

## Article

# Circulation and Stratification Changes in a Hypersaline Estuary Due to Mean Sea Level Rise

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**Abstract:** Hypersaline Hamelin Pool, with mean salinity >65, is located in Shark Bay, Western Australia. The high salinity has reduced its biodiversity, but it is home to a diverse assemblage of modern marine stromatolites. The limited exchange of water between Hamelin Pool and the rest of Shark Bay, due to the presence of the shallow Faure Sill together with high evaporation and low rainfall-runoff have resulted in a hypersaline environment. With climate-change-induced mean sea level rise (MSLR), hydrodynamic processes that maintain the hypersaline environment may be affected and are the focus of this paper. Oceanographic observations, together with hydrodynamic model results, were used to examine the hydrodynamic processes under present and future MSLR scenarios. A large attenuation in the tidal range, changes in the tidal characteristics, and current speeds together with a strong salinity gradient were observed across the Faure Sill under present-day conditions. Under an MSLR scenario of 1 m, the tidal amplitude decreased by up to 10% to the north, whilst to the south, the tidal range increased by up to 15%. Regions of strong vertical stratification were present on both sides of the Faure Sill. The simulations indicated that, under MSLR scenarios, these regions expanded in area and exhibited higher levels of vertical stratification. The salt flux across the Faure Sill was maintained as a diffusive process under MSLR scenarios.



**Citation:** Taebe, S.; Pattiaratchi, C.; Haigh, I.; Kendrick, G. Circulation and Stratification Changes in a Hypersaline Estuary Due to Mean Sea Level Rise. *J. Mar. Sci. Eng.* **2024**, *12*, 579. <https://doi.org/10.3390/jmse12040579>

Academic Editor: Anatoly Gusev

Received: 31 December 2023

Revised: 13 March 2024

Accepted: 18 March 2024

Published: 29 March 2024



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**Keywords:** mean sea level rise; inverse estuary; stratification; hydrodynamic modelling; Shark Bay; Australia

## 1. Introduction

Shark Bay (indigenous name Gathaagudu meaning “two waters”) is a World Heritage site located on the westernmost point of the Australian continent. Gathaagudu reflects the presence of two main water bodies, Freycinet and Hopeless Reaches, which are separated by the Peron Peninsula (Figure 1). The Bay is defined as an inverse estuary, with the salinity within the Bay being higher than the adjacent ocean [1–4]. Hamelin Pool, located at the end of Hopeless Reach (Figure 1), is a hypersaline embayment where the mean salinity exceeds 65 [1,2,5]. It is separated from Hopeless Reach by the presence of the shallow Faure Sill (Figure 1b), a seagrass-stabilised carbonate sediment bank that reduces water exchange between Shark Bay waters and Hamelin Bay [6]. High evaporation (>2 m per annum) and negligible precipitation and runoff have made Hamelin Pool permanently hypersaline, and thus it contains water that is of higher density than the rest of Shark Bay. The hypersaline environment has reduced biodiversity, resulting in unique low diversity, high abundance, and carbonate sediments [6]. It also sustains the world’s most extensive and diverse assemblage of modern marine stromatolites (accretionary structures formed by the trapping and binding of sedimentary grains by cyanobacteria) that grow at rates ranging from <0.1 mm/year to 0.5 mm/year [5,6]. Stromatolites occur in the shallow

nearshore, with coverage extending over 100 km along the coast. They persist as there is little competition with eukaryotic algae and little fish and invertebrates grazing in hypersaline waters [7–9].

Coastal embayments, lagoons, and estuaries may be classified either as hyposaline (salinity lower than that of seawater) or hypersaline (salinity higher than that of seawater). Globally, the majority of embayments, lagoons, and estuaries are hyposaline, whilst hypersaline systems exist mainly in arid regions, which are characterised by low (or seasonal) rainfall and high evaporation [10]. Some of these systems are subject to seasonal changes between hyposaline and hypersaline environments due to seasonal rainfall events, whilst others are permanently hypersaline [11]. Extreme hypersaline environments (e.g., salinity > 60) are found in systems with restricted water exchange, for example, when the exchange with the surrounding water bodies is restricted by constrictions (e.g., lagoon entrances restricted by sandbars) and/or due to the presence of sills. Water bodies that exhibit hyposaline characteristics have been subject to studies mainly concerned with circulation and residence times. These span a range of length scales from the order of kilometres such as Mission Bay, California [10], and Puttalam Lagoon, Sri Lanka, [12] to tens of kilometres such as Ria Formosa in southern Portugal [13] and Laguna San Ignacio, Mexico [14], to hundreds of kilometres or more, like Spencer Gulf, South Australia [15,16], and the Upper Gulf of California, Mexico [17].

As mean sea levels continue to rise with anthropogenic climate change [18] at a predicted accelerated rate over the 21st Century [19], the hydrodynamic processes of marine environments such as sediment transport, inundation events, and water exchange rate may change in marine systems [20–22]. Therefore, there is a concern that the mean sea level rise (MSLR) may influence the flow of ocean water into topographically sheltered basins such as Hamelin Pool and therefore the exchange of water between Hamelin Pool and Hopeless Reach across the Faure Sill. This would in turn change the salinity (density) regime within the embayment, leading to changes in the hydrodynamics and vertical stratification characteristics of Hamelin Pool, thus adversely affecting the World Heritage values in this region. Therefore, the aims of this paper are to gain an understanding of (1) the water exchange processes between Hamelin Pool and Hopeless Reach across the Faure Sill and (2) vertical stratification in Hamelin Pool under present-day and future MSLR scenarios. We used a three-dimensional numerical model, validated using field measurements, to achieve these aims.

This contribution describes the physical setting of the study area in Section 2. The methodologies used to observe oceanic/atmospheric data, set up two-dimensional (2D) and three-dimensional (3D) numerical models, and quantify vertical mixing are explained in Section 3. The analysis of profile observations and hydrodynamic model results, the tidal response of Hamelin Pool to MSLR, and the stratification of the basin are presented in Section 4. The influence of MSLR on stratification and overall conclusions are then discussed in Sections 5 and 6.

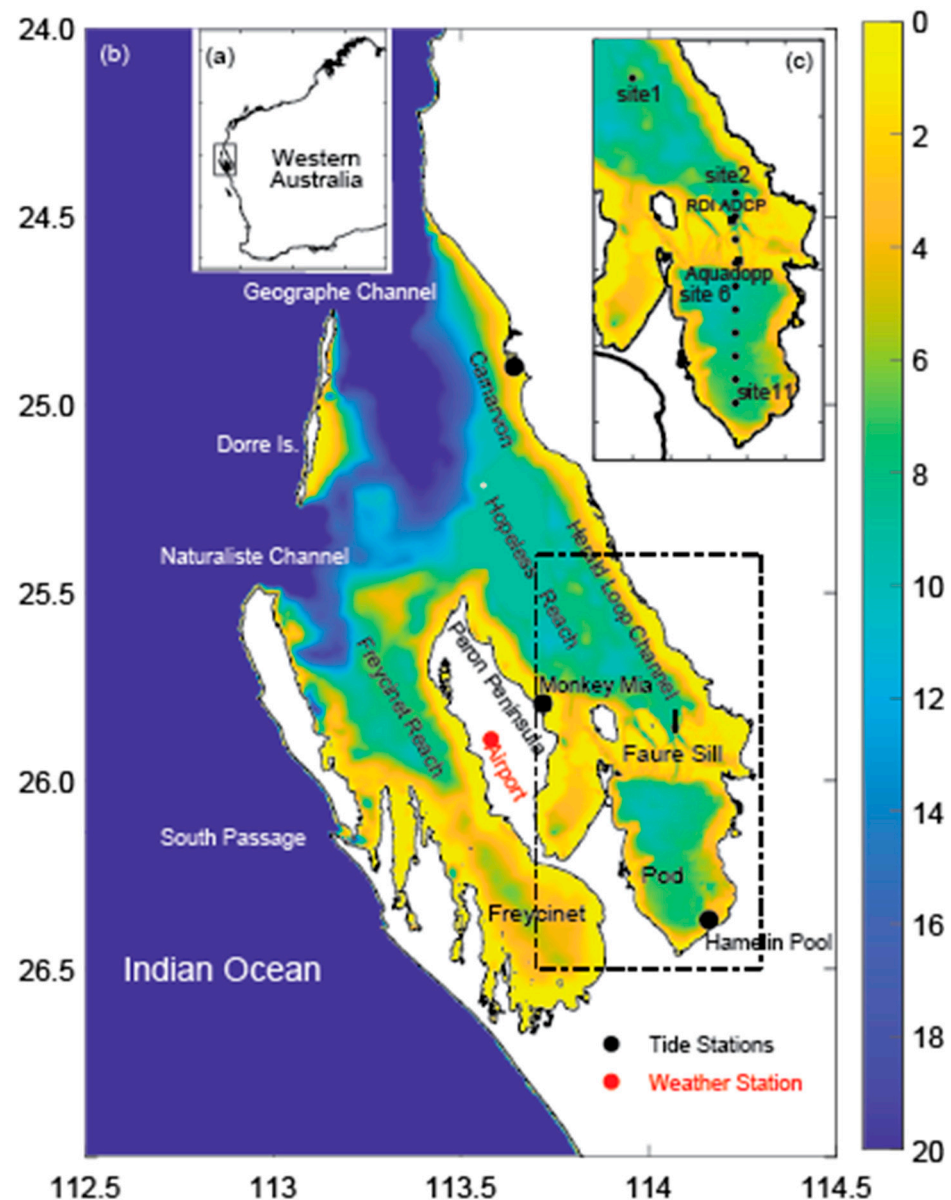


**Figure 1.** (a) Map of Western Australia; (b) Shark Bay bathymetry (in m to local chart datum) and long-term tide and weather stations; (c) Hamelin Pool and Faure Sill with the location of deployed instruments (RDI ADCP, Aquadopp, and two CTDs co-located with them) at either side of the Herald Loop Channel and transect sites for extracting data from the numerical model. The arrow to the north of Faure Sill marks the Herald Loop Channel.

