Gippsland Lakes Ocean Access Program

Water Level and Salinity Modelling and Analysis

Version 0.2

Gippsland Ports
Technical Report
September 2023

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Executive Summary

Gippsland Ports (GP) commissioned Port and Coastal Solutions (PCS) to undertake data analysis and numerical modelling to support the Gippsland Lakes Ocean Access (GLOA) Program (2023-33). The Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW) issued a Request for Further Information (RFI) relating to GPs Sea Dumping Permit Application. This study is aimed at providing additional information as requested by DCCEEW.

Aims: the aims of this study are:

- to analyse available historical tidal records throughout Gippsland Lakes to ascertain whether the harmonic constituents of the tide may have changed significantly in response to dredging practises; and
- to undertake 3-Dimensional (3D) numerical modelling of the Gippsland Lakes for existing conditions and the future proposed dredging. The modelling will be used to show the potential impacts of the proposed dredging on the astronomical tide, water levels and salinity within the Gippsland Lakes.

Water Level Analysis: The analysis of historical measured water level showed an increasing tidal range in Gippsland Lakes over the last 30 years (1994 to 2023), with the rate of increase reducing since 2008. The available data indicated that the change in tidal range which occurred from 2003 to 2008 was due to a gradual ongoing increase in tidal range over this period as opposed to a large jump which occurred over a single year. This suggests that the change was not due to the change from using a side-cast dredge in 2007 to using a TSHD in 2008. The results from the analysis could not identify any drivers responsible for the gradual increase in tidal range which occurred from 1994 to 2002 and again from 2003 to 2008. It was therefore considered most likely that the gradual increase was a result of multiple factors, which could include natural processes and dredging.

Model Setup: A detailed 3-Dimensional hydrodynamic model was setup for the Gippsland Lakes. The model was calibrated and validated using measured water level and salinity data from multiple locations within the Gippsland Lakes over two 12 month periods. The calibration and validation periods covered different conditions and have shown that the model is able to represent the changes in water level and salinity in the Gippsland Lakes resulting from astronomical tides, offshore storm surge, freshwater inputs and evaporation processes.

The 3D hydrodynamic model was setup to represent the existing bathymetry and the future dredged bathymetry. The model was then used to simulate the water level and salinity over two 12 month periods for the following cases:

- offshore forcing due to just astronomical tide, with no offshore storm surge, and with low freshwater inputs; and
- offshore forcing due to the astronomical tide and offshore storm surges along with high freshwater inputs.

Model Results: The results from the numerical modelling predicted similar changes due to the future dredging for both simulations, with the largest changes to both water levels and salinity predicted to occur in the channels around Lakes Entrance and directly offshore of the Entrance Channel. The modelling also predicted some localised areas with very low magnitude changes in lake King and Lake Reeve, but these changes would be too small in extent and magnitude to be measurable. The predicted changes around the Lakes Entrance region are summarised below:

- Hopetoun Channel: the largest predicted change in water level occurred at the western end of Hopetoun Channel, with predicted increases in high water levels and reductions in low water levels resulting in an increase in the maximum water level range of up to 0.025 m. This is the location of the largest depth change due to the future channel extension. The changes in water level in this area were not predicted to result in a change in salinity;

- West of Hopetoun Channel to Metung: this area was predicted to have a small increase in maximum water level range of up to 0.002 m, this increase was predominantly due to a predicted increase in maximum water level. The changes in water level in this area were not predicted to result in a change in salinity;
- Reeve Channel, North Arm, Cunninghame Arm and Entrance Channel: there was predicted to be a reduction in maximum water level range in these channels of typically around 0.002 m, but up to 0.01 m. This reduction in range was due to a combined reduction in maximum water level and an increase in minimum water levels. Within the North Arm and Cunninghame Arm there was also predicted to be an increase in minimum salinity, which resulted in a reduction in the maximum salinity range; and
- Offshore: changes to water levels and salinity offshore of the Entrance Channel was variable between the two simulations, with the changes significantly larger during the surge and freshwater forcing simulation. An offshore area of 10 km by 5 km located approximately 5 km to the south of the Entrance Channel was predicted to have an increase in maximum water level of up to 0.002 m. The offshore areas with predicted changes to salinity were located closer to the Entrance Channel, with areas adjacent to the shoreline up to 3 km to the west and east of the Entrance Channel predicted to have an increase in salinity range of up to 1 practical salinity unit (psu) (the majority is less than 0.1 psu), while an area adjacent to the Entrance Channel extending 2 km to the south was predicted to have a reduction in salinity range of up to 1 psu (the majority is less than 0.1 psu).

Most of these changes occur due to the extension of the western navigable section of Hopetoun Channel as part of the future dredging acting to increase the tidal prism which flows through Hopetoun Channel (both on the flood and ebb flows). This, in turn results in a small reduction in the tidal prism which flows through Reeve Channel and also the channels to the east of Reeve Channel (North Arm and Cunninghame Arm). This small change in the balance of how the tidal prism flows into and out of Gippsland Lakes results in a localised increase in water level range in Hopetoun Channel, and a small increase between Hopetoun Channel and Metung. In contrast, the change results in a reduction in water level range in the channels to the east of Hopetoun Channel. The change in portion of the tidal prism which flows through Hopetoun Channel also means that slightly less of the lower salinity water from the upstream lakes is transported through Reeve Channel during the ebb stage of the tide (or during downstream flows in large flood events), which results in a slight increase in the minimum salinity in the North Arm and Cunninghame Arm. The predicted offshore changes in water level and salinity due to the future dredging are expected to be a result of minor changes in how the ebb tide flows out of the Entrance Channel during periods of high freshwater discharge, which results in localised changes to both water level and salinity.

The predicted changes in water level resulting from the proposed future dredging being relatively localised to the GLOA dredge areas and of small magnitudes (maximum water level range increases of up to 0.025 m) provides further evidence that the historic changes in tidal range experienced in the Gippsland Lakes is unlikely to be a result of changes in dredging approach.

1. Introduction

Gippsland Ports (GP) commissioned Port and Coastal Solutions (PCS) to undertake data analysis and numerical modelling to support the Gippsland Lakes Ocean Access (GLOA) Program (2023-33).

The Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW) issued a Request for Further Information (RFI) relating to GPs Sea Dumping Permit Application. This study is aimed at providing additional information as requested by DCCEEW. The aims of this study are as follows:

- to analyse available historical tidal records throughout Gippsland Lakes to ascertain whether the harmonic constituents of the tide may have changed significantly in response to dredging practises; and
- to undertake 3-Dimensional (3D) numerical modelling of the Gippsland Lakes for existing conditions and the future proposed dredging. The modelling will be used to show the potential impacts of future dredging proposed by GP on the astronomical tide, water levels and salinity within the Gippsland Lakes.

1.1. Project Overview

As part of the GLOA program, GP has obtained State and Commonwealth Approvals to enable the program to be delivered in an environmentally compliant and sustainable manner. While some of the approvals are perpetual, two are due to expire in October 2023 (Sea Dumping Permit and Marine and Coastal Act). Therefore, a tailored Sustainable Sediment Management (SSM) assessment framework was adopted for the GLOA Program (2023-33) to support these future approvals as this framework is considered to represent the port industry best practice.

Maintenance dredging at the Port of Gippsland Lakes is conducted to provide and deliver reliable ocean access to the Gippsland Lakes. Maintenance dredging has been undertaken at the Port for over 130 years with various techniques adopted in the Inner Channels and the Bar. Prior to 2008 maintenance dredging at the Bar was undertaken year-round using a side-cast dredge, then between 2008 and 2016 annual maintenance dredging was undertaken at the Bar and Entrance Channel using a contracted split Trailing Suction Hopper Dredge (TSHD) and since October 2017 ongoing, year-round maintenance dredging has been undertaken in this area using the bottom-door opening TSHD *Tommy Norton*, procured by GP. Dredging in the Inner Channels has generally been ongoing using a Cutter Suction Dredge (CSD).

As part of the GLOA program, GP is proposing to adjust the existing dredge area for some of the channels and the Bar. The proposed extensions and reductions in channel design are shown in Figure 1 relative to the existing design, while the proposed future channel design dredge depths are shown in Figure 2.

Figure 1. Proposed change in dredge areas.

Figure 2. Proposed channel design depths relative to Chart Datum for the future dredged channel configuration.

1.2. Port of Gippsland Lakes

The Port of Gippsland Lakes is located in East Gippsland, Victoria. The Port waters cover approximately 420 km^2 and extend from Sale in the west to Lakes Entrance in the east and include Lake Wellington, Lake Victoria and Lake King. A man-made ocean access was made at Lakes Entrance in 1889 to provide navigable passage between the Gippsland Lakes and the Bass Strait which has contributed significantly to the region since this time.

The dredged areas of the Port can be split into three main zones. The extents of these zones are shown in Figure 3 and are described below along with details of the current maintenance dredging practises undertaken:

- Bar: extends approximately 600 m offshore of the entrance to the Port. The maintained areas consist of a central channel with a width of 80 m which runs through the centre of the region as well as wedges located to the west and east of the channel which extend the dredged area to a width of 450 m at the seaward end of the channel. The total area of the channel and the wedges is 145,000 m^2. The wedges are designed to increase the time before sedimentation impacts the main channel. Before 2008 the Bar was dredged using a side-cast dredge, from 2008 to 2016 annual maintenance dredging programs were undertaken by a TSHD at the Bar and since October 2017 ongoing maintenance dredging has been undertaken by GP's TSHD *Tommy Norton.* Between 2008 and 2017 when annual maintenance dredging programs were undertaken by the TSHD, sand traps up to 3 m deeper than the main channel were sometimes dredged in the wedges to provide additional sedimentation buffer prior to sedimentation influencing the central channel;
- Entrance Channel and Swing Basin: the central channel in the Bar connects to the Entrance Channel adjacent to the seaward limit of the breakwaters and the Entrance Channel and extends to the north-west to the circular Swing Basin. The Entrance Channel is 25 m wide where it connects to the Bar channel (due to restrictions from the adjacent breakwaters) and then widens to a width of 50 m for the majority of its length. The Swing Basin has a radius of 50 m and connects the Entrance Channel to three of the Inner Channels (the Narrows, Hopetoun Channel and Cunninghame Arm). The total area of the Entrance Channel and Swing Basin is 33,000 m^2. As with the Bar, ongoing year round maintenance dredging by the TSHD *Tommy Norton* has been undertaken in the Entrance Channel and Swing Basin since 2017 (and prior to this annual maintenance dredging); and
- Inner Channels: the Inner Channels extend to the north, south-west and east from the Swing Basin. In total there are approximately 2.75 km of channels all at a width of 50 m (except for the North Arm which is 40 m wide with a narrow 15 m wide entrance). The Inner Channels are shown in Figure 3 and include Hopetoun Channel, Cunninghame Arm, North Arm, the Narrows and Reeve Channel. The total area of the Inner Channels is 141,000 m^2. The Inner Channels have historically been maintained by year round ongoing maintenance dredging using a CSD. The dredging is currently undertaken by the CSD *Kalimna* (since 2007), although the TSHD *Tommy Norton* undertakes occasional dredging in areas of the Inner Channels where it can access to help support the CSD *Kalimna*. Maintenance dredging of the Inner Channels has been undertaken by a range of different CSDs since 1963 and prior to this the dredging was undertaken by various bucket, suction and grab dredgers since the 1880's.

Details of the depths required for navigation and the target depths for maintenance dredging (to allow for sedimentation) for the different areas of the Port are provided in Table 1. The depths are quoted relative to Chart Datum (CD), which is 0.76 m below Australian Height Datum (AHD) at Lakes Entrance.

Table 1. Navigation and Dredge depths in the Port.

Location	Navigation Depth (m CD)	Dredge Depth (m CD)
Bar	3.5	5.5
Entrance Channel	3.5	4.5
Swing Basin	3.5	4.5
Cunninghame Arm	3.5	4.5
The Narrows	3.0	4.0
Hopetoun Channel	3.0	4.0
North Arm	3.0	4.0

Figure 3. **Port of Gippsland Lakes dredged areas and Dredge Material Grounds (DMGs).**

The placement of dredged sediment has varied depending on whether it was dredged by a CSD or TSHD, details are provided below:

- TSHD Placement: since 2008 a TSHD has maintained the Bar, Entrance Channel and Swing Basin and the resultant sediment has been placed at two Dredge Material Grounds (DMGs), located 1.5 km to the west and east of the Bar. The DMGs are both 2 km in length and 400 m in width and orientated so their longest side is parallel with the shoreline (Figure 3). They each contain 160 individual placement cells (four rows, A to D, and 40 columns) so that placement can be varied over time. The selection of which DMG should be used for the placement of sediment has historically been determined mainly based on the wave conditions so that the relocation correlates with the natural longshore transport (i.e. if the natural longshore transport at the time was to the west then the West DMG would have been used so that sediment would be transported away from the dredged area). The locations of the two DMGs are aimed to provide an offshore source of sand which over time will be transported onshore to help nourish the adjacent beaches. From 1979 to 2008 sediment dredged from the bar was side-cast a short distance using the *April Hamer* (in the order of 40 m) to the west or east, but it was determined that this approach was not optimum because of how quickly the sediment was being transported back into the dredged areas; and
- CSD Placement: a Sand Transfer System (STS) was setup at the Port prior to 2005 which allows the CSD to connect up to a number of transfer pipelines when dredging the Inner Channels. The transfer pipelines pump the dredged sediment to one of two nearshore beach discharge points, either located 1 km to the west or east of the Entrance. The discharge points are located in the nearshore wave breaking zone so that the sand goes back into the active sediment system as a form of beneficial reuse.

Historical maintenance dredging volumes for the Port are shown in Figure 4. Historically the largest volume of dredging has been at the Bar, with more than 600,000 m^3 dredged each year between 1999 and 2004. Since the TSHD *Tommy Norton* has been undertaking ongoing maintenance dredging at the Bar (October 2017), the annual volume of sediment removed from the Bar has been similar to the annual volume of sediment removed from the Inner Channels.

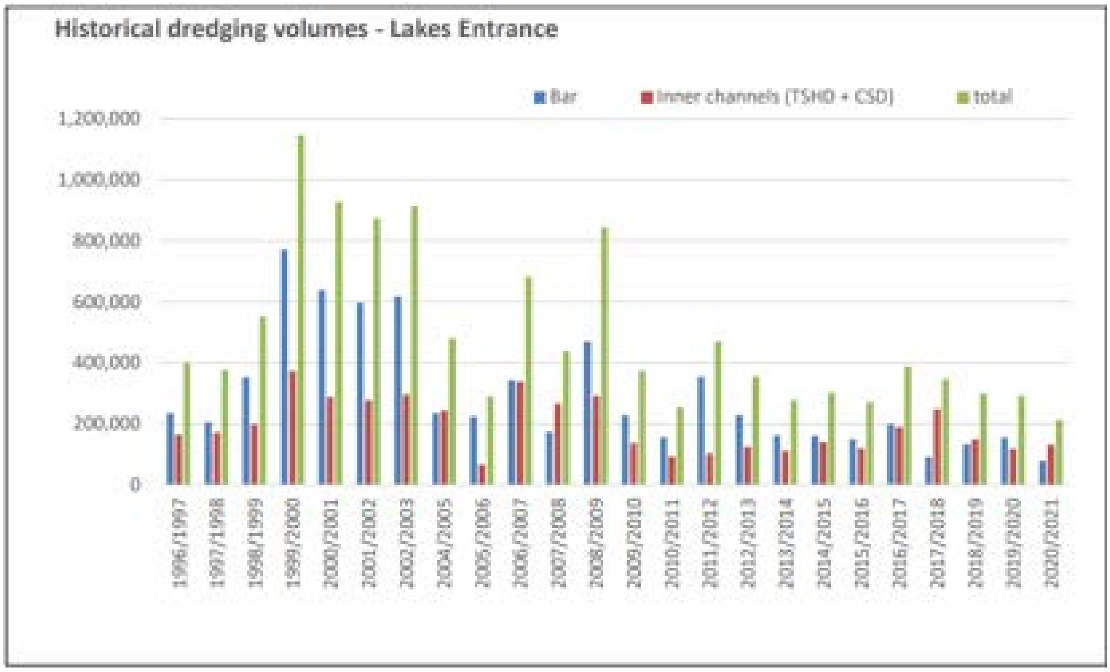


Figure 4. Historical maintenance dredging volumes for the Port of Gippsland Lakes (Gippsland Ports, 2021).

1.3. Report Structure

The report herein is set out as follows:

- a description of the metocean conditions in Gippsland Lakes is given in **Section 2**;
- a review and analysis of historical water level data is provided in **Section 3**;
- the numerical model setup, calibration and validation is detailed in **Section 4**;
- the modelling results are presented in **Section 5**; and
- a summary of the findings is detailed in **Section 6**.

Unless stated otherwise, levels are reported to AHD. Volumes presented throughout are in-situ cubic metres.

Wind and wave directions are reported as the direction the wind and waves are coming from in degrees clockwise from True North. Current direction is reported as the direction the current is going to in degrees clockwise from True North.

2. Metocean Conditions

This section provides an overview of relevant metocean conditions in the Gippsland Lakes based on the available information. The location of sites where data were used for characterisation of the study area is shown in Figure 5 and detailed below:

- Gippsland Ports:
  - Offshore WRB: GP waverider buoy (WRB) measuring wave conditions offshore of Lakes Entrance;
  - Eastern Breakwater: wind data measurement site;
  - Entrance Channel: water level and tidal current measurement site; and
  - Bullock Island: water level and weather (excluding wind) measurement site.
- Department of Energy, Environment and Climate Action (DEECA):
  - automated water level monitoring sites at Bull Bay, McLennan's Strait, Loch Sport, McMillans Strait and Metung;
  - automated salinity monitoring site at Bull Bay; and
  - river discharge data for the Latrobe River, Avon River, Macalister River, Mitchell River, Tambo River and Thompson River (locations not shown on Figure 5).
- Environment Protection Agency (EPA) Victoria:
  - in-situ vessel based salinity and water quality measurements, typically collected every 6 weeks, at Lake Wellington, Lake Victoria, Lake King North, Lake King South and Shaving Point. Data have only been collected at Lake Reeve East and Lake Reeve West since 2020 and so these sites have not been used for this assessment.
- Bureau of Meteorology (BoM):
  - measured wind and rainfall data were sourced from BoM at the weather stations at East Sale and Bairnsdale Airport. Wind data at East Sale were only available up to September 2017; and
  - measured daily evaporation data were sourced from BoM at East Sale and Bairnsdale. Evaporation data at East Sale were only available up to the end of 2014.

2.1. Water Levels

Tidal forcing in the Gippsland Lakes region is relatively weak with tidal ranges of less than 1 m on spring tides at Bullock Island, indicating a micro-tidal system. Gippsland Ports maintains tide gauges at the Entrance Channel and at Bullock Island, while DEECA maintains tide gauges at sites further upstream in Gippsland Lakes. Plots showing the measured water levels at select sites within Gippsland Lakes over a 12 month period and a 28 day period are shown in Figure 6 to Figure 10. The plots show the following:

- the largest variations in water level occur in the Entrance Channel. Water levels at Bullock Island exhibit a smaller tidal range (being around 75% of the range in the Entrance Channel), mainly as a result of the low water levels being elevated;
- a strong semi-diurnal tidal signal is only present at the Entrance Channel and Bullock Island, with semi-diurnal tidal variability of less than 0.2 m present at Metung and smaller variability further upstream; and
- the water levels at the Entrance Channel and Bullock Island are driven predominantly by the astronomical tide, while the largest water level variations further upstream in Lake King, Lake Victoria and Lake Wellington are driven predominantly by other processes (e.g. local wind, offshore storm surge and freshwater inputs).

Figure 5. Location of available measured metocean data for this study. *Note: The locations are colour coded based on the source of the data.*

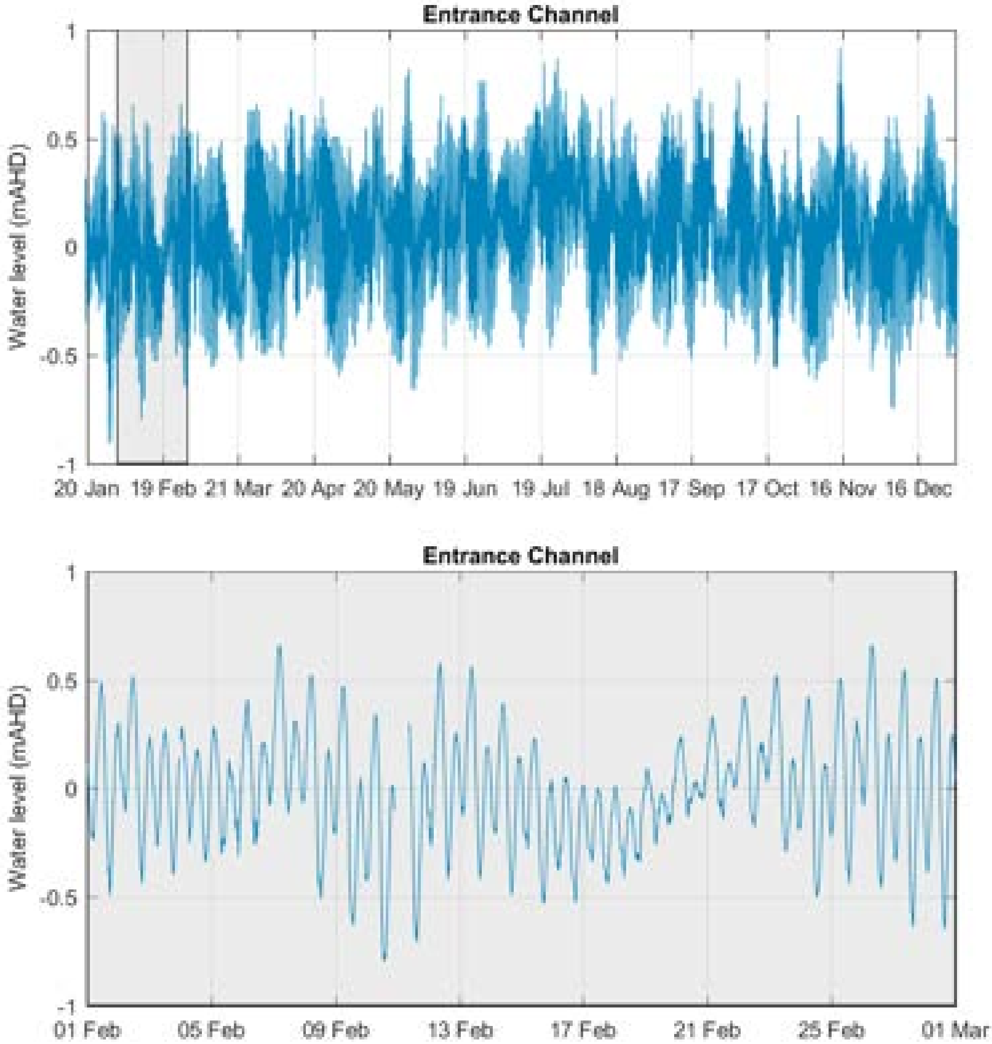


Figure 6. **Measured water levels at the Entrance Channel over 12 months in 2021 (top) and over 28 days (bottom).**

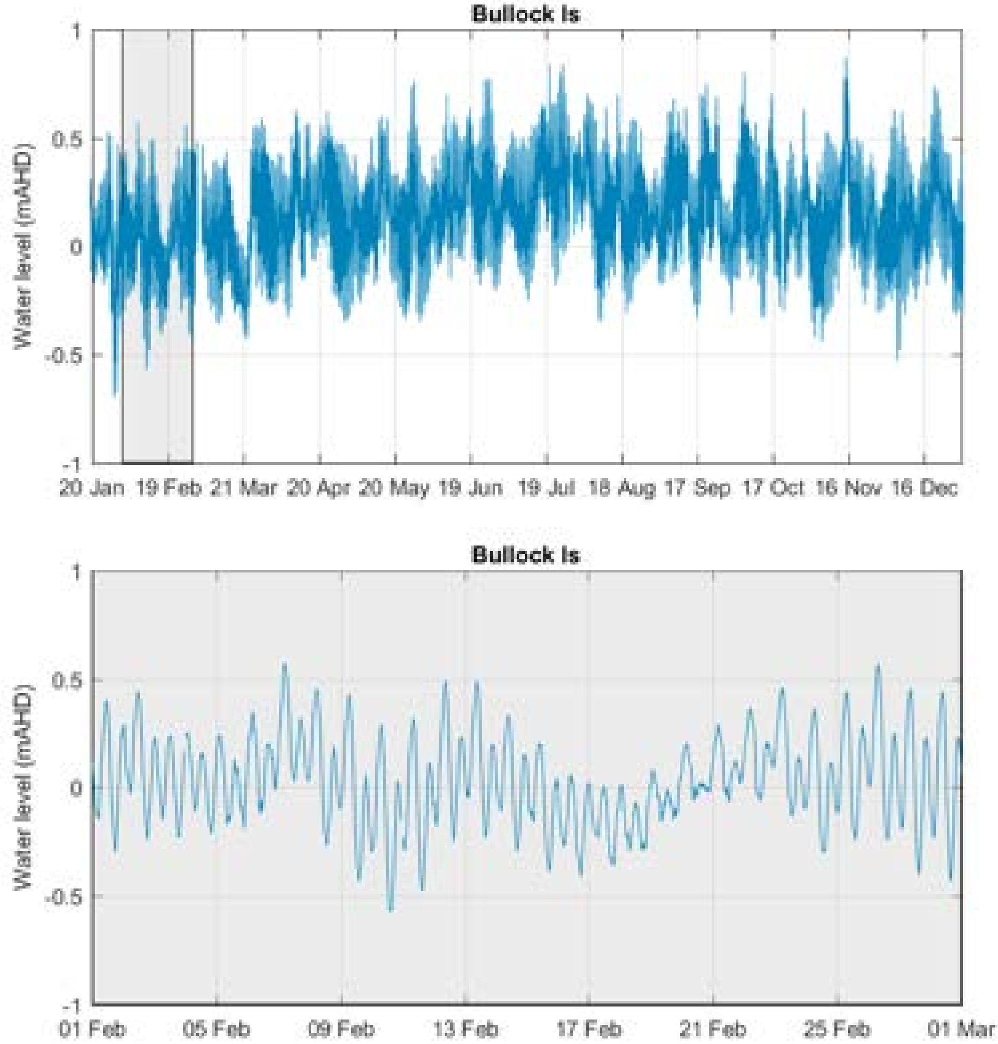


Figure 7. **Measured water levels at Bullock Island over 12 months in 2021 (top) and over 28 days (bottom).**

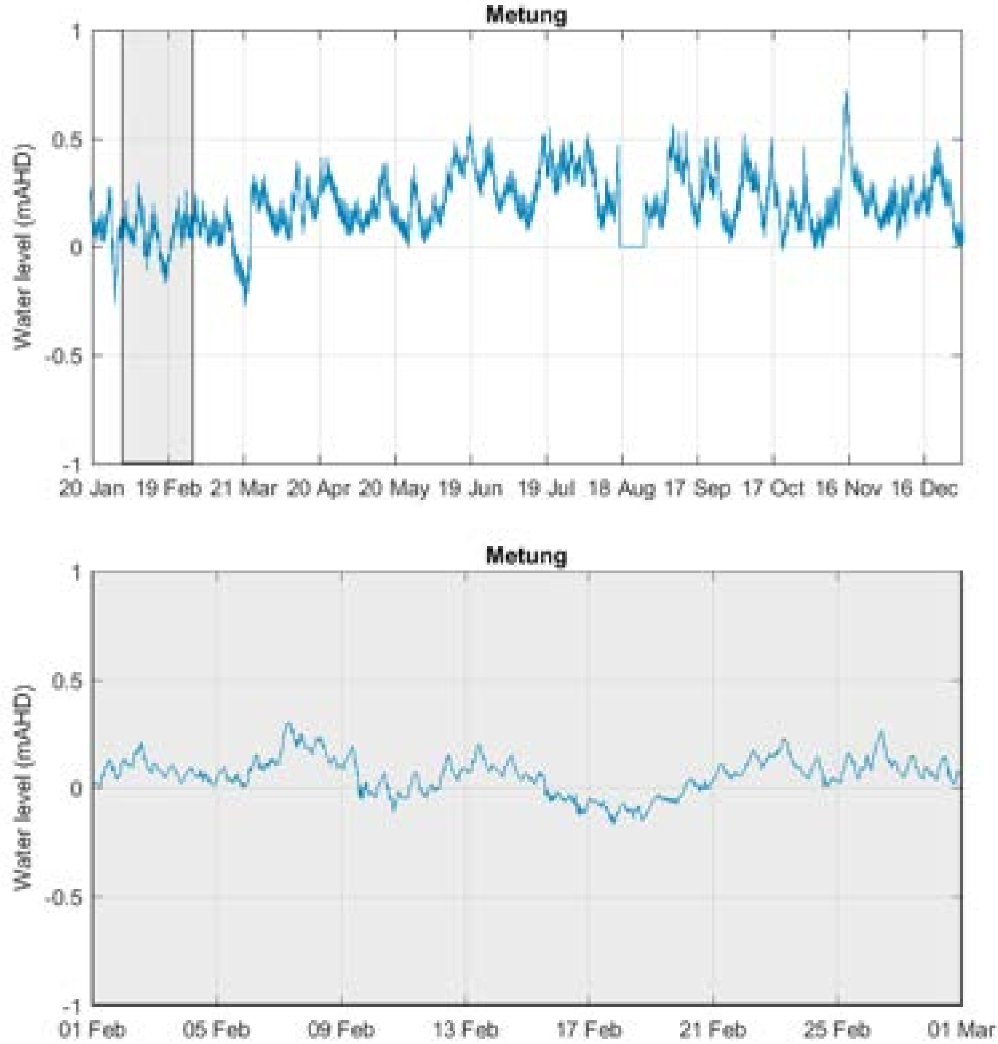


Figure 8. Measured water levels at Metung over 12 months in 2021 (top) and over 28 days (bottom).

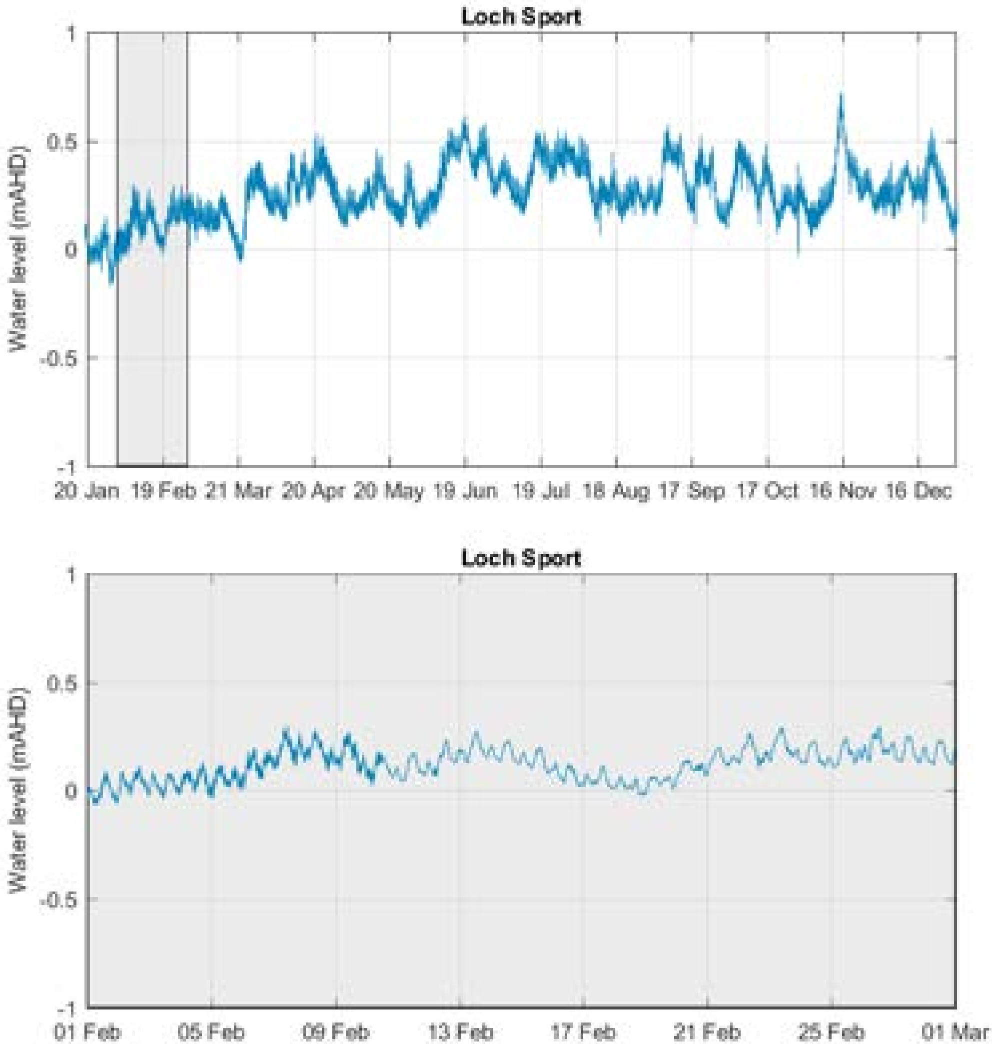


Figure 9. **Measured water levels at Loch Sport over 12 months in 2021 (top) and over 28 days (bottom).**

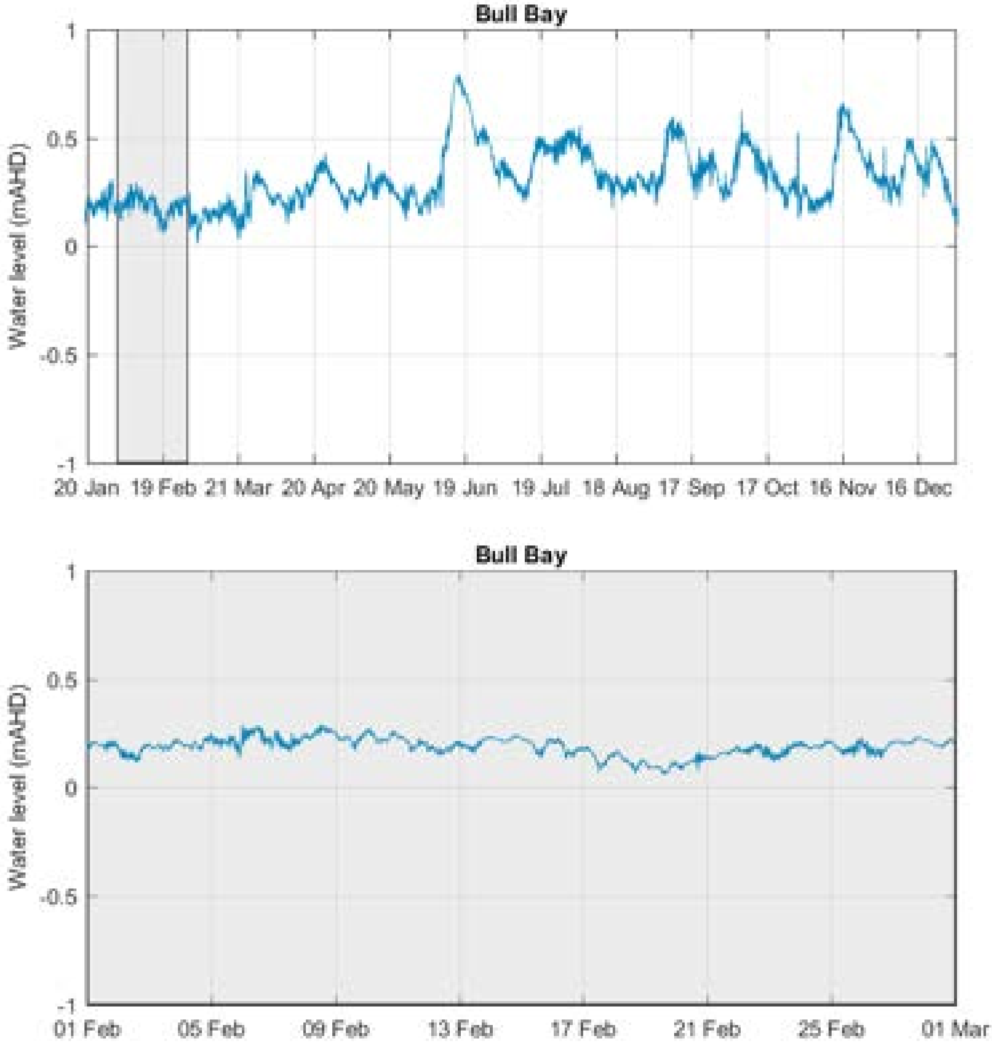


Figure 10. Measured water levels at Bull Bay over 12 months in 2021 (top) and over 28 days (bottom).

