An Improved Gridded Bathymetric Data Set and Tidal Model for the Maldives Archipelago

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Abstract The Maldives faces a unique range of environmental challenges. While the country is almost entirely dependent upon oceanic resources with more than 99% of the area covered by ocean, the absence of a suitable bathymetric map of the seafloor of the Maldives severely limits the adoption and application of modern scientific methods for the prediction of both physical and biological oceanic processes across the country. Here, we present a new bathymetric data set for the country based upon accumulating data from various sources and demonstrate that the synthesis of these provides a far more accurate representation of the shallow water areas of the region than currently available products. We also show that the new bathymetric data set is of sufficiently high resolution to model tidal flows across the archipelago for the first time. The new bathymetric data set provides numerous opportunities to better understand oceanic flow, associated physical and biogeochemical processes, and their correlation to one another across the Maldives archipelago.

Plain Language Summary The seafloor of the Maldives archipelago has been mapped in high resolution for the first time combining all available data sources. To demonstrate the capability of the data set, simulation of tides in the Greater Male’ area is carried out with good comparison to observational data. This new seafloor map opens up a multitude of exciting opportunities to scientifically study different phenomenon in the Indian Ocean island nation, ranging from coastal erosion due to land reclamation to modelling the movement of plankton.

1. Introduction

The Maldives is an archipelago located on the Chagos-Laccadives ridge, a prominent feature of the mid Indian Ocean basin, which runs from 9°S to 14°N of the equator. The Maldives archipelago runs from 0°41′48″S 7°06′30″N, occupying the central and largest part of the ridge (Fürstenau et al., 2010). The central location of the Maldives in the Indian ocean, equidistant from the East African and South East Asian reefs, gives rise to a high diversity of ecological species in the archipelago, with high affinities to both regions, within the larger “Chagos stricture” (Kench, 2011). The Maldives is widely recognized as a marine ecological hotspot, part of the world’s most extensive atoll formation and the seventh largest reef system in the world, containing over 5% of the world’s coral reefs and supporting over 1000 fish, 300 coral and 350 crustacean species (Emerton et al., 2009).

Available sources indicate that little has been done to study the bathymetry of the country over large geographic scales since the development of Admiralty charts over a century ago (Kench, 2011). The first large-scale bathymetric survey of the Maldives was carried out by Commander James Moresby from 1835–1883 (Gardiner, 1902). These charts still form the underling data for navigational charts of the Maldives. Several subsequent expeditions in the early 20th century by J. Stanley Gardiner (1899–1900) (Gardiner, 1903), Alexander Agassiz (1901–1902) (Agassiz, 1903) and the Anglo-Egyptian “John Murray” expedition led by R.B. Seymour Sewell (1933–1934), while focused on other terrestrial and marine research, contributed to the initial bathymetric data (Sewell, 1936).

Later the “Xarifa” expedition (1957–1958) (Hass, 1965) which pioneered remote observations of coral reefs also contributed to the bathymetric surveys. In the late 1960s, the southernmost atoll of Addu was studied in great detail, including detailed bathymetric assessment using soundings (Stoddart, 1966). Using high density echo sounding, this assessment discussed the discrepancies in the earlier bathymetric data previously reported by Gardiner, Agassiz and Sewell in Addu Atoll, and importantly suggested limitations in previous...
studies giving rise to the discrepancies, particularly the lack of spatial coverage. Since these expeditions, no large-scale assessments of the bathymetry of the Maldives has taken place on a scale worthy of note. However, Naseer and Hatcher (2004) studied and classified the coral reefs and atolls of the Maldives using satellite imagery, but emphasis was not placed on deriving bathymetry.

Analysis of bathymetric data from these surveys which exists as navigational chart data shows that, although the data is sparse—up to 13,000 depth points across the archipelago are present in these charts, the majority of these depth points are found in the relatively shallow water areas of the inner atoll basins. These charts provide depth data for all atolls of the Maldives, but depths for the very shallow regions (less than 15 m), which form the fringing and barrier reefs which make up the most prominent features of the contemporary atoll system, are covered only in four atolls, as shown in Table 1 and even for these locations data at these very shallow depths are extremely scarce (Edwards, 1989), with ~1,800 depth sounding points.