## 2. Study Region

Shark Bay is the largest semi-enclosed estuary in Australia, covering an area of  $\sim 22,000 \text{ km}^2$ , and it extends  $\sim 250 \text{ km}$  from north to south and  $\sim 100 \text{ km}$  from east to west (Figure 1). The eastern gulf comprises Hopeless Reach, which connects to the Indian Ocean; the shallow seagrass banks in the Faure Sill; the slightly deeper basins of Hamelin Pool; and the L'Haridon Bight. The western gulf includes Freycinet Reach to the north and Freycinet Basin in the south (Figure 1). In this paper, the focus is on the Hamelin Pool, which has an average depth of 10 m, and the north–south and east–west extend 50 km and 24 km, respectively. It is connected to Hopeless Reach via the Herald Loop Channel and a few other smaller channels, across the Faure Sill (Figure 1b). The mean depth and width of the Faure Sill is 1 m and 30 km, respectively, and it separates Hamelin Pool and Hopeless Reach, each having water depths of 8 m on either side of the Faure Sill (Figure 2). The

Herald Loop Channel (width ~2 km) connects Hamelin Pool and Hopeless Reach across the Faure Sill and has a mean depth of 6 m (Figure 2).

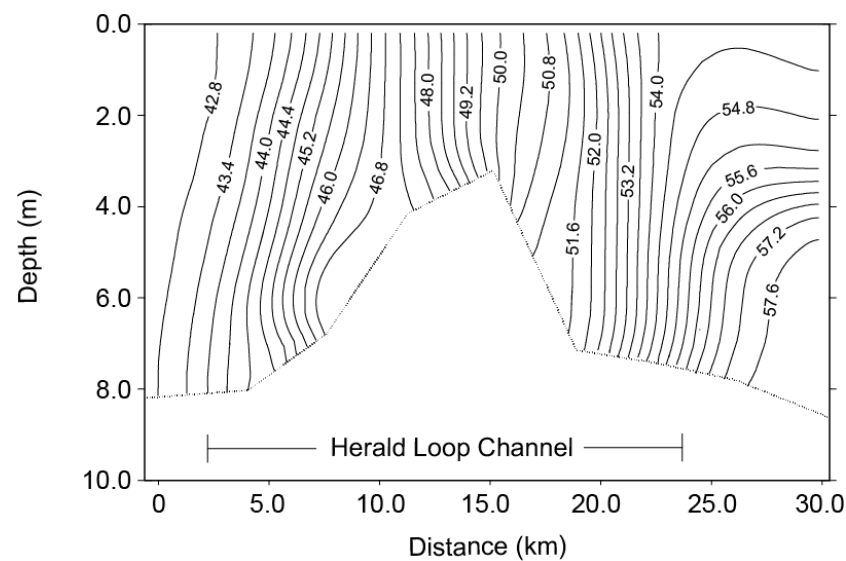


**Figure 2.** North–south CTD transect through Herald Loop obtained during flood tide, August (winter) 1995, showing salinity contours. Hopeless Reach is located to the left, and Hamelin Pool is located to the right. The transect extends approximately from Sites 2 to 6 in Figure 1c (modified from Burling et al. [2]).

Shark Bay is defined as an inverse estuary, with salinity within the Bay higher than in the adjacent ocean and where dense bottom water is exported to the continental shelf [3,4]. In other regions globally, the dense bottom water exiting the estuary moves across the continental shelf and cascades into the deeper ocean [15,23]. In the continental shelf off Shark Bay, the presence of the strong southward-flowing boundary current, the Leeuwin Current, prevents the cascade of the water into the deep ocean; the dense water is transported southwards along the continental shelf as a dense water plume [24].

There is a range of physical forcing mechanisms and processes in Shark Bay. Whilst tidal mixing has been found to be an important factor in regulating saline exchange between Hamelin Pool and the rest of the Bay, density- and wind-driven transport mechanisms also play a role in the exchange process [3,4,25]. A conductivity–temperature–depth (CTD) transect, obtained during winter across the Faure Sill (Figure 2), indicated that, on the southern end of Hopeless Reach and across the Faure Sill, the water column was well mixed, whilst, at the northern end of Hamelin Pool, the water column was stratified [2]. Here, the surface-to-bottom salinity difference was 3.2 in 8 m water depth (Figure 2). There was a horizontal salinity difference of 13.2 across the Faure Sill, with salinity at Hopeless Reach to the north being 42.8, whilst, in Hamelin Pool, it was 56.0, yielding a salinity gradient of  $0.5 \text{ km}^{-1}$ . Burling et al. [2] applied a shallow cavity, natural convection model across the Herald Loop Channel to demonstrate that the contribution of the saline discharge from Hamelin Pool was a steady diffusive process at a rate of  $\sim 3600 \text{ m}^3 \text{ s}^{-1}$ .

Shark Bay is adjacent to a low-relief, arid-to-semi-arid hinterland with negligible runoff influx and where evaporation greatly exceeds precipitation [2]. The annual evaporation and precipitation observed at the Shark Bay Airport weather station in 2011 was 2.60 m and 0.40 m, leading to a 2.20 m net surface water loss in Hamelin Pool with negligible inflow of freshwater. These factors, combined with the hydrologic structure of the water mass and topographic restriction imposed by seagrass banks and sills, result in an increase in salinity along the longitudinal direction away from the Bay entrance with a transition from oceanic (36–40 salinity) to metahaline (40–56 salinity) and hypersaline (56–70 salinity) water [1]. There is a fortnightly modulation of denser water exiting the Bay related to tidal mixing,

with persistent southerly winds during summer playing a significant role in vertical mixing, allowing for stronger vertical stratification during winter [3,4].

The West Australian coastline experiences a range of processes that affect changes in sea level, including astronomical tides, storm surges, the seasonal cycle due to changes in ocean currents, and inter-annual changes due to the El Nino Southern Oscillation (ENSO) effects [26,27]. The major transport mechanism within Shark Bay is due to tide, wind stress, and density gradients [1,3,4,28]. The tidal regime is an important component in any hydrodynamic study of the region. The form factor is often used to explain the tidal characteristics and is defined by the ratio of dominant diurnal components to dominant semi-diurnal components of the tidal amplitude [29]:

$$F_f = \frac{H_{K_1} + H_{O_1}}{H_{M_2} + H_{S_2}} \quad (1)$$

Here,  $H_x$  is the amplitude of the tidal constituent  $x$ . The tidal characteristics are classified as  $F_f < 0.25$  for semi-diurnal tides and  $F_f > 3.0$  for diurnal tides. For  $0.25 < F_f < 1.5$ , the tides are mixed, mainly semi-diurnal, whilst for  $1.5 < F_f < 3.0$ , the tides are mixed, mainly diurnal [29,30]. The tidal range outside the Bay is  $\sim 1.0$  m with a mixed tidal regime. Within Shark Bay, in Freycinet (western) Reach, the tides are mixed but mainly diurnal ( $F_f$  between 1.5 and 2.1), with a mean range of 0.8 m, whilst in Hopeless Reach (Figure 1), the tides are mixed but mainly semi-diurnal ( $F_f$  between 0.69 and 0.99), with a mean range of 1.2 m [28]. These unique tidal characteristics within Shark Bay are due to a near-quarter-wave resonance of the semi-diurnal tide along Hopeless Reach, which results in an increase in the semi-diurnal tide by a factor of 2 through the reflection of the tidal wave at the Faure Sill [28]. A significant feature of the tidal regime is the high degree of tidal attenuation and lag that occurs across the Faure Sill, resulting in strong tidal currents with maxima  $\sim 1 \text{ ms}^{-1}$ . Tidal lags of 3–5 h and the attenuation of 60–70% were predicted by Burling et al. [28] in this region, with the semi-diurnal constituents ( $M_2$  and  $S_2$ ) being attenuated the most, which also exhibited the highest phase lag. The water flow across the Faure Sill passes through an extensive seagrass meadow.

In any water body, there is a balance between the destratifying mechanisms (surface wind, tide, and evaporation/cooling) that promote vertical mixing and the stratifying mechanisms (surface heating, precipitation, freshwater input, and gravitational circulation) that tend to stabilise the water column [16]. For a tidally dominant system, the mixing/stratification balance can be reduced to the ratio of the water depth ( $h$ ) to the cube of surface velocity ( $u$ ),  $h/u^3$  [31]. Tidal fronts were observed at the entrance of each of the gulfs in Shark Bay, and north Hamelin Pool and Freycinet Basin (Figure 4b in [32]). Although mechanisms such as wind and evaporation were not included in this method, the locations of fronts as predicted using the Simpson–Hunter parameter ( $h/u^3$ ) were consistent with the strong gradient in the sea surface temperature of Shark Bay observed in satellite images (Figure 3 in [32]).

### 3. Methodology

This study was based on a combination of field observations and process-based numerical modelling to investigate the present-day hydrodynamics and vertical mixing occurring within the Hamelin Pool and the Faure Sill. The validated numerical model was then used to predict the likely responses of the basin to different MSLR scenarios, and potential energy anomaly (PEA, [33]) was used to quantify changes in the vertical mixing of the system.

#### 3.1. Field Data

In this research, we used a wide range of existing long-term observations of oceanographic and atmospheric parameters at several sites around Shark Bay. Water-level records and predictions, from tide gauges operated by the Western Australian Department of Transport, were obtained for Carnarvon, Monkey Mia, and Hamelin Pool sites in the eastern gulf

(Figure 1b). Records of wind speed and direction, humidity, evaporation, and precipitation were collected from the Australian Bureau of Meteorology weather station located at the Shark Bay Airport between the eastern and western gulfs (Figure 1b).

As previously mentioned, the Faure Sill is a particularly important topographic feature influencing water exchange between Hamelin Pool and the rest of Shark Bay. Hence, to improve our understanding of the hydrodynamic characteristics in this area (and to obtain a dataset to validate the numerical model), we deployed a series of instruments at two sites adjacent to the Herald Loop Channel, 12 km apart from each other (Figure 1c). Two instruments (a 1200 kHz Acoustic Doppler Current Profiler manufactured by Teledyne RD Instruments (Poway, CA, USA) known as RDI ADCP and a 2000 kHz Aquadopp manufactured by Nortek, Rud, Norway) were deployed at 10 m and 8 m mean water depths, respectively. They measured the current velocity throughout the water column at 0.5 m depth interval bins every 5 min between September and November 2011. Water level, temperature, and salinity were also measured at the same sites/period by two Seabird Electronics (Bellevue, Washington, DC, USA) SBE-37 CTDs, hereafter called CTD-North and CTD-South, deployed on the seabed (Figure 1c).

