A New Method of Determining Glass Sponge Reef Adaptive Management Zones for the Hecate Strait and Queen Charlotte Sound Marine Protected Area

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Abstract: The world’s largest living glass sponge reefs, located in the Hecate Strait and Queen Charlotte Sound off British Columbia, are impacted by bottom contact fishing gear. The existing Adaptive Management Zones (AMZs) for the protection of these reefs were determined by considering the potential exposure of glass sponges to suspended sediment due to mobile bottom-contact fishing, but without considering their pumping arrest threshold concentrations. Here, we develop a new method that uses a sediment transport model under horizontally variable near-bottom currents and newly available sponge reef pumping arrest thresholds to determine the size and shape of AMZ for the northern reefs in the Hecate Strait and Queen Charlotte Sound Marine Protected Area. The resulting AMZ is larger than the existing AMZ due to the observation that the largest currents are not always in the direction of the dominant tidal flows, the introduction of the new pumping arrest threshold, and the inclusion of a background sediment concentration. The new AMZ boundary could provide more adequate protection for the glass sponge reefs from the effects of sedimentation induced by mobile, bottom-contact fishing activity. The new method is applicable to other glass sponge reefs in British Columbia waters.

Keywords: glass sponge reefs; adaptive management zone; sediment transport; currents; marine protected area

1. Introduction

Major glass sponge reefs, estimated to be 9000 years old and considered to be the largest living example in the world, are located between Haida Gwaii and the mainland of British Columbia in Hecate Strait and Queen Charlotte Sound (HSQCS) [1]. There are three spatially distinct reef complexes: the Northern Reef, the Central Reefs, and the Southern Reef [2]. The glass sponge reefs in HSQCS are the only known sponge reefs on the rocky outcroppings of the muddy continental shelf [1] and therefore considered to be unique because glass sponges elsewhere are often on steep rocky substrates where little suspended sediment settles [3]. The glass sponge reefs in HSQCS, up to 25 m tall, discontinuously cover an area of about 1000 km² and occur in depths of 30–200 m [2]. These reefs provide refuge, habitat, and nursery grounds for many commercially important aquatic species, for example, Pacific halibut, rockfish, and spot prawn [4,5]. Scientific surveys revealed that the glass sponge reefs in HSQCS were impacted by bottom contact fishing gear, primarily bottom trawl gear [1,4].

Marine Protected Areas (MPAs) play important roles in conserving marine ecosystems worldwide [6]. The HSQCS MPA (Figure 1) was established to protect glass sponge habitats [7] (DFO, 2017). Each reef complex is made up of three management zone types: the core protection zone (CPZ), adaptive management zone (AMZ) (Figure 1), and vertical adaptive management zone (VMZ), as described in detail in [2]. While all harmful human activities are prohibited in the CPZs, the MPA Regulations allow for some limited fishing.
activities in the AMZs and VMZs, including recreational fisheries and Indigenous fishing for Food, Social and Ceremonial purposes. Currently, all commercial bottom-contact fishing and midwater trawling in the MPA is prohibited by the Fisheries Act Variation Orders. While the HSQCS MPA is designed to protect unique marine ecosystems formed by glass sponge reefs, the effectiveness of the MPA depends on how well the AMZ boundaries function as a protective measure. The existing AMZ boundaries within the HSQCS MPA range from 0.6 to 4.5 km from the CPZ boundaries [5]. The glass sponge reefs off British Columbia are the habitat for many commercially important fish and are subject to fishing pressure, such as bottom-contact trawl fishing. The latter can result in direct physical damage to the habitat [2,5] and also negatively impact glass sponge reefs indirectly by suspending a large amount of sediment, which can then be transported into the CPZ [5].

![Map of the HSQCS](image)

**Figure 1.** Map of the HSQCS located in British Columbia, Canada, showing the locations and names of the four glass sponge reefs (grey lines) enclosed by the core protection zones (CPZs, black polygons) and the adaptive management zones (AMZs, red polygons). N, Cn, Cs, and S represent the northern, central northern, central southern, and southern reefs, respectively. The triangle depicts a vertex of the core protection zone for the northern reefs. The open circle and solid circle depict the location of current measurements.