The Maldives is almost entirely dependent upon oceanic resources. However, the absence of a suitable bathymetric map of the seafloor severely limits the adoption and application of modern scientific methods for the prediction of both physical and biogeochemical oceanic processes across the country. Here we present the first large-scale, high-resolution bathymetric data set of the Maldives including the (very) shallow water regions. The data set covers the region from 1.0°S to 7.20°N and 72.0° to 74.0°E at a resolution of 0.35 arc-seconds (~10.5 m), referenced to the WGS84 ellipsoid. In this study, we describe the data sources utilised, how the data set was compiled and draw comparisons with global bathymetry data sets, localized bathymetric field data and regional bathymetric data sets. Through numerical simulation, we demonstrate that the new bathymetry data set enables high-resolution numerical ocean modelling in the Maldives archipelago with results comparable to field data and observations.

2. Methods and Data Sources

2.1. Bathymetric Data

The new bathymetry data set is compiled from three major data sources details of which are presented separately below, with a focus on mapping shallow water regions. For depths shallower than 20 m, we use satellite-derived bathymetry. For depths between 20 and 200 m, we use navigational chart data. For depths greater than 200 m we use GEBCO 2014 data. In total the raw data set contains ~30 million data points before being processed.

2.1.1. Satellite-Derived Bathymetry

Deriving bathymetry from satellite data was undertaken through several steps to address known issues in satellite-derived bathymetry, including cloud coverage and atmospheric and water surface correction (Goodman et al., 2008). Sentinel-2 satellite images courtesy of the European Space Agency (ESA), which offer the highest resolution open source multispectral images available, were used as the primary source. The missing areas of Sentinel-2 coverage were compensated for using images gathered from Landsat 8 Operational Land Imager (OLI) courtesy of the US Geological Survey. To reflect changes in the coastlines in recent years and the availability of data, the images gathered spanned the period from January 2018 to September 2019.

Images gathered from Sentinel-2 were sourced from Level 2 products, which are processed for radiometric, geometric, cloud screening and atmospheric corrections to ensure that the correct image rectifications are

| No. | Geographic atoll               | Admiralty chart description                  |
|-----|--------------------------------|---------------------------------------------|
| 1.  | Ihavandhippolhu Atoll          | No. 2036 Ihavandiffulhu Atoll               |
| 2.  | North Male Atoll               | No. 3323 Male’ Anchorage and Approaches     |
| 3.  | Addu Atoll                     | No. Addu Atoll                              |
| 4.  | Goidhoo Atoll                  | No. 2036 Horsburgh Atoll                    |
applied. When dealing with multiple tiles spanning a large spatial area, the use of pre-processed products reduces the time taken to process the images for the purposes of this work. Landsat images were sourced from Level 1 processing levels, specifically processed at the Standard Terrain Correction (L1TP) level. At this stage the Landsat images are radiometrically calibrated and orthorectified using ground control points and other data for correct relief displacement, reducing the time taken for image rectification. To correct the Landsat 8 images for atmospheric reflectance, we used the DOS (Dark-Object Subtraction) method (Chavez Jr, 1988), which offers a simplistic and well-established method for atmospheric correction of satellite images (Song et al., 2001). While some studies (Song et al., 2001) suggest that atmospheric correction is not necessary in remote sensing and depends on the application, we find that implementing atmospheric correction is a crucial step in deriving bathymetry of highly reflective regions such as the shallow water sandy lagoons and sand banks of the Maldives archipelago.

To derive the bathymetry from the satellite images, the ratio transform algorithm (Stumpf et al., 2003):

$$Z = m_1 \times \frac{\log(R_w(\lambda_i))}{\log(R_w(\lambda_j))} - m_0,$$

(where $Z$ is water depth, $R_w(\lambda_i)$ and $R_w(\lambda_j)$ are the pixel values of the spectral bands, $m_1$ is a tunable constant and $m_0$ is the offset where depth ($Z$) $= 0$), was applied to the Band2 and Band3 band ratios.

These bands represent blue and green spectral bands in both Sentinel-2 and Landsat 8 OLI images and were selected for two reasons. First, the high-resolution available for these bands means they are most well-suited for capturing the geographic features of the shallow water areas of the archipelago. Second, studies in similar tropical areas indicate that the Blue/Green band ratio can be used to depths exceeding 18 m, thereby maximizing the effectiveness of satellite-derived bathymetry in the region. Other multispectral image ratios, such as Blue/Red, are limited to shallower depths of around 5 m (Caballero & Stumpf, 2019), and given the wide range of depths within the archipelago the Blue/Red ratio was not used in this study.

The satellite-derived bathymetry was calibrated using a very high-resolution depth sounding survey carried out on an industrial scale across Emboodhoo Finolhu Lagoon in South Male’ Atoll by LaMer group. Due to the lack of data in other areas of the archipelago, this calibration was utilised across the whole archipelago, with small variations in tuning the coefficients applied (following [Geyman & Maloof, 2019]). These adjustments are required to adjust for areas with significant sea grass and certain types of coral, which provide band ratio pixel values overlapping with deep water areas, leading to potentially unrealistic depth estimations.