### 3.2. Numerical Modelling

To simulate the hydrodynamic processes and water properties within Shark Bay, we configured a numerical model using the MIKE21 and MIKE3 suites of DHI modelling tools [34]. Examining the observations during the field experiment (Figures 3 and 4), it was clear that a significant portion of tidal currents across the Faure Sill is driven by pressure gradients (Figure 3c), which indicate changes in tides (i.e., horizontal flow and 2D in nature). This is evident by the pressure gradient between the southern and northern locations of the Faure Sill (Figure 3c). The presence of horizontal density gradients (Figure 3g) results in a vertical component of the residual flow (i.e., 3D in nature; [2]). Hence, we configured a 2D model of the estuary (i.e., depth-averaged but including salinity and temperature influences on density) to investigate the influence of bathymetry, tidal forcing, and wind forcing in the study area. Subsequent to the validation of the 2D model and forcing, a baroclinic version of the model was configured, with five sigma layers, to examine the 3D current and mixing/stratification regime of Hamelin Pool.

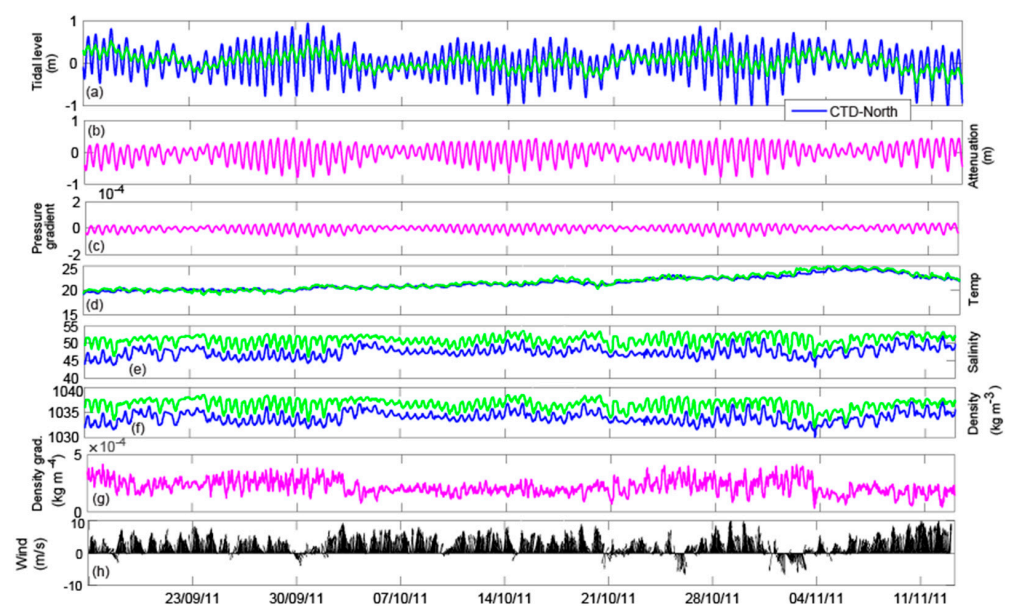


**Figure 3.** Observations at CTD-North (blue) and CTD-South (green): (a) tidal level; (b) attenuation in tidal level in the Herald Loop Channel from north to south; (c) pressure gradient across 12 km distance between 2 CTDs; (d) temperature; (e) salinity; (f) density; (g) density gradient; (h) wind vectors at Shark Bay weather station.

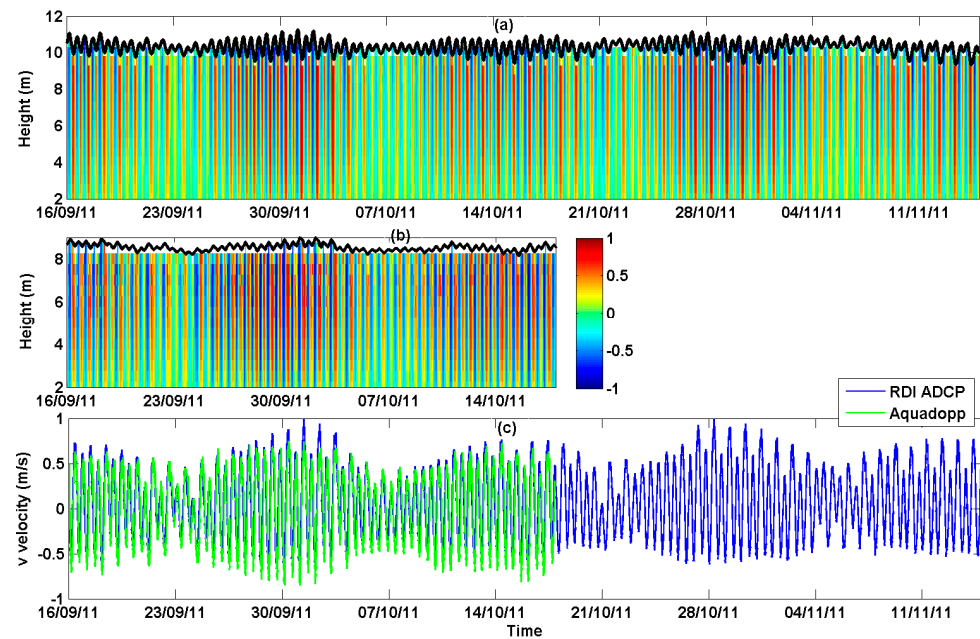


**Figure 4.** Surface water elevation (m) superimposed on the  $v$  velocity profile (m/s) measured by (a) RDI ADCP, (b) Aquadopp, and (c) depth-averaged  $v$  velocity (m/s) at RDI ADCP and Aquadopp.

The model bathymetry was an unstructured triangular mesh, with a resolution varying from  $\sim 1$  km at the continental shelf break to  $\sim 0.1$  km resolution at locations with complex bathymetric features (i.e., Herald Loop Channel and other channels). A range of different bathymetric sources were used to define water depths in the model grid. Bathymetric data for most of Shark Bay and the surrounding continental shelf were obtained from the Geoscience Australia 9 arc second (250 m) dataset [35]. Hamelin Pool bathymetry was available at 500 m resolution from depth soundings collected by the WA Department of Transport.

Modelling studies of Shark Bay were previously restricted by the lack of high-resolution depth information across the topographically complex Faure Sill because of its shallow depth and the limits in acoustic techniques [3]. In this study, we made use of high-resolution hyperspectral data acquired by Curtin University [6]. Airborne hyperspectral data were collected between the 21st and 26th of May 2011 and were processed to provide estimates of high-spatial-resolution bathymetry and habitat classification.

Water levels along the model open boundary were forced by a time series of astronomical tide and storm surge extracted from the Australian-wide hydrodynamic model described in [35], which was validated against records from 30 tide gauges around Australia (see also <https://sealevelx.ems.uwa.edu.au/> accessed on 8 March 2024). The larger-domain model was also forced with tides from a global tidal model [36] and atmospheric pressures and wind fields obtained from the US National Center for Environmental Prediction's global meteorological reanalysis [37,38]. The initial conditions of temperature across Shark Bay were extracted from the GHRSSST Global 1 km sea surface temperature data [39]. The initial conditions of salinity were reconstructed from transect measurements across Cape Peron and the Herald Loop Channel [2] and a few other individual observations in Hamelin Pool. Daily evaporation and precipitation rates and hourly air temperature and humidity values were obtained from Shark Bay weather station (Figure 1) and were applied across the whole domain. Offshore boundary conditions for temperature/salinity were obtained from a larger-scale model of Shark Bay [3,4].

Once the model setup and validation stages were complete, simulations were performed for a two-month period with the present-day MSL and then with different MSLR scenarios. Projections of MSLR for 2100 are available from the Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment Report (AR6) for a number of emission scenarios.

A likely range of 0.45 to 0.82 m for sea level projections for the late 21st century (average over 2081 to 2100) and of 0.52 to 0.98 m by 2100 was predicted in AR6. Therefore, we considered 0.5 m and 1 m MSLR in this study, consistent with Western Australia's coastal planning policy [40]. In the simulations, changes were only made to the mean sea level over the model grid whilst keeping all other (e.g., meteorological) forcing the same. Wandres et al. found that only small changes to the wind speed and direction were predicted in the CMIP models for southwestern Australia.

### Model Performance

The numerical model was run for a two-month period and predicted hourly time-series ( $X_{\text{model}}$ ) of water level, current speed, and direction at different depths, temperatures, salinity levels, and densities were compared with observations ( $X_{\text{obs}}$ ). To quantify model validation, three different measures were used, namely model skill [41]; root mean square error (RMSE); and bias. These parameters are defined as follows:

$$\text{Model Skill} = 1 - \frac{\sum |X_{\text{model}} - X_{\text{obs}}|^2}{\sum (|X_{\text{model}} - \bar{X}_{\text{obs}}| + |X_{\text{obs}} - \bar{X}_{\text{obs}}|)^2} \quad (2)$$

$$\text{RMSE} = \sqrt{(X_{\text{model}} - X_{\text{obs}})^2} \quad (3)$$

$$\text{Bias} = \overline{X_{\text{model}} - X_{\text{obs}}} \quad (4)$$

Model parameters including tidal level, depth-averaged  $u$  (east–west), and  $v$  (north–south) velocities were successfully compared with observations at the northern and southern sites with high model skill values ( $\sim 0.9$ ) obtained for all parameters.

The model was then extended to three dimensions, and predictions were compared with observations using visual and statistical comparisons through the water column. The gravitational circulation was successfully simulated at the northern site with an incoming flow near the surface and an outgoing flow near the bottom (Figure 5a). The residual current observed and predicted at the southern site was more homogenous due to the negligible role of gravitational circulation at this site (Figure 5b).