Glass sponges are highly efficient filter feeders. They constantly pump large volumes of water and filter organic and inorganic particles [8]. However, they can quickly arrest their pumping activities in response to the exposure to suspended sediment. Multiple pumping arrest events may reduce energy uptake of glass sponges, which could negatively affect their health, while the long-term effects of repeated sediment exposure and pumping arrests on their health and population remain a knowledge gap [5]. Grant et al. [9] found...
that in the Strait of Georgia, glass sponges cease pumping (arrest) at suspended sediment concentrations far lower than concentrations that can be triggered by bottom-contact trawling. Subsequently, Grant et al. [5], for the first time, recorded arrests for pumping glass sponges in situ in Hecate Strait in response to elevated suspended sediment concentrations. They found that different species of glass sponges in Hecate Strait respond differently to exposure to suspended sediments. *Rhabdocalyptus dawsoni* and *Heterochone calyx* arrested at sediment concentrations of 2.8–6.4 mg/L and 5–10 mg/L, respectively, while filtration rates from *Farrea occa* were too small to record. The background suspended sediment concentrations had a mean of 2.7 mg/L, with a standard deviation of 0.1 mg/L. Furthermore, they showed that the distance required from the AMZs to the CPZs depends on ocean environmental conditions and suggested that the existing AMZs in the HSQCS MPA may not be adequate to achieve effective conservation. The findings of [5] raised the need for a reassessment of AMZs in the HSQCS MPA.

The existing AMZs in the HSQCS MPA were determined by considering the potential exposure of suspended sediment transported by near-bottom currents to glass sponge reefs but without considering pumping arrest threshold concentrations [2]. Grant et al.’s [5, 9] conceptual work considered measured pumping arrest threshold concentrations without considering the direction of near-bottom currents. In this paper, we present a new method that uses a sediment transport model forced by horizontally variable near-bottom currents [10] and sponge reef pumping arrest thresholds [5] to recalculate the size and shape of AMZ for the northern reef in the HSQCS MPA.

2. Methods
2.1. Sediment Modelling

This study uses a simple sediment transport model to estimate the sediment concentration distribution as a result of mobile, bottom-contact fishing gear. In the model, all particles are assumed to be spheres with no particle flocculation; particle resuspension and water turbulence and stratification are not considered. Suspended bottom sediment concentration is generally steady under tidal flows [5], suggesting these assumptions may be acceptable. Any potential limitations may be addressed in future studies (see Conclusion and Discussions). Observed sediment composition and size data are from [5] and listed in Table 1.

Table 1. Representative sediment classification, grain size, and composition for Hecate Strait. Information is derived from [5]. Note that there are slight differences between our composition percentage values and theirs because we use the sum of the component weights instead of the total weight provided in [5].

| Classification     | Grain Size (um) | Composition by Weight (%) |
|--------------------|-----------------|----------------------------|
| >Fine sand         | >212            | 69.19                      |
| Fine sand          | 212–106         | 15.74                      |
| Very fine sand     | 106–63          | 5.35                       |
| Coarse silt        | 63–45           | 2.93                       |
| Medium silt        | 45–20           | 6.08                       |
| Fine silt          | <20             | 0.72                       |

2.2. Vertical Motion

In the vertical, the particle settling velocity is governed by the Stokes settling equation. The total settling time for a particle suspended at an initial height of 5 m above the seabed is provided for each grain size (Table 2) (from [5]).

The settling velocity depends on the grain size (Tables 1 and 2) and varies from 2.607 cm/s for the >fine sand to 0.025 cm/s for the fine silt. The suspension time depends on both the grain size and the initial suspension height above the seabed. Here, we consider a sediment cloud with the initial suspension height of 5 m above the seabed. The use of 5 m as the initial suspension height is explained in the Analysis and Response section. The
suspension time, which varies linearly with the initial suspension height, is provided for sediment with an initial height of 5 m above the seabed (Table 2). The suspension time for an initial height of 5 m above seabed ranges from 0.05 h for the >fine sand to 5.5 h for the fine silt. For a given grain size, any sediment below 5 m settles prior to the sediment at 5 m.