Detailed harmonic analysis of the available measured water level has been undertaken as part of this assessment (see Section 3). As part of this, a harmonic analysis of the measured water level at each of the sites was undertaken to determine the tidal constituents each year. The tidal constituents have been used to calculate the tidal planes at each site based on the measured water level data from 2022 based on the approach detailed in the Australian Tides Manual (ICSM, 2021) (see Section 3.2 for further details). The tidal planes and associated tidal ranges for the sites are shown in Table 2. The tidal planes calculated were as follows:

- High High Water Solstice Springs (HHWSS);
- Mean High Water Springs (MHWS);
- Mean High Water Neaps (MHWN);
- Mean Low Water Neaps (MLWN);
- Mean Low Water Springs (MLWS); and
- Indian Spring Low Water (ISLW).

The table shows that the total tidal range reduces from 1.17 m at the Entrance Channel, to 0.93 m at Bullock Island and then to 0.18 m at Metung. The total tidal range at MacMillan

Strait and Loch Sport is similar to at Metung, and then it reduces significantly at Bull Bay with a total range of less than 0.04 m.

Table 2. Tidal planes (m AHD) and tidal ranges (m) at sites in the Gippsland Lakes based on 2022 measured water level data.

Tidal Plane	Entrance Channel	Bullock Island	Metung	MacMillan Strait	Loch Sport	Bull Bay
HHWSS	0.69	0.62	0.27	0.37	0.34	0.300
MHWS	0.37	0.37	0.21	0.31	0.27	0.284
MHWN	0.23	0.25	0.19	0.29	0.26	0.283
MSL	0.05	0.12	0.17	0.27	0.23	0.280
MLWN	-0.12	-0.02	0.15	0.26	0.21	0.277
MLWS	-0.26	-0.14	0.13	0.24	0.20	0.276
ISLW	-0.49	-0.32	0.09	0.20	0.15	0.265
Total Range	1.17	0.93	0.18	0.17	0.19	0.035
Spring Range	0.63	0.50	0.072	0.066	0.077	0.007
Neap Range	0.36	0.27	0.035	0.035	0.047	0.006

Note: see Section 3.2 for details of how the tidal planes were calculated. The Total Range is calculated as HHWSS minus ISLW.

2.2. Currents

Flow speeds in the Entrance Channel have been measured by GP. Despite the small tidal range, currents through the Entrance Channel are relatively fast due to the large tidal prism of the Gippsland Lakes and the narrow, restrictive entrance channel. Plots showing the measured current speeds and directions in the Entrance Channel are shown in Figure 11 and Figure 12. The plots show that peak current speeds of more than 2 m/s[1] can occur during larger spring tides (or during periods of high river discharge, such as the periods with speeds of more than 2.5 m/s in June, July and December 2021), while peak current speeds during smaller neap tides are typically between 1 and 1.5 m/s. The currents are orientated approximately north north-west (NNW) on the flood and south south-east (SSE) on the ebb tide (i.e. aligned with the outer part of the entrance channel and the local bathymetry). The peaks in current speed occur close to the times of high and low water, rather than at mid tide.

Annual flow exceedances, calculated by PCS (2021a), are shown for the period 2010 to 2020 in Figure 13. The plot shows that there was a higher occurrence of faster flows in 2016 than during other years and comparably slower flows in 2011 and 2012. This highlights the annual variability in the current speeds in the Entrance Channel, which could be influenced by natural conditions (i.e. flood events and natural changes to the channel bathymetry) and local dredging. To help visualise the annual variability in the flow data the percentiles were presented by PCS (2021b) using box and whisker plots for the period pre September 2017 (when annual maintenance dredging programs were undertaken) and post September 2017 (when ongoing maintenance dredging was undertaken throughout the year) (Figure 14). The plot shows that prior to September 2017, from year to year there was typically more variability in current speeds through the Entrance Channel, while after this time there was less variability in the current speeds. This shows that implementing ongoing maintenance dredging has helped to stabilise current speeds in the Entrance Channel due to the reduction in variability of the Bar and Entrance Channel bathymetry over time.

1 For reference, 1 m/s is 1.94 knots.

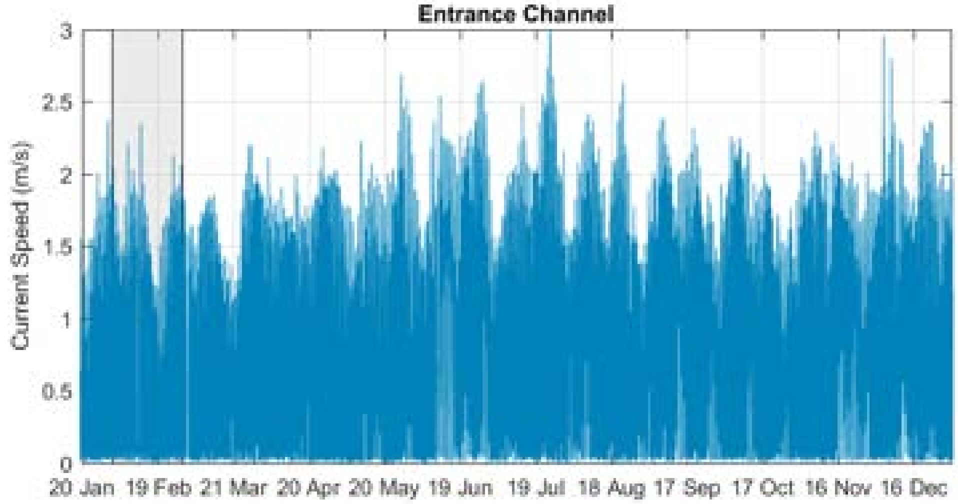


Figure 11. Measured current speed in the Entrance Channel during 2021.

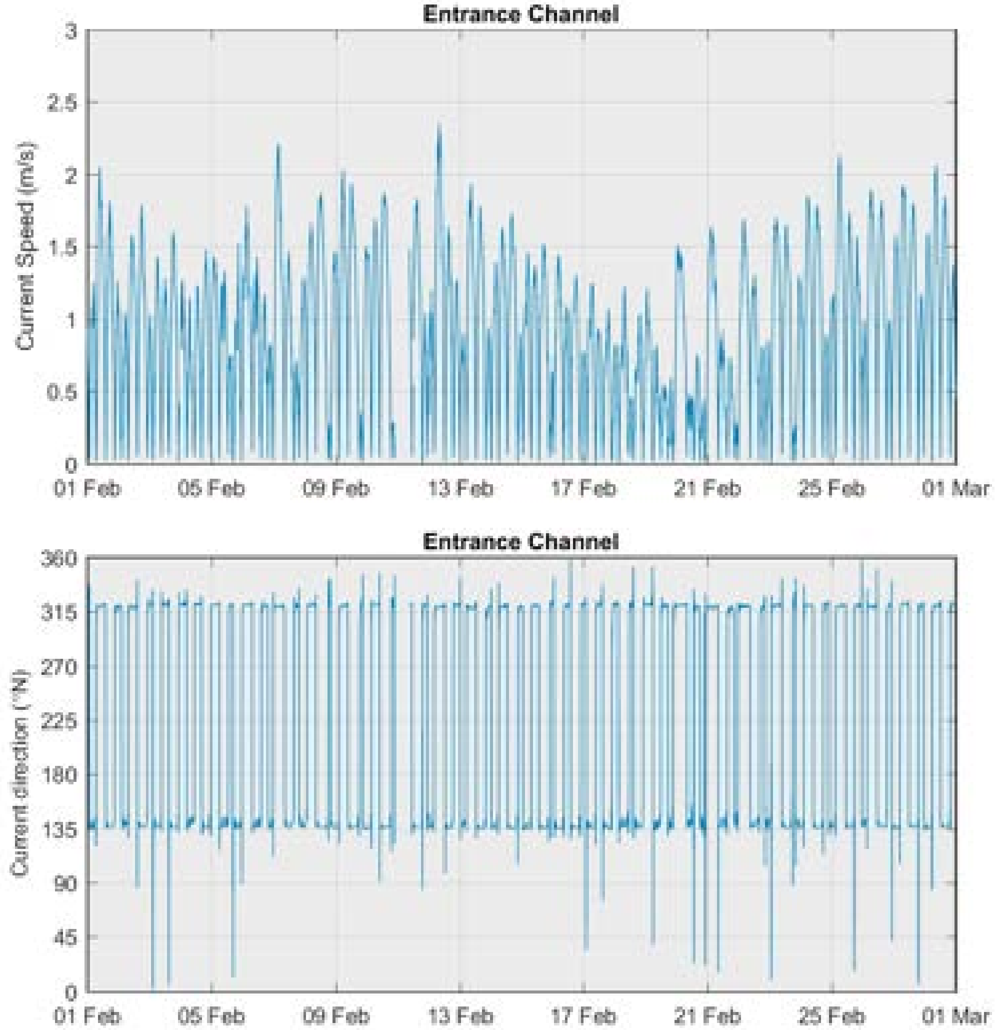


Figure 12. Measured current speed (top) and direction (bottom) in the Entrance Channel in February 2021.

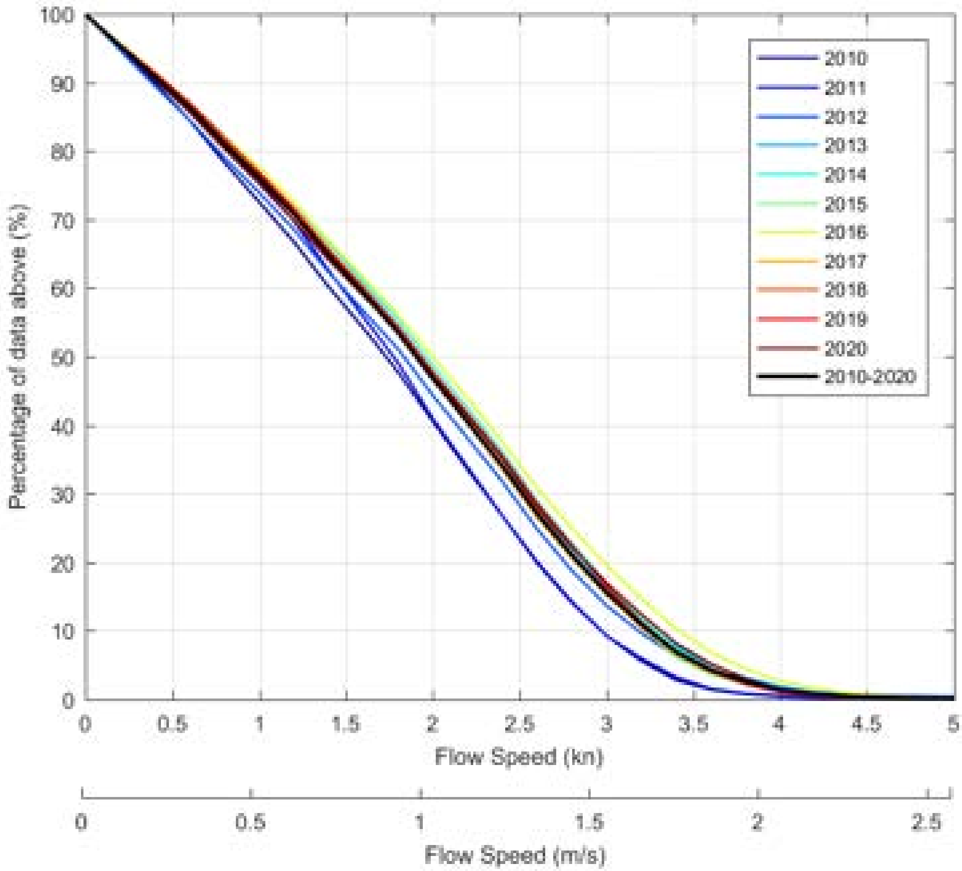


Figure 13. Exceedance plot of current speed in the Entrance Channel (PCS, 2021a).

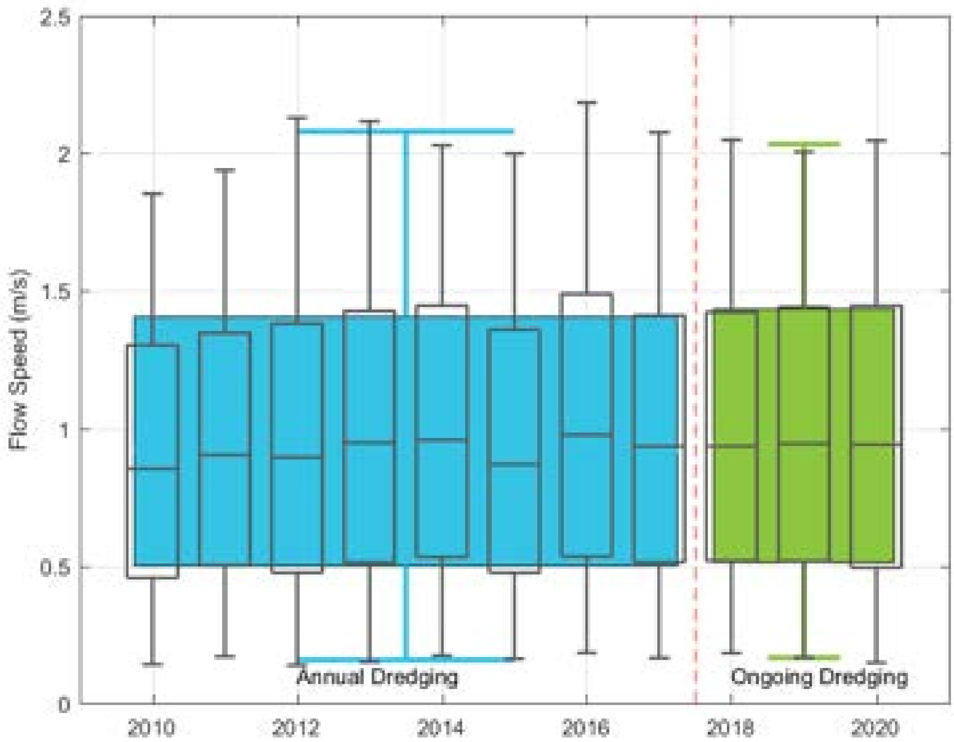


Figure 14. Box and Whisker Plots of Annual Flow Speed Data, with boxes showing 25th, 50th and 75th percentile and whiskers showing 1st and 99th percentiles (PCS, 2021b).

2.3. Wind

Wind data were sourced for this study from weather stations at the Eastern Breakwater (maintained by GP) and East Sale and Bairnsdale Airport (maintained by BoM) (see Figure 5 for location). Wind roses for the concurrent data at the three sites are shown in Figure 15. The roses show that the wind conditions at the Eastern Breakwater and Bairnsdale Airport are similar, but with stronger winds at the Eastern Breakwater. The stronger winds are likely to be due to its location providing wind speeds which are more representative of over water winds. The general trend in wind at East Sale is similar to the other two sites except at this site the winds from the west are clearly the dominant direction both in terms of duration of time they occur and the wind strength, while the other two sites have more variability.

Seasonal wind roses at the Eastern Breakwater are shown in Figure 16. The plots show that there is a degree of seasonal variability with a greater dominance in winds from the northern and western sectors during winter and with a greater dominance in winds from the southern and eastern sectors during the summer months. This likely reflects the occurrence of sea breezes which develop in the summer months (with stronger onshore winds occurring in the afternoon).

Previous analysis presented by PCS (2021a) showed that the annual wind data did not show any noticeable trends in wind over the 10 year period. The wave roses indicated that there was some variability in winds from year to year, but these variations were less significant than the seasonal variations which occurred throughout the year.

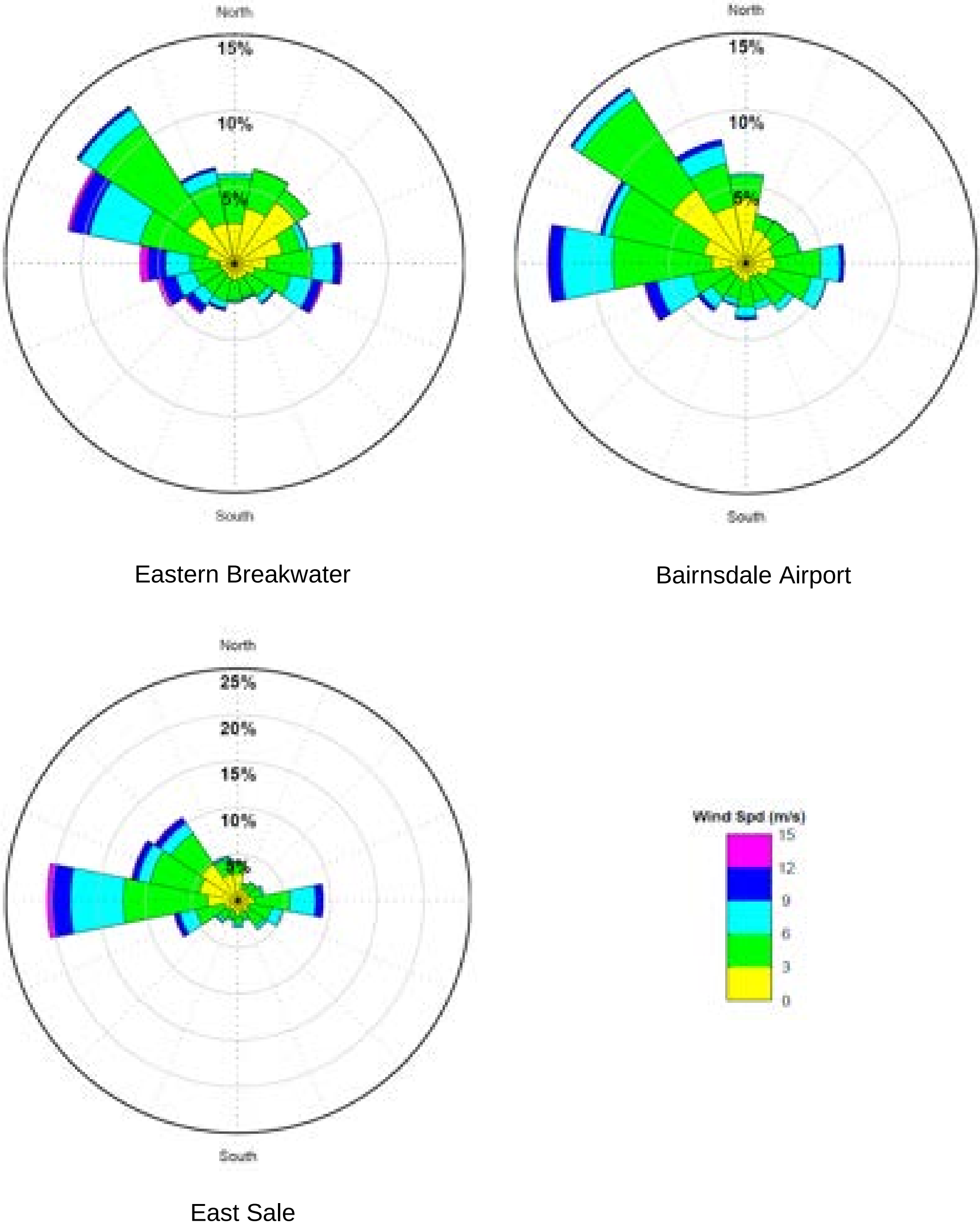


Figure 15. Comparison between wind roses for different location over 20 months of concurrent data.

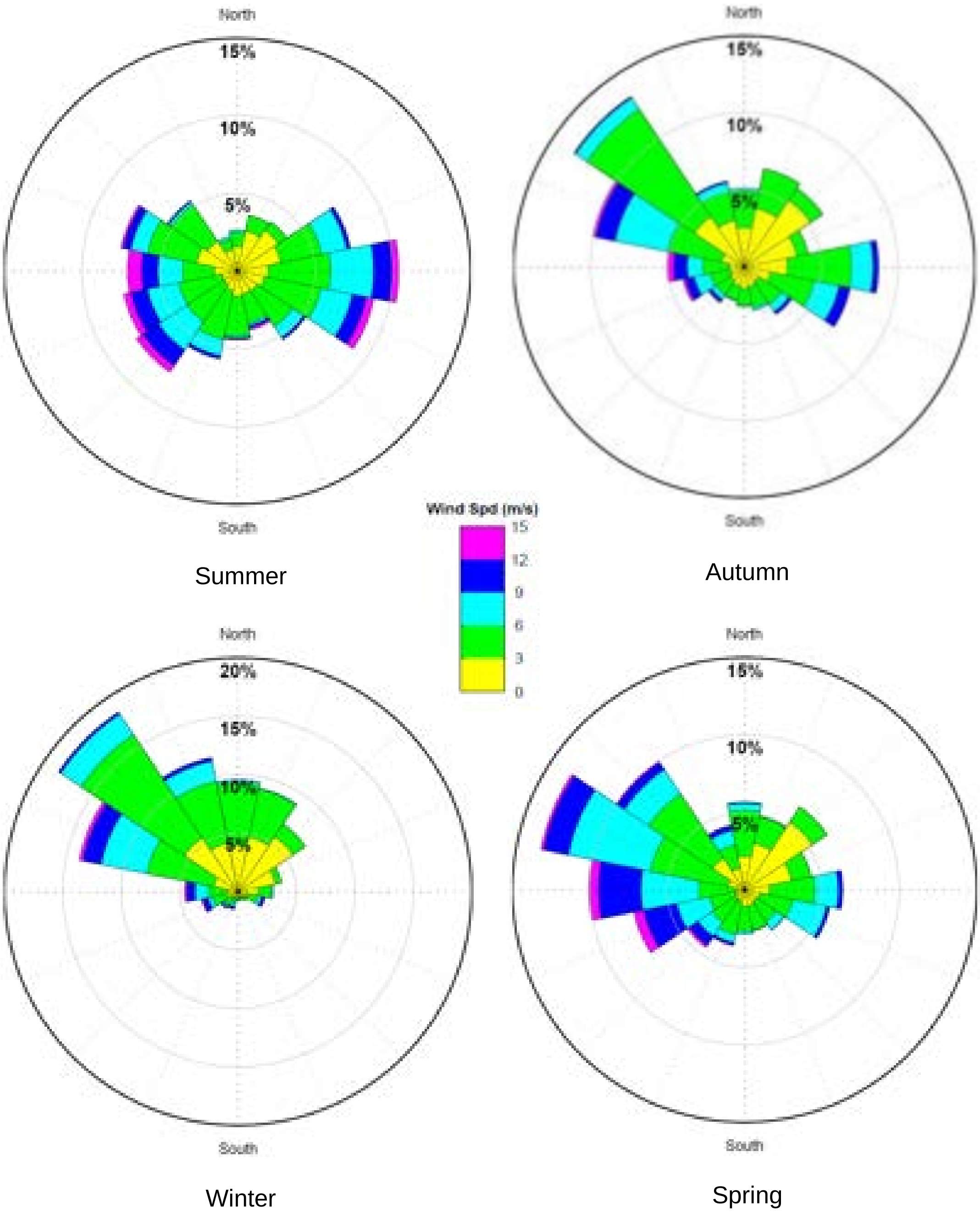


Figure 16. Seasonal wind roses from the Entrance Breakwater.

2.4. Waves

The local wave climate of the East Gippsland coast is largely sheltered from the highly energetic wave climate of the Southern Ocean by the Tasmanian landmass, although some waves do refract around the eastern side of Tasmania. The larger waves which occur offshore of the Entrance Channel are therefore predominantly generated in the eastern Bass Strait by south westerly to southerly winds and in the South Tasman Sea by east to south easterly winds.

Wave data is recorded at the directional Offshore WRB maintained by GP and installed offshore of the Entrance Channel (see Figure 5 for location). The buoy provides measurements of wave height (including significant wave height (H_s)), wave period and wave direction. The wave height and direction from 2010 to 2020 is shown in the form of a wave rose in Figure 17. The plot shows that wave heights offshore of the Gippsland Lakes are relatively small (with 95% of waves with an H_s of less than 2 m) and that the dominant wave direction is from the east south-east to south.

The narrow Entrance Channel means that offshore swell waves do not propagate into the Gippsland Lakes. Although small wind waves can be generated within the Gippsland Lakes during periods of strong wind, they are not considered to be an important process which could influence the water levels or salinity within the Lakes. Therefore, waves are not considered further in this report and are not included in the numerical modelling.

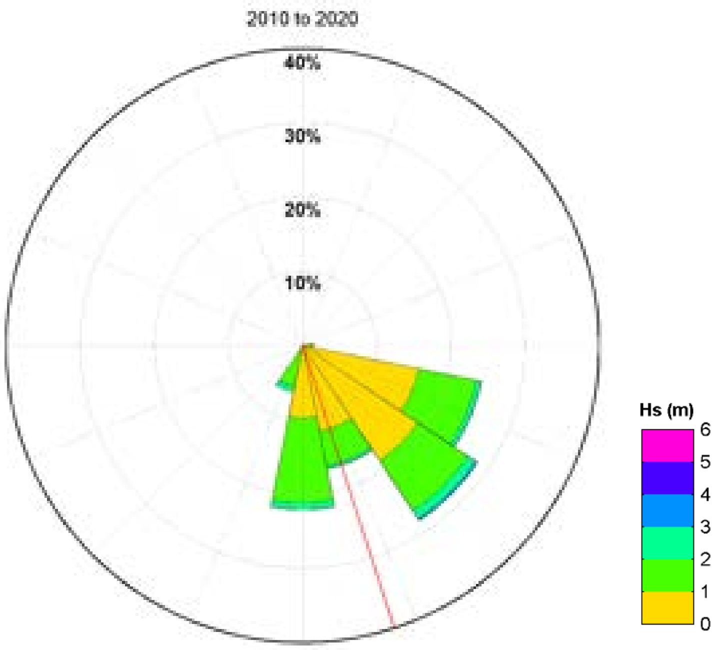


Figure 17. Wave rose at the Offshore WRB (2010 to 2020). *Note: red line shows direction which is perpendicular to the shoreline orientation at the Entrance Channel.*

2.5. Rainfall

Measured annual rainfall data from the BoM sites at East Sale and Bairnsdale Airport over the last 30 years are shown in Figure 18. The plot shows similar patterns in annual rainfall at the two sites, with higher rainfall rates at Bairnsdale Airport on average by 100 mm/yr (annual average over the 30 years = 640 mm/yr compared to 540 mm/yr at East Sale). At both sites the difference between the year with the lower rainfall (2006) and the year with the highest rainfall (2021) was approximately 500 mm, with approximately 900 mm/yr of rainfall at Bairnsdale Airport during the year with the highest annual rainfall. The plot shows that the rainfall rates from 2020 to 2022 were above the annual average (with 2021 having the highest rainfall over the 30 years), while rates from 2017 to 2019 were all below the annual average rainfall, 2016 was above the annual average and 2015 was approximately representative of the annual average rainfall rate.

To show how the rainfall varies seasonally, monthly rainfall totals from January 2015 to August 2023 are shown for Bairnsdale Airport in Figure 19. The monthly average over the whole period is 50 mm/month. The plot shows significant monthly variability in rainfall, ranging from some months experiencing no rainfall to one month experiencing 170 mm (November 2021). The data do not show a clear seasonal variability in rainfall, with the potential for low or high rainfall to occur during any month. However, the data indicate that there is more potential for high rainfall to occur from September to December each year.

It is important to note that the rainfall in the upper catchments which drain into the Gippsland Lakes varies significantly compared to the rainfall which falls directly into the Gippsland Lakes. The rainfall presented in this section is considered to be representative of the rainfall which falls directly into the Gippsland Lakes, while the river discharge data presented in the following section are used to understand how the rainfall in the catchments vary over time as that will control the river discharge.

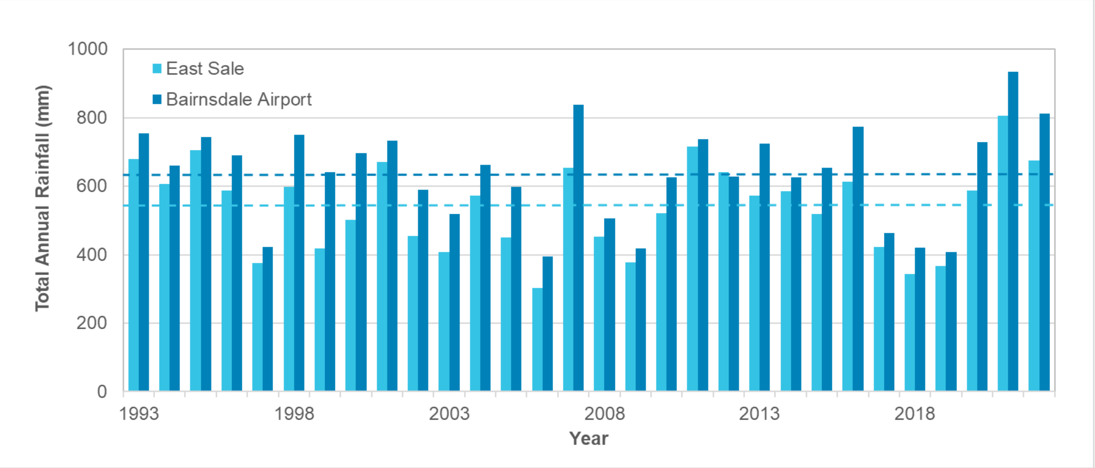


Figure 18. Measured annual rainfall at BoM weather stations from 1993 to 2022. *Note: the dashed lines show the annual average rainfall.*

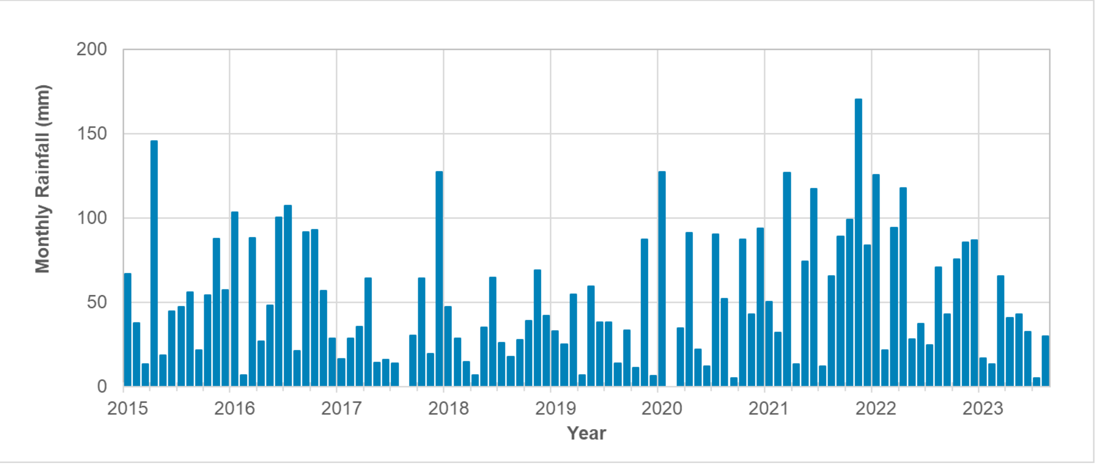


Figure 19. Measured monthly rainfall at the BoM Bairnsdale Airport weather stations from 2015 to 2023.

2.6. River Discharge

The freshwater discharge from the major rivers which drain into the Gippsland Lakes provide the dominant supply of freshwater to the Lakes. Variations in the river discharge have the potential to result in variations in the water level and salinity of the Lakes. Water Technology (2013) provide details of the relative contribution of the different rivers to the Gippsland Lakes:

- Latrobe River (including the Thomson and Macalister Rivers): represents 44% of the mean annual inflow;
- Mitchell River: represents 35% of the mean annual inflow;
- Avon River (including the Perry River): represents 8% of the mean annual inflow;
- Tambo River: represents 11% of the mean annual inflow; and
- Nicholson River: represents 2% of the mean annual inflow.

The locations where these rivers discharge into the Gippsland Lakes are shown in Figure 21. The Latrobe and Avon Rivers discharge into Lake Wellington, while the Mitchell, Nicholson and Tambo Rivers all discharge into the northern half of Lake King.

The river discharge from 2016 to 2023 for the two largest annual freshwater inflows into Gippsland Lakes is shown in Figure 20. The plot shows that both rivers typically exhibit peaks in river discharge at similar times, but that the peak in river discharge is much higher for the Latrobe River (max peak of 100,000 Ml/day compared to 40,000 Ml/day for Mitchell River). The main exception to this pattern is from 2017 to 2019 when the Mitchell River exhibited small peaks in river discharge when the Latrobe River did not. The plot also shows that the river discharge is much more variable than the rainfall. Very low river discharge occurred in 2017, 2018 and 2019 (almost no discharge from the Latrobe and peaks typically below 5,000 Ml/day for the Mitchell River), while multiple large peaks in river discharge (above 40,000 Ml/day for Latrobe River and more than 20,000 Ml/day for Mitchell River) occurred over the second half of 2021.