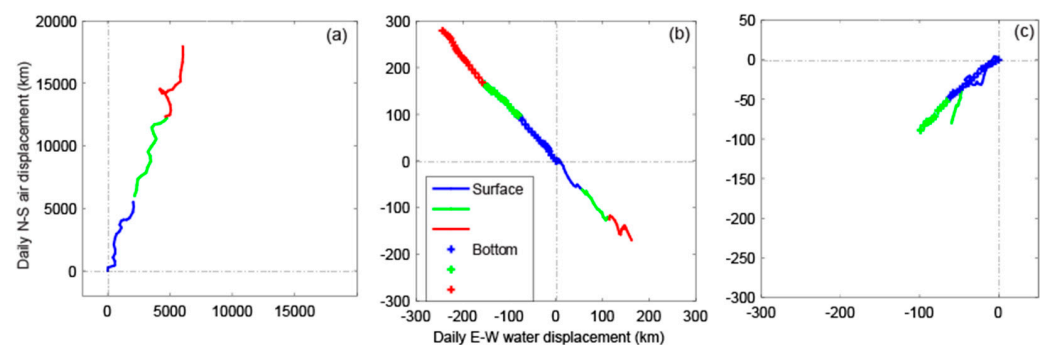


**Figure 5.** Daily progressive vectors of (a) observed wind velocities at Shark Bay weather station; (b) RDI ADCP current velocities at near surface and near bed; (c) Aquadopp current velocities at near surface and near bed. The first 20 days are plotted in blue, the second 20 days in green, and the third 20 days in red.

Time-averaged current velocities at RDI and Aquadopp were examined in observations (0.5 m bins) and the model (five layers in depth). Model predictions successfully simulated two-layer flow at RDI with an ingoing flow at the surface and an outgoing flow at the bottom (Figure 6a). The time-averaged current observed and predicted at Aquadopp was, however, more homogenous through the depth in terms of direction (Figure 6b).

Another set of visual comparisons was performed for the time series of current velocity (surface and bottom) and temperature, salinity, and density (bottom). We defined the

surface and bottom to reflect the data closest to the surface and bottom of a profile available in both measured and predicted data considering their limits and layer thickness. The predicted  $u$  and  $v$  current velocities were compared against observations for both the surface (7 m height) and the bottom (3 m height). Good agreement was observed between the model and observations in the range and variability of all velocities (Figure 7a–d). Tidal variability was dominant in all the time series with higher current velocities at the surface.

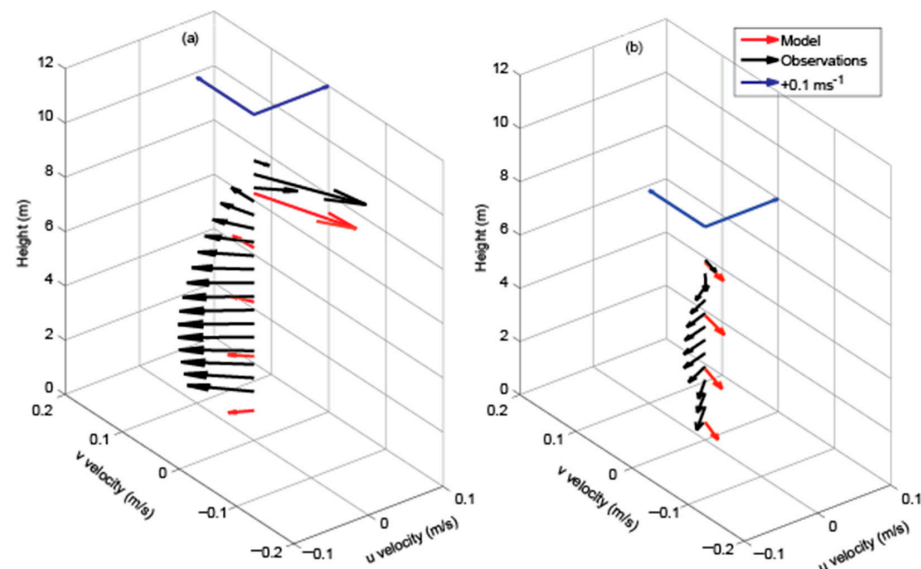


**Figure 6.** Visual comparisons of residual current velocities between the model and observations at (a) RDI ADCP up to 10.3 m above the seabed and (b) Aquadopp up to 6.75 m above the seabed.

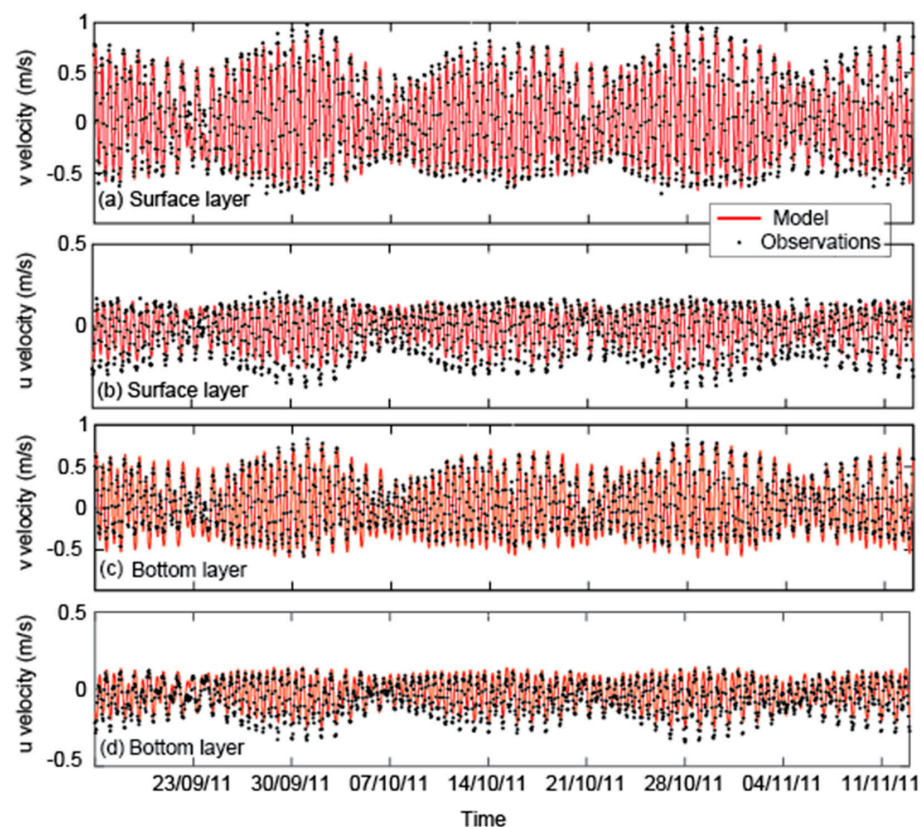


**Figure 7.** Comparison between hydrodynamic model predictions and RDI ADCP observations: (a)  $v$  velocity at the surface layer; (b)  $u$  velocity at the surface layer; (c)  $v$  velocity at the bottom layer; (d)  $u$  velocity at the bottom layer.

The observations and predictions of salinity, density, and temperature were also compared near the seabed at both northern and southern sites. Whilst the salinity and density parameters showed daily variations rather than a continuous increase or decrease, the time series of temperature had an increasing trend from September in Austral winter to November in Austral spring (Figure 8a,b). The variability in density was dominated by the variability in salinity with the temperature signature not observed in the density time series (Figure 8c). Good agreement was observed for each parameter with a small bias in temperature, which increased and decreased periodically (Figure 8a).

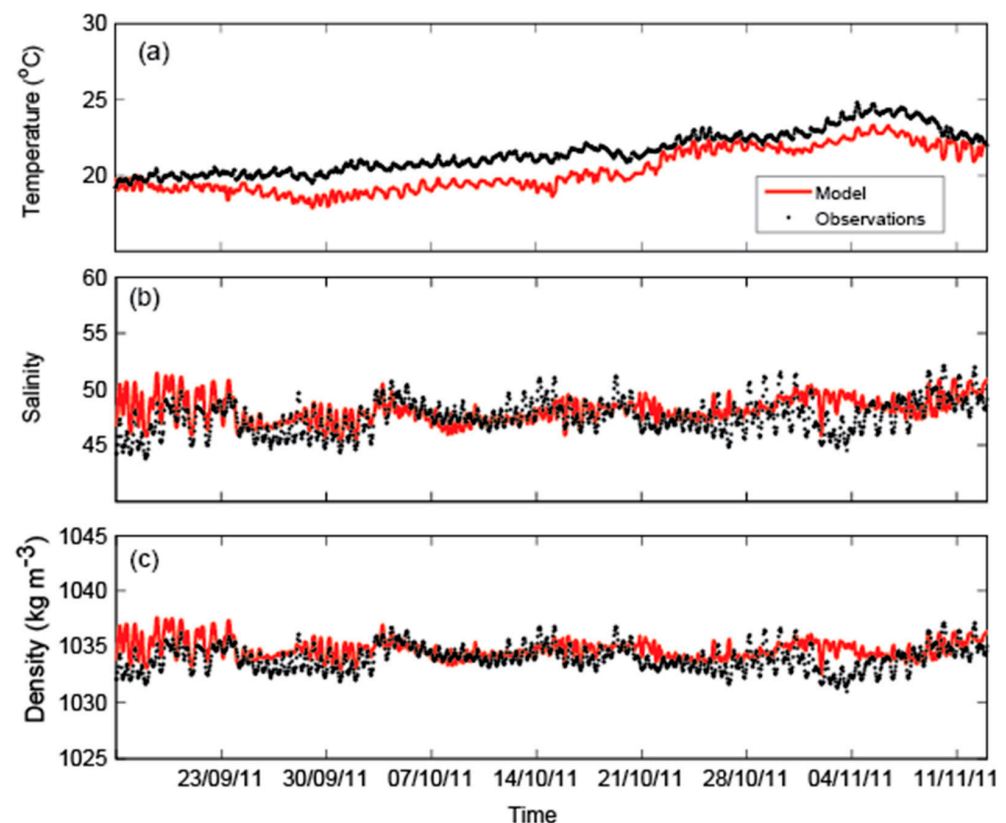


**Figure 8.** Comparison between hydrodynamic model predictions CTD-North observations at the bottom layer: (a) temperature; (b) salinity; (c) density.