This calibration was achieved by adjusting the tuning parameters at locations where extant seagrass is present such that overlapping pixel values are removed at overlapping regions while applying the Stumpf algorithm (Equation 1). We find that this process combined with the gridding procedure described in Section 2.2 produces comparable results to field data. The description of the images used for deriving the bathymetry, the corresponding geographic areas and the equations used to derive the satellite bathymetry for each tile is given in Table 2. The resulting data set provides the majority of the depth points for the raw data and comprises of $\sim$29 million data points.

2.1.2. Digitizing Navigational Chart Data

The extraction of depth soundings from freely accessible navigational chart data available from NAVION-ICS was gathered (with permission) through digitization using QGIS (QGIS Development Team, 2016), by geo-referencing navigational chart images and manually extracting depth soundings as depth points. This data set contains $\sim$13,000 depth sounding points within the Maldives archipelago, the majority of which are at 0–200 m depths within the atoll basins. The data set also contains a large number of depth soundings at 200–600 m depths covering areas of the inter atoll regions within the Maldives ridge. All depth points digitized from navigational charts were used in the study.

2.1.3. Depth Points for Deep Water

For depths greater than 200 m, we use GEBCO 2014 (Weatherall et al., 2015) data to fill in the areas. Observation of the Source Identification Grid for both GEBCO 2014 and 2019 shows that the entirety of this data
The new bathymetry data set is validated. This data set contains \( \sim 1 \) million depth points. Landsat-8 Imagery was used in the northern most areas of the archipelago due to unavailability or partial availability of sentinel-2 imagery in these regions, thus tuning coefficients used for these regions differ significantly from others.
2.2. Gridding Algorithm

The accumulated depth points collected from the three sources of data were filtered and gridded using generic mapping tools (GMT) (Wessel et al., 2013). The initial pre-processing step of subsampling is important in the use of gridding algorithms, particularly when incorporating high density satellite data, to ensure that the input information for the gridding process is below the Nyquist frequency of the final grid (Smith & Wessel, 1990). We used the GMT “blockmedian” filter on the accumulated depth points over 0.35 arcsecond resolution blocks to avoid spatial aliasing and to eliminate redundant data. While other filtering options are available within the GMT framework, blockmedian was specifically used to decrease the influence of potential outliers as highlighted in bathymetry gridding guidelines (Marks et al., 2010).

To produce the gridded bathymetry surface as seen in Figure 1, we used the adjustable tension continuous curvature gridding algorithm (GMT ‘surface’) to grid the data (Smith & Wessel, 1990). This algorithm is an improvement of the bicubic spline interpolation (Briggs, 1974) which implements a tension factor to relax the minimum curvature criterion, increasing stability and reducing the introduction of spurious extrema between observational points (Hell & Jakobsson, 2011). A tension factor of 0.35 was used here to reflect the steep topography of the reef slopes and lagoons, the successful gridding practices used in IBCSO (Hell & Jakobsson, 2011) and as per the GMT guidelines for gridding steep topographic areas. The horizontal resolution of the grid was selected as 0.35 arc-seconds (~10.5 m) based on three considerations: (i) the aim of reflecting the fine spatial scales of the bathymetric features present; (ii) the available highest resolution of satellite data (10 m for Sentinel); and (iii) the steep gradients of the reef and atoll slopes.

3. Validation of the New Bathymetry Data Set

Here we compare the new bathymetry data set with existing bathymetric data sets at two major locations, Hadhunmathi Atoll and Banana Reef in North Male atoll. Sourcing of bathymetric data for validation purposes proved challenging due to scarcity of data and lack of any bathymetric data gathered locally being available in the public domain. Hadhunmathi Atoll was selected to draw comparison with high-resolution satellite-derived bathymetric data available for the shallow regions of the atoll, and Banana Reef was selected to compare with high-resolution multibeam data available for a section of the reef.