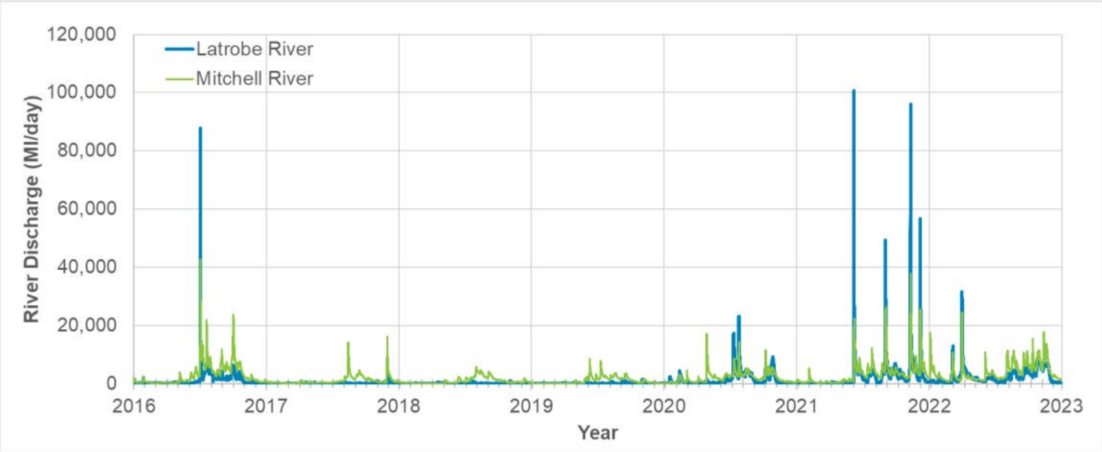


Figure 20. Measured river discharge from 2016 to 2023 for Latrobe and Mitchell Rivers.

Figure 21. Location of the main rivers which discharge into the Gippsland Lakes.

2.7. Evaporation

Evaporation is an important process as it can influence the water levels and salinity in the Gippsland Lakes. The process is particularly important during periods with low freshwater input to the system. Measured daily evaporation rates at the BoM Bairnsdale weather station are shown from 2016 to 2023 in Figure 22. The plot shows that there is a strong seasonal variability in the evaporation rate, with rates dropping to around 2 mm/day during the winter months (May to August) and increasing to more than 6 mm/day (and up to almost 12 mm per day) during the summer months (November to February). Although there is some variability between the years, this is negligible compared to the annual variability in river discharge. It has been noted that Lake Wellington has the potential to lose around one third of its water volume as a result of evaporation during a year with very low river discharges. During conditions such as these when the evaporation rate exceeds the freshwater input (river discharge and rainfall), the evaporation will result in an increase in salinity in the Lakes as the salt in the water does not evaporate.

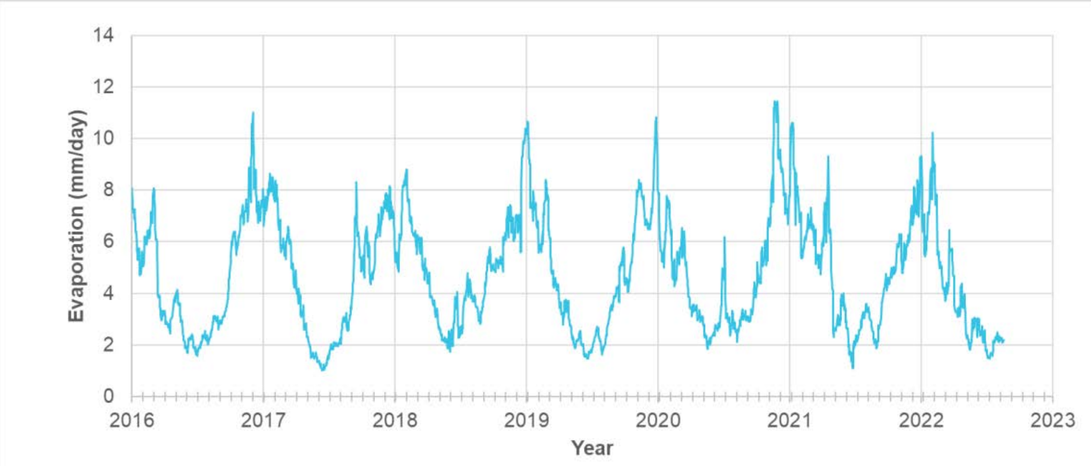


Figure 22. Measured daily evaporation at Bairnsdale from 2016 to 2023.

2.8. Salinity

Salinity has been measured at multiple sites by the EPA at a frequency of approximately every six weeks within the Gippsland Lakes, while DEECA have one continuous logger measuring salinity at Bull Bay in Lake Wellington. The measured salinity in practical salinity units (PSU) at the Bull Bay logger from 2016 to 2023 is shown in Figure 23 and a plot showing the measured surface salinity by the EPA over the same period is shown in Figure 24. The plots show the following:

- the surface salinity at Metung, Lake King North, Lake King South and Lake Victoria are similar, with Metung having slightly higher salinity and Lake Victoria having slightly lower salinity. At all these sites the surface salinity over the 6.5 years shown varies from around 5 psu up to just over 30 psu;
- the salinity in Lake Wellington (at the Lake Wellington and Bull Bay sites) is significantly lower than at the other sites, with the salinity varying from 0 psu to just over 20 psu (the value above 25 psu in the EPA data in 2019 is considered to be erroneous as it is a higher salinity than most of the other sites and is not shown by the measurements at Bull Bay). The salinity measurements at the two sites in Lake Wellington generally agree well; and
- the periods when the salinity drops generally correlate well with the peaks in river discharge shown in Figure 20. In addition, the periods when the salinity is gradually increasing correlate with periods with very low river discharges into Gippsland Lakes.

The EPA also undertake profile measurements at each of their monitoring sites which show how the salinity varies with depth through the water column. Example plots of the vertical salinity profile at all five of the EPA monitoring sites for a period of more typical, higher salinity (April 2017) and a period of lower salinity due to recent high freshwater discharge (October 2016) are shown in Figure 25 and Figure 26. The plots show the following:

- at all the sites there is a significant reduction in salinity (around 10 psu) for the period following a high freshwater discharge event compared to the period with more typical, higher salinity;
- the salinity at Lake Wellington shows little variability with depth, suggesting the shallow water in the lake allows the water column to remain well mixed;
- at Lake Victoria and Lake King North the salinity gradually increases with depth, with the near bed salinity ranging from 3 to 7 psu higher than the surface salinity; and
- at Lake King South and Shaving Point there is more of a step change in salinity with depth, suggesting the presence of a salt wedge at these locations. The magnitude of the change in salinity is significantly larger for the period following the freshwater discharge event, with differences between the surface and near bed salinity of more than 15 psu for this period compared to differences of around 5 psu for the period with higher salinity.

Since the Entrance Channel to the Gippsland Lakes was permanently opened in 1889, there has been a regular supply of seawater with a constant salinity of around 35 psu. The relative amount of advection and dispersion of this seawater within the Gippsland Lakes will vary slightly depending on the water levels and the bathymetry within the Lakes, but it will provide an almost constant source of seawater to the entrance to the Lakes. As a result, the variations in salinity which occur within the Gippsland Lakes are predominantly controlled by the discharge of freshwater into the system from the rivers. In addition, the lack of freshwater discharge and rainfall to the Gippsland Lakes is also important, as this allows evaporation to become an important process to increase salinity in the Lakes. It was noted by Water Technology (2013) that the Lakes can also experience occasional very large flood flows which can introduce large volumes of freshwater into the Lakes, resulting in rapid reductions in salinity in the Lakes. A conceptual representation of the typical spatial distribution of the salinity within the Lakes, shown as both a long section through the water column and a spatial map, developed as part of previous investigations is shown in Figure 27. This helps to summarise how the salinity varies through the Lakes and how the higher salinity waters offshore of the entrance mixes with the lower salinity waters in the Lakes.

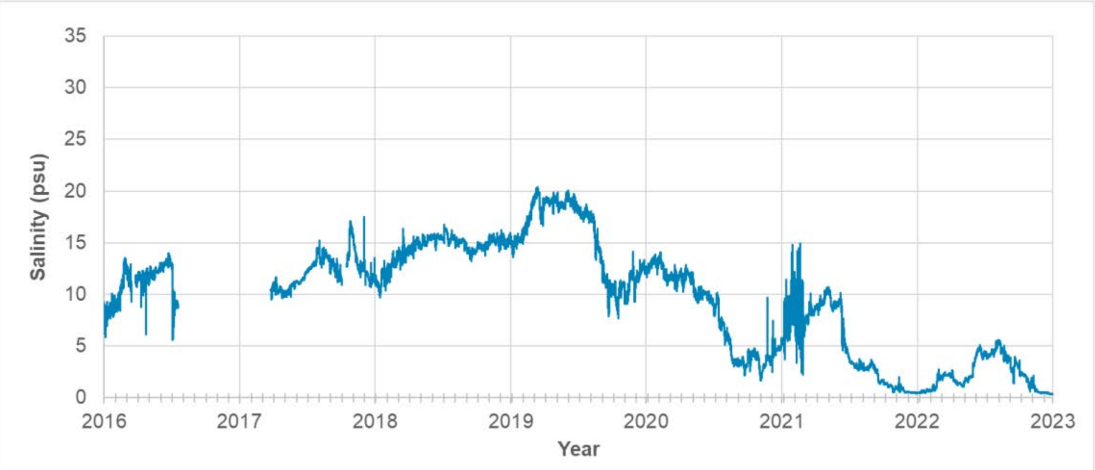


Figure 23. Measured salinity data from 2016 to 2023 at the DEECA logger in Bull Bay.

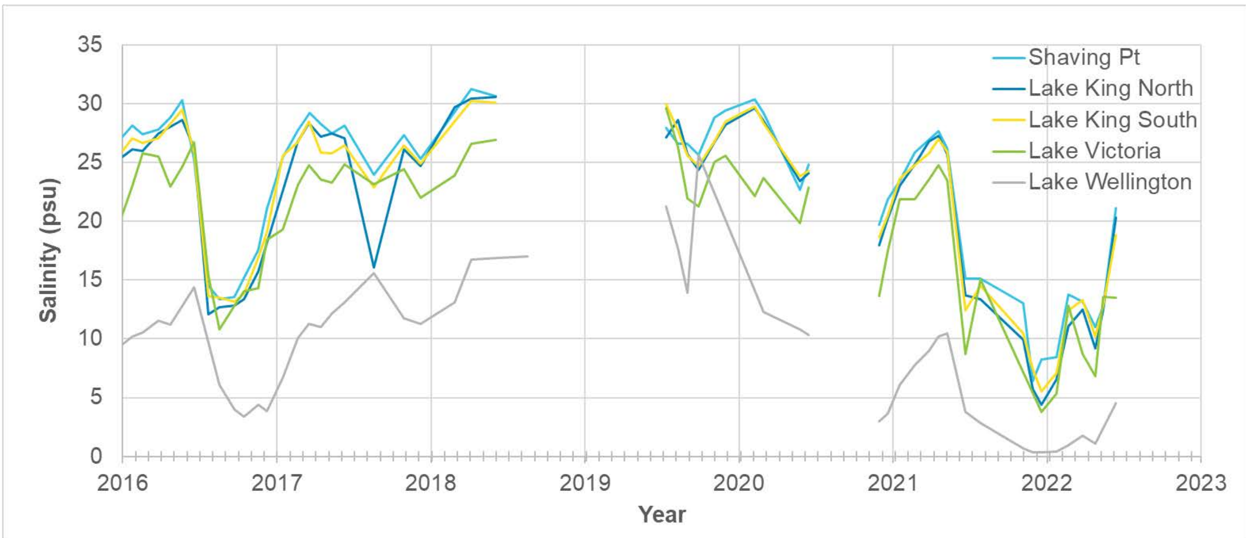


Figure 24. **Measured surface salinity data from 2016 to 2023 at the EPA monitoring sites.**

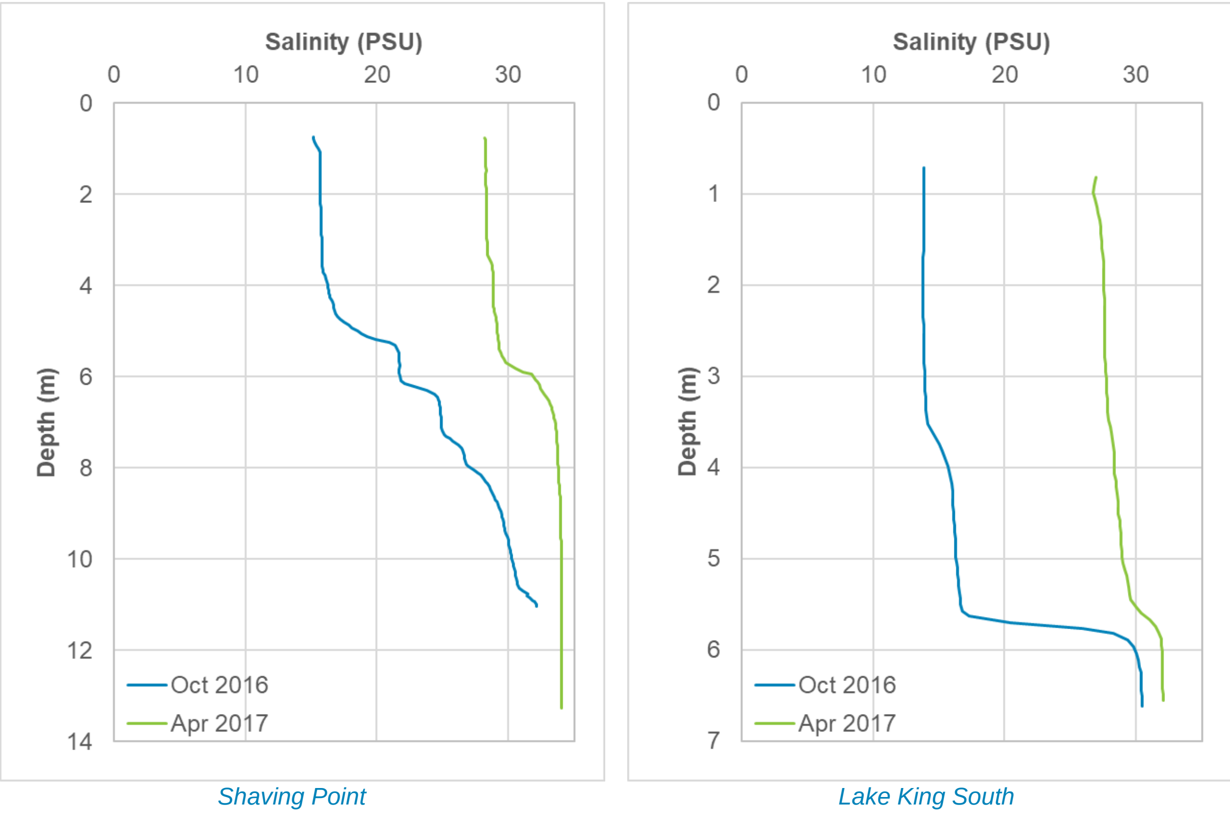
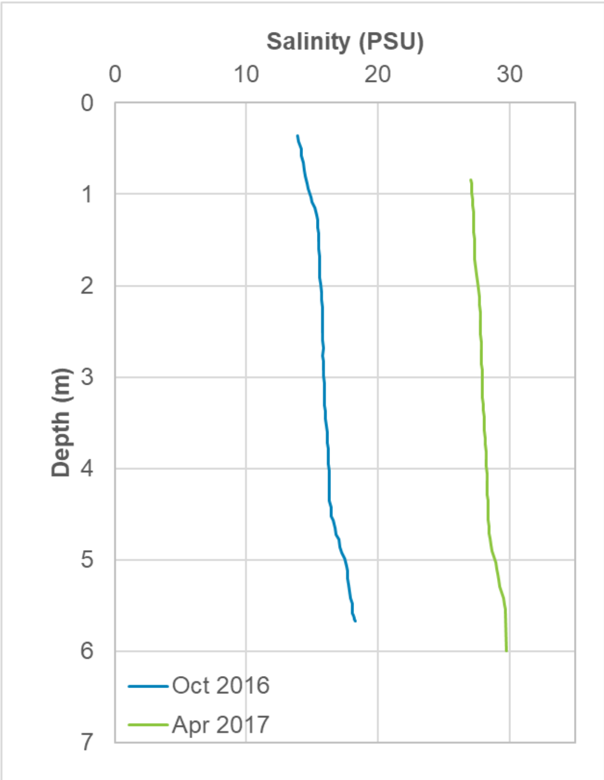
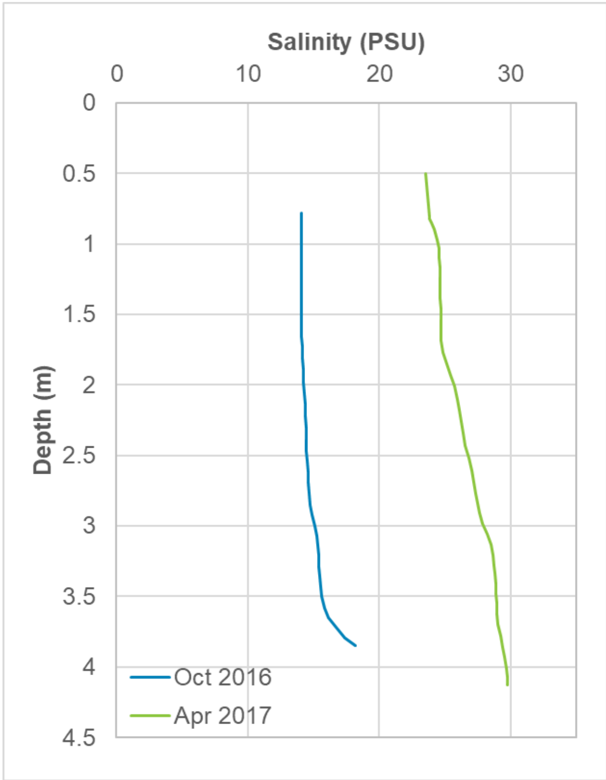


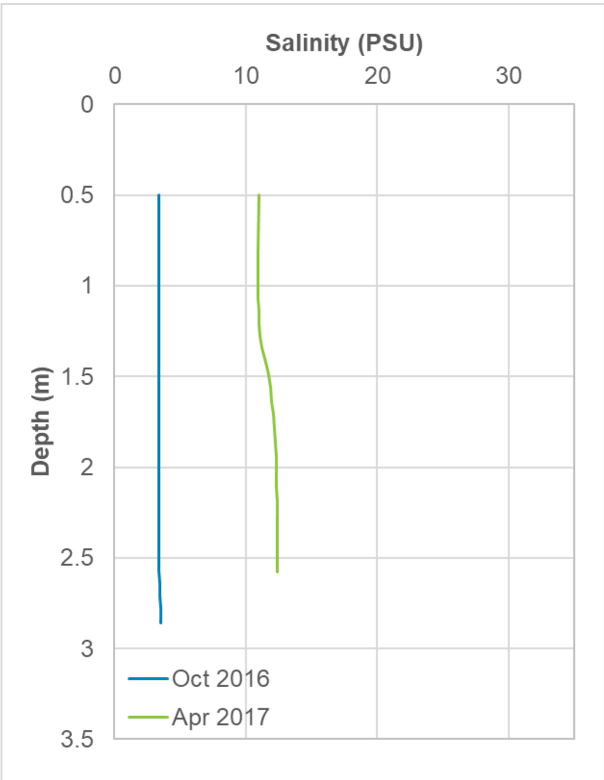
Figure 25. **Salinity profiles at Shaving Point and Lake King South following high freshwater discharge (Oct 2016) and with more typical, higher salinity (Apr 2017).**



Lake King North



Lake Victoria



Lake Wellington

Figure 26. Salinity profiles at Lake King North, Lake Victoria and Lake Wellington following high freshwater discharge (Oct 2016) and with more typical, higher salinity (Apr 2017).

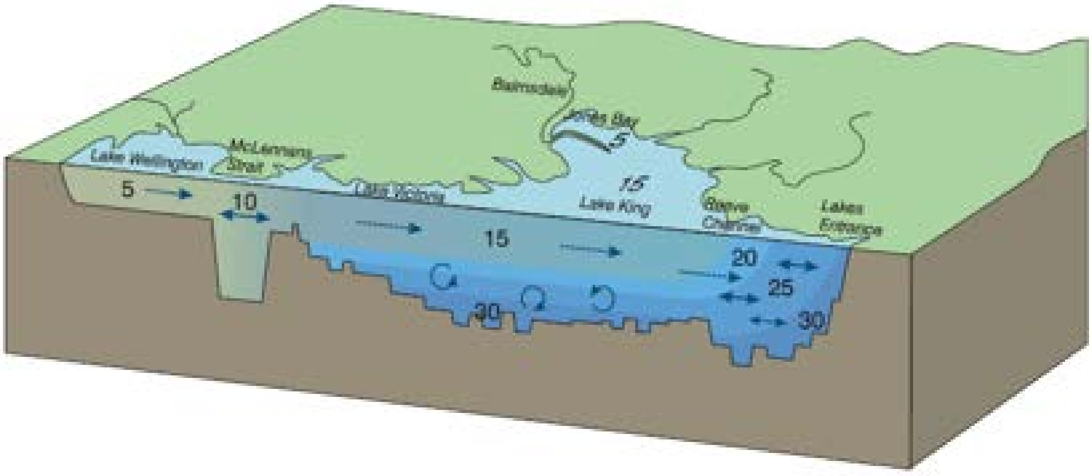


Figure 27. Conceptual representation of the salinity within the Gippsland Lakes, with the values showing the typical salinity (in psu) (Water Technology, 2013).

3. Water Level Analysis

This section is aimed at analysing the available measured water level data from the Gippsland Lakes to determine whether dredging practices could have significantly influenced the astronomical tidal harmonic constituents.

As noted in the previous section, water level data have been collected at multiple locations within the Gippsland Lakes. The periods when data are available varies between the sites as follows:

- Entrance Channel: April 2008 to April 2023;
- Bullock Island: August 1995 to November 2003, and April 2009 to April 2023;
- Metung: November 2010 to July 2023;
- McMillan Strait: October 2010 to May 2023;
- Loch Sport: November 2010 to July 2023;
- McLennan's Strait: November 2010 to May 2023; and
- Bull Bay: March 1975 to July 2023 (gaps from July 1988 to February 1991 and from June 1992 to December 1992).

The water level data collected at Bull Bay in Lake Wellington provides the only continuous dataset which extends over the last 30 years (since 1993). For the analysis all of the measured water level data were converted to AHD.

3.1. Previous Investigations

A previous study undertaken by Water Technology (2013) investigated the effects of the change in dredging practice at the Port of Gippsland Lakes since 2008 on the water levels within the Gippsland Lakes. The change in dredging practices was from side-casting dredged sediment at the Bar (i.e. so the sediment remained adjacent to the Bar) to using a TSHD to relocate the sediment to approved placement sites located 1.5 km to the west and east of the Bar as well as additional maintenance of the Inner Channels. As part of the study, water level data at Bullock Island was analysed from 1998 to 2000 and from 2009 to 2012 and water level data at Bull Bay was analysed from 1991 to 2013. The assessment showed that there was a small increase in the amplitude of the M_2 tidal constituent (principal Lunar semi-diurnal constituent) at Bullock Island of around 0.05 m between 2000 and 2009 (when there was no data available), while at Bull Bay there was a gradual increase in the amplitude of the M_2 tidal constituent from 1991 to 2013 of less than 0.002 m. The results also showed that since 2008 there has been less variability in the water levels, indicating more consistent water levels following the change in dredging practice. The study concluded that the increase in amplitude of the M_2 tidal constituent between 2000 and 2009 could be due to the initial trial into the use of a TSHD which commenced in 2008.

A recent investigation undertaken by PCS (2023) analysed measured water level data at the Entrance Channel and at Bullock Island from 2008 to the end of 2022. The assessment identified the peak water level and peak storm surge events over the period and considered the relative influence of varying drivers on these. The assessment found that multiple potential drivers are often elevated during periods with high water levels. The wind speed was shown to often result in a direct instantaneous correlation with periods of elevated water levels indicating that the wind conditions are an important driver. Some events which lasted for multiple days were shown to occur several days after a period of elevated wind speed and rainfall, for these events the river level appears to coincide with the period of elevated water levels, suggesting that the freshwater discharge into the Lakes is also an important driver.

3.2. Analysis

To determine how astronomical tidal influences have changed over time at each of the monitoring sites a harmonic analysis was undertaken on annual measured water level data from each site. Analysing the measured water levels over a 12 month period ensures that any shorter duration processes which can influence water levels, such as river discharge, ocean storm surge, atmospheric pressure and wind setup, should not influence the major tidal constituents. The harmonic analysis was undertaken using the MIKE 21 Tidal Analysis toolbox and the analysis provided annual major and minor tidal constituents (between 60 and 68 constituents) at all the sites.

Due to the small astronomical tidal range within the Gippsland Lakes, the amplitude of the major tidal constituents (e.g. S_2, M_2, K_1 and O_1) are very small (less than 0.03 m away from Lakes Entrance). Therefore, instead of presenting the small changes in individual tidal constituents, the tidal constituents have been used to calculate the following tidal planes based on the approach detailed in the Australian Tides Manual (ICSM, 2021):

- HHWSS = $Z_0 + M_2 + S_2 + (1.4 \times (K_1 + O_1))$
- MHWS = $Z_0 + (M_2 + S_2)$
- MHWN = $Z_0 + \text{abs}(M_2 - S_2)$
- MLWN = $Z_0 - \text{abs}(M_2 - S_2)$
- MLWS = $Z_0 - (M_2 + S_2)$
- ISLW = $Z_0 - (M_2 + S_2 + K_1 + O_1)$

Note: Z_0 = Mean sea level, M_2 = Principal Lunar semidiurnal constituent, S_2 = Principal Lunisolar semidiurnal constituent, O_1 = Principal Lunar diurnal constituent, K_1 = Principal Lunisolar diurnal constituent.

These calculated tidal planes were then used to calculate the total tidal range (HHWSS – ISLW), the mean spring tidal range (MHWS – MLWS) and the mean neap tidal range (MHWN – MLWN) for each year and for each site. The changes to these astronomical tidal ranges were then used to infer the relative change in the astronomical tide over time.

3.3. Results

Plots showing the total, spring and neap tidal ranges at the two sites with the longest available water level datasets are shown in Figure 28. The tidal range for the two sites are plotted on separate y-axes due to the difference in range between the sites. Similar relative ranges in the y-axes have been adopted so that the two datasets are as closely comparable as possible. The plots show a similar trend of increasing tidal ranges from 1993 to 2023 at both sites. When the results just at Bullock Island are considered, it appears that a major change occurred between 2003 and 2009 which resulted in a significant increase in all of the tidal ranges. However, when the results at Bullock Island are considered alongside the results at Bull Bay it can be seen that the relative increase in tidal range at both sites is similar and that the relative changes between the 1995 to 2002 and the 2009 to 2023 tidal range data from Bullock Island correlate well with the data at Bull Bay. This indicates that the changes to the tidal range data from 2003 to 2008 at Bull Bay can be used to provide an indication as to how the tidal range changed at Bullock Island over this period. However, it is important to note that the total tidal range at Bull Bay is small (total range of 0.02 to 0.04 m), meaning that the relative changes in tidal range are in millimetres compared to changes of tens of centimetres at Bullock Island. The very small tidal range at Bull Bay results in some uncertainty in the predicted changes in tidal range at this site. The results at Bull Bay show that there was a reduction in tidal range from 2002 to 2003 and then a gradual increase in tidal range from 2003 to 2008. This gradual increase suggests that the change in tidal range from 2003 to 2008 was a gradual ongoing change and not due to a single major change. If the tidal range results at both sites are considered just for the period since 2008, the linear trendlines would not be as steep, suggesting that the rate of increase in tidal range has reduced since 2008.

Results for the other measurement sites have also been plotted relative to the changes at Bullock Island to show whether they follow a similar trend with an increasing tidal range (Figure 29 and Figure 30). As these other measurement sites only have data since 2008 at the earliest, only the results for Bullock Island since 2009 have been plotted and so the tidal range changes are only representative of this period with a slower increase. The results show the following:

- the tidal range at the Entrance Channel has increased from 2008 to 2023, with a similar increase in tidal range to Bullock Island over the same period. Over this 15 year period the increase in total tidal range at the sites was less than 0.1 m, while the spring tidal range increase was up to 0.08 m;
- the total and spring tidal ranges at Metung, Macmillan Strait and Loch Sport have all increased from 2010 to 2023, with increases in the total tidal range of 0.01 to 0.02 m and increases in the spring tidal range of 0.006 to 0.008 m. The neap tidal range has also increased at Metung and Loch Sport, while at Macmillan Strait there has been a slight reduction in the neap tidal range (all neap tidal range changes were less than ±0.005 m from 2010 to 2023). Overall, the trends at the sites appear to correlate well with the changes at Bullock Island (except for the reduction in neap tidal range at Macmillan Strait).

To better understand how the total tidal range has changed at all the sites over a comparable time period, the equations for the linear trendlines shown on Figure 28 to Figure 30 over the 2008 to 2023 period were used to calculate the total tidal range at each site in 2008 and in 2023 and the percent change between the two dates (Table 3). The percent change shows similar increases in the total tide range of 7% and 8% at Bullock Island and the Entrance Channel. The percent increase in total tidal range increases with distance upstream into the Lakes, with an increase of 11% at Metung and 14% at Loch Sport. However, the percent increase at Bull Bay of 2% is significantly smaller than at the other sites, suggesting that the reduction in tidal signal caused by McLennan's Strait also results in a reduction in tidal range change in Lake Wellington.

Table 3. Predicted Total Tidal Range at the monitoring sites in 2008 and 2023.

Location	2008 Tidal Range (m)	2023 Tidal Range (m)	Change (%)
Entrance Channel	1.136	1.226	8%
Bullock Island	0.935	0.998	7%
Metung	0.138	0.153	11%
MacMillan Strait	0.168	0.191	13%
Loch Sport	0.233	0.265	14%
Bull Bay	0.132	0.135	2%

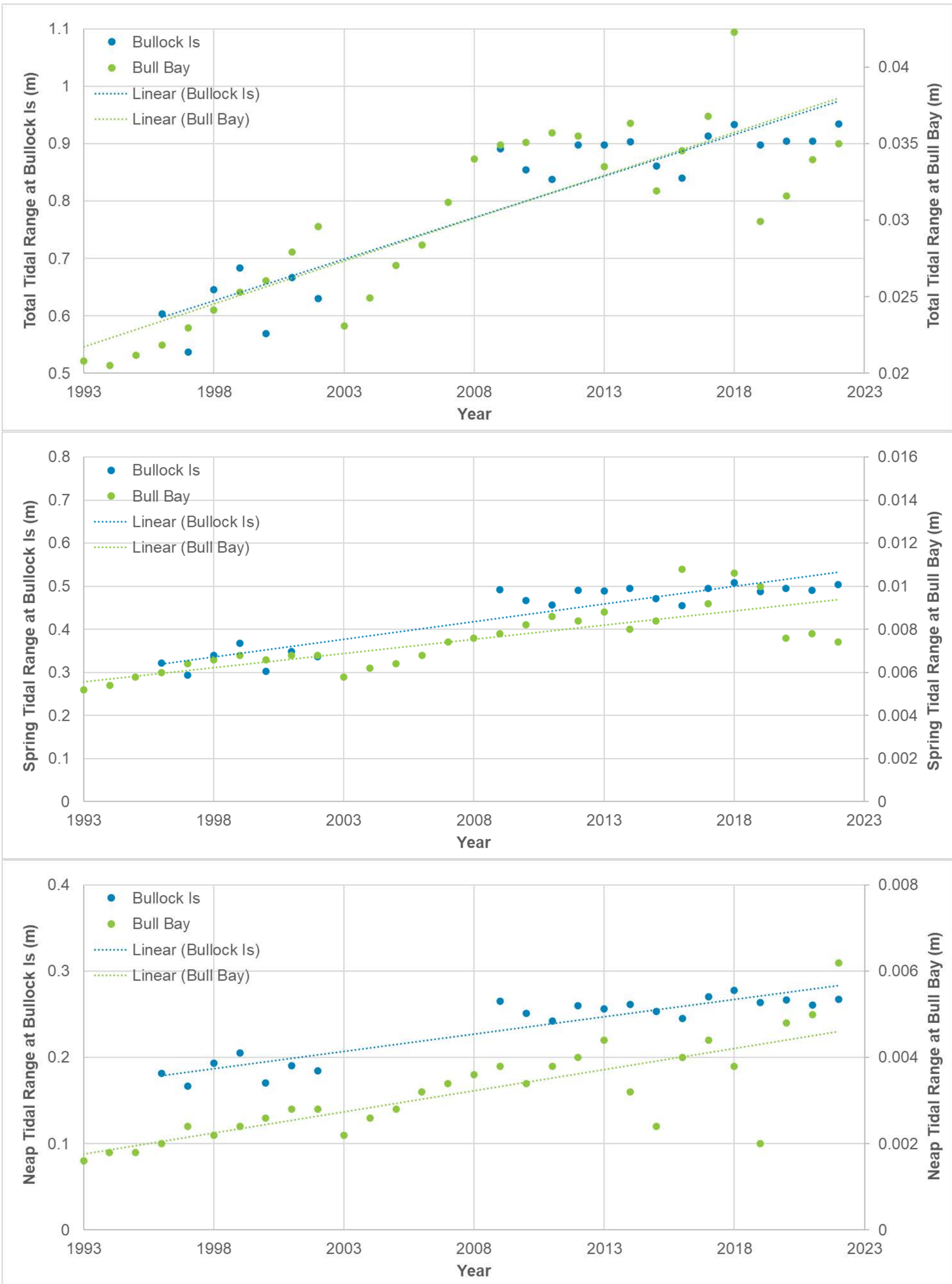


Figure 28. Total, spring and neap annual astronomical tidal range at Bullock Island and Bull Bay.

