Toby Inlet Sediment Study

Prepared for the City of Busselton

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Executive summary

The Toby Inlet Sediment Study was undertaken by Ottelia Ecology on behalf of the City of Busselton, and contributes to the implementation of the Toby Inlet Waterway Management Plan (City of Busselton, 2019). The study was funded via by Department of Water and Environmental Regulation's (DWER) Revitalising Geographe Waterways Program. The specific aims of the study were to:

1. Identify the priority areas for sediment management within Toby Inlet.
2. Determine sediment composition and volume for these areas, building on previous sediment investigations.
3. Assess potential outcomes and impacts of sediment removal from priority areas.
4. Undertake an assessment of the feasibility of removing sediment and evaluate the likely costs and benefit of strategic sediment removal.

Sediments in Toby Inlet

Four zones of sediment condition were identified in Toby Inlet, with priority for sediment removal allocated to Zones 2 (from McDermott St to east end of Wilson Ave) and 3 (between McDermott St and the Footbridge). Together these zones occupy a length of 3.7 km. A total of 60300 m^3 of soft sediment, comprised of monosulfidic black ooze (MBO) has accumulated in this area and areas where sediment was at least 80cm deep were recorded in both zones. The total sediment accumulation roughly equates to 2.8 times the average annual amount of seagrass wrack deposited from seagrasses meadows onto Geographe Bay beaches (Oldham et al 2010).

Accumulated MBO sediment in Zones 2 and 3 was found to be having multiple severe impacts over a significant proportion of the Toby Inlet. These include physical degradation of the estuary with loss of habitat for both fish and waterbirds; potential ongoing impacts on water quality; loss of amenity; and the loss of recreational access. High total organic carbon sediments in Toby Inlet likely reflects excessive macroalgal growth and decay which contributes to poor estuarine sediment health. Build-up of organic sediments creates an internal nutrient source and may have contributed to past low oxygen in the inlet. Although recent improved management of the Toby Inlet mouth by opening the sand bar has improved water quality, the legacy of past regular macroalgae blooms has left the majority of the inlet with very poor habitat quality and virtual complete loss of macrophytes from the system. The restoration of habitat values in Toby Inlet is unlikely to be achieved without removal of accumulated black sediment.

Removal of sandy sediments accumulated in the upper inlet (Zone 1) was not recommended so as to preserve the threatened ecological community of subtropical and temperate coastal saltmarsh, and in recognition that sediments here were associated with a lower level of amenity and ecological impact. Rehabilitation of Zone 1 is recommended as an alternative to removal. Sediments in Zone 4, located downstream of the footbridge were mainly sandy, with minimal MBO deposits. However, removal of accumulated seagrass wrack mixed with sand is recommended to improve tidal water exchange.

Importantly, the acid neutralising capacity of sediments in Toby Inlet was found to substantially exceed potential acidity, meaning disturbance of sediment is highly unlikely to result in acidification issues. Further, heavy metal concentrations in sediment samples were all below ecosystem protection criteria. These findings are important as previous studies recommended against removal of sediment due to concerns about the potential for acidification and subsequent release of heavy metals. The potential for deoxygenation of the water column remains an important potential impact of concern associated with sediment disturbance.

Sediment management approaches

Six different sediment management approaches were evaluated. The two approaches recommended in this report involve staged removal of sediment from zones 2 and 3, working progressively from downstream to upstream, combined with removal of the small island of accumulated seagrass wrack downstream of the footbridge. This approach, while likely very costly, was considered to have the best chance of restoring habitat and amenity values of the inlet and could be staged in a way that reduces the risk of fish becoming separated in isolated pools at low tide.

Other approaches evaluated included: leaving sediment in-situ; deepening the mouth of the inlet; removing small isolated zones of sediment and removing sediment from zone 2 only. Each of these options have merits, but were set aside due to concerns related to effectiveness in solving the identified issues caused by accumulated sediment; the fluid consistency of sediment, which can easily flow back into small zones of removal; and potential adverse effects on water quality of the inlet during summer, particularly at low tide.

Sediment removal options

The substantial volume of sediment that has accumulated in Toby Inlet presents a logistical challenge for any future removal project. It is important to avoid potential impacts on sensitive seagrass meadows in Geographe Bay and to minimise the extent and duration of drops in dissolved oxygen that could pose a risk to fish and other aquatic life. Accordingly, any future sediment removal process should be undertaken with a slow and staged approach, possibly over a period of five to ten years so as to carefully manage the potential impacts associated with disturbing these sediments during removal.

Sediment removal from zones 2 and 3 was found to be feasible, despite the challenges presented by the substantial volume to be removed. Three techniques are recommended for pilot projects, with each being suitable for different locations in the inlet. Small scale pilot projects will enable evidence of likely effectiveness and impacts to be gathered. The three techniques are:

- Suction pump sediment and dewater using mobile containerised filter press system. This involves using suction pump to remove sediment to temporary holding tanks, adding flocculent and dewatering using a mobile compact filter press. Mobile compact technology would need to be moved to a number of stations along the inlet for this to occur (Zones 2 and 3).
- Slow and staged sediment raking to enable natural flow to move sediment into the ocean during winter (Zone 3 only). This involves using a purpose built device attached to a small boat to mechanically stir sediment under high flow conditions in winter thereby allowing controlled, staged dispersal to sea.
- Suction pump to liquid waste disposal tankers and transport to wastewater treatment plant (WWTP) (Zone 2 only). This involves the use of liquid waste disposal trucks to pump sediment slurry and transport for disposal to the Quindalup WWTP.

Of the three techniques recommended sediment raking was found to have the lowest likely cost of implementation, though has the greatest potential to reduce dissolved oxygen in water around the disturbance area. The extent, duration and outcomes of such impacts would require evaluation through small scale pilot projects. Potential impacts on seagrass meadows from this technique would need to be mitigated through careful selection of both timing and scale of works undertaken.

The used of liquid waste disposal trucks to remove and transport sediment from the inlet to a waste water treatment plant was recently undertaken with success in the Vasse Estuary exit channel. There are few expected negative impacts from this technique but its potential is limited to Zone 2 during summer at low tide, when there is minimal water covering sediments. Even under these conditions this option is likely to have the highest cost of implementation given the extensive transport costs.

The use of a mobile, compact containerised filter system has potential to greatly reduce transport costs yet there are limited available hire options in Western Australia. An expression of interest process to invite technology companies to present a cost effective solution for hire (or sale) to the City of Busselton is recommended.

Recommendations

Considering the outcomes of sediment investigations, current and future impacts of sediment accumulation in Toby Inlet, and assessment of sediment removal options, recommendations are as follows:

1. Sediment removal from Toby Inlet should be pursued to restore ecological values and amenity, targeting Zone 3 as a priority, followed by Zone 2.

   Removal would require a staged approach starting at the lower end of the Inlet and progressively moving upstream.

   Such works should only be commenced subject to consultation with the South West Land and Sea Council and in accordance with State Government approvals processes.

2. Further evaluate the potential for sediment raking to remove sediment through a small scale pilot project in the downstream end of Zone 3 during high flow conditions in winter, when dissipation of flows from the Inlet into Geographe Bay are likely to be rapid. This would be facilitated by the following actions:

   - Monitoring of this pilot for effectiveness and water quality impacts both within downstream areas of Toby Inlet and in nearshore areas of Geographe Bay to enable informed evaluation of the likely impacts of wider scale staged sediment raking.
   - Prior to commencement of this project, removal of the small island of seagrass wrack mixed with sand that is located downstream of the footbridge (in Zone 4) would improve tidal water exchange and outward flow of suspended sediment.
   - Flow velocity data collection in the Toby Inlet during winter would aid in the evaluation of sediment raking and future sediment removal proposals.

3. Develop pilot projects for direct sediment removal from Zones 2 and 3 in the Toby Inlet to further inform appropriate techniques and costs for larger scale removal, including:

   - Suction pump sediment and dewater using mobile containerised filter-press system. (Zones 2 and 3). Expressions of interest would be required to access a suitable dewatering plant.

- Suction pump to liquid waste disposal tankers and transport to WWTP (Zone 2 only).

4. Develop a larger and longer term program of sediment removal for Toby Inlet to be developed based on the outcomes and key findings from the pilot projects. In addition, such a program would require:
   - Measurements of the salinity of sediments in Toby Inlet be made during winter to assist in evaluating potential re-use options for sediment.
   - Undertake site assessments and consultation with landholders adjoining Toby Inlet to identify potential locations for short term dewatering stations along the inlet.
   - Preparation of an acid sulfate soils management plan.
   - Liaison with the Department of Water and Environmental Regulation to outline the aims of sediment removal being for restoration purpose, and to confirm the approvals processes in this context.
5. Undertake weed control and rehabilitation through revegetation of appropriate local native species in Zone 1, rather than removing sediments, so as to preserve the threatened ecological samphire community and maintain shallow feeding habitat for shore birds.

Background and scope

Toby Inlet is a unique and highly-valued estuary in Quindalup, Western Australia that is recognised for its regionally significant ecological, rural landscape and cultural values (WAPC, 1998). The accumulation of sediments in Toby Inlet has led to strong community concern regarding the loss of social and ecological values of the Inlet over the past twenty years, or more. Catchment development, hydrological changes, high nutrient inputs and a history of severe macroalgal blooms have led to an accumulation of both sandy sediments and fine, black, sulfidic sediments known as monosulfidic black ooze (MBOs). Concern about the impacts of these sediments has persisted and intensified over the past ten years or more, and a recent community views study identified sedimentation as the primary issue of concern regarding management of Toby Inlet (Andrew Huffer and Associates, 2016). Issues arising from these sediments include reduced visual amenity, unpleasant odours, reduced on-water recreational access, loss of recreational fishing values and impeded fish passage.

In 2019 the Toby Inlet Waterway Management Plan (City of Busselton, 2019) identified the need to manage existing sediment in the inlet to improve water quality, water flow and amenity of the inlet. The plan identified the investigation of sediment removal from the inlet as a key management strategy with actions to include the following:

- Define priority areas for sediment management and determine sediment composition and volume for these areas, building on previous sediment investigations.
- Assess potential outcomes and impacts of sediment removal from priority areas and undertake a cost benefit analysis of strategic sediment removal.
- Assess whether sediment agitation would facilitate mobilisation and flushing of sediment deposits from Toby Inlet.

In November 2020, the City of Busselton commissioned Ottelia Ecology to undertake a study of the Toby Inlet sediments with funding provided by Department of Water and Environmental Regulation's (DWER) Revitalising Geographe Waterways Program. The specific aims of this study were to:

- Identify the priority areas for sediment management within Toby Inlet.
- Determine sediment composition and volume for these areas, building on previous sediment investigations.
- Assess potential outcomes and impacts of sediment removal from priority areas.
- Undertake an assessment of the feasibility of removing sediment and evaluate the likely costs and benefit of strategic sediment removal.

The outcomes of the study are expected feed into strategic decision making by the City of Busselton regarding future management of sediments within Toby Inlet, help inform whether removal of sediments should be attempted (or not), and assist in responding to ongoing community concerns regarding sedimentation of the inlet.

The study area

Description and values

Toby Inlet is a small estuary located near the town of Dunsborough, Western Australia, about 250 km South of Perth. The Inlet has an unusual estuarine morphology, being an elongated channel that flows parallel to the coastal dunes for over 5.5 km (Figure 1). This long stretch of water lies adjacent to Caves Road, thereby providing an important scenic focal point to the entrance of the Dunsborough town site, a popular tourist destination in WA. Upstream of Caves Road, Toby Inlet extends to a chain of wetlands that are seasonally inundated and are unaffected by tidal exchange. This sediment study was limited to the tidal channel downstream of the Caves Road Bridge. The catchment comprises a combination of land uses including urban, light industry, rural residential (lifestyle blocks) and agricultural areas. Urban residences adjoin a large portion of the foreshore.

Figure 1: Aerial view of Toby Inlet (COB, 2019)

Toby Inlet is seasonally open to Geographe Bay, a sheltered, north facing marine embayment that forms part of the Ngari Capes Marine Park and supports large and diverse temperate seagrass meadows. The inlet provides similar ecological functions to other sheltered bar-built estuaries in south-western Australia. Importantly, it is one of only two natural discharge points providing a link between marine waters and estuarine habitat in southern Geographe Bay. The other is Wonnerup Inlet to the north, which forms part of the Ramsar-listed Vasse Wonnerup wetland system. All waterways between these systems have been artificially cut through to the ocean, and their straight drainage channels that lie perpendicular to the coast do not replicate the form or function of natural estuaries.

The aquatic environment of Toby Inlet provides habitat for fish, waterbirds, frogs, and aquatic macroinvertebrates (COB, 2019). Despite a relatively narrow foreshore, the fringing vegetation along the banks of the inlet are largely in good condition (Clay, 2006; COB, 2019), which is unusual for an urbanised estuary. Vegetation on foreshore reserves of the inlet provide important habitat for the threatened Western Ringtail possum and Quenda. The Coastal Saltmarsh Threatened Ecological Community occurs in some parts of the inlet (COB, 2019).

Toby Inlet has experienced water quality issues over a long period of time. Blooms of macroalgae, unpleasant odour, loss of amenity and fish kills have all lead to community concern regarding the health of the inlet (COB, 2019). A review of dissolved oxygen data collected as part of DWER regular monitoring indicates that low dissolved oxygen levels occurred regularly in summer at monitoring sites for many years and are a possibly cause of previous fish kills (Figure 2). Improved management of the sand bar at the mouth of the inlet since 2018 appears to have improved water quality in recent years.

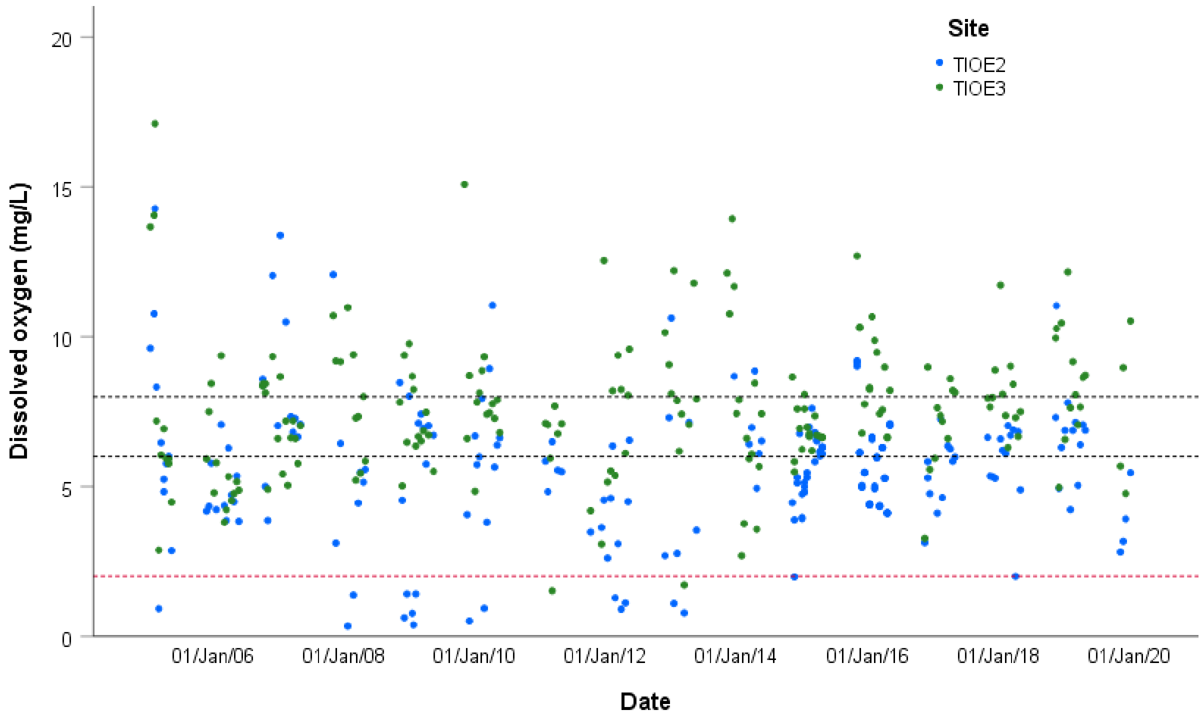

Figure 2: Dissolved oxygen in the Toby Inlet (mid reaches) between 2006 and 2020. Black dashed lined indicate ANZECC & ARMCANZ 2000 ecosystem protection guideline range for estuaries. Red dashed line is critical threshold level for aquatic organisms (Boulton et al. 2014). DWER sampling locations TIOE2 and TIOE3 are equivalent to sampling sites TISED7and TISED6 in this report respectively

Toby Inlet has long been important to the fabric of the Quindalup and Dunsborough local communities. The strength of these community ties are reflected by the long volunteer commitment provided by the Toby Inlet Catchment Group, which commenced in 1998 and continues to this day.

Historical changes

The Toby Inlet and its catchment has experienced extensive modification since European settlement. Drainage works undertaken in the early 1800s and then expanded in the 1920s have resulted in a substantial proportion of natural flow being diverted away from the inlet. Prior to these changes the Carbunup River, Annie Brook and Station Gully waterways all likely flowed through Toby Inlet to the sea via a chain of wetlands that lie to the south of the Caves Road (Frazer and Hall, 2017). These drainage works were aimed at improving agricultural productivity within low lying land by allowing winter flow to be passed directly into the sea. Such changes have irreversibly altered the hydrodynamics of the estuary and transformed the inlet into a low flow environment that is poorly scoured. Today Toby Inlet receives an average inflow volume of approximately 7 to 8 GL in winter and 3 to 4 GL in spring (Frazer and Hall, 2017). There are no measured data on flow velocity in the Toby Inlet. Flood flows in the inlet were modelled by the Water Authority in 1990 and range from 6 m^3/s under a 1 year flood event to 22m^3/s under a 100 year flood event (MP Rogers and Associates, 1999).

Toby Inlet was a focal point for the timber town of Quindalup that was settled in the mid -1800s. A homestead and outbuildings from this settlement are still in use on and near the banks of the inlet. Further urban development surrounding Toby Inlet did not substantially commence until the late 1960s to early 1970s when land on the coastal side of the inlet was subdivided. Development of this area was largely comprised of holiday homes and deep sewer was not constructed as part of the subdivision. Anecdotally, Toby Inlet was used as a slipway during the 1960s and 1970s and was dredged to maintain access for small boats during winter, at a time when a harbour had not yet been constructed in Busselton.

The photo series below from 1970s illustrates the early development of new roads and coastal subdivisions along Toby Inlet (Figures 3A to 3D). They depict low density housing interspersed with native bushland along the length of the inlet. In these photographs there are two discharge points (estuary mouths) visible where Toby Inlet drains to Geographe Bay (Figure 3C). The upper most mouth is shown with a dredge in place a short distance upstream (Figure 3D). The upper reaches of Toby Inlet was relative clear of sandy deposits at this time (Figure 3A).

3A) Toby Inlet 1970 Upper Inlet

3B) Toby Inlet 1970 mid-section vicinity of Lagoona Pl to Stroud St

3C) Toby Inlet Lower Inlet 1970 showing two mouths.

3D) Toby Inlet 1970 enlargement of the upper mouth, likely showing dredge in operation.

Figure 3: A to D Historical aerial photo sequence of Toby Inlet in 1970 Upper to Lower Inlet.