The statistical results for validation parameters are given in Table 1. The predicted hydrodynamic parameters (model  $u$  and  $v$  velocities at the surface and the bottom) showed a very good comparison against observations, with less than  $0.04 \text{ ms}^{-1}$  bias, less than  $0.18 \text{ ms}^{-1}$  RMSE, and above 0.9 model skill for all sites/depths. The predicted water property parameters (bottom temperature, salinity, and density) showed small bias and RMSE values and an acceptable model skill value at both sites.

**Table 1.** Statistical comparisons of model parameters at surface and bottom layers versus RDI ADCP and Aquadopp observations using model skill, RMSE, and bias.

|                                       | RDI Model Skill | RDI RMSE | RDI Bias | Aquadopp Model Skill | Aquadopp RMSE | Aquadopp Bias |
|---------------------------------------|-----------------|----------|----------|----------------------|---------------|---------------|
| Surface $v$ ( $\text{ms}^{-1}$ )      | 0.97            | 0.14     | −0.01    | 0.98                 | 0.15          | −0.04         |
| Surface $u$ ( $\text{ms}^{-1}$ )      | 0.94            | 0.06     | 0.03     | 0.96                 | 0.05          | 0.03          |
| Bottom $v$ ( $\text{ms}^{-1}$ )       | 0.96            | 0.14     | −0.03    | 0.95                 | 0.18          | −0.03         |
| Bottom $u$ ( $\text{ms}^{-1}$ )       | 0.91            | 0.06     | 0.04     | 0.96                 | 0.04          | 0.02          |
| Bottom Temp ( $^{\circ}\text{C}$ )    | 0.81            | 1.33     | −1.22    | 0.45                 | 1.56          | −1.48         |
| Bottom salinity                       | 0.63            | 1.56     | 0.58     | 0.57                 | 2.04          | −1.25         |
| Bottom density ( $\text{kg m}^{-3}$ ) | 0.60            | 1.31     | 0.76     | 0.65                 | 1.33          | −0.57         |

### 3.3. Vertical Mixing

The stratification status of an estuarine system can be defined by the potential energy anomaly (PEA; [42]). This is the amount of energy per unit volume, which must be provided in order to change a stratified water column to its corresponding homogeneous state. The potential energy anomalies of the present-day MSL and the 0.5 m and 1 m MSLR scenarios were computed for three different periods (two days of neap tides, two days of spring tides, and a full spring/neap tidal cycle) as follows [42]:

$$\phi = \frac{g}{H} \int_{-H}^0 (\bar{\rho} - \rho)gz \, dz \quad (5)$$

where  $\phi$  is the potential energy anomaly ( $\text{Jm}^{-3}$ );  $g$  is the gravitational acceleration ( $\text{ms}^{-2}$ );  $H$  is the total fluid column depth (m);  $\bar{\rho}$  is the depth-average density of the fluid column ( $\text{kg m}^{-3}$ );  $\rho$  is the density of each layer of the fluid ( $\text{kg m}^{-3}$ );  $z$  is a vertical coordinate measured positive upward from the sea surface (m); and  $dz$  is the thickness of each layer in the numerical model (m). The potential energy anomaly of a homogeneously mixed fluid would be zero, whereas higher values indicate increasing vertical stratification. The PEA (Equation (2)) approach was also used by Lupiola et al. [43] to examine changes in vertical stratification due to climate change effects in the Suances estuary located along the Cantabrian coast of Spain.

## 4. Results

### 4.1. Present-Day Dynamics

Exchange processes between Hamelin Pool and Hopeless Reach at the present-day MSL can be described through field observations collected at two sites, located at either end of the Herald Loop Channel (Figure 1). The observations of the water level at both ends of the Herald Loop Channel revealed the interesting effect of the shallow Faure Sill on tidal range and frequency. The tidal range significantly decreased from 2 m at the northern site to less than 0.5 m at the southern site, with a 1.65 h phase lag between the sites (Figure 3a; Table 2). A horizontal height gradient of  $\sim 10^{-4}$  was generated by the  $>1.0$  m attenuation in the tidal range during spring tides over the 12 km distance between the two sites (Figure 3b,c).

**Table 2.** Tidal components and form factor from tide gauges in Shark Bay and 2-month deployments (CTD-North and CTD-South) in the Herald Loop Channel. The sites are listed in the eastern and western gulfs from north to south (Figure 1) with amplitude (H in m) and phase (g, in degrees).

|              | M <sub>2</sub> |     | S <sub>2</sub> |     | K <sub>1</sub> |     | O <sub>1</sub> |     | F <sub>f</sub> |
|--------------|----------------|-----|----------------|-----|----------------|-----|----------------|-----|----------------|
|              | H              | g   | H              | g   | H              | g   | H              | g   |                |
| Carnarvon    | 0.32           | 306 | 0.14           | 14  | 0.22           | 294 | 0.14           | 277 | 0.79           |
| Monkey Mia   | 0.38           | 7   | 0.17           | 77  | 0.23           | 320 | 0.16           | 297 | 0.69           |
| CTD-North    | 0.41           | 140 | 0.21           | 260 | 0.16           | 255 | 0.15           | 92  | 0.52           |
| CTD-South    | 0.12           | 188 | 0.06           | 310 | 0.06           | 257 | 0.10           | 136 | 0.90           |
| Hamelin Pool | 0.11           | 131 | 0.04           | 197 | 0.09           | 57  | 0.06           | 43  | 0.99           |

The near-bed temperature showed similar variability and magnitude at both sites, with a 5 °C increase over 7 weeks with continuous day and night variability due to the presence/absence of solar heating (Figure 3d). Although the bottom temperature was virtually homogeneous during the period of observation, salinity was  $\sim 5$  higher at the southern site as a result of the higher evaporation and limited exchange across the sill (Figure 3e). Semi-diurnal variability was observed in the salinity time series at both sites. Due to the salinity gradient, the water density was higher by  $\sim 3 \text{ kg m}^{-3}$  at the northern site, generating a  $\sim 0.4 \text{ kg m}^{-3}\text{km}^{-1}$  density gradient through the channel (Figure 3f,g). The observed density gradient was consistent with previous measurements of salinity made over a transect in the Herald Loop Channel (Figure 6 in [1]).

The wind parameters measured at Shark Bay Airport (10 m above sea surface) showed a dominant southerly direction during the field experiment (Figure 3h). The predominant southerly wind is a well-known feature of Shark Bay with a stronger magnitude in summer [1,3,4].

Current velocity profiles in the north–south direction (i.e.,  $v$  velocity), superimposed on the tidal level, revealed the influence of the tide in driving currents through the whole water column at both study sites (Figure 4). Strong current velocities (max  $\sim 1 \text{ ms}^{-1}$ ) were observed at both sites during the flood (i.e., negative  $v$ ) and ebb (i.e., positive  $v$ ). The significant influence of tide in driving currents is clearly evident in Figure 4. Stronger currents through the water column are synchronised with spring tides and weaker currents with neap tides. The semi-diurnal flood/ebb flow was continuously observed at both ends of the Herald Loop Channel with a smaller magnitude at neap tides. The magnitude of current speed was usually higher at the surface due to the reduced influence of bottom friction and the presence of wind. No time lag was observed between the surface and bottom currents. The depth-averaged  $v$  velocity, however, showed a transition from an ebb-dominated current (positive  $v$  velocity) in the northern end of the channel to a flood-dominated current (negative  $v$  velocity) in the southern end (Figure 4c).

No significant agreement was observed between the consistent northeasterly displacement of the wind vector, calculated from the meteorological measurements at the Shark Bay weather station (Figure 5a) with the surface water displacement at either side of the Herald Loop Channel (Figure 5b,c). The surface progressive vectors at both sites were directed into Hamelin Pool following the orientation of the channel (i.e., southeasterly surface currents at the northern site and southwesterly surface currents at the southerly site). The classical gravitational circulation structure of outflow at the bottom and inflow at the top was a strong feature at the northern site (Figure 5b). There was no observed change to the residual currents generated by gravitational circulation at the end of the tidal channel, and the system was dominated by flood currents, i.e., a southwesterly current at the surface and bottom layers, due to topography (Figure 5c).

#### 4.2. Tidal Response to MSLR

The form factors (Equation (1)) from one-year observations at three permanent and temporary tide gauges in the eastern reach of Shark Bay were adapted from Burling et al. [28] and are shown in Table 1. They were also computed for the two CTD datasets collected in the Herald Loop Channel (Table 2). All observations were classified as mixed tide with the mainly semi-diurnal components being Hopeless Reach and Hamelin Pool.

The form factor was larger at the southern sites (in Hamelin Pool) compared to the northern sites due to the filtering of semi-diurnal components by the shallow sill whilst preserving diurnal and lower frequencies (Table 2). The form factor decreased from Carnarvon to Monkey Mia and CTD-North due to the quarter-wave resonance of the semi-diurnal tide components ( $M_2$  and  $S_2$ ) by the presence of the Faure Sill and progressively increasing their amplitude (see also [28]). The diurnal components that propagate into the Hamelin Pool contributed to an increase in the form factor at CTD-South and at the Hamelin Pool site, further indicating a decrease in semi-diurnal components across the Faure Sill (Table 2).

Current velocities and tidal levels along a 100 km transect (Figure 1c) were extracted from the 2D model output to investigate the hydrodynamic response of the system to the 0.5 m and 1 m MSLR. Both tidal amplitudes and currents changed as a result of the increase in the mean level with the change centred on the location of the Faure Sill (Figure 9). The tidal amplitude was predicted as a decrease from north to south that would be a minimum ( $\sim 10\%$  at 1 m MSLR) at the channel entrance (at the 50 km mark, Figure 9d). The tidal amplitude then increased in Hamelin Pool ( $\sim 15\%$  at 1 m MSLR). The decrease/increase in the tidal amplitude was dependent on the level of mean sea level rise; 1 m MSLR resulted in a larger decrease in the tidal amplitude at the northern end of the sill and a maximum increase in Hamelin Pool (Figure 9a). The changes in the tidal amplitude

were also dependent on the tidal constituent as reflected in the changes to the form factor,  $F_f$  (Figure 9b). In the north,  $F_f$  increased to the north of the sill and decreased to the south of the sill. This is mainly due to the changes to the semi-diurnal tidal constituents, which decreased to the north and increased to the south of the sill (Figure 9b). These changes may be interpreted as increasing water levels above the sill (due to the MSLR) allowing more tidal energy, particularly at the semi-diurnal frequencies, to penetrate into Hamelin Pool, resulting in a smaller form factor compared to the present-day MSL. This also resulted in less reflection tidal energy at the semi-diurnal frequencies back to into Hopeless Reach. Relative changes in the  $v$  component of the velocity showed an increase at all sites (Figure 9c), namely up to a 20% increase with 0.5 m MSLR and a 40% increase with 1 m MSLR. The sites around the channel entrance were also sensitive to MSLR with the north–south component of velocity at Sites 4 and 5 at the channel exit (around the Aquadopp location) predicted to be less sensitive.

