damselfish had a preference for live coral over partially dead and dead coral when settling in clear water (70-80% of the time), but no preference in water with suspended sediment, with individuals randomly settling onto all three habitats (Wenger et al., 2011). A similar behaviour was observed with Blue-green Puller (*Chromis viridis*) being unable to distinguish live and dead coral, in the presence of suspended sediment (O'Connor et al., 2016). Settling on sub-optimal habitat can lead to reduced fitness and growth (Feary et al., 2009), as well as increased risk of predation (Coker et al., 2009). Dredging activities carried out during key settlement events could reduce successful recruitment for species that rely on specific habitat types during settlement and could ultimately lead to negative implications for future local populations.

3.2 Physiological changes

Suspended sediment can induce a wide range of physiological effects on exposed fishes. For instance, suspended sediment can cause gill irritation (i.e., observed in Coho Salmon (Oncorhynchus kisutch) by gill flaring and increased coughing (Berg and Northcote, 1985; Servizi and Martens, 1992), and tissue damage, leading to changes in gill morphology (Au et al., 2004; Cumming and Herbert, 2016; Hess et al., 2017, 2015; Lowe et al., 2015; Wong et al., 2012). These changes may include reductions in length of gill lamellae, hyperplasia (proliferation of cells), excessive mucus discharge, and epithelium lifting, as observed in several coral reef damselfish (i.e. Common Clownfish (*Amphiprion percula*), Black Anemonefish (*Amphiprion melanopus*), Spiny Chromis (*A. polyacanthus*)) and a grouper species (Orange-spotted Grouper (*Epinephelus coioides*)) (Au et al., 2004; Hess et al., 2017, 2015; Wong et al., 2012). Whether these structural changes of the gill caused by sediment particles translate to reduce oxygen uptake, leading to poorer metabolic performance is unknown. Trials with three damselfish (*A.melanopus*, *A. percula* and *A. polyacanthus*) showed that sensitivity to changes in gill morphology induced by suspended sediment may be species-specific. *A. melanopus* exhibited impaired oxygen uptake, while *A. percula* and *A. polyacanthus* were unaffected, despite all having induced gill impairments, similar to those listed above (Hess et al., 2017). While dredging activities are likely to cause structural changes to the gills of fishes exposed to suspended sediment, the sensitivity to gill damage and oxygen uptake may vary among species, with some having a competitive advantage and/or greater tolerance. Suspension feeding bivalves have been shown to be vulnerable to elevated levels of sediment due to their filtering mechanisms, resulting in significant ciliary damage of the gill filaments with no recovery (Cheung and Shin, 2005), decreases in clearance rates (Bricelj and Malouf, 1984), and oxygen consumption (Alexander et al., 1994; Grant and Thorpe, 1991). In comparison to other taxa, bivalves in general may be more resilient to increases in suspended sediment (i.e. 87% survival, at 1000 mgL^{-1} for 14 days (Cheung and Shin, 2005), and 100% survival after 96 hours (Shin et al., 2002) due to their ability to reject solid particles via the labial palps located in the mantle cavity (Morton, 1987; Seed and Richardson, 1999).

Fish that are exposed to suspended sediment have exhibited an increase in susceptibility to pathogenic bacteria on their gills. Hess et al. (2015) found different and increased numbers of bacterial pathogens on the gills of larval clownfish (*A. percula*) following sediment exposure compared to those under controlled conditions (clear water). The absence of particular bacterial phylotypes in control fish also suggested that transmission is likely through the sediment particles (Hess et al., 2015). Similar findings were discovered for juvenile Pink Snapper (*C. auratus*) which had gill lesions caused by epitheliocystis (Lowe et al., 2015), and yearling Steelhead (*Salmo gairdneri*) where mortality was linked to the bacteria, *Vibrio anguillarum*, after suspended sediment exposure (Redding et al., 1987). The proliferation of pathogenic bacteria has been linked to increased mucus secretion, which is a stress response to repair and reduce binding of suspended sediment particles to the gills (Ferguson et al., 1992; Hess et al., 2015; Lowe et al., 2015). The compound effect of gill damage, increased susceptibility, and pathogens being carried by sediment particles could lead to sub-lethal and lethal impacts from dredging activities on fish, particularly those less mobile or sessile species or life stages.

3.3 Effects on egg and larval development

Early life stages, such as eggs and larvae, are the most vulnerable to elevated levels of suspended sediment causing sublethal and lethal impacts (Magris and Ban, 2019; Wenger et al., 2017). Benthic eggs are particularly vulnerable to the deposition of suspended sediment (i.e. sedimentation), which can lead to egg smothering and reductions in water flow which can deprive eggs of oxygen (Greig et al., 2007, 2005). Because of these hypoxic conditions, egg development and/or hatching success can be reduced, a response which is thought to be species specific (Rombough, 1988). White Perch (*Morone Americana*) experienced 100% mortality when eggs were covered by 2 mm of sediment (i.e., complete coverage of egg) (Morgan et al., 1983). Morgan et al. (1983) also found that 0.8 mm of sediment resulted in significant hatching delays. Reproductive strategies that involve paternal care may be able to mitigate sedimentation stresses, by fin fanning, egg nipping, or mouthing (Berkman and Rabeni, 1987). However, this will depend on the rate of smothering, and may lead to overexertion. Suspended sediment in the water also negatively impacts the development and hatching success of eggs, although results vary, and are likely to be species-specific. For example, the hatching success (i.e., number of eggs hatched) of Striped Bass (*Morone saxatilis*) and White Perch (*M. Americana*) were not significantly affected by 50-5250 and 20-2300 mgL^{-1} of suspended sediment, respectively. However, eggs experienced delays in hatching when striped bass eggs were exposed to concentrations above 980 mgL^{-1}, and 1900 mgL^{-1} for white perch eggs (Morgan et al., 1983). The hatching success of Red Seabream (*Pagrus major*), Blackhead Seabream (*Acanthopagrus schlegelii*), Barred Knifejaw (*Oplegnathus fasciatus*) and Chicken Grunt (*Parapristipoma trilineatum*) (Isono et al., 1998), Atlantic Herring (*C. harengus*) (exposure to 500 mgL^{-1}) (Kiørboe et al., 1981), and Pink Snapper (*C. auratus*) (exposed to 10,000 mgL^{-1}) (Partridge and Michael, 2010) also showed no significant impacts from suspended sediment, and furthermore did not cause any delays in embryo development.

Time of exposure post-spawning may have an influence on the effects of suspended sediment on egg development, particularly those that have adhesive properties. For example, Pacific Herring (*Clupea pallasi*) eggs exposed to elevated levels of sediment (250 - 500 mgL^{-1}) immediately after dispersal (within 2 hours) caused permanent sediment attachment to the outside of eggs, which led to egg-on-egg attachment and/or abnormal larval development. No effects were observed post egg dispersal (outside of the 2 hour window), suggesting that eggs become more resilient to sediment attachment after adhesive hardening (Griffin et al., 2009). Similar effects were observed with Spear Squid (*Loligo bleekeri*) eggs laid on wave-dissipating blocks within Matsumae port, Japan. Here, decreases in survival rate were linked to decreased oxygen levels caused by the adherence of suspended sediment and diatoms on egg capsules (Kitahara et al., 2004). Sediment can adhere to pelagic eggs of Red Seabream (*P. major*) and blackhead seabream (*A. schlegelii*), causing eggs to settle to the bottom, with significant effects observed when sediment levels were above 320 mgL^{-1}, and complete settlement of eggs at 10000 mgL^{-1} (Isono et al., 1998). This impact was not observed when Pink Snapper (*C. auratus*) eggs were subject to the same concentration, but differences were thought to be due to the sediment type used and the physical and chemical properties of each (kaolinite vs. calcarenite) (Partridge and Michael, 2010).