Sources of sediment

Two sources of sedimentation in Toby Inlet have been previously identified: eroded soils transported to the inlet from the catchment; and accumulation of organic material within the inlet (City of Busselton, 2019; Env Australia, 2007; Ward et al 2009). Sandy sediments downstream of the Caves Road Bridge are believed to have accumulated over the past 20 years as a result of erosion within the wider catchment as land was cleared for subdivisions and drainage works extended (Env Australia, 2007). High nutrient inputs from the septic systems of adjoining urban development, agricultural fertilizer use and other catchment sources, contribute to regular severe macroalgae blooms in summer over the past twenty years (DOW, 2010). The long morphology of Toby Inlet combined with the lack of flow has often resulted in such blooms being trapped within the inlet where they sank to the bottom, adding to sediments as they decomposed. Past aerial photographs of Toby Inlet illustrate the formation of macroalgae blooms in the upper inlet during November 2001 (Figure 4) and severe macroalgae blooms in the same area during 2007 (Figure 5).

Figure 4: November 2001 Upper Toby Inlet, macroalgae blooms visible – mouth closed.

Figure 5; March 2007 Upper Toby Inlet, severe macroalgae blooms visible – mouth open.

Sulfidic sediment in Toby Inlet

Past studies of the sediments in Toby Inlet undertaken in 2007 (Env Australia, 2007) and in 2009 (Ward et al., 2009) identified the presence of monosulfidic black ooze (MBO) sediments at multiple locations in the inlet, though sampling extent was limited in both cases. MBO sediments are a form of potential acid sulfate soils (PASS) and cause acidification and low oxygen when disturbed or exposed to air, depending on their specific properties (Sullivan et al. 2018). MBO sediments typically form in estuaries when large volumes of organic matter, such as algae, decompose under low oxygen conditions. Sulfate-reducing bacteria (those able to use sulfate from seawater instead of oxygen) dominate the decomposition process and produce gases such as hydrogen sulfide as a by-product. When dissolved iron and other metals are also present, sulfide minerals can be formed with some of this hydrogen sulfide. Ward et al. (2009) identified that MBO sediments in the upper Toby Inlet were likely to have been caused by macroalgae blooms, and tend to accumulate in the following circumstances:

a) Low energy depositional conditions (low flow conditions);
b) Conditions that favour persistence of primary aquatic productivity (persistent algal blooms);
c) Anaerobic conditions that favour reducing microbial communities (low oxygen conditions that allow sulfide reducing bacteria to dominate decomposition).

The ENV Australia (2007) study concluded that disturbance of MBOs in the Toby Inlet had potential for substantial impact on aquatic systems of the inlet and beyond, and that any such disturbance should only be undertaken following further investigations and under an approved management plan. Ward et al. (2009) noted the sediments had high carbonate content, and may have sufficient acid neutralizing capacity (ANC) to neutralize any acid produced. They also recommended that any future disturbance activities would need to consider strategies to minimize environmental impacts, including understanding the chemical properties of the MBO materials, the presence of contaminants, acid neutralizing capacity and deoxygenation potential.

Once large volumes of MBO sediments accumulate in natural systems they can contribute to long term water quality problems by causing reductions in dissolved oxygen (leading to fish kills) and release nutrients back into the water column. These impacts are known are known as 'premobilisation impacts' and must be weighed up against the risks posed by 'post mobilization impacts' (Sullivan et al, 2018). The Australian Government guidance on management of monosulfidic black ooze (Sullivan et al. 2018) notes that techniques for the long term removal and management of these sediments are still very early in development. The potential for disturbance of MBO sediments to cause deoxygenation and acidification in waterways depends on the volume and characteristics of the MBO and the volume and characteristics of the receiving waters (Sullivan, 2018). It is not uncommon for MBO sediments to be removed (with management) as part of access maintenance for canal development and estuarine boat ramps. MBOs have been removed from canal developments in Busselton and Mandurah as well as from the Vasse Estuary exit channel in recent years without adverse water quality and ecological impacts (DWER, 2019).

There are few examples of large scale removal of sediments for the purposes of estuarine restoration in Australia, except for flood mitigation (City of Launceston, 2019) or sediment decontamination (Swanson et al, 2017). Examples of sediment removal for the purposes of ecological restoration are emerging overseas. For example, in the Indian River Lagoon (Florida) the collapse of seagrass meadows due to poor water quality led to accumulation of rotted plant material on the estuary floor, creating an inhospitable environment for plants and animals; indirect nutrient fluxes into overlying waters that fueled algal blooms; and placed stress on pelagic and benthic aquatic fauna (Windsor, 2016). In that system, sediment removal now forms part of a comprehensive ecological restoration program as it was decided that the long term ramifications of leaving high volumes of organically loaded sediments in the estuary outweighed the risks associated with removing it (Windsor et al, 2016).

Recent management

A substantial investment in management of water quality issues has been undertaken in the Toby Inlet catchment over the past ten years. These have included:

- Summer opening of the mouth of the Toby Inlet by the City of Busselton;
- Urban and agricultural fertilizer management as part of wider catchment management initiatives and implementation of the Water Quality Improvement Plan for Geographe Bay (DOW, 2010), the Toby Inlet Management Plan (Clay, 2005) and the Revitalising Geographe Waterways Program;
- Community awareness of nutrient management techniques and benefits of native gardens via the 'Bay OK Program';
- Fencing and restoration of riparian vegetation on streams in the catchment by the Toby Inlet Catchment Group and GeoCatch;
- A $5 million Water Corporation project to extend connection of deep sewer along Geographe Bay Road to enable future connection of residences that adjacent to Toby Inlet, as recommended by DOW (2010). This sewer line does not extend to the lower reaches of the inlet.

Improvements to water quality within Toby Inlet have been observed following summer opening of the Toby Inlet mouth. Since that time there has been limited growth of macroalgae in the Toby Inlet. The resolution of this key source of sediment formation lends weight to the consideration of sediment removal, presuming it can be achieved safely, as it now seems likely that if sediments were removed from the inlet they are unlikely to reform quickly.

Part A: Qualitative investigations

Zones of sediment in Toby Inlet

A reconnaissance visit undertaken on November 7 2019 confirmed that different areas of Toby Inlet comprise sediments of different materials. These include sand and silt washed from the catchment as well as sulfidic black sediments (monosulfidic black ooze), which have likely formed in the estuarine sediments due to eutrophication and limited flushing. Both forms of sediment are the subject of community concern. For the purposes of the describing the condition of sediments in Toby Inlet, four separate zones have been defined (Figures 6 to 11). These include:

- Zone 1 – sandy sediments of the upper catchment. A variety of wading water birds were observed feeding in these areas. Dead melaleucas in this upper zone may be indicative of historical hydrological change (or changes to salinity regime) and there is substantial weed invasion within the riparian vegetation in this zone. Important samphire communities (subtropical and temperate coastal saltmarsh) have colonised the edges of the upper inlet and these are protected via their listing at state level as a priority ecological community, and threatened ecological community at a federal level.
- Zone 2 – Fine black sediments exposed at low tides. This zone occurs in the upper inlet between Stone Street and just downstream of Wilson Cresent. At low tide there is very little water cover over the deep (40 to 80 cm) black sulfidic sediment in the Toby Inlet noting that assessments were undertaken at typical summer tide heights. The length of this zone was 900m.
- Zone 3 - Fine black sediment with shallow water cover. The reaches of the Toby Inlet, between the footbridge and Stone Street, visual amenity is less severely affected than upstream due to deeper water over laying sediment, but overall visual amenity is moderate to poor. Some fish life was observed in the shallow water lying above sediments in this zone, although the shallow water means they are vulnerable to predation. The depth of sulfidic sediment remains between 50 and 80 cm, severely impacting recreational boating access and providing limited habitat for aquatic species. The length of this zone was 2800m.
- Zone 4 - Clean sandy sediments with varying amounts of seagrass wrack in the lower inlet. Downstream of the footbridge through to the mouth of the inlet the sediments are clean and sandy with patches of seagrass wrack. Fish were abundant in this area and crabs were also observed. Downstream of the footbridge a longer term accumulation of seagrass wrack has created a small island and this possibly influences tidal exchange and flushing.

Figure 6: Summary of sediment condition in Toby Inlet.

Figure 7: Zone 1: Sandy sediments have deposited in the upper portion (approx..500 m) of Toby Inlet between the Caves Rd bridge and just downstream of Wilson Ave.

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Figure 8: Zone 2 – Fine black sediments exposed at low tide in the upper inlet between Stone Street and just downstream of Wilson Avenue.

Figure 9: Figure 8: Zone 2 Further examples of poor visual amenity, limited recreational access and very poor habitat values in the upper Toby Inlet.

Figure 10: Zone 3: Fine black sediments covered with shallow water at low tide.

Figure 11: Zone 4 – Clean sandy sediments of lower inlet.

Aerial assessment

The following series of aerial photos captured during January 2020 illustrate the extent of sedimentation in the Toby Inlet (Figure 12A – 12F) from the air. Accumulated sediment is more visible in the photos in the upper inlet (Figures 12A and 12B) owing to low water levels in these areas at the time of photography. The upper zone of Figure 12A also illustrates the accumulation of sandy sediments from the catchment that have resulted in a narrowing of the channel in this area. Surveys and sampling outlined in the following sections have demonstrated that deep sediment extends from this upper inlet area all the way to the footbridge in the lower Inlet, some 3.7km distance downstream. The clean sandy base of the estuary is clearly visible in Figures 12E and 12F.

Figure 12A) Toby Inlet upper inlet

Figure 12B) Toby Inlet upper McDermott St to Lagoona Pl

Figure 12C) Toby Inlet Robbies Close to Campion Way

Figure 12D) Toby Inlet Campion Way to Stroud Street

Figure 12E) Stroud Sreet to below the footbridge

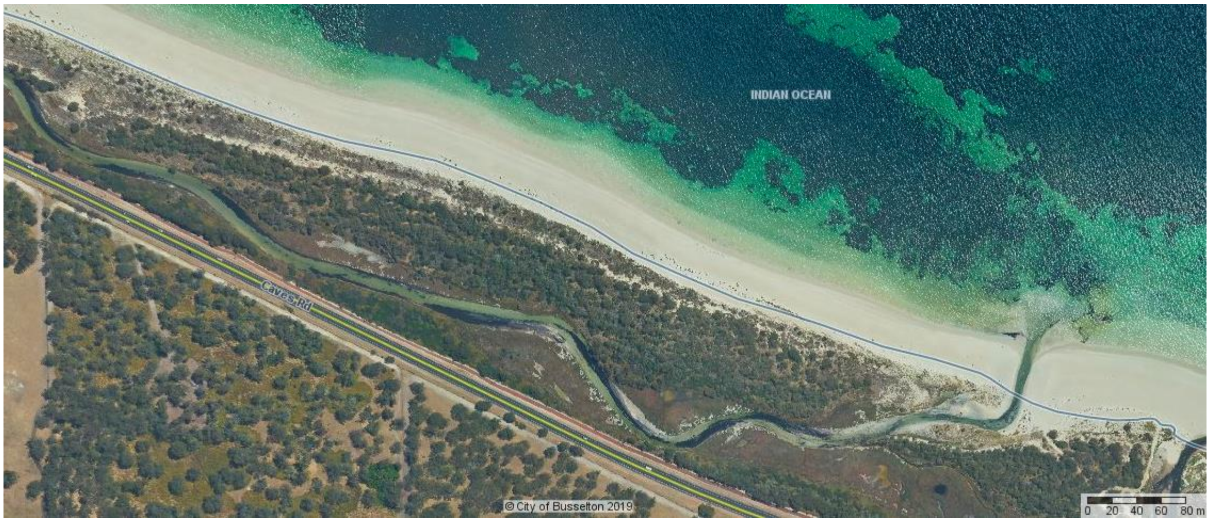


Figure 12F) Toby Inlet below footbridge to mouth

Figure 12: A to F - Aerial photo series of Toby Inlet from upper to lower Inlet in January 2020 (COB, 2020)

Community views

Community consultation to canvas and clarify issues of concern relating to Toby Inlet was undertaken in 2016 by the City of Busselton during the development of the Waterway Management Plan. This consultation identified sedimentation as the most significant concern, with many of the others issues identified also arising from sedimentation. These other issues included amenity (odour), water quality, water flow, impacted ecology and poor recreational access (AHA, 2016; COB, 2019). Suggested actions to alleviate these issues included management of the mouth of the inlet to improve water exchange, restoring habitat, removing sediment, improving access and improving flow. Managing the summer opening of the mouth in recent years seems to have at least partially addressed many of these concerns. Removal of sediment as part of a wider restoration project will assist in addressing many of the remaining issues.

For this study, attendees of a meeting with the Toby Inlet Catchment Group were asked to record notes on large scale maps regarding their specific concerns with respect to sediments in Toby Inlet. Some of the information received was general and related to the wider inlet, while some was specific to certain locations. Attendees identified the most concern about sediments in the upper and middle stretches of the Inlet, yet many perceived that issues could resolved by removing sediment from the lower end of the Inlet (to help facilitate flushing from the sea (Table 1). The general comments included the following:

- Concern that the ‘rate’ and ‘amount’ of flow has been affected by all the dams across creeks in the catchment.
- The health of the Inlet has improved in the last 2 years. Smell has reduced and clarity has improved.
- Opinion that sedimentation issues relates to Station Gully Drain and the Dunsborough Lakes development. Given both remain dredging is needed then prevent re-silting.

Attendees were also invited to provide quotes that describe how they perceive the Toby Inlet to have changed over time. Many of the attendees were either long term residents, or had visited the Toby Inlet regularly during the 1960s and 1970s and then moved to Quindalup in later life. These quotes provide valuable insight into the timeframe of changes in the inlet. The majority of these quotes make references to changes in recreational access, fishing, birdlife or visual amenity (Table 2)

Table 1: Comments received from community regarding specific locations of the inlet.

Location	*Comments provided by community members*
Wilson Ave	New large samphire flats
Between McDermott and Geographe Close	2 Ft of sediment. Shallow smelly, toxic slush. No smell, no mosquitoes but is a battle to paddle board now. In the 1980s we could easily motor dinghy here and had crabs and mullet
Between Geographe Close and Stone St	I understand 'Bayshore' and 'Whitesands' resorts are on deep sewerage and they connect to the line running along Caves Road – Accordingly the pipe and a corresponding bund should be removed when the resorts are connected to the new infill system – flow improved!
Across Inlet from Robbies Close (Caves Road Side)	Very happy for you to dump excess sediment in these spots (until removal). We have been experimenting using an air compressor to loosen sediment and created some holes and channels. We have seen blue swimmer here in last six months! I believe sediment has risen in the last 3 years.
Robbies Close	My feelings are after living on the inlet for 25 years – when the mouth opening is blocked it causes a big problem of algae build-up. When golf club starting displacing water into the inlet there was a build-up of silt and less marine life was in the inlet at Robbies Close. Whatever the pipe that was put across Campion Way - this caused sediment and blocked water. 10 years ago it was much deeper.
Between Footbridge and Mouth	I think some dredging from the cycle way Bridge to the opening would increase the flow both winter and summer and would increase flow all the way along the Inlet. Dredge from ocean to footbridge. Would have to help upstream. Start dredging from eastern end What is to be achieved by removing the silt? Suggest to remove the silt derived from seagrass from mouth to footbridge Entrance Backwater (Chain Ave) into a samphire flat with dredged fill from Toby Inlet.

Table 2: Quotations received from community members regarding recollections of Toby Inlet from the past

Name / knowledge of Toby Inlet	*Quote Provided – Recollections of Toby Inlet*
Dorothy Sellholm – permanent resident now – visitor prior from 1973	*"Our family have been in Quindalup since before the 1970's – Ian Robertson used to catch mullet in Toby's as bait. When we left WA in 1981 the Inlet was still in reasonable condition and quite deep – about 6 foot. 2001 – we returned permanently to acid sulfate soils as identified by studies by Brian Clay – Black ooze was present and at this stage there are spots where the slush is dangerous and neighbours dogs failed to be able to get out."*
Alison Brown – Resident now – visitor prior from the 1950s	*"In the 1950s as a teenager, my family used to holiday here in camps, subsequently in approximately 1953 purchased property and built in 1954. In those days the Inlet was dredged near Stockyard Gully (west of) and the opening to the ocean was a deep fast flowing tidal inlet. As the tide came in the water teemed with mullet, herring and bream which locals netted, also crabs. In 2002/3 when I came to live there were dinghies still being driven past my property (274 Geographe Bay Road). After the causeway was put in (in the 60s I think), the tidal flow lessened, and after the Lakes development there was a rapid rise in siltation. A core sample taken that was requested by concerned residents over a period of many years showed 80% build-up in the last 4 years. Since then, every year siltation has increased to the point that only a trickle of water remains after the winter rains (season), exposing large areas of mud flats that are smelly and inhospitable to marine life. In the last 3-4 years even pelicans are unable to swim anymore. • Remove the causeway drain pipe to help flow at the Stockyard end and dredge. • Dredge the Inlet at the western end to encourage flushing. • Remove and dredge the silt at intervals from east end.*
Lisa – Resident for 6 years	*I think the sediment has risen substantially in the last 3-4 years. Consider creating a channel. Happy for you to gain access through 1102 (Caves side)*
Gabrielle Ahun-Mally – Resident for 25 years	*When I first looked at our block on Robbies Close the mouth was blocked and the inlet at our block was 70% covered in algae. When opened it was flushed out. There was abundant sea life and it was relatively deep. When golf course was started and displaced water it had a build-up of silt, and sea life was not nearly so abundant – little if any. In the last 5 years it has become very shallow and when has been left clocked at the mouth there has been devastating algal growth and dead marine life, very very sad. I am not sure if dredging is the answer / the offspill from Gold Club is a problem / when the mouth is blocked it is devastating for us at Robbies Close.*
Anna Marchesani –	*I used to be able to <u>row</u> across the Inlet from 1168 Caves over to Whitesands and Bayshore and go to beach.*

Name / knowledge of Toby Inlet	*Quote Provided – Recollections of Toby Inlet*
Resident 30 years	*We could cross row to beach, eat crabs and Bream.* *Last 6 years – no fish and no crabs. About 2 foot sediment. Smells and looks toxic. I have photos.* *About ten years ago there were banks and banks of wet (dead) fish.*
Terry and Michelle Cornelius – Residents for 31 years and visited prior to that from mid 1960s	*Travelled down to Yallingup, surfing from mid '60s crossing over old timber bridge into Dusnborough. There was a dredge in Tobys just east of the cycle bridge, the remains are still visible today.* *In the late '80s we built on the beach front one East side of Mary Brook Drain. We regularly boated up Tobys from the ocean catching crabs.*
Floyd Irvine – Resident for 20 years	*Fishing about 1999 – used to fish for Black Bream in the inlet. Remember once catching Herring / Tailor / Trumpeter / Estuary Perch (sea trumpeter), Flathead / Flounder / Whiting (sand/yellowfin) (probably also mullet), King George – All in one season.* *Bottom used to have a bit of sludge on it but lots of sand bottom, patches of weed (growing) – nearly up to the old bridge / Caves Road. Further down near the mouth / drain – lots of yellow eye mullet and sometimes mullet.* *About 10 years ago I waded in there and the mud was up to my knee in a places we used to work across fairly clean bottom.* *Probably about 10 years ago I used to fly fish around where bridge is – some sludge about 6" with clean patches. And Crabs!* *Used to be a slipway.*

Part B: Sediment properties

Methods

Samples for sediment characterization were collected from ten sites along Toby Inlet, determined in collaboration with DWER and CoB (Figure 13). Sample sites were chosen to provide a roughly even spread of sites along sections of the inlet that were known to contain deep black sediment or blockages of accumulated seagrass. Sites TISED9 and TISED10 were relocated given seagrass wrack that had accumulated in the lower inlet during the time of site reconnaissance had largely cleared by the time sampling was undertaken in early December. These sites were relocated further upstream to provide a better coverage of the major areas of sediment accumulation. This relocation of sites has resulted in site numbers not being completely ascending from upper to lower reaches of the inlet.