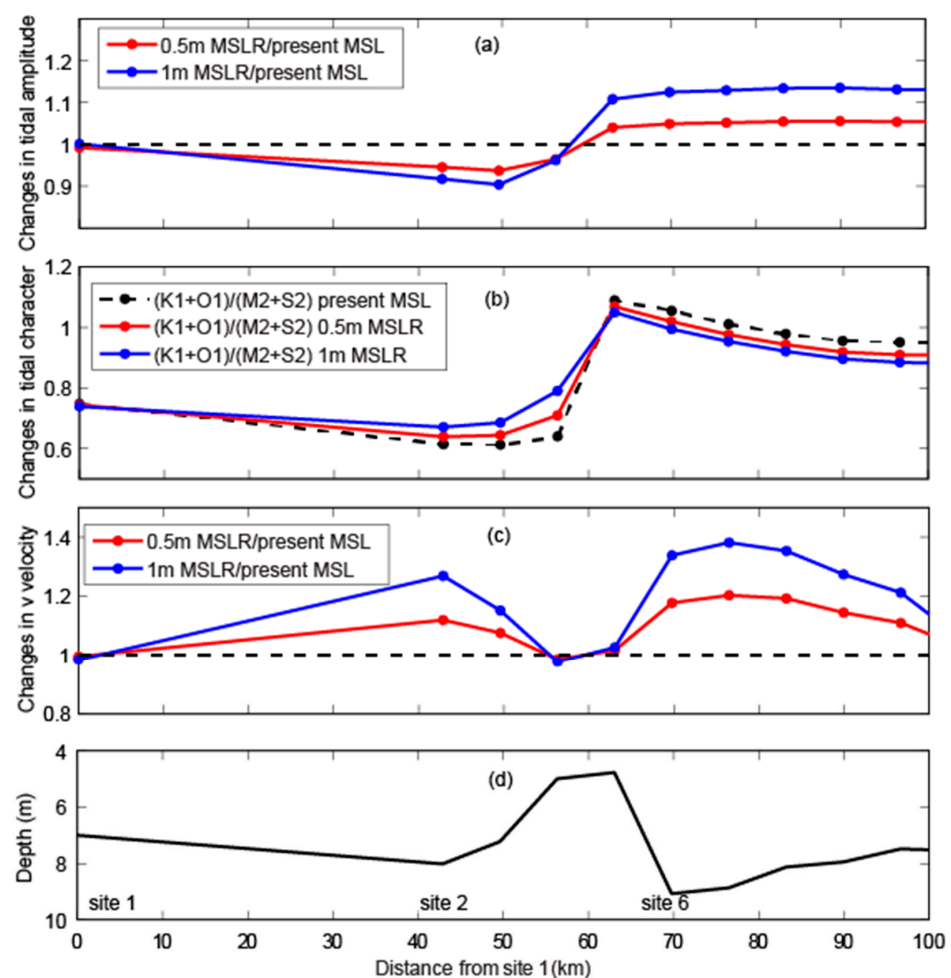


**Figure 9.** (a) Relative changes in tidal amplitudes, i.e., no change is equal to 1; (b) changes in tidal characteristics estimated from four dominant tidal components in form factor (Equation (1)); (c) relative changes in depth-averaged current  $v$  velocity; (d) bathymetry transect from Site 1 in Hopeless Reach to Site 11 in Hamelin pool (Figure 1c).

#### 4.3. Vertical Stratification

The vertical structure of density and current speeds across the Faure Sill and within the Hamelin Pool was further investigated by examining the mean density and current speed at the surface and differences in depth over a fortnightly spring/neap tidal cycle (Figure 10). The influence of the Faure Sill in controlling the density distribution is evident with Hamelin Pool water being denser (by around  $12 \text{ kg m}^{-3}$ ) than the waters to the north

(Figure 10a) with the sill forming the boundary between the high- and low-density waters. The effect of Earth's rotation is also evident with a clockwise 'rotation' of the boundary between the higher- and lower-density water (Figure 10a). Here, lower-density water from Hopeless Reach is seen to encroach into Hamelin Pool more along the eastern boundary whilst the higher-density water is encroaching more into Hopeless Reach along the western margin (Figure 10a). The width of the Faure Sill is 30 km, and the internal Rossby radius of deformation is  $\sim 5$  km. Strong vertical stratification was present in two regions (Figure 10c): (1) to the north of the Faure Sill where the Herald Loop Channel connects to Hopeless Reach and forms two deep channels where water exiting the Faure Sill is transported northwards [31] and (2) immediately to the south of the Faure Sill where the lower-salinity water coming across the Faure Sill contributes to the vertical stratification. Strong currents were predicted on the Faure Sill, particularly along the channels (Figure 10b), and the currents were attenuated immediately to the south of the sill in the Hamelin Pool. This results in vertically mixed conditions on the sill and strong vertical stratification to the south of the sill (Figure 10c) similar to those observed in field measurements (Figure 2). In the southern regions of Hamelin Pool, bottom currents were stronger than those at the surface due to the vertical stratification and residual flows (Figure 10d).

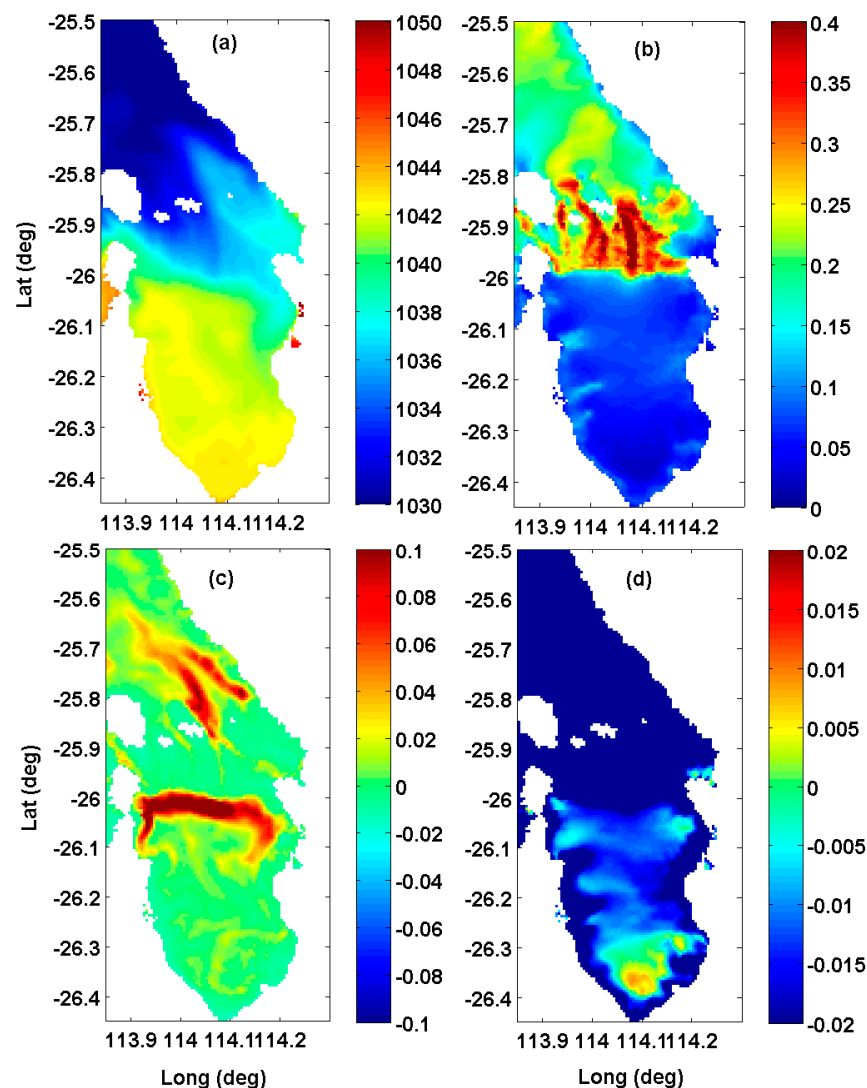


**Figure 10.** (a) Surface density ( $\text{kg m}^{-3}$ ) and (b) surface current speed ( $\text{ms}^{-1}$ ) at Faure Sill and Hamelin Pool; time-averaged for 2 weeks; (c) vertical density gradient, i.e., bottom density–surface density ( $\text{kg m}^{-3}$ ); (d) vertical current speed gradient, i.e., bottom current speed–surface current speed ( $\text{ms}^{-1}$ ).

The temporal and spatial distribution of vertical stratification and variability under different tidal regimes were examined using the potential energy anomaly,  $\varphi$  (Equation (2)), and the results (Figure 11) were, as expected, consistent with the spatial distribution of the vertical density gradient (Figure 10c). The two regions of high vertical stratification identified previously, namely the deeper channels to the north of the Faure Sill and immediately to the south of the Faure Sill, were also reflected in the potential energy anomaly distribution (Figure 11c). As values of  $\varphi$  allowed for the quantitative measurement of stratification through the whole water column, we used the spatial distribution of  $\varphi$  to identify regions of relatively higher/lower stratification. There were some interesting and contrasting observations between stratification predicted for spring and neap cycles. The maximum predicted values of stratification were found at the southern end of the Herald Loop Channel due to the higher velocities transporting lower-salinity water into the Hamelin Pool (Site 6, Figure 11). This is confirmed by the maximum predicted stratification occurring during spring tides; here, the increased buoyancy flux (transport of larger volumes of lower-density water) during spring tides contributed to the maximum vertical stratification. However, in other regions, stratification was smaller when compared to neap tides (Figure 11a,b). There were larger areas with increased stratification during neap tides due to weaker tidal currents (Figure 11b): In Hopeless Reach, there was increased stratification in more channels, whilst to the south of the sill, there were regions of higher stratification extending almost across the whole sill, particularly along the relatively deeper western end (Figure 11b). These results indicated that, in general, higher stratification was present during neap tides due to decreased vertical mixing by tidal action. However, the advection of lower-salinity water during spring tides at the southern end of the Herald Loop Channel also resulted in higher vertical stratification.