Larvae are more vulnerable to effects of suspended sediment than eggs, with the severity largely determined by the exposure duration, type of sediment, and exposed development stage. Generally, the longer the exposure, the less tolerant larvae become, leading to more lethal impacts. For example, 1 hour exposure to 10000 mgL^{-1} of sediment hour did not cause significant mortality to Red Seabream (*P. major*) larvae. However, when exposed to the same sediment concentration for 12 hours, over 50% mortality occurred (Isono et al., 1998). Similar trends were experienced with Barred Knifejaw (*O. fasciatus)* and Chicken Grunt (*P. trilineatum*) but these larvae were more sensitive at lower concentrations (Isono et al., 1998). The impact of suspended sediment on fishes has also been linked to the physical characteristics of sediment. Larger and more angular particles are suggested to be more aggressive (O'Connor et al., 1976). In comparison to juvenile and adult fish, larvae are very small and fragile, making them more prone to physical damage, such as gill abrasion and gill clogging by sediment particles (O'Connor et al., 1976; Appleby and Scarratt, 1989; Isono et al., 1998). As larvae have higher oxygen requirements than later life stages, any impairments to oxygen uptake are likely to lead to more severe or lethal impacts. These effects, however, are less likely to occur with newly hatched larvae, which have closed mouths and operculum, and instead use their body epithelium for oxygen uptake. For example, newly hatched Pink Snapper (*C. auratus*), had a much higher tolerance (12 h LC50 [i.e., 50% lethal concentration] of 2020 mgL^{-1}) for suspended sediment than later developed larvae that had open-mouths and operculum to uptake oxygen (12 h LC50 of 157 mgL^{-1}) (Partridge and Michael, 2010).

Suspended sediment has been demonstrated to influence the pelagic larval duration of fish and settlement. For example, under elevated levels of sediment (0-45 mgL^{-1}), the larval duration of *A. percula* was significantly increased by 1 day (medium pelagic larval duration = 12 days), with some larvae taking up to 22 days to settle, while control fish typically took 11 days. Successful settlement was also reduced for fish exposed to suspended sediment, with only 40-46% settling, compared to 75% of fish under control conditions (Wenger et al., 2014). Larvae have naturally high mortality rates, and extended pelagic durations could lead to altered population dynamics, due to lower recruitment success (Bertram and Leggett, 1994; Ed, 1987), and larger dispersals due to an extended pelagic phase (Lester et al., 2007; Shanks, 2009). Activities such as dredging that create sediment plumes during larval development and settlement of fish could have serious implications for new recruits, and therefore could create cascading effects on future populations.

4 Site-specific knowledge of Cockburn Sound species

From the existing literature, it is evident that the effects of suspended sediment vary among fish species, with the severity depending on the concentration, duration of exposure, type of sediment and life stage. To mitigate impacts from dredging activities, it is useful if Critical Environmental Windows for species (i.e., important life stage periods such as spawning and recruitment) and threshold tolerances to elevated suspended sediment are known. Such data can be used to time dredging activities avoiding these windows and help develop NOEC (No Observed Effect Concentration) curves to ensure suspended sediment levels do not reach lethal concentrations for a population. To facilitate appropriate management strategies for the proposed port in Cockburn Sound, it is essential that data is collected on species that could be affected by dredging activities, particularly those considered to be ecologically, socially, or economically important, and of concern to the community.

4.1 Species of concern

To determine the species of concern within Cockburn Sound, four workshops were held with a range of stakeholders who were tasked to identify important species based on environmental, recreational (fishing and diving/snorkelling), commercial, social, distinctness, and research value. In total 65 species/family/order were identified (see appendix for full list (Appendix: Table A1)), with the top 10 ranking species listed below (see Table 1 for known spawning and recruitment data of each species).

1. Pink Snapper (*Chrysophrys auratus*)
2. Blue Swimmer Crab (*Portunus armatus*)
3. Southern Calamari (*Sepioteuthis australis*)
4. Western Australian Salmon (*Arripis truttaceus*)
5. King George Whiting (*Sillaginodes punctatus*)
6. Australian Herring (*Arripis georgianus*)
7. West Australian Seahorse (*Hippocampus subelongatus*)
8. Southern Garfish (*Hyporhamphus melanochir*)
9. Sandy Sprat (*Hyperlophus vittatus*)
10. Australian Sardine (*Sardinops sagax*)

Table 1. Spawning and recruitment data for the top 10 ranked species of concern for Cockburn Sound

Common Name	Scientific Name	Description	Diet	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval duration	Recruitment Period	Recruitment Habitat	Distribution	Observed Suspended Sediment Effects	References
Pink Snapper	*Chrysophrys auratus*	A temperate species that supports significant commercial and recreational fisheries. Adult fish typically occur around rocky reefs.	Feed on crustaceans, fish, echinoderms and molluscs.	August - January (Peak: November). Spawning is correlated to water temperature (15.8 - 23.1 °C) and the lunar moon, in addition to winds.	Typically form spawning aggregations in marine embayments and also occur around reef environments where they spawn. Also reports of offshore spawning areas. Cockburn Sound constitutes as one of three important spawning grounds for snapper within the WCB. Spawning events have been documented at night within the Sound following the high tide.	Pelagic eggs. ~20 days	17-33 days Retained in spawning area (marine embayments)	Unknown	Bays, inlets, and estuaries with soft, muddy bottoms. Cockburn Sound experiences a high retention of eggs and larvae.	Widely distributed throughout temperate waters of Australia. The most northern distribution in Western Australia is Onslow. This species is not endemic to Australia, with the species occurring in New Zealand.	No effect was observed with eggs at 10,000 mgL^{-1} for 24 hours. The LC50 for closed mouth larvae was 2020 mgL^{-1} for 12 hours, with first observed effects at 157 mgL^{-1}. The LC50 for open mouth larvae was 157 mgL^{-1} for 12 hours with first observed effects at 4 mgL^{-1}.	(Bertram et al. 2022; Breheny et al., 2012;Crisafulli et al. 2019; Fairclough et al. 2013; Fairclough et al. 2021; French et al. 2012; Gomon et al., 2008; Sanders, 1974; Sim-Smith et al., 2012; Wakefield et al., 2011, 2013, 2015; Wakefield, 2010)
Blue Swimmer Crab	*Portunus armatus*	A subtropical/temperate species that is highly targeted by commercial and recreational fisheries.	Opportunistic feeders that mainly consume molluscs, crustaceans, polychaetes, and brittle stars.	September - January Cockburn Sound: mating occurs (January - April) Strongly influenced by water temperature	In oceanic waters near months of estuaries, and adjacent coastal waters with sandy/muddy, weedy, and/or seagrass habitat. Cockburn Sound constitutes an important spawning area for the Blue Swimmer Crab, along with the Peel-Harvey Estuary, and Swan-Canning Estuary.	10-18 days	3-6 weeks Dependent on water temperature Distributed in the upper 20 m water column, followed by the surface. Can disperse up to 300 km. In Cockburn Sound they are retained in the embayment.	November - March	Estuaries and coastal embayment with sandy/muddy, weedy, and/or seagrass habitat (< 50m). Cockburn Sound is self-recruiting, with little movement in or out of the Sound.	Widely distributed in Australia from Esperance up along the coast of Western Australia and around to the South coast of New South Wales. Also confined to the South Australia Gulf. The Blue Swimmer Crab is not endemic to Australia, with distributions across the Indo-West.	N.A.	(de Lestang et al., 2003; Johnston et al., 2020; Kangas, 2000; Patel et al., 1979; Potter et al., 2001; Williams, 1982)
Southern Calamari	*Sepioteuthis australis*	A subtropical/temperate species that commonly occurs over seagrass beds and reef habitats. Southern Calamari are commercially important species that are also highly targeted by recreational fisheries. They also have a relatively short-life span (~ 1 year).	Highly visual and predatory feeders, target small fish and crustaceans (e.g., shrimp).	All year around (Peak September - December). Spawns multiple times during the breeding season. Have visual cues for mating and display courtship behaviour.	Seagrass/macroalgae/low reef relief rocky reef habitats where eggs can be attached. Regions of limestone within Cockburn Sound may constitute important habitat for squid to attach eggs, although no observations have been made. Rather, the low relief reef offshore of Cockburn Sound is suggested to be the main spawning habitat, with the Sound providing suitable habitat for refuging and foraging.	52 (16°C) - 61(13°C) days to hatch, varying with temperature.	30-60 days [Based on *Sepioteuthis australis*] (Sugimoto and Ikeda, 2012)	Continual recruitment	Seagrass/macroalgae/low reef relief. Whether Cockburn Sound acts as a nursery for recruits is unknown.	Widely distributed along southern Australia, ranging from Exmouth to the west and southern Queensland to the east. The Southern Calamari is not endemic to Australia, with distribution ranging to New Zealand.	N.A.	(Coulson et al., 2016; Pecl, 2004; Pecl and Moltschaniwskyj, 2006; Steer et al., 2003; Sugimoto and Ikeda, 2012; Yeoh et al., 2021)