Table 2. Sediment settling velocity and suspension time for each grain size.

| Classification    | Settling Velocity (cm/s) | Suspension Time (h) for the Initial Height of 5 m |
|-------------------|--------------------------|--------------------------------------------------|
| >Fine sand        | 2.607                    | 0.05                                             |
| Fine sand         | 1.470                    | 0.09                                             |
| Very fine sand    | 0.425                    | 0.33                                             |
| Coarse silt       | 0.184                    | 0.75                                             |
| Medium silt       | 0.067                    | 2.08                                             |
| Fine silt         | 0.025                    | 5.50                                             |

2.3. Horizontal Motion

In the horizontal, sediment motion is forced by tidal and non-tidal currents. The particle dispersion is not considered. The horizontal travel distance and direction for the particle before settling on the seabed is calculated by multiplying 4 h averaged velocities by the settling time since the settling time for the sediment that could cause arresting of *R. dawsoni* (threshold of 2.8–6.4 mg/L) is about 4 h for the study area (see the Analysis and Response section for detail).

The horizontal ocean currents that are used in forcing sediment transport are derived from a three-dimensional ocean circulation model for the British Columbia coastal and shelf waters [10], based on the Regional Ocean Modeling System (ROMS). The model has a resolution of 3 km on the horizontal and 30 layers on the vertical. The model includes eight major tidal constituents and circulation due to atmospheric forcing, river runoff, and large-scale oceanic forcing. We used hourly bottom-layer currents for each hour in the first half of 2007. The bottom layer has a horizontally varying thickness; nevertheless, the detail of which is unavailable for us to consider here.

The hourly model bottom currents are shown for a CPZ vertex location (triangle, Figure 1) in the northern reef (Figures 2 and 3). The temporal variations in the model currents are dominated by semidiurnal tidal currents, with spring-neap fluctuations (Figure 2). The model currents show a dominant flow direction in the northwest–southeast direction (Figure 3). Strong currents, including the maximum current, occur roughly in the major flow direction.

Next, we compared the model bottom currents with observed currents. Grant et al. [5] collected near-bottom current data at a site (solid circle, Figure 1) near the above vertex location for a period shorter than a month. Their observed currents, averaged over 4 h during flood tide cycles, were 0.274 and 0.120 m/s at 5 and 1 m above the seabed. The maximum model bottom current averaged over 4 h at the nearby CPZ vertex (triangle, Figure 1), was 0.368 m/s during the first half of 2007. It was expected that the maximum 4 h model current would be greater than the observed 4 h current because the latter is based on a data record shorter than a month [5] and does not capture a complete spring-neap tidal cycle or as many storm events in half a year. Therefore, it is reasonable to assume that the modelled bottom currents can approximately represent the currents experienced by suspended sediments at about 5 m above the seabed.
Figure 2. Time series of the hourly eastward and northward bottom currents at a CPZ vertex (triangle, Figure 1) of the northern reef. The currents are from [10].

Figure 3. The scatter plot of the hourly model bottom currents at a CPZ vertex (triangle, Figure 1) of the northern reef for half a year. The maximum hourly current is depicted by the blue triangle. There are also moored current metre data at about 7 m above the seabed at a nearby site (open circle, Figure 1) in the northern reef from July 2017 to June 2018. The time series data for 2018 show semidiurnal tidal variations, with spring-neap tidal fluctuations (Figure 4). The scatter plot shows a dominant east–west flow direction, but the maximum current is almost perpendicular to the dominant direction (Figure 5). Strong currents can occur in any direction. The data for the second half of 2017 (not shown) have overall...
consistent flow patterns with those in the first half of 2018, which justifies the present use of half a year of model currents. The observed maximum 4 h current was 0.367 m/s for the first half of 2018, with the dominant flow direction in the east–west direction. The maximum 4 h model current magnitude at the nearby CPZ vertex (triangle, Figure 1) was 0.368 m/s for the first half of 2007, with the dominant direction in the northwest–southeast direction. In addition, there is a high degree of temporal variability in the observed currents not seen in the modelled currents. It is important to keep in mind that there is good model–observation agreement in the magnitude of the maximum current, and there is a large model–observation discrepancy in the direction of strong currents, including the maximum current.