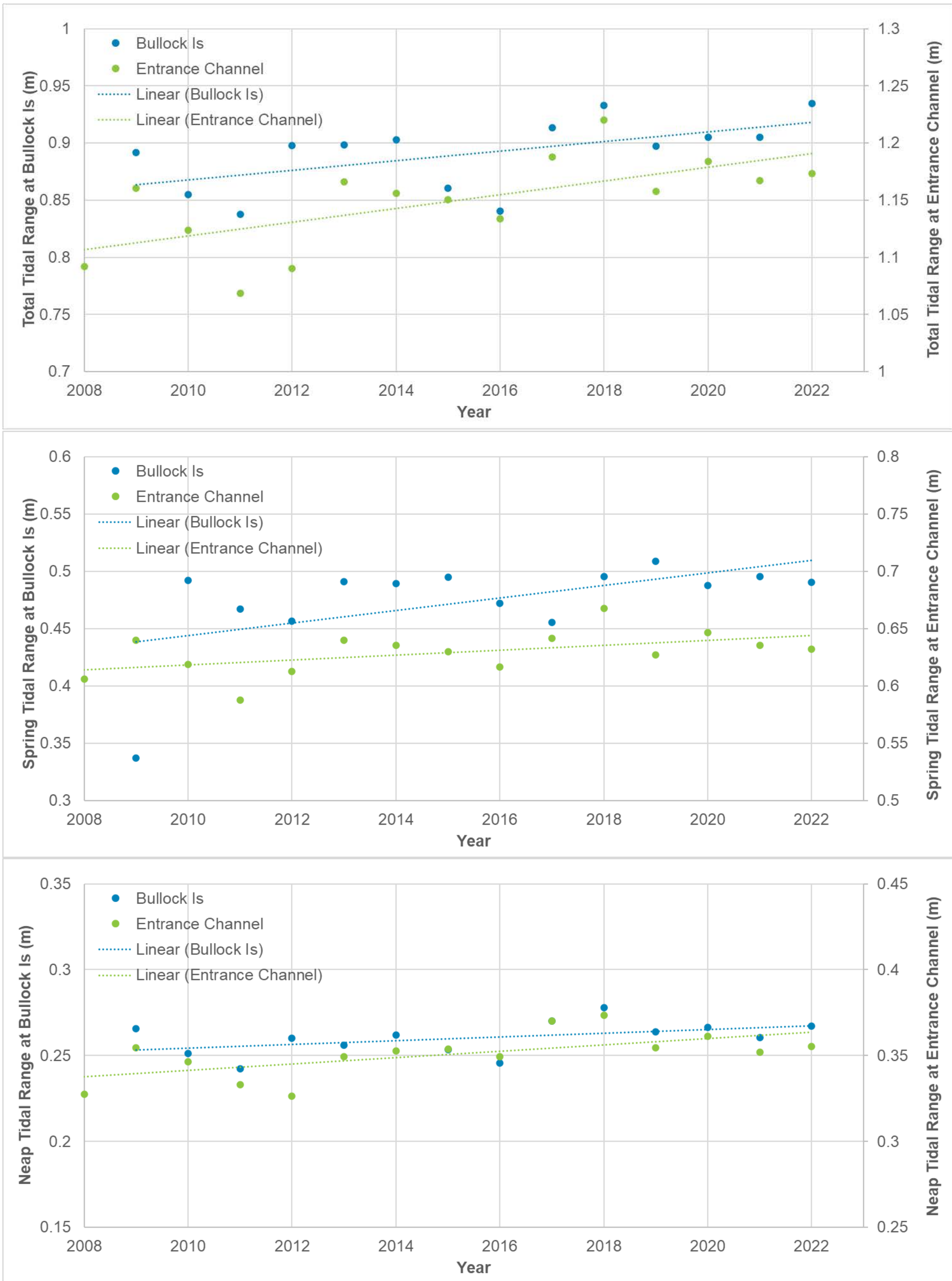


Figure 29. Total, spring and neap annual astronomical tidal range at Bullock Island and the Entrance Channel.

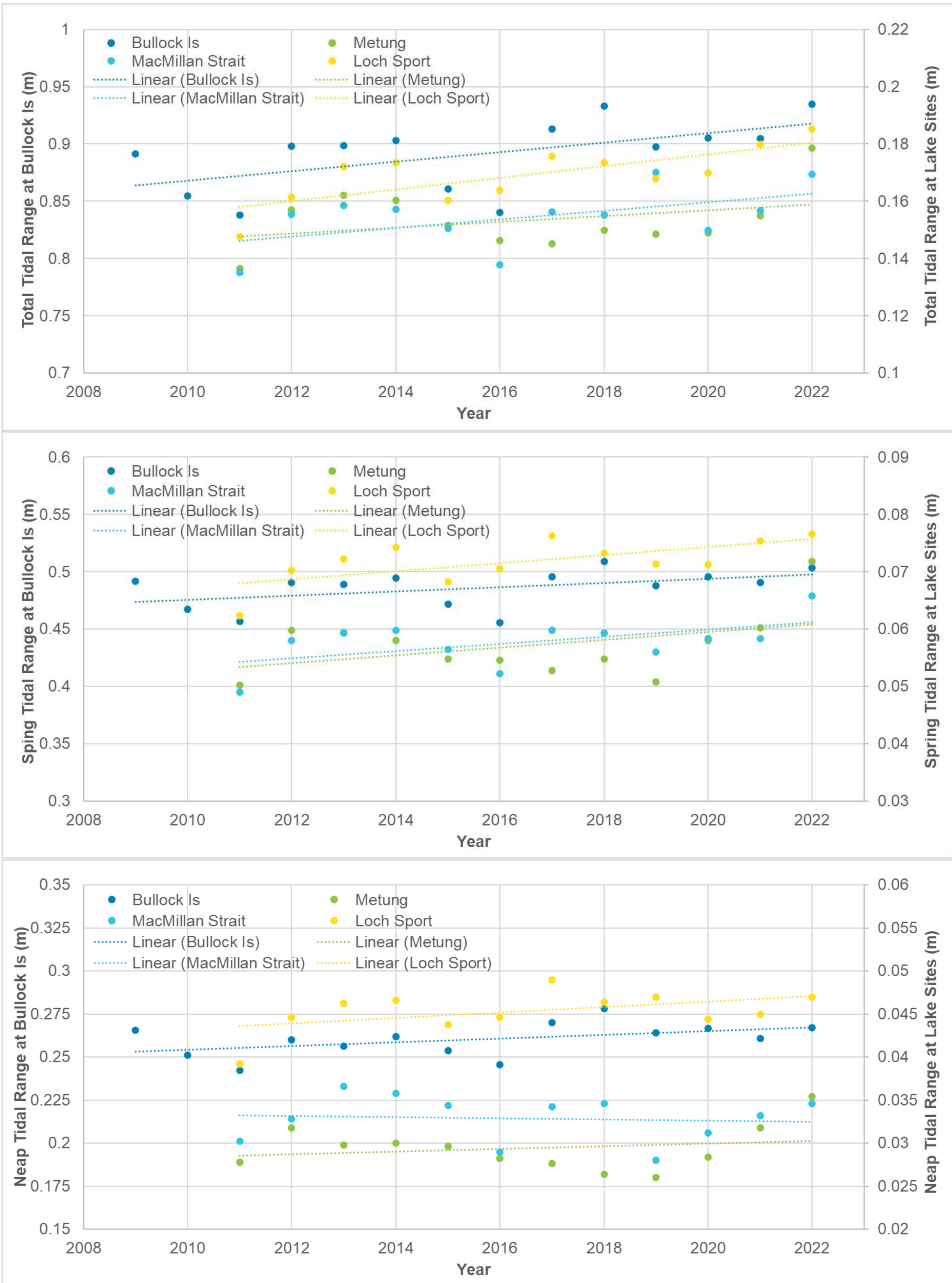


Figure 30. Total, spring and neap annual astronomical tidal range at Bullock Island, Metung, MacMillan Strait and Loch Sport.

3.4. Discussion

This assessment has shown an increasing tidal range in Gippsland Lakes over the last 30 years, with the rate of increase reducing since 2008. This also corresponds to the changes previously observed by Water Technology (2013). Further to the findings from Water Technology (2013), this assessment has used the annual changes in tidal range at Bull Bay to indicate the changes in tidal range at Bullock Island. Based on this, the change in tidal range which occurred from 2003 to 2008 appears to have been due to a gradual ongoing increase in tidal range over this period as opposed to a large jump which occurred over a single year. This suggests that the increase was not due to the change from using a side-cast dredge in 2007 to using a TSHD in 2008. To help try and understand what other processes could have influenced this increase in tidal range, the change in total tidal range has been plotted along with rainfall, Southern Oscillation Index (SOI) and dredge volumes in Figure 31. The plot shows the following:

- there is no correlation between the increase in tidal range and the annual rainfall in the Gippsland Lakes region. The tidal range data were also compared with the river discharge data and as with the rainfall data there was no direct correlation;
- the consistent increase in tidal range at Bull Bay which occurred from 1994 to 2002 and again from 2003 to 2008 coincides with periods of La Nina (sustained SOI above 7), El Nino (sustained SOI below -7) and Neutral SOIs, indicating that the increases are not due climatic variability due to El Nino Southern Oscillation; and
- there is no correlation between the total volume of sediment dredged at Lakes Entrance and the tidal range. However, since the volume of sediment dredged and the volume of sediment relocated (either to the offshore DMGs or the nearshore beach discharge points) has been similar (i.e. since 2008), the rate that the tidal range has been increasing has reduced. This could be a coincidence and due to natural processes, but it does also provide further evidence that the change in dredging approach since 2008 has not resulted in an increase in tidal range in the Lakes.

The results from this analysis have not identified a driver which is responsible for the gradual increase in tidal range which occurred from 1994 to 2002 and again from 2003 to 2008. It is therefore considered most likely that this gradual increase was a result of multiple factors, which could include natural processes (e.g. changes in the 18.6 year lunar nodal cycle and natural changes in bathymetry in the Lakes) and maintenance dredging.

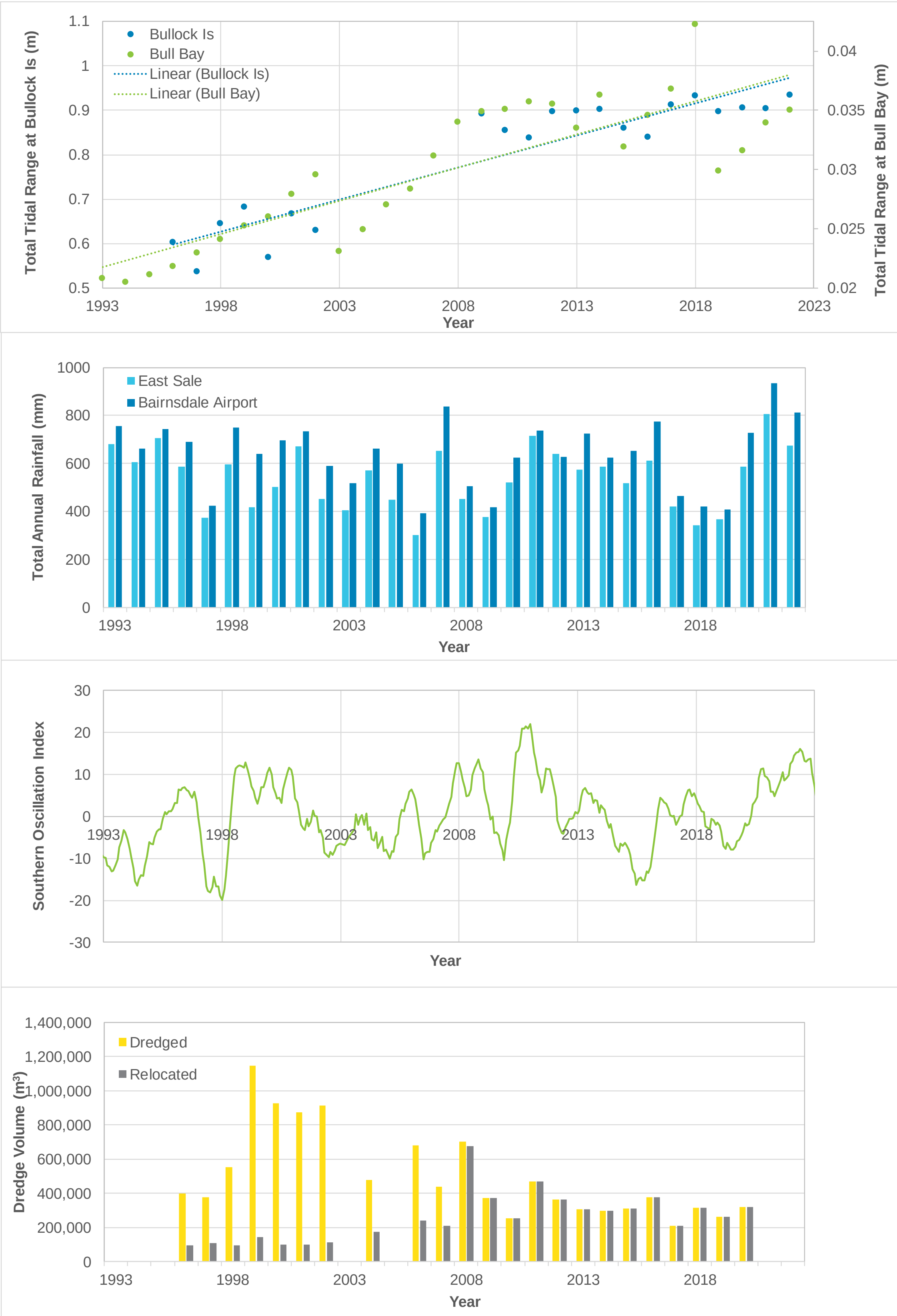


Figure 31. **Change in total tidal range from 1993 to 2023 (top) along with total annual rainfall (mid top), southern oscillation index (mid bottom) and Lakes Entrance dredge volumes (bottom).** *Note: the years with no dredging are due to missing data and not no dredging occurring.*

4. Numerical Model Setup

This section provides details of the setup, calibration and validation of the hydrodynamic model developed as part of this assessment.

PCS previously developed and calibrated a 2-Dimensional (2D) hydrodynamic model of Gippsland Lakes for GP to assess potential dredge design options for the GLOA Program (PCS, 2021b). The model was calibrated using measured water level and current data from the Entrance Channel and Bullock Island (just water level data). This 2D hydrodynamic model has been used as the initial basis for the 3D hydrodynamic model developed for this assessment.

4.1. Software

The numerical modelling has been undertaken using the MIKE software suite. The MIKE software has been developed by the Danish Hydraulics Institute (DHI) and is internationally recognised as state of the art and has been adopted by PCS, and others globally, in similar projects. The MIKE3 FM hydrodynamic (HD) module, which was developed for applications within oceanographic, coastal and estuarine environments, has been used for the hydrodynamic modelling. The module is based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. The model consists of continuity, momentum, temperature, salinity and density equations and is closed by a turbulent closure scheme. The spatial discretization of the equations is performed using a cell-centred finite volume approach (DHI, 2017).

4.2. Model Mesh

The flexible mesh (FM) version of MIKE has been adopted due to its ability to adjust the spatial resolution of the model mesh throughout the domain. This allows suitable model resolutions to be adopted throughout (i.e. higher resolution in areas of interest or areas with narrow channels and lower resolution in the offshore areas away from areas of interest) which ensures model efficiency so that simulation times are not compromised by the model resolution.

The model mesh extends over the Gippsland Lakes including Lakes Wellington, King and Victoria and offshore of the Entrance Channel a distance of approximately 3.7 km, to water depths of around 45 m AHD (Figure 32). The mesh resolution is coarsest in the offshore areas, with the triangular element lengths of around 700 m. The highest resolution is in the Entrance Channel at Lakes Entrance with element lengths of 25 m (Figure 33), while in McLennans Strait the element lengths were approximately 70 m (Figure 34).

The model is run in 3-Dimensional (3D) mode, with 5 equally spaced layers in the vertical, each accounting for 20% of the water column depth. The sigma layer approach is adopted which means that the thickness of layers varies with water depth (both spatially and temporally).

4.3. Bathymetry

The model bathymetry was developed using bathymetric surveys of the Bar, Entrance Channel, Inner Channels and other areas of the Lakes undertaken by GP. For the offshore areas, the GP survey data for the DMG's was combined with the Geosciences Australia 'Australian Bathymetry and Topography Grid' (Whiteway, 2009), which combines available survey data to provide a gridded bathymetric dataset on a 9 arc second grid (equivalent to approximately 200 m x 250 m at Gippsland).

The model calibration and validation periods cover two separate 12 month periods (2017 and 2021 calendar years). Two different model bathymetries were therefore developed based on the January/February 2021 survey data of the Bar, Entrance Channel and Inner Channels and the January/February 2017 survey data of these areas (repeat surveys of other areas of the Gippsland Lakes were not available). This approach ensures that the bathymetry around Lakes Entrance is representative for the periods that the model is calibrated and validated.

To represent the bathymetry for the impact modelling, the most recent available bathymetry for the Bar, Entrance Channel and Inner Channels (June 2023) has been used. Further details of how the bathymetry is represented for the two modelled scenarios is provided below:

- Existing Case: this represents the existing approved dredge footprint. For this, the bathymetry from June 2023 was adopted for the Bar, Entrance Channel and Inner Channels and in any areas where the bathymetry was shallower than the approved dredge depths (detailed in Table 1) the model depth was changed to the dredge depth. In areas where the bathymetry was already deeper than the dredge depth (e.g. at the southern ends of the Entrance Channel and Bar) the June 2023 depth was adopted. The model mesh and bathymetry for this Existing Case is shown in Figure 36; and
- Future Case: this represents the proposed future dredge footprint. For this, the Existing Case bathymetry was adopted and then the bathymetry in the proposed future dredge footprint was changed to the dredge depths (as detailed in Section 1.1). The model mesh and bathymetry for this Future Case is shown in Figure 37. Comparison with the bathymetry for the Existing Case shows that the largest change in bathymetry due to the future dredging is the western extension of Hopetoun Channel.

4.4. Boundaries

Hydrodynamic boundary conditions for the three offshore boundaries were developed based on the measured water levels from the gauge at the Entrance Channel. To allow just the astronomical tidal forcing to be represented at the offshore boundaries, a harmonic analysis of the water level boundary conditions has been undertaken and the resultant harmonic constituents used to predict water levels which just represent the astronomical tidal forcing.

River discharges have also been included for the major rivers within the Gippsland Lakes. The river discharges were represented in the model as point source freshwater inflows for the Latrobe River (including the Thompson and Macalister Rivers), Avon River, Mitchell River, Tambo River and Nicholson River. The river discharge data were sourced from the DEECA monitoring stations for the various rivers.

4.5. Meteorological Conditions

The hydrodynamic model was also setup to include the influences of the wind, rainfall and evaporation to ensure that their potential influence on the water levels and salinity in the Gippsland Lakes were represented. Further details on these are provided below:

- Wind: measured wind data collected by GP at the Eastern Breakwater was adopted in the model;
- Rainfall: measured half hourly rainfall data from the BoM weather station at Bairnsdale Airport was used to represent the rainfall input direct to the Gippsland Lakes; and
- Evaporation: measured daily evaporation data from the BoM weather station at Bairnsdale was the only measured evaporation data available in the region from 2016 to 2023 (data at East Sale was available up to January 2015) and so was used to represent the evaporation from the Gippsland Lakes.

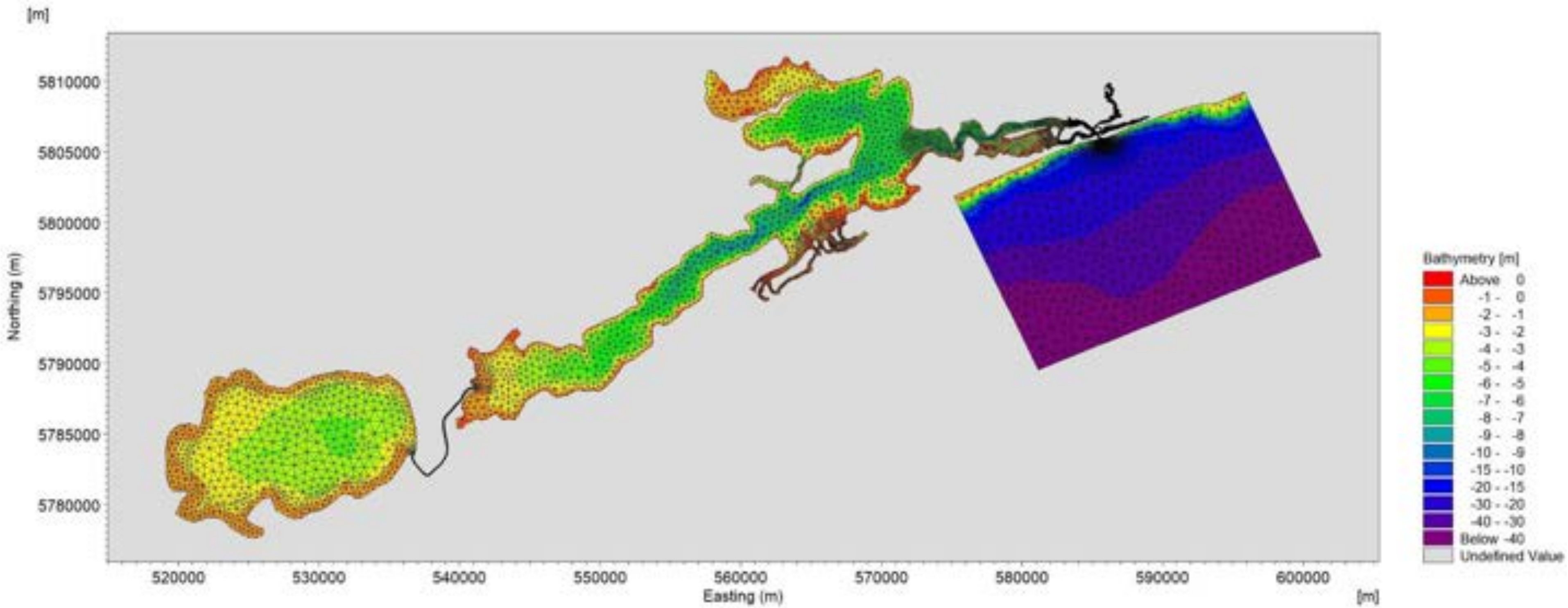


Figure 32. Model mesh and bathymetry for the Gippsland Lakes model.

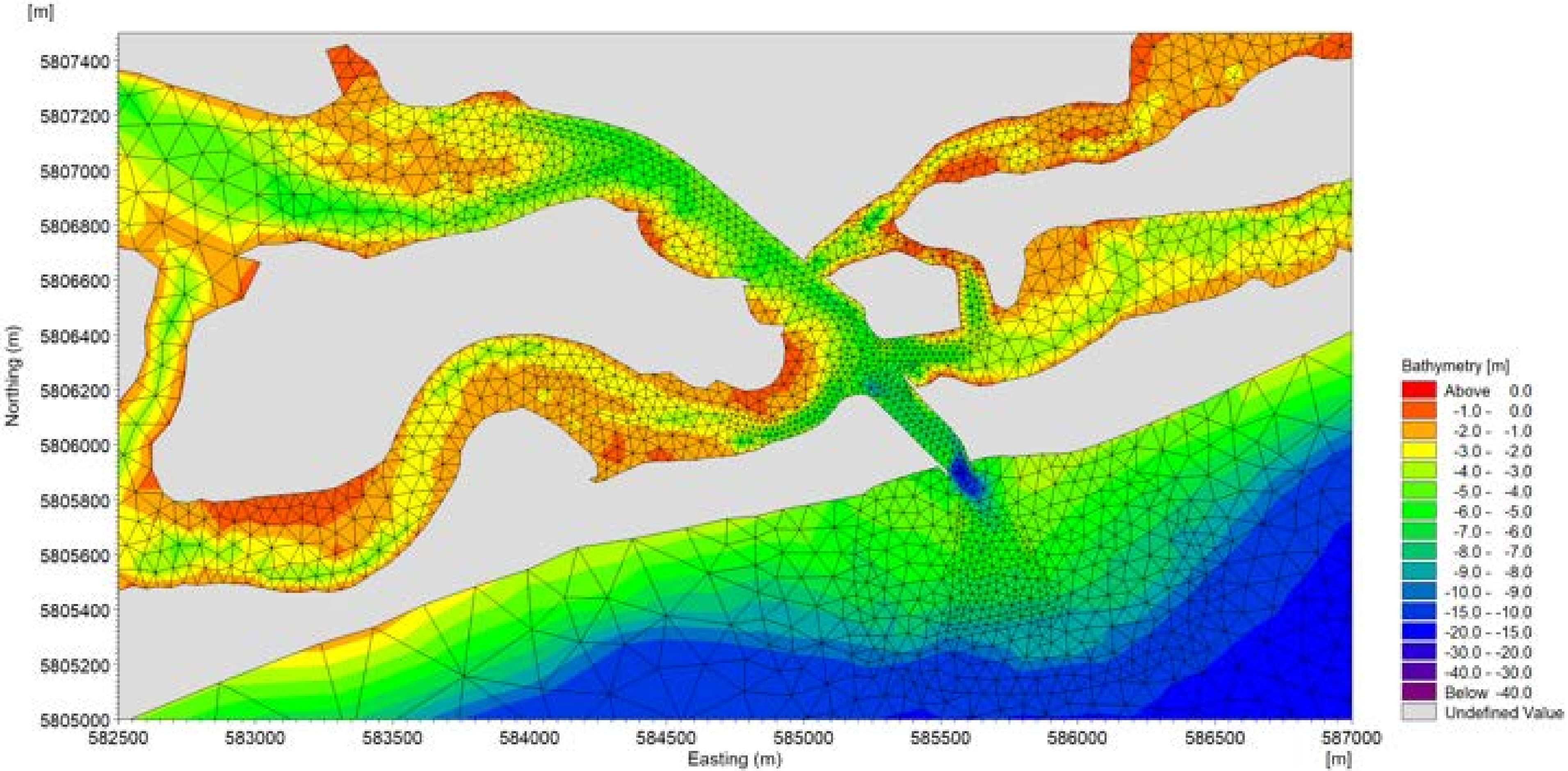


Figure 33. Close up of the model mesh and 2023 bathymetry at Lakes Entrance.

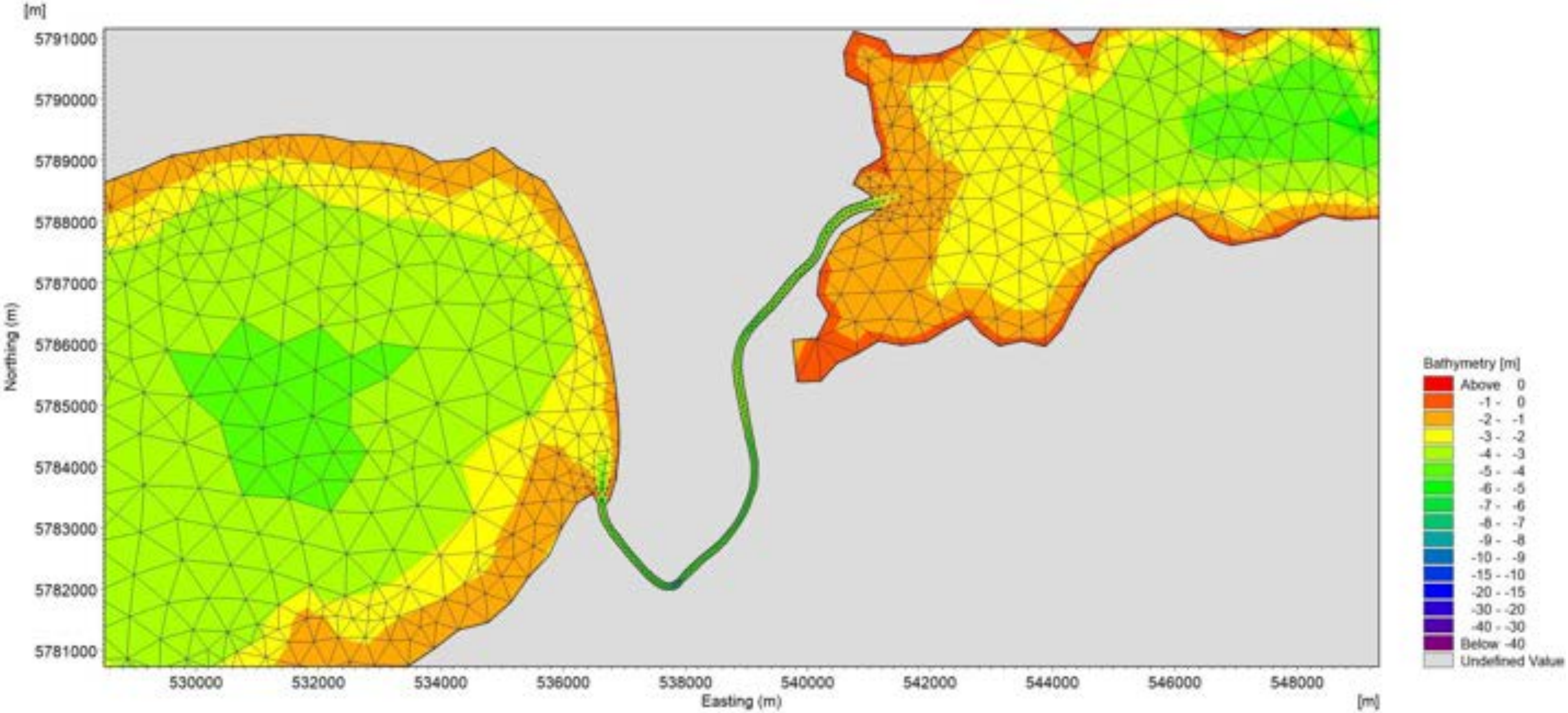


Figure 34. Close up of the model mesh and bathymetry at McLennans Strait.

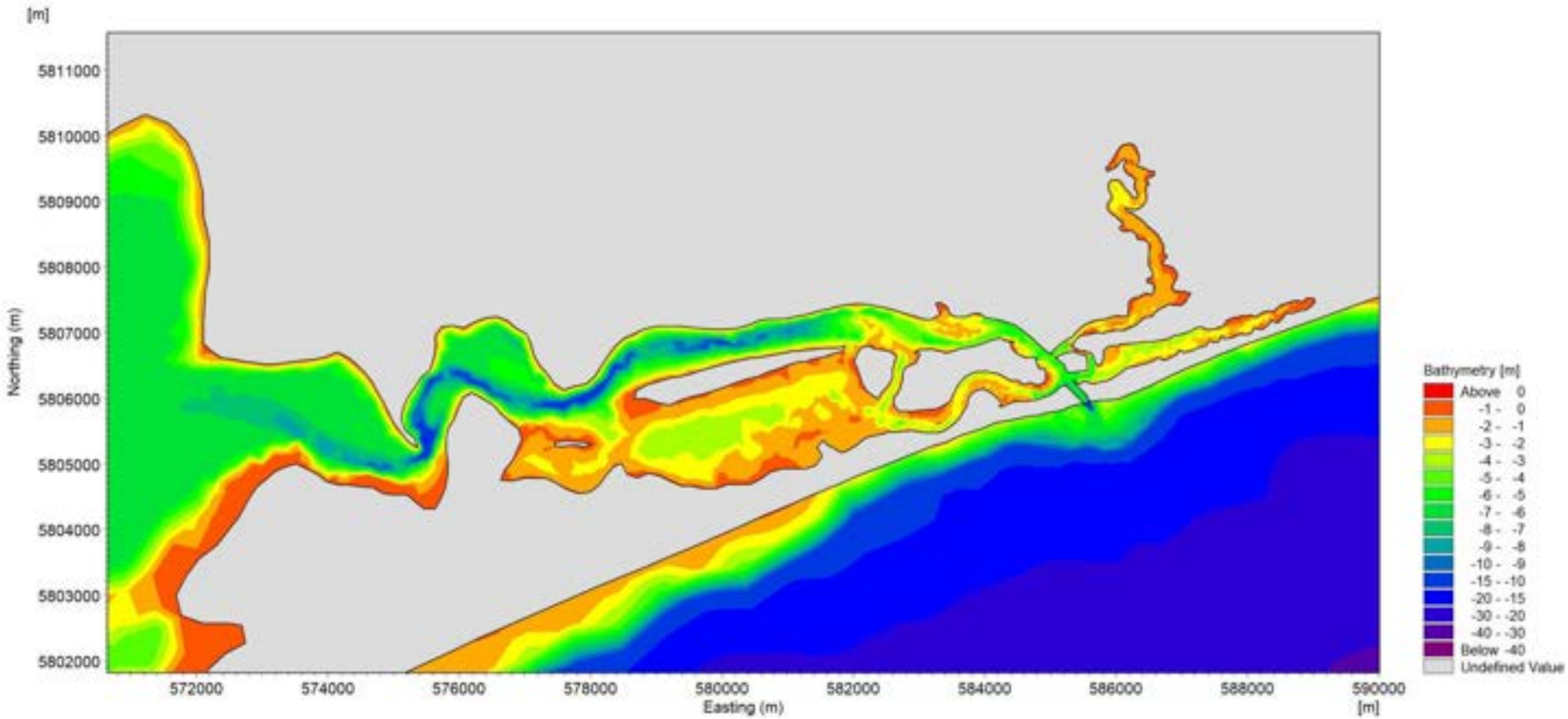


Figure 35. Close up of the model bathymetry around Lakes Entrance.