Common Name	Scientific Name	Description	Diet	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval duration	Recruitment Period	Recruitment Habitat	Distribution	Observed Suspended Sediment Effects	References
Western Australian Salmon	*Arripis truttaceus*	Temperate species found in coastal waters near reefs and the surge zone. A popular recreational fish and is commercial fished.	Predominantly feeds on small fish, such as Anchovy, Pilchards, and Sandy Sprat.	February - June (Peak: April - May) Spawning coincides with the strongest flow of the Leeuwin Current.	Southwards of Perth (Rottnest Island). Mainly between Cape Leeuwin and Busselton. No reported data of spawning in Cockburn Sound.	~40 hours Pelagic eggs are transported to the southeast of Australia by the Leeuwin Current.	Unknown, but suggested to be 4- 6 months Pelagic larvae are transported to the southeast of Australia by the Leeuwin Current.	Unknown	Sheltered bays and coastal waters with soft substrate. Transported eggs and larvae settle along the west and south coast of Australia, Victoria and Tasmania.	Endemic to Australia, mainly found along the western and southern coastline of Australia.	N.A.	(Ayvazian et al., 2004; Cappo et al., 2000; Gomon et al., 2008; Hoedt and Dimmlich, 1994; Lenanton, 1982; Malcolm, 1960; Moore, 2012; Neira et al., 1998; Paulin, 1993)
King George Whiting	*Sillaginodes punctatus*	Temperate species. Adults occur around reefs surrounded by weedy or sandy bottoms. Commonly caught by both recreational and commercial fisheries.	Predominantly feed on crustaceans and polychaetes. Juveniles eat copepods.	June to September (WCB)	Offshore around reefs (6-50 m water depths).	Pelagic eggs. ~2 days to hatch at a temperature of $19^{O}C$ [South Australia].	~3-5 months Remain near surface offshore. Passively transport to shallower water.	Late September - November (Migrate into nearshore waters)	Sandy/seagrass areas nearshore, estuaries, coastal embayments. Mangles Bay at the southern end of Cockburn is a known nursery for King George Whiting.	Endemic to Southern Australia. Jurien Bay southwards within Western Australia.	N.A.	(Ayvazian and Hyndes, 1995; Drew et al., 2020; Gomon et al., 2008; Hyndes and Potter 1997; Hyndes et al., 1996, 1997, 1998; Jenkins, 2005; Jenkins and May, 1994; Potter et al., 1996; Rogers et al., 2021)
Australian Herring	*Arripis georgianus*	A pelagic coastal species that is popular with recreational fishers. Also commonly caught commercially.	Feed on crustaceans, small fish, polychaetes, molluscs, and macro-algae.	April - June (Peak: late may- early June) Multiple Spawner. Spawns in southern sections of Western Australia Broadcast spawners.	Around the reefs, sand, and weedy areas (Migrate to the south-west coast of Australia).	Unknown *Arripis truttaceus* eggs take approximately 40 hours to hatch.	Unknown Pelagic eggs and larvae recruit into local coastal waters and are transported from southern-western Australia to southern Australia (as far as Victoria) by the Leeuwin Current.	June-September (variable between regions-increases with distance from spawning area).	Sheltered waters near shore, estuaries and bays (West and South coast of Australia).	Endemic to Australia with distributions ranging in Southern Australian waters, running from Shark Bay to Victoria.	N.A.	(Ayvazian et al., 2004; Fairclough et al., 2000; Gaughan et al., 2006; Gomon et al., 2008; Lenanton, 1982; Neira et al., 1998; Smith and Brown, 2014; Valesini et al., 1997)

Common Name	Scientific Name	Description	Diet	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval duration	Recruitment Period	Recruitment Habitat	Distribution	Observed Suspended Sediment Effects	References
West Australian Seahorse	*Hippocampus subelongatus*	The West Australian Seahorse is Endemic to Western Australia and typically inhabits muddy and silty habitats. They are also collected for the aquarium trade.	Predominantly feed on benthic and epibenthic crustaceans.	October- March	Sheltered bays (including estuaries) with muddy and silty substrate. Also around rocky reef macroalgae, sea squirts, sponges, man-made structures (e.g., jetty pylons), and seagrass habitats.	Gestation ~3 weeks at 23^{o}C.	-	Unknown	Sheltered bays (including estuaries) with muddy and silty substrate. Also around rocky reef macroalgae, sea squirts, sponges, man-made structures (e.g., jetty pylons), and seagrass habitats.	Endemic species are restricted to the west coast of Australia, ranging from Abrolhos Island to Cape Leeuwin. Despite their apparent range, Hs are only known to be abundant in the Swan River and Cockburn Sound.	N.A.	(Jones and Avise, 2001; Moore, 2001)
Southern Garfish	*Hyporhamphus melanochir*	A temperate species that occurs around seagrass beds in shallow waters. Southern Garfish are endemic to Australia and are recreationally and commercially caught.	Feeds on invertebrates, plant matter, and planktonic crustaceans.	September - April (Peak: November/December)	Near vegetation throughout the species range. Cockburn Sound constitutes an important spawning habitat.	Demersal eggs with adhesive filament to attach to vegetation. ~10-15 days (20-26^{o}C) and ~29 days (15-25^{o}C)	Unknown Found close to close to seagrass beds on the surface of water (minimal dispersal from spawning site)	Unknown	Inshore waters and estuaries, typically found near seagrass beds. Cockburn Sound is a self-replenishing population.	Endemic to Australia, with distribution occurring in southern Australia. They range from Lancelin southwards within Western Australia.	N.A.	(Collette, 1974; Gomon et al., 2008; Jones et al., 2002; Jordan, 1999; Lenanton, 1982; Noell, 2005; Smith et al., 2017)
Sandy Sprat	*Hyperlophus vittatus*	A small pelagic schooling baitfish that inhabits shallow sandy areas, and seagrass beds in ebayments or estuaries. Sandy Sprats are endemic to Australia and are commercially fished.	Predominantly feed on copepods and other planktonic crustaceans.	May - September (Peak: June - July)	Nearshore waters (< 14 km from the coast), including embayments. Spawning is documented in Cockburn Sound	Pelagic eggs ~58-67 hours (2-3 days) at mean temp of 17^{o}C.	Unknown	Unknown	Estuaries and protected inshore marine waters. (Transport by passive tidal movements).	Endemic to Australia, with distribution in temperate waters ranging from Kalbarri in the west to Moreton Bay in the east.	N.A.	(Gaughan et al., 1996, 1990; Goh, 1992; Gomon et al., 1994; Potter et al., 1993; Rogers and Ward, 2007; Tregonning et al., 1996)
Australian Sardine	*Sardinops sagax*	A pelagic species that forms large schools. Appears at the surface during summer and occupies deeper depths during winter An important commercial fish.	Feeds on plankton.	All year around. (Peak: June - August and December - February)	Shelf Waters (Leeuwin Current origin)	Pelagic eggs ~2 days	~1-2 months	Continues recruitment (Peak: December)	Shelf Waters (Leeuwin Current origin). Also shallow inshore waters.	Widely distributed in temperate waters of Australia, from Shark Bay in the west to Rockhampton in the east. This species is not endemic to Australia, with wide distribution across temperate waters of the world.	N.A.	(Breheny et al., 2012; Fletcher et al., 1994; Gaughan et al., 2002, 1990; Muhling et al., 2008; Neira et al., 1998)

