Marine dredging and disposal operations and the risk of marine Invasive Non-Native Species (INNS)

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Report details

Author(s)

Dr Kate Dey – APEM Ltd.

Dr Paul Stebbing – APEM Ltd.

Natural England Project Manager(s)

Jan Maclennan and Amanda Yeoman-Roberts

Contractor

APEM ltd.

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Foreword

Natural England commissioned an evidence review on the risk from navigational dredging and disposal activities as a pathway of introduction and spread for non-native species (NNS). Natural England have limited information on the mechanisms by which this activity could spread NNS. Natural England were keen to understand the survival rates of species from dredging activity and through disposal, particularly for coastal inshore beneficial use / beneficial placement disposal sites as well as understand the subsequent (if any) risk to statutory protected sites and the wider seas. This information where appropriate is aimed at helping to inform Natural England’s advice to regulatory bodies and conversations with industry.

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Executive summary

Invasive non-native species (INNS) have negative impacts on ecosystem services and are a major contributor towards biodiversity loss. As such, their spread poses a threat to species and habitats within designated protected areas in England. One of the most cost-effective actions that can be taken in relation to INNS is to prevent their introduction and spread from occurring. This is because once an INNS has been introduced to a new area, the increased costs and reduced feasibility of management as the population grows become substantial.

To prevent INNS spread, the pathways via which they can spread must first be identified. With respect to dredging operations, these pathways include the vessels and equipment used which could introduce INNS to the dredging site if imported from elsewhere, and to the disposal site when dredged sediment is moved. Specifically, research has evidenced that INNS can be moved from one location to another via ballast water, hull fouling or in niche areas of vessels. The recognition of vessel movement as a pathway and its associated vectors (delivery mechanisms) has resulted in regulation such as The Merchant Shipping (Control and Management of Ships' Ballast Water and Sediments) Regulations 2022, which has catalysed biosecurity action. However, the potential pathway of dredged material during dredging operations has received little research and regulatory attention.

It is possible that INNS present at a dredging site may be taken up with the excavated dredged material and be transported to the disposal site, via a pathway for INNS spread that would not naturally occur. Accidental spillage during transfer may also facilitate the spread of INNS along the route of the dredge vessel. However, it is not currently known whether INNS could survive the mechanical or hydraulic processes of dredging, the environmental conditions within the dredged material, or environmental conditions at disposal sites. If mortality occurs, then this mitigates the risks of spread.

The results from this review outline the high degree of variability of the navigational dredging process. Furthermore, the equipment and methods used, in addition to INNS and site characteristics, are highly likely to influence the risk that the transfer of dredge material may present as a viable pathway. Specifically, these factors influence whether the conditions required for pathway viability are met. These are that INNS:

- are present at the dredging site
- are entrained
- survive entrainment
- survive transfer
- survive discharge
- survive at the disposal site
- establish at the disposal site.

There was a substantial lack of research to support or oppose the viability of the potential pathway as a whole, however, the likelihood of each condition being met was assessed, mainly using qualitative data. It was concluded that all conditions were unlikely to be met in most scenarios, indicating that dredged material movement is a low-risk INNS pathway, although without substantial evidence to support this statement a high confidence could not be applied. Considering the lack of data and the high variability of influential factors, it was not possible to rule out that in some, probably rare, scenarios the pathway could be viable. A precautionary approach to the assessment and mitigation of INNS via this potential pathway should therefore be taken to ensure compliance with licensing and legislative requirements. This approach could take the form of a biosecurity plan (which includes risk assessment), as per licence requirements in Wales, with supporting guidance that aligns with biosecurity actions already undertaken by stakeholders within the dredging industry.

While biosecurity planning is becoming commonplace within the industry with respect to the movement of vessels and equipment to the dredging site, there is a need for more focus on the potential transference of INNS from the dredging site to the disposal site. Specifically, the potential pathway of dredged material movement needs to be better understood and where possible and necessary, mitigated. To achieve this, biosecurity guidance at the national level could be created in relation to dredging operations to standardise approaches and to ensure they are kept up to date. Such national guidance should highlight dredged material transfer as a potential INNS pathway and identify mitigation measures that could be taken to minimise risk. However, such action should be appropriate to the level of risk that the dredging operation presents, which is currently difficult to assign. Furthermore, at present, effective and practical mitigatory actions are difficult to identify.

Overall, more research is needed to determine if it is possible for INNS to survive the dredging process, and to enable a quantified risk assessment that can more accurately identify where the key risk areas in the processes are, as well as if and what biosecurity action is required for specific scenarios. The targeted monitoring of INNS at dredging sites, at disposal sites, and in dredged material, would greatly contribute to a future understanding of this potential INNS pathway. Additionally, further research into potential mitigation measures would enhance the effectiveness of biosecurity in instances where this potential pathway may be viable.

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1. Introduction

Non-native species (NNS) are organisms (including plants, animals and their propagules) that have been introduced either accidentally or intentionally by human activities to an area outside their native range. Many NNS do not cause impacts to the area where they have been introduced. However, around 10% of NNS cause significant negative environmental and/or economic impacts and are termed invasive non-native species (INNS[1]) (Williamson & Fitter, 1996). The environmental impacts that INNS cause include direct and indirect competition with native species, the introduction and spread of novel diseases, and habitat alteration, leading to INNS being recognised as a major driver of global biodiversity loss (IPBES, 2023). In addition, INNS negatively impact local economies through direct effects on ecosystem services, such as recreation and tourism, public utilities and infrastructure, aquaculture and fisheries, as well as indirectly through costs associated with INNS treatment, management and control (Vilà & Hulme, 2017). Specific infrastructure impacts can include fouling and smothering of equipment (outfalls and intakes) and port structures such as piles and pontoons. It has recently been estimated that INNS cost the UK economy £4 billion per annum (Eschen et al., 2023). Therefore, the need to prevent further impact caused by INNS is highly important in protecting global biodiversity and the economy. This is reflected in the Convention on Biological Diversity (CBD) which requires each contracting party to prevent the introduction of, and to control or eradicate INNS which threaten ecosystems, habitats or species (CBD, 2014). The CBD sets out a hierarchical approach to INNS management with a key focus on prevention of introduction (followed by rapid response and long-term management).

INNS spread through various human-made pathways, which are means and routes by which they are introduced into new areas. While INNS also spread via natural means, human-made pathways enable INNS to overcome natural dispersal barriers (Blackburn et al., 2011), such as tidal or wind-driven water currents or adverse environmental conditions (Nishizaki and Ackerman, 2019) and can enhance propagule pressure at the receptor site which facilitates population establishment (Blackburn et al., 2015). Major pathways in the marine environment include aquaculture (via movement of contaminated stock or fouled equipment), recreational boating (via hull fouling) and shipping (via ballast water and hull fouling) (Molnar et al., 2008). To prevent the introduction of INNS from occurring, it is essential that the pathways by which they are moved are identified and managed. Understanding how these pathways facilitate the movement of INNS informs the development of evidence-based best practice and biosecurity plans that reduce the chance of introduction and spread of INNS. The identification of key pathways and the

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[1] Please note that throughout this report we used the term INNS to also include NNS unless a distinction is required.

development of pathway action plans (PAPs) is part of the GB Invasive Non-Native Strategy (GBNNSS, 2023) and is required under the Invasive Alien Species Regulation (2014) (retained), aligning with the hierarchical management approach outline by the CBD.

In the marine environment, dredging and associated activities may present a pathway for the introduction and spread of INNS. The movement of INNS could potentially occur via a number of vectors, such as by dredging vessels and supporting vessels in ballast water, in niche areas (e.g., propeller shafts and anchor wells), on vessel hulls, as well as on/in any equipment that has been in direct contact with the dredged material, such as suction tubes, dragheads and excavation buckets. In addition to INNS potentially being translocated with the movement of vessels and equipment, it is possible that INNS present at the dredging site may be taken up with dredged material and transported to the disposal site, thereby acting as a pathway for spread (Reine et al., 1998). However, the mechanical or hydraulic processes by which dredging is carried out (Armstrong et al., 1987) and the associated environmental conditions (Bolam, 2010), may result in the mortality of any INNS which may be taken up with dredged material, thus reducing the risks of establishment at the disposal site.

1.1 Objectives

Natural England (NE) want to better understand the risk of spreading INNS via navigational dredging and disposal activities as a pathway and how any identified risks could be reduced. This is part of ongoing efforts to minimise impacts on marine habitats and species, both in protected sites and wider seas via dredging processes. This understanding will inform evidence-based advice on impact pathways of activities, and best practice biosecurity and management in support of the delivery of the GB Non-native Species Strategy (NNSS) and UK Marine Strategy. This review is the first major step towards addressing this knowledge gap and will help inform advice provided by regulatory bodies.

For this report, **navigational dredging** is defined as the removal of material from the seabed to deepen and maintain berths and channels for the purpose of navigation (MMO, 2023a). This process results in billions m^3 of sediment being dredged around the world annually (Iotzov et al., 2014; Sato & Isobe, 2015). Aggregate dredging is outside the scope of this report.

This review aims to:

1. Outline the mechanisms by which navigational dredging operations could transport and transfer INNS.

2. Review the current evidence and literature available on the potential risk of INNS spread.

3. Identify key factors influencing the potential risk presented by this pathway, with a particular focus on the different stages of the navigational dredging process and the survivability of INNS.

4. Identify environmental assessments and biosecurity actions already undertaken by the dredging industry and any potential opportunities.

5. Provide recommendations for future biosecurity actions and best practice to mitigate potential risks.

6. Highlight evidence gaps and recommend next steps.

2 Methodology

2.1 Literature review

A review of scientific literature was conducted using Google Scholar by inputting combinations of themed search strings, outlined in Appendix 1. Abstracts of the first 100 documents returned by the search were reviewed for relevance and either accepted for further reading or rejected. A search for grey literature was also conducted by inputting the same search strings into the standard Google search and reviewing the first 100 documents. Similarly, the first page of each resource was reviewed for relevance and either accepted for further reading or rejected. Specific relevant resources were also targeted, including websites and online documents published by: Marine Management Organisation (MMO), Natural England (NE), Natural Resources Wales (NRW), Central Dredging Association (CEDA), International Association of Dredging Companies (IADC), Van Oord, Boskalis and ABPmer. In total, 97 resources informed this report.

2.2 Interviews

Semi-structured interviews were undertaken by APEM ltd. with five key industry representatives to capture targeted information and knowledge that had not been obtainable through the literature and/or required clarification. An online interview lasting approximately one hour was conducted with each representative. The interviews followed an open discussion format based around questions concerning key points of the study. This approach was taken so that questions could be tailored to the experience of the interviewee and to encourage organic conversation / the amount of information that could be gathered. Interviews were centred on the questions outlined in Appendix 2. Where the response of an interviewee directly informed the text, this has been indicated by the citation “personal communication”. The following industry representatives were interviewed:

- Alex Pepper, UK Major Ports Group

- Jim Warner, Harwich Haven Authority
- Mark Simmonds, British Ports Association
- Mark Russell, British Marine Aggregate Producers Association
- Russell Bird, Peel Ports

3 Marine INNS

The dredging of marine sediment could theoretically result in the entrainment of a wide variety of animals, plants and any other organisms, such as pathogens, that are in/on the seabed (benthic species) or suspended in water (pelagic species). Larvae, eggs, algal spores and other immature stages must be considered, along with mature individuals. Below are some examples of benthic and pelagic INNS that are currently on the UK Marine Non-Indigenous Species Priority List (GBNNSS, 2020) (originally created to deliver the non-native species descriptor of the UK Marine Strategy):

Figure 1. Slipper limpet (*Crepidula fornicata*). © Henry Frye, CC0, via Wikimedia Commons

Slipper limpet (*Crepidula fornicata*)

A mollusc with a kidney-shaped, white to brown coloured shell that grows to approximately 40-50 mm in length and forms stacks of individuals (Figure 1). Stacks often comprise 5-6 individuals (= approximately 10-15 cm in height). Found in the intertidal and subtidal, down to a depth of approximately 60 m, on a wide variety of substrates, from mud to rock. Prefers typical seawater salinity (approximately 35 ppt) but tolerates lower salinities. Eggs of females are fertilised by sperm and are incubated. One female can release 10-20,000 larvae. Stacks develop when the pelagic larvae settle on shells of mature individuals and grow into adults. Densities of slipper limpets on the seabed can reach 10,000 individuals/m^2. Vast areas of slipper limpets can cause space and food competition with other benthic species such as shellfish. (Rayment, 2008; Blanchard, 2009).

Figure 2. Carpet sea squirt (*Didemnum vexillum*). © U.S. Geological Survey/photo by Dann Blackwood (USGS), Public domain, via Wikimedia Commons.

Carpet sea squirt (*Didemnum vexillum*)

Tiny, tube-like individuals comprise vast colonies that create leathery, whiteish or orange-coloured mats on the seafloor (Figure 2). Found in the intertidal and subtidal, down to a depth of approximately 65 m, on a variety of hard substrates (gravel, cobble, rocks), and some stable soft substrates. Prefers typical seawater salinity but tolerates lower salinities. Colonies begin to form once pelagic larvae settle on a suitable surface and begin to self-replicate. Mats can also develop from older ones that have been broken up into fragments and have drifted to a new location. Vast mats can cause space and food competition with other benthic species, and shellfish can become smothered by the mats and die. (Dijkstra, 2009; Gibson-Hall and Bilewitch, 2018).

Figure 3. Chinese mitten crab (*Eriocheir sinensis*). © GerardM at Dutch Wikipedia & Ron Offermans, CC BY-SA 3.0, via Wikimedia Commons

Chinese mitten crab (*Eriocheir sinensis*)

A greyish green to dark-brown coloured crab, with a shell of up to 80 mm in width (Figure 3). The crab's name is derived from its hairy claws. Found in brackish and fully saline waters from where it migrates from freshwater rivers to breed. Inhabits the intertidal and subtidal, down to a depth of approximately 10 m. Females can produce up to 1 million eggs, which are brooded on their undersides and hatch into pelagic larvae. Once developed into the typical crab form, the crabs move into rivers to mature. Crabs burrow into riverbanks, causing erosion and compromising flood defences. They can also form such high densities that they block commercial water intakes. (Bacevièius and Gasiûnaitë, 2008, Qin, 2023).

Figure 4. Wireweed (*Sargassum muticum*). © Lamiot, CC BY-SA 4.0, via Wikimedia Commons

Wireweed (*Sargassum muticum*)

A brown alga that forms strands that can reach 1.5 m in length (Figure 4). Found in the intertidal and subtidal, down to a depth of approximately 20 m, either attached to the seabed or floating on the sea's surface, aided by tiny air sacks. Prefers typical seawater salinity but tolerates lower salinities. One mature algal frond can produce both male and gametes which fertilise to form a new individual. Algal fragments can regenerate but this has not been recorded in temperate regions such as the UK. Fragments of sexually reproductive plants can drift and survive for multiple months. Wireweed can create dense underwater canopies, shading out plants on the seabed and can wrap around fishing gear, propellers and other equipment, limiting their use. Wireweed can also reduce accessibility to waterbodies. (Lewis, 2009).

4 Pathways and vectors

INNS could be moved by dredging activity by a variety of associated pathway and vectors. **Pathways** are the means and routes by which INNS are moved to new environments. **Vectors** are the delivery mechanisms of INNS. The pathways that navigational dredging may create in relation to the movement of INNS can broadly be categorised as:

1. The movement of vessels and equipment involved in a dredging operation to the dredge site (which may lead to the introduction of INNS from outside of the dredge site).
2. The movement of vessels, equipment and dredged material from the dredge site to the disposal site (which may lead to the introduction of INNS from dredge site to the dredge disposal location).

Pathway 1 is considered unlikely when resident dredging vessels and equipment are used, since INNS are unlikely to be spread by these vectors beyond the area in which they would spread naturally. If vessels and equipment are sourced from outside of the immediate area, there is a potential risk of the introduction of INNS in vessel ballast and hopper water, and on vessels hulls and dredging equipment (as outlined below). It is possible that INNS would also be in any residual dredged material. However, as vessels and dredging equipment are typically subject to routine maintenance schedules, it is unlikely this vector would be present in substantial quantities to pose a significant risk. This review will focus on **Pathway 2**, as there is more uncertainty with regards to the potential risk of moving INNS it presents, particularly with regards to the movement of dredged material between dredging and disposal sites (Appendix 3). Although, it is important to also consider **Pathway 1** in vessel or site-specific biosecurity plans, and to assess all potential vectors relating to each pathway.

Vectors of both potential pathways include:

- vessel ballast water
- vessel hopper water
- vessel hull
- dredging equipment
- dredged material.

Ballast water is the water stored within an internal cavity of a vessel to provide stability. It is taken in, or discharged when a vessel’s load changes, and can contain INNS, particularly in the form of eggs, larvae and other plankton. This vector is largely managed through actions determined by the Ballast Water Management Convention (BWMC) 2004 and The Merchant Shipping (Control and Management of Ships’ Ballast Water and Sediments) Regulations 2022.

Hopper water is the water that is taken into the hopper (the cavity where dredged material is stored) of a vessel to provide stability. Water present in the hopper is not strictly considered to be ballast water under the BWMC. However, “Maritime and Coastguard

Agency guidance states that water carried in the hopper of a dredger, which is used for ballasting purposes, must be managed in accordance with the BWMC if the vessel undertakes international voyages. If the vessel operates domestically within UK waters the requirements of the Convention do not apply. If the vessel enters the water of another State then the Convention will apply" (ABPmer, 2018a). Similar to ballast water, the risk that hopper water presents can be managed by strategically exchanging hopper water at specific locations (APBmer, 2018a).

The **hull** of a vessel can become colonised by animals and algae, including, INNS, forming a layer called biofouling. This vector is largely managed through actions determined by voluntary IMO Biofouling Guidelines (IMO, 2023).