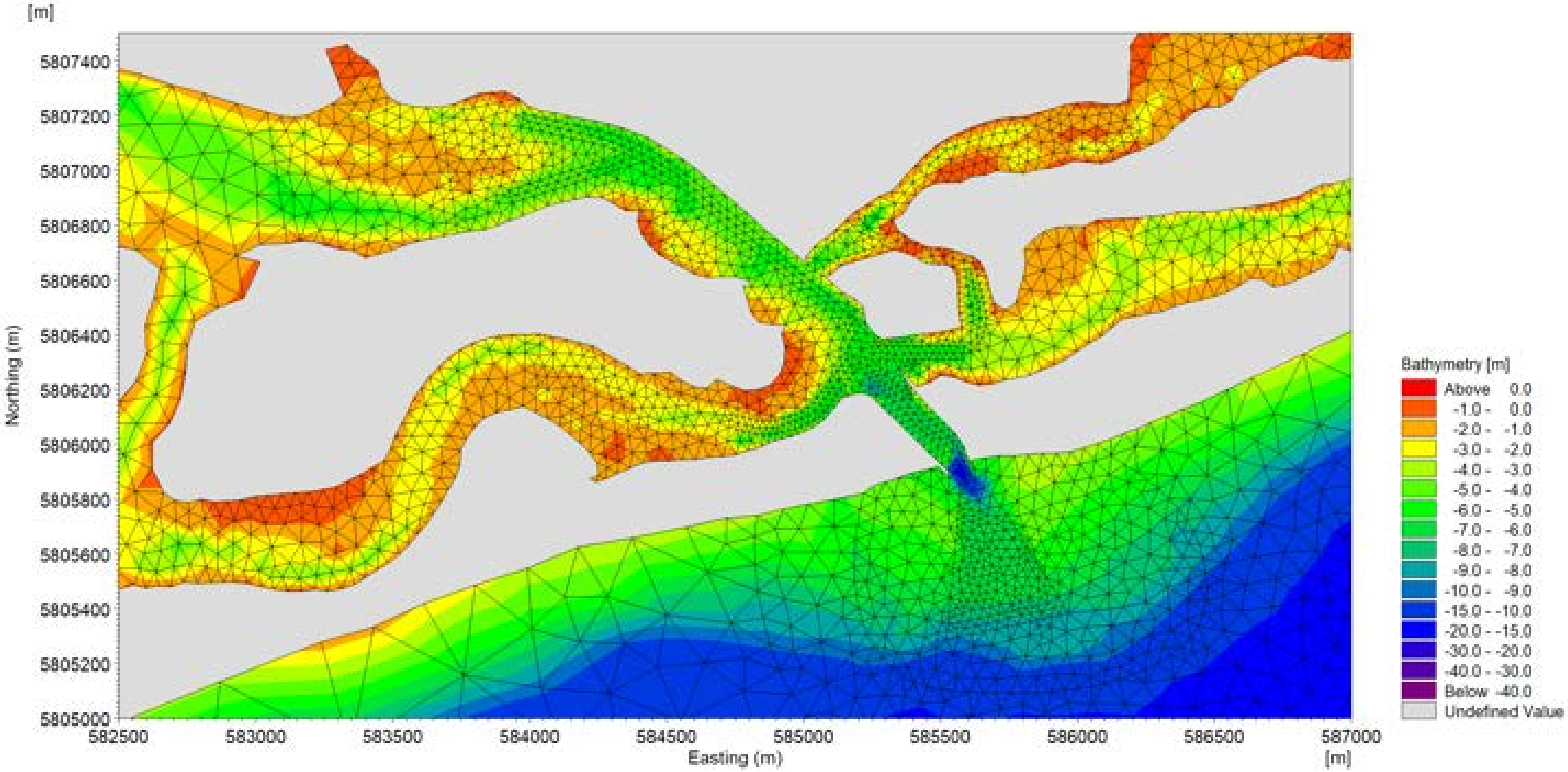


Figure 36. **Close up of the model mesh and bathymetry around Lakes Entrance for the 2023 Design Depth bathymetry (Existing Case).**

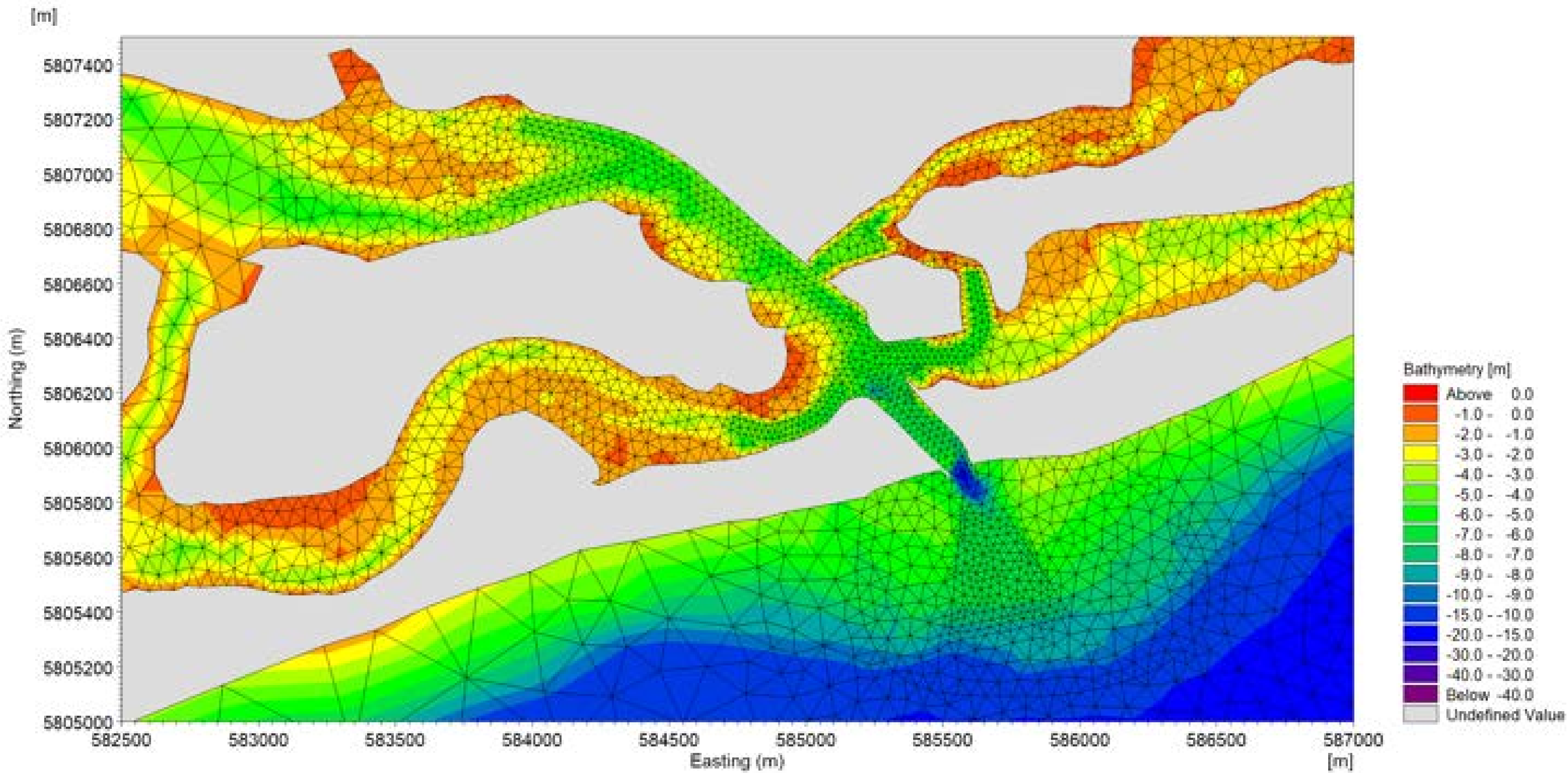


Figure 37. Close up of the model mesh and bathymetry around Lakes Entrance for the 2023 Future Dredge bathymetry (Future Case).

4.6. Calibration and Validation

The model calibration and validation are presented in Appendix A. Modelled water levels, currents and salinity have been compared with measured data over the following periods:

- calibration period: January to December 2021. These 12 months represent a period with significant variability in salinity due to high river discharges into Gippsland Lakes; and
- validation period: January to December 2017. These 12 months represent a period with relatively low river discharge into Gippsland Lakes and so are representative of different conditions to the calibration period.

The model calibration and validation is presented in Appendix A. Overall, the comparison between the measured and modelled data has demonstrated the following:

- the model can be considered to provide a good representation of the measured water levels at both the tidal dominant sites (Entrance Channel and Bullock Island) and the sites within the Lakes;
- the model is able to provide a good representation of the current speed and direction in the Entrance Channel;
- the calibration and validation of the currents and water levels at the Entrance Channel provides confidence that the model is able to accurately represent the tidal prism for the Gippsland Lakes;
- the model is able to represent changes in the salinity in the Gippsland Lakes spatially (in the horizontal and vertical) and temporally; and
- the calibration and validation periods covered different conditions and have shown that the model is able to represent the changes in salinity in the Gippsland Lakes resulting from river discharge, rainfall, saline intrusion through the Entrance Channel and evaporation processes.

4.7. Simulation Periods

This assessment is aimed at showing the potential impacts of the proposed dredging at Lakes Entrance on the astronomical tide, water levels and salinity within the Gippsland Lakes. To allow this, the numerical model will setup to simulate the following:

- Astronomical Forcing: offshore forcing due to just the astronomical tide, with no offshore storm surge included. The model is setup to simulate this over 12 months during 2017, this period is representative of relatively low river discharge and rainfall inputs. The results from the simulation are used to show how the proposed future dredging influences the following:
  - variations in water level due to astronomical tide (and other processes within the Gippsland Lakes); and
  - variations in salinity due to the astronomical tide (and other processes within the Gippsland Lakes).
- Surge and Freshwater Forcing: offshore forcing due to the astronomical tide and offshore storm surges along with high freshwater inputs into the Gippsland Lakes. The model is setup to simulate this over 12 months during 2021, this period is representative of high freshwater inputs to the Gippsland Lakes. From January to the end of May 2021 is representative of low freshwater inputs with offshore storm surges and astronomical tides being dominant driver for water levels at Lakes Entrance. The period from June to December 2021 is representative of high freshwater inputs when a combination of offshore storm surges, astronomical tides and freshwater discharge from Gippsland Lakes all influence the water levels at Lakes Entrance. The results from the simulation are used to show how the proposed future dredging influences the following:

- water level variation due to elevated ocean levels from Bass Strait storm surges (and other processes within the Gippsland Lakes); and
- salinity due to elevated ocean levels from Bass Strait storm surges (and other processes within the Gippsland Lakes).

5. Model Results

The results from the model simulations have been processed and are presented in the following sections. The following results from the existing condition simulations are presented to show the existing variability in water level and salinity within the Gippsland Lakes:

- spatial maps showing statistical values (minimum, maximum and percentiles (5th, median and 95th)) of the modelled water level and salinity over the 12 month simulations;
- spatial maps showing the maximum and 90th percentile range in water level and salinity over the 12 months (i.e. maximum water level minus minimum water level and 95th percentile minus 5th percentile); and
- long section from Lake Wellington to offshore of the Entrance Channel showing salinity through the water column at specific times.

To show how the proposed future dredging impacts the water levels and salinity in the Gippsland Lakes the following plots are presented:

- spatial maps showing the change in the statistical values (minimum, maximum and percentiles (5th, median and 95th)) of the modelled water level and salinity over the 12 month simulations due to the proposed future dredging;
- spatial maps showing the change in maximum and 90th percentile range in water level and salinity over the 12 months due to the proposed future dredging; and
- time series plots of water level and salinity for the existing and future dredging cases as well as the difference between the two at the EPA and DEECA monitoring sites.

The spatial map plots are all shown for the following three different spatial extents to allow the full spatial extent to be seen as well as more detailed representation of all the Lakes:

- All Lakes;
- Lakes Entrance, Lake King and eastern Lake Victoria; and
- Western Lake Victoria and Lake Wellington.

For the difference plots the results from the existing case have been taken away from the future dredged case (i.e. future dredged – existing). Therefore, a positive change in water level or salinity shows that the future proposed dredging is predicted to result in an increase in water level or salinity and the opposite for a negative change.

5.1. Existing Conditions

Select plots from the existing case simulations of the Gippsland Lakes are presented in the following sub-sections. A full set of all the plots detailed in the previous section is provided in Appendix B.

5.1.1. Water Levels

Spatial map plots showing the maximum and minimum water levels over the 12 month simulation for the astronomical forcing simulation (2017) are shown in Figure 38 and Figure 39, while the maximum water level range over this period is shown in Figure 40.

The plots clearly show how the offshore maximum water level, minimum water level and maximum tidal range is restricted within the Gippsland Lakes. The minimum water level experiences the largest variation from offshore to within the Lakes, with the offshore minimum water level increasing from less than -0.5 m AHD to more than -0.1 m AHD for all lakes upstream of Metung.

The maximum water level range over the 12 months highlights the restriction in water level range within the Lakes, with maximum water level range at the western end of Rigby Island being approximately half of the maximum offshore water level range. The maximum water level range within the majority of Lake King, Lake Victoria and Lake Wellington is less than 0.4 m.

Spatial map plots showing the maximum and minimum water levels over the 12 month simulation for the surge and freshwater forcing (2021) are shown in Figure 41 and Figure 42, while the maximum water level range over this period is shown in Figure 43. Comparison between the maximum and minimum water levels predicted for the surge and freshwater forcing simulation compared to the astronomical forcing simulation shows that the maximum water levels within the Gippsland Lakes increased from less than 0.5 m AHD to between 0.75 to 1 m AHD, while there was only a small reduction in the minimum water levels. The plot of the maximum water level range over the surge and freshwater forcing simulation shows that all of the Lakes Entrance region had a maximum range of more than 1.1 m, compared to a maximum range which was below 1 m for the astronomical forcing simulation. The maximum range in water level within Lake King and Lake Victoria increased from less than 0.4 m for the astronomical forcing simulation to more than 0.9 m for the surge and freshwater forcing simulation. Within Lake Wellington the maximum range in water level increased from less than 0.4 m for the astronomical forcing simulation to more than 0.8 m for the surge and freshwater forcing simulation. The dominant driver for these higher maximum water levels within the Gippsland Lakes will have been predominantly a result of the very high freshwater discharge from the rivers in the Gippsland Lakes as opposed to the offshore storm surge.

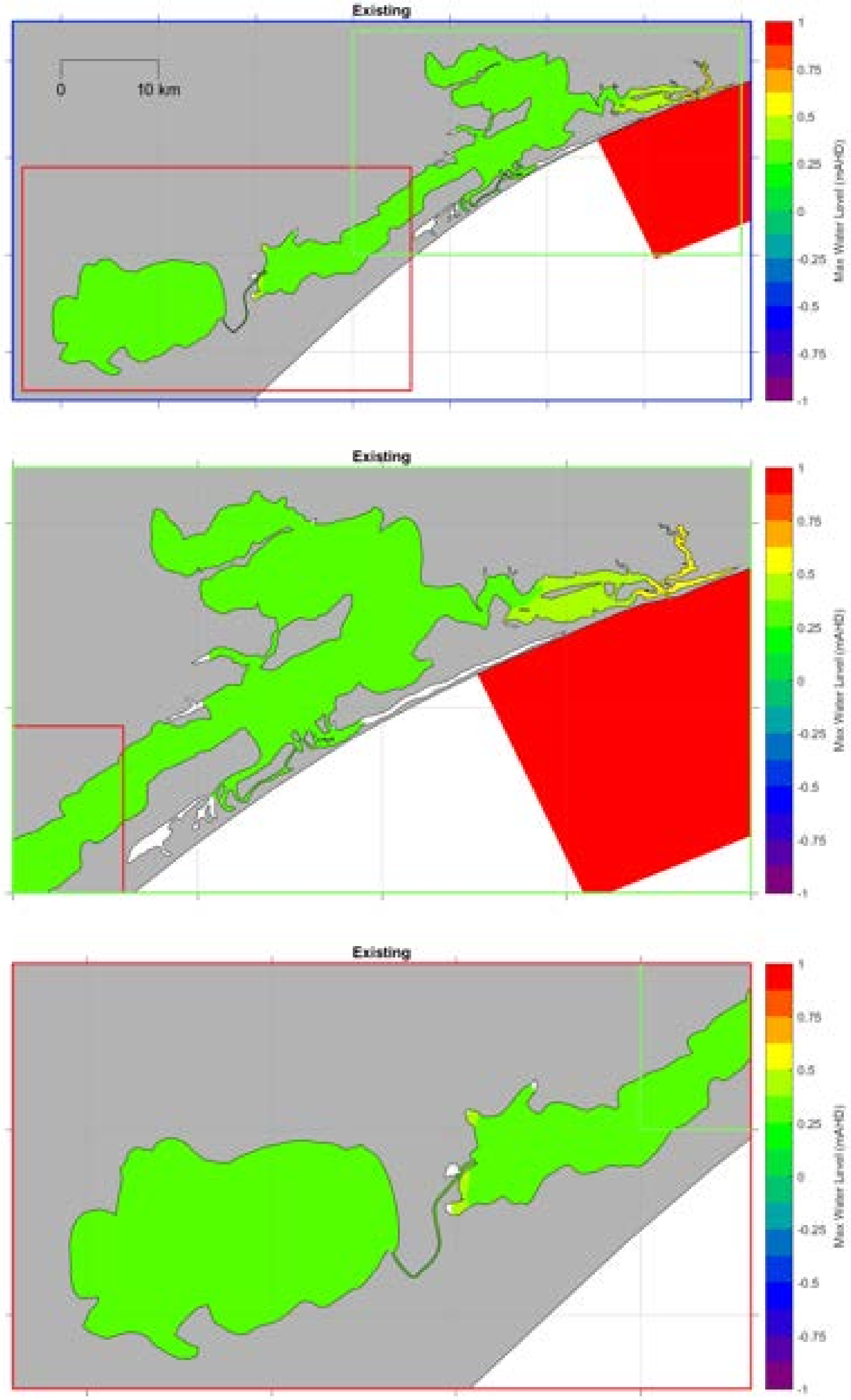


Figure 38. Modelled maximum water level over 12 months with astronomical forcing.

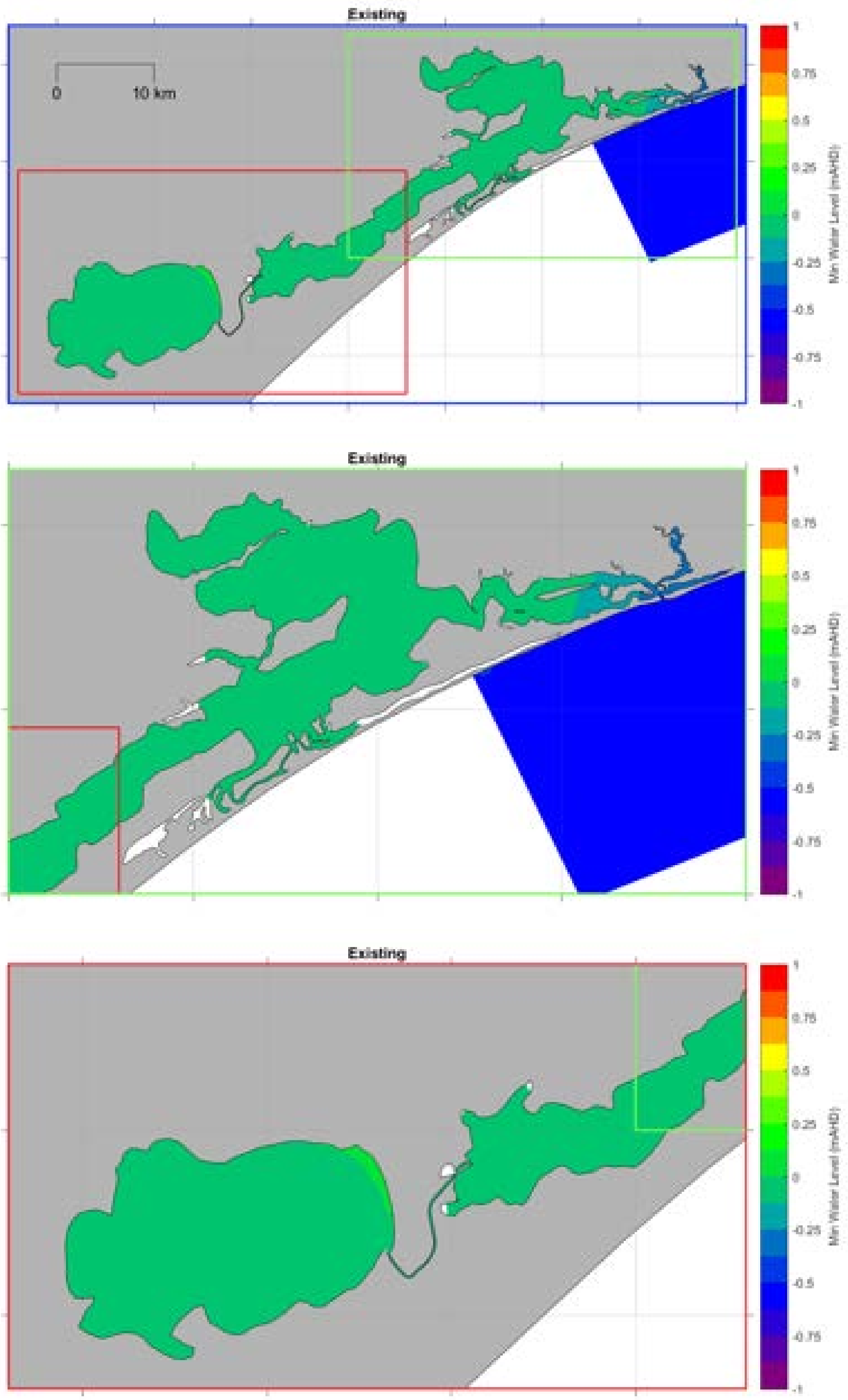


Figure 39. Modelled minimum water level over 12 months with astronomical forcing.

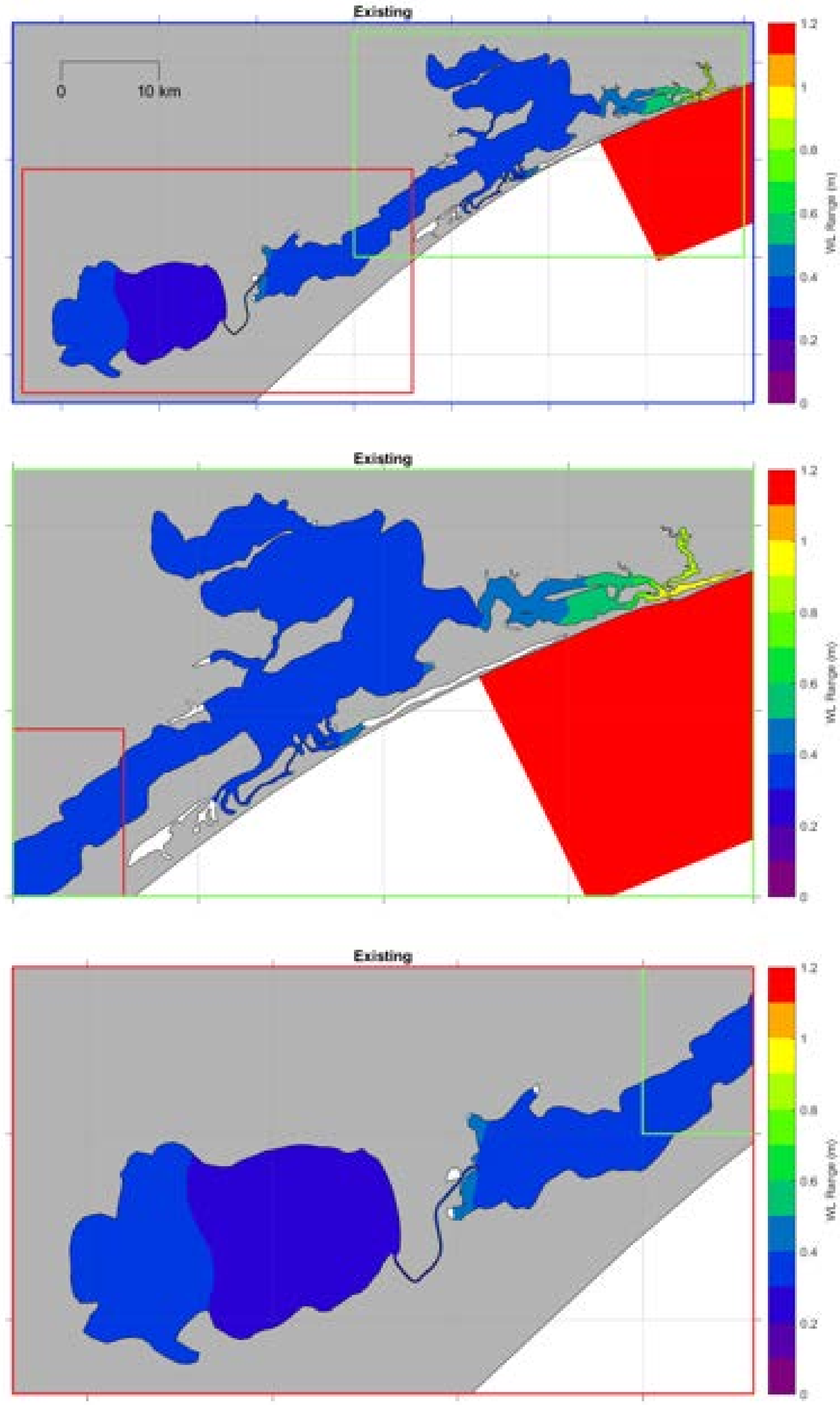


Figure 40. Modelled maximum range in water level over 12 months with astronomical forcing.

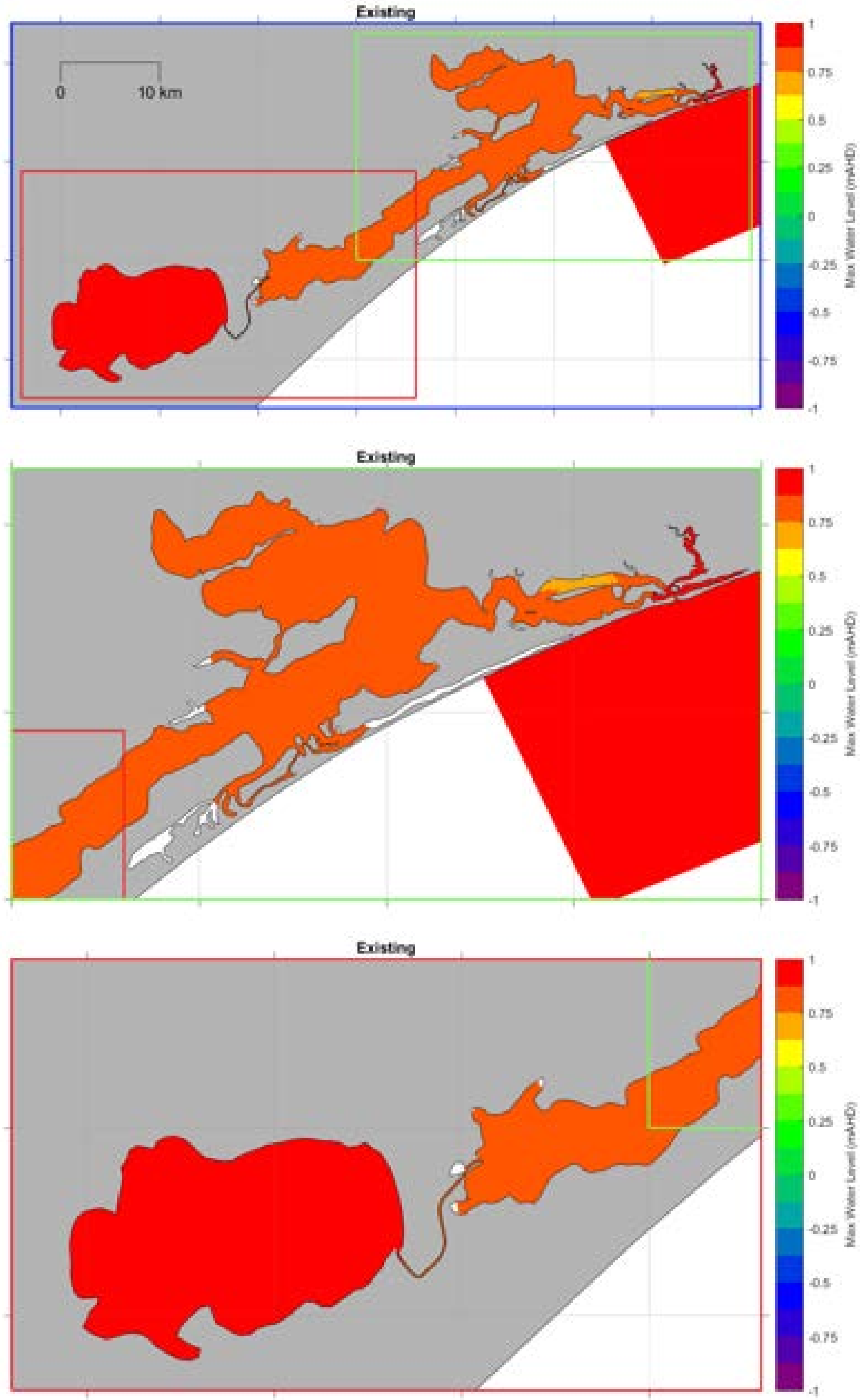


Figure 41. Modelled maximum water level over 12 months with surge and freshwater forcing.

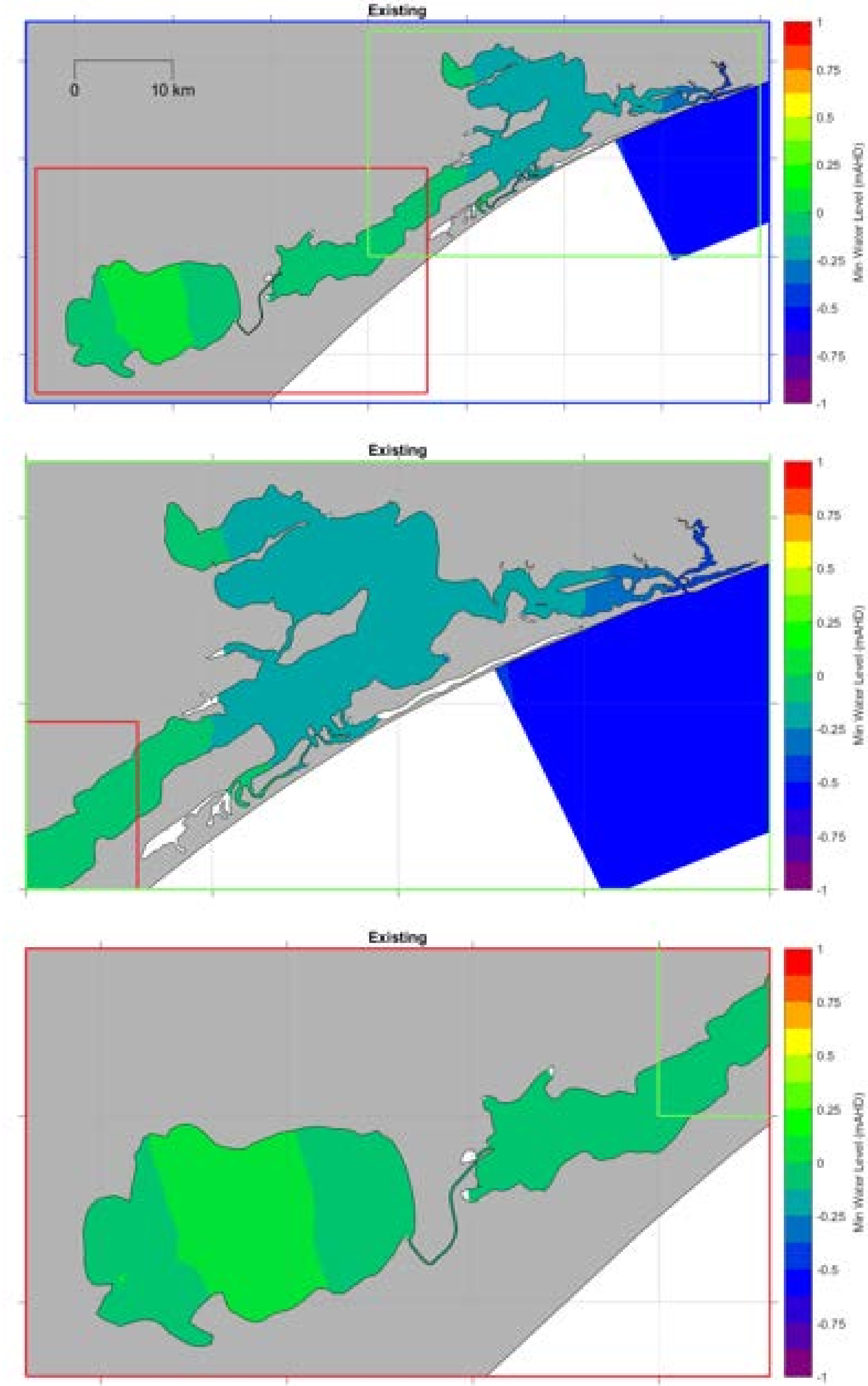


Figure 42. Modelled minimum water level over 12 months with surge and freshwater forcing.

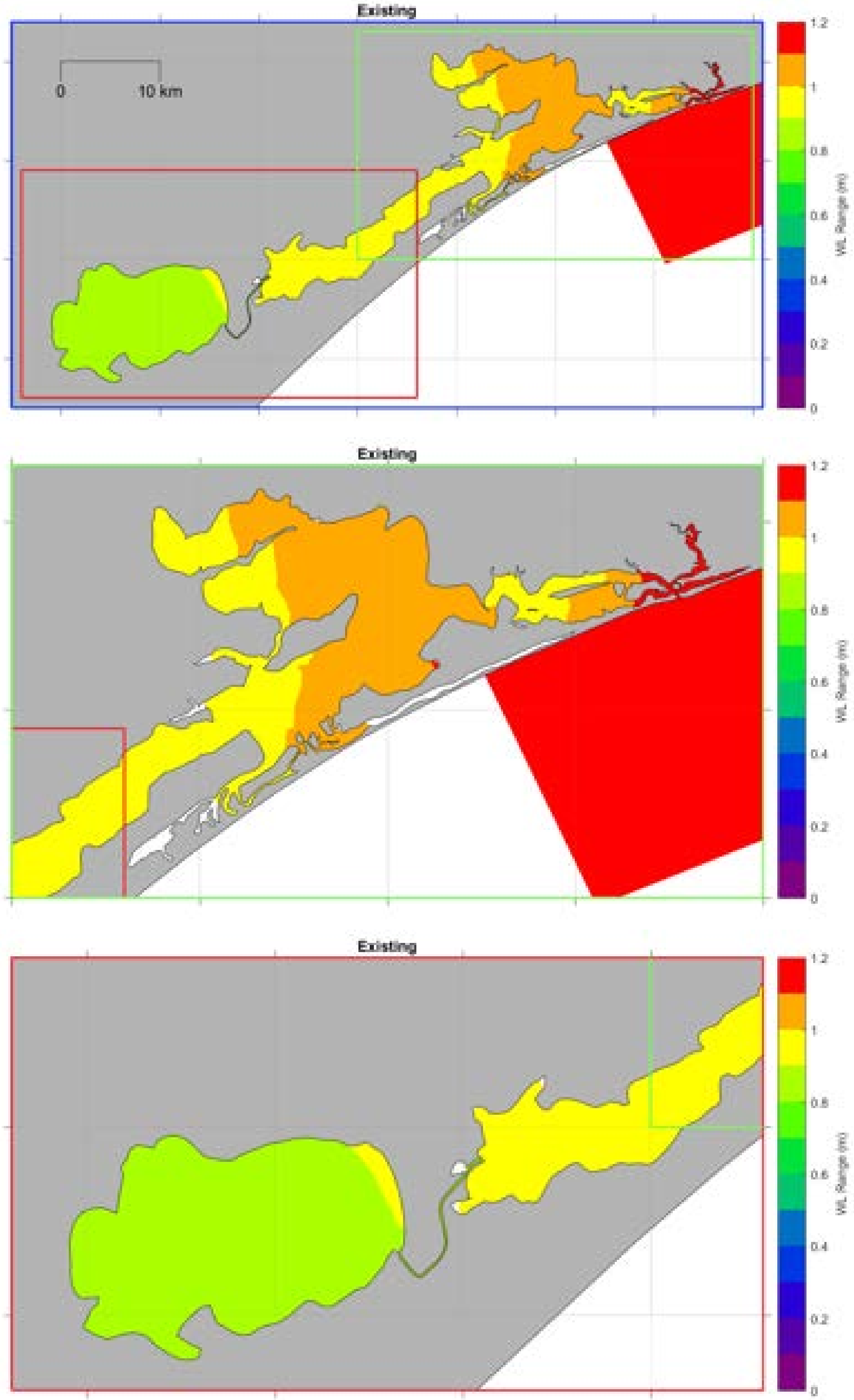


Figure 43. Modelled maximum range in water level over 12 months with surge and freshwater forcing.

5.1.2. Salinity

The spatial patterns and magnitudes of salinity in the surface and the bed layers of the model for the statistics presented are similar and so only the surface layer results are presented in this main section of the report as these show slightly more variability compared to the bed layer. Plots showing the salinity in the bed layer of the model are included in Appendix B.