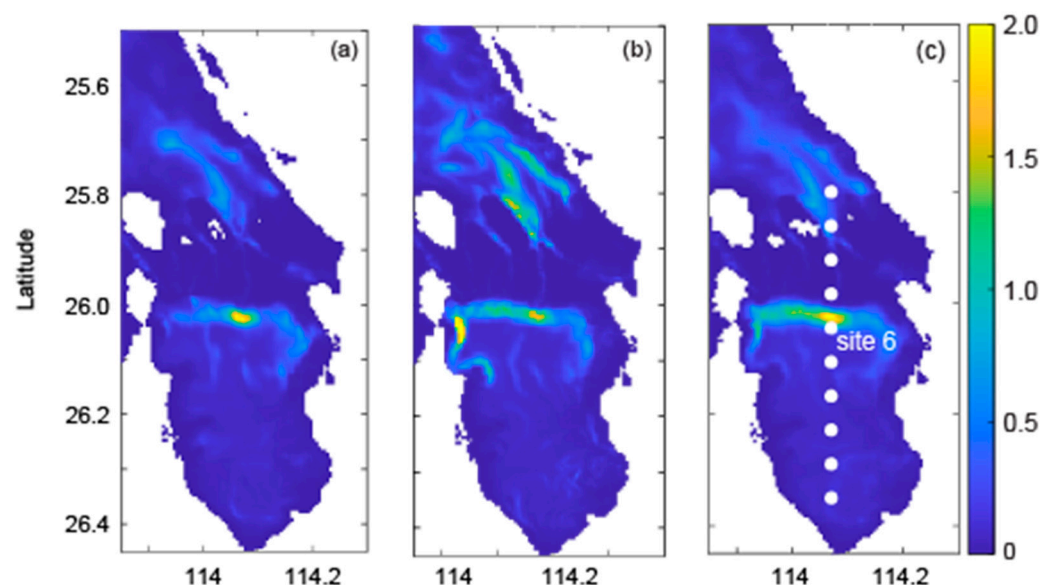


**Figure 11.** Potential energy anomaly,  $\varphi$  ( $\text{Jm}^{-3}$ ), of Faure Sill and Hamelin Pool at present-day MSL for different periods: (a) spring tide averaged for 2 days; (b) neap tide averaged for 2 days; (c) full spring-neap tidal cycle averaged over 2 weeks.

The results of model simulations with the MSLR predicted similar regions as present-day conditions, but the regions of higher stratification were expanded compared to those predicted under present-day conditions (Figures 11 and 12). Regions of increased stratification were higher for the 1 m MSLR when compared to the 0.5 m MSLR (Figure 12c,f). This is mainly due to the increased mean water levels over the sill, which will allow for increases in volume fluxes over the sill. On the flood stage, an increased volume of lower-density water will be transported over the sill to promote stratification at the northern end of Hamelin Pool, whilst during the ebb, an increased water flow, concentrated along the Herald Loop

Channel, will discharge higher-density water into the deep channels in Hopeless Loop. As would be expected, under neap tides, regions of higher stratification covered a larger area (Figure 12b,e). As per present-day conditions, the maximum stratification occurred at the southern end of the Herald Loop Channel (Site 6) during spring tides.

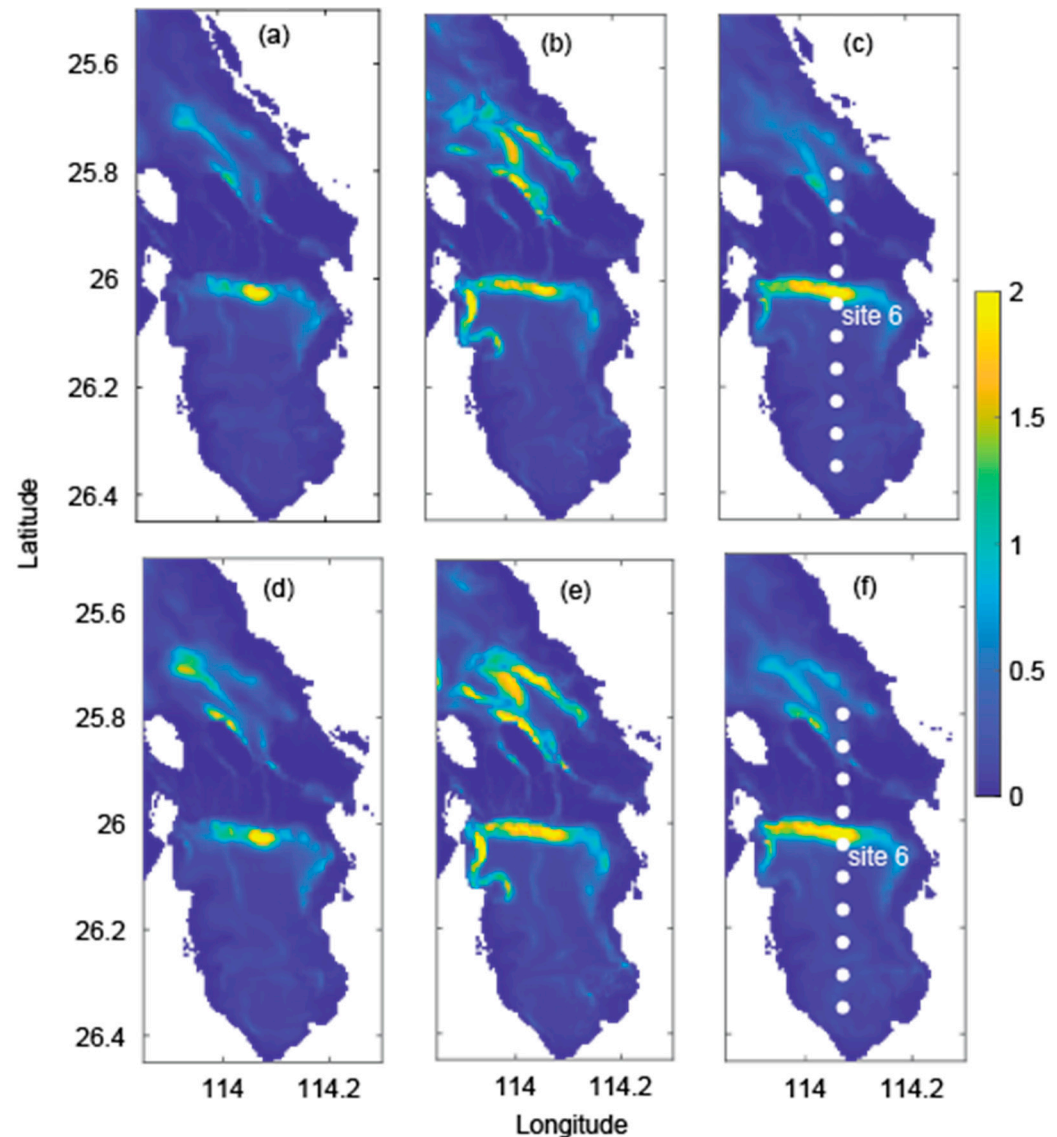


**Figure 12.** As Figure 11 but (a–c) +0.5 MSR and (d–f) +1.0 MSR.

To examine the temporal variability at Site 6, a time series of tidal levels (also at Site 1) and  $\phi$  was extracted over the fortnightly spring–neap cycle (Figure 13). The water-level time series indicated a tidal attenuation between Site 1 (middle of Hopeless Reach, Figure 1a) and Site 6 (north Hamelin Pool) of up to 0.8 m and a phase lag of ~4 h (Figure 13a). In general, the maxima in  $\phi$  occurred during spring tides and lower values during neap tides, with no major differences between the present-day MSL and the 0.5 m and 1 m MSLR conditions (Figure 13b). A closer inspection of the time reveals some interesting features. The tidal regime is mixed with a large diurnal inequality. This leads to a modulation of the tidal currents over a diurnal cycle with the occurrence of one flood phase with a higher range and stronger currents (‘large’ flood) and vice versa. This is reflected in the time series of  $\phi$ , with the maxima occurring at the end of the ‘large’ flood (at high water) reflecting the increased vertical stratification due to the transport of lower-salinity water along the Herald Loop Channel. During the subsequent flood phase, which is much weaker, there is significantly reduced vertical stratification. There is no vertical stratification during either

of the ebb tidal phases (Figure 13b). Neap tides are characterised by lower values of  $\varphi$ . The time series of  $\varphi$  also revealed the influence of wind in the system. There were two unusual events: (1) the flood tide immediately after 25 October 2011, which recorded the highest value of  $\varphi$  over the fortnight, and (2) lower values of  $\varphi$  during spring tides between 29 and 31 October 2011. During Event 1, there were northerly winds (Figure 3h), which increased the mean water level at the sill, thus increasing the amount of water flowing into Hamelin Pool. During Event 2, there were very strong southerly winds, in excess of  $10 \text{ ms}^{-1}$ , which would have promoted vertical mixing.