3.1. Comparison at Haddhunmathi Atoll

In order to validate the new bathymetry data set we select Hadhunmathi Atoll, shown in Figure 2, and compare against available data at four locations which exhibit varying benthic features and spatial resolutions. These locations range from transects across two types of lagoons (shallow and deep) a transect across a narrow artificial pass cut across a shallow lagoon, a typical feature of many Maldivian lagoons, as well as a region with significant marine growth which impacts upon the derivation of bathymetry from satellite imagery. The comparison is conducted using the following four data sets:

1. GEBCO 2014 global bathymetry data set
2. GEBCO 2019 global bathymetry data set
3. Improved bathymetry data set of the Indian Ocean (Sindhu et al., 2007), which improves upon the ETOPO2v2 data set across the Indian ocean using Admiralty chart data. Here we use the higher resolution 2 arc-minute data set, referred to as “Indiano2”
4. A high-resolution bathymetric survey of the shallow water regions of Hadhunmathi Atoll commissioned by the Maldivian Government and United Nations Development Program (UNDP) for the Low Emission Climate Resilient Development Program (LECReD). This data set is derived from Worldview-II satellite data calibrated against field data, and is referred to as “LecReD”

Figure 3a compares the bathymetry across a lagoon located on the western side of the atoll (Figure 2, transect 1), representative of similar lagoons which make up the outlying areas of Maldivian atolls. According to Luthfee (1995) this lagoon is significant since it hosted large islands with significant populations which have since eroded away, with high erosion rates continuing today. Figure 3b compares the data sets across the Northern extremities of the larger North Western Lagoon of the atoll (Figure 2, transect 2), known as “Verehi Falhu” (Luthfee, 1995). This area is reported to have high rates of sediment accumulation leading to...
the need for frequent dredging to create channels providing access to the islands. The erosion and accretion at these sites have not been studied before, however improvements in bathymetry data sets as presented here will potentially pave the way for such studies.

Depth comparison at these transects shows that there is a general agreement between the new bathymetry data set and the LecReD bathymetry. However, none of the global or regional bathymetry data sets provide comparable results, with GEBCO 2014 providing the best results; the GEBCO 2019 and Indiano2 bathymetry data set differ significantly. The performance of the Indiano2 data set can be attributed to the fact that

Figure 1. Figure (a) shows an image of the new bathymetry data set with all geographic atolls labeled. The atolls are labeled as: 1 - Ihavandhippolhu, 2 - Makunudhoo, 3 - Thiladhunmathi, 4 - Eithigili Alifushi, 5 - N.Maalhosmadulu, 6 - Fadhoothere, 7 - S.Maalhosmadulu, 8 - Goldhoo, 9 - Faadhippolhu, 10 - Kaashidhoo, 11 - Gaafaru, 12 - N.Maale', 13 - S.Maale', 14 - Thoddoo, 15 - Rasdhoo, 16 - Ari, 17 - Felidhe', 18 - Vattaru, 19 - Mulaku, 20 - N.Nidlande', 21 - S.Nilande, 22 - Kolhumadulu, 23 - Hadhunmathi, 24 - Huvadhu, 25 - Fuvahmulaku, 26 - Addu. Figures (b–d), show three-dimensional images of the new bathymetry data set with the bathymetry vertically exaggerated for visualisation of the shallow water lagoons. Figures (e–g) show the new bathymetry surface for (e) Huvadhu Atoll, (f) Kolhumadulu and Hadhunmathi Atoll and (g) the region around Maalahosmadulu Atolls.
the 2 arc-minute resolution is not adequate to capture the spatial features, and also since it uses Admiralty charts, which do not contain bathymetry for shallow water areas. The reason for divergence between GEBCO 2019 and GEBCO 2014 is unclear, but it may arise due to the gridding algorithm used. Although the GEBCO 2019 data set is gridded at a higher resolution (15 arc-seconds) in comparison to GEBCO 2014 (30 arc-seconds), the GEBCO 2019 grid may not have reached convergence, an issue with the use of bicubic spline interpolation (Briggs, 1974) and derivative methods such as the bicubic splines continuous curvature gridding algorithm (Smith & Wessel, 1990), where maxima and minima are produced in the form of interpolation artifacts in between observational data when gridding sparse data at higher resolutions (Hell & Jakobsson, 2011), causing divergence in the data sets. Additionally, all points of the GEBCO 2019 data set across the Maldives are derived from the interpolation of predicted satellite-derived gravity data, while GEBCO 2014 reports to have additional depth points derived from ship tracks.

Transect three, (Figure 2, transect 3) compares the depth of a dredged narrow channel in the same lagoon as transect two. Figure 3 (c) shows that, despite the narrow spatial scale of the feature (20 m including shallow areas), the new bathymetry data set is capable of capturing the depths of the channel, and is comparable to the high-resolution LecRed data set, providing support that the methods used in this study can be used to accurately monitor these channels remotely.