Sediment cores were collected by wading into shallow water using an Uwitec sediment corer, which allows sectioning of the core without disturbing the core in its entirety. Three replicate cores were collected from each site (approximately within a 1 m x 1 m quadrant area). Each core was photographed, the layers of sediment measured, and description recorded of the sample profile.

Subsampling from cores at each site included the top 20cm of surface sediments and the bottom 20cm of the organic sediment layer (each labelled accordingly). Subsamples from the 3 cores at each site were combined for analysis. Samples were transferred into labelled double zip lock plastic bags and exposure was minimised.

Sediment pH was measured for all samples in the field using a Utec multiparamter pcs tester probe immediately after collection by placing the probe into a bagged sample while concurrently holding the bag sealed around the top of the probe. A 225ml aliquot for acid volatile sulfur (AVS) and reduced inorganic sulfur (RIS) analysis was transferred into a clean plastic vial (tightly packed without headspace) and the vial placed back into the plastic bag containing the rest of the sediment. All samples were placed in an Eski with ice slurry immediately after collection then transferred into a freezer as soon as possible.

Samples were analysed at a NATA registered laboratory (ALS) for:

- Reduced inorganic sulfur
- Acid volatile sulfuur (AVS)
- Nutrients (TN, TP)
- Acid neutralising capacity
- Heavy metals and metalloids (Fe, Al, As, Cd, Cr, Cu, Mn, Ni, Zn, Pb, Hg, Se, Ag, Sb)
- Total organic carbon
- Particle size

Detection limits for all analysis are located in Appendix A.

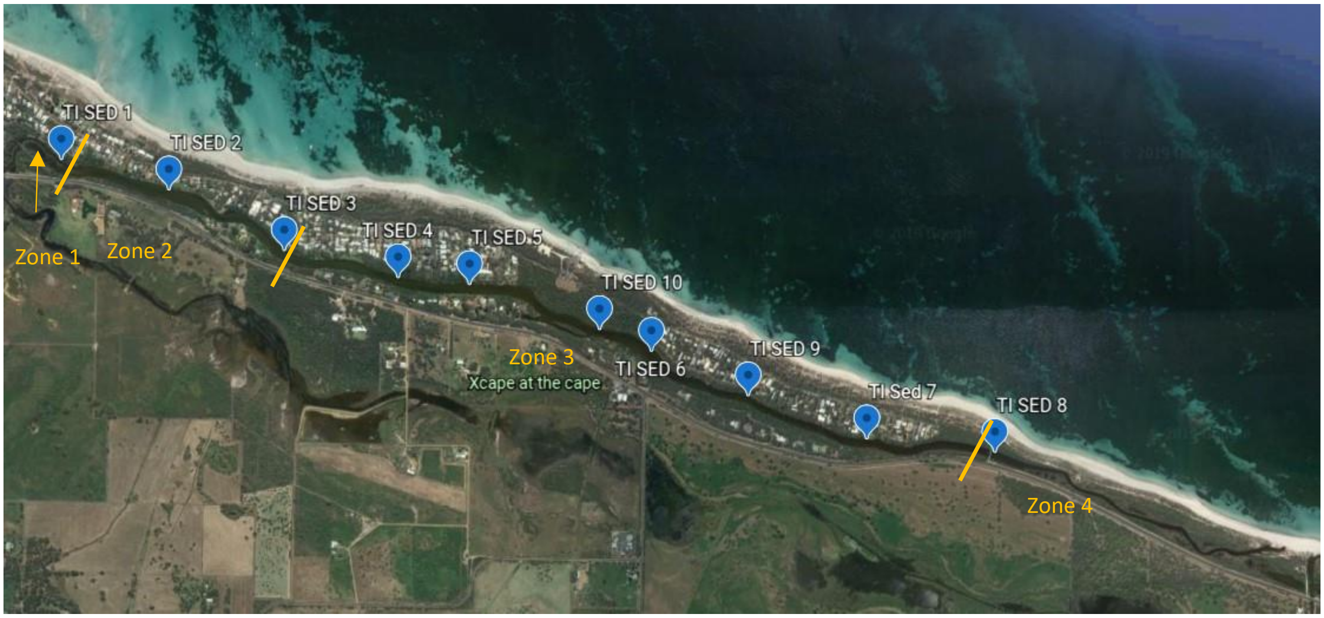


Figure 13: Location of sediment cores collected for analysis and description of profiles. Note that sites ordered from upper to lower inlet are not presented entirely in numerical order.

Results and Implications

Sediment core profiles

All sites except the upper most site TISED 1 (near Wilson Ave), the site located near Campion Way TISED 6, and the lower most site TISED 8 near the footbridge, recorded a minimum of 40 cm of fine black sediment, in some instances with portions of sand (Figures 14 A to J). Most sites also recorded a thin (5 to 20mm) layer of orange to brown layer over the fine black sediment. The orange / brown layer is likely to be the result of oxidisation of iron within the upper layer of the black sediment, where it has contact with oxygenated waters of the inlet.

The deepest areas of fine black sediment were recorded at sites TISED 4 and TISED 9, where up to 60 and 80 cm was recorded respectively. Both sites are located in areas where residential development occurs on both sides of the inlet. Site TISED 6 is located within or close to a sand bund associated with installation of sewer and water services that cross the inlet in at this location (near Campion Way) , which accounts for the different sediment characteristics and depth at that location. TISED 8 located near the footbridge contained a substantial amount of recent seagrass wrack material and this area is subject to seasonal wrack deposition and tidal flushing.

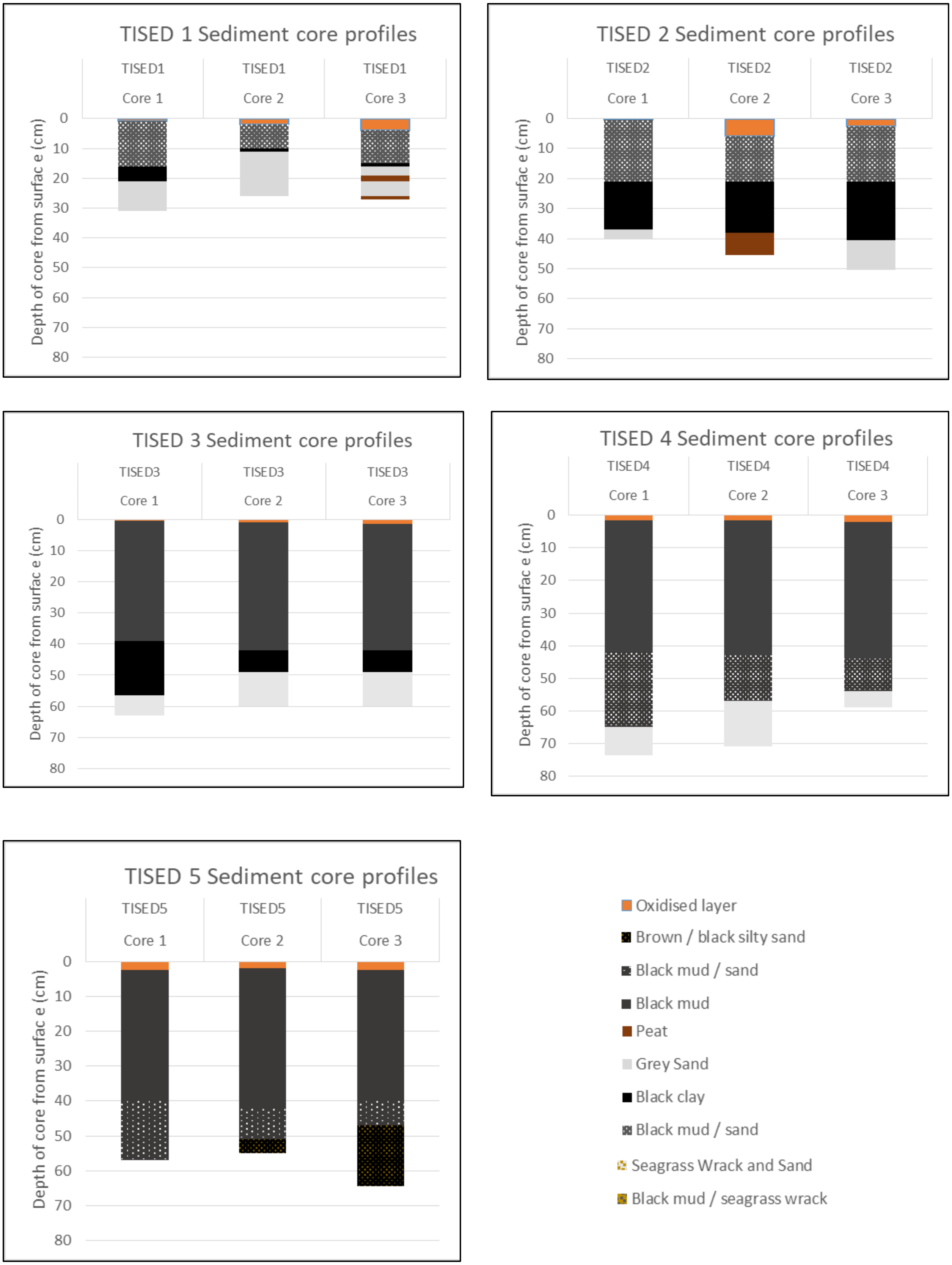


Figure 14: Sediment core profiles ate sites TISED1 to TISED5

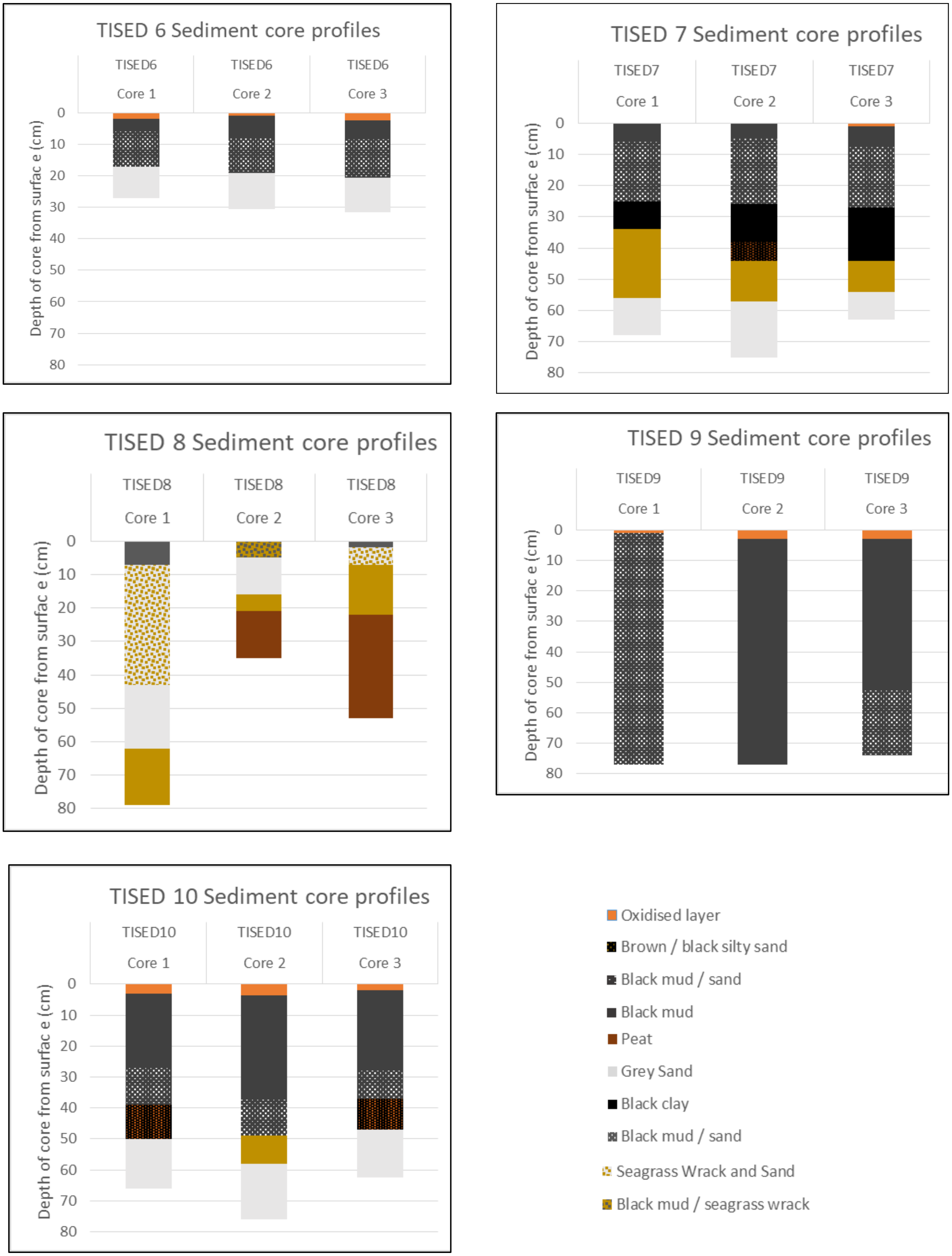


Figure 15: Sediment core profiles at sites TISED 6 to TISED 10.

Acid sulfate soils

Potential acidity was present at all sites. Surface Acid Volatile Sulfur (AVS) was greater than 0.01% at all sites, thereby meeting criteria to be considered as monosulfidic black ooze (Figure 16). However, more specific break down of the AVS has not been analysed. Aside from site TISED6 and TISED10 there was a general decreasing trend in AVS within surface sediments from upper to lower inlet sampling locations. Note that size 6 was an unusually sandy and was more similar in particle size to TISED1 where insufficient sample size was available for this measurement.

AVS in surface sediments was greater than or equal to 0.01% at all sites except TISED1 and TISED6 (both sandy sites). Using the action criteria of 0.03 %S (DER 2015) surface and bottom sediments at all sites showed acid forming potential (net acidity ranged from 0.14 to 1.25 %S). Elevated AVS in surface sediments indicates a high risk of deoxygenation of surrounding waters if sediments are disturbed.

The pH of sediments ranged from 7.9 to 8.6 at all sites indicating conditions were not acidic at the time of sampling. Acid Neutralising Capacity (ANC) was significantly higher than net acidity at all sites (Figure 18). When ANC is taken into account this resulted in net acidity and liming rates calculated as below limits of reporting at all sites (< 0.02 %S and <1 kg $CaCO_3$/t respectively). The high acid neutralising capacity is likely explained by the local Quindalup Dunes, which contain a high fraction of calcareous sands with a strong ability to neutralise acid. Note that DER guidelines (DER 2015) do not accept high ANC as a rationale for avoiding the application of lime to dredged sediments for the management of potential acid sulfate soils given the potential for ground shell fragments to cause overestimation of ANC. Therefore net acidity is presented with ANC excluded (Figure 19) which is equivalent to sulfur % (Figure 17).

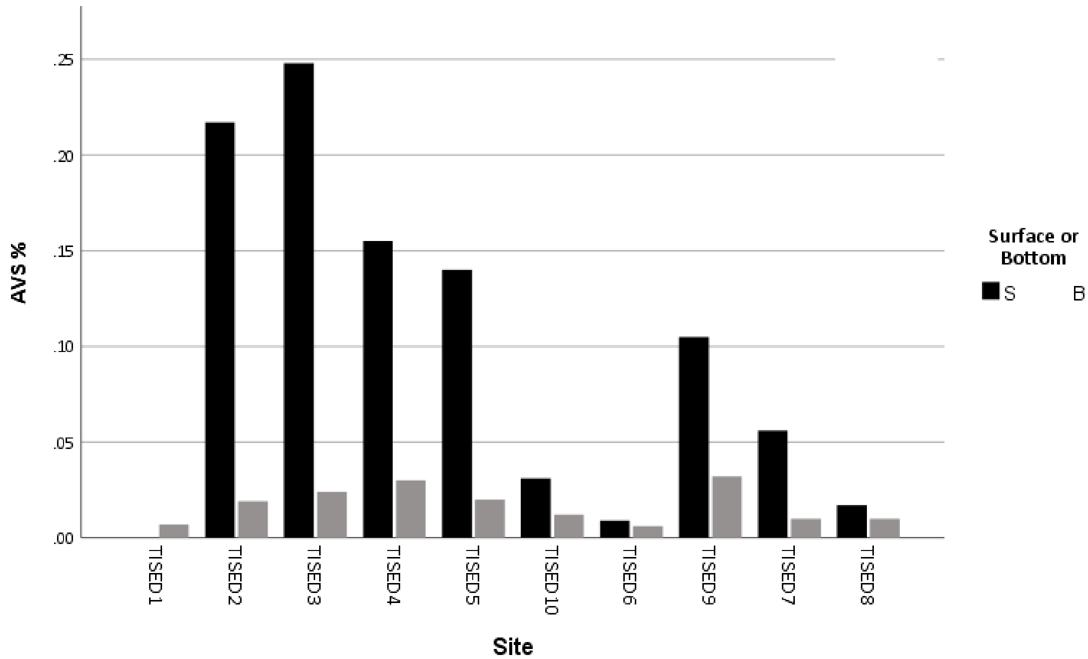


Figure 16: Acid Volatile Sulfur (%S) of surface and bottom sediments in the Toby Inlet Sites. Note: sites in plots above and all following have been ordered according to their location in the Toby Inlet (upper through to lower). LOR: 0.001 S%

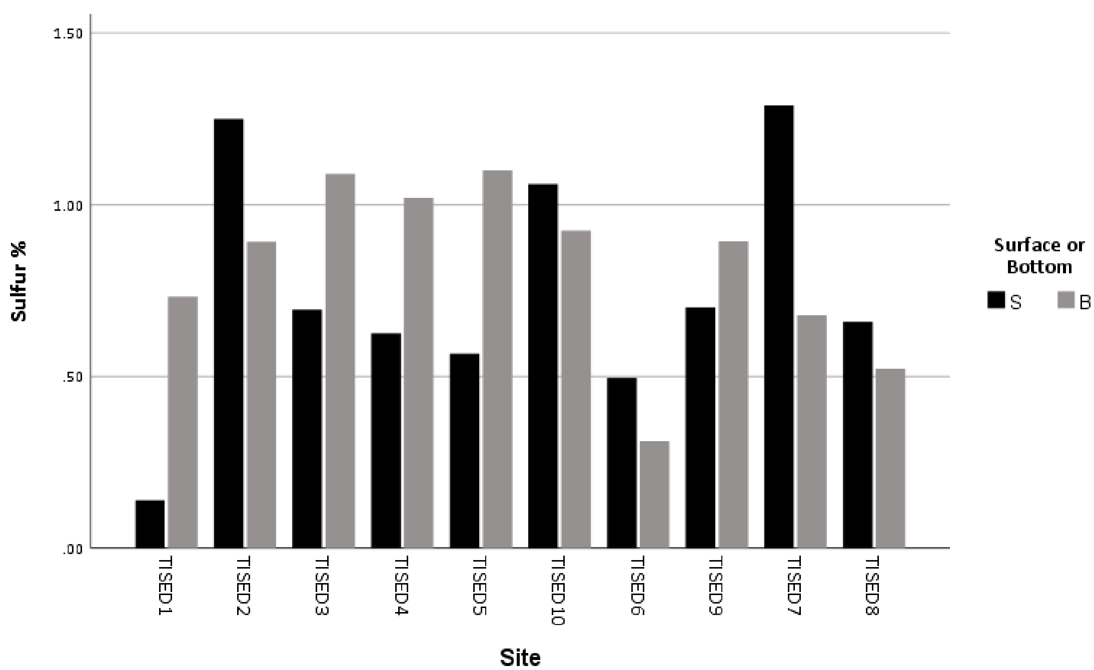


Figure 17: Chromium reducible sulfur in surface and bottom sediments of the Toby Inlet LOR: 0.005 S%