Dredging equipment may become covered in residues of dredged material which could contain INNS. This vector can be addressed by cleaning equipment i.e., by following general biosecurity best practices (Cook et al., 2014). Dredging equipment is usually inspected and cleaned between dredging operations as part of maintenance procedures (personal communication). Although the structural complexity of equipment (e.g., dragheads/cutterhead, suction tubes, pumps) may limit the effectiveness of cleaning.

Dredged material that is intentionally moved from a dredging site to a disposal site may contain INNS within it (whether that be in the sediment or water component). No current practices could be identified that address this potential risk of INNS introduction (personal communication), most likely because the potential risk this vector presents is unknown. This review will therefore focus on this vector, although, **it is important to also consider all potential vectors in vessel or site-specific biosecurity plans.**

5 Navigational dredging

Broadly, there are two types of navigational dredging: **maintenance dredging** and **capital dredging** (MMO, 2023a). Both types will be considered in this review, and examples can be found in Appendix 3.

Maintenance dredging is the routine removal of recently accumulated sediments to maintain the designated depth of a navigational channel and is the most common navigational dredging operation that takes place (MMO, 2023a). Maintenance dredging sites are usually in the subtidal i.e., near shore, but deep enough for vessel access. Maintenance dredge campaigns typically take place as required (every few weeks, months or years depending on the environment), to ensure that navigational channels remain open for vessels. Relatively fine sediments that can be readily suspended in water (e.g., clay, mud, sand, and fine gravel (IADC, 2014b)) are most common in maintenance dredging as such sediments are particularly prone to infilling previously dredged areas and therefore require regular removal (ABPmer, 2014). Dredged material is commonly discharged at an offshore disposal site or less frequently on land. Alternatively, dredged material may be disposed of at a coastal beneficial use site. In most cases resident dredging vessels and equipment are used for maintenance dredging, but this is not always the case (personal communication).

Capital dredging is the creation or deepening of navigational channels and takes place less often than maintenance dredging, as it is carried out when the need arises e.g., to accommodate larger vessels or remove material deemed unsuitable for the foundation of a construction project (MMO, 2023a). More specifically, capital dredging is dredging to a depth not previously dredged, or to a depth not dredged within the last 10 years (MMO, 2023a). Like maintenance dredging, capital dredging sites are usually in the subtidal i.e., near shore but deep enough for vessel access. Capital dredging can involve dredging a wide variety of sediment types that have been laid down over many 1,000s or more years, often resulting in mixtures of rock, gravel, sand, mud and clay (ABPmer, 2014; Bray, 1979; Manning et al., 2021; UN.ESCAP, 1991). Dredged material is typically discharged at an offshore disposal site or on land. Examples of capital and maintenance dredging can be found in Appendix 3. In most cases vessels and equipment are sourced from outside of the immediate area, but this is not always the case (personal communication).

6 Dredging methods and processes

To determine the potential risk that navigational dredging operations may present with regards to the movement of INNS in dredged material, the dredging methods and processes used must first be understood. As the dredging process is highly variable, this will influence the likelihood of INNS entrainment and survival, thus influencing the spread of viable propagules and therefore the risk of introduction and establishment.

The dredging process can be broken down into three stages with regards to the movement of dredged material, called **Dredging**, **Transfer** and **Disposal**. At the dredging stage, dredged material is extracted using one of two main methods: hydraulic (by which dredge material is removed via suction) or mechanical (by which the dredge material is removed by digging machinery) dredging. Alternatively, hydrodynamic dredging may be used which works by disturbing or fluidising sediment at the dredging site, resulting in transport via gravity and / or currents (IADC, 2013, 2017). Since the deposition location is local to the dredging site and would not facilitate the spread of INNS beyond areas in the immediate vicinity to which they could naturally disperse, this method is not a focus of this review.

After the dredged material has been removed, it is transported to a disposal site. If a hydraulic dredger has been used, the dredged material is sometimes transported by the dredger itself. Other means of transporting dredge material include a barge or pipeline. Dredged material will then typically be discharged at a designated offshore disposal site or on the coast where it may be used beneficially in some way (e.g., to create a flood defence or habitat).

The machinery, equipment and methods used for each of these processes are highly variable and dependent on many factors, including the characteristics of the dredging site (e.g., sediment type, space available for manoeuvring equipment, wave action), the amount of sediment being moved, and the distance to the disposal location (Manning et al., 2021; UN.ESCAP, 1991). These variations are very likely to impact INNS survival and therefore risk of transfer, introduction (at the dredge site) and establishment. Summary flowcharts for hydraulic and mechanical dredging operations are outlined in Figure 5 and Figure 6, respectively.

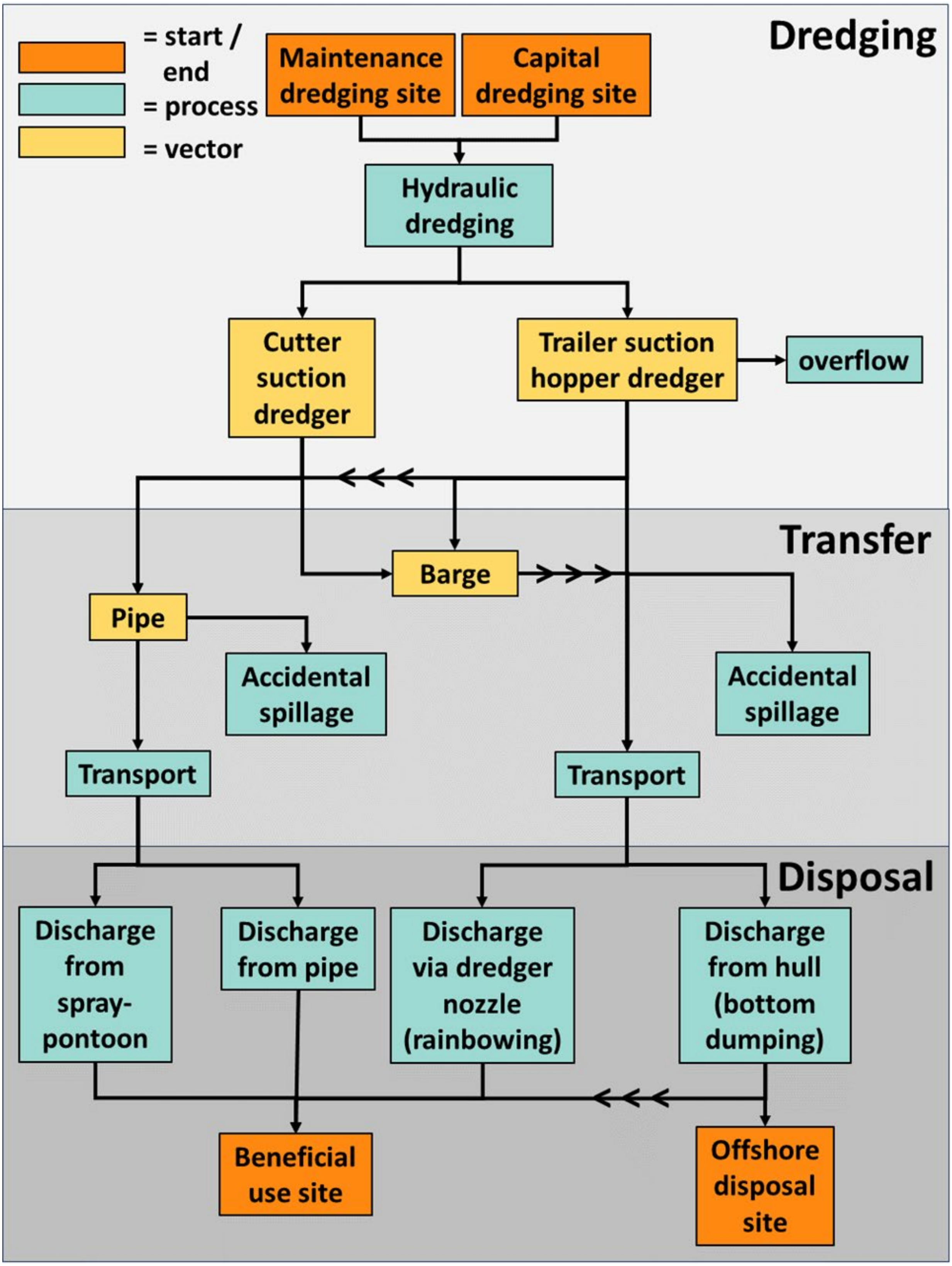

Figure 5. Flowchart illustrating the three stages of hydraulic dredging operations: Dredging, Transfer and Disposal. Typical start and end points, processes and vectors are shown. Arrows show the descending vertical or horizontal direction of flow. Where multiple routes between boxes are possible, chevrons indicate where the flow is one-way © APEM 2024.

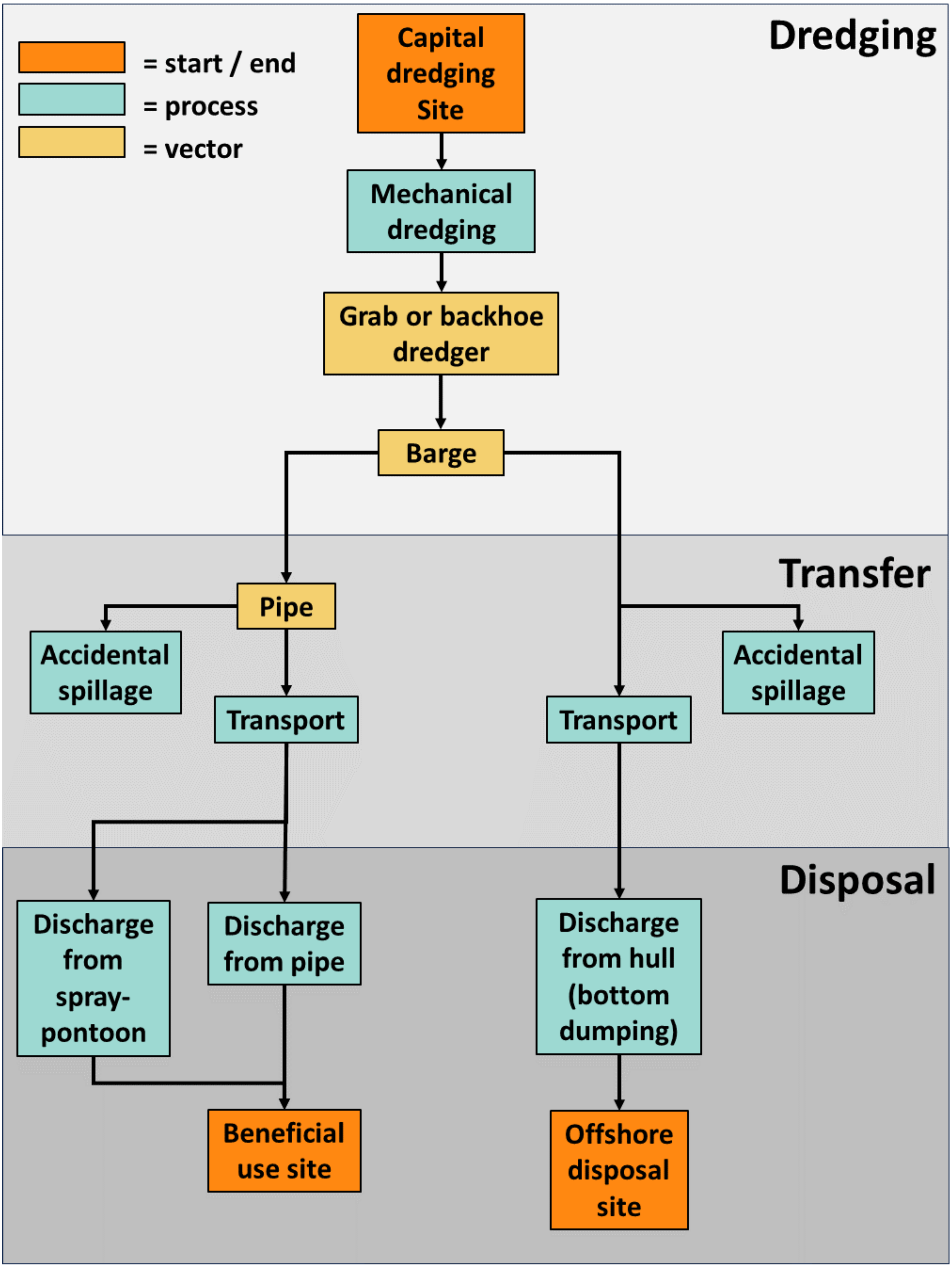

Figure 6. Flowchart illustrating the three stages of mechanical dredging operations: Dredging, Transfer and Disposal. Typical start and end points, processes and vectors are shown. Arrows show the descending vertical or horizontal direction of flow. Where multiple routes between boxes are possible, chevrons indicate where the flow is one-way © APEM 2024

6.1 Dredging

6.1.1 Mechanical dredging

This type of dredging is used to remove mixed, well-consolidated sediments relatively close to shore, which mechanical dredging is often more suitable for than hydraulic (IADC, 2017; UN.ESCAP, 1991). Mechanical dredging involves the use of an excavator to remove sediment from the seabed which enables the creation of precise contours for berths within ports and harbours (ABPmer, 2014; Bray, 1979; Manning et al., 2021; UN.ESCAP, 1991). The most widely used mechanical dredgers are the **grab dredger (GD)** and the **backhoe dredger (BHD)** (IADC, 2017; UN.ESCAP, 1991). The GD comprises a crane that lowers a cable attached to a bucket which fills with sediment. The bucket generally consists of two main parts which shut together on contact with the seafloor. The crane is mounted on a pontoon which may be fixed in place with spuds. Excavated sediment is emptied from the bucket onto a barge for transport, or sometimes a GD will have its own hopper and so transports sediment to the disposal site (IADC, 2017). Instead of a crane, a BHD comprises a mechanical hydraulic arm that lowers an open bucket. Sediment is excavated using a scooping action. Similar to a GD, a BHD is often mounted on a pontoon that can be fixed in place by spuds (IADC, 2017). Buckets generally have a capacity of around 10-30 m^3 (Van Oord, 2020). In the context of navigational dredging, mechanical dredging is most commonly used in capital dredging operations.

6.1.2 Hydraulic dredging

This type of dredging involves the removal of sediment via suction, resulting in a mix of both sediment and large amounts of water entering the dredger (Manning et al., 2021; UN.ESCAP, 1991). Hydraulic dredging is most suited to the dredging of relatively fine sediments that can be readily suspended in water (e.g., clay, mud, sand, and fine gravel (IADC, 2014b)). The most commonly used hydraulic dredgers are the trailer suction hopper dredger (TSHD) and the cutter suction dredger (CSD) (UN.ESCAP, 1991). Both TSHDs and CSDs dredge the seabed using a centrifugal pump to pull sediment and water into a suction pipe (IADC, 2014a, 2014b). Hydraulic dredgers typically move at slow speeds of about 1.5 to 3 nm per hour and can dredge at water depths of approximately 2-35 m (IADC, 2014a; Ramirez et al., 2017; UN.ESCAP, 1991), although one of the largest TSHDs in the world can dredge at a depth of 155 m (IADC, 2014b). In the context of navigational dredging, hydraulic dredging is most commonly used in maintenance dredging operations.

6.1.2.1 Trailer suction hopper dredger

These dredgers are typically 100-200 m in length and are self-propelled (IADC, 2014b). Dredging by a TSHD can be carried out as the vessel sails (IADC, 2014b). The TSHD has one or two suction pipes (0.8-1.3 m diameter) which end in dragheads (often likened to a hoover) through which the sediment and water enters (IADC, 2014b). Dragheads can vary in design but may have high pressure water jets and teeth to facilitate the cutting and loosening of the sediment (IADC, 2014b). Dredged material travels up the suction pipe and enters the hopper (hold) of the TSHD which can have a capacity of 3,000-46,000 m^3 (IADC, 2014b). Dredged material can exit via the overflow of a TSHD dredger or hopper barge once the hopper is near-full (Boskalis, 2023; Jan De Nul Group, 2022b). If the sediment has had time to settle, or the anti-turbidity value is closed, the dredged material exiting the overflow will mainly consist of water (Jan De Nul Group, 2022b). Draining water from the dredged material is advantageous because it maximises the amount of sediment in the hold (IADC, 2014b).

6.1.2.2 Cutter suction dredger

These dredgers vary greatly in size but are often <100 m since they typically do not have a hopper in which to store sediment, although very large CSDs can be >100 m (IADC, 2014a). CSDs can be either self- or non-propelled, with the latter effectively being a pontoon (IADC, 2014a). Unlike a TSHD, a CSD is stationary when dredging and pivots on pilings (spuds) using a system of wires and anchors (IADC, 2014a). The suction pipe forms part of a robust structure called a ladder which ends in a rotating cutterhead with toothed blades (IADC, 2014a). The ladder is moved in an arc-like motion on the seabed as the cutterhead cuts into sediment which is then pulled into the suction pipe (IADC, 2014a; Jan De Nul Group, 2022a). A CSD is therefore typically used to dredge hard sediments, including rock, that a TSHD cannot dredge, however some TSHD dragheads can also dredge rock, and CSDs can be used to dredge finer sediments (IADC, 2014b, 2014a). Dredged material is pumped into a separate vessel (barge) for transport or is pumped into a pipeline that delivers the dredged material to shore (IADC, 2014a).

6.2 Transfer

Once dredged material has been removed, it may be stored in the hopper of the dredger or be decanted into a barge for transport (IADC, 2014a, 2014b, 2017; UN.ESCAP, 1991). The sediment is then moved to a disposal location by the dredger (if it is a TSHD) or barge, or via pipework which connects to the dredging vessel (IADC, 2014a, 2014b, 2017; UN.ESCAP, 1991). Pipes may be floating and anchored to the seabed, or lie on the seabed, and typically consist of multiple pipe sections (UN.ESCAP, 1991). Distances over which sediment is transferred are often shorter if the sediment is to be used beneficially (Manning et al., 2021), compared to when it is to be disposed of at sea (Boskalis Westminster, 2012, 2023) (Appendix 3). It is possible that accidental spillage of dredged material occurs during transfer which could spread INNS if they have survived the dredging and transfer processes.