Figure 4. Time series of the hourly observed eastward and northward near-bottom currents at a site (130°23′ W, 53°6.5′ N, open circle, Figure 1) in the northern reef.

Figure 5. The scatter plot of the hourly observed near-bottom currents at a site in the northern reef (open circle, Figure 1) for half a year. The maximum hourly current is depicted by the blue triangle.
2.4. Estimation of Impact Distance

The modelled sediment concentration distribution was compared with the known impact threshold concentrations of glass sponge reefs to estimate the potential impact distance of the sediment plume due to bottom-contact fishing every hour for half a year. We used a threshold concentration of 2.8 mg/L for \textit{R. dawsoni} and 5 mg/L for \textit{H. calyx} in the HSQCS MPA, respectively [5]. These threshold concentrations are at the lower ends of the pumping arrest concentration ranges of 2.8–6.4 mg/L and 5–10 mg/L for \textit{R. dawsoni} and \textit{H. calyx}, respectively. The background sediment concentration of 2.7 mg/L is close to the lower ends of the observed threshold concentrations and therefore is accounted for in order to protect the reefs from arresting. When the background concentration of 2.7 mg/L is accounted for, the effective threshold concentration for the fishing-induced sediment is 0.1 mg/L for \textit{R. dawsoni} and 2.3 mg/L for \textit{H. calyx} in the HSQCS MPA, respectively.

The initial concentration, grain size, and suspension height of sediment, as well as ocean bottom currents, determine the sediment travel distance and concentration distribution. The concentration distribution can be used to determine whether a species may be impacted by a sediment plume and to determine the impact distance. Figure 6 show the variation of the sediment height above the seabed with the distance travelled for each grain size for an initial height of 5 m above the seabed and a typical current speed of 0.35 m/s. It can be seen that the fine silt travels farthest (6.9 km) before settlement.

![Figure 6](image_url)

\textbf{Figure 6.} Distance each grain size found in the HSQCS MPA travels for an initial height of 5 m above seabed under a representative maximum 4 h current of 0.35 m/s.

Otter trawls, shrimp trawls, hook and line longlines, and prawn traps are commonly used fishing gears in the waters around the HSQCS MPA, with otter trawls and shrimp trawls causing much greater disturbance on bottom sediment than the other two [2]. Otter trawls could generate suspended sediment concentrations as much as 200 mg/L within 2 m above the seabed [11]. The sediment concentration at 4 m is below 40 mg/L (20% of the maximum concentration of about 200 mg/L). The sediment can rarely reach 5 m and above. With some measures applied (e.g., jumper doors), suspended sediment concentrations could be reduced to as low as 20–100 mg/L. Shrimp trawls could generate suspended sediment concentrations as much as 550 mg/L at 1–2 m above the seabed, with the values...
As a precautionary measure, we used a shrimp trawl as the proxy for mobile, bottom-contact fishing activities in this study. As such, we used vertically variable initial sediment concentrations of 550, 550, and 430 mg/L at 1, 2, and 3 m above the seabed, respectively. Nevertheless, there are no data for shrimp trawl above 3 m. Thus, we further made use of the above percentage values relative to the maximum concentration from the otter trawl. The initial sediment concentrations used at 4 and 5 m above the seabed are 110 (20% of 550) and 14 (2.5% of 550) mg/L, respectively, with no sediment above 5 m.

Next, we calculated the variations of the sediment concentration with distance travelled as follows, using the model bottom current (with the implicit assumption that the variation in the current speed and direction with height can be neglected):

(a) Specify the initial concentration, which is partitioned across the particle size classes according to the sediment fractions in Table 1;
(b) Each fraction then settles at the rate determined by its settling velocity;
(c) A given size fraction is removed from the calculation once it settles to the bottom (see Table 2 for the time each size fraction with an initial height of 5 m is in the water column);
(d) Once a size class settles to the bottom, it does not become resuspended.