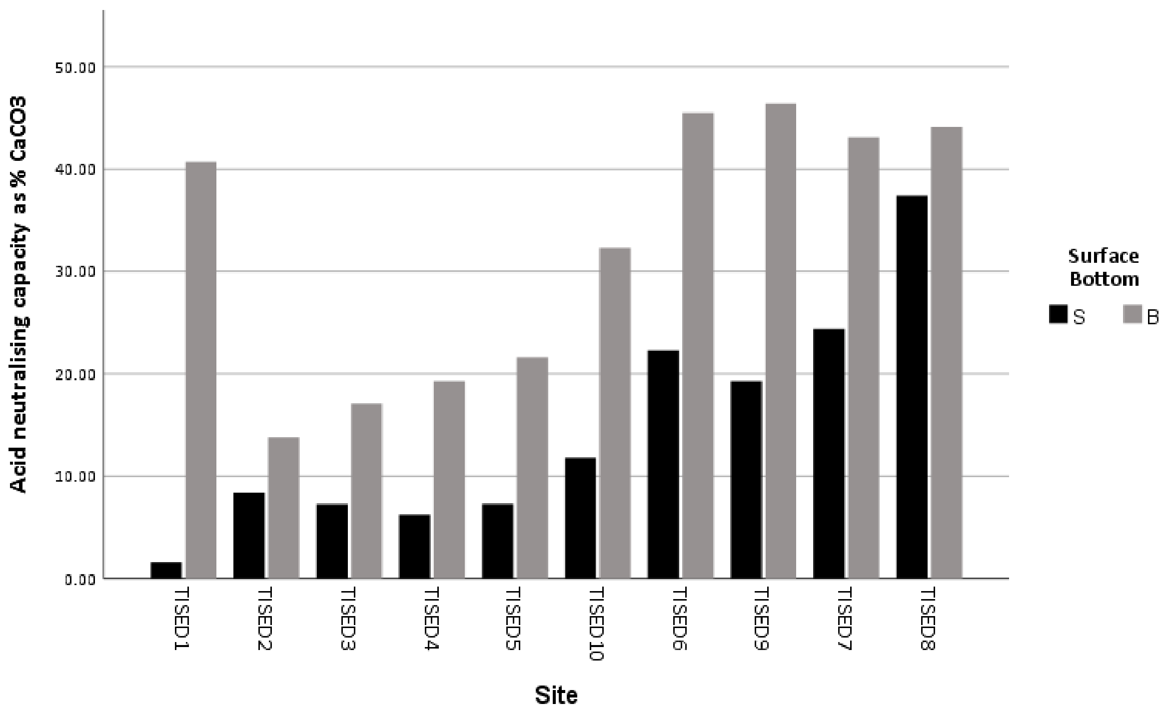


Figure 18: Acid neutralising capacity (CaC03 %) of surface and bottom sediments of Toby Inlet. LOR: 0.01 CaC03 %

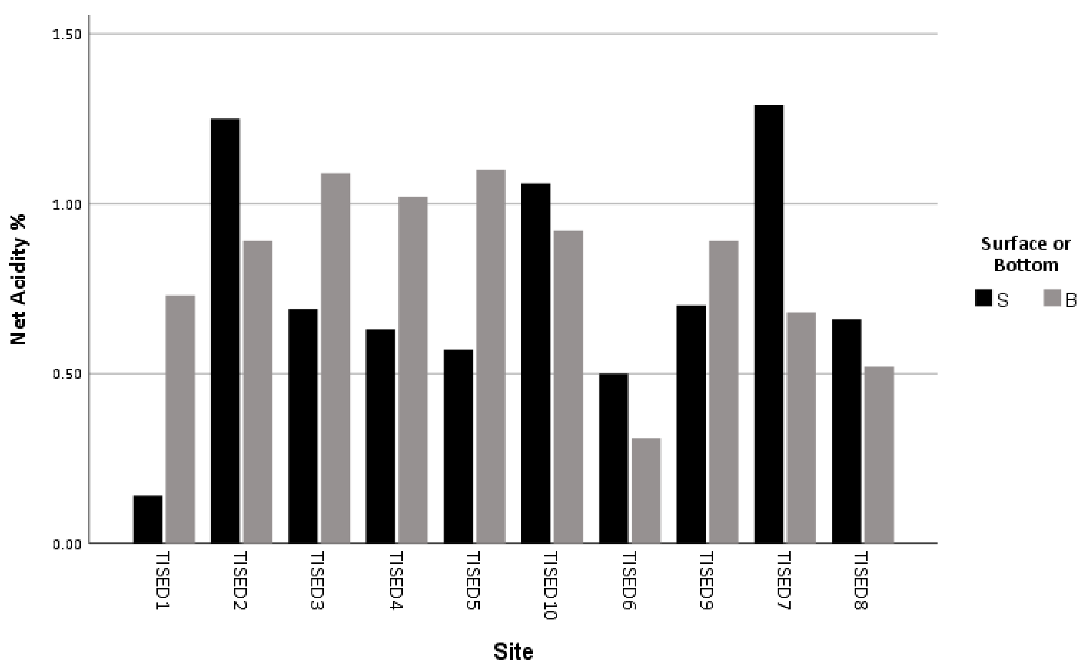


Figure 19: Net acidity excluding acid neutralising capacity of surface and bottom sediments in Toby Inlet. LOR 0.02 S%

Particles size and soil classification

Across all sites surface sediments were associated with a greater fraction of very fine sediment than bottom samples (Figure 20). Surface sediments had the greatest fraction of fine particles at sites TISED 2, 3, 4 5 and 10, all located upstream of Campion Way. Sites at TISED 1, TISED 6 and TISED 8 were associated with the largest grain size in both top and bottom sediments. These reflect the sandiest sites and those with the least concern regarding sediment quality.

While some larger sand fragments were mixed in with fine sediment samples, a large proportion of surface sample particles in Zone 2 and 3 were smaller than 0.075 mm and the major proportion of particles (greater than 60% in surface samples and 50% in bottom samples) were smaller than 0.3 mm at all sites except TISED1 and TISED6. At below 0.2 mm to 0.3 mm, disturbed sediment particles delivered to Geographe Bay would be expected to remain in suspension and be dispersed by currents rather than quickly settling (Pattiaratchi & Wijeratne, 2011). Within the inlet, high flow conditions are likely to carry very fine particles that are re-suspended following disturbance some distance downstream, though this distance cannot be calculated without flow velocity data. Fine sediment particles are also likely to require artificial flocculation and filtering in order to be separated from water for disposal after removal via a dredge.

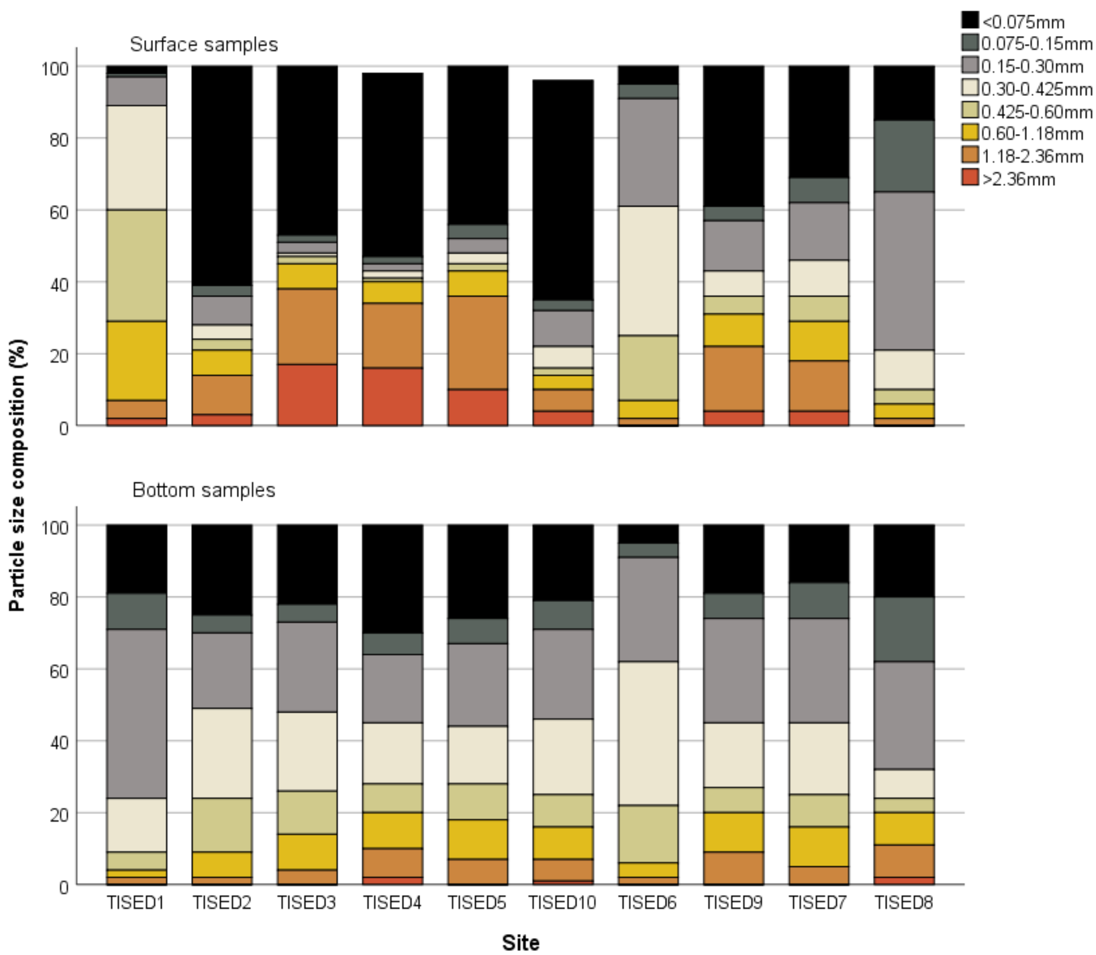


Figure 20: Sediment particle size in surface and bottom core samples from Toby Inlet (analysed using the hydrometer method).

Moisture Content

Sediments at all sites except TISED1 and TISED2 in the upper inlet had a moisture content above 50% (Figure 21). Sites TISED 3, TISED5, TISED6 and TISED7 had moisture content above 80%. The high degree of moisture content in most samples is an important consideration for removal of sediment given the need to minimize the water content of sediment in order to reduce the cost of transport. The low moisture content of samples at TISED2, where sediment was also deep, presents an opportunity for alternative removal methods compared to other locations, involving direct pumping of sediment for transport using liquid waste disposal trucks. Such methods are uneconomical where a high volume of water lies over sediment.

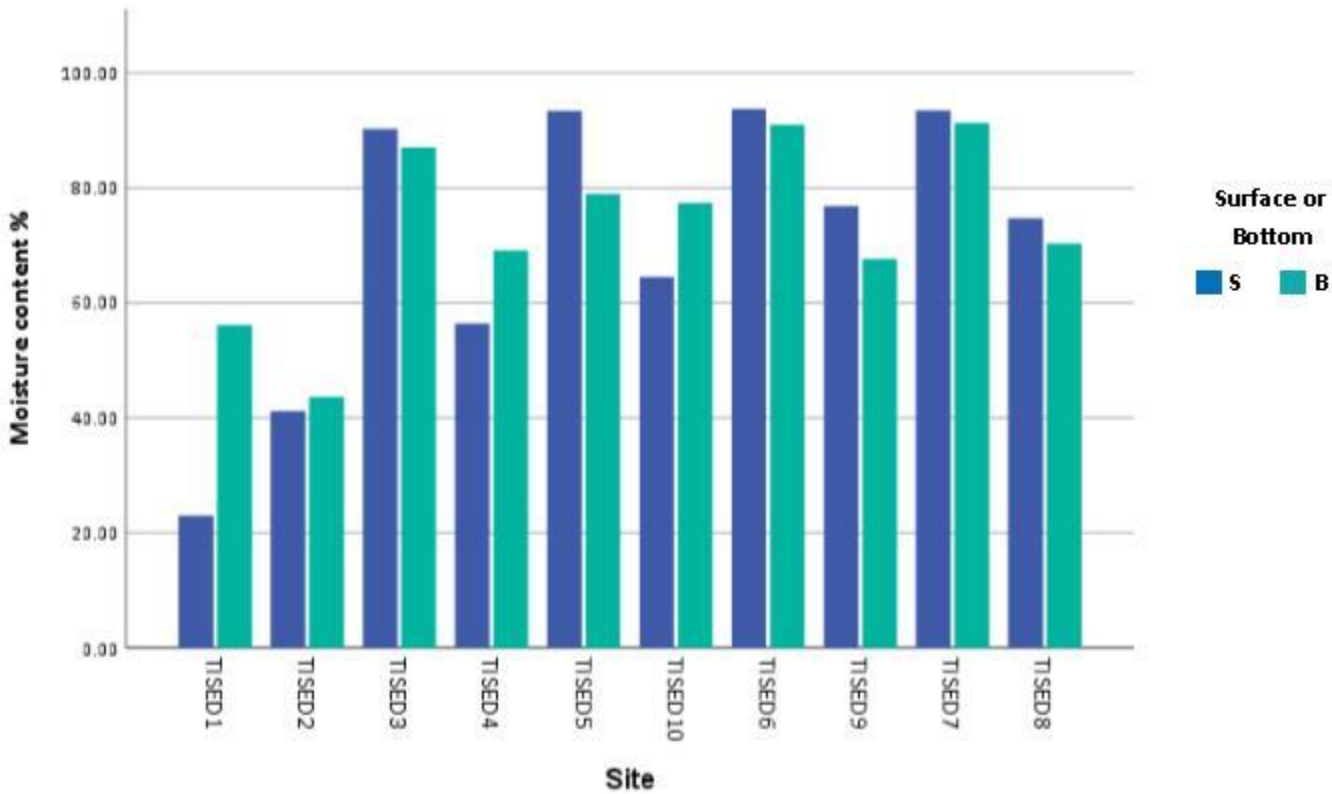


Figure 21: Moisture content in surface and bottom core samples from Toby Inlet.

Total organic carbon

Total organic carbon (TOC) was high at all sites except the sandy sites TISED1 and TISED6 (Figure 22), and was much higher in surface sediments than bottom sediment at all sites except TISED1 and TISED8. The very high TOC % at TISED8 is not of concern given that was comprised of recently deposited seagrass wrack and is likely to be flushed during tidal exchange and seasonal flows. High TOC can indicate poor estuarine sediment health and may be associated with low oxygen conditions associated with decomposition processes as well as release of nutrients back into the water column.

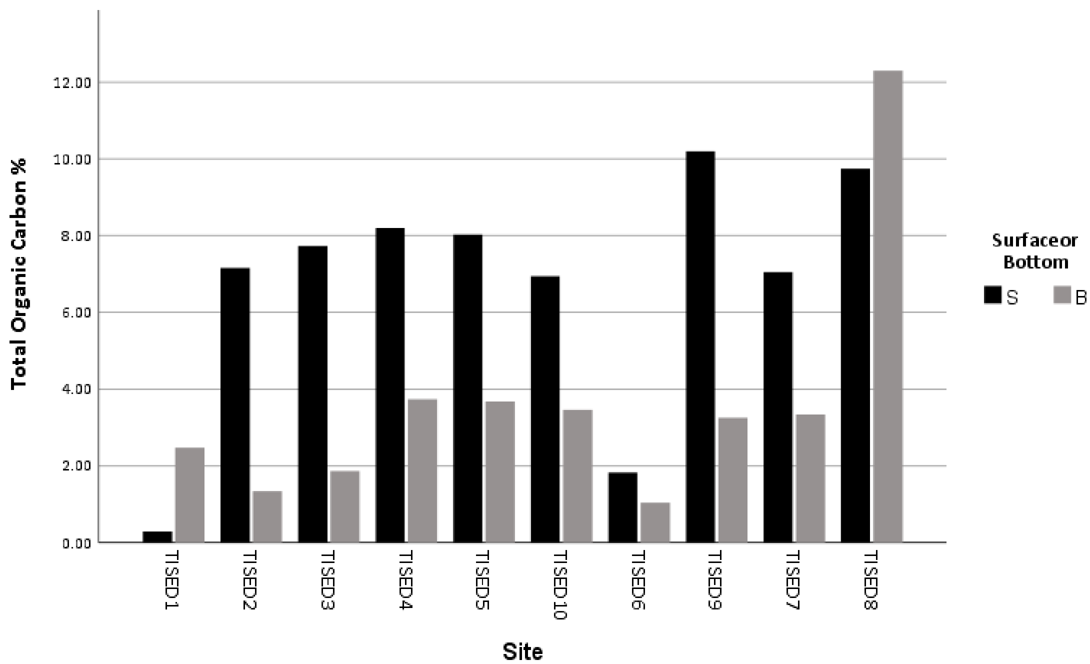


Figure 22: Total organic carbon (%) in surface and bottom sediments in the Toby Inlet. LOR 0.02 C%.

Metals

All metals and metalloids were below the ANZECC Default Guideline Value (DGV) for sediments in both surface and bottom sediments (Tables 4 and 5) (where such guidelines exist (ANZECC and ARMCANZ, 2000). The same guideline levels as the ANZECC DVG and ANZECC DGV-High are also used in the *National Ocean Disposal Guidelines for Dredged Materials*. These results indicate that sediment are not considered contaminated from an ecological health perspective. Despite this, chromium, lead and nickel concentrations were above the criteria levels for disposal to a Class 1 or 2 landfill in WA without leachate testing (DWER, 2019), therefore leachate testing and subsequent evaluation is required for any removal project that involves disposal to landfill. All other concentrations were below these guidelines and such leachate testing would not be required for other disposal options.

Table 4: ANZECC default sediment guideline (DGV) and DGV – high for sediments Australian estuaries, and guidelines for disposal of sediments to Class 1,2 and 3 landfill without prior leachate testing (ANZECC and ARMCANZ, 2000, DWER, 2019).[1]

	ANZECC DGV (mg/kg)	*ANZECC DGV-high (mg/kg)*	*Class 1 and 2 landfill guideline for no leachate test (mg/kg)*	*Class 3 landfill for no leachate test (mg/kg)*
Antimony	2	25		
Arsenic	20	70	14	140
Cadmium	1.5	10	0.4	4
Chromium	80	370	10	100
Copper	65	270		
Lead	50	220	2	20
Manganese				
Nickel	21	52	4	40
Selenium			2	20
Silver	1	4	20	200
Zinc	200	410		
Mercury	0.15	1	0.2	2
Aluminum	5 % by weight		5 % by weight	10 % by weight
Iron				

[1]Ddifference of limits of reporting for cadmium across sites occurred as a result of high moisture content in some samples. These differences did not affect evaluations against guidelines.

Table 5: Metal content of sediments in Toby Inlet. Red values indicate that leachate testing is required prior to disposal to landfill.