6.3 Disposal

6.3.1 Beneficial use

The beneficial use of dredged material is becoming increasingly common due to the numerous environmental advantages (Manning et al., 2021). Under The Waste (England and Wales) Regulations 2011 and the Waste Framework Directive in the European Union, dredged sediment is regarded as waste, and therefore the “waste hierarchy” should be applied – this ranks waste management options in order of preference, from most to least favourable, giving priority to preventing waste. This means that dredged sediment should be used for a beneficial use project wherever possible, and disposal at sea (see below) should be a last resort (MMO, 2019). However, offshore disposal is more common at present. The beneficial use of sediment includes habitat creation, in addition to the creation of flood and erosion defences (Manning et al., 2021). Such projects are typically coastal (intertidal) and local (typically < 5 km as per Appendix 3) to the dredging site to: 1) streamline logistics and costs; 2) ensure sediment is not lost from the estuarine or coastal system and; 3) to ensure that the physical and chemical characteristics of dredged sediment are similar to those at the receptor site (i.e., to minimise environmental impact) (Manning et al., 2021; OSPAR, 1998).

Dredged material may be transported from the dredger or hopper barge using hydraulic pumping, either via a fixed or floating pipeline, or directly from the vessel itself which is known as “rainbowing” (when dredged material is pumped into the air (IADC, 2014b)). Alternatively, a pipeline may connect from the vessel to a spray-pontoon which, similar to rainbowing, pumps dredged material into the air (Jan De Nul Group, 2022a). Other methods include bottom dumping, whereby dredged material is released from the vessel, and mechanical placement, whereby dredged material is excavated from the vessel. During bottom dumping, dredged material exits via hatches (doors) in the bottom of the hull (water jets may be used to wash out any remaining sediment (Jan De Nul Group, 2022b)) or via the hull of a “split” barge or dredger which splits longitudinally (UN.ESCAP, 1991). Sediment is then moved onshore by excavators or other machinery to achieve the desired profile (Manning et al., 2021).

6.3.2 Offshore disposal

If sediment cannot be used beneficially it may be disposed of at an authorised offshore disposal site (MMO, 2019) which is usually tens of metres below chart datum (CD) and deeper than the dredging site. In the UK, disposal at sea can only take place in accordance with OSPAR regulations which determine that chemical contaminants within sediment must be below a certain threshold (MMO, 2015, 2023b; OSPAR, 1998). Sediment is typically deposited at the disposal site using bottom dumping (IADC, 2014b; MMO, 2015, 2019, 2023b; OSPAR, 1998). A disposal site as close as possible to the dredged area is selected for the same reasons as listed above, although the most suitable site is often >10 km away and the transport of dredged material may take hours (Figure 7 and Appendix 3). For example, the offshore disposal site called Inner Gabbard is typically used to dispose of dredged material from Harwich Harbour, Essex. It takes about 30 minutes to load the sediment at the dredging site and 1.5 hours for the TSHD to reach the offshore disposal site of Inner Gabbard. The round trip is approximately 65 km, from the harbour to the disposal site, and takes about 4-5 hours (Project 10 in Appendix 3) (personal communication; Harwich Haven Authority, 2024).

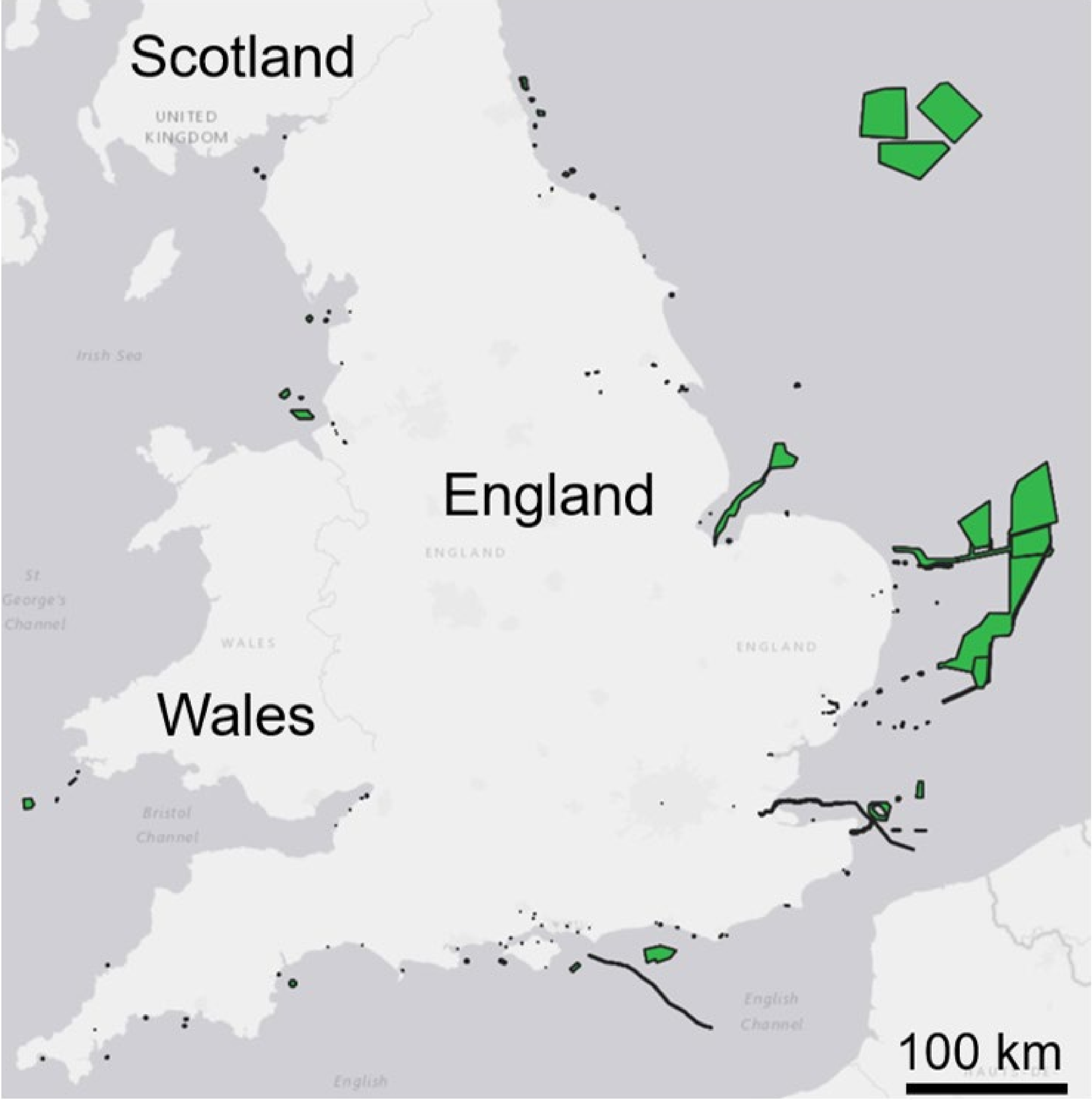

Figure 7. The location of offshore disposal sites (green polygons) in England that are currently active (“open”). Data obtained from Cefas (2022), published under Open Government Licence (OGL). © APEM 2024

7 Dredging pathway conditions assessment

Due to the high level of variation in the process used for the three stages of dredging (Dredging, Transfer and Disposal) it is challenging to assess the movement of dredged material for navigational dredging as a pathway for INNS translocation. Additionally, characteristics of the dredging and disposal sites (e.g., depth and sediment type) and traits of the INNS must be considered. For instance, INNS are typically associated with anthropogenic disturbance (Airoldi & Bulleri, 2011; Byers, 2002; Dolbeth et al., 2007) (which is common at dredging locations), and the environmental tolerances of different species will determine their likelihood of survival throughout the dredging process.

Due to the high number of contributing factors, and their likely differing impacts, a holistic review is required for an effective pathway assessment to be conducted. However, empirical data for many of these factors is substantially lacking. To examine the viability of the potential pathway without sufficient evidence requires the extrapolation of relevant information from research that is focussed on one aspect of the pathway, or on a topic that is relevant to the pathway (not a direct study). Therefore, it is important to acknowledge that the following assessment requires further refinement and investigation for a clear evidence-based conclusion to the potential risk the pathway poses.

Here, a preliminary qualitative assessment is presented that identifies the conditions that must be met for INNS to be successfully introduced from a disposal site to a dredging site, and the factors which may influence the likelihood of these conditions being met. The identified conditions are that **INNS must:**

1. be present at the dredging site
2. be entrained (taken up) by the dredger
3. survive entrainment
4. survive transfer
5. survive discharge
6. survive at the disposal site
7. establish (reproduce and persist long-term) at the disposal site.

This assessment examines each of these conditions and the relevant influential factors relating to the dredging and disposal site, dredging process and INNS characteristics. For each factor, whether it would result in a higher or lower likelihood of a condition being met has been discussed. Where available, scientific literature has been utilised and referenced, and as previously stated in the Methodology Section (2), information relating to personal communication with industry has been referenced as such. Where no references have been included in the following sections, the statements and assumptions are based on expert knowledge of the authors. The results are summarised in a table at the end of each section. To guide future research, these tables also indicate where the influence of a factor was difficult to derive due to data deficiency, and where the identification of a quantified threshold is required to determine the influence of a factor.

It should be noted that in addition to INNS survival, fitness should also be considered, since it is a measure of reproductive success. For instance, an INNS may survive the dredging process but not be healthy enough to reproduce and survive longer term. Thereby the risk of introduction is reduced. To simplify the review, and due to a lack of information with respect to this potential pathway, fitness is no longer referred to in this assessment, but it should be assumed that factors which reduce the chance of survival also reduce fitness. Additionally, these conditions are gated, for example, for INNS to be entrained they must first be present at the dredge site, and they must survive entrainment to be transferred. If any of these conditions are not met, then there is hypothetically no risk of transference.

7.1 Dredging

7.1.1 Condition 1: INNS are present at the dredging site

Influential factors: introductory pathways, artificial substrates, anthropogenic disturbance, dredging frequency (outlined in more detail in the following text and summarised in Table 1).

It is highly likely that INNS will be present in the vicinity of a navigational dredge site as they are usually in or near areas of industrial and/or recreational activity (e.g., ports, harbours, shipping channels, marinas). This is because the abundance of marine INNS tends to be higher in locations where there are pathways of introduction/spread and artificial habitats to colonise (Johnston et al., 2017). Such sites are also often polluted and anthropogenically disturbed environments in which INNS typically thrive (Airoldi & Bulleri, 2011; Byers, 2002; Dolbeth et al., 2007), since many INNS have broad environmental tolerances and reproduce rapidly, thus facilitating survival in harsh environmental conditions and enabling relatively fast recolonisation after mortality events (Piola & Johnston, 2008; Winemiller, 1992). Considering this, sites that have been previously dredged (i.e., those where maintenance dredging occurs, or capital dredging is being undertaken to alter previously existing channels), may be particularly likely to have INNS present than those that have not been dredged before, although no comparative assessment could be found to support this. Conversely, benthic INNS assemblages may be small and present in low densities because they have been removed by previous dredging activity (see Condition 2). Although it should be noted that in this scenario there may still be propagules (e.g., gametes, larvae, spores) of benthic species in the water originating from nearby populations.

Dredging frequency will impact the presence and abundance of all organisms, including INNS. While INNS are often quick to recolonise when compared to other species (Piola & Johnston, 2008; Winemiller, 1992), this process still takes time. Benthic communities can take weeks to months to recover from the environmental changes caused by dredging activity (Guerra-García et al., 2003). Specifically, dredged sites can result in a shift to finer sediments, a higher organic carbon content and a reduction in oxygen levels (Krause et al., 2010). Additionally, dredging can result in the creation of a fluid muddy layer (personal communication; Wurpts, 2005) which may not be colonisable by certain benthic species (including INNS). It is therefore highly likely that there will be an absence of benthic INNS at locations that are regularly dredged. Although no literature on the effect of dredging frequency or the fluidisation of mud on the presence of benthic INNS could be found. Similarly, there may be a threshold of anthropogenic disturbance above which most species, including INNS would be absent.

Other considerations

Sediment type will determine the benthic community at the dredging site and therefore what INNS are present (JNCC, 2023). Benthic INNS can be found on/in nearly all sediment types (including mud, sand, gravel and rock), in both the intertidal and subtidal. INNS that are pelagic, including the larval stages of benthic species and any other propagules, should also be considered, since water is inevitably moved with sediment during the dredging process.

7.1.1.1 Summary

INNS are **more likely** to be present at the dredging site when:

- introductory pathways are present
- artificial substrates are present
- anthropogenic disturbance is medium**
- dredging frequency is medium**

INNS are **less likely** to be at the dredging site when:

- introductory pathways are absent
- artificial substrates are absent
- anthropogenic disturbance is low**, or high**
- dredging frequency is low**, or high**

(**denotes where a quantified threshold is needed to determine the influence of a factor).

Table 1. Summary of the factors that could influence the likelihood of Condition 1 “INNS are present at the dredging site” being met. Factors have been assigned a “higher” or “lower” likelihood category where data allowed. Where the influence of a factor was difficult to derive due to data deficiency, this has been indicated. Where the identification of a quantified threshold is required to determine the influence of a factor, this has been indicated. The information in this table is based on a combination of data from scientific literature (see text for details) and the professional opinion of the authors of this review. Cells were left blank where the author considered column headings to be irrelevant. This is not an exhaustive list of factors and should be updated as more research is carried out to fill knowledge gaps. Some cells are left blank.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Site	Introductory pathways	Present	X				More likely for INNS to have been introduced and therefore be present.
Site	Introductory pathways	Absent		X			Less likely for INNS to have been introduced and therefore be present.
Site	Artificial substrates	Present	X				More likely for INNS to have been introduced and therefore be present.
Site	Artificial substrates	Absent		X			Less likely for INNS to have been introduced and therefore be present.
Site	Anthropogenic disturbance	Low		X		X	Less likely for INNS to be present due to preference for disturbed environments.
Site	Anthropogenic disturbance	Medium	X			X	More likely for INNS to be present due to preference for disturbed environments.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Site	Anthropogenic disturbance	High		X		X	Less likely for INNS to be present due to environmental tolerances being exceeded. However, if INNS are near the dredging area, any pelagic propagules (inc. larvae) could be entrained.
Site	Dredging frequency	Low		X		X	Less likely for INNS to be present due to minimal disturbance.
Site	Dredging frequency	Medium	X			X	More likely for INNS to be present due to disturbance.
Site	Dredging frequency	High		X		X	Less likely for benthic INNS to be present because they are removed by frequent dredging. However, if INNS are near the dredging area, any pelagic propagules (inc. larvae) could be entrained.

7.1.2 Condition 2: INNS are entrained

Influential factors: organism characteristics, dredger type, and dredged seabed area (outlined in more detail in the following text and summarised in Table 2).

During dredging operations, INNS and other organisms (if present) may be excavated by dredgers along with the dredged material. This process is called entrainment (Reine et al., 1998). Organisms that are likely to be entrained are algae and relatively small, benthic, slow-moving, or sessile animals that are not able to move away from the draghead or bucket (e.g., shellfish, crabs and shrimp (Miró et al., 2022; Reine et al., 1998)), as well as any eggs or other propagules. However, larger and more mobile animals such as turtles and fish can also become entrained due to the suction forces used for hydraulic dredging (Reine et al., 1998).

A study of the swimming performance of paddle fish (*Polyodon spathula*) (<115 mm eye-to-fork length) in laboratory conditions concluded that entrainment was likely within a 1.25 m radius of a cutterhead with a diameter of 0.3-0.7 mm, and a water velocity of 0.3-0.8 m/s (Hoover et al., 2009). Although it is important to note that this study was based on cutterheads used in freshwater systems. The diameter of suction pipes used in marine environments can range from 0.8-1.3 m (IADC, 2014b), and the water velocity in the suction pipe can vary from 2-10 m/s (van der Spek et al., 2016), therefore presenting a greater risk of entrainment.

While suction can enhance the likelihood of entrainment of mobile organisms, coarse grills fitted to the draghead (to prevent update of cobbles) may prevent the entrainment of larger organisms, although these are not always used (personal communication). With regards to CSDs, grids may be placed on the suctionhead and the cutterhead and a stone box and grids are placed in the suction pipe to prevent uptake of cobbles (UN.ESCAP, 1991). Mechanical dredgers such as GDs and BHDs use buckets to excavate sediment, so there is no barrier to prevent the entrainment of INNS, although mechanical dredging does not use suction so mobile organisms are more likely to escape. Additionally, the upper seabed layers that organisms tend to colonise may be dispersed into the water due to water resistance as the bucket is raised from the seabed. This would depend on the bucket design (i.e., on open bucket vs a closed grab). Surface layers of seabed and the organisms within it are also less likely to be entrained when deeper, thicker, layers are targeted for removal using a TSHD, as is the case for some maintenance dredging campaigns in shipping channels (upper sediment layers are more fluid than deeper layers and so are less problematic for ship movement) (personal communication). However, in such instances, propagules in water could still be entrained, and it is likely that some of the surface layers would inadvertently be suctioned. If INNS are present in the surface layer, they would most likely be in the upper 10-15 cm (Colen 2019).

The volume of sediment being dredged over a project period can vary from thousands to millions m^3 (Appendix 3). It is logical to assume that the greater the seabed surface area that is dredged (and generally the more volume) the higher the chance of entrainment, and the higher the total number of a particular species that could be transferred (Pearson et al., 2002). While entrainment rates could be low per m^3 for some species, the typically quantities of sediment dredged for capital and maintenance dredging could result in high abundance figures. For example, mean entrainment rates estimated for Dungeness crabs (*Metacarcinus magister*) in relation to dredging using a TSHD range from 0.05-10.78 crabs per cubic yard, depending on location and crab size (Reine et al., 1998). A dredging operation could in theory result in 1,000s or 10,000s crabs being entrained (Pearson et al., 2002).