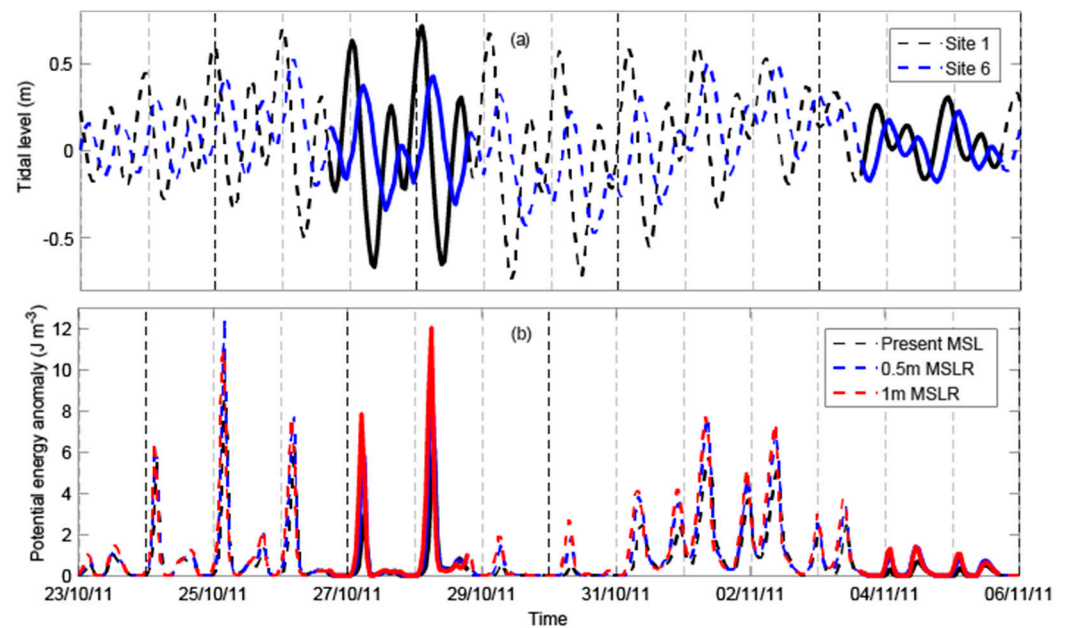


**Figure 13.** (a) Time series of tidal levels at Site 1 (Hopeless Reach) and Site 6 (north Hamelin Pool) associated with a two-week period shown in Figure 10c. (b) time series of potential energy anomaly. The spring and neap periods in Figure 10a,b are shown in bold.

## 5. Discussion

The field observations of hydrodynamic parameters (currents, temperature, and salinity) on the Faure Sill were focussed on the Herald Loop Channel, connecting Hamelin Pool to Hopeless Reach in Shark Bay. The observed parameters at the present-day MSL were simulated using a 3D numerical hydrodynamic model. The study then focussed on the response of the system to the MSLR and therefore the likely conditions under 0.5 m and 1 m increases in the MSLR. The relative deepening of Faure Sill and in Hamelin Pool due to the MSLR resulted in an increase in the tidal range, current speed, and stratification of the Hamelin Pool basin.

### 5.1. Hydrodynamic Response to MSLR

Many studies have predicted that tidal amplitudes in coastal regions and estuarine systems will generally increase in response to the MSLR [44,45]. Pickering et al. [45] found that, in European shelf seas, the semi-diurnal constituent ( $M_2$  in particular) decreased in regions where there was tidal resonance such as the Bristol Channel and the Gulf of St. Malo, whilst other regions experienced an increase. Similar results were found in this study, which is also a region of tidal resonance. To the north of the Faure Sill, the tidal amplitude decreased, whilst in Hamelin Pool, to the south of the sill, the tidal amplitude increased. Here, it is postulated that changes to the tidal amplitudes were due to an increase in the mean water level over the Faure Sill, which changed the tidal energy reflection/transmission characteristics across the sill. The model results also indicated an increase in tidal current speeds on both sides of the sill (up to 40% in Hamelin Pool), most

likely due to changes in the phases of the tidal constituents. These changes in the current speed may influence the vertical stratification regime in the system (see below).

### 5.2. Stratification Response to MSLR

The stratification status of the Shark Bay region was previously more broadly investigated through studies at the entrance to Shark Bay and through the location of tidal fronts and exchange with the ocean [3,4,31]. In estuaries and coastal seas, the vertical structure of the water column is determined by a balance between the stratifying influences (solar heating, freshwater input, and gravitational circulation) competing against the mixing potential of tide, wind, and evaporative cooling. Wind stress and surface evaporation contribution as mixing processes are unlikely to change with the MSLR (it is assumed in this study that there is no significant change in the wind field or evaporation status resulting from climate change). Similarly, surface heating and freshwater input as processes that promote stratification are also not expected to change significantly under MSLR scenarios. Hence, the vertical structure of the water column under the MSLR in the present study is assumed to be due to changes in (a) the mean gravitational circulation (driven by mean horizontal density gradients); (b) tidal mixing; and (3) buoyancy flux across the Faure Sill, which will have a localised effect in the regions closer to the sill. Two major regions of vertical stratification were recognised from numerical simulations: (1) to the north of the Faure Sill where the Herald Loop Channel connects to Hopeless Reach and forms deep channels where water exiting the Faure Sill is transported northwards, and (2) immediately to the south of the Faure Sill where lower-salinity water coming across the Faure Sill contributes to vertical stratification. The simulations also indicated that under the MSLR, these regions expand in area and are more highly stratified. Both regions were affected by an increased input of buoyancy: during the ebb tide, additional higher-salinity water is transported northwards, whilst during the flood tide, additional lower-salinity water is transported southwards.

The time series of the potential energy anomaly ( $\varphi$ ) at the southern end of the Herald Loop Channel revealed some insight into the cycle of stratification and destratification: Maximum stratification was predicted during the spring tide at the end of the 'long' flood, and low vertical stratification at all other times. The lack of stratification during the 'long' ebb can perhaps be explained by (inverse) tidal straining, which leads to periodic stratification and destratification in partially mixed estuaries [46]. In classical estuaries, during the ebb phase, less dense surface water is advected over higher-density water in the bottom layer enhancing the vertical stratification, whilst during the flood phase, higher-density water flows over lower-density water on the bottom, inducing convective overturn and destratification. This process is termed SIPS (strain-induced periodic stratification) [46]. In the case of inverse estuaries, the reverse happens, with stratification during the flood (lower-density water over higher-density water) and destratification during the ebb. The cycle of stratification during the 'long' flood and destratification during the 'long' ebb, predicted at Site 6, is an example of this process for an inverse system.

The salt flux across the Faure Sill can be considered to be represented by two terms (see, for example, [47,48]): (1) flux by advection and (2) diffusive fluxes. Burling et al. [2] applied a shallow-cavity natural convection model across the Herald Loop Channel to demonstrate that the contribution of the saline discharge from Hamelin Pool is a steady diffusive process and will be preserved under MSLR scenarios as there will not be any significant change in the mean water depth in relation to the total length of the Herald Loop Channel across the Faure Sill, and as such, the saline discharge from Hamelin Pool will be expected to remain as a diffusive process. It is likely that the advective component of the flux will increase slightly, as shown by the increased regions of vertical stratification to the north of the Faure Sill.

### 5.3. Seagrass Response to MSLR

The strong stratification and exchange of waters occur between Hamelin Pool and the ocean across the Faure Sill. The MSLR results in an increased exchange and increased release of energy during the spring tides. What this potentially means for the seagrass communities that stabilise the Faure Sill is unknown, but increased currents would threaten to erode the seagrasses occurring in the relatively stable channels [49]. Increased water depths would allow for the greater colonisation of seagrass communities on the Faure Sill to the level of cover they enjoyed during the last high sea level stand observed along the central west coast of Australia some 1500 years before the present. Seagrasses and their associated biota were impacted by an extreme marine heat wave in the summer of 2011, when temperatures were 4 °C warmer, as described by [50]. Losses of 1069 km<sup>2</sup> of a total seagrass extent in the Shark Bay ecosystem of 4366 km<sup>2</sup> (2010) were observed between 2010 and 2014 [51]. Interestingly, two of the largest areas of loss were to the north in Hopeless Reach and in the southern Faure Sill, where it enters Hamelin Pool. Synergistic climate change stressors on seagrasses like the mean sea level rise and warming sea temperature could destabilise the Faure Sill through the death of the dominant sediment binding temperate seagrasses *Posidonia australis* and *Amphibolis antarctica*, and the destabilisation and movement of sediments as current speeds increase with the MSLR. With seagrass loss, sediment destabilisation was observed on other shallow banks and sills in Shark Bay after the 2011 extreme MHW [52].

## 6. Conclusions

Oceanographic processes in Hamelin Pool in Shark Bay, particularly tidal dynamics and water exchange, are strongly controlled by the shallow Faure Sill. The deepening of the Faure Sill, because of the MSLR, will result in changes in the tidal regime on either side of the sill. To the north, the tidal amplitude decreased by up to 10%, whilst to the south, the tidal range increased by up to 15% at the 1 m MSLR. There were also changes to the tidal currents with an increase predicted on both sides of the sill and up to 40% increase in Hamelin Pool for the 1 m MSLR. These changes were due mainly to alteration to the semi-diurnal tidal wave reflection/transmission characteristics at the sill.

Strong vertical stratification was present in two regions: (1) to the north of the Faure Sill, where the Herald Loop Channel connects to Hopeless Reach and forms two deep channels where the water exiting the Faure Sill is transported northwards, and (2) immediately to the south of the Faure Sill where the lower-salinity water coming across the Faure Sill contributes to the vertical stratification. The simulations indicated that under the MSLR, these regions expanded in area and exhibited higher levels of vertical stratification. This was due to an increased input of buoyancy: During the ebb tide, additional higher-salinity water was transported northwards, whilst during the flood tide, additional lower-salinity water was transported southwards. An inverse SIPS condition was used to explain the vertical stratification occurring during the flood and destratification during the ebb. The salt flux across the Faure Sill will be maintained as a diffusive process under an MSLR scenario.

**Author Contributions:** S.T., C.P., I.H. and G.K. designed the field experiments; S.T. analysed the data and performed the numerical simulations under supervision from C.P., I.H. and S.T. prepared the manuscript with input from all co-authors, and C.P. provided input and review on all aspects of the study. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was Australian Government NHT II Caring for our Country funding (OC11-00643) managed by the Western Australian Marine Science Institution (WAMSI). G.K. was also funded through ARC Linkage and Discovery grants (ARC DP180100668, LP160101011).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to data sharing agreements.

**Acknowledgments:** The authors are grateful to Diana Walker from the University of Western Australia for her support, the remote sensing team of Curtin University for hyperspectral bathymetry, and the Western Australian Marine Science Institution for coordinating the project.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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