	Antimony	Arsenic	Cadmium	Chromium	Copper	Lead	Manganese	Nickel	Selenium	Silver	Zinc	Mercury	Aluminum	Iron
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Limit of reporting	0.5	1	0.1	1	1	1	10	1	0.1	0.1	1	0.01	50	50
TISED1-S	<0.50	<1.00	<0.1	2.1	<1.0	1.6	11	<1.0	<0.1	<0.1	3	<0.01	820	3430
TISED1-B	<0.50	1.71	<0.1	10.4	1.2	4.6	64	1.9	0.4	<0.1	7	0.01	3720	6360
TISED2-S	<0.50	3.07	<0.4	11.6	8.2	9.4	174	4.4	0.7	<0.4	38.1	0.04	9260	18200
TISED2-B	<0.50	2.67	0.2	10.4	4.2	9.5	116	3	0.4	<0.1	19.2	0.04	7610	13500
TISED3-S	<0.50	2.28	<0.4	7.3	5.2	4.1	83	3.1	<0.4	<0.4	23.7	0.03	4650	8810
TISED3 - B	<0.50	1.92	0.2	11.4	4.9	9.4	64	3.1	0.5	<0.1	20	0.04	9000	13600
TISED4-S	<0.50	2.16	<0.5	6.3	5.4	3.8	61	2.9	<0.5	<0.5	22.1	0.03	4180	7550
TISED4-B	<0.50	2.13	0.2	13.4	5.1	8.4	69	4.8	0.7	<0.1	21.9	0.06	7470	12400
TISED5-S	<0.50	2.25	<0.5	7.2	5.9	4.1	66	3	0.8	<0.5	26.4	0.03	4330	7930
TISED5-B	<0.50	2.17	0.3	14.2	5.1	8	57	4.8	0.7	<0.1	22.4	0.08	7010	11400
TISED6-S	<0.50	1.8	<0.1	8.9	1.7	3.3	37	1.4	0.2	<0.1	6.9	0.01	3840	5160
TISED6-B	<0.50	2.02	0.1	10.6	1.8	2.6	32	1.7	0.3	<0.1	6.8	0.02	2780	3720
TISED7-S	<0.50	2.94	0.4	16.4	7.8	7	66	5.3	0.8	<0.2	27.8	0.04	7490	12900
TISED7-B	<0.50	2.45	0.3	17.3	4.8	6	34	4.4	0.6	<0.1	15.1	0.1	5520	9070
TISED8-S	<0.50	2.13	0.3	12.5	3.7	3.7	30	3.2	0.5	<0.1	13.2	0.02	3480	6010
TISED8-B	<0.50	1.56	0.4	11.2	3.7	3.3	34	4.7	0.6	<0.1	8.3	0.02	2550	4840
TISED9-S	<0.52	2.27	<0.5	10.9	5.4	3.2	34	3.6	<0.5	<0.5	21.3	<0.02	3250	6400
TISED9-B	<0.50	1.76	0.3	17	5.5	7.8	35	3.9	0.6	<0.1	18.8	0.03	7620	10500
TISED10-S	<0.50	2.07	<0.4	11.2	5.6	6.5	80	4.1	<0.4	<0.4	23.6	0.03	7330	11300
TISED10-B	<0.50	1.97	0.2	14.5	4.5	6.4	45	4.1	0.6	<0.1	17.1	0.07	6060	8880

Nutrients

Total phosphorus and total nitrogen were elevated at sites TISED2, 3, 4, 5 ,7 and 9 (Figures 23, 24). These locations roughly align with the areas of higher density adjoining residential development, particularly locations where residential development occurs on both sides of the inlet. This result is not unexpected as the majority of residential development around Toby Inlet was unsewered until recently. Water Corporation has recently completed construction of a new sewer line to these areas and individual connections will now need to follow. Total nitrogen followed a very similar pattern to total phosphorus (Figure 21). Both phosphorus and nitrogen were higher in surface sediments than bottom sediments and were much lower at the sandy sites TISED 1 and TISED 6.

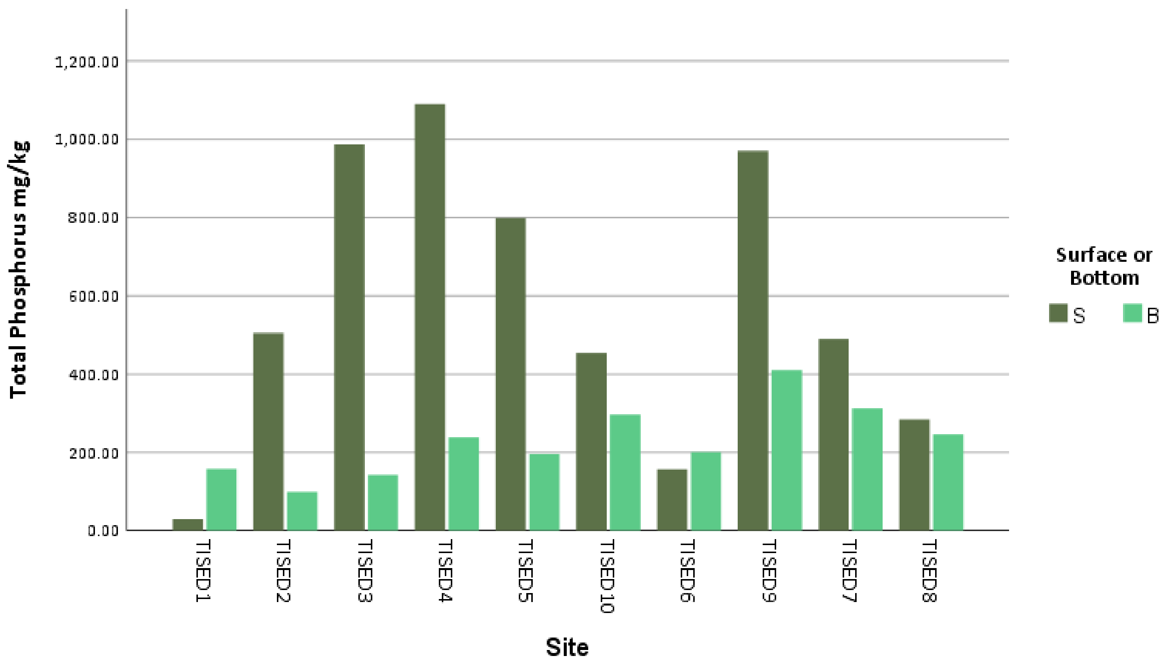


Figure 23: Total phosphorus in surface and bottom sediments in Toby Inlet. LOR: 2 mg/kg

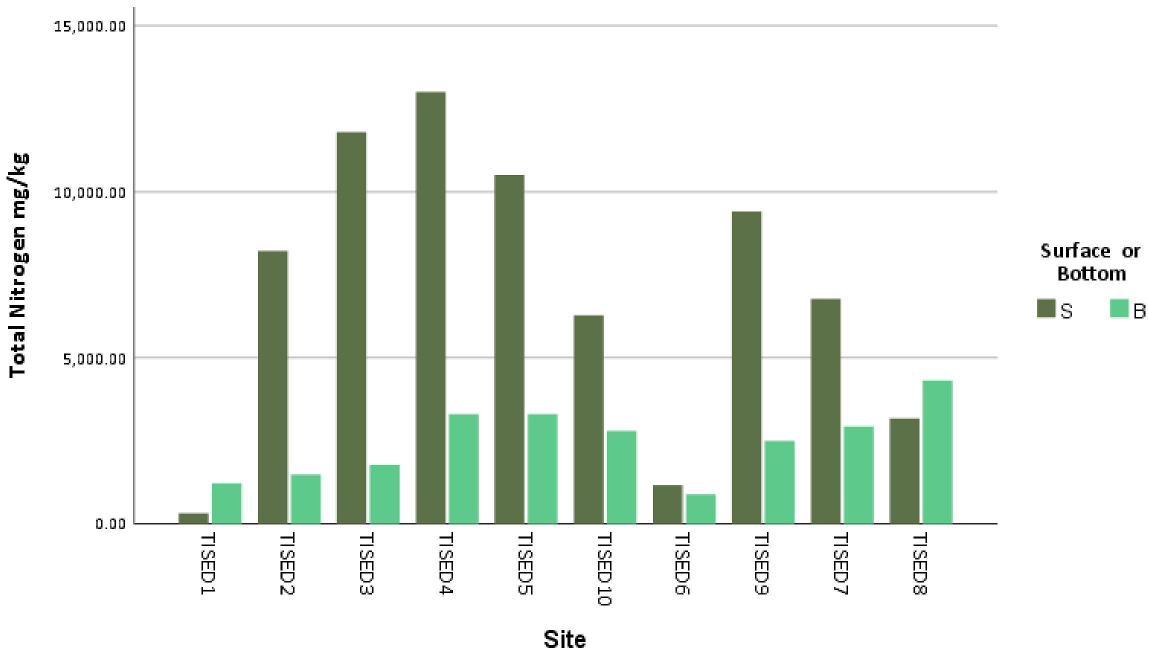


Figure 24: Total nitrogen in surface and bottom sediments in Toby Inlet. LOR: 20 mg/kg.

Part C: Sediment depth and volume

Methods

A survey of the depth and volume of sediment in Toby Inlet was undertaken by Apex Envirocare in January 2020. The inlet perimeter was established using satellite imagery and AEC mapping software prior to mobilisation to site. A small twin hulled craft was used to travel along the inlet and measurements of sediment and water depth were taken every 50m to 100m by taking core samples of the sediment at 3 point across the width of the inlet. Averages of the surrounding areas were used to provide data for sections of the inlet that were not accessible due to minimal water levels. Data for the upper reaches of the inlet (Upstream of Stone Street) was provided by Ottelia Ecology. 5 transects with measurements taken of sediment depth and water depth were taken at 5 points across the width of the inlet at each transect location.

Sediment depth and GPS locations were recorded for each site. Using the GPS and depth input information and the specialist mapping software, a base profile and a sediment profile of the estuary was generated. These showed sediment depths and distribution along with the depths of the inlet. The total inlet and sediment volumes were then calculated. This information was then broken down into 5 individual areas. Air photos have been superimposed behind these maps to help the reader orient the locations of maps along the inlet. Note that there are minor inaccuracies between the air photo layers and the mapping layer due to minor air photo distortion.

For comparison with the areas described in the preceding section 'Sediment Condition' Sections 1 and 2 combined correspond with 'Zone 2: Fine black sulfidic sediments exposed at low tide'; while sections 3, 4 and 5 correspond with Zone 3: Fine black sulfidic sediments with shallow water cover at low tide'. Remaining areas were not surveyed sediment depth and volume (Figure 22).

Figure 22: Location of sections of Toby Inlet surveyed for sediment depth. .

Results

A total of 60300 m^3 of soft sediment was calculated as having accumulated in the surveyed area of Toby Inlet (Table 6). This is roughly equivalent to 2.8 times the volume of seagrass wrack that is estimated to annually wash up on Geographe Bay beaches (Oldham, 2010).

All sections of the inlet surveyed contained areas of accumulated sediment at least 0.8m deep. The deepest zones of sediment accumulation were recorded in sections 4 and 5, where isolated areas of sediment were 1.25 and 1.5m deep respectively. At the time of survey, the upper area of the inlet (Sections 1 and 2 within Zone 2) was associated with a very high sediment to water volume ratio (Table 6, Figures 23 to 27), noting that measurements were taken at low tide.

On average across the survey area, for every 1m^2 of the inlet surveyed, there was 0.42m^3 of sediment measured, taking account of all variations across the channel. The average volume of sediment accumulated in the inlet per m^2 gradually increased as distance from the mouth decreased, with section 5 showing an average volume of 0.52 m^3/m^2. This slight increase likely reflects a gradual increase in depth of the natural estuary floor, thereby allowing a greater depth of sediment to accumulate in areas that would have once been deep pools.

Table 6: Sediment volume in surveyed sections of the Toby Inlet

Sediment Condition Zone	**Section of Inlet**	**Inlet Volume m^3 (Sediment and water)**	**Sediment Volume m^3 (Sediment only)**	**Proportion of sediment to water %**	**Perimeter m**	**Area m^2**	**Average m^3 of sediment per m^2 of area surveyed**
Zone 1	Sediment depth and volume not surveyed						
Zone 2	1	6048	5588	92	758	14160	0.39
Zone 2	2	10420	9266	89	1246	21630	0.43
Zone 3	3	17364	12820	74	1743	29320	0.44
Zone 3	4	27359	17350	63	2090	35990	0.48
Zone 3	5	23780	15272	64	2073	29230	0.52
Zone 4	Sediment depth and volume not surveyed						
	Total	**84971**	**60296**	**71**	**7588**	**130630**	**0.46**

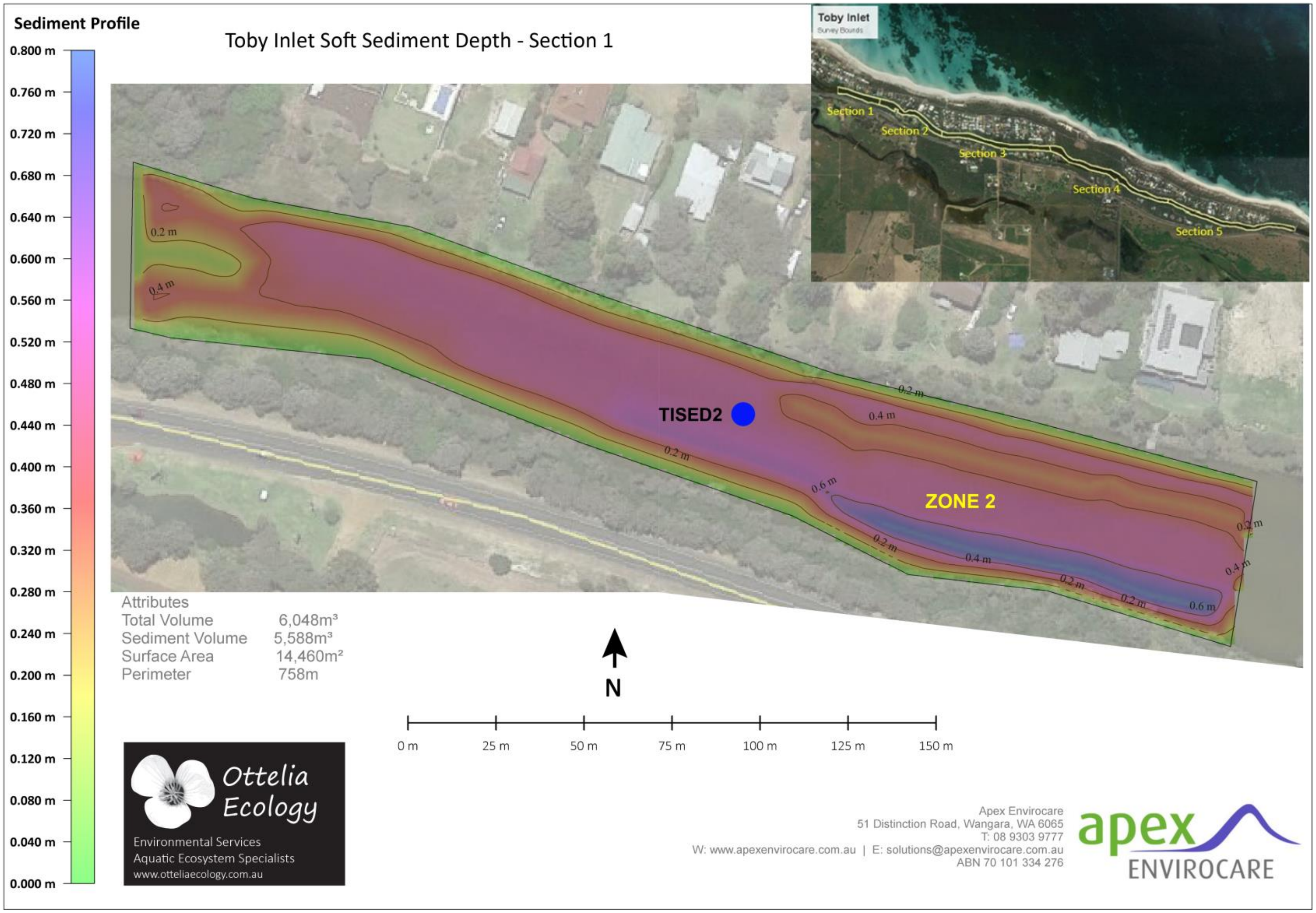


Figure 23: Soft sediment depth in section 1 (located in Zone 2).

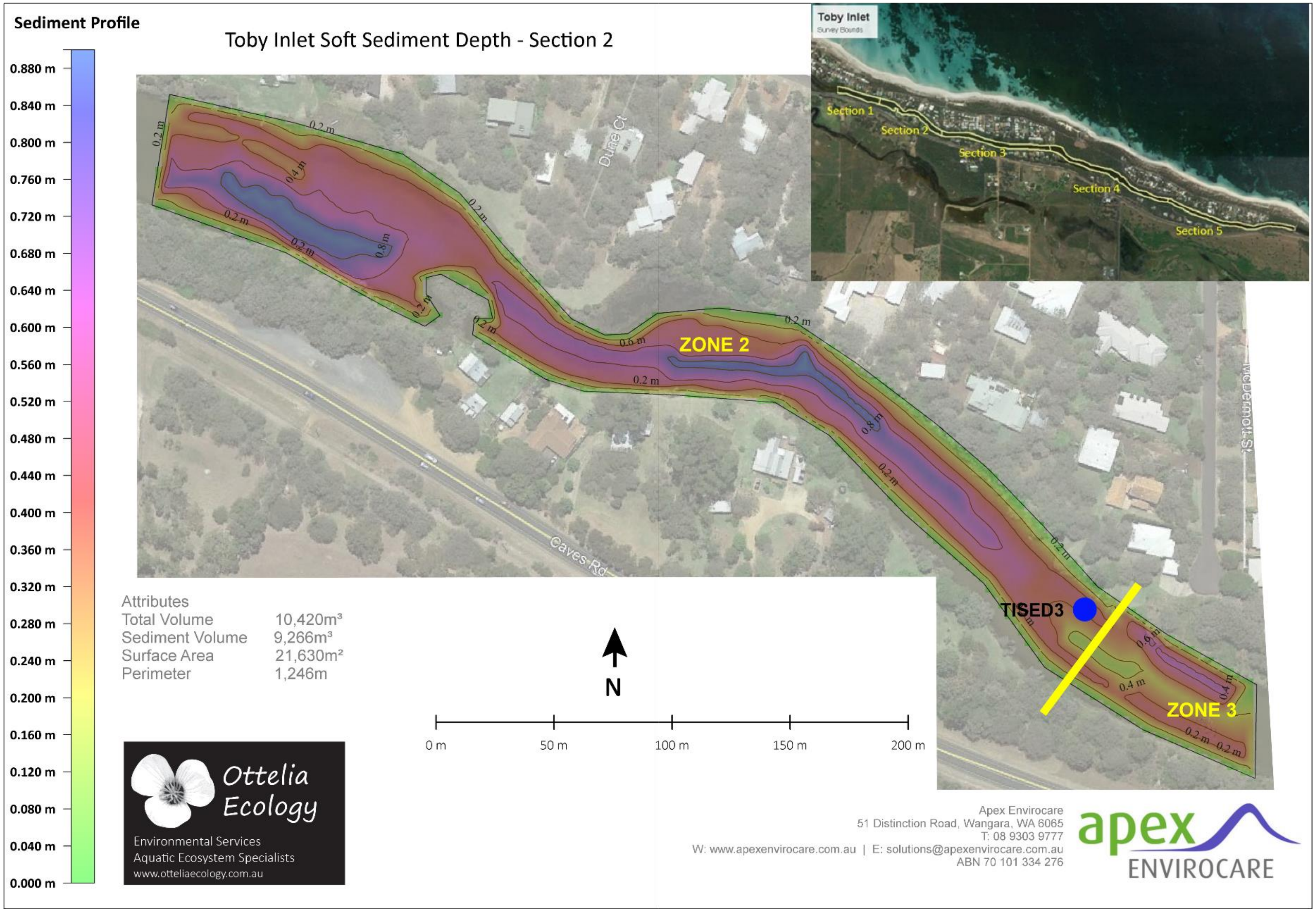


Figure 24: Soft sediment depth in section 2 (located in Zone 2).