4.1.1 Spawning and recruitment of species of concern

Of the top ten species of concern, six are endemic to Australia (Western Australian Salmon, King George Whiting, Australian Herring, West Australian Seahorse, Southern Garfish, Sandy Sprat), with the West Australian Seahorse being endemic to WA. The majority of species also have a high recreational and/or commercial value that support major fisheries within the Cockburn Sound, while the Western Australian seahorse is highly sought after for the aquarium industry. Knowledge on the spawning periods of fish indicates that spawning among these species mainly occurs in the warmer months (September - April) (Table 2). Exceptions to this included Australian Herring, Sandy Sprat, and King George Whiting, all of which mainly spawned in the cooler months, although overlaps exist for the months of April and September (Table 2). For two of the species, Southern Calamari and Australian Sardine, their spawning period extends all year around, providing continual recruitment (Table 2). For some species Cockburn Sound is an important spawning area. For example, the Sound is one of three identified spawning areas for Pink Snapper in the West Coast Bioregion, with Warnbro Sound, and Owen Anchorage being the other two areas between Kalbarri and Geographe Bay (Breheny et al., 2012; Lenanton, 1974; Wakefield, 2006). Similarly, Cockburn Sound serves as an important spawning habitat for the Blue Swimmer Crab, Southern Garfish, and Sandy Sprat, where high retention of eggs and larvae have been documented (de Lestang et al., 2003; Gaughan et al., 1990; Smith et al., 2017). It is unknown whether Southern Calamari, Western Australian Salmon, and King George Whiting use the Sound to spawn, although it is suggested that these species more likely spawn offshore of Cockburn Sound with more suitable habitat and adult life stages migrating to deeper water (Coulson et al., 2016; Hyndes et al., 1998). The Sound, however, constitutes an important nursery for juvenile King George Whiting (Hyndes et al., 1998), and likely the Southern Calamari (Coulson et al., 2016), as it provides suitable foraging and refuging habitat (i.e., seagrass beds). For the Australian Salmon, herring, and sardine the Sound does not serve as a nursery, instead pelagic eggs and larvae are transported by the Leeuwin current to South Australia and as far as Tasmania, where shallow coastal waters serve as nursery areas (Ayvazian et al., 2004, 2000; Muhling et al., 2008).

Table 2. Spawning and recruitment times of the top 10 species of concern within Cockburn Sound. Spawning periods are indicated with red and peak times are highlighted darker. Recruitment periods are indicated in blue.

Species	Spawning (S)/ Recruitment (R)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pink snapper	S												
	R	Unknown											
Blue Swimmer Crab	S												
	R												
Southern Calamari	S												
	R												
Western Australian Salmon	S												
	R	Unknown											
King George Whiting	S												
	R												
Australian Herring	S												
	R												
West Australian Seahorse	S												
	R	Unknown											
Southern Garfish	S												
	R	Unknown											
Sandy Sprat	S												
	R	Unknown											
Australian Sardine	S												
	R												

4.1.2 Knowledge of the effects of total suspended sediment on species of concern

Among the ten species of concern, only *C. auratus* has been assessed for the effects of suspended sediment. This study involved simulated exposures to calcarenite-based dredge material (2 to 140 µm particle size) found in Cockburn Sound on the eggs and larvae (open and closed mouths) of *C. auratus* (Partridge and Michael, 2010). *C. auratus* eggs were very tolerant to increases in sediment concentration, with no observed effect to egg buoyancy or hatch rate when exposed up to 10,000 mgL^{-1} of sediment for 24 hours, despite sediment adhesion to eggs starting at 3200 mgL^{-1}. Newly hatched larvae with closed mouths and operculum were also relatively tolerant to suspended sediment with the first observed effects at 150 mgL^{-1} and an LC50 (50% mortality) at 2020 mgL^{-1} for 12 hours. However, once the larvae's mouth opened, first observed effects were recorded at 4 mgL^{-1} with a LC50 at 157 mgL^{-1} for 12 hours. Furthermore, a reduction in feeding was observed in larvae with increasing sediment concentration (Partridge and Michael, 2010). The trigger values presented in this study for *C. auratus* larvae (closed and open mouth) provide a useful starting point for the development of a NOEC curve for Cockburn Sound species (Figure 3). While previous NOEC curves exist for fish (marine and freshwater), the trigger values may not be directly applicable to Cockburn Sound. This is because species and sediment type--specific effects likely exist, as suggested from the literature collated within this review. Improving the reliability of the trigger values and forming a more representative NOEC curve, will therefore require studies on local species and sediment, similar to the study presented above.

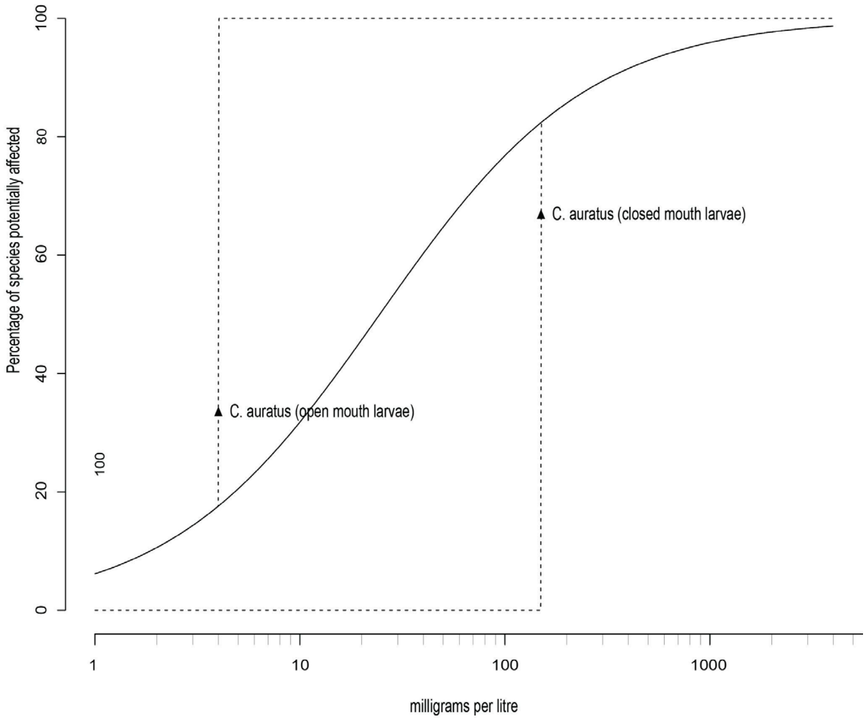

Figure 3. Burr Type III cumulative probability distribution for suspended sediment concentrations (mg L-1) that impact C. auratus. Dashed lines represent bootstrapped 95% confidence intervals. Fit and confidence intervals estimates were calculated by the Burrlioz 2.0 software (CSIRO 2015).