Transect four (Figure 2, transect 4) examines the treatment of different benthic features by the data sets, and the effect of these features on the satellite-derived bathymetry. The transect is dotted with sea grass and shallow corals. Ahmed Jameel (2012) and Ahmed Jameel (2014) report that the bathymetry of areas with similar benthic features in the atoll is in the range of 0.40 to −4 m. Comparing the bathymetry profiles, the LecRed data set severely over-estimates the depth. This can be attributed to the fact that linear regression methods for deriving bathymetry from satellite data are heavily reliant on the reflected wavelengths from the bottom of the surface. However, benthic features such as sea grass and some types of coral, common in the lagoons of the Maldives, have low reflectance even in shallow water areas, leading to misinterpretation of these shallow water areas as deep water areas according to the method used to derive the depth (Geyman & Maloof, 2019). In comparison, the new bathymetry data set derived from the method described in Section 2.1.1 provides much better representations of the bathymetry.

3.2. Comparison With Multibeam Data Set

Next we compare the new bathymetry data set with depth points from a survey carried out at a reef off the coast of Hulhumale’ island by Water Solutions Pvt. Ltd. using a high-resolution Teledyne ODOM MB2 Multibeam Echosounder. The data set covers the Eastern section of the reef in a swath of ∼400 m in length and ∼10 m in width. This reef, more commonly known as "Banana Reef", is a world world-renowned dive spot famed for its ecological diversity and different coral species. The site has been a protected marine area since 1995. Comparison of the data set with 50 randomly selected depth points across the reef, in Figure 4 shows that, despite its 0.35 arc-second resolution, the new bathymetry data set compares well with the high-resolution multibeam data.

4. Tidal Modelling

In Section 1 we argued the need for an improved bathymetric data set of the Maldives archipelago, and in Section 2 derived such a data set from a variety of sources before comparing the new bathymetry data set against different existing bathymetry data sets in Section 3. In this section, we assess the improvement offered by the new data set by qualitatively and quantitatively comparing the results of a tidal model using both existing and new bathymetry data sets. For existing bathymetry data sets, GEBCO 2019 was selected
Figure 3. Depth profile comparison at Hadhunmathi Atoll along four different transects shown in Figure 2. The new bathymetry data set compares well with high-resolution field calibrated data sets (a–c), but none of the global data sets are comparable. (d) shows that treatment of sea grass and related features by the new bathymetry data set is more accurate; in comparison the high-resolution LecRed data set tends to over-estimate the depth.
for a variety of reasons. First, GEBCO 2019 presents the highest resolution of all publicly available data sets and, while GEBCO 2014 was found to contain fewer interpolation artefacts, there was no difference between GEBCO 2014 and GEBCO 2019 in the spatial extent where the tidal modelling was carried out. Meanwhile, the low spatial resolution of the Indiana2 data set makes its use impractical for such a small spatial extent.

In this study we use the Thetis coastal ocean model, a (2D (Angeloudis et al., 2018) and 3D (Kärnä et al., 2018; Pan et al., 2019)) flow solver built upon the Firedrake finite element solver framework (Rathgeber et al., 2016). Here we use the 2D implementation of Thetis which solves the depth-averaged shallow water equations in non-conservative form:

\[
\frac{\partial \eta}{\partial t} + \nabla \cdot (H_d \mathbf{u}) = 0, \tag{2}
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - \nu \nabla^2 \mathbf{u} + f\mathbf{u}^\perp + g \nabla \eta = -\frac{\tau_b}{\rho H_d}, \tag{3}
\]

where \( \eta \) is the free surface displacement (m), \( H_d \) is the total water depth (m), \( \mathbf{u} \) is the depth-averaged velocity (m s\(^{-1}\)) comprising \( u \) and \( v \) the \( x \)- and \( y \)-components respectively, and \( \nu \) is the kinematic viscosity of the fluid (m\(^2\) s\(^{-1}\)). The term \( f\mathbf{u}^\perp \) accounts for the Coriolis force, where \( f = 2\Omega \sin(\zeta) \), \( \Omega \) the angular rotation of the Earth, \( \zeta \) the latitude and \( \mathbf{u}^\perp \) the velocity vector rotated 90\(^\circ\).