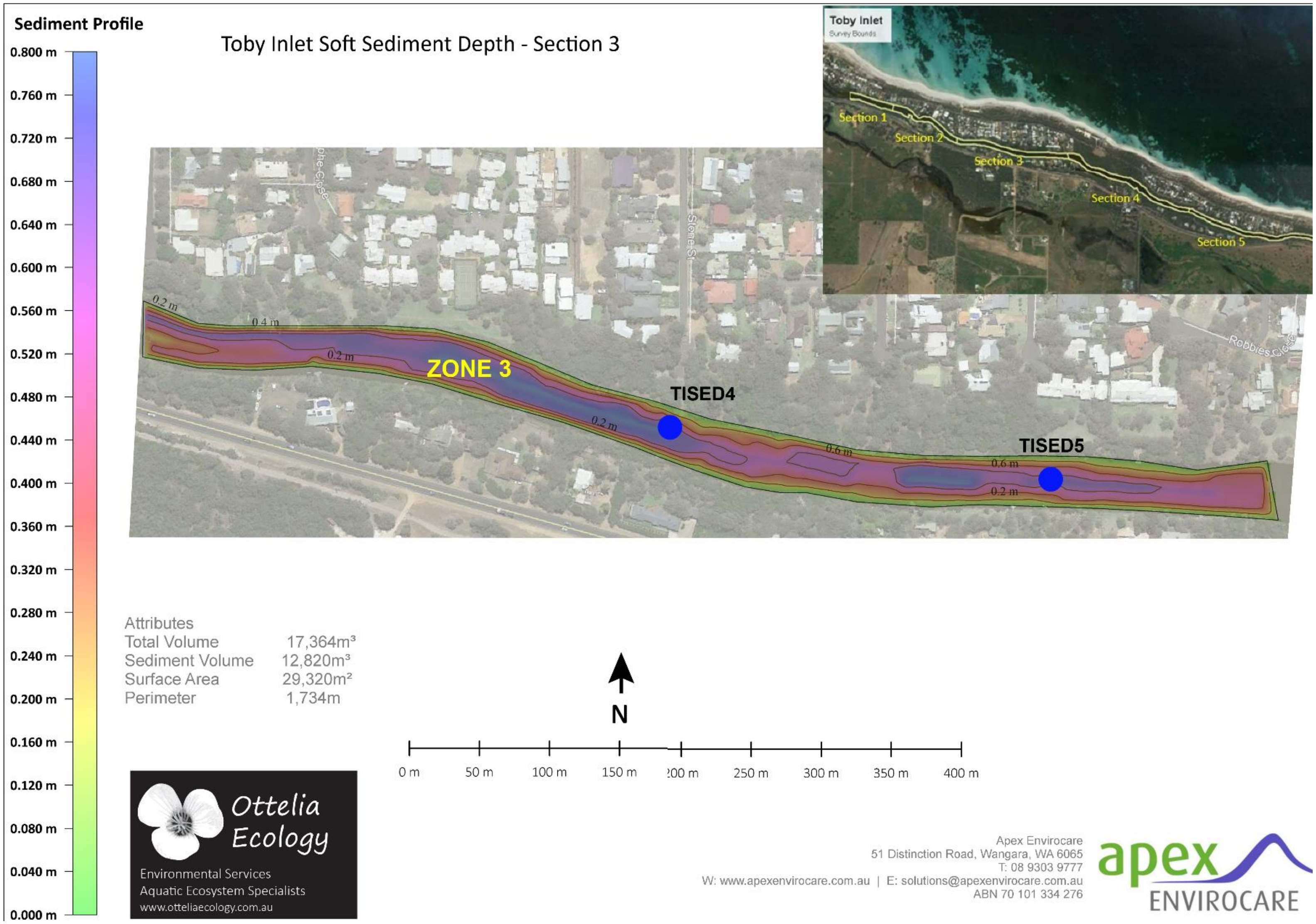


Figure 25: Soft sediment depth in section 3 (located in Zone 3).

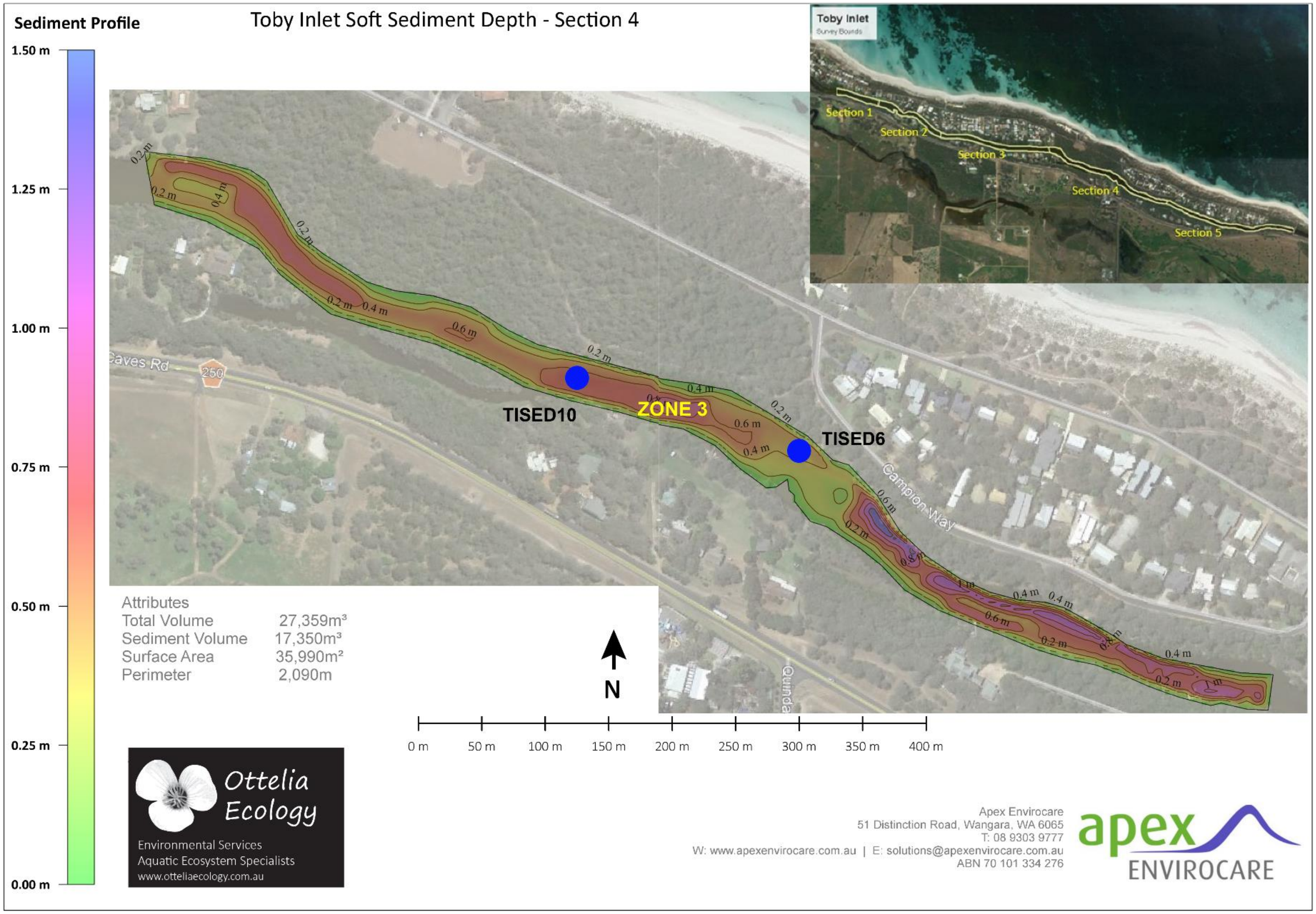


Figure 26: Soft sediment depth in section 4 (located in Zone 3).

Figure 27: Soft sediment depth in section 5 (located in Zone 3).

Key findings from part A, B and C investigations

Impacts of sediments on values and likely benefits of removal

Sediment accumulation has significantly impacted the ecological, heritage and cultural values of the Toby Inlet. Local residents and community members have described a significant deterioration in the health of the inlet over the past ten to twenty years. A summary of the inlet values, impacts of sedimentation and likely benefits of removing sediment (if removal can be achieved safely) is provided in Table 7 below.

Table 7: Toby Inlet Values, impacts of sedimentation on the values and likely benefits of sediment removal.

Value category	*Description of current (or past) values*	*Impacts of sedimentation*	*Likely benefits of sediment removal*
Fish	Toby Inlet provides important habitat for fish: recent surveys recorded 12,438 fish from 17 species (Tweedley et al. 2018). Estuarine species that spend their entire life cycle in the inlet were dominant, but recruitment of juvenile marine species present. Examples of recreationally important species recorded include: Black Bream *Acanthopagrus butcheri,* Mullet *Mugil caephalus,* Smalltooth flounder *Pseudohombus jenynsil* Healthy estuaries are vitally important habitat for hundreds of fish species. Approx. 75 % of Australian commercially caught fish and up to 90% of recreational species spend at least part of their life cycle within estuaries (Tweedley et al., 2018).	Fish kills have been reported in 1983 and 2014. The 2014 event was attributed to fish stranding as a direct result of the separation of shallow pools at low tide by accumulated sediment (Brearly, 2005; Frazer and Hall, 2018) Shallow water conditions and an absence of aquatic plants severely limit opportunities for fish to shelter from predators, meaning predation is likely to be high (Tweedley, pers. com., 2020). High risk of low oxygen conditions in the water column arising from large volumes of MBO sediments in the inlet - high ongoing risk of fish kills.	Improved habitat and reduced predation of fish by raptors. Improved connectivity along the length of the inlet and reduced risk of fish stranding. Improved opportunity to restore aquatic macrophytes within the inlet, which would substantially improve both feeding opportunities (arising from increased macroinvertebrates) that and shelter opportunities. Greater abundance of fish, due to expanded habitat, supporting recreational fishing.
Crabs	Anecdotally, crabs were regularly caught in the Toby Inlet during the 1970s and 1980s, (Clay, 2005). Crabs are	Smothering of clean sandy habitat suitable for benthic dwelling crustaceans such as crabs.	Restoration of suitable habitat for crabs, providing the majority of accumulated sediment can be

Value category	*Description of current (or past) values*	*Impacts of sedimentation*	*Likely benefits of sediment removal*
	not commonly seen now other than in the very lower mouth.	High risk of low oxygen conditions in the water column arising from large volumes of MBO sediments in the inlet	removed from downstream sections of the inlet.
Waterbirds	Toby Inlet provides an important drought refuge for waterbirds. Surveys have identified 68 species including 28 species of water birds (Clay, 2005). Species recorded nesting in the inlet have included: • Black Swans • Australian Wood duck • Australian Shelduck Seabirds such as kestrels and ospreys are regularly sighted feeding in the inlet. An Osprey nest with chicks was also observed in a large tree near the banks of the inlet at McDermott St during sampling for this report.	Anecdotally, waterbird abundance and diversity have significantly reduced in the past ten years. Shallow water conditions in summer have reduced the suitability of the inlet as a summer refuge for waterbirds. Some species of large birds such as black swans and Pelicans can no longer swim in the shallow waters. Severe degradation of feeding habitat arising from deep accumulations of MBO sediments.	Restored habitat for wading, diving and paddling waterbirds. Improved habitat for fish will benefit piscivorous bird species. Restored aquatic macrophytes would like result in improved feeding habitat arising from increased macroinvertebrates; and provide nesting material for swans.
A unique and healthy estuarine ecosystem	Toby Inlet is one of only two estuarine systems that discharge into southern Geographe Bay, the other being the Vasse Wonnerup wetland system. Toby Inlet has a unique estuarine morphology being a long elongated channel running parallel to the coastal dunes. Despite extensive hydrological change, Toby Inlet retains many of the elements of a functioning natural estuary including: • extensive fringing native vegetation in good	Smothering of benthic habitats, potentially impacting ecology (City of Busselton, 2019). Blocking of water flow in the inlet, preventing flushing of nutrients and organic material from the system. (City of Busselton, 2019). Reduced habitat quality for fish and waterbirds, absence of aquatic macrophytes.	Water quality improvement is expected due to flow management and sewer connection; sediment removal will increase aquatic habitat areas and improve benthic habitats, restoring estuarine ecological functions.

Value category	Description of current (or past) values	Impacts of sedimentation	Likely benefits of sediment removal
	condition (City of Busselton, 2019); • Diverse natural fish populations (Tweedley et al, 2018).		
Important Visual amenity / special character	Toby Inlet has been recognised for its regionally significant ecological, rural landscape and cultural values (WAPC, 1998). The inlet is included within a Wetland Amenity area within the Leeuwin Naturaliste Ridge Statement of Planning Policy (WAPC, 1998). The elongated inlet flows very close to Caves on the approach to the Dunsborough townsite. It provides an important scenic focal point to the entrance the Dusnborough / Yallingup area - one of the most highly visited tourist destinations in WA. Toby Inlet and its associated foreshore form an important part of the character of the Quindalup area. The City of Busselton has recognised the importance of this character via the Quindalup Special Character Policy, which refers to the foreshore vegetation and open water vistas of the inlet as important components.	Loss of open water vistas and unpleasant odours of exposed sediment during low water levels have impacted severely on visual amenity. (City of Busselton, 2019) During summer the water levels are very low, in some places sediments are exposed at low tide. When this occurs the visual amenity is very poor.	Improved open water vistas, reduction in odour and improved overall visual amenity.
On water recreation	Historically, Toby Inlet was a popular location for fishing (including crabbing) and it was possible to travel up and down much of the length of inlet by small boat (canoe or small dinghy).	Reduced depth restricting severely restricts recreational activities such as use of watercraft (City of Busselton, 2019) Rotted jetties along the mid to upper length of	Improved water depth in the inlet would provide a return of recreational opportunities in the inlet that were available prior to sedimentation.

Value category	*Description of current (or past) values*	*Impacts of sedimentation*	*Likely benefits of sediment removal*
	Residents of southern bank of Toby Inlet (those alongside Caves Road) would previous row across the inlet in order to access the beach at Geographe Bay.	the inlet provide evidence of a change in water level that has precluded recreational access along this section of the inlet for many years	
Indigenous cultural values	Wetlands and estuaries are traditionally important places for aboriginal people. They provided opportunities for hunting as well as seasonal camping sites. Toby Inlet was used regularly by the Wardan people of the local area.	Sediment accumulation has led to loss of recreation and fishing opportunities.	Removal of the legacy load of sediments from the inlet (if undertaken safely) to enable restoration of a healthy estuarine system would over time restore many of the values that were of cultural importance.
Historical significance	Toby Inlet was a focal point for Quindalup, a timber town that was settled in the mid-1800s. A homestead and a few outbuilding from this settlement are still in use on and near the banks of the inlet. The inlet is named after Captain Jacob Toby who sailed the Schooner “Ellen” and would barter knives, sugar and tea in exchange for fresh goods from the local villagers.	Sedimentation has significantly impacted the way the inlet is used by local people compared to the period of the early settlement of Quindalup. It seems likely that the inlet was much deeper at that time.	Improved water depth in the inlet would provide a return of recreational opportunities in the inlet that were available during early settlement.

Spatial assessment of sediment impacts

Community feedback, field observations and measurement of sediment depth and characteristics informed an evaluation of the impacts of sedimentation on different parts of the inlet. A summary of impacts is provided in Table 8. Overall, sediments were found to be having multiple severe impacts in Zones 2 and 3 in Toby Inlet in terms of physical degradation of the inlet habitat; the likely ongoing impacts of sediments on water quality; loss of amenity; and loss of recreational opportunities. Zones 2 and 3 occupy a significant proportion of Toby Inlet spanning a 3.7 km stretch upstream of the footbridge.

Zone 1 has accumulated sandy sediments which has impacted visual amenity, yet these sediments are not as concerning as parts of the inlet where fine black sediments predominate. Shorebirds were observed making use of shallow water habitats for feeding along the sandy shoreline areas of Zone 1. This was not observed in other areas of the inlet. There is limited suitable feeding habitat for waders elsewhere in the inlet and piscivorous species such as pelicans can no longer paddle in the inlet at low tide. There has been an anecdotal loss of these birds from the system as a whole.

Zone 2 was the most severely impacted by sediment accumulation across all value categories at low tide.

Zone 3 had slightly deeper water cover over sediments which gradually increased with distance towards the mouth. High to severe impacts on visual amenity, recreational access, fish habitat and waterbird habitat were identified from the accumulation of deep fine black sediment in Zone 2 and 3 in the Toby Inlet.

Visual amenity and fish habitat were improved under high tide (higher water level) conditions in all areas, however it is not possible to prevent the impacts of very low tides without removing sediment from these areas. While fish have been recorded along the length of the inlet, their available habitat has been substantially reduced. In some parts fish are likely to have only 10 to 15 percent of their available water volume area available as a result of deep sediment accumulation. This leaves them very prone to high levels of predation by raptors, and the shallow conditions can also lead to high water temperature and low oxygen levels. Shelter from predation is virtually absent in these impacted areas as well due to an absence of aquatic plants within the channel, which cannot grow within the deep black sediment.

Recreational access for fishing and boating (whether by canoe or powerboat) is limited along most of the inlet except at very lower areas from Bloor St downstream.

Zone 4 was largely unaffected by sedimentation.

Table 8: Degree of impact of sedimentation on ecological and amenity values of Toby Inlet

	Degree to which the value is impacted by sediment accumulation during summer at specified location within Toby Inlet - low tide scenario			
Value	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
Visual amenity	HIGH	SEVERE	MODERATE	MINOR
Recreational access (boating, fishing)	N/A	SEVERE	HIGH	NONE
Fish habitat (available water for passage)	SEVERE	SEVERE	HIGH	NONE
Waterbird habitat (Suitable feeding habitat)	MINOR	SEVERE	SEVERE	NONE

None: No impact on value by sedimentation or sedimentation not present in this location
Minor: Some loss of value or a change in the type of value (e.g. change in waterbird species using area)
Moderate: Value still present but is being affected
High: Significant impact on the value
Severe: Complete or virtual complete loss of value at the location

Risks associated with removing sediment

Data from this study demonstrates that the acid neutralising capacity of sediments in Toby Inlet, likely arising from calcareous sands of the Quindalup Dune, exceeds potential acidity by an order of magnitude. This means that acidification within the inlet is unlikely to result from disturbance of sediment. Heavy metal concentrations in sediments are all below the ANZECC criteria, therefore sediments are not considered contaminated. These two results are important since earlier studies had raised concerns about the possibility of acidification leading the release of heavy metals from sediments into the water, which could have serious consequences for aquatic life.