The variations of the sediment concentration with distance travelled are shown in Figure 7, for the initial concentrations of 550, 550, 430, 110, and 14 mg/L at 1, 2, 3, 4, and 5 m above the seabed, respectively. The intersection point between the sediment concentration curve and the threshold line indicates the impact distance. It can be seen from Figure 7 that sediment at 4 m above the seabed has the largest impact distance, 5.1 km, for *R. dawsoni*, while sediment at 3 m above the seabed has the largest impact distance, 2.3 km, for *H. calyx*. Therefore, we considered the impact of the sediment at 4 m only, using the effective threshold for *R. dawsoni*.

![Figure 7](image-url)

**Figure 7.** Change in concentration (C (mg/L)) of the sediment with distance under a representative maximum 4 h current of 0.35 m/s. Values are based on initial sediment concentrations of 550, 550, 430, 110, and 14 mg/L at 1, 2, 3, 4, and 5 m above seabed, respectively. The effective pumping arrest threshold concentrations of *R. dawsoni* and *H. calyx* for the fishing-induced sediment are also shown (dashed line).
It should be noted that Figures 6 and 7 are similar to Figure 7c of [5]. It is unclear why their sedimentation concentration curve becomes zero without reaching the fine silt settlement distance.

3. Determination of AMZs

Using a precautionary approach, we calculated the AMZ boundaries so that the sediment concentration in the CPZ would not exceed the pumping arrest threshold of *R. dawsoni* (2.8 mg/L) when the background concentration of suspended sediment is accounted for. We chose *R. dawsoni* because it has the lowest observed pumping arrest threshold among the three species of glass sponges in the HSQCS MPA.

3.1. Baseline Approach

In the baseline approach, we estimated the AMZ boundary by applying the maximum 4 h model currents for half a year in all directions, consistent with Grant et al.’s [5] conceptual approach. The baseline approach is robust in the present application because (1) the maximum 4 h model current magnitude agrees well with the maximum observed current magnitude and (2) the observed strong currents, including the maximum current, can be in any direction.

We calculated the vertices of the AMZ, which ensures that the distance from the AMZ boundary to the CPZ boundary is not less than the maximum impact distance during half a year. For a typical CPZ, there are concave and convex vertices (Figure 8). For each concave CPZ vertex, we bisected the vertex angle outside the CPZ. The centre of a circle, which has a radius of one maximum impact distance and is tangential to the two segments that intersect at the CPZ vertex, is the corresponding vertex of the AMZ. For each convex CPZ vertex, we extended the two segments that intersect at the vertex. The centre of a circle, which has a radius of one maximum impact distance and is tangential to the two extension segments, is the corresponding vertex of the AMZ.

3.2. Alternative Approach

As an alternative approach, we estimated the AMZ boundary using both the magnitude and direction of the 4 h model currents. As the current changes with time, the impact distance and direction change for a given location, with a local impact area generally resembling an ellipse. In the alternative approach, we developed an iterative search method to determine the AMZ boundary that accounts for both the current magnitude and direction. We chose minimum and maximum zonal coordinates at least one maximum impact distance from the most western and eastern CPZ vertices, respectively. For a given zonal coordinate, we first chose an appropriate starting location; we proceeded northward every 100 m until there were no ellipse points inside the CPZ and recorded the last zonal and meridional coordinate; then, we proceeded from the starting location southward every 100 m until no ellipse points inside the CPZ and recorded the last zonal and meridional coordinate. Afterwards, we changed the zonal coordinate by 100 m and repeated the above northward and southward search. Finally, we generated the alternative AMZ boundary that tightly encloses the area formed by the points with the recorded zonal and meridional coordinates and has the same number of vertices as the CPZ. Since the AMZ boundary is 1000 m away from the CPZ boundary, the 100 m spatial resolution is considered sufficient.
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![Figure 8](image.png)

**Figure 8.** Schematic diagram on how to determine the AMZ vertex for the convex and concave CPZ vertices, respectively. At a convex vertex, the interior angle is smaller than 180°, while at a concave vertex, the interior angle is greater than 180°.