The model uses a discontinuous Galerkin finite element discretization (DG-FEM), using the \( P_1^{DG} - P_1^{DG} \) velocity-pressure finite element pair. For timestepping, a semi-implicit Crank-Nicolson approach is applied with a constant time step of \( \Delta t \). The model treats wetting and drying according to Kärnä et al. (2011), which introduces a modified bathymetry \( \tilde{h} = h + f(H) \), which ensures a positive total water depth, with \( f(H) \) defined as:

\[
f(H) = \frac{1}{2} \left( \sqrt{H^2 + \alpha^2} - H \right). \tag{4}
\]

where \( H \) is the water Height, and \( \alpha \) is a tunable constant. Bed shear stress \( \tau_b \) is implemented through the Manning’s \( n \) formulation as

\[
\frac{\tau_b}{\rho} = gn^\frac{1}{3} \left| \frac{u}{H_d^{1/3}} \right|. \tag{5}
\]

We use the tidal model to simulate flow across the Greater Male’ area in North Male’ Atoll, for a period of one month. The region consists of the islands of Male’, Hulhumale’, Hulhule’ and Villingilli, along with other small islands as shown in Figure 6a. The spatial extent of the domain covers \( \sim 20 \) km in the \( x \)-direction by \( 12 \) km in the \( y \)-direction. The area holds significance for the archipelago since this small area houses more
than a third of the entire population of the country (National Bureau of Statistics, 2019). The tidal model was run using the new bathymetry data set as well as the GEBCO 2019 data set.

4.1. Model Setup

The mesh for the model was set up using “qmesh”, a Python package for constructing flexible unstructured meshes for geophysical models (Avdis et al., 2016; Avdis et al., 2018). The use of unstructured meshes offers significant advantages in representing small spatial features across large geographical extents due to their flexibility of resolution and geometry. Coastlines were extracted from Band8A (Narrow infrared) contours of Sentinel-2 satellite images. While other sources provide coastline data across the Maldives in varying degrees of accuracy, we find that extraction of coastline contours from satellite imagery is the best way to handle extremely complex coastlines such as those in the Maldives. The resolution of the triangular elements making up the multi-scale unstructured mesh varied from approximately 50 m at island coastlines to 5 km in open regions, with additional refinement to 100 m at lagoon boundaries. The mesh used for the simulation, shown in Figure 6b, was generated in the UTM43N coordinate reference system and is comprised of 38,931 nodes and 77,904 triangular elements.

A uniform Manning drag coefficient was applied across the domain. According to various studies (e.g., Rosman & Hench 2011), drag parameters across coral reefs are poorly understood and depend on many factors, requiring further study as well as the potential to be used in a model calibration exercise, which is not conducted here. Instead, the value applied here was selected as the often used as default 0.025 sm$^{-1/3}$.

The wetting and drying constant $\alpha$ parameter (Kärnä et al., 2011) was set to 2 m. A minimum depth of 1 m was applied to the GEBCO 2019 bathymetry, which was found to be required due to the unrealistically high positive topographic values.

The tidal model was forced with 11 tidal constituents (M2, S2, N2, K2, O1, P1, Q1, M4, MS4, and MN4) at the open boundaries using the TPXO database (Egbert & Erofeeva, 2002). These tidal constituents were selected based on the harmonic analysis of long term tide gauge data from the tide gauge located in the harbor of Hulhule’ Island, summarised in Table 3. Applying the form number or amplitude ratio, defined as:

$$F = \frac{K1 + O1}{M2 + S2},$$

(6)

to classify the tidal regime, (where $F < 0.25$ is classified as semi-diurnal, $0.25 < F < 1.5$ mixed semi-diurnal dominant, $1.5 < F < 3$ mixed diurnal dominant, and $F > 3$ diurnal) (Defant, 1961), the tides in the region can be classified as mixed semi-diurnal, with a form factor of $\sim 0.4$. It is noticeable that while the tidal amplitude is very low with a maximum tidal range of $\sim 1$ m, there is no major tidal constituent contributing close to 50% of the total, with six constituents each contributing 5% or more.

4.2. Model Assessment

The results of the simulations are compared against tide gauge observations in the case of tidal elevations, with tidal velocities obtained with the two bathymetry data sets also qualitatively compared to one another. The bathymetry evaluated on the mesh is seen in Figure 5c for GEBCO 2019 and Figure 5d for the new bathymetry. The topographic features of the area are well represented in the new bathymetry, while GEBCO 2019 shows no such features, and is dominated by the manually set 1 m minimum depth introduced to account for the spurious positive topographic values.