The potential for deoxygenation of the water column remains the most important potential impact of concern associated with sediment disturbance in Toby Inlet. AVS in surface sediment was as high as 0.25 % in surface sediments in Zone 2 and up to 0.15% in the upper reaches of Zone 3. The actual hazard that MBOs pose to waterways depends on the characteristics of the receiving waterbodies that the MBOs may be dispersed into, with the following features leading to a lower risk: (from Sullivan et al, 2018)

- High volume of the waterbody receiving the MBOs. The larger the volume of the waterbody receiving the MBOs, the greater the ability of the waterbody to dilute impacts;
- The exchange or replenishment of the waters in the waterbody. Regular tidal exchange or inflows and outflows of water leads to greater dilution and reduction in impacts from MBOs dispersed into the waterbody.
- The resilience of waters in the waterbody. Waters that are well oxygenated themselves and with high buffering capacity, such as seawater, have a higher ability to accommodate changes.

Low levels of dissolved oxygen below 2mg/L have potential to lead to a fish kill. However, Toby inlet has a long history of low oxygen levels below this threshold, which are likely to have contributed to previous fish kills. The high total organic carbon suggests that sediments in Toby Inlet may have contributed to low oxygen levels. Accordingly, leaving accumulated sediment within Toby Inlet also presents an ongoing risk of fish kills. To manage this risk, a slow and staged approach to removal is necessary, undertaken progressively each winter when water levels are high and there are improved opportunities for fish to move away from sites of disturbance; or via direct pumping of exposed sediment in summer when there are no fish present in these areas.

Potential impacts of low oxygen water and dispersal of fine sediment particles on the seagrass meadows of Geographe Bay is an important consideration for any future sediment removal operation. The timing, volume and method of removal, in addition to the status of the Toby Inlet mouth are all factors that can influence the degree of risk posed to these meadows. Removal of sediment in summer with the mouth closed would pose a low risk to the seagrass meadows due to the physical barrier of the sand bar (which can be manipulated). However risks to aquatic life within the inlet during summer when the mouth is closed and the water levels are low would be very high. Under this scenario fish may have limited opportunities to escape from zones of low oxygen and a fish kill may result. During winter the likelihood of sediment being suspended in flows and dispersed in Geographe Bay are high. For example, dredges working in a narrow, flowing channel would result in mobilisation of sediment that may flow out to sea. Silt curtains would be ineffective if placed in the channel at a time of year when water is flowing through the channel.

Constraints to removing sediment

Removal of sediment from Toby Inlet presents a complex problem, owing to the huge volume of sediment that is required to be removed, limited adjoining space, high value riparian vegetation and sensitive downstream ecosystems. Details regarding the key constraints are outlined in Table 9.

Table 9: Key constraints to removing sediment in the Toby Inlet

Constraint	*Comment*
Large Volume	• The large volume of sediment within Toby Inlet is the most significant constraint for removal both in terms of cost and logistics. • Removal of sediment and disposal to landfill is impractical if undertaken in one year - a staged approach to removal will be more practical from a logistical and financial perspective, and to allow for trials of various approaches.
Limited space	• The urbanised nature of Toby Inlet's surrounds means that there is very little adjoining space to facilitate the types of removal techniques that have been used to remove MBOs elsewhere. Sediment removal typically involves a need to dewater or dry sediments either within a temporary drying pond or with the use of geotextile bags that trap sediments while allowing filtered water to flow out. There is insufficient space around Toby Inlet to dewater sediments via drying ponds. • Use of geotextile bags are impractical for removal of appreciable quantities of sediment from Toby Inlet, given the space requirements for these exceed the space available on nearby cleared foreshore areas.
Important adjoining values on bank	• High value riparian vegetation along Toby Inlet should be protected from disturbance as part of any proposed sediment removal program. This includes coastal saltmarsh ecological communities and foreshore vegetation providing Western Ringtail Possum habitat.
Sensitive downstream ecosystems	• The sheltered environment of Geographe Bay (in summer) receiving Toby Inlet drainage, supports important seagrass meadows and forms part of the Ngari Capes Marine Park. Sediment management must evaluate potential impacts on seagrasses.
Sediment characteristics	• Sediments are very fine and have high moisture content. Proposals that involve direct removal and transport away from the inlet will need to involve techniques that minimise the amount of water transported with sediment. • High AVS and carbon content in sediments indicate a strong possibility that disturbance may lower oxygen within the water with potential impacts on fish. This factors requires management by staging removal carefully and ensuring the surrounding water levels (volume of water over sediment) are high and has exchange due to flow. Summer removal should be avoided except in locations where sediment is exposed at low tide (and therefore fish are not present).

Opportunities for removing sediment

Despite the large number of constraints there are many potential opportunities that are worth giving due consideration for future sediment removal options. These are outlined in Table 10 below.

Table 10: Opportunity for removing sediment in the Toby Inlet

Opportunity	*Description*
Estuary morphology	• The long and narrow morphology of the Toby Inlet combined with its close proximity to Caves Road means access to the wider waterbody along much of the inlet is good for most sections. • The long morphology of Toby Inlet also means that winter flows are able to carry suspended sediments out into Geographe Bay at a time of year when residence time is low (a few days), and water is often turbid as a result of seagrass senescence.
Ability to manipulate mouth opening	• Water levels in the Toby Inlet can be manipulated to some degree via artificial opening (and potentially closing) of the bar in summer or winter.
High sediment to water ratio in some locations	• At low tide, Zone 2 has a very low water to sediment ratio. This may present an opportunity for direct pumping of sediment from this zone for liquid waste disposal. Cartage of the sediment slurry to the Water Corporation Waste Water Treatment Plant would need to be negotiated. This technique is unlikely to be cost effective in other parts of the inlet.
Close proximity to Quindalup WWTP and Vidler Road Waste Facility	• The Quindalup wastewater treatment plan and Vidler Road waste disposal facility are both located within 8km of Toby Inlet, meaning disposal of sediment to either facility would not entail high transport costs.
High acid neutralising capacity of sediments	• Sediments have a very high acid neutralising capacity, meaning that acidification of sediments and water in the inlet as a result of disturbance are unlikely.

Evaluating sediment management approaches

A wide variety of broad management approaches were considered as part of this project. There are many ways that sediment removal, or management could be tackled, and each has their own specific advantages, limitations and risks. These are summarized in Table 11 below.

Table 11: Merits and limitations of sediment management approaches in Toby Inlet.

Approach	*Merits of approach*	*Limitations and risk*
Leave sediment in-situ (do not attempt removal)	➢ Water quality in Toby Inlet has improved since changes in the management of the sand bar at the mouth of the inlet. ➢ Lowest cost management option. ➢ Is consistent with current government guidelines that advise against disturbance of sulfidic sediments where possible.	➢ Will not address impacts of accumulated sediment on aquatic fauna and flora habitat values; visual amenity and recreational access. ➢ Does not acknowledge the strong community sentiment to address the above issues either by sediment removal or other means.
Remove seagrass and sand island near the footbridge to improve water exchange	➢ May improve tidal exchange. This could be assessed with the model developed by Frazer & Hall (2017). ➢ Relatively low cost to implement given the small size of this island. ➢ Would complement other sediment removal techniques (ie silt raking).	➢ It is unclear whether seagrass wrack accumulations in winter could move further upstream in winter, thereby adding to sediment accumulation in the lower inlet over time. ➢ Potential benefits are likely to be limited to the lower reaches where the influence of tides on water exchange is greatest. ➢ Improving tidal water exchange is unlikely to increase shear on the sediment sufficiently to enable natural scouring (Frazer & Hall, 2017).
Deepen the mouth of the Inlet to improve tidal exchange	➢ Low cost option. ➢ At high tides, improved summer water levels would improve amenity.	➢ Hydrological modelling recommends against maintaining a deep opening at the Toby Inlet mouth (Frazer & Hall, 2017) to prevent very low water levels in the upper inlet at low tides. Similar conditions in the past contributed to fish kills when fish were trapped in isolated pools in the upper inlet at low tide.
Remove sediment from specific areas of the inlet (e.g. channels and pools)	➢ Will enable smaller, more affordable removal projects. ➢ Allows for improvement in techniques over time	➢ Sediment accumulation is extensive and it is difficult to prioritise small-scale removal. ➢ Sediment is very fluid and is likely to flow back into the removal areas.

		➢ Community consultation has not provided consensus about priority areas, rather the concern is spread along the length of the inlet.
Removal of sediment from Zone 2 only (or starting removal with Zone 2)	➢ Water cover at low tide is minimal in the upper inlet so it is the most severely impacted in terms of visual amenity and habitat values. ➢ Removal of sediment from Zone 2 is the least complicated from a logistical perspective.	➢ If sediment were removed only from the upper inlet (Zone 2) deeper pools of water may be isolated at low tide, which can trap fish and may lead to fish kills. These risks could be assessed using the model developed by Frazer & Hall (2017). ➢ Removal techniques suitable for Zone 2, while logistically simple are nonetheless very expensive.
Undertake staged removal of sediments starting at the downstream end and working upstream	➢ Manageable removal over time commensurate with available budget. ➢ Avoids risk of creating isolating pools associated with sediment removal in the upper inlet. ➢ Would aim to gradually increase length of the clean sand base from downstream to upstream that currently exists in Zone four, i.e. to gradually increase the zone of the estuary that has good habitat values. ➢ A combination of sediment removal techniques could be used over time for each area of the inlet. ➢ Some lower costs techniques for sediment removal could be considered in the lower inlet. ➢ As with above approach, allows for improvement in techniques over time.	➢ There is some risk of movement of sediment from upstream areas into downstream removal areas over time. ➢ It would take many years before sediment were removed from the upper inlet, where impacts on amenity and habitat are currently the greatest. ➢ Removal of sediment from the mid reaches of the estuary (upstream area of zone 3) is constrained by limited adjoining space and the long distance from the inlet mouth. ➢ To achieve complete removal of sediment from zones 2 and 3 a very significant investment over a long period of time is likely to be required.

Part D: Review of sediment removal techniques

Summary of evaluation

A comparison of the technical feasibility, environmental risk and cost implications of five sediment removal techniques were evaluated. These included:

1. Suction pump sediment from inlet and dewater using industrial mobile filter technology or mechanical containerised dewatering.
2. Slow and staged sediment raking to flush small volumes of sediment to the ocean during winter over a number of years.
3. Suction pump to tankers and transport to WWTP.
4. Dredge to geotextile bags.
5. Drainage and excavation.

The option to dredge and dewater sediment in drying ponds was not investigated as it was immediately identified as unfeasible due to the limited space available around Toby Inlet. The option to dredge directly to Geographe Bay was not investigated further as this would disperse a large load of sediment, presenting an unacceptable risk to seagrass systems in Geographe Bay, and was unlikely to receive approval.

Of the above options evaluated, only the first three were found to have either a moderate or high chance of being technically feasible in at least part of the Toby Inlet (Table 12). Given the elongated shape of Toby Inlet, different sediment removal techniques will be best suited to different zones of the inlet. Options 1 and 2 will require further investigative trials before decisions can be made regarding their implementation. Option 3 is likely to only be able to be considered in zone 2 within the upper inlet as its implementation in the mid to lower inlet would be cost prohibitive. Further details about each technique are provide below

Table 12: Comparison of sediment removal options for the Toby Inlet

Technique	*Brief description*	*Technical feasibility*	*Environmental Risk*	*Cost implications*
Suction pump sediment and dewater using mobile containerised system	Suction pump sediment to holding tanks, add flocculent and dewater using a mobile filter press.	Moderate, emerging A portable compact filter technology such as Z filter would be needed. Such technologies are emerging for this purpose.	Moderate Risks manageable if appropriately timed, though some dispersal of sediment and low oxygen plumes may still occur.	High Range from $200,000 to $500,000 excluding sediment disposal and equipment purchase
Slow and staged sediment raking and flush to ocean during winter	A purpose built device attached to a small boat and used to drag or mechanically stir sediment under high flow conditions in winter thereby allowing controlled, staged dispersal to sea.	High A purpose built, boat mounted device would not be complicated to build and operate.	Moderate Risks are manageable only if undertaken in very small stages over a long period of time. Careful timing and comprehensive monitoring needed to minimise impacts.	Low Estimates are approx. $20,000 to $25,000 per year
Suction pump to tankers and transport to WWTP	Use of liquid waste disposal trucks to pump sediment slurry and transport for disposal to the Quindalup WWTP.	High Previously proven but does result in large volumes of water being carted with sediment which greatly increases expense. Only the upper portions of the inlet are likely to be feasible.	Low Appropriate selected suction pumps can result in limited disturbance of sediment. Comprehensive monitoring and careful site selection would be needed to reduce physical impacts to fringing vegetation.	Upper inlet: Very High, range from $200,000 to $700,000 for Zone 2 Lower Inlet: Likely to be cost prohibitive
Dredge to geotextile bags	Use of a dredge to remove sediment and pump to or geotextile bags	Not feasible Insufficient space for geotextile bag	N/A	N/A
Drainage and excavation	Separation of sections of the inlet, dewatering and excavation of sediment	Low Difficult to guarantee machine access, very large scale of dewatering	Very High Damage to fringing vegetation, trapping of fish in pools, exposure of sediment to air in-situ all highly undesirable.	Very High Likely to be cost prohibitive

Detailed description of sediment removal options

Suction pump and use mobile containerised dewatering system

<u>*Description*</u>

Technologies for separating solids from wastewater have been used in the mining and food production industries for some time, and adaptation for other solid separation applications are emerging. Their primary use is to remove as much water as possible from a slurry, thereby enabling a more economical option to transport dry waste away for either re-use or disposal. The use of a suction pump to remove sediment is a lower cost option compared to a small dredge and, with the correct choice of equipment, can also result in less dispersal of sediment in the water column. These pumps are less efficient at pumping sediment as they tend to move a very high volume of water with sediment, a feature that is best avoided if passive dewatering methods are proposed (such as drying pond or geotextile bags). The high water content of slurry delivered by a suction pump is much more suited to the used of containerised mechanical or filter press dewatering systems. In fact, these systems are unlikely to cope with the high sediment to water ratio that would be delivered by a dredge, since their components and pumps may become blocked.

There are a variety of different types of mechanical dewatering technologies available and their suitability varies greatly according to budget, site characteristics and the degree of dewatering required. All require the use of flocculating agents to aid dewatering of fine solid particle. Some examples of options include:

- Screw press
- Belt press (e.g Z filter, though there are other forms)
- Chamber press
- Filter press

These examples are extremely efficient at removing water from slurry and result in a very dry filter cake that can easily be transported. They are used across a wide variety of industries in Australia to dewater waste streams prior to re-use or disposal, including wastewater treatment plants, mining, textiles production, food production and paper production. A number of east coast based Australian companies offer mobile containerised mechanical and filter presses that can be brought to site and moved as required. Most examples require the use of power and water, some require compressed air and most require the use of flocculating polymers to separate solids from slurry as part of the process.

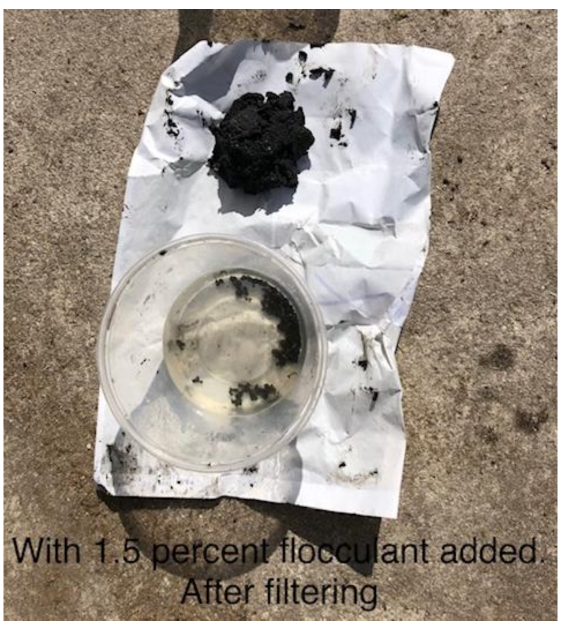
Given the limited space available around Toby Inlet this option presents as one of very few feasible solutions for the dewatering of sediment removed from the wider inlet. Further investigation would be required to consult with landholders to identify potential temporary dewatering 'stations' along the inlet, confirm suitable flocculent polymers (ensuring these are not toxic to aquatic life), establish whether power and water can be provided as required to each station, and select the most cost-effective technology.

<u>Case example</u>

One example that was investigated is the Z-filter, which is currently being trialled on a Scott Coastal Plain dairy to dewater wash down water from the milking area. The Z-filter technology is portable, if skid mounted, is capable of handling large volumes of waste water (up to 150 m^3 per day) and is demonstrating promising results in the dairy trial. This is an example of a modified belt press that operates within a Z shaped conveyer belt to compress the slurry through an enclosed filter membrane known as a filter sock. Sediment samples from the Toby Inlet were taken to the trial site and passed through a spare filter sock without compression and, with the aid of a flocculent, the majority of sediment particles were quickly filtered from the sample (Figure 25 a, b and c). The figure below shows photos of the Z filter equipment (Figure 25 a), the dry filter cake after processes dairy wash down effluent (Figure 25 b) and the (largely) clear filtrate that resulted from experimentally passing a sample of Toby Inlet sediment through the equipment's filter sock using a flocculating agent.

a)

b)



C)

Figure 25: A to C - Z Filter on the dairy trial site, b) Filtered solids from dairy effluent and c) Filtered sediment from Toby Inlet having passed through a Z Filter sock without compression, with 1.5 percent flocculent added.

Cost implications

Depending on technology selected, the purchase price of these options with associated infrastructure, at the lower end of price range is likely to be at least $200,000 and $400,000, with some companies offering hire and others offering buy-back schemes following completion of a project. It is expected that most options would require transportation from interstate. If this option is pursued it is suggested that an expression of interest process be undertaken to invite submissions from suitable companies to submit priced design solutions for the project.

Environmental risk and management

The use of mechanical or containerised filter technology only addresses the issue of how to dewater sediments from Toby Inlet once removed. A sediment removal management plan would need to be prepared to identify the methods of limiting dispersal of sediments, staging of works, precautionary liming of sediment and disposal (or re-use) of sediment solids.

A sump pump attached to a floating pontoon was used to pump sediment from the Vasse Estuary exit channel in June 2017. Monitoring data indicated that very little sediment was disturbed using this technique, noting that the surge barriers provided a very effective physical barrier to the downstream system (DWER, 2019).

It is likely that winter removal of sediment would pose least risk to fish and other aquatic life, yet this does raise the issue of how best to minimise the disposal of sediment particles and plumes of low oxygen water under winter flow conditions. There are currently no measured data available for winter flows from Toby Inlet, such baseline data would help to evaluate the potential risks of sediment transport.

Controlled and staged sediment raking

<u>Description</u>

Sediment raking involves controlled mechanical suspension of sediment in the water column to allow currents to carry sediments out of the estuary and allow them to disperse in ocean currents. The aim of sediment raking is to attempt to periodically enhance the scouring effect of a high flow event, thereby allowing small amounts of sediment suspension under selected and controlled conditions, and then allow natural currents to move sediments out of the estuary. It is a much lower cost option compared to dredging as it removes the need to 'dispose' of sediments and involves considerably simpler technology. This option was also recommended for investigation in the Toby Inlet Waterway Management Plan (COB, 2019).

Sediment raking has also been referred to as 'scouring' and is commonly used to flush accumulated sediment from constructed lakes. This technique has been used in other areas to remove accumulated sediments from water supply dams and canal developments (including Port Geographe). A cautious approach to undertaking small scale pilot project would provide useful information regarding the likely effectiveness and potential impacts of this as a staged removal technique.