4. Results

Maps are generated to show the calculated AMZs (baseline and alternative), along with the glass sponge reefs, CPZs, and existing AMZs (Figure 9). From the baseline approach using the maximum current magnitude, the distance between the proposed baseline AMZ boundary and CPZ boundary varies spatially from 3.5 to 10.0 km and, overall, is larger than that between the existing AMZ boundary and CPZ boundary (Figure 9), resulting in the increase in the proposed baseline AMZ size (Table 3) by 556 (237%) square kilometres for the northern reef. The proposed alternative AMZ from the alternative approach is also larger than the existing AMZ but to a smaller (approximately one-third) degree than the baseline AMZ (Table 3). Both the existing AMZ and the alternative AMZ are determined by considering both the magnitude and direction of the modelled currents and are therefore limited by the discrepancy in the modelled currents, as discussed in the Background section. Allowing the maximum currents to occur in any direction in the baseline approach accounts for approximately two-thirds of the increase in the baseline AMZ area over the existing AMZ area.
In the alternative approach, the AMZ boundary is estimated using both the magnitude and direction of the 4 h model currents. Boutillier et al.’s [2] tidal excursion approach also used both the magnitude and direction of Masson and Fine’s [10] model currents in estimating the existing AMZs. Therefore, the alternative approach can also serve to demonstrate and explain why we do not recommend Boutillier et al.’s [2] approach. As the current changes with time, the impact distance and direction change for a given location. During the 6 months of our simulations, the local impact area generally resembles an ellipse largely determined by the bottom tidal currents. For example, the approximate

![Figure 9. Map of the northern reef, CPZ, existing AMZ, new baseline AMZ, and new alternative AMZ.](image-url)

### Table 3. Comparison of CPZ and AMZ areas (square kilometres) for the northern (N) reef.

| Region | CPZ | Existing AMZ | Baseline AMZ | Alternative AMZ |
|--------|-----|--------------|--------------|-----------------|
| N      | 524 | 235          | 791          | 468             |

To verify the robustness of the baseline approach and result, we applied the baseline approach and the alternative approach using observed currents (see Figures 4 and 5) to determine AMZs for the northern reef, assuming that the near-bottom currents in the northern reef are horizontally invariable. This comparison between the baseline and alternative approaches determines whether or not using flow direction information makes a difference. Figure 10 show that the AMZs determined using the two approaches are close and within 10% of each other (841 square kilometres from the baseline approach and 762 square kilometres from the alternative approach). This is expected since large currents occur not only in the major flow direction but also in the minor flow direction. The baseline AMZ (791 square kilometres, Table 3) agrees within 10% with the above AMZs from the observed currents, but the alternative AMZ (468 square kilometres, Table 3) is 39% smaller (Figure 10). As shown, the underestimation is in the southwest–northeast extent, clearly due to the model underestimation of the ocean currents in that direction (see Figures 3 and 5). This result indicates that the baseline approach is robust by applying the maximum model current to all directions, effectively mitigating the deficiency that the model does not reproduce large currents in the southwest–northeast direction. That being said, it is recognized that the verification is for the northern reef only.
size and shape of the ellipse for the northern reef can be estimated by multiplying the model velocities in Figure 3 by the 4 h integration time. However, the actual impact area should resemble a circle that can be estimated by multiplying the observed velocities in Figure 5 by 4 h integration time. While the major (long) axis of the impact ellipse based on the model velocity is close to the diameter of the impact circle based on the observed velocity, the minor (short) axis of the impact ellipse is much shorter than the diameter of the impact circle. Therefore, both the alternative approach and Boutillier et al.’s [2] approach substantially underestimate the local impact area. On the other hand, the baseline approach that uses the model maximum current magnitude results in an impact circle that approximates the impact area based on the observed velocity.

Figure 10. Map of the northern reef, CPZ, existing AMZ, and baseline AMZs using observed and modelled currents, as well as alternative AMZs using the observed and modelled currents.