The maximum surface salinity over the 12 month astronomical forcing simulation is shown in Figure 44 while the corresponding plot for the surge and freshwater forcing is shown in Figure 45. The plots show the following:

- for both simulations there is a gradual reduction in surface salinity from the Entrance Channel, where the maximum salinity was above 32.5 psu, to Lake Wellington where the maximum salinity was mainly 10 to 15 psu (salinity of more than 20 psu in the area adjacent McLennan’s Strait);
- the maximum surface salinity in Lake King was between 25 and 30 psu, while in Lake Victoria it was between 22.5 and 27.5 psu; and
- the largest difference in maximum salinity between the two simulations is an area with salinity of more than 30 psu extending upstream of Metung into Lake King for the simulation with surge and freshwater forcing, while this area has a maximum salinity below 30 psu for the simulation with astronomical forcing.

The minimum surface salinity over the 12 month simulations with astronomical forcing and surge and freshwater forcing are shown in Figure 46 and Figure 47, respectively. In addition, the maximum range in salinity over the two 12 month simulations are shown in Figure 48 and Figure 49. The plots show the following:

- for the simulation with the astronomical forcing and low freshwater input the areas with a salinity of less than 10 psu are limited to where major rivers discharge into the lakes, namely Lake Wellington and the northernmost region of Lake King. The remaining areas of the Gippsland Lakes are mainly between 15 and 25 psu;
- almost all of the Gippsland Lakes are below 10 psu for the simulation with the surge and freshwater forcing (only the northern end of North Arm is above), with the reduced salinity also extending up to 10 km offshore of the Entrance Channel. The significantly lower salinity in this simulation is primarily due to the higher freshwater inputs into the Gippsland Lakes during this simulation compared to the astronomical forcing simulation which has relatively low freshwater inputs; and
- the maximum range in salinity is significantly larger for the surge and freshwater forcing simulation compared to the astronomical forcing simulation. For the latter simulation the range was less than 10 psu throughout the Gippsland Lakes except for the northernmost region of Lake King where it was more than 20 psu and within McLennan’s Strait where it was up to 15 psu. In contrast, for the surge and freshwater forcing simulation the maximum range in salinity was between 20 and 30 psu for Lake King and Lake Victoria and between 10 and 20 psu for Lake Wellington.

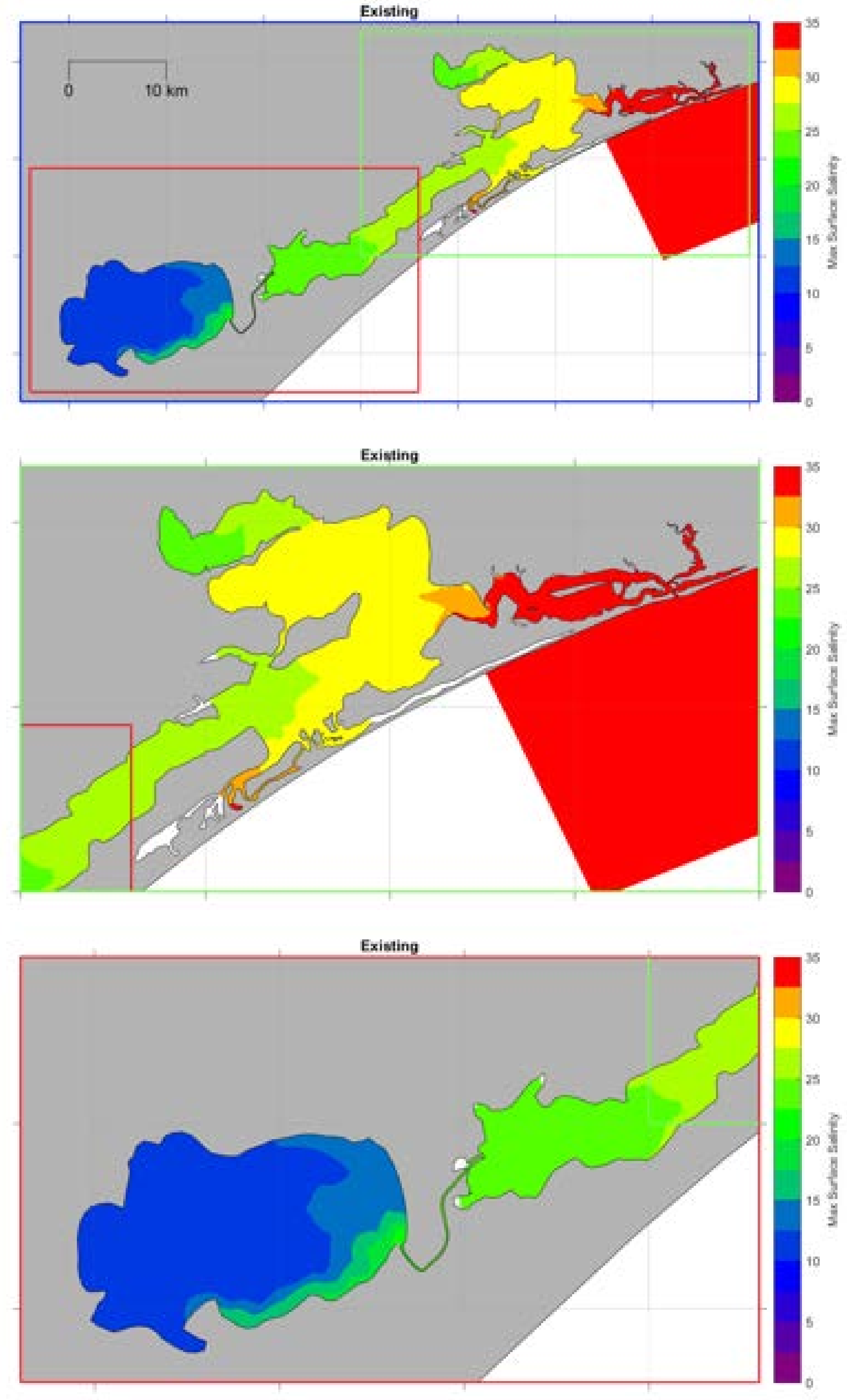


Figure 44. Modelled maximum surface salinity over 12 months with astronomical forcing.

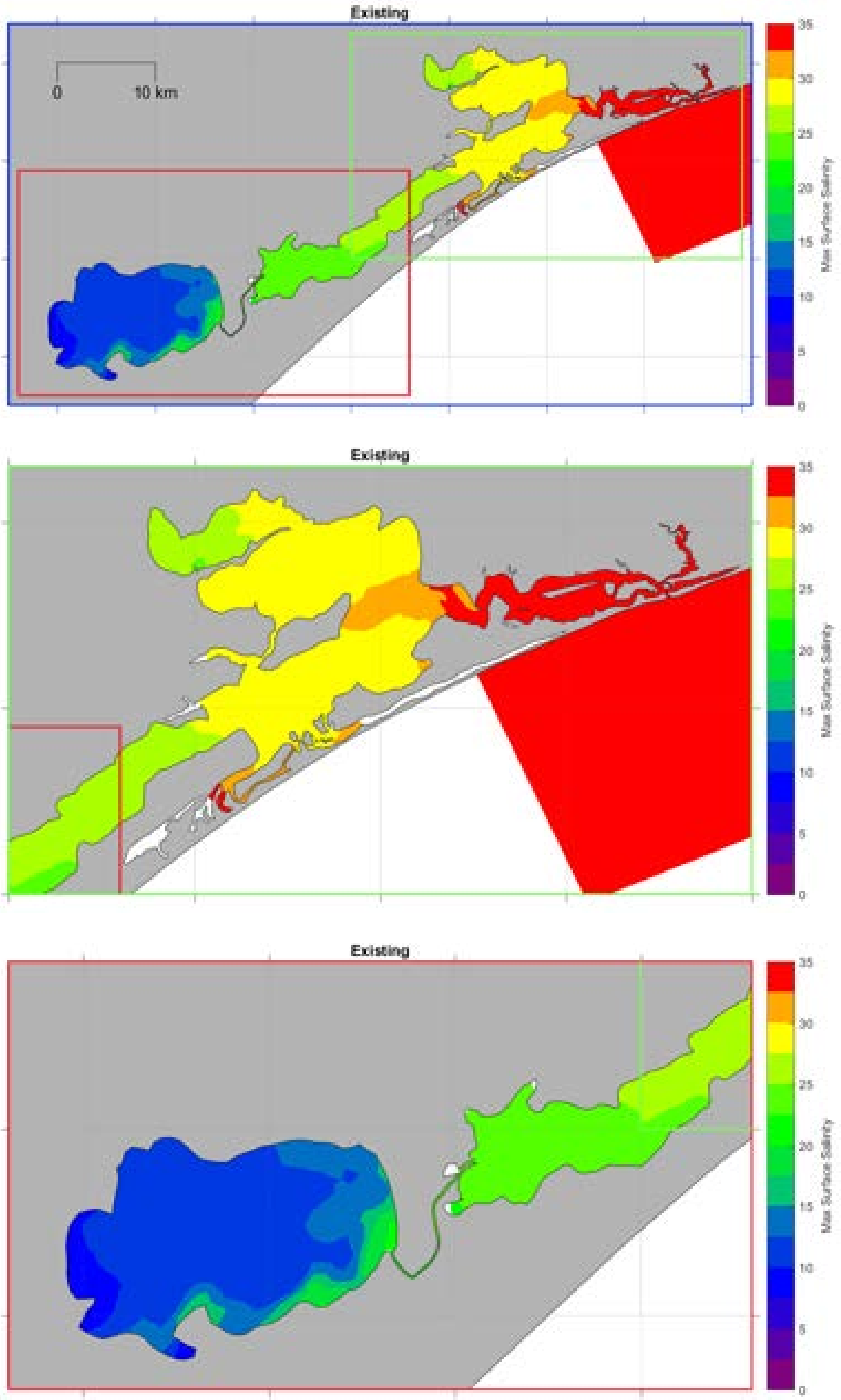


Figure 45. Modelled maximum surface salinity over 12 months with surge and freshwater forcing.

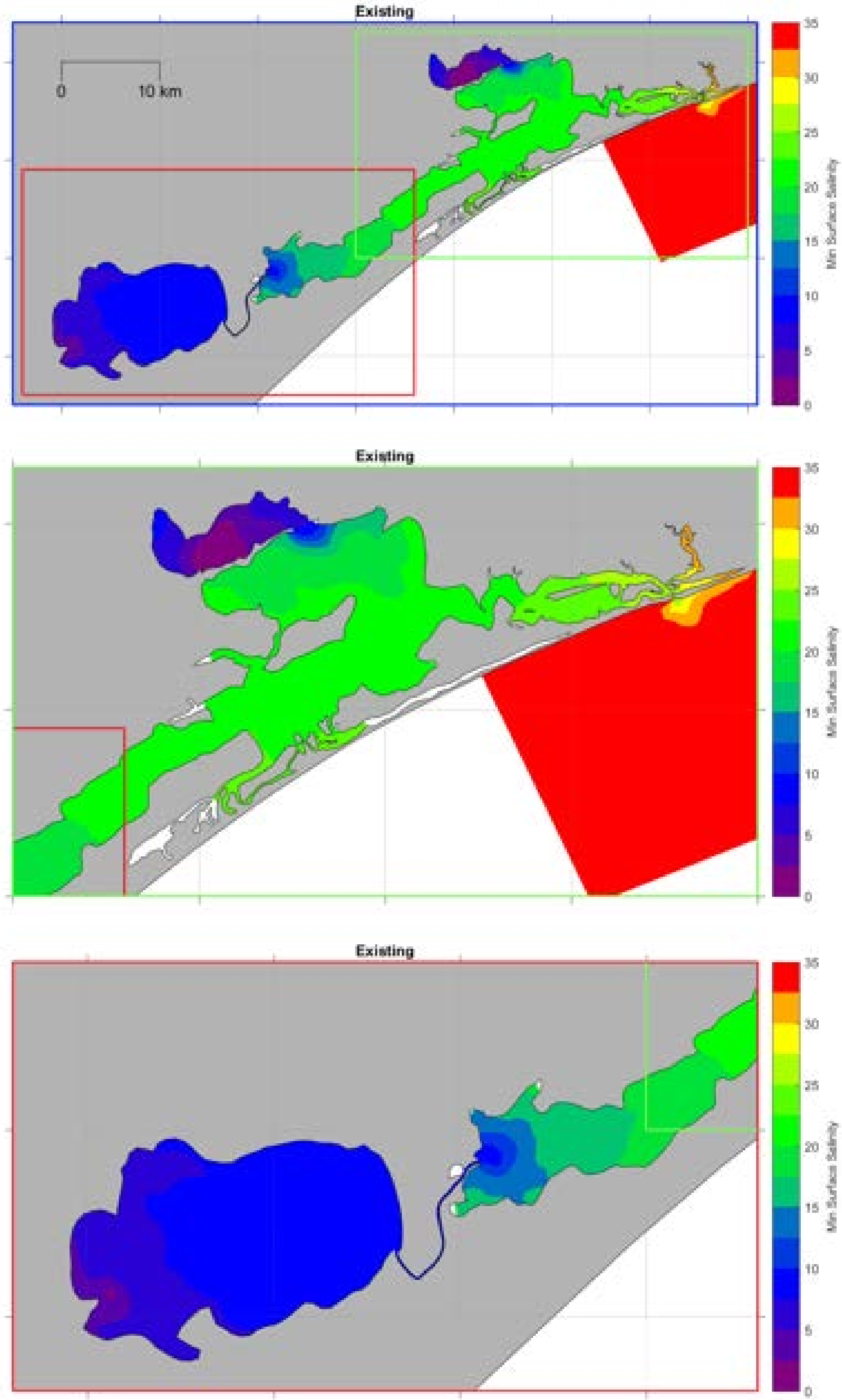


Figure 46. Modelled minimum surface salinity over 12 months with astronomical forcing.

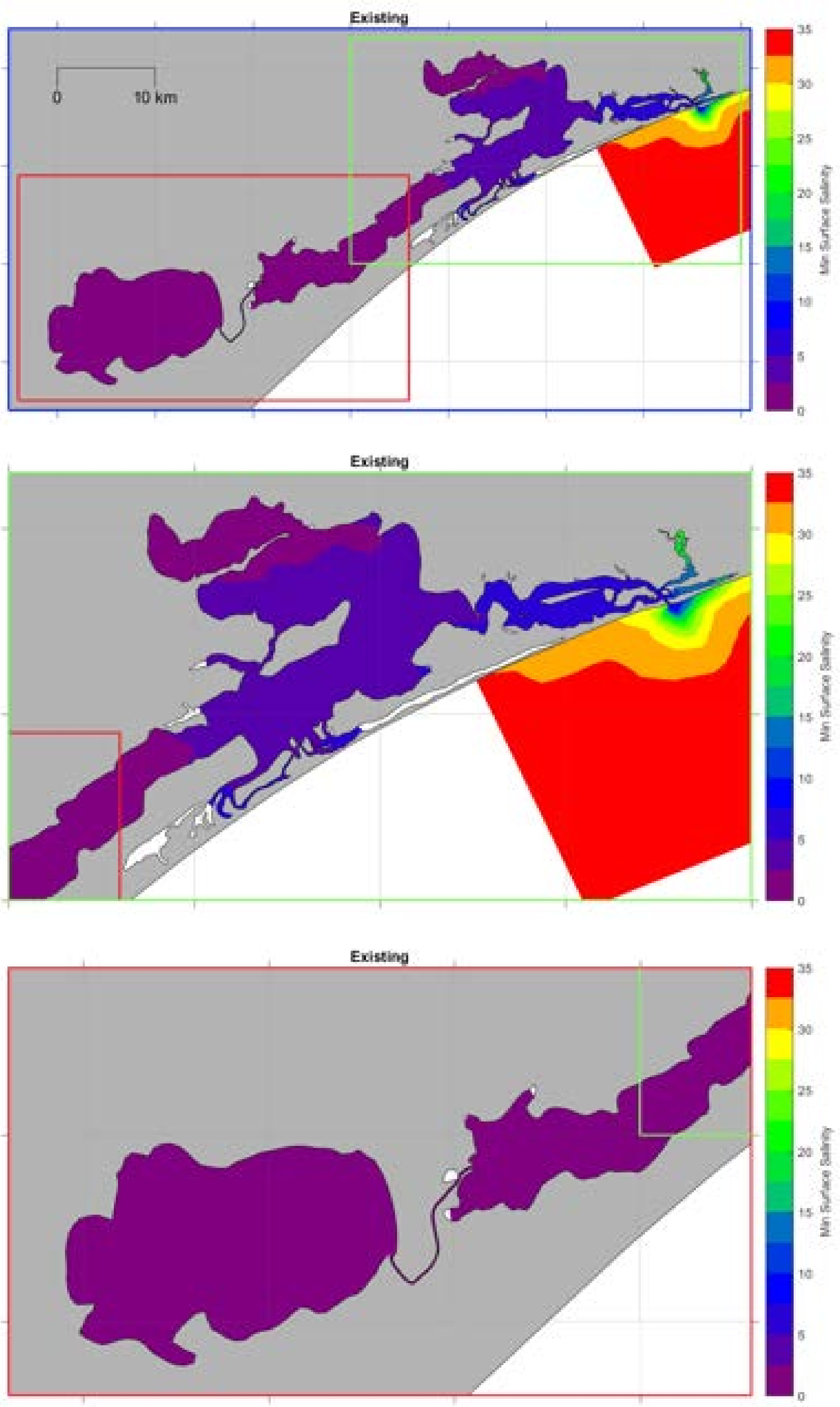


Figure 47. Modelled minimum surface salinity over 12 months with surge and freshwater forcing.

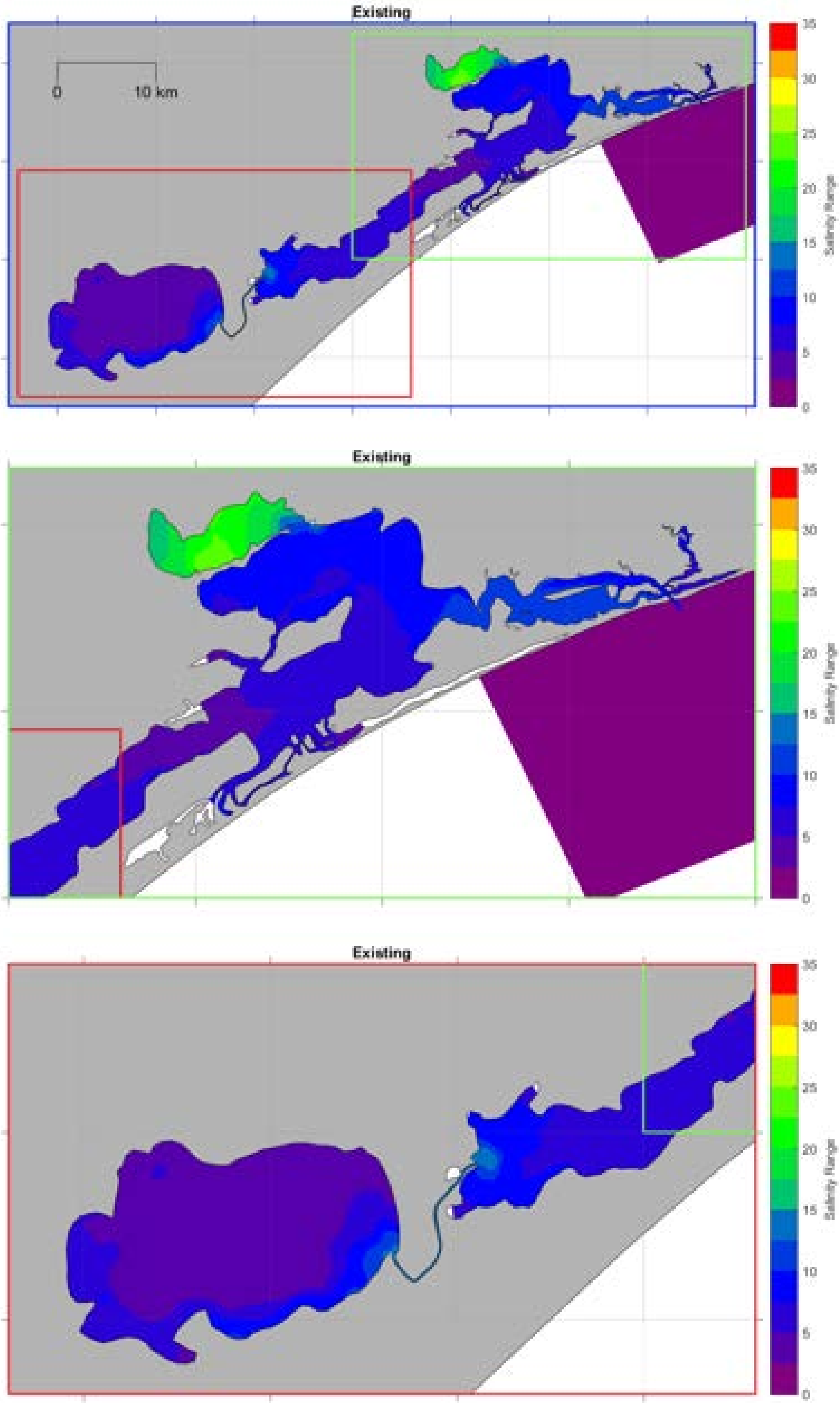


Figure 48. Modelled maximum range in surface salinity over 12 months with astronomical forcing.

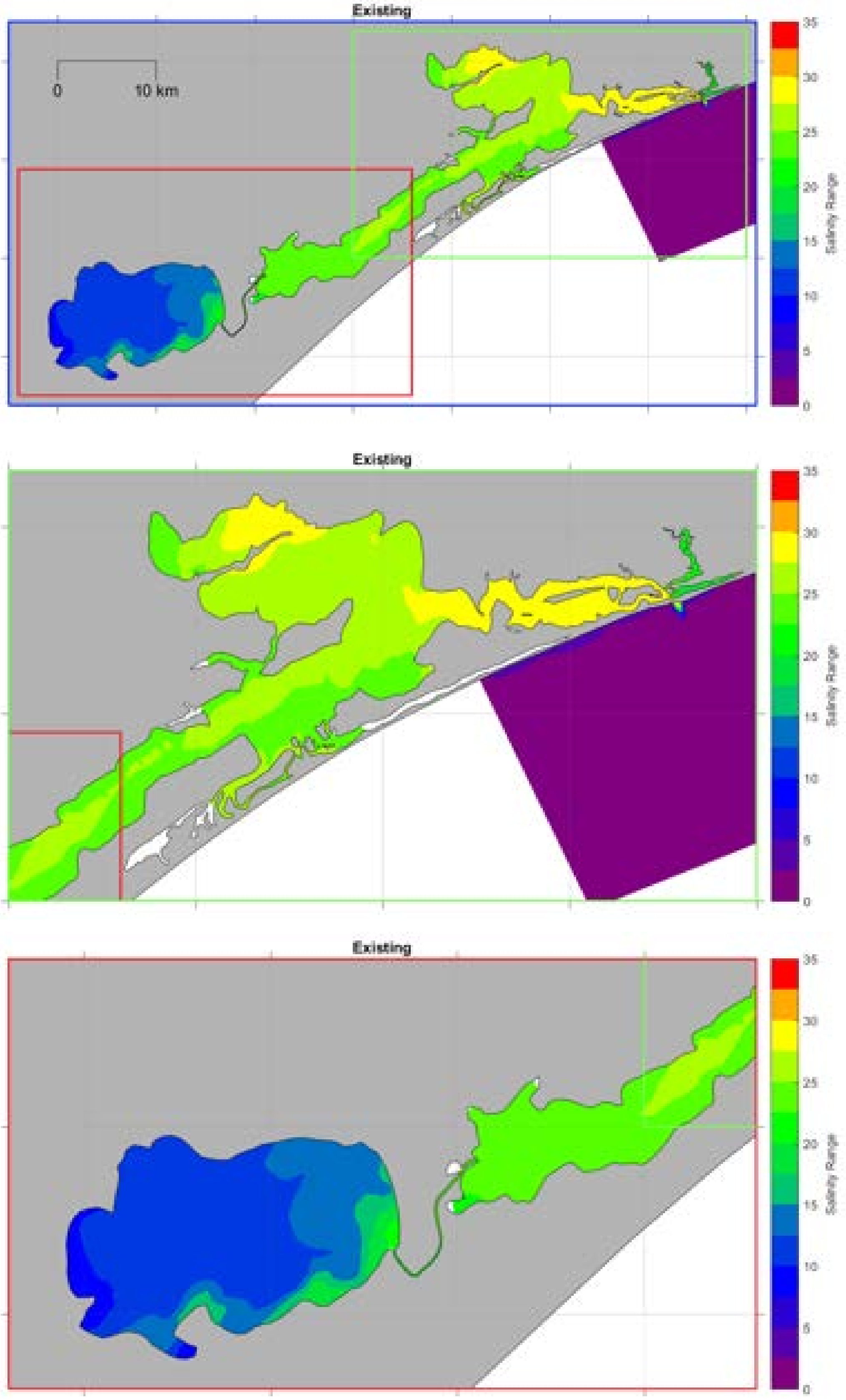


Figure 49. Modelled maximum range in surface salinity over 12 months with surge and freshwater forcing.

To demonstrate how the salinity within Gippsland Lakes can vary over time, the modelled instantaneous salinity through the water column is shown for a long section extending from the western end of Lake Wellington to offshore of the Entrance Channel (Figure 50). Plots of the salinity are shown at varying times for the surge and freshwater forcing simulation in Figure 51 to Figure 54. Details of the plots are provided below:

- 17/04/2021: this period is representative of relatively stable conditions in Gippsland Lakes, with low freshwater inputs (i.e. this plot can be considered to be approximately representative of the salinity distribution for much of the astronomical forcing simulation). The plot shows a gradual reduction in salinity from the Entrance Channel to Lake Wellington. In addition, there is a salt wedge visible in Lake King and Lake Victoria, with variations in salinity of around 2.5 psu between the surface layer and bed layer;
- 06/07/2021: this plot shows the salinity shortly after a high freshwater discharge event in the Gippsland Lakes. At Loch Sport the salinity has reduced by more than 10 psu from April 2021 to July 2021, while at the Entrance Channel the salinity has dropped by around 5 psu over this period. The plot shows that there is still variability in salinity through the water column in Lake Victoria and Lake King. Salinity of more than 34 is only present in the bottom half of the water column offshore of the Entrance Channel, with the salinity directly offshore of the Entrance Channel in the surface layers having been reduced due to the freshwater discharge out of the Gippsland Lakes;
- 19/09/2021: this plot shows the salinity in the Gippsland Lakes after 3 months of ongoing freshwater input. The salinity in Lake Wellington and McLennan's Strait has reduced to less then 4 psu, while the salinity in the remaining areas of the Gippsland Lakes is predominantly below 12 psu. The only area with a salinity of above 14 psu is offshore of the Entrance Channel, where the bottom half of the water column has salinity above 34 psu. The plot shows that despite the reduction in salinity throughout the Gippsland Lakes there is still some stratification present in Lake Victoria; and
- 23/12/2021: this plot shows the salinity in the Gippsland Lakes after 6 months of ongoing freshwater discharge. The salinity has reduced to less than 1.5 psu from Lake Wellington to Loch Sport, while the salinity upstream of Metung remains below 9 psu. Between Metung and the western end of the Reeve Channel there is an area where the near bed salinity is around 22 psu, while the surface salinity is around 12 psu. Other than this area, there are no other areas within the Gippsland Lakes with a salinity above 20 psu. The plot shows clear stratification in the salinity from Loch Sport to the Entrance Channel and in the area directly offshore.

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Figure 50. Map showing the location of the long section through Gippsland Lakes.

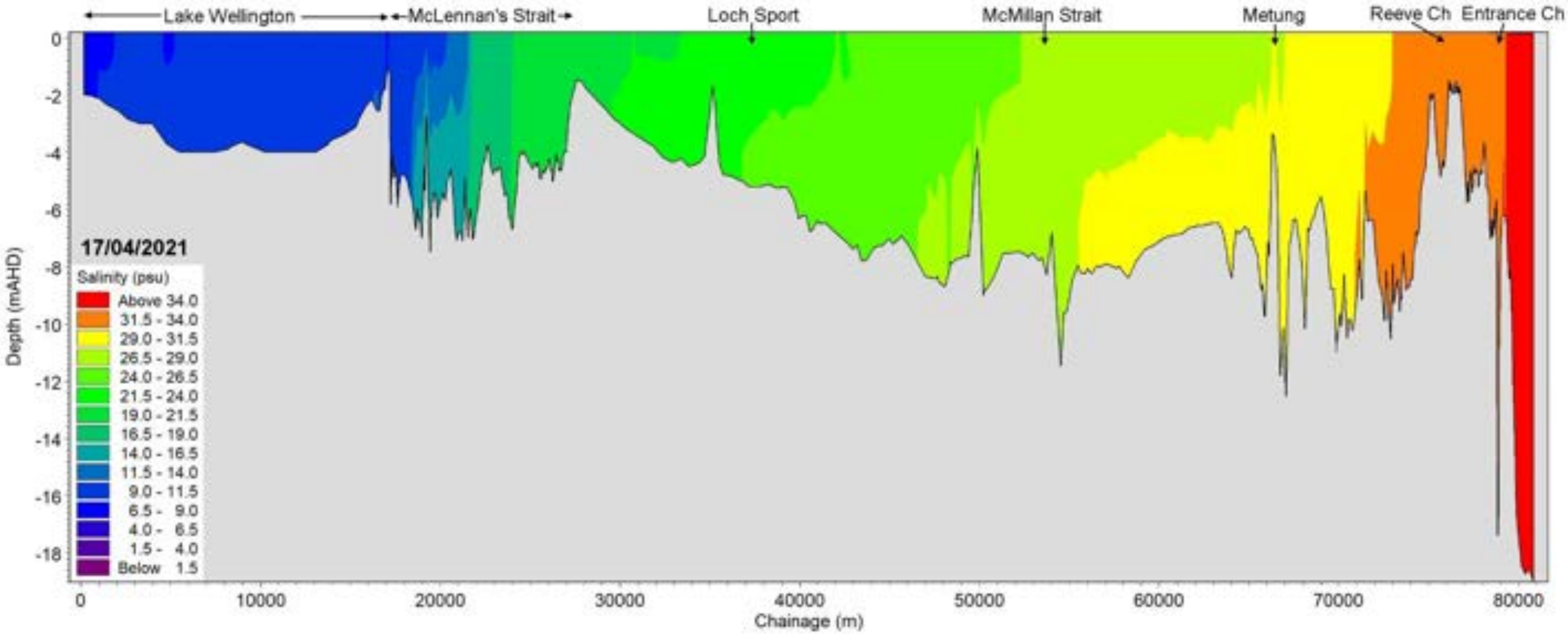

Figure 51. Modelled salinity through the water column along a long section through Gippsland Lakes from Lake Wellington to offshore of Lakes Entrance on 17/04/2021 when the salinity was relatively stable.

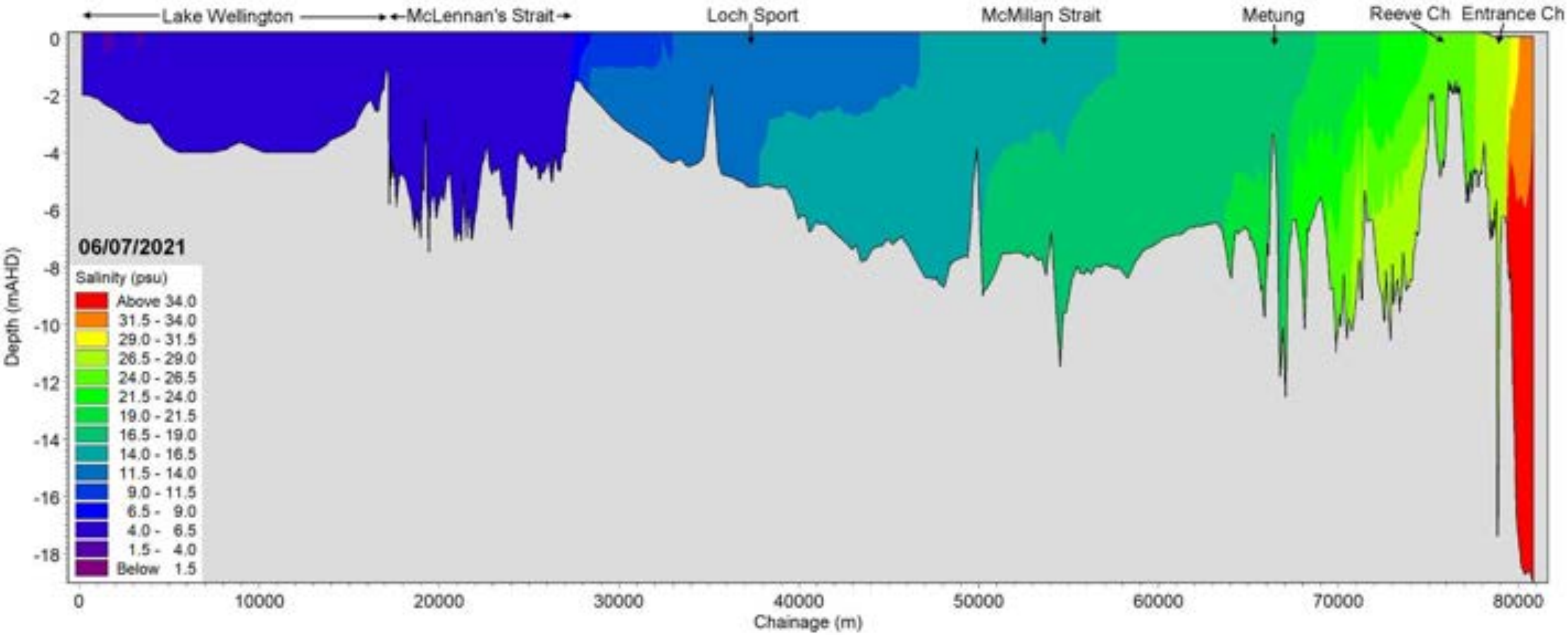

Figure 52. Modelled salinity through the water column along a long section through Gippsland Lakes from Lake Wellington to offshore of Lakes Entrance on 06/07/2021 following a large river discharge and rainfall event.