Summary

INNS are **more likely** to be entrained when:

- organisms are small**
- organisms are sessile
- dredger type is hydraulic
- depth of sediment to be dredged is <15 cm below seabed surface
- dredged seabed area is large**

INNS are **less likely** to be entrained when:

- organisms are large**
- organisms are mobile
- depth of sediment to be dredged is >15 cm below seabed surface
- dredged seabed area is small**

(**denotes where a quantified threshold is needed to determine the influence of a factor).

Table 2. Summary of the factors that influence the likelihood of Condition 2 "INNS are entrained" being met. Factors have been assigned a "higher" or "lower" likelihood category where data allowed. Where the influence of a factor was difficult to derive due to data deficiency, this has been indicated. Where the identification of a quantified threshold is required to determine the influence of a factor, this has been indicated. The information in this table is based on a combination of data from scientific literature (see text for details) and the professional opinion of the authors of this review. Cells were left blank where the author considered column headings to be irrelevant. This is not an exhaustive list of factors and should be updated as more research is carried out to fill knowledge gaps. Some cells are left blank.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Organism	Organism characteristic	Large		X		X	Less likely to pass through grills or any other filters.
Organism	Organism characteristic	Small	X			X	More likely to pass through grills or any other filters.
Organism	Organism characteristic	Mobile		X			More likely to escape entrainment, if it is large/fast enough to move away from the suction field.
Organism	Organism characteristic	Sessile	X				Less likely to escape entrainment.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Dredging process	Dredger type	Hydraulic	X				More likely for pelagic and benthic mobile organisms to be entrained due to suction. Less likely for an individual to be entrained if a filter is used.
Dredging process	Dredger type	Mechanical			X		Less likely for pelagic and benthic mobile organisms to be entrained due to no suction. Possibly less likely for benthic species to be entrained if upper layers of excavated sediment are dispersed as the bucket is raised. More likely for an individual to be entrained due to lack of filter.
Dredging process	Depth of sediment to be dredged	<15 cm below seabed surface	X				More likely for benthic INNS to be in sediment.
Dredging process	Depth of sediment to be dredged	>15 cm below seabed surface		X			Less likely for benthic INNS to be in sediment.
Dredging process	Dredged seabed area	Large	X				More likely for an individual to be entrained.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Dredging process	Dredged seabed area	Small		X			Less likely for an individual to be entrained.

7.1.3 Condition 3: INNS survive entrainment

Influential factors: organism characteristics, dredger type, sediment type (outlined in more detail in the following text and summarised in Table 3).

To survive entrainment by hydraulic dredgers, INNS would have to be able to survive physical pressures caused by suction, abrasion, impact (on the pipe lining, grills etc.) and high levels of turbidity that occur within the suction pipe. It is very likely that some INNS are more likely to survive these conditions than others. For instance, many pelagic organisms such as fish are not adapted to high levels of suspended sediment (which can cause gill injury and reduced oxygen uptake (Wenger et al., 2017)), and generally have a soft, relatively fragile, exterior and are therefore vulnerable to injury. Conversely, organisms with shells and exoskeletons when adults, such as molluscs and crustaceans, are adapted to benthic environments where sedimentation can occur, and may be more resilient to the physical pressures that could arise during the dredging process. For example, a study of the impact of entrainment of freshwater mussels with a suction dredge (0.1 m diameter nozzle) evidenced no physical damage or mortality after entrainment (Krueger et al., 2007). Although, many benthic species, including mussels and other shellfish, have larval juvenile stages which lack a protective hard shell or exoskeleton. Similarly, propagules such as eggs may be susceptible to damage upon entrainment due their soft composition (Wenger et al., 2017) thus voiding their viability. Organisms that can regenerate from fragments (e.g., colonial animals and algae) may be more likely to survive. However, an assessment of what taxa and life stages can survive entrainment could not be found.

The stresses imposed on organisms by hydraulic dredging can be likened to those caused by entrainment by power plant cooling water intakes: mechanical buffeting, acceleration, velocity sheer forces, and changes in hydrostatic pressure (Marcy et al., 1978). However, despite these forces, as well as temperature and chemical changes, species survival rates in relation to cooling water intakes can be relatively high: survival rates of finfish larvae and macroinvertebrates are typically reported as >50%, sometimes 90-100% (Mayhew et al., 2000). It is therefore possible that some organisms that are entrained by hydraulic dredges survive, however studies on survival rates after entrainment are largely limited to adults of a few animal species (commercially and ecologically important species that are easy to detect and identify) (Reine et al., 1998). Mechanical dredgers typically excavate sediment by lifting it using a bucket, probably leaving the sediment and organisms more intact and causing less physical stress than hydraulic dredgers would, although the action of excavation would still create pressure in and around the bucket. Additionally, the emptying and consequent fall of sediment from the bucket and into the hopper could cause mortality, although no specific studies have been found on this topic.

Environmental conditions within a suction pipe would be different from the natural environment. For instance, sediment mixing can result in a reduction in oxygen, changes in nutrient levels and the resuspension of toxic chemicals such as heavy metals (Bradshaw et al., 2021; Wenger et al., 2017). Organisms with broad environmental tolerances such as many INNS (Sakai et al., 2001), particularly the adult stages of animals, and mature and immature algal forms, would therefore be more likely to survive entrainment. Although passage through the suction pipe is likely to only last seconds, so broad environmental tolerances is more relevant to Condition 4 (INNS survive transfer). Minimal sediment mixing would occur within the bucket of a mechanical dredger, although mixing would probably occur on impact when sediment is released into the hopper.

Estimates of Dungeness crab mortality caused by entrainment determined that hydraulic dredging (including TSHD) caused a much higher mortality rate than mechanical dredging (with a GD) (80-100% compared to 10% respectively), although the study acknowledged that little mortality data existed on the impact of entrainment by a GD (Armstrong et al., 1987). Similarly, reported mortality rates for turtles entrained by TSHD are high (Reine et al., 1998) due to blunt trauma but also potentially gas embolism because of decompression sickness (Harms et al., 2020). If organisms were entrained by a CSD, the teeth of the cutterhead would probably cause injury and death.

Bivalve larvae entrained by a TSHD are assumed to suffer 100% mortality due to the mechanical forces caused by pumping of the dredged material (in addition to smothering under sediment, anoxia, starvation and desiccation) (Reine et al., 1998) although a direct assessment of this could not be found. Mortality rates for many species and life stages after entrainment are still unknown but will probably vary with size. For example, larger Dungeness crabs are more likely to suffer from mortality due to entrainment than smaller ones (Araújo et al., 2005; Armstrong et al., 1987).

Sediment particle size and weight probably influence survival potential in terms of crushing pressure and the potential for abrasion and blunt force trauma, however an assessment of this could not be found.

Summary

INNS are **more likely** to survive entrainment when:

- organisms are small**
- organisms have a robust exterior
- organisms are regenerative
- organisms are benthic
- organisms have broad environmental tolerances

INNS are **less likely** to survive entrainment when:

- organisms are large**
- organisms have a fragile exterior
- organisms are not regenerative
- organisms are pelagic
- organisms have narrow environmental tolerances
- dredger type is hydraulic**

(**denotes where a quantified threshold is needed to determine the influence of a factor).

Table 3. Summary of the factors that influence the likelihood of Condition 3 “INNS survive entrainment” being met. Factors have been assigned a “higher” or “lower” likelihood category where data allowed. Where the influence of a factor was difficult to derive due to data deficiency, this has been indicated. Where the identification of a quantified threshold is required to determine the influence of a factor, this has been indicated. The information in this table is based on a combination of data from scientific literature (see text for details) and the professional opinion of the authors of this review. Cells were left blank where the author considered column headings to be irrelevant. This is not an exhaustive list of factors and should be updated as more research is carried out to fill knowledge gaps. Some cells are left blank.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Site	Sediment type	Mud, sand, gravel			X		Impacts physical forces such as the degree of abrasive action and sediment weight which would probably impact mortality.
Organism	Organism characteristic	Large		X		X	More likely to be subject to blunt force.
Organism	Organism characteristic	Small	X			X	Less likely to be subject to blunt force, and more likely to fit between interstitial spaces of sediment if small enough.
Organism	Organism characteristic	Robust exterior	X				More likely to tolerate physical forces and desiccation.
Organism	Organism characteristic	Fragile exterior		X			Less likely to tolerate physical forces and desiccation.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Organism	Organism characteristic	Regenerative	X				More likely to survive if fragmented.
Organism	Organism characteristic	Not regenerative		X			Less likely to survive if fragmented.
Organism	Organism characteristic	Benthic	X				More likely to survive turbidity and sedimentation.
Organism	Organism characteristic	Pelagic		X			Less likely to survive turbidity and sedimentation.
Organism	Organism characteristic	Broad environmental tolerances	X				More likely to survive changes in environmental conditions.
Organism	Organism characteristic	Narrow environmental tolerances		X			Less likely to survive changes in environmental conditions.
Dredging process	Dredger type	Hydraulic		X	X		Less likely to survive due to physical forces induced by suction and injury caused by the draghead or cutterhead.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Dredging process	Dredger type	Mechanical			X		More likely to survive due to no suction forces, although mortality could result from pressures in sediment caused by excavation and falling from bucket into the hopper.

7.2 Transfer

7.2.1 Condition 4: INNS survive transfer

Influential factors: dredged material composition, organism characteristics, sediment type, water content of dredged material, dredged material volume in hopper, transfer method, transit time (outlined in more detail in the following text and summarised in Table 4).

If any INNS were to enter a dredge hopper or barge via the entrainment processes described, many would probably be crushed, apart from those at the top of the dredged material pile. The chance of organisms being at the top of the dredged material pile would depend on the proportion of dredged material comprising upper layers of the seabed, since most infauna in mudflats live in the upper 10-15 cm (Colen 2019). If most of the dredged material comprises sediment from lower layers (>15 cm depth), then the majority of organisms would probably be buried. Conversely, if the majority of dredged material comprises sediment from upper layers (<15 cm depth) then while many organisms would be buried, it is likely that some would be present at the surface. Likelihood of burial would also be higher when dredged material volumes are high, as would the pressures exerted on organisms in the lower layers (assuming higher volumes correlate with deeper depths).

Survival would be influenced by an organism’s characteristics. Propagules and smaller organisms such as larvae and meiofauna (animals < 1mm in length) occupy the interstitial space of settled sediment and so may avoid crushing at the transfer stage, if they survived entrainment. However, they are also typically soft-bodied and relatively fragile. Additionally, the geochemistry of the sediment and its interstitial water would have been affected by the mixing of sediment upon entrainment, possibly resulting in sub-optimal conditions for survival (Meyers et al., 1988). As previously mentioned, sediment mixing can result in a reduction in oxygen, changes in nutrient levels and the resuspension of toxic chemicals such as heavy metals (Bradshaw et al., 2021; Wenger et al., 2017).

The burial of benthic epifaunal taxa (on sediment), or infauna taxa (within sediment) past the point at which they can reach the surface, would smother organisms, impeding their ability to respire and feed and resulting in death if they are not able to return to a suitable depth (Roberts et al., 1998, Bolam, 2010, Powell-Jennings & Callaway, 2018). However, mortality caused by a lack of oxygen and food usually occurs after days as opposed to hours (Roberts et al., 1998, Bolam, 2010, Powell-Jennings & Callaway, 2018), with the latter being more relevant to the transfer process (Boskalis Westminster, 2012). Furthermore, many benthic species are somewhat resistant to burial due to adaptation to natural sedimentation events. However, such events would probably only result in burial under a few millimetres or centimetres as opposed to metres – the latter would be more likely in a hopper.

High levels of organic content (typical of muddy and silty sediments) have been shown to negatively impact survival after burial (Bolam, 2010). This is probably because it exacerbates the detrimental effects of sediment deposition which are the lowering of oxygen levels and the increase in ammonia and sulphide (Bolam, 2010; Maurer et al., 1985). These chemical changes could particularly impact juvenile life stages of animals which generally have narrower environmental tolerances than adults (e.g., Nishizaki and Ackerman, 2019). Many adult bivalve species, including mussels and oysters, are relatively resistant to adverse environmental conditions due to their ability to close their shell for hours, preventing exposure (e.g., Anestis et al., 2007). Mature stages of algae can also be tolerant to a wide range of conditions, whereas some immature stages and gametes can have narrower environmental tolerances than mature stages (e.g., Engelen et al., 2015).

The water content of dredged material could influence the ability of organisms to survive the transfer process since prolonged exposure to dry conditions (and associated temperature changes) and a lack of oxygen can result in organism death. Benthic species with a shell or exoskeleton may be more likely to survive these stressors. For example, adult mussels can survive for hours out of water during periods of low tide by closing their shells and can respire anaerobically during this time (Anestis et al., 2007). Intertidal benthic species are particularly well-adapted to exposure to air as they must survive this daily due to tidal ebb and flow. However, many benthic species have larval juvenile stages which cannot survive desiccation.

Generally, sediment consisting of larger grain sizes, such as gravels, retain less water (are free draining) when compared to finer sediments such as silt and mud. Therefore, if larger grain sizes are mechanically dredged, water would most likely drain from the grab or bucket during excavation or once piled on a barge or in a hopper, resulting in a lower dredged material water content and higher sediment consolidation (Manning et al., 2021). In contrast, hydraulic dredging results in very fluid dredged material: nine to ten times more water than sediment may be suctioned (COPRI of ASCE, 2021), although the density of the mixture can vary depending on the hardness of the sediment (IADC, 2014b). Once the dredged material is in the hopper, sediment settles to the bottom and water rises to the top. Water may therefore only be retained in the higher levels of the dredged material pile if it does not enter the overflow. The volume of water that is squeezed into the upper sediment layers is probably dependant on transit time and the weight of the dredged material. Shorter transfer times and small loads of muddy or silty dredged material may be particularly susceptible to water retainment, although an assessment of this could not be found.

Beneficial use projects, particularly the creation of sea defences and beach nourishment, often use pipelines to deliver sediment to the coast (Manning et al., 2021). Pipelines may be floating, on the seabed, or buried, and typically comprise multiple sections (UN.ESCAP, 1991). Longer pipe networks (they can be >1 km) require multiple booster pumps to maintain enough pressure to transport the dredged material (IADC, 2014b; UN.ESCAP, 1991). Velocities used for transporting different sediment types can range from 2-5.5 m/s (UN.ESCAP, 1991). Such velocities are likely to cause substantial abrasive action

(UN.ESCAP, 1991). Considering this, and the likely physical stress from passing through multiple pumps, organism survival rates may be low, however an assessment of this could not be found.

Beneficial use projects also typically use hopper barges that have a smaller capacity than the hopper of a dredger (Appendix 3, Ramirez et al., 2017). These smaller transport vessels are often more suitable because they can access relatively shallow and geographically complex coastal areas that larger vessels cannot. Such projects are likely to obtain sediment from a local source so that the sediment characteristics match those at the disposal site and so that sediment is not lost from the local system (sediment cell) (Manning et al., 2021). The combination of smaller loads (weaker crushing forces) and relatively short transit times (limited exposure to stressful conditions) could result in a higher likelihood of organism survival. In comparison, the transport of dredged material to an offshore disposal site is usually done by a TSHD or large barge, over several kilometres, potentially decreasing survival likelihood.

It is possible that dredged material and therefore INNS would be accidentally released on route to the disposal site. Transport through pipelines could result in accidental spillage, perhaps at joins, or undetected cracks (UN.ESCAP, 1991). Rough seas and full loads could result in accidental spillage from the hopper (if it is not enclosed). However, a hopper will rarely be full, since its carrying capacity is more limited by maximum tonnage than sediment volume (UN.ESCAP, 1991), and if a material is sticky, the hopper will only be partially full in order to aid the successful discharge of dredged material (UN.ESCAP, 1991). Furthermore, if rough seas are apparent, the hopper is generally not entirely filled to prevent the chance of spillage (personal communication). Spillage via the overflow on route to the disposal site is also unlikely since use of the overflow is often only permitted at the dredging site (personal communication). Overall, spillage is a minimal risk since it is within the interests of all stakeholders to prevent the loss of dredged material (personal communication). Should spillage occur, the potential survival and successful translocation of INNS can be assessed by considering the same conditions and factors as discussed in this section (7), albeit, some factors may no longer be relevant (e.g., discharge method), and “spillage” would be occurring instead of “discharge”.

Summary

INNS are **more likely** to survive transfer when:

- dredged material comprises mostly sediment <15 cm below seabed surface
- organisms are small**
- organisms have a robust exterior
- organisms are regenerative
- organisms are benthic
- organisms are intertidal
- organisms have broad environmental tolerances
- water content of dredged material is high**
- dredged material volume in hopper is low**

- transit time is short**

INNS are **less likely** to survive transfer when:

- dredged material comprises mostly sediment >15 cm below seabed surface
- organisms are large**
- organisms have a fragile exterior
- organisms are not regenerative
- organisms are pelagic
- organisms are subtidal
- organisms have narrow environmental tolerances
- dredger type is hydraulic**
- transfer method is dredger, barge or pipeline*
- water content of dredged material is low**
- dredged material volume in hopper is high**
- transit time is long**

(*denotes where the influence of a factor is difficult to derive due to data deficiency

**denotes where a quantified threshold is needed to determine the influence of a factor).

Table 4. Summary of the factors that influence the likelihood of Condition 4 “INNS survive transfer” being met. Factors have been assigned a “higher” or “lower” likelihood category where data allowed. Where the influence of a factor was difficult to derive due to data deficiency, this has been indicated. Where the identification of a quantified threshold is required to determine the influence of a factor, this has been indicated. The information in this table is based on a combination of data from scientific literature (see text for details) and the professional opinion of the authors of this review. Cells were left blank where the author considered column headings to be irrelevant. This is not an exhaustive list of factors and should be updated as more research is carried out to fill knowledge gaps. Some cells are left blank.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Site	Sediment type	Mud, sand, gravel			X		Impacts physical forces such as the degree of abrasive action and sediment weight which would probably impact mortality. Finer grain size would have higher water content but higher levels of organic matter.
Dredging process	Dredged material composition	Mostly sediment <15 cm below seabed surface	X				More likely to survive due to a higher chance of being in upper layers of dredged material in hopper (i.e., not being crushed).
Dredging process	Dredged material composition	Mostly sediment >15 cm below seabed surface		X			Less likely to survive due to a higher chance of being in deeper layers of dredged material in hopper (i.e., being crushed).
Organism	Organism characteristic	Large		X		X	More likely to be subject to blunt force.