4.2.1. Comparison of Harmonic Constituents With Tide Gauge Data

Here we compare the observed and modeled amplitudes and phases of the four major harmonic constituents at Hulhule’ Island harbour. We do not compare the tidal constituents obtained using the GEBCO 2019 bathymetry since a large extent of the bathymetry for the simulation was carried out using a manually set minimum value rather than being derived from the bathymetry itself, and because GEBCO source data as shown by the Source Identifier grid is sparse at the location being modeled making it poorly suited for such a detailed comparison. The new bathymetry data set produces simulated amplitudes that are within an error
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Comparison of Tidal Velocities

Here we compare the tidal velocities from simulations using the new bathymetry data set and GEBCO 2019. The maximum simulated velocity magnitudes are shown in Figure 5e for GEBCO 2019 and Figure 5f for...
The relationship between the bathymetry and velocity is apparent, with high velocities forming on the rims of the submerged reefs. The simulation that used the GEBCO 2019 bathymetry fails to capture any details due to the missing bathymetric features.

Figure 6. Figures (a) and (b) show the velocity patterns around region A, (Kohdhipparu Falhu) obtained using the GEBCO 2019 and the new bathymetry data sets respectively. (c) and (d) shows velocity patterns around region B, (Bandos area) obtained using the GEBCO 2019 and the new bathymetry data sets respectively.

The new bathymetry. The relationship between the bathymetry and velocity is apparent, with high velocities forming on the rims of the submerged reefs. The simulation that used the GEBCO 2019 bathymetry fails to capture any details due to the missing bathymetric features.

Table 3
Summary of Harmonic Tidal Constituents From a Tide Gauge Located at Hulhule' Island Harbour (Data Available for Years 1988–2019)

| Constituent                          | Amplitude | Phase   | % Contribution |
|--------------------------------------|-----------|---------|----------------|
| Principal lunar semidiurnal (M2)     | 0.2439    | 227.46  | 37.15          |
| Principal solar semidiurnal (S2)     | 0.1377    | 270.14  | 20.99          |
| Lunar diurnal (K1)                   | 0.1038    | 349.26  | 15.81          |
| Lunar diurnal (O1)                   | 0.0522    | 354.62  | 7.95           |
| Solar diurnal (P1)                   | 0.0367    | 341.43  | 5.58           |
| Larger lunar elliptic semidiurnal (N2)| 0.0359    | 209.38  | 5.58           |
| Lunisolar semidiurnal (K2)           | 0.0276    | 275.8   | 4.20           |
| Larger lunar elliptic diurnal (Q1)   | 0.0135    | 2.280   | 2.05           |
| Shallow water overtides of principal lunar (M4) | 0.0031    | 188.15  | 0.47           |
| Shallow water quarter diurnal (MS4)   | 0.0015    | 266.37  | 0.22           |
| Shallow water quarter diurnal (MN4)   | 0.0008    | 95.42   | 0.12           |

Note. Amplitudes are given in metres and phase in degrees. Tide gauge data obtained from UHSLC (Caldwell et al., 2015).
While we were unable to access site-specific current data for a quantitative comparison of tidal currents, some data are sparsely provided in environmental impact assessment surveys and studies across different localized parts of the archipelago. It has been reported that low velocities (∼0.31 m/s) are observed in shallow water regions, with a general increase in velocity towards the deep channels (Saleem, 2018) in the atoll rims and in between the atolls. The simulation using the new bathymetry data set is consistent with these observations, whereas the GEBCO-based simulation does not exhibit such patterns.

Figures 6a and 6b shows the tidal velocity patterns around Kudavattaru Falhu. The natural island at the North Eastern corner of the lagoon (Kohdhipparu) has modified artificial coastlines, while the island at the South Western side of the lagoon is being reclaimed for industrial purposes. Simulations based on the new bathymetry data set show that the newly reclaimed island may be susceptible to high flow velocities enhanced by the topography of the lagoon and interaction with the eddy patterns around Kohdhipparu Island. These flow patterns are predicted to be further complicated by the reclamation of a third island in the area in the lagoon, to the west. The GEBCO-based simulation, shown for the same simulation time does not capture such features.

Figures 6c and 6d compares tidal velocities simulated using GEBCO-based bathymetry with the new bathymetry data set, in the area around Bandos for the same simulation time. The area is occupied by two islands (Bandos (Greater Bandos) and Kuda Bandos (Lesser Bandos)), with a lagoon adjacent to Kuda Bandos. The simulation with the new bathymetry predicts tidal jets in the channel between the islands, due to acceleration of flow through the narrow channel, further enhanced by the lagoon on the eastern side of Kuda Bandos, and the formation of complex eddy patterns combined with the island wake dynamics. While no formal field data exists to corroborate this prediction, studies at locations with similar topography provides similar patterns of flow with unstable jets producing pairs of eddies, with two-dimensional modelling techniques replicating field and experimental data (Lambrechts et al., 2008). Since the GEBCO-based bathymetry contains no topographical representation of the bathymetry, it fails to predict such phenomena.