4.1.3 Cockburn Sound Specific Considerations

The material that will be dredged in Cockburn Sound will mainly consist of carbonate muddy sand (>80% $CaCO_3$), with a grain size ranging from 120-430 µm (mean = 290 µm, sd = 280 µm) (Eastern Shoal; Fig 1.)(Evers Consult, 2008 as cited in Fitzpatrick et al., 2009; Skene, et al., 2005). The fine material (< 63 µm) within the mixture ranges from 11-50% with an average of 27% (Skene et al., 2005). A more gravely shelly carbonate mixed with quartz exists closer to the shoreline along the southern eastern margins of the Shoal (near Kwinana Beach), consisting of fine and very coarse sediment (mean = 430 µm, sd = 360 µm). Within this mixture the calcium carbonate fraction represents >55%, and the fine material (<63 µm) represents < 5% (Skene et al., 2005).

Dredging activities involving hard limestone can produce clays (4 µm) and fine silt (8 µm) size particles up to small rocks (Jones et al., 2016; Fitzpatrick et al., 2009; Mulligan, 2009). Modelling of dredging activity using a large cutter suction dredger within the Sound indicated that the median concentration of suspended sediment at the source of the disturbance would be 25 mgL^{-1} between June and August, and 50 mgL^{-1} between January and March (Fitzpatrick et al., 2009). Previous dredging works within the Sound also indicated that the typical particle size found in the plume ranged from 2 - 140 µm, with 80% of the plume consisting of particles between 4-25 µm (Nyegaard, 2007 as cited in Partridge and Michael, 2010). As with Partridge and Michael (2010), existing knowledge of dredging activities within the Sound will need to be incorporated into the experimental design for any studies assessing the likely effects of suspended sediment for this development. Using similar particle sizes, composition, and concentration of sediment should achieve effects similar to those that may be experienced during the proposed development, providing relevant and site specific NOEC curves for management.

5 Conclusion

This review has identified many knowledge gaps and very little site-specific information on the effects of increased TSS associated dredging on fishes in Cockburn Sound. In the absence of information, it is necessary to take a precautionary approach and follow the guidance outlined in Wenger et al. (2018) that to protect 95% of fishes from dredging-induced mortality suspended sediment concentrations should be maintained below 44 mg/L and for less than 24 hours.

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7 Appendices

Table A 1.Spawning and recruitment data for species of concern within Cockburn Sound. In order of species listed during each workshop. Abbreviation Bioregions: NCB = North Coast Bioregion, GCB = Gascoyne Coast Bioregion, WCB = West Coast Bioregion, SCB = South Coast Bioregion.

Common Name	Scientific Name	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval Duration	Recruitment Period	Recruitment Habitat	Bioregions (WA)	References
Blue Swimmer Crab	*Portunus armatus* (*Portunus pelagicus* was used in many historical papers due to taxonomic uncertainty. This species is in NT only and throughout many parts of Asia).	September - January Cockburn Sound: mating occurs (January - April) Strongly influenced by water temperature	In oceanic waters near months of estuaries, and adjacent coastal waters with sandy/muddy, weedy, and/or seagrass habitat. Cockburn Sound constitutes an important spawning area for the Blue Swimmer Crab, along with the Peel-Harvey Estuary, and Swan-Canning Estuary.	10-18 days	3-6 weeks Dependent on water temperature Distributed in the upper 20 m water column, followed by the surface. Can disperse up to 300 km. In Cockburn Sound they are retained in the embayment.	November - March	Estuaries and coastal embayment with sandy/muddy, weedy, and/or seagrass habitat (< 50m). Cockburn Sound is self-recruiting, with little movement in or out of the Sound.	WCB, GCB, NCB, SCB	(de Lestang et al., 2003; Johnston et al., 2020; Patel et al., 1979; Potter et al., 2001; Williams, 1982)
King George Whiting	*Sillaginodes punctatus*	June to September (WCB)	Offshore around reefs (6-50 m water depths).	~2 days to hatch at a temperature of 19°C [South Australia] Pelagic eggs	~3-5 months Remain near surface offshore. Passively transport to shallower water.	Late September - November (Migrate into nearshore waters)	Sandy/seagrass areas nearshore, estuaries, coastal embayments. Mangles Bay at the southern end of Cockburn is a known nursery for King George Whiting.	Endemic to Australia WCB, SCB	(Ayvazian and Hyndes, 1995; Drew et al., 2020; Gomon et al., 2008; Hyndes and Potter 1997; Hyndes et al., 1996, 1997, 1998; Jenkins, 2005; Jenkins and May, 1994; Potter et al., 1996; Rogers et al., 2021)
Australian Herring	*Arripis georgianus*	April - June (Peak: late may- early June) Multiple Spawner. Spawns in southern sections of Western Australia. Synchronised with peak Leeuwin Current flow.	Around the reefs, sand and weedy areas (Migrate to the south-west coast of Australia).	Unknown *Arripis truttaceus* eggs take approximately 40 hours to hatch.	Unknown. Pelagic eggs and larvae are transported from southern-western Australia to southern Australia (as far as Victoria) by the Leeuwin Current.	June- September (variable between regions- increases with distance from spawning area).	Sheltered waters near shore, estuaries and bays (South coast of Australia).	Endemic to Australia GCB, WCB, SCB	(Ayvazian et al., 2004; Fairclough et al., 2000; Gaughan et al., 2006; Gomon et al., 2008; Lenanton, 1982; Neira et al., 1998; Smith and Brown, 2014; Valesini et al., 1997)
Southern Calamari	*Sepioteuthis australis*	All year around (Peak September - December). Spawns multiple times during the breeding season.	Seagrass/macroalgae/low reef relief rocky reef habitats where eggs can be attached. Regions of limestone within Cockburn Sound may constitute important habitat for squid to attach eggs, although no observations have been made. Rather, the low relief reef offshore of Cockburn Sound is suggested to be the main spawning habitat, with the Sound providing suitable habitat for refuging and foraging.	52 (16°C) - 61(13°C) days to hatch, varying with temperature.	30-60 days [Based on *Sepioteuthis australis*] (Sugimoto and Ikeda, 2012)	Continual recruitment	Seagrass/macroalgae/low reef relief. Whether Cockburn Sound acts as a nursery for recruits is unknown.	GCB, WCB, SCB	(Coulson et al., 2016; Pecl, 2004; Pecl and Moltschaniwskyj, 2006; Steer et al., 2003; Yeoh et al., 2021)
Samson Fish	*Seriola hippos*	October - March	Aggregations around structure (e.g., seamounts, FADs, wrecks etc. (West of Rottnest Island)	Unknown Pelagic eggs	Unknown	Unknown	Inshore on the surface, underneath floating structures (detached seagrass, algae, etc.)	GCB, WCB, SCB	(Hutson et al., 2007; Mackie et al., 2009; Neira et al., 1998; Rowland, 2009)
Southern Sand Flathead	*Platycephalus bassensis*	October – March (Peak: October - December) [Southern and Eastern Tasmania] August - October [Port Phillip Bay]	Estuaries, coastal embayments, inshore shelf waters	Unknown Pelagic eggs	Unknown	February - December [Southern and Eastern Tasmania]	Unvegetated habitats	Endemic to Australia WCB, SCB	(Brown, 1977; Jordan, 2001; Tracey et al., 2020)