Factor type	**Factor**	**Factor detail**	**Higher likelihood**	**Lower likelihood**	**Data deficient**	**Requires quantified threshold**	**Justification**
Organism	Organism characteristic	Small	X			X	Less likely to be subject to blunt force, and more likely to fit between interstitial spaces of sediment if small enough.
Organism	Organism characteristic	Robust exterior	X				More likely to tolerate physical forces and desiccation.
Organism	Organism characteristic	Fragile exterior		X			Less likely to tolerate physical forces and desiccation.
Organism	Organism characteristic	Regenerative	X				More likely to survive if fragmented.
Organism	Organism characteristic	Not regenerative		X			Less likely to survive if fragmented.
Organism	Organism characteristic	Benthic	X				More likely to survive turbidity and sedimentation.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Organism	Organism characteristic	Pelagic		X			Less likely to survive turbidity and sedimentation.
Organism	Organism characteristic	Intertidal	X				More likely to survive lack of water / exposure to air
Organism	Organism characteristic	Subtidal		X			Less likely to survive lack of water / exposure to air.
Organism	Organism characteristic	Broad environmental tolerances	X				More likely to survive changes in environmental conditions.
Organism	Organism characteristic	Narrow environmental tolerances		X			Less likely to survive changes in environmental conditions.
Dredging process	Transfer method	Dredger, barge or pipeline		X	X		All methods of transfer will impose stresses on the organisms (e.g., burial, crushing, abrasion and/or changes in environmental conditions) and therefore could cause mortality.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Dredging process	Water content of dredged material	High	X			X	More likely to survive due low lower likelihood of desiccation and oxygen starvation.
Dredging process	Water content of dredged material	Low		X		X	Less likely to survive due to higher likelihood of desiccation and oxygen starvation.
Dredging process	Dredged material volume in hopper	High		X		X	Less likely to survive due to higher likelihood of being buried and crushed.
Dredging process	Dredged material volume in hopper	Low	X			X	More likely to survive due to lower likelihood of being buried and crushed.
Dredging process	Transit time	Long		X		X	Less likely to survive due to prolonged exposure to stressful conditions.
Dredging process	Transit time	Short	X			X	More likely to survive due to brief exposure to stressful conditions.

7.3 Disposal

7.3.1 Condition 5: INNS survive discharge

Influential factors: organism characteristics, sediment type and discharge method (outlined in more detail in the following text and summarised in Table 5).

The influences of organism characteristics and sediment type and likely to be similar to those discussed in Conditions 2, 3 and 4. Additionally, characteristics must be considered that make an organism likely to escape from sediment as it descends through water on discharge, thereby minimising the organism’s exposure to turbidity and sedimentation, and preventing it from becoming buried (see Condition 6 section). For instance, if very small, an organism may naturally separate from sediment as it descends through the water column. Furthermore, if mobile, an organism can swim away. In summary, a pelagic organism is more likely to be able to separate from falling sediment and therefore survive, although no evidence could be found to support this theory which will most likely be influenced by organism type.

Discharge method will determine the physical stresses imposed on organisms and potentially the likelihood of burial. When dredged material is disposed of at a licensed offshore disposal area it is discharged via hatches on the underside of the hull, or the hull itself splits longitudinally to release the dredged material. This is a more passive process than hydraulic methods such as rainbowing or pipeline release and so may enhance organism survival.

Dredged material is sometimes transferred to coastal areas for beneficial use (e.g., sea defence or beach replenishment) via rainbowing. This involves the pumping of the dredged material in the hopper out through a hose with a nozzle, causing it to arc through the air onto/close to the shore (IADC, 2014b). Similarly, a pipeline may connect from the vessel to a spray-pontoon which sprays dredged material onto shore (Jan De Nul Group, 2022a). The high pressures required, and the impact of the dredged material on the water or shoreline, may result in mortality, although no assessment of this could be found. Alternatively, dredged material may be deposited on the shore via a pipeline (Manning et al., 2021). In addition to causing physical stress, rainbowing, spray-pontoon and pipeline discharge methods would cause sediment to become mixed, possibly altering the chemical properties of the sediment (Maurer et al., 1985).

Another option for discharge is excavation from the hopper by a mechanical dredger, which may minimise sediment mixing, but only to an extent, since sediment will mix on impact with the sea or shore. Additionally, the action of excavation would create pressure on the sediment (and the organisms within it) that is in and around the bucket.

Summary

INNS are **more likely** to survive discharge when:

- organisms are small**
- organisms are mobile
- organisms have a robust exterior
- organisms are regenerative
- organisms are benthic
- organisms have broad environmental tolerances
- discharge method is bottom dumping*

INNS are **less likely** to survive discharge when:

- organisms are large**
- organisms are sessile
- organisms have a fragile exterior
- organisms are not regenerative
- organisms have narrow environmental tolerances
- discharge method is pipeline, rainbowing or spray-pontoon*

(*denotes where the influence of a factor is difficult to derive due to data deficiency

**denotes where a quantified threshold is needed to determine the influence of a factor).

Table 5. Summary of the factors that influence the likelihood of Condition 5 "INNS survive discharge" being met. Factors have been assigned a "higher" or "lower" likelihood category where data allowed. Where the influence of a factor is difficult to derive due to data deficiency, this has been indicated. Where the identification of a quantified threshold is required to determine the influence of a factor, this has been indicated. The information in this table is based on a combination of data from scientific literature (see text for details) and the professional opinion of the authors of this review. Cells were left blank where the author considered column headings to be irrelevant. This is not an exhaustive list of factors and should be updated as more research is carried out to fill knowledge gaps. Some cells are left blank.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Site	Sediment type	Mud, sand, gravel			X		Impacts physical forces such as the degree of abrasive action and sediment weight which would probably impact mortality.
Organism	Organism characteristic	Large		X		X	More likely to be subject to blunt force. Less likely to separate from sediment as it descends to the seabed, thereby maximising exposure to turbidity and sedimentation
Organism	Organism characteristic	Small	X			X	Less likely to be subject to blunt force, and more likely to fit between interstitial spaces of sediment if small enough. More likely to separate from sediment as it descends to the seabed, thereby

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
							minimising exposure to turbidity and sedimentation.
Organism	Organism characteristic	Mobile	X				More likely to escape from sediment as it descends to seabed, thereby minimising exposure to turbidity and sedimentation.
Organism	Organism characteristic	Sessile		X			Less likely to escape from sediment as it descends to seabed, thereby minimising exposure to turbidity and sedimentation.
Organism	Organism characteristic	Robust exterior	X				More likely to tolerate physical forces and desiccation.
Organism	Organism characteristic	Fragile exterior		X			Less likely to tolerate physical forces and desiccation.
Organism	Organism characteristic	Regenerative	X				More likely to survive if fragmented.
Organism	Organism characteristic	Not regenerative		X			Less likely to survive if fragmented.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Organism	Organism characteristic	Benthic	X				More likely to survive turbidity and sedimentation.
Organism	Organism characteristic	Pelagic			X		Less likely to survive turbidity and sedimentation. More likely to survive since it may be able to separate from sediment as it descends to seabed.
Organism	Organism characteristic	Broad environmental tolerances	X				More likely to survive changes in environmental conditions.
Organism	Organism characteristic	Narrow environmental tolerances		X			Less likely to survive changes in environmental conditions.
Dredging process	Discharge method	Bottom dumping	X		X		More likely to survive due to it being a passive process driven by currents and gravity.
Dredging process	Discharge method	Pipeline, rainbowing, spray-pontoon		X	X		Less likely to survive due to forces imposed and sediment mixing.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Dredging process	Discharge method	Mechanical / excavation			X		More likely to survive due the lack of hydraulic pressure, although mortality could result from pressures in sediment caused by excavation and falling from the bucket, and sediment mixing is still likely.

7.3.2 Condition 6: INNS survive at disposal site

Influential factors: organism characteristics, the depth of the deposited sediment layer, the method of dredged material spread, and the habitat at the disposal site (outlined in more detail in the following text and summarised in Table 6).

The influences of organism characteristics and sediment type and likely to be similar to those discussed in Conditions 2, 3 and 4.

Sediment (and organisms) that has/have reached the seafloor at an offshore disposal site will typically have descended through at least several metres of water to the seabed, for instance the depth at the offshore disposal site called Inner Gabbard in the UK is about 55 m below CD (Cefas, 2022). Tidal currents can result in relatively shallow sediment mounds spread across a wide area (Smith & Rule, 2001), although most of the discharged sediment is usually deposited within c. 200 m of the release point (H. Bokuniewicz, 1985; H. J. Bokuniewicz & Gordon, 1980; Gordon, 1974). So called “dispersive” sites have a minimal impact on benthic community structure at the disposal site (Bolam et al., 2011; Roberts & Forrest, 1999; Smith & Rule, 2001). Such conditions would presumably also enhance the ability for organisms introduced in dredged sediment to become unburied, survive and spread, although no assessment of this could be found. Conversely, some disposal sites are less dispersive, resulting in large sediment piles accumulating in a relatively small area.

Burial on the seabed could result in organism mortality due to smothering and the consequent impediment to respiration and feeding, although this will depend on burial depth and the type of organism (Roberts et al., 1998, Bolam, 2010, Powell-Jennings & Callaway, 2018). Generally, the discharge of dredged material which creates a layer of sediment >15 cm in depth can prevent the migration of benthic species back to the sediment surface, although the exact depth threshold depends on the species (Roberts et al., 1998). In a laboratory experiment, 81.5% of slipper limpets (*Crepidula fornicata*) died after burial by 2-6 cm over a period of 2-30 days (Powell-Jennings & Callaway, 2018). The only individuals that emerged were buried under 2 cm of sediment: 7% emerged after 7 days and the remaining 15% after 20 days (Powell-Jennings & Callaway, 2018). Similarly, the polychaete worms *Tharyx* sp. and *Streblospio shrubsolii* showed poor vertical migration after burial by 6 cm of sediment over a four-day experimental period. Although, in the same study, the oligochaete worm *Tubificoides benedii* showed some vertical migration and the gastropod mollusc *Hydrobia ulvae* was able to recover completely from 16 cm of sediment (Bolam, 2010). Responses to burial are therefore species-specific and are dependent on a species’ mobility (some species are unable to move when adults – such as oysters), living position (in terms of sediment depth) and physiological tolerances (namely anoxia, typically below the first few cm of sediment)) (Bolam, 2010; Hinchey et al., 2006). Furthermore, recovery from burial is dependent on feeding method. Kranz (1972) (cited in Bolam et al. 2010) studied the burrowing of 30 species and concluded that “mucus feeders and labial palp feeders were the most susceptible to burial, followed by suspension feeders, none of which could cope with more than 1 cm of sediment overburden. Infaunal non-siphonate suspension feeders could cope with 5 cm while the most resistant, deep burrowing siphonate suspension feeders could escape from 50 cm of overburden".

The burial and smothering of the benthic community on the seabed can result in the increased abundance of taxa that were common at the dredged site, as observed by (Jones, 1986) (cited in Smith & Rule, 2001) (whether their numbers were enhanced by individuals that survived the dredging process is unclear). Similarly, sediment deposition can lead to a decrease in some taxa and an increase in the abundance of opportunistic taxa (De Grave & Whitaker, 1999; Harvey et al., 1998; Roberts et al., 1998). This is probably related to the typically broad environmental tolerances and high reproductive potential of opportunistic taxa (including INNS), facilitating survival and rapid recolonisation after mortality events (Sakai et al., 2001).

When dredged material is discharged along the coastline via various methods for beneficial use projects, large piles of dredged material often form as a result, but are then profiled by excavators and other land-based machinery. While the spreading of dredged material may uncover previously buried organisms, the mechanical action could cause mortality. Dredged material is also often moved above the high-water mark (e.g., for saltmarsh restoration) where sessile marine organisms would not survive. In contrast, dredged material discharged at offshore disposal sites would only be subject to natural forces (i.e. water currents).

The more similar the habitat of the dredging and disposal site, the more likely that organisms that are discharged with dredged material will survive. Both beneficial use and offshore disposal sites have the potential to have habitats that are similar or dissimilar to those at the dredging site – this would be determined by environmental factors such as salinity, temperature, sediment particle size, water depth, wave action and current velocity. Beneficial use sites are usually closer to the dredging site than offshore disposal sites and are therefore potentially more similar (Manning et al., 2021), although sediment used for beneficial use projects is often obtained from the subtidal and placed in the intertidal (Appendix 3). Additionally, as mentioned, dredged material is often moved above the high tide mark. In circumstances when the dredging and disposal sites are not similar, and dredged material is deposited below the high-water mark, INNS may still be able to survive at the disposal site if they have broad environmental tolerances (Sakai et al., 2001).

Summary

INNS are **more likely** to survive at the disposal site when:

- depth of deposited sediment layer on seabed is <15 cm
- habitat at disposal site is the same as the dredging site
- organisms have a robust exterior
- organisms are regenerative
- organisms are benthic
- organisms are mobile benthic species

- organisms are infaunal
- organisms have broad environmental tolerances
- method of dredged material spread uses mechanical forces*

INNS are **less likely** to survive at the disposal site when:

- depth of deposited sediment layer on seabed is >15 cm
- habitat at disposal site is different to the dredging site
- organisms have a fragile exterior
- organisms are not regenerative
- organisms are pelagic
- organisms are sessile benthic species
- organisms are epifaunal
- organisms have narrow environmental tolerances
- method of dredged material spread uses natural forces*

(*denotes where the influence of a factor is difficult to derive due to data deficiency).

Table 6. Summary of the factors that influence the likelihood of Condition 6 “INNS survive at disposal site” being met. Factors have been assigned a “higher” or “lower” likelihood category where data allowed. Where the influence of a factor was difficult to derive due to data deficiency, this has been indicated. Where the identification of a quantified threshold is required to determine the influence of a factor, this has been indicated. The information in this table is based on a combination of data from scientific literature (see text for details) and the professional opinion of the authors of this review. Cells were left blank where the author considered column headings to be irrelevant. This is not an exhaustive list of factors and should be updated as more research is carried out to fill knowledge gaps. Some cells are left blank.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Site	Depth of deposited sediment layer on seabed	<15 cm	X				More likely to survive due to lower likelihood of burial and negative effects.
Site	Depth of deposited sediment layer on seabed	>15 cm		X			Less likely to survive due to lower likelihood of burial and negative effects.
Site	Habitat at disposal site	Same as dredging site	X				More likely to survive as environmental tolerances are less likely to be breached.
Site	Habitat at disposal site	Different to dredging site		X			Less likely to survive as environmental tolerances are more likely to be breached.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Organism	Organism characteristic	Robust exterior	X				More likely to tolerate physical forces and desiccation.
Organism	Organism characteristic	Fragile exterior		X			Less likely to tolerate physical forces and desiccation.
Organism	Organism characteristic	Regenerative	X				More likely to survive if fragmented.
Organism	Organism characteristic	Not regenerative		X			Less likely to survive if fragmented.
Organism	Organism characteristic	Benthic	X				More likely to survive turbidity and sedimentation.
Organism	Organism characteristic	Pelagic		X			Less likely to survive turbidity and sedimentation. Less likely to recover from burial due to a lack of adaptation to burial.
Organism	Organism characteristic	Mobile benthic species	X				More likely to recover from burial because they can move.
Organism	Organism characteristic	Sessile benthic species		X			Less likely to recover from burial because they cannot move.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Organism	Organism characteristic	Epifaunal		X			Less likely to recover from burial due to a lack of adaptation to burial.
Organism	Organism characteristic	Infaunal	X				More likely to recover from burial due to adaptation to burial.
Organism	Organism characteristic	Broad environmental tolerances	X				More likely to survive (if environmental conditions are different to the dredging site).
Organism	Organism characteristic	Narrow environmental tolerances		X			Less likely to survive (if environmental conditions are different to the dredging site).
Dredging process	Method of dredged material spread	Mechanical forces		X	X		Less likely to survive due to mechanical forces.
Dredging process	Method of dredged material spread	Natural forces	X		X		More likely to survive due to natural forces (i.e., currents, gravity).

7.3.3 Condition 7: INNS establish at disposal site

Influential factors: organism characteristics, the habitat at the disposal site, and discharged sediment volume (outlined in more detail in the following text and summarised in INNS are **more likely** to establish at the disposal site when:

- habitat at the disposal site is the same as the dredging site
- organism reproduces asexually
- organism self-fertilises
- discharged sediment volume is high**

INNS are **less likely** to establish at the disposal site when:

- habitat at the disposal site is different to the dredging site
- organism reproduces sexually
- organism cross-fertilises
- discharged sediment volume is low**

(**denotes where a quantified threshold is needed to determine the influence of a factor).

Table 7).