These simulations demonstrate that the new bathymetry data set, with the Thetis coastal ocean model, has the capability to predict complex, small-scale flow patterns around lagoons and islands, representing a significant improvement on existing bathymetry data sets.

### 5. Conclusion

A new gridded bathymetry data set has been constructed for the whole of the Maldives archipelago in high-resolution, combining various data sets freely available in the public domain. The new bathymetry data set combines GEBCO bathymetry with Admiralty chart depth data at deep oceanic and atoll basins and uses satellite-derived bathymetry to map the bathymetry of shallow water regions not mapped before. The resulting bathymetry data set was compared with several alternative sources of bathymetry, including localized high-resolution data, for validation including those based upon field measurements and commercial satellite imagery. In both cases, the new bathymetry compares well, and at times performs better. Additionally, in line with observations of Hell and Jakobsson (2011) we also demonstrated that improvements in bathymetric data in remote areas such as the Maldives archipelago are essential to maintain the integrity of gridded global bathymetry data sets which appear to be getting worse at regions where data is sparse with subsequent finer resolutions. Methods for improving existing global bathymetry gridding methods require more data in areas where data is lacking and while field data gathering methods for large-scale shallow water areas with dynamic coastlines are unfeasible in the short term, the approaches used in this study can be used to improve such areas with minimal resources and effort.

### Table 4

**Summary of Comparison: Harmonic Constituent Amplitude (metres) for Simulations Using the New Bathymetry Data Set**

| Constituent | Gauge | New bathymetry |
|-------------|-------|----------------|
|              | Amplitude (m) | Amplitude (m) | % Error |
| M2          | 0.2362  | 0.2231  | 5.59    |
| S2          | 0.1548  | 0.1423  | 8.07    |
| K1          | 0.1160  | 0.1149  | 0.99    |
| O1          | 0.0618  | 0.0573  | 7.21    |

### Table 5

**Summary of Comparison: Harmonic Constituent Phases (degrees) and Error (degrees) for Simulations Using the New Bathymetry Data Set**

| Constituent | Gauge | New bathymetry |
|-------------|-------|----------------|
|              | Phase (deg) | Phase (deg) | Error (deg) |
| M2          | 223.59  | 229.71  | −6.12    |
| S2          | 267.71  | 273.42  | −5.71    |
| K1          | 348.27  | 340.17  | 8.10     |
| O1          | 355.58  | 354.64  | 0.94     |
The main limitation of the new bathymetry data set is the limited availability of ground truth data. While high-resolution bathymetric field data obtained across a large lagoon was used to obtain ground truths, the data set can be improved by having multiple ground truth points in shallow water areas across the entire archipelago. These ground truth points could possibly be aligned with satellite image tiles such that at least a certain amount of truth points exist within each satellite image tile. Additionally, the Admiralty chart data which includes data over the past century, needs to be further validated since it is highly likely that changes would have occurred altering the bathymetry at these locations.

We subsequently used the high-resolution gridded bathymetry data set in order to perform high-resolution simulations of tidal flow across an area of North Male’ Atoll. Simulation of oceanic flow across the Maldives archipelago has not been possible before due to the highly complex geometry and lack of high-resolution bathymetry data. We demonstrated here that simulations using the new high-resolution bathymetry data set can predict small scale flow features, which have been modeled and observed in other locations with similar bathymetric setting. The new bathymetry data set opens up a multitude of physical and biogeochemical modelling opportunities hitherto unexplored, from responses of island morphology to sea level rise scenarios and land reclamation, to the spawning and dispersal of marine fauna. Rasheed et al. (2020) used the new bathymetry data set presented here to identify the bed sediment properties of North Male’ atoll with results agreeing well with field data, and further studied the changes to the bed shear stress induced by island scale coastal modification, demonstrating the potential use of the new bathymetry data set in a practical context. Bathymetry improvements using the methods presented in this study can be adopted for other similar remote areas for bathymetry improvement at large-scale, with minimal resource input and with results demonstrated here to be comparable to well-established and hugely more resource intensive methods of bathymetry derivation.

**Data Availability Statement**

The gridded new bathymetry data set can be accessed temporarily from the link below. The data set will be moved to a permanent location once the manuscript has been accepted for publication. [https://imperialcollegebox.com/s/y8vlfv0aq37hzmlus744azpsyez2yar](https://imperialcollegebox.com/s/y8vlfv0aq37hzmlus744azpsyez2yar)

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