Common Name	Scientific Name	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval Duration	Recruitment Period	Recruitment Habitat	Bioregions (WA)	References
Southern Bluespotted Flathead	*Platycephalus speculator*	December – April (Peak: December - February) Related to salinity (i.e., less than 30% (in Wilson inlet)).	Typically at sea, but also occurs in estuaries with Sandy weedy habitat	Unknown Pelagic eggs	Unknown	Unknown	Inshore, Estuaries with Sandy weedy habitat	Endemic to Australia GCB, WCB, SCB	(Hyndes et al., 1992)
Tailor	*Pomatomus saltatrix*	September - May Multiple spawn groups (local and remote) that form a single breeding stock	Inner shelf	~46-48 hours to hatch Pelagic eggs	18-25 days [Eastern USA](Hare and Cowen, 1993)	Unknown	Estuaries and shallow coastal areas	NCB, GCB, WCB, SCB	(Lenanton et al., 1996; K. A. Smith et al., 2013)
Spanish Mackerel	*Scomberomorus commerson*	October – January Water temperature may influence spawning	Aggregations around reef	Unknown	< 3 weeks	Unknown	Unknown	NCB, GCB, WCB	(Mackie et al., 2005)
Scaly Mackerel	*Sardinella lemuru* (And other local and seasonal "forage fish" - others are covered in Whitebait and Anchovy)	December - March (Peak: January - February) Coincides with maximum temperature	Offshore	24 hours	Unknown	March - August (Peak: May - July)	Inshore	NCB, GCB, WCB, SCB	(Gaughan, 2000)
Razor Clams	*Pinna bicolor*	November - January (Peak: December) [South Australia] Temperature and food most likely influence spawning times	Intertidal zone - 20m, with shelly/fine sand near seagrass habitat	Unknown	3-4 weeks	December - May	Intertidal zone - 20m, with shelly/fine sand near seagrass habitat	WCB, SCB	(A. Butler, N. Vicente, B. D. Gaulejac, 1993; Butler, 1987)
Octopus (Western Rock Octopus)	*Octopus djinda*	Throughout the year	Rocky reef, seagrass, and sandy habitat (offshore)	~30 days	Unknown	Continuous recruitment	Inshore rocky reefs, seagrass, sandy habitats	Endemic to WA GCB, WCB, SCB	(Amor and Hart, 2021; Joll, 1976; Leporati et al., 2015)
Silver Trevally (Skippy)	*Pseudocaranx sp. (georgianus/wright)*	July - December (Peak: September - December)	Near reefs	Unknown Pelagic eggs	Unknown	Unknown	Inshore waters (<20m) over bare sand and near structures. Also, estuaries and bays.	GCB, WCB, SCB	(Farmer et al., 2005; Lenanton and Potter, 1987).
Western Australian Salmon	*Arripis truttaceus*	February - June (Peak: April - May) Spawning coincides with the strongest flow of the Leeuwin Current.	Southwards of Perth (Rottnest Island). Mainly between Cape Leeuwin and Busselton. No reported data of spawning in Cockburn Sound.	~40 hours Pelagic eggs and larvae are transported to the southeast of Australia by the Leeuwin Current.	Unknown, but suggested to be 4- 6 months. Pelagic larvae are transported to the southeast of Australia by the Leeuwin Current.	Unknown	Sheltered bays and coastal waters with soft substrate. Transported eggs and larvae settle along the coast of South Australia, Victoria and Tasmania.	Endemic to Australia WCB, SCB	(Cappo et al., 2000; Gomon et al., 2008; Hoedt and Dimmlich, 1994; Lenanton, 1982; Malcolm, 1960; Moore, 2012; Neira et al., 1998; Paulin, 1993)
Western Rock Lobster	*Panulirus cygnus*	August - February Peak: November Influenced by offshore SST and westerly winds	Deep reef	4-8 weeks	9-11 months	September - February	Inshore limestone Reef	Endemic to WA GCB, WCB, SCB	(Bellchamber et al., 2012; Jernakoff, 1990)
Southern Gar Fish	*Hyporhamphus melanochir*	September - April (Peak: November/December)	Near vegetation throughout the species range. Cockburn Sound constitutes an important spawning habitat.	~10-15 days (20-26ºC) and ~29 days (15-25ºC) Demersal eggs with adhesive	Unknown Found close to close to seagrass beds on the	Unknown	Inshore waters and estuaries, typically found near seagrass beds. Cockburn Sound is a self-replenishing population.	Endemic to Australia WCB, SCB	(Collette, 1974; Gomon et al., 2008; Jones et al., 2002; Jordan, 1999; Lenanton, 1982; Noell, 2005; Smith et al., 2017)

Common Name	Scientific Name	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval Duration	Recruitment Period	Recruitment Habitat	Bioregions (WA)	References
				filament to attach to vegetation.	surface of water (minimal dispersal from spawning site)				
Abalone (Roe's Abalone)	*Haliotis roei*	July - December Peak: July - August Some ripe throughout the year Influenced by temperature and food availability	Shallow limestone reef (platforms)	~24 hours	~7 days	July - December	Shallow limestone reef (platforms)	Endemic to Australia NCB, GCB, WCB, SCB	(Freeman, 2001; Hancock, 2000; Wells and Keesing, 1989)
Mulloway	*Argyrosomus japonicus*	November – April Spawning occurs when water temperature >19°C	Nearshore coastal reefs, deep river systems (Estuaries, coastal zones)	28-30 hours (23°C) Pelagic eggs	Unknown	~ 4 weeks after hatching	Estuaries	GCB, WCB, SCB	(Battaglene and Talbot, 1994; Farmer, 2008; Farmer et al., 2005; Taylor et al., 2006)
Yellowtail Kingfish	*Seriola lalandi*	December - February Form spawn aggregations Influenced by water temperature	Open ocean, sheltered waters (e.g., embayments)	Buoyant eggs 103-108 hours [California]	Unknown	Unknown	Unknown	GCB, WCB, SCB	(Hutson et al., 2007; Moran et al., 2007)
Australian Anchovy	*Engraulis australis*	Throughout the year Peak: November - February	Inlets, bays, estuaries	Unknown Buoyant pelagic eggs	Unknown	Unknown	Shelf Waters near upwelling zones	GCB, WCB, SCB	(Dimmlich and Ward, 2006)
Western King Wrasse	*Coris auricularis*	April - June	Inshore reefs (rocky and coral reefs surrounded by sand patches)	Unknown	Unknown	Unknown	Inshore reefs (rocky and coral reefs surrounded by sand patches)	GCB, WCB, SCB Endemic to Western Australia	(Lek, 2011)
Western Butterfish	*Pentapodus vitta*	October - January [Shark Bay]	General habitat: seagrass beds and reef areas, coastal bays	Unknown	Unknown	Unknown	Estuaries	Endemic to WA NCB, GCB, WCB, SCB	(Mant et al., 2006; Neira et al., 1998)
Seahorses (West Australian Seahorse)	*Hippocampus subelongatus*	October- March	Sheltered bays (including estuaries) with muddy and silty substrate. Also around rocky reef macroalgae, sea squirts, sponges, man-made structures (e.g., jetty pylons),and seagrass habitats.	Gestation ~3 weeks at 23°C.	-	Unknown	Sheltered bays (including estuaries) with muddy and silty substrate. Also around rocky reef macroalgae, sea squirts, sponges, man-made structures (e.g., jetty pylons),and seagrass habitats.	Endemic to WA WCB	(Jones and Avise, 2001; Moore, 2001)
Flyingfish	*Exocoetidae* E.g., Cosmopolitan Flyingfish (*Exocoetus volitans*)	All year around	Oceanic waters [Gulf of Mexico]	Buoyant pelagic eggs	~1-2 weeks	Unknown	Unknown	NCB, GCB, WCB, SCB	(Bradbury et al., 2008; Collette, 1984; Hunte et al., 1995; Stevens et al., 2003)
Goatfish (Bluespotted Goatfish)	*Upeneichthys vlamingii* (Most common in Cockburn Sound)	Unknown	Unknown	Unknown	Unknown	Unknown	Sheltered bays	WCB, SCB	
Gummy Shark	*Mustelus antarcticus*	November - February	Unknown	Unknown	-	Unknown	Unknown	Endemic to Australia WCB, SCB	(Lenanton et al., 1990)