Specific environmental conditions are required for marine organisms to reproduce (e.g., Steen 2004). Therefore, if a mature INNS survives at the disposal site, it may not be able to produce gametes. If a mature INNS does produce gametes, they will not necessarily reach maturity since juvenile forms of organisms often have narrower environmental tolerances (Steen 2004; Nishizaki and Ackerman, 2019). Organisms that can reproduce asexually may be most likely to establish at a disposal site since more vulnerable juvenile stages are not produced. Additionally, asexual reproduction does not rely on the presence of conspecifics, so new colonies can be created from one individual. This is also true for species which can self-fertilise. Conversely, sexual reproduction and cross-fertilisation requires individuals of both sexes, at a particular density threshold, so that reproduction can be successful (i.e., eggs and sperm are present and are likely to meet) (Blackburn et al., 2015).

Offshore disposal typically involves the dredging and transport of large volumes of dredged material (Appendix 3). This could result in higher numbers of mature individuals arriving at a location. The higher the number of individuals, the higher the likelihood of population establishment (Blackburn et al., 2015). Conversely, beneficial use projects often involve smaller volumes of dredged material (Manning et al., 2021, Appendix 3) which could result in the opposite of the above scenario, although an assessment of this could not be found.

Summary

INNS are **more likely** to establish at the disposal site when:

- habitat at the disposal site is the same as the dredging site
- organism reproduces asexually
- organism self-fertilises
- discharged sediment volume is high**

INNS are **less likely** to establish at the disposal site when:

- habitat at the disposal site is different to the dredging site
- organism reproduces sexually
- organism cross-fertilises
- discharged sediment volume is low**

(**denotes where a quantified threshold is needed to determine the influence of a factor).

Table 7. Summary of the factors that influence the likelihood of Condition 7 "INNS establish at disposal site" being met. Factors have been assigned a "higher" or "lower" or likelihood category where data allowed. Where the influence of a factor was difficult to derive due to data deficiency, this has been indicated. Where the identification of a quantified threshold is required to determine the influence of a factor, this has been indicated. The information in this table is based on a combination of data from scientific literature (see text for details) and the professional opinion of the authors of this review. Cells were left blank where the author considered column headings to be irrelevant. This is not an exhaustive list of factors and should be updated as more research is carried out to fill knowledge gaps. Some cells are left blank.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Site	Habitat at disposal site	Same as dredging site	X				More likely to survive as environmental tolerances (with regards to reproduction) are less likely to be breached.
Site	Habitat at disposal site	Different to dredging site		X			Less likely to survive as environmental tolerances (with regards to reproduction) are more likely to be breached.
Organism	Organism characteristic	Reproduces asexually	X				More likely to be able to reproduce because no other individuals are needed.
Organism	Organism characteristic	Reproduces sexually		X			Less likely to be able to reproduce because multiple individuals are needed at a certain threshold density.

Factor type	Factor	Factor detail	Higher likelihood	Lower likelihood	Data deficient	Requires quantified threshold	Justification
Organism	Organism characteristic	Self-fertilises	X				More likely to be able to reproduce because no other individuals are needed (although this is not always the case).
Organism	Organism characteristic	Cross-fertilises		X			Less likely to be able to reproduce because multiple individuals are needed at a certain threshold density.
Dredging process	Discharged sediment volume	High	X			X	More likely to establish due to higher propagule pressure.
Dredging process	Discharged sediment volume	Low		X		X	Less likely to establish due to lower propagule pressure.

8 Contextualisation of the conditions assessment

The dredging pathway Conditions Assessment (Section 7) can be used to explore if a scenario is more, or less, likely to introduce INNS to a disposal site (by considering site and dredging process factors). The assessment can also be used to explore the likelihood of introducing a specific INNS by considering its characteristics. It is important to note that in many instances the influence of a factor is difficult to derive due to data deficiency (denoted by *) and/or the need to quantify a threshold (denoted by **), as outlined in Tables 1-7. Example assessments are provided below as two case studies focused on scenarios with mature slipper limpets, these are provided for demonstration purposes only to present the thought process behind an assessment using Conditions 2-7.

8.1 Case study 1

8.1.1 Site

The dredging site is a coastal, subtidal marina, with typical seawater salinity (approximately 35 ppt), where sediment must be frequently removed to maintain the required depth for boat access. At the dredging site there is recreational boating, marina infrastructure and moderate levels of pollution. The dredged material is muddy and will be discharged at a dispersive offshore disposal site, which has typical seawater salinity, forming a deposited sediment layer of <15 cm deep. At this location, a large volume of dredged material will be discharged in water that is 40 m deep, which is deeper than the water at the dredging site.

8.1.2 Dredging process

A large area of seabed is to be dredged. A BHD (mechanical) dredger will be used to remove the sediment which will include upper layers of the seabed (<15 cm depth), although it will mostly comprise deeper layers. The water content of the dredged material is expected to be high due to it being muddy (water will not easily drain from the sediment), although water levels will be lower than if a hydraulic dredger was used. The dredged sediment will be transported by a large barge with a hopper over a long transit time (3 hours). This relatively large volume of dredged material will be discharged via bottom dumping from the barge and be dispersed by natural forces at the disposal site.

8.1.3 Organism

The slipper limpet (Section 3) has been detected within the wider area of the dredging site. It has a robust shell and is relatively large, growing 40-50 mm in length, and forming stacks approximately 10-15 mm high. It has broad environmental tolerances, and it is an intertidal and subtidal, benthic, sessile, epifaunal INNS which cannot regenerate if fragmented. It reproduces sexually and cross-fertilises to produce gametes.

8.1.4 Conditions assessment

Condition 1: INNS are present at the dredging site?

Factors increasing the likelihood of the condition being met

The site has pathways present which are likely to have introduced INNS. Additionally, artificial substrates are present, anthropogenic disturbance is medium**, and dredging frequency is medium** facilitating the presence and establishment of INNS, including the slipper limpet.

Conclusion

It is likely that Condition 1 will be met.

Condition 2: the slipper limpet would be entrained?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to be entrained because it is sessile and so cannot escape entrainment by the bucket of the BHD. Additionally, the area of the seabed being dredged is large**, and the dredged sediment will include top layers (upper 15 cm) of the seabed where slipper limpets can be found.

Factors with uncertain or unlikely influence

The effect of the use of a mechanical dredger* is difficult to determine due to a lack of research. It is possible that top layers of sediment and therefore the slipper limpet would be lost as the bucket is raised, although some slipper limpets may be retained.

The slipper limpet it is relatively large** and is therefore unlikely to pass through any filters, however, it is unlikely that filters are being used in this scenario due to the use of a mechanical dredger.

Conclusion

It is likely that Condition 2 would be met.

Condition 3: the slipper limpet would survive entrainment?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to survive entrainment, due to its hard, robust exterior protecting it from physical impact. Also, the slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded, and its benthic living position means it is likely to survive any turbidity and sedimentation generated by the entrainment process.

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to survive entrainment because it is relatively large** and is therefore likely to be subject to blunt force during the excavation and deposition of material. The slipper limpet also lacks the ability to regenerate if fragmented.

Factors with uncertain or unlikely influence

The effect of the muddy substrate* and use of a mechanical dredger* is difficult to determine due to a lack of research. Both factors are likely to impact the amount of abrasion and other physical forces exerted on the slipper limpet as it falls from the bucket of the dredger and contacts the hopper/hopper contents.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper limpet would be exposed to during entrainment, are required to determine if Condition 3 would be met.

Condition 4: the slipper limpet would survive transfer?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to survive transfer, due to its hard, robust exterior protecting it from crushing forces which it could be subject to if buried. The slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded. Also, its benthic living position and intertidal (and subtidal) habitat means it is likely to survive any turbidity, sedimentation, and lack of water resulting from the transfer process. Additionally, water content of the dredged material will be high** due to the substrate being muddy, thereby reducing the likelihood of desiccation and oxygen starvation (although deeper sediment layers may have less water due to crushing pressure from upper layers, forcing it to rise).

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to survive transfer because all methods of transfer* are likely to be stressful for the slipper limpet due to physical impact and/or an altered environment. The transit time will be long**, maximising the time the slipper limpet is exposed to any detrimental conditions. Also, the dredged material volume in the hopper will be high** and the dredged material will comprise mostly sediment from >15 cm below the seabed surface, with both factors increasing the likelihood of burial. The high volume of dredged material in the hopper will also enhance the amount of pressure imposed on slipper limpets in deeper layers (assuming higher volumes are correlated with deeper depths).

Factors with uncertain or unlikely influence

The slipper limpet is relatively large** and so likely to be subject to blunt force, and it lacks the ability to regenerate if fragmented. However physical impact arising from motion is unlikely due to the lack of suction forces.

The effect of the muddy substrate* is difficult to determine due to a lack of research but is likely to impact the physical forces exerted on the slipper limpet.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper would be exposed to during transfer, are required to determine if Condition 4 would be met.

It is important to note that the slipper limpet could be released into the environment via accidental spillage during the transfer stage. Although, as outlined previously (Section 7.2.1), spillage is deemed to be a minimal risk.

Condition 5: the slipper limpet would survive discharge?

Factors increasing the likelihood of the condition being met

The slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded, and its benthic living position means it is likely to survive any turbidity and sedimentation generated by the entrainment process. Bottom dumping* of the dredged material may also facilitate survival due it being a relatively passive process, unlikely to cause physical impact.

Factors with uncertain or unlikely influence

The slipper limpet has a hard, robust exterior protecting it from physical impact. Conversely, the slipper limpet it is relatively large** and therefore more likely to be subject to blunt force, and it lacks the ability to regenerate if fragmented. However, since bottom dumping* is a relatively passive process, none of these factors may be influential.

The effect of the muddy substrate* is difficult to determine due to a lack of research but it is likely to impact the amount of abrasion and other physical forces exerted on the slipper limpet as the dredged material is discharged.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper would be exposed to during discharge, are required to determine if Condition 5 would be met.

Condition 6: the slipper limpet would survive at the disposal site?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to survive at the disposal site because it is a benthic species and therefore likely to survive turbidity and sedimentation. Also, the slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded. Specifically, the salinity and water depth at the disposal site is suitable for slipper limpet survival. Furthermore, the slipper limpet has a hard, robust exterior, and dredged material will be dispersed by natural forces*, limiting the physical stresses imposed on the slipper limpet.

Factors with uncertain or unlikely influence

The slipper limpet is a sessile benthic species, and epifaunal, so it is unlikely to recover from burial, especially if buried >2 cm deep (Powell-Jennings & Callaway, 2018). Although considering the shallow deposited layer (<15 cm), some slipper limpets could end up on top of the deposited sediment, so these factors may have minimal influence.

The slipper limpet cannot regenerate if fragmented. However, since bottom dumping is a relatively passive process, fragmentation is unlikely.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper limpet would be exposed to at the disposal site, are required to determine if Condition 6 would be met.

Condition 7: the slipper limpet would establish at the disposal site?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to establish at the disposal site because the discharged sediment volume is high**, resulting in high propagule pressure.

Factors with uncertain or unlikely influence

The slipper limpet has broad environmental tolerances with regards to survival, although tolerances with regards to reproduction are typically narrower. More information would be required with regards to the environmental conditions at the disposal site to determine if the slipper limpet could reproduce.

The slipper limpet reproduces sexually and cross-fertilises, reducing the likelihood of reproduction. However, if a large number of slipper limpets were introduced to the site due to the high volume of discharged sediment, this will not be an inhibitory factor.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper limpet would be exposed to at the disposal site, are required to determine if Condition 7 would be met.

8.2 Case study 2

8.2.1 Site

The dredging site is an estuarine subtidal shipping channel, with typical seawater salinity, where sediment must be very frequently removed to maintain the required depth for ship transit. At the dredging site there is recreational boating, port and marina infrastructure nearby, and high levels of pollution. The dredged material is muddy and will be discharged at a coastal beneficial use site, with typical seawater salinity, forming a deposited sediment layer of >15 cm deep. At this location, the small volume of dredged material will be discharged in the intertidal.

8.2.2 Dredging process

A small area of seabed is to be dredged for the beneficial use project (as part of a larger operation involving offshore disposal that will not be considered here). A TSHD (hydraulic) dredger fitted with a grill on the draghead will be used to remove the sediment which will comprise upper layers of the seabed (<15 cm depth), although it will mostly comprise deeper layers. The water content of the dredged material is expected to be high due to it being muddy (water will not easily drain from the sediment) and hydraulicly dredged. The dredged sediment will be transported in the hopper of the TSHD over a short transit time (0.5 hours). The relatively small volume of dredged material will be discharged via rainbowing from the TSHD. Diggers and other machinery will be used to spread the dredged material at the disposal site to create the desired profile for habitat creation.

8.2.3 Organism

The slipper limpet (Section 3) has been detected within the wider area of the dredging site. It has a robust shell and is relatively large, growing 40-50 mm in length, and forming stacks approximately 10-15 mm high. It has broad environmental tolerances and is an intertidal and subtidal, benthic, sessile, epifaunal INNS which cannot regenerate if fragmented. It reproduces sexually and cross-fertilises to produce gametes.

8.2.4 Conditions assessment

Condition 1: INNS are present at the dredging site?

Factors increasing the likelihood of the condition being met

The site has introductory pathways present which are likely to have introduced INNS. Additionally, artificial substrates are present, facilitating the presence and establishment of INNS, including the slipper limpet.

Factors decreasing the likelihood of the condition being met

The slipper limpet and other INNS are unlikely to be present because anthropogenic disturbance is high**, and dredging frequency is high**, potentially inhibiting the survival and establishment of any organisms.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions are required to determine if Condition 1 would be met.

Condition 2: the slipper limpet would be entrained?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to be entrained because it is sessile and so cannot escape entrainment by the draghead of the TSHD. Additionally, the dredged sediment will include top layers (upper 15 cm) of the seabed and therefore include the surface where slipper limpets can be found, increasing the likelihood of entrainment.

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to be entrained because the area of the seabed being dredged is small**.

Factors with uncertain or unlikely influence

The slipper limpet is relatively large** and there is a grill on the draghead of the hydraulic dredger which may prevent entry into the section tube. However, whether the slipper limpet passes through the grill depends on the size of the slipper limpet individuals and stacks, the size of the grill being used, the orientation at which the slipper limpets hit the grill, and if the grill becomes partially blocked by larger components of sediment (cobbles and pebbles).

Conclusion

More information regarding factor influences, thresholds, weightings and interactions are required to determine if Condition 2 would be met.

Condition 3: the slipper limpet would survive entrainment?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to survive entrainment, due to its hard, robust exterior protecting it from physical impact. Also, its benthic living position means it is likely to survive any turbidity and sedimentation generated by the entrainment process.

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to survive entrainment because it is relatively large** and is therefore likely to be subject to blunt force. The slipper limpet also lacks the ability to regenerate if fragmented. Use of the hydraulic dredger will increase the chance of blunt force and fragmentation due to suction forces.

Factors with uncertain or unlikely influence

While the slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded, the hydraulic dredge is likely to generate very different conditions to those on the seabed due to suction forces and high levels of sediment mixing, thereby potentially pushing its tolerances to the limit.

The effect of the muddy substrate* and use of a mechanical dredger* is difficult to determine due to a lack of research. Both factors are likely to impact the amount of abrasion and other physical forces exerted on the slipper limpet.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper would be exposed to during entrainment, are required to determine if Condition 3 would be met.

Condition 4: the slipper limpet would survive transfer?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to survive transfer due to its benthic living position and intertidal (and subtidal) habitat which means it is likely to survive any turbidity, sedimentation, and lack of water resulting from the transfer process. Also, the slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded. Furthermore, water content of the dredged material will be high** due to the substrate being muddy and use of the hydraulic dredger, thereby reducing the likelihood of desiccation and oxygen starvation (although deeper sediment layers may have less water due to crushing pressure from upper layers, forcing it to rise). The transit time will be short**, minimising the time the slipper limpet is exposed to any detrimental conditions.

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to survive transfer because all methods of transfer* are likely to be stressful for the slipper limpet due to physical impact and/or an altered environment.

Factors with uncertain or unlikely influence

The dredged material will comprise mostly sediment from >15 cm below the seabed surface, increasing the likelihood of burial. Conversely, the dredged material volume in the hopper will be low*, minimising the likelihood of burial and amount of crushing pressure imposed on slipper limpets in deeper layers (assuming lower volumes are correlated with shallower depths). Additionally, the slipper limpet has a hard, robust exterior protecting it from crushing pressure which it could be subject to if buried.

The slipper limpet is relatively large** and so likely to be subject to blunt force, and it lacks the ability to regenerate if fragmented. However physical impact arising from motion is unlikely due to the lack of suction forces during transfer.

The effect of the muddy substrate* is difficult to determine due to a lack of research but is likely to impact the amount of physical force exerted on the slipper limpet.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper limpet would be exposed to during transfer, are required to determine if Condition 4 would be met.

It is possible that the slipper limpet is released into the environment via accidental spillage during the transfer stage. Although, as outlined previously (Section 7.2.1), spillage is deemed to be a minimal risk.

Condition 5: the slipper limpet would survive discharge?

Factors increasing the likelihood of the condition being met

The slipper limpet's benthic living position means it is likely to survive any turbidity and sedimentation generated by the discharge process. Also, it has a hard, robust exterior protecting it from physical impact.

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to survive discharge because it is relatively large** and therefore more likely to be subject to blunt force, and it lacks the ability to regenerate if fragmented. The likelihood of blunt force impact and fragmentation can be considered relatively high due to the hydraulic rainbowing method.

Factors with uncertain or unlikely influence

The slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded. However, since the environmental conditions generated by rainbowing are largely unknown, the environmental tolerance limits of the slipper limpet may still be breached.

The effect of the muddy substrate* is difficult to determine due to a lack of research but is likely to impact the amount of abrasion and other physical forces exerted on the slipper limpet.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper limpet would be exposed to during discharge, are required to determine if Condition 5 would be met.

Condition 6: the slipper limpet would survive at the disposal site?

Factors increasing the likelihood of the condition being met

The slipper limpet is likely to survive at the disposal site because it is a benthic species and therefore likely to survive turbidity and sedimentation. Also, the slipper limpet has broad environmental tolerances, meaning these tolerances are unlikely to be exceeded. Specifically, the salinity and water depth at the disposal site is suitable for slipper limpet survival.