To show the sensitivity of the impact distance to the current data length, we used observed currents from July 2017 to June 2018 instead of those from January to June 2018. The maximum distance between the CPZ to AMZ increases from 6.4 to 7.4 km. The maximum distance may further increase to some degree when longer current data are available and used in the calculation.

Another aspect is related to the use of the vertically invariable near-bottom current. Observations indicate that near-bottom horizontal currents in the study area vary from 0.27 at 5 m above the seabed to 0.12 m/s at 1 m above the seabed during flood tides [5]. By assuming a logarithmic distribution of the near-bottom horizontal current, it can be found that the impact distance may be overestimated by 20% as a result of not accounting for the vertical variation of the horizontal current.

5. Conclusions and Discussion

A sediment transport model forced by bottom currents was used to estimate the AMZ for the Northern Reef in the HSQCS MPA in order to protect glass sponge reefs from the indirect effects of mobile, bottom-contact fishing gear. The AMZ boundaries were calculated so that the glass sponge reefs were not subject to sediment concentrations in excess of the lowest observed pumping arrest threshold of R. dawsoni. The present
The current study incorporates observed pumping arrest thresholds, explicitly accounts for background sediment concentrations, and recognises the fact that large currents can occur in any direction. The current study is therefore considered an advancement on Boutillier et al.’s [2] work that determined the existing AMZ.

Two approaches were developed to determine the AMZ boundary. The baseline approach applies the maximum model current magnitude to all directions, while the alternative approach uses both the magnitude and direction of the model currents. The baseline approach is considered robust because the maximum model current magnitude agrees well with the observed data, and the observed strong currents, including the maximum current, can be in any direction. It was also shown that the alternative approach, and the approach used to estimate the existing AMZs, would underestimate impact areas because the modelled strong currents, including the maximum current, have large discrepancies in direction with the observed data.

Comparing the proposed baseline AMZs with the existing AMZs showed a considerable difference, with the proposed baseline AMZs larger than the existing AMZs. The increased area of the baseline AMZ over the existing AMZ was due to the new results accounting for the observation that the largest currents are not always in the direction of the dominant tidal flows, the introduction of the new pumping arrest threshold, and the background sediment concentration in determining the AMZ boundary. Conservative (precautionary) options were adopted for some key model inputs (e.g., lowest observed pumping arrest threshold and highest fishing impacts (shrimp trawl sediment profile)). The cumulative effects of using the conservative options led to large AMZs.

A number of assumptions were made about the ocean currents and sediment-related features that may introduce uncertainties in the results. Discrepancies between the model and observed bottom currents were identified. Further work can be conducted to reduce these uncertainties and discrepancies:

(a) Improve circulation models to produce more accurate magnitude and direction of ocean currents, especially strong currents that can affect sediment transport most. The circulation models should sufficiently resolve the vertical structure of near-bottom currents to allow the use of different horizontal currents at different heights as sediment settles down. The models could include the effects of the reefs on the near-bottom currents.

(b) Collect more ocean current data in reef areas for the validation of circulation models and for directly forcing sediment transport models if appropriate.

(c) Observe bottom-contact fishing activity near the areas of interest to better quantify the range of disturbance heights and concentrations for different gear types, as well as horizontal extent. An improved understanding of the size distribution of the suspended sediment would also be useful.

(d) Use a more complex sediment transport model that considers more physical processes such as sediment dispersion and temporal changes in the natural suspended sediment concentration due to changes in the currents and waves.

(e) Improve the knowledge of the pumping arrest thresholds and seasonal and spatial variations of the background sediment concentrations. Improve understanding of the impacts of arrests on health and population of glass sponges to guide how the pumping arrest thresholds should be chosen and applied. Existing data on the physiology of glass sponges in British Columbia waters could be reanalysed to revisit thresholds.

It is recognised that the sponges filter at low excurrent velocities; however, instruments to record filtering are specialised and approaches to positioning instruments are challenging. The biology of glass sponges is special, and fieldwork on them is extremely difficult due to their fragile nature and their deep-sea habitat. It is also challenging to think of ways in which the effect of sediment-induced arrests on populations of glass sponges could be determined in the field without causing extensive damage to a population of these sponges.
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