Common Name	Scientific Name	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval Duration	Recruitment Period	Recruitment Habitat	Bioregions (WA)	References
School Shark	*Galeorhinus galeus*	Every 2 -3 years December - January [southern Australia]	Unknown	Gestation: 12 months	-	Unknown	Inshore waters	NCB, GCB, WCB, SCB	(Pogonoski et al., 2002)
Echinoderms (common species include Crinoidea (featherstars) - Comatula purpurea; Asteroidea (seastars) - Astropecten preissi, Luidia australiae, Stellaster inspinosus; Ophiuroidea (brittlestars) - Macrophiothrix spongicola; Echinoidea (urchins) - Temnopleurus michaelseni; Holothuroidea (sea cucumbers) - Cercodema anceps, Colochirus quadrangularis)	E.g., *Peronella lesueuri* (Sand dollar)	Peak December - February	Coral reef, limestone reef, and benthic sediment	Unknown	3-4 days [*P. japonica*]	December	Coral reef, limestone reef, and benthic sediment	NCB, GCB, WCB, SCB	Yeo, 2013
Whitebait (Sandy Sprat)	*Hyperlophus vittatus*	May - September (Peak: June - July)	Nearshore waters (< 14 km from the coast), including embayments. Spawning is documented in Cockburn Sound	~58-67 hours (2-3 days) at mean temp of 17^{o}C. Pelagic eggs	Unknown	Unknown	Estuaries and protected inshore marine waters. (Transport by passive tidal movements).	Endemic to Australia	(Gaughan et al., 1996, 1990; Goh, 1992; Gomon et al., 1994; Potter et al., 1993; Rogers and Ward, 2007; Tregonning et al., 1996)
Phoronids (horseshoe worms)	*Phoronida* spp.	Unknown Asexual	Embedded in substrate or attached to structure (i.e., reef and mollusc shells)	-	-	Unknown	Embedded in substrate or attached to structure (i.e., reef and mollusc shells)	NCB, GCB, WCB, SCB	(Emig et al., 1977)
Polychaetes	Class Polychaeta E.g., *Sabella Spallanzanii* (invasive species)	March - August [Port Phillip Bay]	Sub-tidal sheltered habitat	~24 hours	4 weeks	Unknown	Sub-tidal sheltered habitat	WCB, SCB	(Giangrande et al., 2000)
Arrow calamari squid (Gould's squid)	*Nototodarus gouldi*	Throughout the year Peak: February - March	General habitat: Offshore >825m Suggested: upper 100 m of water column	1-2 months Free floating jelly mass	Unknown	Unknown	Coastal waters	WCB, SCB	(Norman and Reid, 2000; Uozumi et al., 1995; Yeoh et al., 2021)
Longspine Stinkfish	*Pseudocalliurichthys goodladi* Previously known as *Callionymus goodladi*	Unknown	Unknown	Unknown	Unknown	Unknown	Coastal embayments, and estuaries	Endemic to WA NCB, GCB, WCB, SCB	(Breheny et al., 2012; Gaughan et al., 1990)
Smooth stingray	*Dasyatis brevicaudata*	Presumed Summer - Autumn	Unknown	Unknown	Unknown	Unknown	Unknown	GCB, WCB, SCB	(Le Port et al., 2012)
Black stingray	*Bathytoshia lata* Previously known as *Dasyatis thetidis*	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	GCB, WCB, SCB	-
Cuttlefish (Sepia spp.) Giant Cuttlefish	E.g., *Sepia apama*	May - August Form aggregations	Shallow coastal waters. Females attach eggs to subtidal rocky reefs to the underside of ledges, caves and rocks.	3 - 5 months	Unknown	Unknown	Unknown General habitat: Seagrass and rocky reef	Endemic to Australia GCB, WCB, SCB	(Hall and Hanlon, 2002)
Western King Prawns	*Melicertus latisulcatus*	December - February [Cockburn Sound]	Central Basin	~24 hours	~40 days	April - May	Shallow sand banks along shoreline	NCB, GCB, WCB, SCB	(Penn, 1980; Shokita, 1984)