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to survive at the disposal site because it is a sessile benthic species, and epifaunal, so it is unlikely to recover from burial, especially if buried >2 cm deep (Powell-Jennings & Callaway, 2018). Burial is likely considering the deep deposited layer (> 15 cm).

Factors with uncertain or potential no influence

Physical force* will be used to profile the dredged material at the disposal site, so physical stresses are likely, and the slipper limpet cannot regenerate if fragmented. Although considering the slipper limpet has a hard robust exterior it may be protected from physical force.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper limpet would be exposed to at the disposal site, are required to determine if Condition 6 would be met.

Condition 7: the slipper limpet would establish at the disposal site?

Factors decreasing the likelihood of the condition being met

The slipper limpet is unlikely to establish at the disposal site because the habitat is different to that at the dredging site due to deeper water, so its environmental tolerances regarding reproduction (which are often narrower than those regarding survival) are likely to be exceeded. Also, the slipper limpet reproduces sexually and cross-fertilises, reducing the likelihood of reproduction. Finally, the discharged sediment volume is low**, resulting in low propagule pressure.

Conclusion

More information regarding factor influences, thresholds, weightings and interactions, and the environmental conditions the slipper limpet would be exposed to at the disposal site, are required to determine if Condition 7 would be met.

8.3 Organism influence

The likelihood of a condition being met will vary depending on the organism (i.e., the species and its life stage). Additionally, every organism is likely to have a selection of characteristics that both increase and decrease the chance of a condition being met. These statements are evidenced in Table 8 which shows the relevant organism characteristics and their influence on each condition, for mature slipper limpets (*Crepdidula fornicata*), mature carpet sea squirts (*Didemnum vexillum*), mature chinese mitten crabs (*Eriocheir sinensis*), mature wireweed (*Sargassum muticum*), and the pelagic larvae / gametes of these species. Condition 1 (INNS are present at the dredging site) is not applicable to this assessment because it is already assumed the relevant organism is present at the dredging site. As a result of the lack of current evidence, interactions between factors and the magnitude of their respective influence has not been accounted for.

Table 8. A summary of the organism characteristics and their influence on Conditions 2-7 being met, for mature slipper limpets (*Crepdidula fornicata*), mature carpet sea squirts (*Didemnum vexillum*), mature chinese mitten crabs (*Eriocheir sinensis*), mature wireweed (*Sargassum muticum*), and the pelagic larvae / gametes of these species. Condition 1 (INNS are present at the dredging site) is not applicable because it is already assumed the relevant organism is present at the dredging site. An increase or decrease in the likelihood of the relevant condition being met is indicated by "+" and "-" respectively.

Species	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6	Condition 7
Slipper limpet: mature	**-** large **+** sessile	**-** large **+** robust exterior **-** not regenerative **+** benthic **+** broad environmental tolerances	**-** large **+** robust exterior **-** not regenerative **+** benthic **+** intertidal (and subtidal) **+** broad environmental tolerances	**-** large **-** sessile **+** robust exterior **-** not regenerative **+** benthic **+** broad environmental tolerances	**+** robust exterior **-** not regenerative **+** benthic **-** sessile benthic species **-** epifaunal **+** broad environmental tolerances	**-** reproduces sexually **-** cross-fertilises

Species	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6	Condition 7
Carpet sea squirt: mature	+ small (fragments) + sessile	+ small (fragments) + robust exterior + regenerative + benthic + broad environmental tolerances	+ small (fragments) - fragile exterior + regenerative + benthic + intertidal (and subtidal) + broad environmental tolerances	+ small (fragments) - sessile - fragile exterior + regenerative + benthic + broad environmental tolerances	+ robust exterior + regenerative + benthic - sessile benthic species - epifaunal + broad environmental tolerances	+ reproduces asexually
Chinese mitten crab: mature	- large - mobile	- large + robust exterior - not regenerative + benthic + broad environmental tolerances	- large + robust exterior - not regenerative + benthic + intertidal (and subtidal) + broad environmental tolerances	- large + mobile + robust exterior - not regenerative + benthic + broad environmental tolerances	+ robust exterior - not regenerative + benthic + mobile benthic species - epifaunal + broad environmental tolerances	- reproduces sexually - cross-fertilises
Wireweed: mature	+ small (fragments) + sessile	+ small (fragments) + robust exterior + regenerative + benthic + broad environmental tolerances	+ small (fragments) + robust exterior + regenerative + benthic + intertidal (and subtidal) + broad environmental tolerances	+ small (fragments) - sessile + robust exterior + regenerative + benthic + broad environmental tolerances	+ robust exterior + regenerative + benthic - sessile benthic species - epifaunal + broad environmental tolerances	+ reproduces asexually + self-fertilises

Species	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6	Condition 7
Pelagic larvae / gametes	**+** small **+** (relatively) sessile	**+** small **-** fragile exterior **-** not regenerative **-** pelagic **-** narrow environmental tolerances	**+** small **-** fragile exterior **-** not regenerative **-** pelagic **-** narrow environmental tolerances	**+** small **-** sessile (relatively) **-** fragile exterior **-** not regenerative **-** narrow environmental tolerances	**-** fragile exterior **-** not regenerative **-** pelagic **-** narrow environmental tolerances	N/A – larvae and gametes cannot reproduce, although could develop into sexually mature individuals.

9 Conditions assessment summary

In summary, the Conditions Assessment (Section 7) and the contextualisation of the assessment (Section 8) concludes that **the transfer of INNS from a dredging site to a disposal site, via the movement of dredged material, is an unlikely pathway of introduction in most scenarios.** This is because of:

1) the numerous influential factors (relating to the dredging process, site and organism) which facilitate and/or inhibit this potential pathway, and;

2) the unlikely circumstance that all seven gated conditions outlined in this document would be met.

However, there are many knowledge gaps that must be filled to increase the certainty of this conclusion and to enable a quantified assessment which would help to assign risk values (Tables 1-7). Therefore, it is important to acknowledge that the successful transfer of INNS via the dredged material pathway could be possible in some scenarios, albeit probably few. Considering this, a precautionary approach to mitigating any potential feasible risk is recommended which compliments existing biosecurity approaches and further facilitates compliance with licensing and legislative requirements.

10 General conclusions and recommendations

10.1 Potential next steps

10.1.1 Biosecurity plan requirement

Legislation requires that the environmental impacts from dredging need to be considered for dredging operations to be permitted (a full list of conventions, regional directives and national legislation that must be adhered to when carrying out an activity that could introduce and/or spread INNS in England is listed in Appendix 4). Since INNS have the potential to cause environmental impacts, the risk of transferring them to dredging sites and to disposal sites should be assessed, i.e. a biosecurity plan should be produced which includes potential mitigation measures. However, a requirement to produce a biosecurity plan is not explicitly outlined in marine licensing guidance in England (Appendix 4). Therefore, it is recommended that a similar biosecurity planning approach to that adopted in Wales is considered. In Wales, the creation of a biosecurity plan is mandatory for dredge and/or disposal licence applications, unless the activity is exempt (NRW, 2023). Exemptions could be identified based on lower risk factors, where/when enough data is available to justify this.

10.1.2 Biosecurity plan guidance

While there are clearly legislative drivers and an awareness of INNS and biosecurity within the navigational dredging industry (personal communication), a standardised biosecurity approach to: 1) the movement of vessels and equipment to the disposal site, and 2) the movement of vessels, equipment and dredged material from the dredge site to the disposal site, could not be identified. This is probably due to a lack of openly accessible, tailored guidance. General good practice guidance for England and Wales on how to create a marine biosecurity plan is outlined in Payne et al., 2015 (edited by Natural England and Natural Resources Wales). Further general marine biosecurity planning advice and resources are provided by the Great British Non-native Species Secretariat (GBNNSS) (GBNNSS, 2024). These resources are linked to from an advice page produced by the EA on how to comply with The Water Environment (Water Framework Directive) Regulations (WER) regulations in England, with respect to a marine licence application (Environment Agency, 2023).

An example of tailored biosecurity guidance from a similar industry sector, is the biosecurity form with accompanying guidance that has been created by ABPmer for the British Marine Aggregate Producers Association (BMAPA) (ABPmer, 2018a) which was catalysed by a marine licence requirement for aggregate dredging in the Bristol Channel (ABPmer, 2018b) where both Welsh and English licence requirements apply. Within the guidance document, dredged material is acknowledged as a potential vector. The guidance includes how to assign a risk rating score of “1”, “2” or “3” to the likelihood of introduction (reflective of “very unlikely”, “possible” and “very likely). Example conditions include habitat suitability and frequency of vessel activity. Potential mitigation and control measures are identified for ballast sediment, hopper water, biofouling, residual cargoes, hopper washing and spoil cargoes.

Since the creation of a biosecurity plan is mandatory for dredge and/or disposal licence applications in Wales (unless exempt) (NRW, 2023), Natural Resources Wales has produced a biosecurity plan form (NRW, 2024b) and guidance (NRW, 2024a) which could be used to inform the development of similar documents for licensing applications in England. A specific category for “B.2 assessing pathway risks associated with the transfer of non-biological material and water” is included in the guidance which covers sediment transfer. Risk levels in relation to the probability of transporting INNS between locations are “high”, “medium” and “low”, which is influenced by presence/absence of INNS at the dredging site, transit time and environmental conditions of dredging and disposal sites. Suggested management (mitigation and control) measures could not be found within the guidance (NRW, 2024a).

In summary, more tailored, widely accessible guidance should be created for assessing the potential introduction of INNS to the dredging site, and from the dredging site to the disposal site. To achieve this, existing guidance produced by the marine aggregate sector and Natural Resource Wales should be considered. Guidance should outline that the movement of dredged material must be acknowledged as a potential pathway for INNS introduction and spread. Where possible, the factors that have been outlined in this review should be used to assess the potential risk of INNS being introduced and spread via dredged material. To aid this approach, a risk assessment tool could be created. However, as outlined in this review, current knowledge gaps and a lack of quantified thresholds make this challenging. In combination with the production and dissemination of biosecurity guidance, efforts should be made to raise general awareness of INNS and biosecurity, to facilitate the understanding and implementation of biosecurity actions.

10.1.3 Research and development

The Conditions Assessment (Section 7) and its contextualisation (Section 8) highlighted that with respect to a specific dredging operation, it is likely that there will always be a mix of site and dredging process factors that could result in a higher or lower likelihood of INNS being introduced. Similarly, most if not all, marine INNS will have a mixture of characteristics that could result in a higher or lower likelihood of survival during the dredging process, so it is a challenge to identify INNS that are more or less likely to survive, and therefore be moved. The creation of an accessible tool should be explored to help biosecurity planners determine the risk of INNS being introduced via dredged material, with regards to a specific dredging operation. The Conditions Assessment (Section 7) within this document should be used as a framework for such a tool. Where possible, the tool would need to account for gated conditions, thresholds of factor influence, factor weightings (magnitude of influence) and interactions between factors. The tool could produce a risk score that can be used to determine the level of biosecurity action required.

To maximise the effectiveness of such a tool, and a general understanding of the potential INNS pathway risk dredged material presents, substantially more research is required. Topics, that if more thoroughly researched would help to determine pathway risk, include the impact of:

- Dredger type on INNS being entrained.
- Sediment type and dredger type on INNS surviving entrainment.
- Sediment type and transfer methods on INNS surviving transfer.
- Sediment type, pelagic organisms, and discharge method on INNS surviving discharge.
- Method of dredged material spread on INNS surviving at the disposal site.

Additionally, the identification of quantifiable thresholds is required regarding the impact of:

- Dredging frequency on INNS presence at the dredging site.
- Anthropogenic disturbance on INNS presence at the dredging site.
- Organism size on INNS being entrained and surviving the entrainment, transfer and discharge.
- Water content of dredged material, volume of dredged material in the hopper and transit time on INNS surviving transfer.
- Discharged sediment volume on INNS establishing at the disposal site.

To determine if specific INNS are more or less likely to survive the movement of dredged material, the environmental conditions that INNS are exposed to during the whole dredging process need to be identified. These environmental conditions should include water content, salinity and physical forces. If these are determined, then they can be compared with the environmental tolerances of particular INNS to help predict their likelihood of survival.

10.1.4 Mitigatory actions

Identifying and implementing mitigatory actions are an essential part of a biosecurity plan. Mitigatory actions to address the risks posed by vessel ballast water (The Merchant Shipping Regulations 2022), hull fouling (IMO Biofouling Guidelines (IMO, 2023)) and hopper water (ABPmer, 2018a) are apparent, although evidence of broad-scale implementation of these across England was difficult to obtain. A wider survey within industry to determine this could be undertaken. Although, considering the high degree of awareness regarding these vectors within the industry, and the business risk that introducing INNS presents (personal communication), broad-scale implementation of these measures is highly likely.

Dredging equipment is typically cleaned between dredging operations (personal communication), although the extent to which it is cleaned, how it is cleaned, and how often it is cleaned was difficult to identify. While equipment is sometimes flushed with seawater (personal communication), this would not ensure that INNS are removed or killed. Additionally, structurally complex and enclosed pieces of equipment (e.g., dragheads/cutterheads, suction tubes, pumps) may be difficult to thoroughly clean. Research into current and potentially improved methods of equipment cleaning should be considered. The inspection of equipment for INNS should be included in biosecurity plans and potentially combined with any general maintenance inspections to maximise time efficiency.

No current international mitigation measures with regards to the movement of dredged material could be identified (personal communication), most likely because the potential risk this vector presents is largely unknown. However, some practices may inadvertently reduce this risk. For instance, sometimes deeper, thicker layers of sediment are hydraulically dredged that lie beneath the more fluid surface layers, which may reduce the likelihood of entrainment (personal communication). Additionally, some methods, such as hydraulic dredging, may enhance sediment mixing and therefore promote the exposure of INNS to adverse conditions. Potential mitigation measures should be based around reducing the likelihood of INNS:

Being present (Condition 1)

- Ensure robust general biosecurity practices are carried out at the dredging site.
- Carry out dredging during times when INNS are naturally less abundant, with respect to both mature and immature forms.

Being entrained (Condition 2)

- Use a mesh as fine as possible on equipment to filter out larger INNS.
- Use methods and technologies that reduce the need for hydraulic or mechanical dredging, such as anti-sedimentation structures, remobilising sediment systems and sand by-passing plants (Bianchini et al. 2019; Spearman, and Benson, 2022).
- Target deeper layers of sediment (>15 cm below seabed surface) when using a hydraulic dredge to avoid dredging sediment that may contain INNS.

Surviving entertainment and transfer (Conditions 3 and 4)

- Use the maximum possible pumping velocity to increase the degree of physical forces and abrasive action exerted on INNS.
- Enhance the mixing of sediment to promote exposure of INNS to adverse conditions (e.g., reduced oxygen, changes in nutrient levels, and the resuspension of toxic chemicals such as heavy metals).
- Treat the sediment to expose INNS to conditions that exceed their environmental tolerances (e.g., with freshwater, heat, vibration, or ultraviolet light).
- Bury upper sediment layers (particularly the upper 15 cm) with deeper sediment layers in the hopper to smother and crush INNS.
- Extend dredged material transfer times to prolong the exposure of INNS to detrimental conditions.

Surviving discharge (Condition 5)

- Use hydraulic methods such as pipeline, rainbowing, and spray-pontoon discharge to increase the degree of physical forces and abrasive action exerted on INNS.
- Use the maximum possible pumping velocity to increase the degree of physical forces and abrasive action exerted on INNS.

Surviving and establishing at the disposal site (Conditions 6 and 7)

- Deposit sediment from lower layers of the seabed on top of sediment from upper layers of the seabed to maximise burial of INNS.
- Deposit dredged material in layers >15 cm deep to maximise burial of INNS.
- Dispose of dredged material at a site with a different habitat to the dredging site to exceed the environmental tolerances of INNS.
- Maximise the mechanical forces used to move and profile the deposited material at the disposal site to increase the chance of injury to INNS.
- Discharge low sediment volumes to lower INNS propagule pressure (although this conflicts with ensuring maximising INNS burial).
- If using dredged material for beneficial use, place the sediment above the high-water mark and allow to dry out before using it in the intertidal or subtidal. This will desiccate INNS. (Note: Drying times will be dependent on many factors such as substrate type and sediment depth and could take several weeks).

Research will need to be conducted to determine if any of these mitigation measures would be effective and work in practice. It is likely that the practical and logistical constraints of dredging operations would mean some measures are not possible to implement. Effectiveness is also likely to vary depending on the INNS. It should also be noted that with respect to Conditions 1-7, mitigation for later conditions may not be required if earlier conditions are mitigated and proven to be effective.

10.1.5 Monitoring

Monitoring of INNS presence and abundance at the dredging site and disposal site is an essential part of a biosecurity plan. It facilitates the ability to assess the risk of introduction of INNS, and ensures a rapid response if INNS are introduced. Regarding the former, if there are no INNS present at the dredging site, then Condition 1 is not met, and INNS introduction can be considered as low risk.

Monitoring of INNS at dredging and disposal sites is already voluntarily undertaken by some port authorities to inform their own biosecurity plans (personal communication). Furthermore, both pre-project and post-project monitoring is already a requirement of some dredging licences if it is deemed necessary on review of an assessment of potential environmental impact (MEMG, 2003). In these instances, monitoring is either undertaken by the licensee or the regulatory authority (MEMG, 2003). Specifically, data may be collected at dredging and disposal site on physical characteristics, water quality, seabed characteristics (including benthic community) and hydrodynamics, depending on the need identified (Lonsdale et al., 2023; MEMG, 2003). In Wales, an assessment of INNS present at the dredging site is mandatory to fulfil the biosecurity plan licensing requirement.