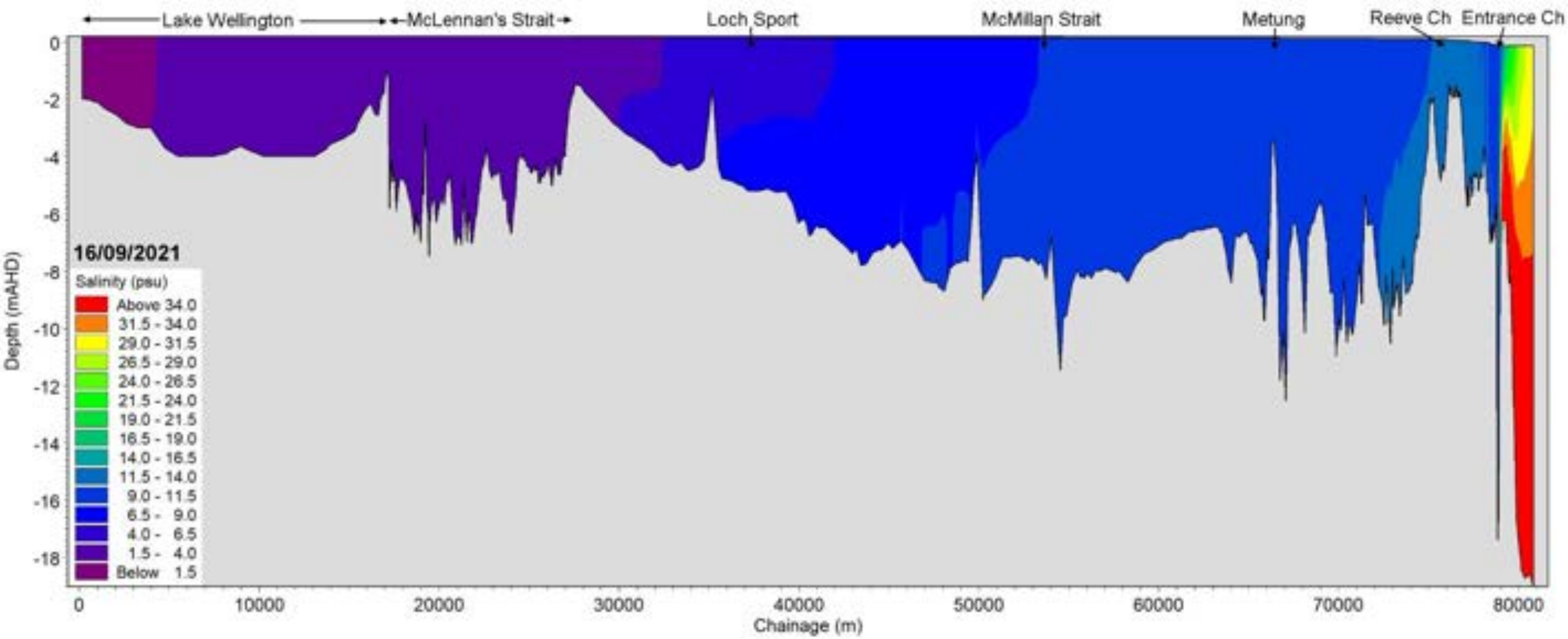

Figure 53. **Modelled salinity through the water column along a long section through Gippsland Lakes from Lake Wellington to offshore of Lakes Entrance on 19/09/2021 following three months of relatively high river discharge and rainfall.**

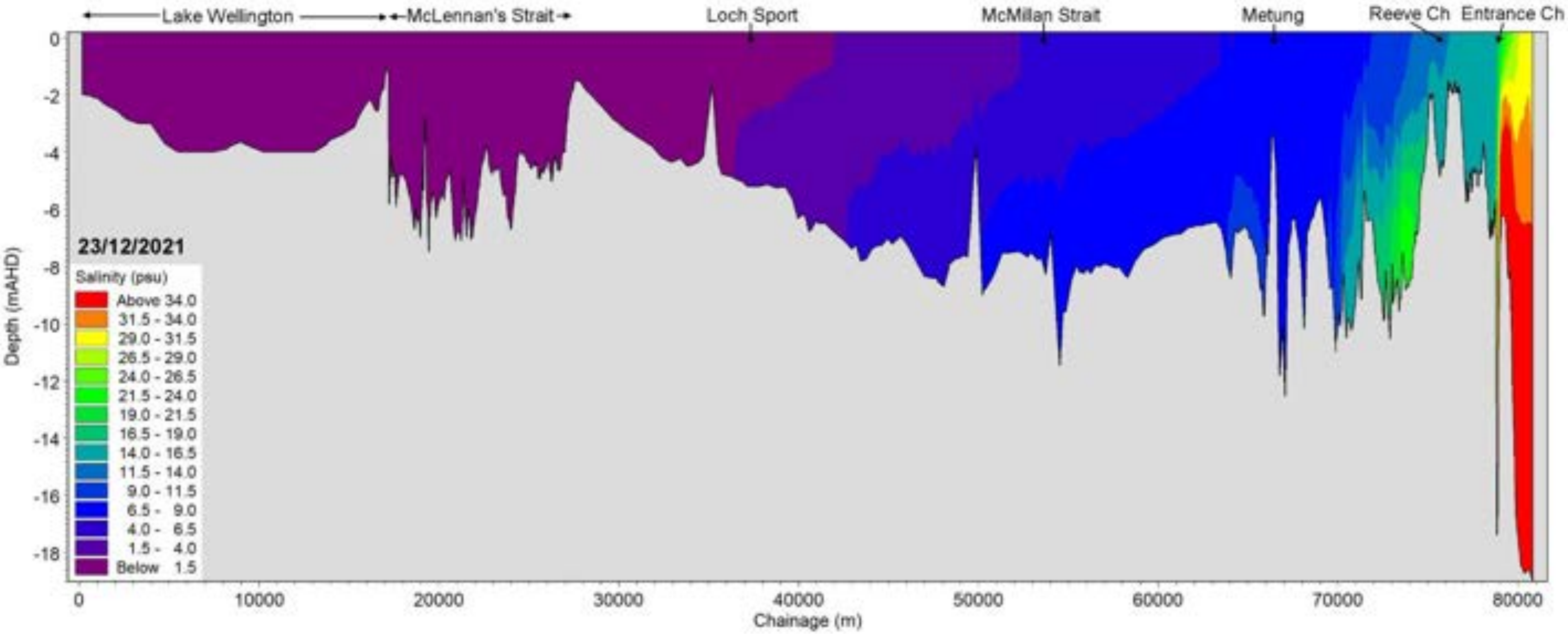

Figure 54. Modelled salinity through the water column along a long section through Gippsland Lakes from Lake Wellington to offshore of Lakes Entrance on 23/12/2021 following six months of relatively high river discharge and rainfall.

5.2. Predicted Impacts

Plots of the modelled water level and salinity statistics for the existing and future cases appear identical and so plots of the future water level and salinity statistics are not presented, but rather plots showing the change in water level and salinity statistics between the future and existing cases are shown. Select plots which show the largest predicted changes are presented in this main section of the report and a full set of spatial statistical maps showing the change in water level and salinity due to the proposed future dredging case are provided in Appendix B.

The spatial map plots show changes to water level down to ±0.001 m and changes to salinity down to ±0.05 psu. These limits are considered to represent lower thresholds that instruments would be able to accurately measure to. It is also important to note that although a numerical model can be used to show changes at and below these thresholds, very small magnitude changes predicted by a model can be a result of minor numerical instabilities in the model as opposed to actual changes which could be measured. Typically, modelled actual changes which could be measured appear as higher magnitude changes and occur over continuous regions, while changes which could not be measured and could be a result of minor numerical instabilities are small magnitude and occur in localised patches which are often a long distance away from where the actual changes occur.

5.2.1. Water Levels

Results showing the change in water level due to the future dredging are presented separately for the astronomical forcing and surge and freshwater forcing model simulations in the following sections.

The largest changes predicted to the water level due to the future dredging are to the maximum and minimum water level and maximum water level range over the 12 month duration. Therefore, plots showing the change in water level for these are presented in the following sections, along with time series plots showing changes over the entire 12 month period at the GP and DEECA monitoring sites.

5.2.1.1. Astronomic Forcing

The change in maximum and minimum water levels over the 12 month astronomical forcing simulation are shown in Figure 55 and Figure 56, while the change in maximum water level range over the 12 months is shown in Figure 57. The plots show the following:

- maximum water level: the main changes are predicted to occur in the channels around Lakes Entrance. There is predicted to be a small reduction of less than 0.002 m in the Entrance Channel and Cunninghame Arm. There is predicted to be a larger increase of up to 0.02 m in Hopetoun Channel, with an extended area of increased water level of up to 0.002 from Hopetoun Channel in the south and the western end of Reeve Channel in the north to just downstream of Metung. The model also shows localised areas with increases and decreases in maximum water level adjacent to Banksia Peninsula, these changes are small and very localised and would not be measurable (they are also not present in the 95th percentile water level changes plot in Appendix B). The model also predicts a localised change with an increase in maximum water level of less than 0.002 m in Lake Reeve, these could be actual changes but they are not present on the 95th percentile water level changes plot and so do not occur during all higher waters;
- minimum water level: the changes to the minimum water level are restricted to the channels around Lakes Entrance. The largest change is predicted to be a reduction in minimum water level of up to 0.015 m in Hopetoun Channel. In the Entrance Channel, Reeve Channel and North Arm there is predicted to be an increase in minimum water levels of less than 0.002 m, while in Cunninghame Arm the increase in slightly higher at around 0.005 m; and

- maximum water level range: the change in maximum water level range shows changes in the same areas as the changes in maximum and minimum water level. The model predicts localised changes adjacent to Banksia Peninsula, in Lake Reeve and in the northern Half of Lake King which generally show increases of up to 0.002 m. Due to the spatial patterns of these changes and the fact that they are not predicted for the 90th percentile water level range (see Appendix B) they are not considered to be measurable changes and could be the result of minor numerical instabilities as opposed to actual changes. The largest and spatially most continuous changes, which could potentially result in actual measurable changes, are restricted to the channels around Lakes Entrance, extending from the Entrance Channel to just downstream of Metung. The largest predicted change is an increase in maximum water level range of up to 0.02 m over a 1 km length of Hopetoun Channel. Between Hopetoun Channel to the south, the western end of Reeve Channel to the north and Metung there is predicted to be an increase in maximum range of up to 0.002 m. In the Entrance Channel and North Arm there is predicted to be a reduction in maximum range of up to 0.002 m, while in Cunninghame Arm the reduction is predicted to be up to 0.01 m.

To show how these changes to water level statistics relate to changes over time, time series plots of existing and future water levels as well as changes in water level due to the future dredging at the long term water level monitoring sites maintained by GP and DEECA are shown in Figure 58 to Figure 64. The absolute levels are shown in metres relative to AHD while the changes are shown in centimetres. The plots show that at the sites away from Lakes Entrance, any changes are predicted to be very small (< 0.001 m), with the magnitude of the predicted changes reducing with distance away from Lakes Entrance. The only sites where consistent, ongoing changes to water level are predicted as a result of the future dredging are the Entrance Channel and Bullock Island:

- Entrance Channel: water levels show a consistent reduction in water level of up to 0.002 m, and the time series plot showing the water levels over a 30 day period show that these reductions occur at each high water; and
- Bullock Island: water levels are predicted to experience increases of up to 0.01 m and decreases of up to 0.005 m. The time series plot showing the water levels over a 30 day period show that the increases in water level occur at low water, while the decreases in water level occur at high water. Therefore, the changes are showing an overall reduction in tidal range at Bullock Island (as shown by the change in maximum water level range plot).

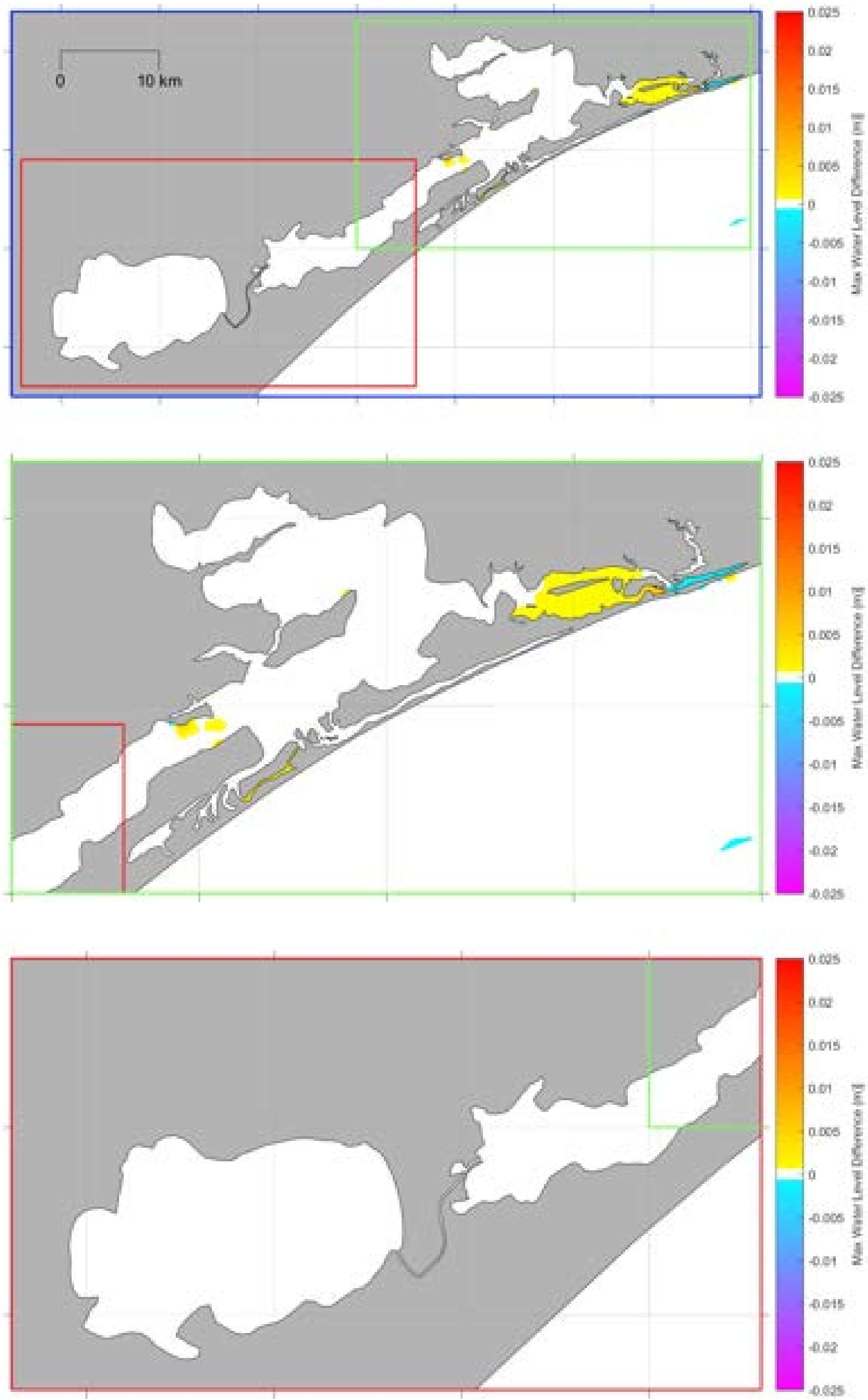

Figure 55. **Modelled change in maximum water level over 12 months with astronomical forcing due to the future dredging.**

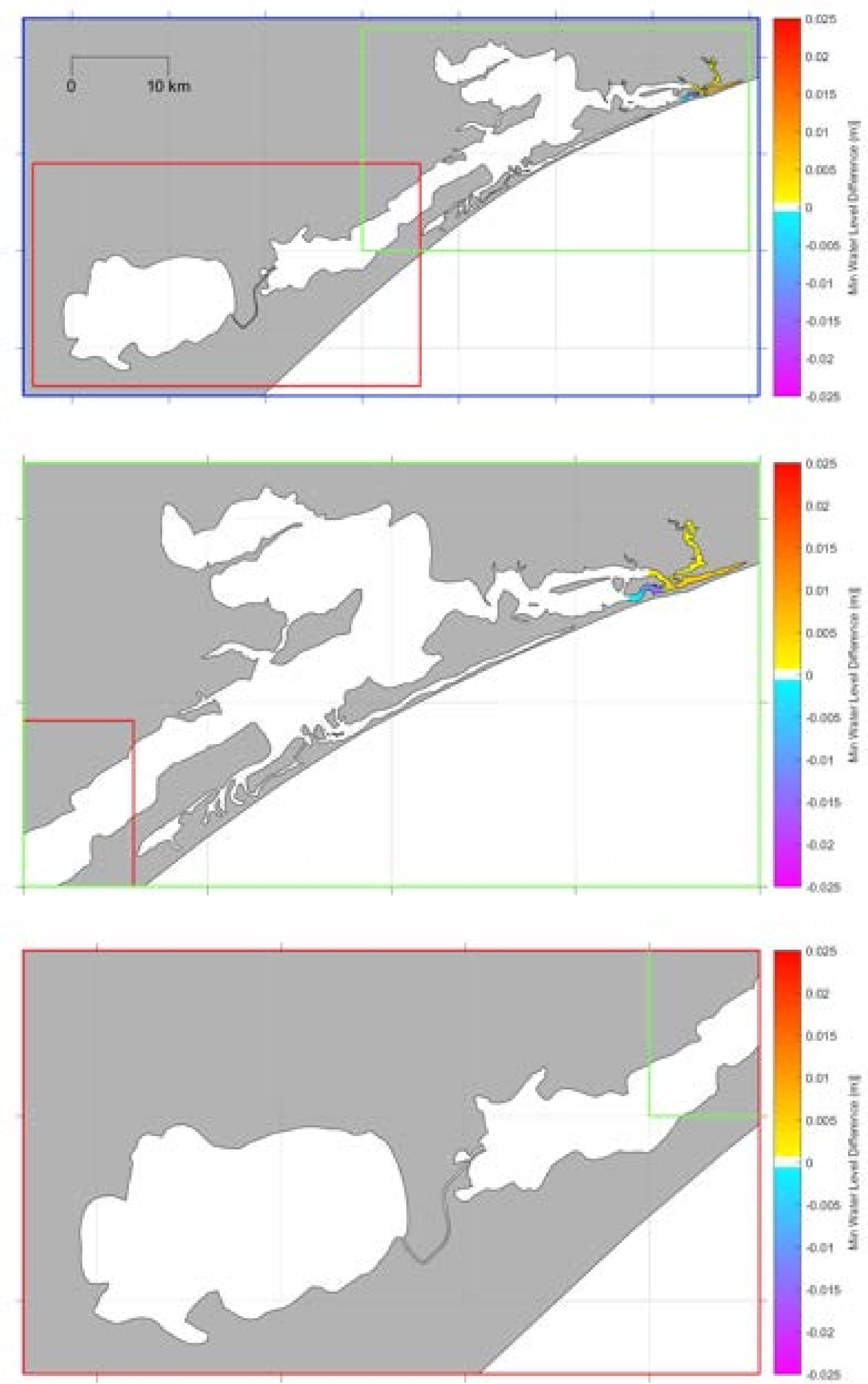

Figure 56. Modelled change in minimum water level over 12 months with astronomical forcing due to the future dredging.

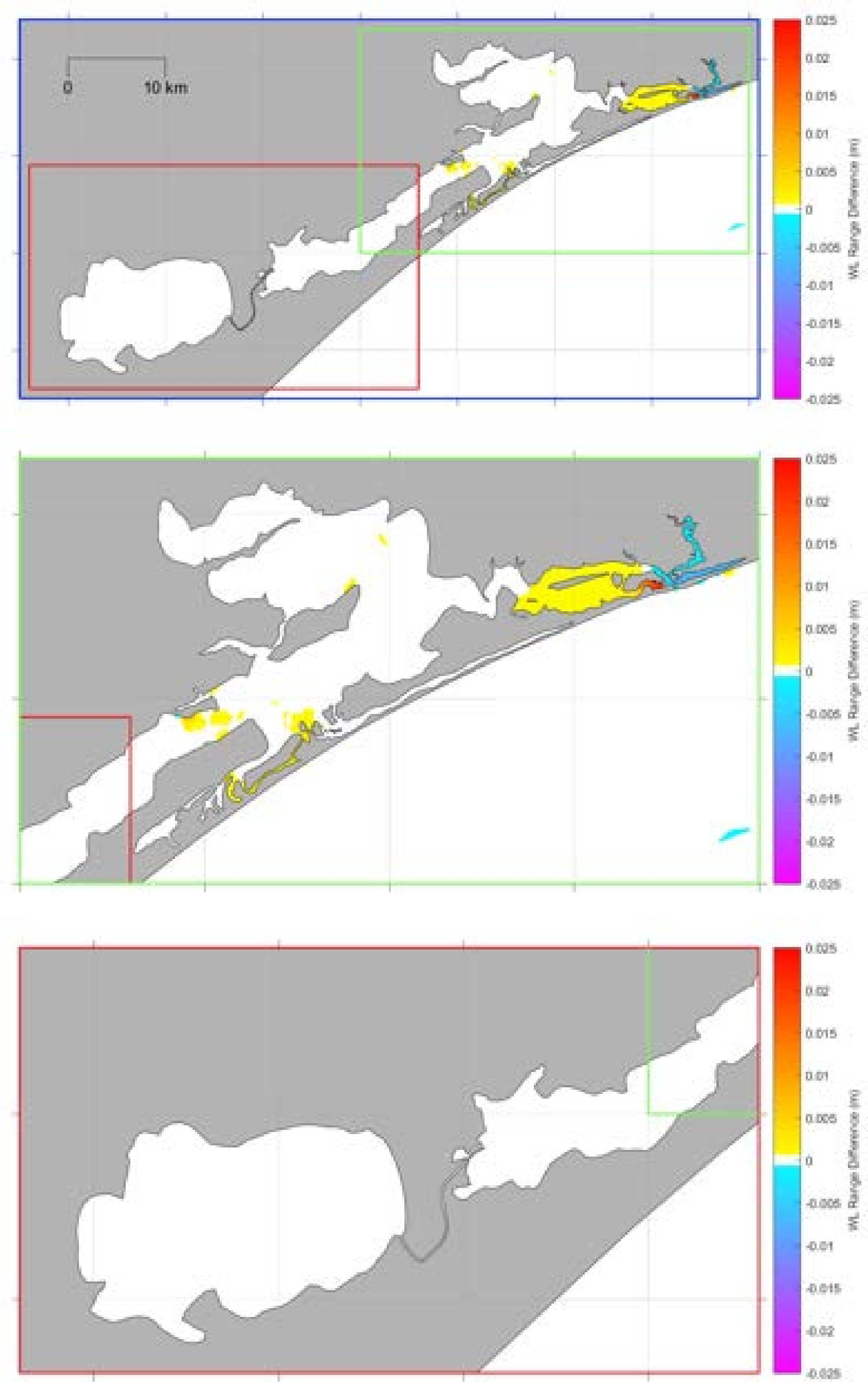

Figure 57. Modelled change in maximum water level range over 12 months with astronomical forcing due to the future dredging.

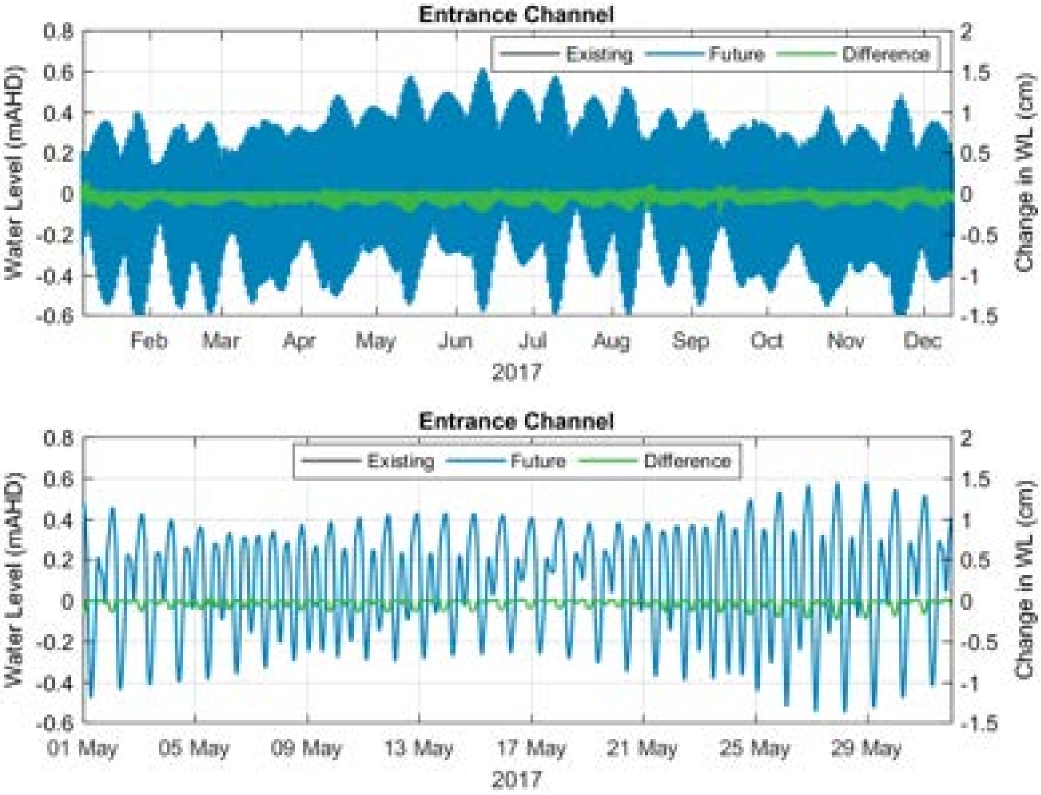

Figure 58. Modelled water levels and change in water level at the Entrance Channel for the astronomical forcing simulation over 12 months (top) and 1 month (bottom).

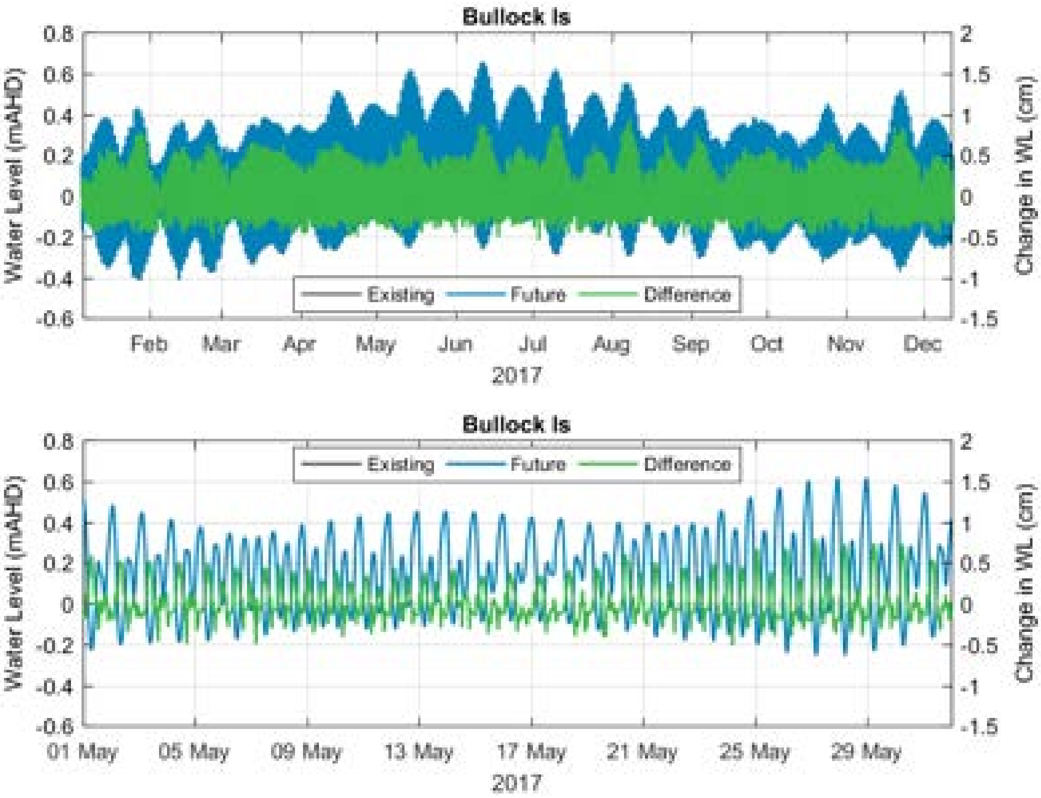

Figure 59. Modelled water levels and change in water level at Bullock Island for the astronomical forcing simulation over 12 months (top) and 1 month (bottom).

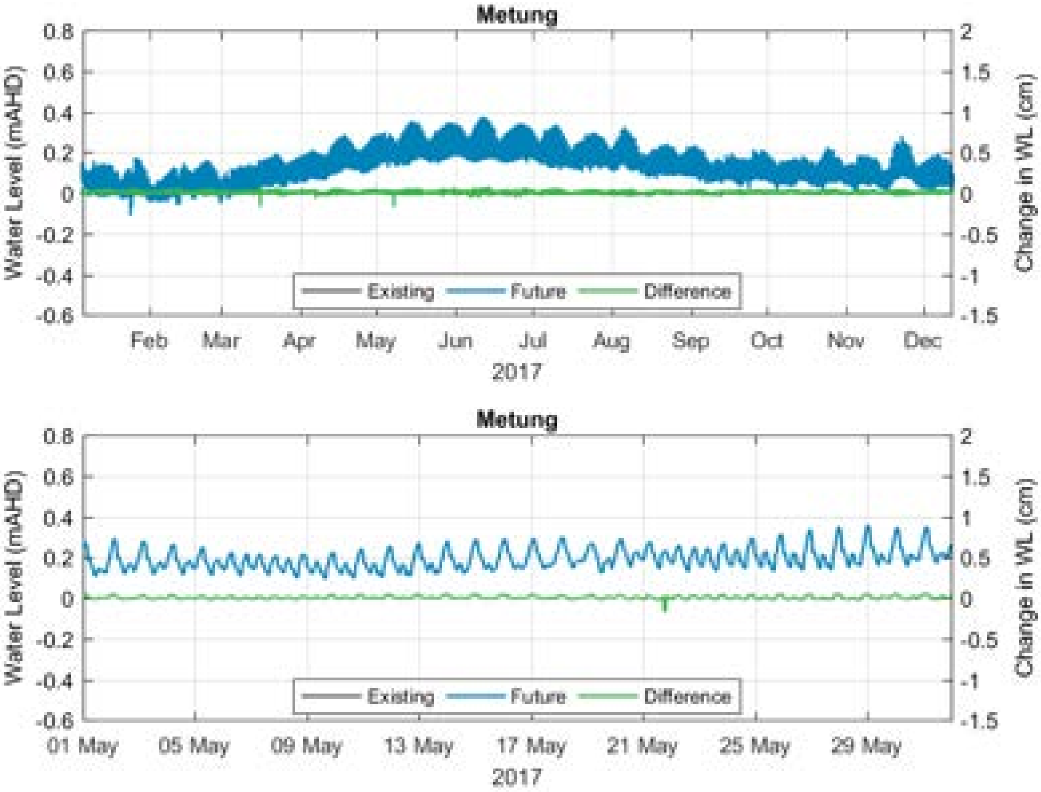

Figure 60. Modelled water levels and change in water level at Metung for the astronomical forcing simulation over 12 months (top) and 1 month (bottom).

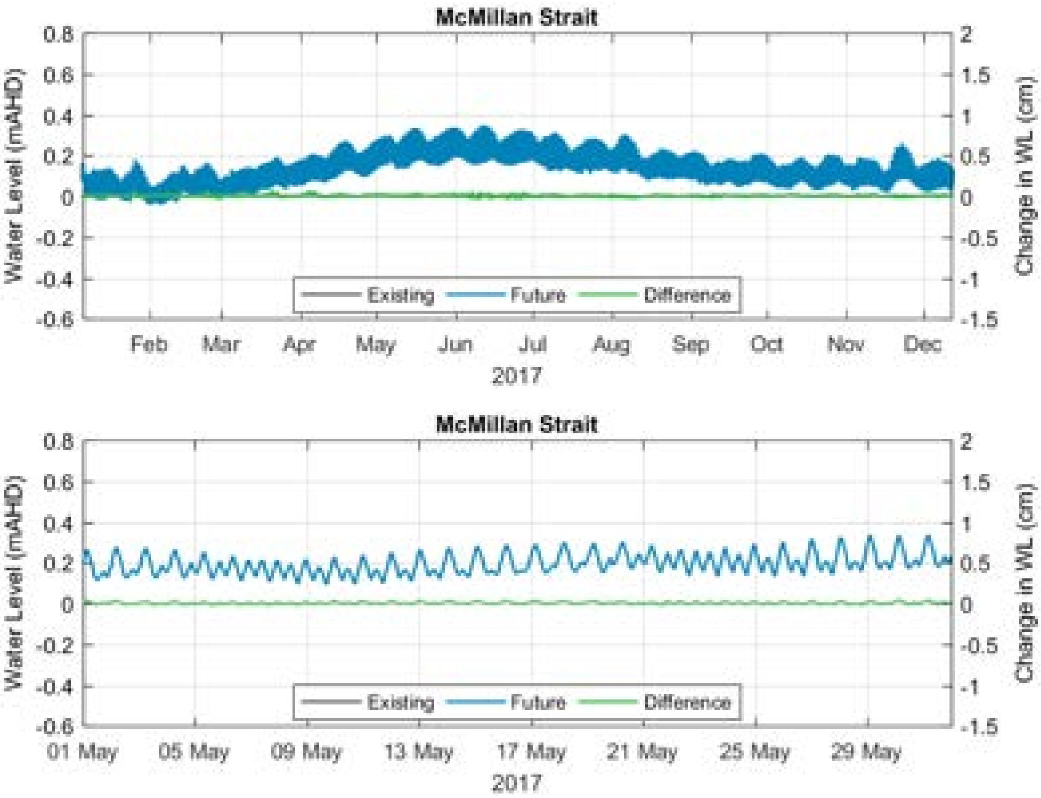

Figure 61. Modelled water levels and change in water level at McMillan Strait for the astronomical forcing simulation over 12 months (top) and 1 month (bottom).