Common Name	Scientific Name	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval Duration	Recruitment Period	Recruitment Habitat	Bioregions (WA)	References
		Influenced by water temperature (17-25 $^{\circ}$C)			[Spencer Gulf]				
Flounder (Smalltooth flounder) (Pseudorhombus jenynsii) - Bothidae & Pleuronectidae spp.	*Pseudorhombus jenynsii*	~September - February	General habitat: sandy muddy habitat, < 70 m. Outside estuaries.	Unknown	Unknown	Unknown	Estuaries and shallow coastal waters (e.g., marine embayments)	Endemic to Australia NCB, GCB, WCB, SCB	(Coulson et al., 2021; Gomon et al., 2008; Young and Potter, 2003)
Nudibranch	*Order Nudibranchi*	Unknown	General habitat: Shoreward fringing reefs	Lay planar shaped egg masses. ~5-7 days to hatch (*Chromodies* spp.])	Several weeks (planktonic larvae]) Few hours to days (Lecithotrophic larvae)	Influenced by the Leeuwin Current	Unknown	NCB, GCB, WCB, SCB	(Arnold, 2014; Todd, 1981; Trickey et al., 2013; Wilson, 2002)
Rock crabs	Ozius truncatus	October - February (Peak: November – January) [New Zealand]		2 months (brooded by females)	~1 month	4-6 weeks after hatching (~December)	Crevices	WCB, SCB	(Sivaguru and Mclay, 2010)
Eagle ray (Southern Eagle Ray)	*Myliobatis tenuicaudatus*	Summer months (~December - February)	Shallow nearshore sandy habitats	Unknown	Unknown	Unknown	Estuaries	WCB, SCB	(Gomon et al., 2008)
Sea snakes (Yellow-bellied sea-snake)	*Pelamis platura*	Most likely in warmer months	Unknown	Gestation: ~5 months [captivity]	Unknown	Unknown	Small individuals have been found in mangroves and intertidal habitat	NCB, GCB, WCB, SCB	(Greer, 1997)
Pipefishes	E.g., *Stigmatopora nigra*	Throughout the year (Peak: September – January)	Shallow seagrass beds	Unknown	Unknown	Unknown	Bays, estuaries and shallow coastal waters	WCB, SCB	(Dawson, 1985; Duque-Portugal, 1989)
Great White Shark	*Carcharodon carcharias*	3-year reproductive cycle ~September - February	Unknown	Gestation: up to 18 months	Unknown	Unknown	Unknown	GCB, WCB, SCB	(Francis, 1996)
Port Jackson Shark	*Heterodontus portusjacksoni*	Ovulates: August - December/January	Inshore reefs to deposit eggs (wedged into crevices)	10-11 months	-	Unknown	Coastal embayments with sandy, weedy habitat	WCB, SCB	(Jones et al., 2008; Powter and Gladstone, 2009; Rodda and Seymour, 2008)
Common blowfish (Weeping Toadfish)	*Torquigener pleurogramma*	October - January (Peak: November - December)	Coastal waters near mouths of estuaries/rivers	Unknown Pelagic eggs	Unknown	July - August	Estuaries	Endemic to Australia GCB, WCB, SCB	(Leis and Carson-Ewart, 2004; Potter et al., 1988)
Blue Mussels	*Mytilus galloprovincialis*	June - October (Peak: July - September) Influenced by Leeuwin Current	Intertidal zone, with rocks, piles and sand flats <10m	<48 hours [Tasmania]	>12 days	Unknown	Intertidal zone, with rocks, piles and sand flats <10m	WCB, SCB	(Carl et al., 2012; Eads et al., 2016; Gaitán-Espitia et al., 2016; Ompi and Svane, 2018)
Pink Snapper	*Chrysophrys auratus*	August - January (Peak: November). Spawning is correlated to water temperature (15.8 - 23.1 $^{\circ}$C) and the lunar moon, in addition to winds.	Typically form spawning aggregations in marine embayments and also occur around reef environments where they spawn. Also reports of offshore spawning areas. Cockburn Sound constitutes as one of three important spawning grounds for snapper within the WCB. Spawning events have been documented at night within the Sound following the high tide.	Pelagic eggs. ~20 days	17-33 days Retained in spawning area (marine embayments)	Unknown	Bays, inlets and estuaries with soft muddy bottoms. Cockburn Sound experiences a high retention of eggs and larvae.	GCB, WCB, SCB	(Bertram et al. 2022; Breheny et al., 2012; Crisafulli et al. 2019; Fairclough et al. 2013; Fairclough et al., 2021; French et al., 2012; Gomon et al., 2008; Sanders, 1974; Sim-Smith et al., 2012; Wakefield et al., 2011, 2013, 2015; Wakefield, 2010)
Yelloweye Mullet	*Aldrichetta forsteri*	March - August	Close to the mouths of estuaries/estuaries, marine embayments, with sandy muddy habitat.	Pelagic eggs	~19-25 days	Unknown	Coastal waters (surf zones), estuaries, and rivers.	GCB, WCB, SCB	(Chubb et al., 1981; Lenanton, 1982; Pellizzari, 2001; Thomson, 1957)

Common Name	Scientific Name	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval Duration	Recruitment Period	Recruitment Habitat	Bioregions (WA)	References
			Lower west coast of WA						
Blue Sprat	*Spratelloides robustus*	October – February Likely influenced by SST and food availability.	Unknown	Unknown	Unknown	Unknown	Inshore	Endemic to Australia NCB, GCB, WCB, SCB	(Rogers et al., 2003)
Southern School Whiting	*Sillago bassensis*	September - April Peak: December - February	Unknown	Unknown	Unknown	Unknown	Sheltered inshore waters, surf zones	Endemic to Australia WCB, SCB	(Hyndes and Potter, 1997, 1996)
Yellowfin Whiting	*Sillago schomburgkii*	October - March (Peak: December - February)	Estuaries, nearshore with sandy habitat	Unknown Pelagic eggs	~1 month	Unknown	Estuaries, nearshore with sandy habitat	Endemic to Australia GCB, WCB, SCB	(Brown et al., 2013; Hyndes and Potter, 1996)
Pilchards/ Australian Sardine	*Sardinops sagax*	All year around. (Peak: June - August and December - February) Influenced by the Leeuwin Current	Shelf waters (Leeuwin Current origin)	~2 days Pelagic eggs	~1-2 months	Continues recruitment (Peak: December)	Shelf waters (Leeuwin Current origin). Also shallow inshore waters.	GCB, WCB, SCB	(Fletcher et al., 1994; Gaughan et al., 2002, 1990; Muhling et al., 2008; Neira et al., 1998)
Silverbelly	*Parequula melbournensis*	Throughout the year	Offshore, over sandy/patchy seagrass habitat	Unknown	Unknown	Throughout the year	Inner shelf water, high in the water column or around reefs	Endemic to Australia WCB, SCB	(Sarre et al., 1997)
Sea Mullet	*Mugil cephalus*	March – September Tides suggested to influence spawning	Offshore waters (i.e., water surface over the continental shelf)	36-30 hours (24^{O}C) 48-50 hours (22^{O}C) Temperature dependent	~42 days	~May - November	Estuaries with sandy, weedy habitat	NCB, GCB, WCB, SCB	(Chubb et al., 1981; Kuo et al., 1973)
Tarwhine	*Rhabdosargus sarba*	May - December (Peak: June - November)	Around reefs	Unknown	Unknown	Unknown	Unvegetated nearshore	GCB, WCB, SCB	(Hesp and Potter, 2003; Hesp et al., 2004)
Western Shovelnose Stingaree	*Trygonoptera mucosa*	May - July (late autumn - mid winter)	Unknown General habitat: Sandy habitat near seagrass	Gestation: 10-12 months	-	April - May (Mid - late autumn)	Unknown	Endemic to Australia WCB, SCB	(White et al., 2002)
Wobbegong (Western Wobbegong)	*Orectolobus hutchinsi*	Once every 2-3 years	Unknown General habitat: Intertidal - 100m, rocky reef, and seagrass habitat	Gestation: 9-11 months	-	Parturition: July - September	Unknown	Endemic to WA GCB, WCB	(Chidlow, 2003; Chidlow et al., 2007)
Robust Garfish (Three-by-two Garfish)	*Hemiramphus robustus*	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Endemic to Australia NCB, GCB, WCB	-
Leaping Bonito	*Cybiosarda elegan*	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	NCB, GCB, WCB	-
Oriental Bonito	*Sarda orientalis*	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	NCB, GCB, WCB, SCB	-
Yellowtail Scad	*Trachurus novaezelandiae*	Unknown for WA. ~October	Continental shelf waters	Unknown Pelagic eggs	Unknown	Unknown	Shallow soft sediment habitat	GCB, WCB, SCB	(Neira et al., 2015)

Common Name	Scientific Name	Spawning Period	Spawning Habitat	Egg Duration	Pelagic Larval Duration	Recruitment Period	Recruitment Habitat	Bioregions (WA)	References
		[Eastern Australia]							
Tiger Shark	*Galeocerdo cuvier*	In Australian waters [Queensland]: December - February (Once every two years)	Unknown	~13-16 months	-	December - February	No established nursery (inshore)	NCB, GCB, WCB, SCB?	(Heupel et al., 2007; Simpfendorfer, 1992)
Whiskery Shark	*Furgaleus macki*	Mate: August - September Ovulation: Late January - early April (Once every two years)	Nearshore, inshore waters	Gestation: 7-9 months	-	Parturition: August - October	Deeper water >100 m	Endemic to Australia GCB, WCB, SCB	(Simpfendorfer et al., 2000; Simpfendorfer and Unsworth, 1998; Springer et al., 1994)
Bighead Gurnard Perch	*Neosebastes pandus*	May - July	General habitat: Inshore reef and soft substrate	Unknown	Unknown	Unknown	Waters of the southern Coast of Western Australia, influenced by the Leeuwin Current.	Endemic to Australia WCB, SCB	(Coulson, 2021; Gomon et al., 2008)

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WESTERN AUSTRALIAN
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