In England, Cefas monitor the particle size and benthic community at a selection of offshore disposal sites every year, depending on which ones are highlighted by “a tier-based approach that classifies a number of possible issues or environmental concerns that may be associated with dredged material disposal into a risk-based framework” (Bolam et al., 2022). However, a targeted assessment of INNS presence or absence at disposal sites was not found by the literature review. Conversely, in Wales, NRW conducted surveys of several offshore disposal sites in 2016 and 2018, specifically in response to some sites having received dredged material that may have contained the INNS *C. fornicata* (Baldock et al., 2018). This INNS was detected, although no specimens were found alive. The study acknowledged that the results could have been influenced by the survey methodology.

A standardised methodology that is tailored to monitoring INNS should be incorporated into biosecurity planning guidance in England and should be utilised for routine monitoring of disposal sites by Cefas. Without an INNS-specific methodology, INNS could be undetected since they can be low in abundance and sparsely distributed, particularly when at an early stage of establishment (Blackburn et al., 2011). Furthermore, without a standardised monitoring methodology, licence approvals with respect to the biosecurity plan would not be consistent.

INNS data from both the dredging site and the adjacent area should be obtained where possible. This is because mature INNS in the adjacent area may also be present at the dredging site (and so can be used if data from the dredging site cannot be obtained), and immature forms and propagules (e.g., gametes, larvae spores) may spread into the dredging site from adjacent areas. Considering the latter point, both the sediment and water should be analysed for INNS, e.g., using eDNA analysis, where suitable (Larson et al., 2020). To compliment on-the-ground monitoring, existing datasets should be analysed, such as:

- National Biodiversity Network
- OneBenthic Non-native Species Tool
- GB Non-native Species Information Portal

Monitoring efforts should be focussed on the detection of INNS species outlined by the UK Marine Non-Indigenous Species Priority List (UK Marine Strategy), the UK Technical Advisory Group (UTAG) aquatic invasive species list (Water Environment Regulations) and INNS identified as high-risk by Great British Non-native Species Secretariat risk assessments. Monitoring of organisms (if present) in dredged material that is held in the hopper would also help to assess the viability of this potential pathway and facilitate scientific research.

10.1.6 Recommendations summary

- Consider a biosecurity planning approach similar to that adopted in Wales.
- Create standardised biosecurity plan guidance at the national level.
- Explore the development of a risk assessment tool.
- Carry out research to fill identified knowledge gaps and to determine quantified thresholds for factor influence.
- Carry out research to identify effective and practical mitigatory action and implement these actions via biosecurity plans.
- Monitor INNS to determine if an introduction has occurred/when management and control is required, and to inform pathway risk assessment.

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12 Glossary

Benthic organism: animals or plants that occupy the seabed.

Ballast water: water stored within an internal cavity of a vessel to provide stability.

Biosecurity: measures that prevent the movement of harmful organisms such as pathogens and invasive non-native species (INNS).

Capital dredging: dredging to a depth not previously dredged, or to a depth not dredged within the last 10 years.

Cross-fertilisation: the fusion of male and female gametes from different individuals of the same species.

Dredged material: sediments, organic matter, water and any other components of the seabed and its surrounding water body that is extracted by a dredger.

Fitness: the ability of an organism to reproduce.

Gamete: a haploid reproductive cell that fuses with another cell to produce a new individual.

Hopper water: water that is taken into the hopper (the cavity where dredged material is stored) of a vessel to provide stability.

Hydraulic dredging: dredging involving the removal of sediment via suction, resulting in a mix of both sediment and large amounts of water entering the dredger.

Intertidal: denoting the area of a seashore which is covered at high tide and uncovered at low tide.

Invasive non-native species (INNS): Non-native species that cause negative environmental and/or economic impacts.

Maintenance dredging: the routine removal of recently accumulated sediments to maintain the designated depth of a navigational channel.

Mechanical dredging: the use of an excavator to remove sediment from the seabed which enables the creation of precise contours for berths within ports and harbours

Navigational dredging: the removal of material from the seabed to deepen berths and channels for the purpose of navigation.

Non-native species (NNS): organisms (including plants, animals, and their propagules) that have been introduced either accidentally or intentionally by human activities to an area outside their native range.

Organism: a single animal, plant or other living thing.

Pathway: the means and routes by which INNS are moved to new locations.

Pelagic organism: animals or plants that occupy the water column.

Established population: a group of animals or plants that are successfully reproducing, forming self-sustaining, long-term populations.

Propagule: any biological material that can give rise to a new individual organism.

Rainbowing: when dredged material is pumped into the air from a dredger.

Self-fertilisation: the fusion of male and female gametes from the same individual of a species.

Spray-pontoon: a floating structure which pumps dredged material into the air.

Subtidal: denoting the area of ocean that is always underwater, even at low tide.

Vector: the mechanism via which INNS are moved to new locations.

13 Appendices

13.1 Appendix 1

The following search strings were used to search for literature on Google Scholar and Google's generic search. Specifically, one of the two Dredging search strings were combined with one or both of the other two search strings outlined below:

Dredging

- "Dredg*" AND ("sediment" OR "aggregate") AND ("navigational" OR "capital" OR "maintenance" OR "mechanical" OR "beneficial use" OR "hydraulic" OR "disposal" OR "deposit" or "dumping" OR "treatment") AND ("mechanism" OR "method*" OR "process")

- "Dredg*" AND ("sediment" OR "aggregate") AND ("navigational" OR "capital" OR "maintenance" OR "mechanical" OR "beneficial use" OR "hydraulic" OR "dispos*" OR "deposit*" or "dump*" OR "treatment")

Invasive non-native species (INNS)

- (Invasive OR "invasive species" OR "non-native" OR "INNS" OR "IAS" OR "alien species" OR "non-indigenous" OR "NIS" OR "NNS" OR "biological pollution" OR "biological organisms") AND ("vector" OR "pathway" OR "introduc*" OR "spread")

INNS survival, environmental conditions/impact

- ("mortality" OR "surviv*" OR "impact" OR "effect" OR “conditions”) AND ("species" OR "habitat" OR "ecosystem" OR ecology" OR "environ*" OR "benth*")

13.2 Appendix 2

Interviews with industry representatives were centred on the following questions:

- What biosecurity processes are used within the industry to prevent INNS spread (with a focus on sediment transfer)?
- What monitoring of INNS carried out by industry (at the dredging site, disposal site and in the hopper, if done/required)?
- What do you believe the likelihood of entrainment of INNS to be (from a technical perspective)?
- What do you believe the likelihood of survivability of INNS during the dredging process to be?
- What do you believe the likelihood of accidental spillage of dredged material/INNS on route to the disposal site to be?

13.3 Appendix 3

Examples of dredging projects which involved capital and maintenance dredging sites, and beneficial use and offshore disposal sites, to demonstrate the variability of the projects and processes. Ordered by the most common scenarios: i) maintenance dredge site – offshore disposal site; ii) capital dredge site – offshore disposal site; iii) maintenance/capital dredge site – beneficial use site. Disposal site depths were taken from a disposal site dataset obtained from Cefas (2022), published under Open Government Licence (OGL). Locations for projects 1-3 are shown in Figure 7.

Project number	Dredging site type	Required depth below chart datum at dredging site (m)	Dredging site location	Time-frame or dredging frequency	Volume of sediment moved (m^3)	Sediment type dredged	Dredger type	Dredger length and hopper capacity	Method of dredged material transport	Barge hopper capacity (m^3)	Disposal location	Disposal site type	Disposal process	Distance from dredging to disposal site (km)	Depth of disposal site (m)	Reference
1	Maintenance	14.5	Harwich, Essex	5 times per year	500,000 per campaign	Silt	TSHD	No data found.	No data found.	No data found.	Inner Gabbard	Offshore disposal	Bottom dumping	~30	55	(Harwich Haven Authority, 2024)
2	Maintenance	9-16	Southampton Water, Hampshire	Every 6 months	300,000 - 500,000 per year	Silt	TSHD	No data found.	No data found.	No data found.	Nab Tower	Offshore disposal	Bottom dumping	~28	40	(ABPmer, 2014)
3	Maintenance	9.1	Tilburyness Shoal, River Thames, London	Every 3 years	700 per year	Sand	TSHD	No data found.	No data found.	No data found.	South Falls	Offshore disposal	No data found.	~100	40	(Nicholson and Meakins, 2007)
4	Maintenance	14	Tilbury Power Station, River	Every 6 months	40,000 per year	Silt	TSHD	No data found.	No data found.	No data found.	South Falls	Offshore disposal	No data found.	~100	40	(Nicholson and Meakins, 2007)

Project number	Dredging site type	Required depth below chart datum at dredging site (m)	Dredging site location	Time-frame or dredging frequency	Volume of sediment moved (m^3)	Sediment type dredged	Dredger type	Dredger length and hopper capacity	Method of dredged material transport	Barge hopper capacity (m^3)	Disposal location	Disposal site type	Disposal process	Distance from dredging to disposal site (km)	Depth of disposal site (m)	Reference
			Thames, London													
5	Maintenance	9.1	Divers Shoal, River Thames, London	Every 3 years	No data found.	Fine sand and silt	TSHD	No data found.	No data found.	No data found.	South Falls	Offshore disposal	No data found.	~100	40	(Nicholson and Meakins, 2007)
6	Maintenance	9	Coalhouse Shoal, River Thames, London	Every 3 years	1,000 per year	Sand and gravel	TSHD	No data found.	No data found.	No data found.	South Falls	Offshore disposal	No data found.	~100	40	(Nicholson and Meakins, 2007)
7	Maintenance	10.2	Sea Reach, River Thames, London	Every 3 months	4000 per year	Sand	TSHD	No data found.	No data found.	No data found.	South Falls	Offshore disposal	No data found.	~100	40	(Nicholson and Meakins, 2007)
8	Capital	N/A	Southampton, Hampshire	Mar-Apr 2013	270,000	Silt, mud, clay	BHD	46 m, 8.5 m^3 bucket	Split barges	No data found.	Nab Tower	Offshore disposal	Bottom dumping	~28	40	(Boskalis Westminster, 2012)
9	Capital	N/A	Portsmouth, Hampshire	2015-17	3 million	Silt, sand, gravel, clay, peat	TSHDs, BHD	70-98 m, 1,300-4,500 m^3 hopper; 46 m,	TSHDs, barges	No data found.	Nab Tower	Offshore disposal	Bottom dumping	~28	40	(Boskalis Westminster, 2023)

Project number	Dredging site type	Required depth below chart datum at dredging site (m)	Dredging site location	Time-frame or dredging frequency	Volume of sediment moved (m^3)	Sediment type dredged	Dredger type	Dredger length and hopper capacity	Method of dredged material transport	Barge hopper capacity (m^3)	Disposal location	Disposal site type	Disposal process	Distance from dredging to disposal site (km)	Depth of disposal site (m)	Reference
								8.5 m^3 bucket								
10	Capital	N/A	Harwich Harbour and approach, Essex	2021-23	26 million	Clay, mud sand, gravel, stone	TSHD, BHD	186 m, 21,665 m^3 hopper; 69 m, 10 or 30 m^3 bucket	TSHD, split barges	2,850	Inner Gabbard	Offshore disposal	Bottom dumping	~30	55	(Harwich Haven Authority, 2021a,b; Dredging Today, 2021; Dredging Today, 2022)
11	Capital	N/A	Port of Harwich, Essex	2021-22	98,000	Sand, gravel	TSHD	No data found.	TSHD, pipeline	No data found.	Blackwater estuary, Essex	Beneficial use (flood risk reduction, habitat)	Rainbowing, pipeline	~30	Intertidal	(ABPmer, 2023)
12	Maintenance	No data found.	Deben estuary, Suffolk	2015-18	1,725	Silt	GD	No data found.	Barge	50	Deben estuary, Suffolk	Beneficial use (habitat)	GD placement	~1	Intertidal	(ABPmer, 2023)
13	Maintenance	No data found.	Blackwater estuary, Essex	2001	2,000	Silt	BHD	No data found.	Barge	No data found.	Blackwater estuary, Essex	Beneficial use (habitat)	BHD placement	~2	Intertidal	(ABPmer, 2023)

Project number	Dredging site type	Required depth below chart datum at dredging site (m)	Dredging site location	Time-frame or dredging frequency	Volume of sediment moved (m^3)	Sediment type dredged	Dredger type	Dredger length and hopper capacity	Method of dredged material transport	Barge hopper capacity (m^3)	Disposal location	Disposal site type	Disposal process	Distance from dredging to disposal site (km)	Depth of disposal site (m)	Reference
14	Maintenance	No data found.	Chichester, Hampshire	Feb 2023	4,500	Silt, mud	BHD	No data found.	Split barge	200	Chichester, Hampshire	Beneficial use (habitat)	Bottom dumping	~3	Intertidal	(CHC, 2022; CHaPRoN, 2023; ABPmer, 2023, Solent Seascape Project, 2023)
15	Maintenance	No data found.	Lymington Estuary, Hampshire	2014-21	40,000	Silt	BHD	No data found.	Barges	No data found.	Lymington Estuary, Hampshire	Beneficial use (habitat)	Bottom dumping	~1	Intertidal	(ABPmer, 2023)
16	Maintenance	No data found.	Brightlingsea, Essex	2017	No data found.	Silt	CSD	No data found.	No data found.	No data found.	Brightlingsea, Essex	Beneficial use (habitat)	No data found.	~0.5-1.5	Intertidal	ABPmer, 2023)
17	No data found	N/A	Lymington, Hampshire	2012-13	4,450	Silt	BHD	No data found.	Barge, pipeline (100 m)	70	Lymington, Hampshire	Beneficial use (habitat)	Pipeline	~1	Intertidal	(ABPmer, 2023)
18	No data found	N/A	Port of Harwich, Essex	1992, 1995	5,175	Sand, shingle, silt	TSHD	73 m, 1,500 m^3 hopper	TSHD, pipeline	N/A	Blackwater estuary, Essex	Beneficial use (habitat)	Rainbowing, pipeline	~7	Intertidal	(ABPmer, 2023)

13.4 Appendix 4

Conventions, regional directives and national legislation that must be adhered to when carrying out an activity that could introduce and/or spread INNS in England. Also detailed in this table is the relevant protected area designation (where applicable), a description of the convention/directive/legislation, a description of how INNS are referred to in the convention/directive/legislation (where applicable), and relevant licensing guidance (where applicable).

Convention / directive legislation	Relevant designation	Description	INNS reference in convention / directive / legislation	Licensing guidance for dredging/disposal operations
Convention on Biological Diversity	N/A	A commitment to the conserve global biological diversity	INNS are identified as a major threat to biodiversity. Their impacts must be avoided where possible or reduced, by identifying and managing pathways and preventing the introduction and establishment of priority species.	None.
Ramsar Convention 1976	Ramsar site	A commitment to the conservation and sustainable use of Ramsar sites (wetlands)	None.	Dredging / disposal operations need to be assessed for potential impacts on Ramsar sites.
Invasive Alien Species Regulation 2014	N/A	N/A	Live species on the list of alien species of union concern may not be intentionally brought into the EU's territory. Nor may they be kept, bred, transported to, from or within the EU,	None.

Convention / directive legislation	Relevant designation	Description	INNS reference in convention / directive / legislation	Licensing guidance for dredging/disposal operations
			or sold, grown or released into the environment.	
Marine Strategy Regulations 2010	N/A	Aims to achieve or maintain good environmental status in UK seas.	Marine management strategies must ensure that INNS do not adversely alter ecosystems.	None.
Wildlife and Countryside Act 1981	SSSI	Protects native species and SSSIs.	It is prohibited to release, or allow to escape, any non-native species into the wild, including those listed under Schedule 9.	Dredging/disposal operations need to be assessed if there is the potential for significant damage to interest features of a SSSI.
The Water Environment (Water Framework Directive) Regulations (WER) 2017	WER waterbodies	Aims to achieve good environmental status in waterbodies, including those designated to protect or develop economically significant shellfish production.	Not explicitly referred to, but INNS are recognised as a threat to the environmental status of waterbodies by the UK Technical Advisory Group on the Water Framework Directive who produced a list of aquatic alien species.	Dredging operations must not alter the ecological status of waterbodies outlined by the WER (Environment Agency, 2023). A Water Framework Environmental Assessment must be

Convention / directive legislation	Relevant designation	Description	INNS reference in convention / directive / legislation	Licensing guidance for dredging/disposal operations
				produced for a dredging licence application. This should include an INNS assessment if the activity could introduce or spread INNS to a waterbody. How the risk of introducing INNS is removed or reduced must be demonstrated - a biosecurity plan is suggested as an option (Environment Agency, 2023).
Habitats Regulations 2017 (England and Wales)	SPA, SAC	Protects SPAs and SACs.	None.	Dredging (disposal) operations must not have a likely significant effect on Special Protected Areas (SPAs), Special Areas of Conservation (SACs) or Ramsar sites (Defra, 2007).

Convention / directive legislation	Relevant designation	Description	INNS reference in convention / directive / legislation	Licensing guidance for dredging/disposal operations
				Guidance for this is provided by the Maintenance Dredging Protocol for England (MDP) (Defra, 2007; MMO, 2023). INNS are not mentioned in the MDP.
Marine and Coastal Access Act 2009	MCZ	Outlines a marine planning system that incorporates policies of England and the devolved administrations and provides the principle statutory means by which requirements of the Marine Strategy Regulations are met. Provides for the designation of MCZs.	None.	Dredging operations should not have a significant effect on the qualifying features of a Marine Conservation Zone (MCZ) or hinder MCZ objectives (MMO, 2022). Dredging operations should comply with marine plans which support the Act. Marine plans state that proposals must put in place appropriate

Convention / directive legislation	Relevant designation	Description	INNS reference in convention / directive / legislation	Licensing guidance for dredging/disposal operations
				measures to avoid or minimise significant adverse impacts that would arise through the introduction and transport of INNS (Defra, 2021; MMO, 2024).

www.gov.uk/natural-england