If this technique were investigated, there is likely to be benefits in removing a small island comprised of sand and accumulated seagrass wrack downstream of the footbridge to improve tidal flushing and enhance removal. This action could be undertaken using a long reach excavator from the bank on the Caves Road side.

<u>Case example</u>

Sediment raking (referred to as silt raking in this example) was undertaken on a large scale in the Tamar Estuary in Tasmania between 2012 and 2018 with the aim of improving flood protection (City of Launceston, 2019). Sediment raking commenced in the Tamar Estuary at a time when dredging was deemed to be uneconomical. The scale of the operation in that system resulted in it being a controversial option, and it was found to be ineffective in moving sediments due to the estuary morphology, and resulted in negative water quality impacts (City of Launceston, 2019). Despite these issues, the comparisons between the size and morphology of the Tamar Estuary, which is a substantial and wide flooded river valley, and the small, elongated narrow channel of the Toby Inlet should be noted. The morphology of Toby Inlet lends itself to evaluation of sediment raking as a technique that may be very effective in scouring sediment, at least in the lower inlet. A pilot project to evaluate effectiveness and environmental impacts is recommended. Measurement of winter flow velocity would be needed to inform such a project.

A more relevant case example to consider is the mobilisation of sediment that naturally occurs from Toby Inlet under flood conditions. While this has not been quantified (nor impacts measured), air photos taken soon after a 1 in ten year flood event in July 2016 demonstrate that sediment does move out of the inlet under high flow events (Figure 29).

<u>Cost implications</u>

Without a field trial it is not known how long it would take to mobilise specific volumes of sediment using this technique, making cost estimates difficult. Construction of boat mounted machinery to undertake sediment raking is expected to cost approximately $10,000 and could be operated for about $150.00 per hour. A five day trial could therefore cost in the order of $20,000 to $30,000 allowing for initial construction, implementation, monitoring and evaluation. Implementation after the initial trial would only require the hourly operating budget plus monitoring.

Environmental risk and management

Disturbing sediments within Toby Inlet may result in low oxygen levels in the water column immediately around the disturbance area and further downstream as the plume disperses. If undertaken during high flows in winter these impacts may be short lived, but this requires evaluation using a very small scale trial coupled with careful monitoring. It should be noted that low oxygen levels have been a long term problem in summer, and sediments are likely to be have contributed to that problem.

A large scale sediment raking operation undertaken in a single season would be very unwise given the potential to smother seagrass meadows in the nearshore area of Geographe Bay in the vicinity of the Toby Inlet mouth. A careful and staged program of removal that involved timing of works during high flow events is likely to have minimal impacts on seagrass meadows, since low volumes of fine particles would be highly likely to be rapidly dispersed under these conditions. A pilot project would enable more accurate evaluation and assessment to be undertaken to inform planning and investment.

The overall impacts of some sediment dispersal into Geographe Bay during winter would require evaluation though is expected to be fairly low providing a slow and staged approach to removal under the right conditions. Previous modelling has found that sediment particles under 0.3mm are likely to remain in suspension in Geographe Bay and be carried away by currents (Patiaratchi & Wijeratne, 2011). During winter and spring the conditions in Geographe Bay are often very turbid as a result of winter storm surges resuspending seagrass wrack that has accumulated in the meadows over summer and autumn (Oldham et al., 2010). Similarly, recent flood events such as occurred in 2016 appear to have resulted in some scour of sediment from Toby Inlet and subsequent dispersal in Geographe Bay as seen in air photos taken soon after a 1 in ten year rain event in 2016 (Figure 26). Annual monitoring of the seagrass meadows in Geographe Bay found that meadows at the closest site to Toby Inlet have been stable over the past ten years with some minor fluctuations have the highest shoot densities of the monitoring sites (McMahan & Dunham, 2018).

Figure 26: Plume of dark water flowing from Toby Inlet and Station Gully into Geographe Bay, July 2016 (Photograph by DWER).

Suction pump to tankers and transport to WTP

Description

This technique would involve the use of liquid waste disposal trucks to suction pump sediment slurry into trucks for transport to the Wastewater Treatment Plant in Quindalup. Sediment slurry would be added to drying ponds (pending permission from Water Corporation). As sediment would be transported wet and blended with other liquid waste stream pre-treatment of sediment with lime would not be required.

A variety of different liquid waste disposal companies operate in the local area, and the types of pumps, size and configuration of trucks all differ. Some trucks are able to completely open at the back – which would enable more efficient removal of sediment slurry and resolve issues associated with sediment settling at the base of the truck.

Suction pumping typically moves a high volume of water with sediment leading to uneconomical transportation costs where a high water to sediment volume is present. However it may be one of the best options available for summer removal of sediment from the upper inlet (Zone 2, sections 1 and 2), where a high sediment to water ratio is present in summer at very low tides. The close proximity of Caves Road to the inlet allows access for trucks and water levels in the inlet can be mechanically manipulated in summer by opening and closing the inlet mouth.

Case example

This technique was used to remove a small volume (approx. $300m^3$) of sulfidic black ooze from the upstream side of the Vasse surge barriers (DWER, 2019). Sediment was removed using a suction pump mounted on a floating pontoon and transferred in liquid waste disposal trucks to the Busselton waste water treatment plant, where it was added sewerage sludge, and dried and disposed of as part of standard operations (DWER, 2019). Water quality was not negatively impacted during the removal process, but was a high cost option with the project costing over $100,000 due to the high transport cost.

Cost implications

Pumping of sediment and transportation using liquid waste disposal trucks is a very high cost option so is unlikely to be suitable for widespread application in the Toby Inlet, given the scale of sediment accumulation there. However, it is potentially very suitable for removal of sediment in sections 1 and 2 given sediment in these areas can be exposed at low summer tides. Cost estimates using this technique have a very wide range (Table 13) given the variation in technology available, a formal expression of interest process would be best undertaken to gauge a more accurate assessment of likely cost. Note that in the table below Contractor 1 provided their standard daily rate for these estimates, though indicated a lower rate would be available for a large project.

Table 13: Cost estimates received for pumping and transportation of sediment slurry to the Quindalup WWTP (Cost estimates based on volume of sediment only).

Zone	*Section*	*Sediment volume m³*	*Contractor 1 transport cost estimate*	*Contractor 2 transport cost estimate*
2	1	5588	$ 279,400.00	$ 58,115.20
2	2	9266	$ 463,300.00	$ 96,366.40

Environmental management

Managing access for trucks, pump equipment and labour would be critical to preventing damage to valuable fringing vegetation around the Toby Inlet if this option is implemented. Water quality monitoring combined with curtain separation of the works area would also be required.

Drainage and Excavation

Description

Separation of sections using barriers followed by dewatering then mechanical excavation of sediment has been used in the past to remove sediment from infrastructure works areas within the channels, rivers and estuaries. This approach was used in the Vasse Estuary exit channel in 2004 when the Vasse surge barrier structure was replaced. This is a high cost approach and high disturbance approach that is likely to cause damage to valuable surrounding fringing vegetation, significant disruption to adjoining residences and also lead to odour problems as sediment is exposed. Due to the combination of these issues, this option was not considered feasible from a practical, environmental and social perspective and was not investigated further.

Dredge to Geotextile Bags

Description

Sediment removal using a small dredge followed by dewatering with geotextile bags has been used previously to remove sediment from boat ramps in the Peel Inlet, and a variety of water detention basins and is also used de-sludge agricultural wastewater treatment ponds. Sediment is pumped into filter bags with a flocculating polymer added and the bags allowed to passively dewater until sediment is dry enough for disposal.

The large volume of sediment accumulated in Toby Inlet means that many bags would be needed requiring a very large area of land to implement this option. Only small strips of cleared areas are available around the inlet and these occupy only a fraction of the space that would be required to dry sediment from the inlet. For example, each 1000m^3 geotextile tube has a lay-flat size of 30m x 17m (or 510m^2) and should hold between 1500m^3 and 2000m^3 of sediment (as it sits in-situ). A total of 40 tubes of this size occupying an area of 20,400m^2 (2.4 ha) would be required to implement this option. Re-use of tube lay down areas would have very limited application for a staged operation, given the elongated shape of the inlet, and the high cost of mobilizing and demobilizing dredge equipment. As a result of these space limitations, this option is deemed not to be feasible.

Cost implications

If dredging to geotextile bags were feasible, it would be a high cost option. Estimates are provided in Table 14 below.

Table 14: Estimates of the cost of using a small dredge to remove sediment from Toby Inlet with dewatering via geotextile bags (costs are conservative estimates and exclude, monitoring, treatment of sediment and disposal).

Toby Inlet Section (zone)	*Sediment volume m3*	*Dredge labour and operation*	*Geotextile tubes (n of 1000m^3 bags)*	*Polymer for flocculation*	*Potable water for polymer*	*Total dredging cost*
	Mobilisation	$ 15,000				$ 15,000
1 (Zone 2)	5588	$ 111,760	$ 59,605 (4)	$ 3,725	$ 2,794	$ 177,885
2 (Zone 2)	9266	$ 185,320	$ 98,837 (6)	$6,177	$ 4,633	$ 294,968
3 (Zone 3)	12820	$ 256,400	$ 136,747 (9)	$ 8,547	$ 6,410	$ 408,103
4 (Zone 3)	17350	$ 347,000	$ 185,067 (12)	$ 11,567	$ 8,675	$ 552,308
5 (Zone 3)	15272	$ 305,440	$ 162,901 (10)	$ 10,181	$ 7,636	$ 486,159
	De-mobilisation	$ 15,000				$ 15,000
Total	60,296	$ 1,235,920	$ 643,157 (40)	$ 40,197	$ 30,148	$ 1,949,423

Approval considerations

At present there are limited policy and regulations that directly address the removal and management of MBOs for restorative purposes (Sullivan et al 2018). These limitations arise from the recent identification of monosulfidic black oozes (MBOs) and the hazards they present, and the fact that options available for the management and removal of MBOs from waterways are still in their infancy (Sullvan et al, 2018).

Approval for any sediment removal works in Toby Inlet will need to have due regard to State approvals processes and regulations. It is not anticipated that any federal legislation would be triggered by removal of sediment from Toby Inlet. The federal Sea Dumping Act (1981) does not apply in waters within the limits of a State or the Northern Territory. There do not appear to be any triggers for application of the EPBC Act 1999.

Key considerations from State regulations are:

- Development of an Acid Sulfate Soils Management Plan is required for projects that disturb over 100m^3 of Potential Acid Sulfate Soils (PASS), or any dredging projects (unless an exemption is granted by DWER);
- DER (2015) Guidelines for the disturbance of Acid Sulfate Soils state that projects likely to disturb over 1000m^3 of PASS and are located within a linear environment require a sampling density every 100m for the area proposed to be disturbed, unless grounds for an exemption can be satisfied;
- Approval from DBCA must be sought for 'dredging or dredge spoil dumping' within the General Use Zone of the Ngari Capes Marine Park. It is unclear whether sediment raking within Toby Inlet to encourage natural flushing to sea would be considered by the Department as 'dredge spoil dumping' since the method of transport of sediment to sea would be natural flow. It would, however, be appropriate for the City to consult directly with DBCA prior to undertaking any pilot project to ascertain whether formal approvals were required.
- While disposal to landfill has not be recommended in this report, chromium, lead and nickel concentrations are above the criteria for disposal to a Class 1 or 2 landfill in WA without leachate testing. Therefore leachate testing and subsequent evaluation is required for any future removal project that involves disposal to landfill.
- Aboriginal Heritage Act (1972): Referral of any proposal to the South West Boodjara Working Party is appropriate.

The *National Acid Sulfate Soil Guidance Overview and management of monosulfidic black ooze (MBO) accumulations in waterways and wetlands* (Sullivan et al, 2018) provides some broad guidance on methods of managing and removing MBOs from waterways. The following extract is relevant for the consideration of sediment raking in Toby Inlet:

> *'Within waterway disposal of MBOs*
> ***Given the lack of proven best management practices for the land-based disposal of MBOs and the problems associated with that option, the disposal of MBO materials within waterways is often practiced.***
>
> ***Whether disposal of MBOs within waterways creates environmental issues will depend on a range of factors including: the volume and characteristics of the MBO mobilised (for example***

concentration of monosulfides, contaminant concentrations), and the volume and characteristics of the receiving waters (for example buffering capacity). Clearly it has been shown that deoxygenation and/or acidification does not always occur following the disposal of MBOs by this practice when the receiving waters can cope with the stresses placed upon it by the disposed MBO material (Morgan et al., 2010).

When this practice is being considered then assessments should be made to assess the hazard posed by the MBO materials to be disposed of in the waterway, and the capacity of the receiving waters to cope with those stresses.

During and after the disposal a rigorous water quality monitoring program with specified water quality targets should be implemented to ensure the predicted capacity of the receiving waters to cope with the MBOs materials is not exceeded. Prior to the works commencing a contingency plan should be established to provide an acceptable course of action should these targets not be met.

Consideration should also be given to ensure the location of MBO disposal sites are always submerged and will not be exposed during low tides, and that the disposed MBO materials do not cause unacceptable harm to the disposal sites via smothering.'

The *National Acid Sulfate Soil Guidelines: Guidance for the Dredging of Acid Sulfate Soil Sediments and Associated Dredge Spoil Management* (date) provides guidance on removal of acid sulfate soil material. An extract is provided below, bolded text indicates that the measure is particularly relevant to the recommendations of this report, or the techniques assessed in this report:

'There exists a wide range of measures that may be considered for minimising and mitigating dredge related impacts, many of which are beneficial to minimising risks due to ASS. Such measures include those to:

• reduce or avoid a dredging requirement (modify position of channel);

• increase natural sediment transport (thus reduce or avoid dredging requirement);

• reduce impacts of dredging (reduce area or depth of material dredged, modify dredging technique and rate);

• prevent dispersion of sediment (for example use of silt curtain);

• reduce short-term impacts to the water column (for example aeration to improve DO levels);

• reduce impacts of dredging on biological receptors (for example adapt dredging programme);

• offset dredging impact by replenishing lost sediment or beneficial use of dredged material elsewhere;

• reduce impacts of disposal: prevent dispersion of sediment; improve DO concentrations (increased surface water mixing – air exchange, whilst monitoring impact on oxidation that leads to harmful levels of acidification); minimise impacts to biological receptors (modify disposal timing);

• avoid or reduce impacts of disposal: prevent (for example treatment of acidity through liming) or contain the extent of release of contaminants into the water column for example contain silt within silt curtain or other separation techniques); and,

• offset disposal impact: re-establish characteristic biota (fish and plants habitats).

The most important measures that are specific to ASS include:

• avoiding areas with high existing and/or potential acidity;

• avoiding ASS in sensitive environments;

• keeping hazardous ASS water-saturated (under water, inundated) to minimise oxidation; *and,*

• covering and containing disturbed hazardous ASS to minimise oxidation and water movement (runoff, leachates, effluents).

Recommendations

Considering the outcomes of sediment investigations, current and future impacts of sediment accumulation in Toby Inlet, and assessment of sediment removal options, recommendations are as follows:

1. Sediment removal from Toby Inlet should be pursued to restore ecological values and amenity, targeting Zone 3 as a priority, followed by Zone 2.

   Removal would require a staged approach starting at the lower end of the Inlet and progressively moving upstream.

   Such works should only be commenced subject to consultation with the South West Land and Sea Council and in accordance with State Government approvals processes.

2. Further evaluate the potential for sediment raking to remove sediment through a small scale pilot project in the downstream end of Zone 3 during high flow conditions in winter, when dissipation of flows from the Inlet into Geographe Bay are likely to be rapid. This would be facilitated by the following actions:

   - Monitoring of this pilot for effectiveness and water quality impacts both within downstream areas of Toby Inlet and in nearshore areas of Geographe Bay to enable informed evaluation of the likely impacts of wider scale staged sediment raking.
   - Prior to commencement of this project, removal of the small island of seagrass wrack mixed with sand that is located downstream of the footbridge (in Zone 4) would improve tidal water exchange and outward flow of suspended sediment.
   - Flow velocity data collection in the Toby Inlet during winter would aid in the evaluation of sediment raking and future sediment removal proposals.

3. Develop pilot projects for direct sediment removal from Zones 2 and 3 in the Toby Inlet to further inform appropriate techniques and costs for larger scale removal, including:

   - Suction pump sediment and dewater using mobile containerised filter-press system. (Zones 2 and 3). Expressions of interest would be required to access a suitable dewatering plant.
   - Suction pump to liquid waste disposal tankers and transport to WWTP (Zone 2 only).

4. Develop a larger and longer term program of sediment removal for Toby Inlet to be developed based on the outcomes and key findings from the pilot projects. In addition, such a program would require:

   - Measurements of the salinity of sediments in Toby Inlet be made during winter to assist in evaluating potential re-use options for sediment.
   - Undertake site assessments and consultation with landholders adjoining Toby Inlet to identify potential locations for short term dewatering stations along the inlet.
   - Preparation of an acid sulfate soils management plan.
   - Liaison with the Department of Water and Environmental Regulation to outline the aims of sediment removal being for restoration purpose, and to confirm the approvals processes in this context

5. Undertake weed control and rehabilitation through revegetation of appropriate local native species in Zone 1, rather than removing sediments, so as to preserve the threatened ecological samphire community and maintain shallow feeding habitat for shore birds.

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Appendix A Raw Data

Table A: Raw acid sulfate soils, nutrient, moisture content and total organic carbon data.

Site	Surface or Bottom	Moisture content	Total P	Total N	CRS	TOC	Net acidity	AVS	ANC as % CaCO3
TISED1-S	S	23	30	330	0.139	0.29	0.14	----	1.59
TISED1-B	B	41.2	158	1230	0.732	2.47	0.73	0.007	40.7
TISED2-S	S	90.2	505	8220	1.25	7.16	1.25	0.217	8.4
TISED2-B	B	56.4	99	1480	0.892	1.34	0.89	0.019	13.8
TISED3-S	S	93.4	987	11800	0.694	7.73	0.69	0.248	7.27
TISED3 - B	B	64.5	142	1780	1.09	1.86	1.09	0.024	17.1
TISED4-S	S	93.7	1090	13000	0.626	8.2	0.63	0.155	6.24
TISED4-B	B	76.8	238	3300	1.02	3.74	1.02	0.03	19.3
TISED5-S	S	93.5	799	10500	0.566	8.02	0.57	0.14	7.28
TISED5-B	B	74.7	196	3300	1.1	3.68	1.1	0.02	21.6
TISED6-S	S	56.1	157	1170	0.496	1.82	0.5	0.009	22.3
TISED6-B	B	43.7	201	890	0.311	1.04	0.31	0.006	45.5
TISED7-S	S	87	490	6770	1.29	7.05	1.29	0.056	24.4
TISED7-B	B	69.1	313	2940	0.678	3.34	0.68	0.01	43.1
TISED8-S	S	78.9	284	3170	0.659	9.74	0.66	0.017	37.4
TISED8-B	B	77.4	246	4320	0.522	12.3	0.52	0.01	44.1
TISED9-S	S	91	970	9400	0.701	10.2	0.7	0.105	19.3
TISED9-B	B	67.6	411	2500	0.893	3.25	0.89	0.032	46.4
TISED10-S	S	91.3	455	6280	1.06	6.94	1.06	0.031	11.8
TISED10-B	B	70.3	297	2800	0.925	3.46	0.92	0.012	32.3