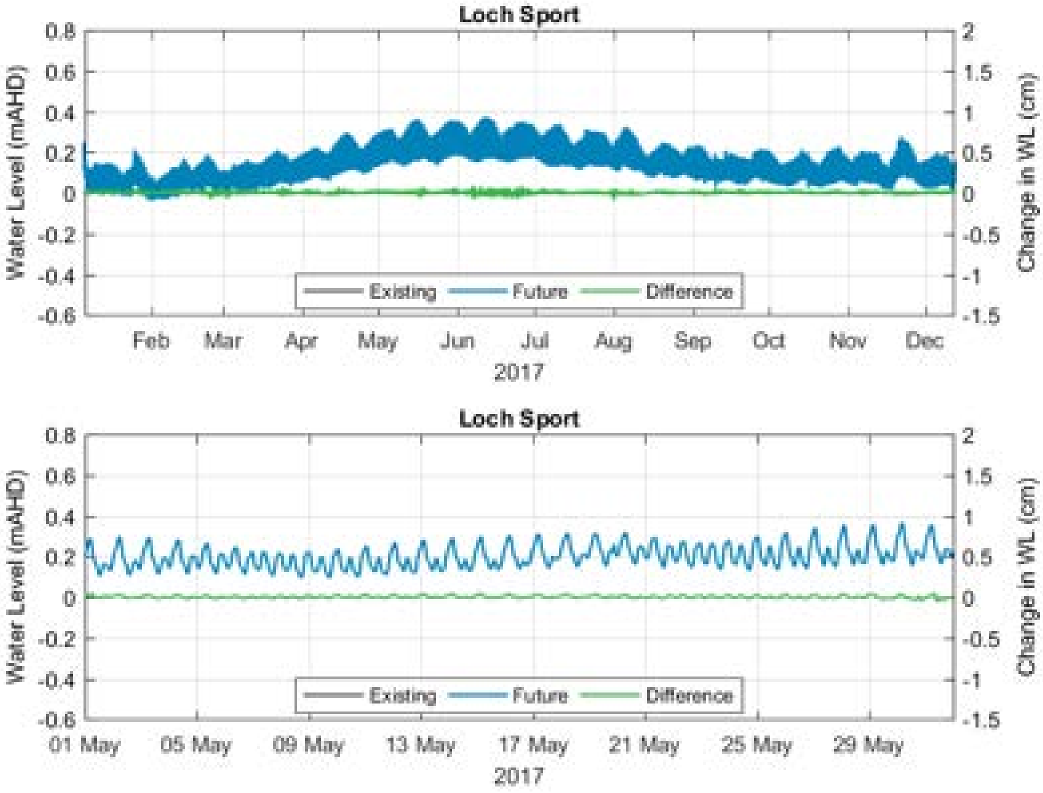

Figure 62. Modelled water levels and change in water level at Loch Sport for the astronomical forcing simulation over 12 months (top) and 1 month (bottom).

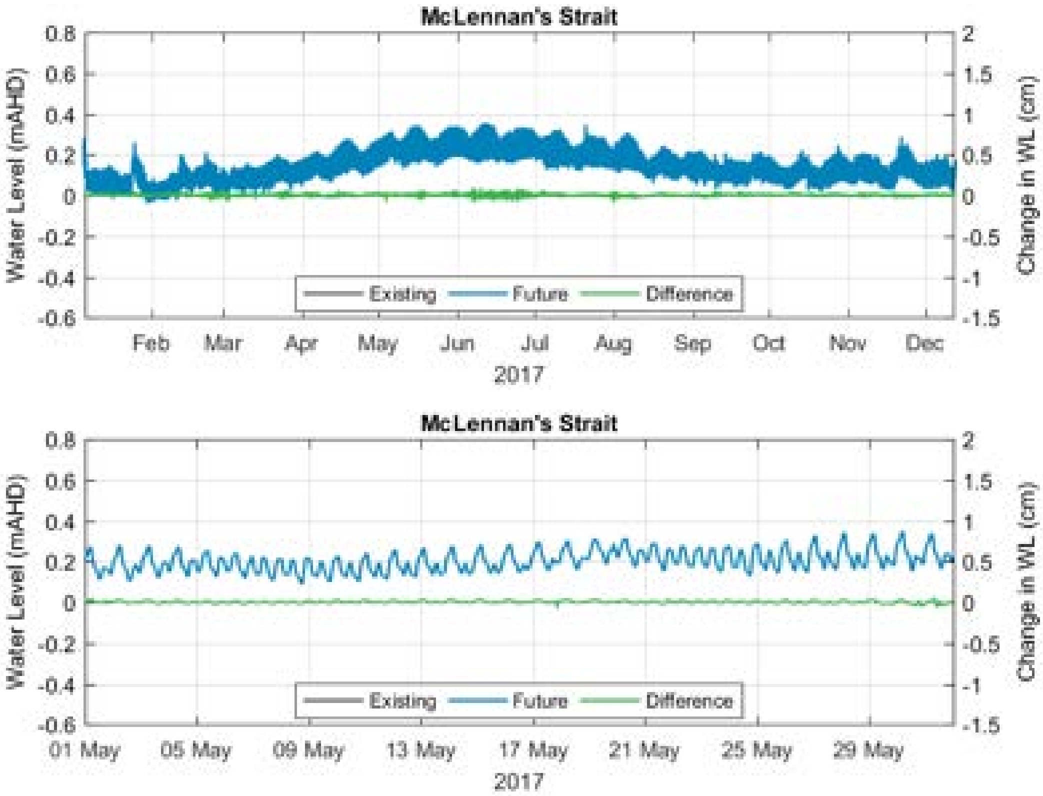

Figure 63. Modelled water levels and change in water level at McLennan's Strait for the astronomical forcing simulation over 12 months (top) and 1 month (bottom).

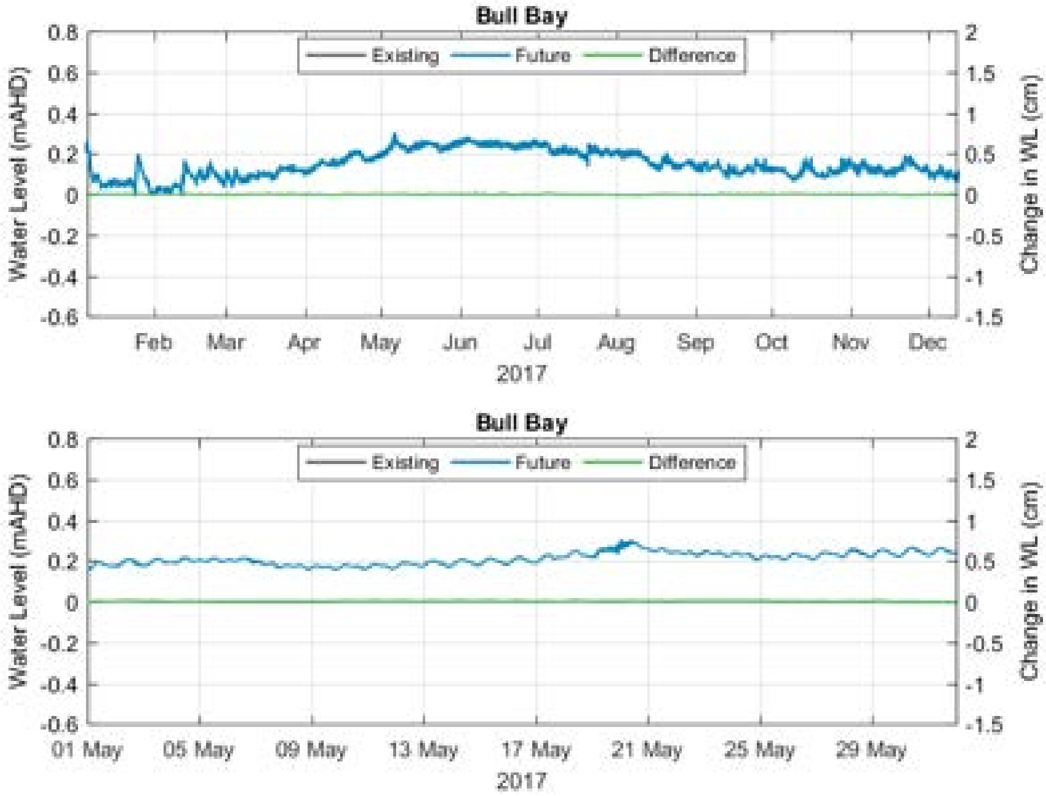

Figure 64. Modelled water levels and change in water level at Bull Bay for the astronomical forcing simulation over 12 months (top) and 1 month (bottom).

5.2.1.2. Surge and Freshwater Forcing

The change in maximum and minimum water levels over the 12 month surge and freshwater forcing simulation are shown in Figure 65 and Figure 66, while the change in maximum water level range over the 12 months is shown in Figure 67. The results show similar spatial patterns and magnitudes of change to the results for the astronomical tide, with the largest changes predicted to occur in the channels around Lakes Entrance with only low magnitude isolated patches of change predicted further upstream in the Gippsland Lakes (which are unlikely to be measurable changes). A summary of the changes which the plots show is provided below:

- maximum water level: the main changes are predicted to occur in the channels around Lakes Entrance. There is predicted to be a small reduction of less than 0.002 m in the Entrance Channel and Cunninghame Arm. There is predicted to be a larger increase of up to 0.02 m in Hopetoun Channel, an area of increased water level of up to 0.002 extending approximately 3 km upstream of Hopetoun Channel in the south and the western end of Reeve Channel in the north. The model also shows a localised area with a predicted increase in maximum water level adjacent to Banksia Peninsula, this change is not expected to be actual changes but due to minor numerical instabilities (it is not present in the 95th percentile water level changes plot in Appendix B). The model also predicts a large area offshore of the Entrance Channel (approximately 10 km by 5 km) with a predicted increase in maximum water level of less than 0.002 m. This change is not present on the 95th percentile water level changes plot and so is only a small magnitude change to the maximum water level in this area;
- minimum water level: the changes to the minimum water level are restricted to just the channels around Lakes Entrance. The largest change is predicted to be a reduction in minimum water level of up to 0.01 m in Hopetoun Channel. In the Entrance Channel, Reeve Channel and Cunninghame Arm there is predicted to be an increase in minimum

water levels of less than 0.002 m. There are also predicted to be localised increases and decreases in water level of less than 0.002 m along the offshore shoreline to the west and east of the Entrance Channel, these changes are not expected to be actual changes but are likely to be due to minor numerical instabilities; and

- maximum water level range: the change in maximum water level range shows changes in the same areas as the changes in maximum and minimum water level. The model predicts localised increases adjacent to Banksia Peninsula of up to 0.002 m. The largest and spatially most continuous changes, which could potentially represent actual measurable changes, are restricted to the channels around Lakes Entrance, extending from the Entrance Channel to approximately 3 km upstream of the western ends of Hopetoun Channel and Reeve Channel. The largest predicted change is an increase in maximum water level range of up to 0.02 m over a 1 km length of Hopetoun Channel, with an increase of around 0.01 m extending a further 1.5 km upstream of Hopetoun Channel and an increase of up to 0.002 m extending a further 2 km upstream. There is predicted to be an increase in maximum water level range of up to 0.002 m extending approximately 3 km upstream of the western end of Reeve Channel. In the Entrance Channel and North Arm there is predicted to be a reduction in maximum range of up to 0.002 m, while in Cunninghame Arm the reduction is predicted to be up to 0.01 m. As for the maximum water level changes, there is also predicted to be a small magnitude increase (less than 0.002 m) in the maximum water level range for a large offshore area (approximately 10 km by 5 km). This change is not present on the 90th percentile water level range changes plot and so is only a small magnitude change to the maximum water level range in this area.

To show how these changes to water level statistics relate to changes over time, time series plots of existing and future water levels as well as changes in water level due to the future dredging at the long term water level monitoring sites maintained by GP and DEECA are shown in Figure 69 to Figure 74. The plots show that at the sites away from Lakes Entrance, any changes are predicted to be very small (< 0.001 m), with the magnitude of the predicted changes reducing with distance away from Lakes Entrance (i.e. the changes are smallest at Bull Bay). The plots at the sites away from Lakes Entrance do not show any noticeable difference in the change in water level predicted from January to the end of May when there was low freshwater inputs and the change predicted from June to December when freshwater inputs were high. This shows that water levels in these areas are not predicted to change due to the future dredging either during periods with offshore storm surge or high freshwater discharge. The only sites where consistent, ongoing changes to water level are predicted as a result of the future dredging are the Entrance Channel and Bullock Island. At the Entrance Channel the changes in water level due to the future dredging switches from being just reductions in water level from January to the end of May when there were low freshwater inputs to both positive and negative changes in water level for the period from June to December when freshwater inputs were high. Based on this change, additional plots of the water levels and changes over 30 day periods in April (when there were multiple offshore storm surges from 8th April to the 24th April) and in November (when the highest water level occurred due to freshwater inputs) are presented at the Entrance Channel and Bullock Island. The plots show:

- Entrance Channel: over the period with low freshwater input (January to the end of May) the water levels show a consistent reduction in water level of up to 0.002 m. The plot of water levels in April 2021 shows that the reductions occur each high water and that the reductions continue to occur during periods with offshore storm surge. Over the period with high freshwater discharge (June to December) the plots show the potential for larger changes to water levels, with reductions of up to 0.005 m and increases of up to 0.012 m. The plot of the water levels in November and December 2021 show that while the reductions typically continue to occur at high water, the increases can also occur during the flood and ebb stages of the tide as well as at the smaller high water each day during neap tides; and

- Bullock Island: water levels at Bullock Island are predicted to experience increases of up to 0.01 m and decreases of up to 0.005 m. The plot of the water levels over the two 30 day periods show that the increases in water level consistently occur at low water, while the decreases in water level consistently occur at high water. Therefore, the changes are showing an overall reduction in tidal range at Bullock Island (as shown by the change in maximum water level range plot) during both offshore storm surges and high freshwater input events.

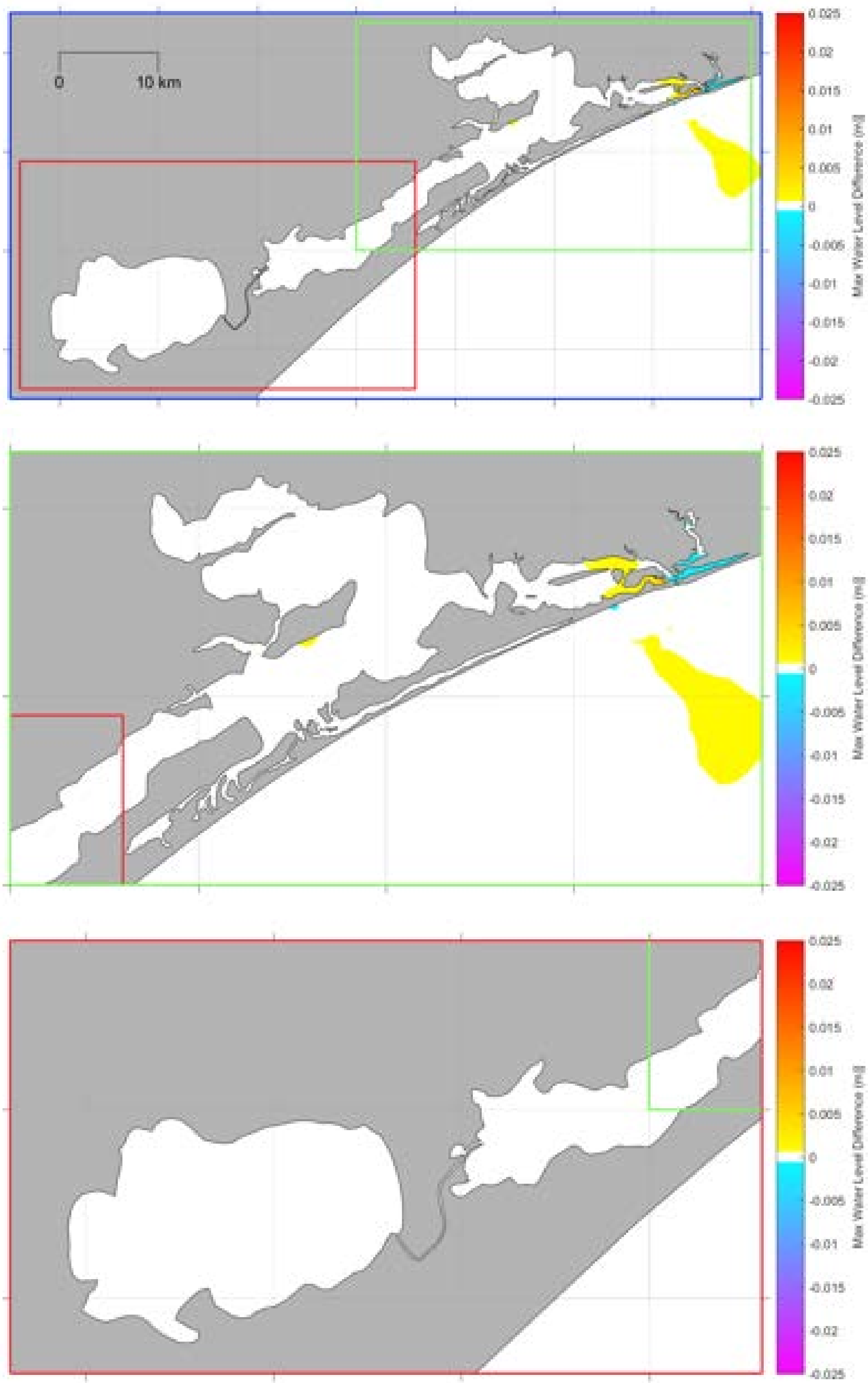

Figure 65. Modelled change in maximum water level over 12 months with surge and freshwater forcing due to the future dredging.

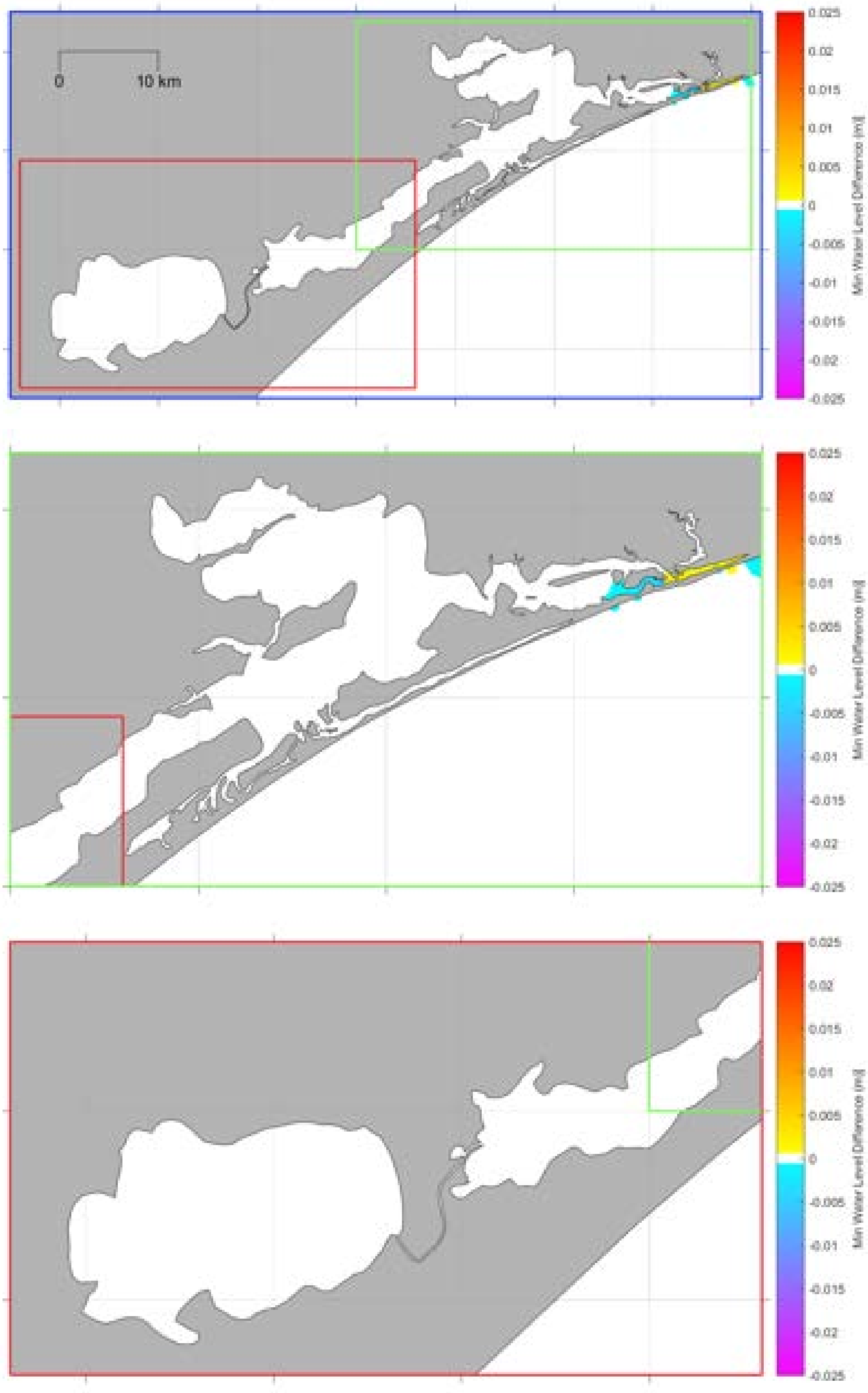

Figure 66. Modelled change in minimum water level over 12 months with surge and freshwater forcing due to the future dredging.

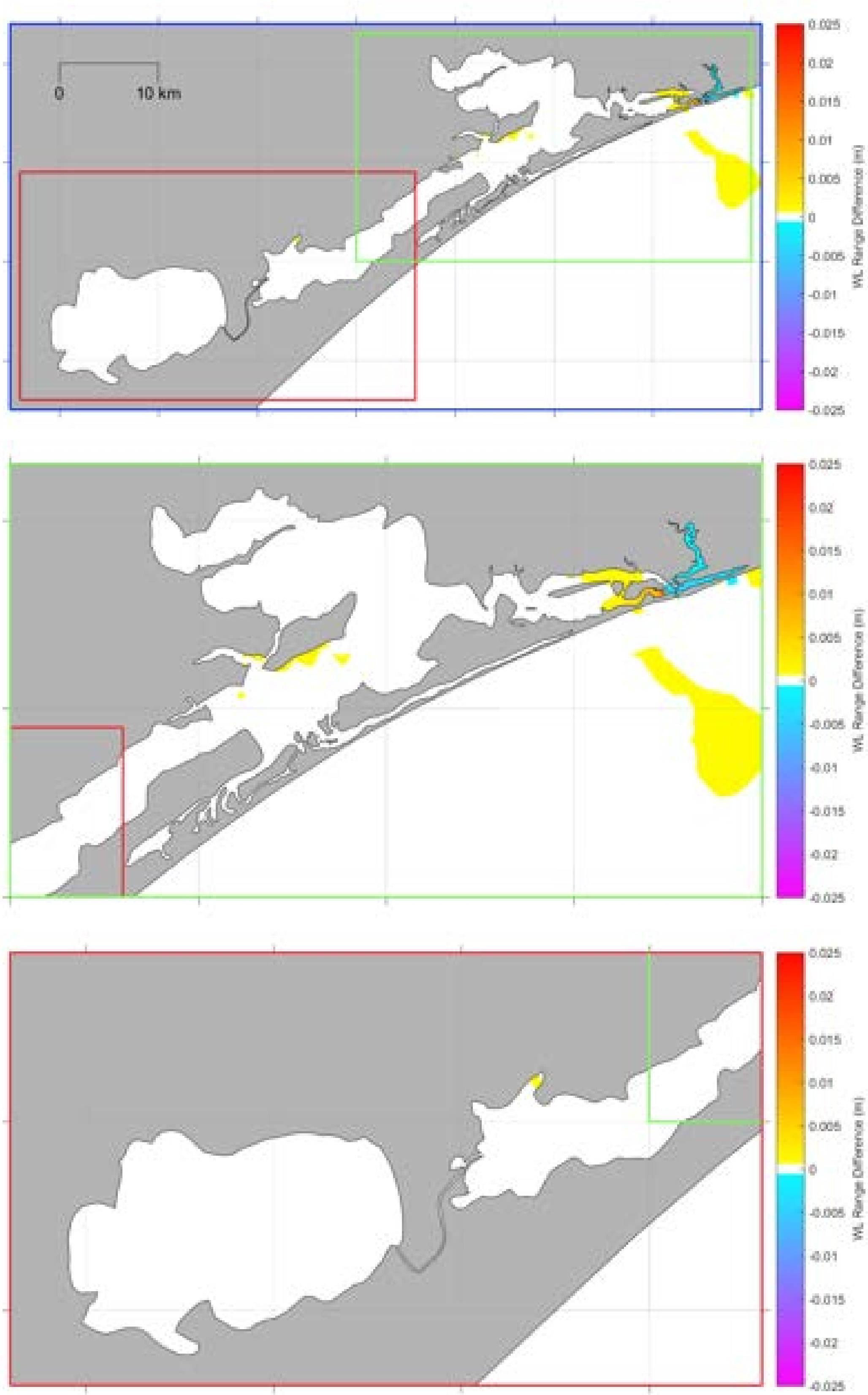

Figure 67. Modelled change in maximum water level range over 12 months with surge and freshwater forcing due to the future dredging.

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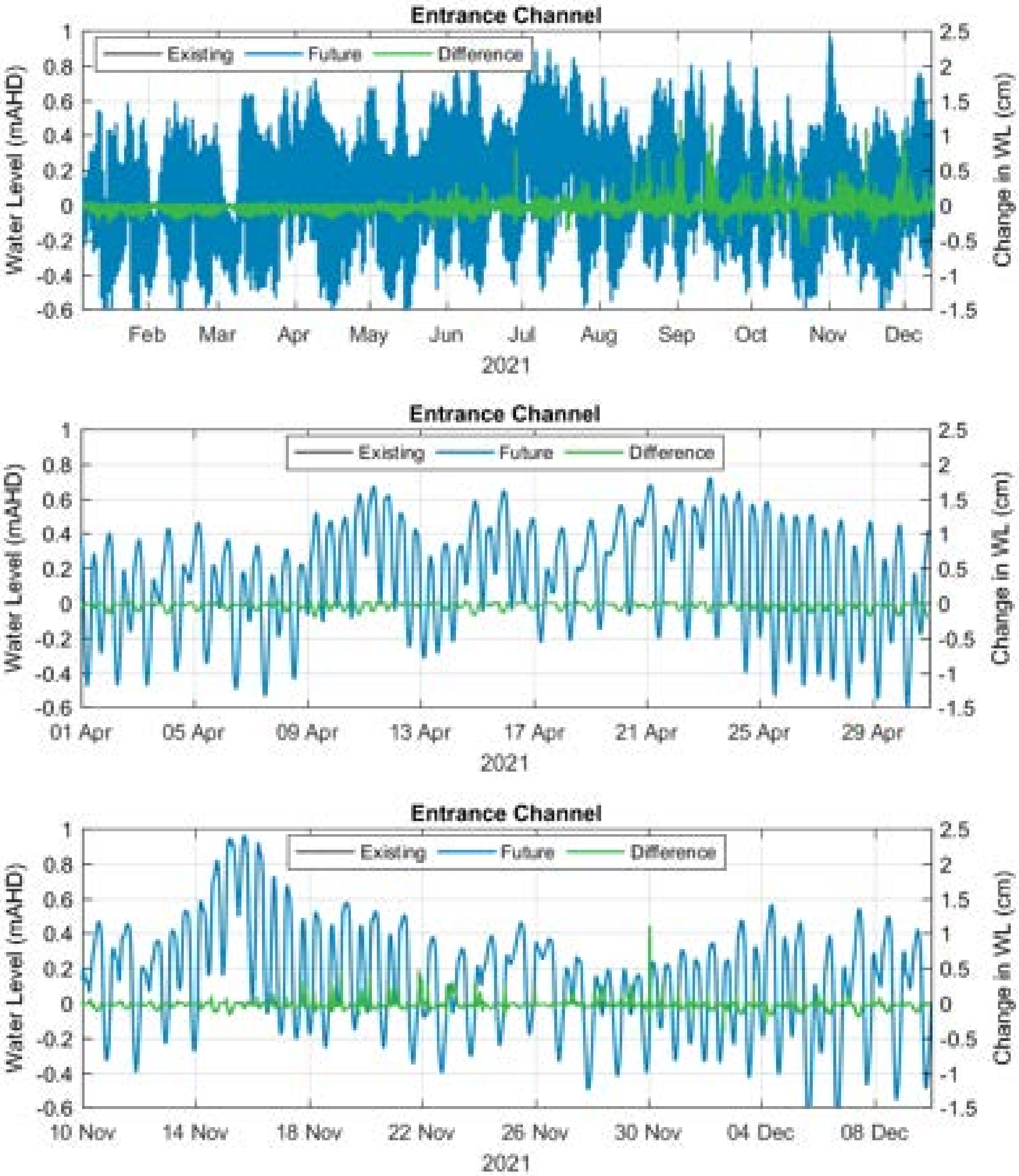

Figure 68. **Modelled water levels and change in water level at the Entrance Channel for the surge and freshwater forcing simulation over 12 months (top), 1 month during low freshwater input (middle) and 1 month during high freshwater input (bottom).**

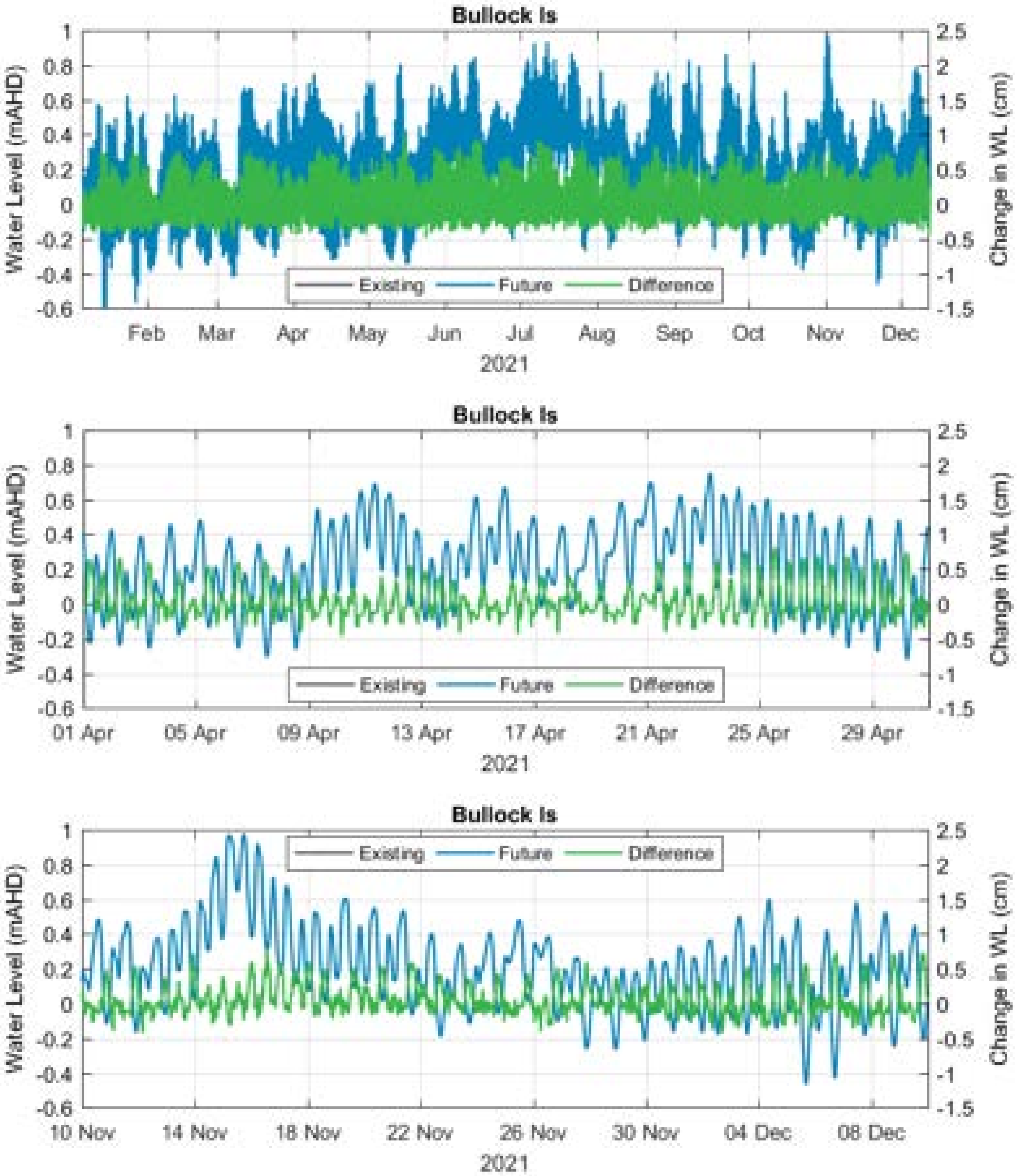

Figure 69. Modelled water levels and change in water level at Bullock Island for the surge and freshwater forcing simulation over 12 months (top), 1 month during low freshwater input (middle) and 1 month during high freshwater input (bottom).

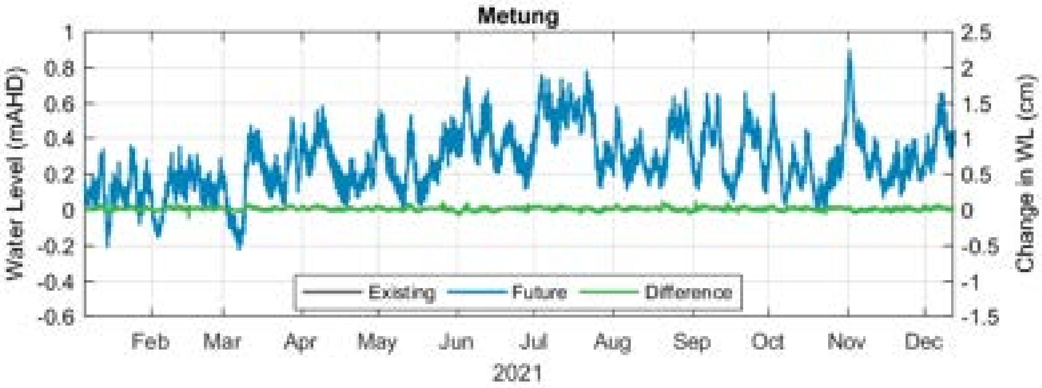

Figure 70. **Modelled water levels and change in water level at Metung for the surge and freshwater forcing simulation over 12 months.**

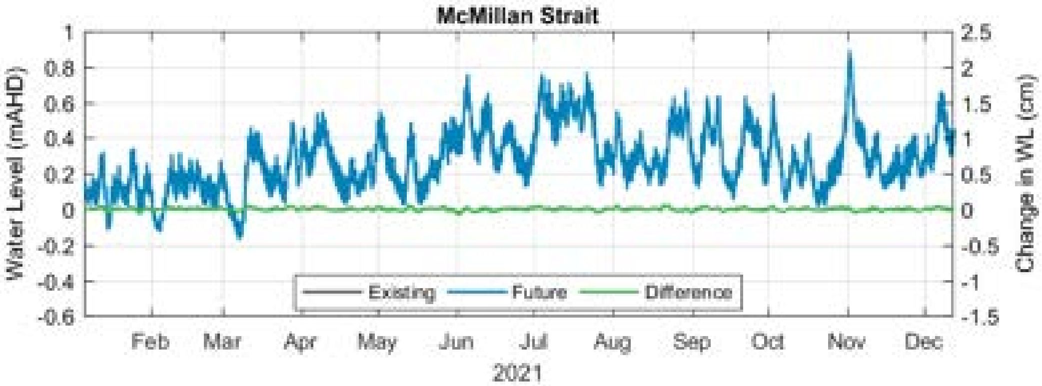

Figure 71. **Modelled water levels and change in water level at McMillan Strait for the surge and freshwater forcing simulation over 12 months.**

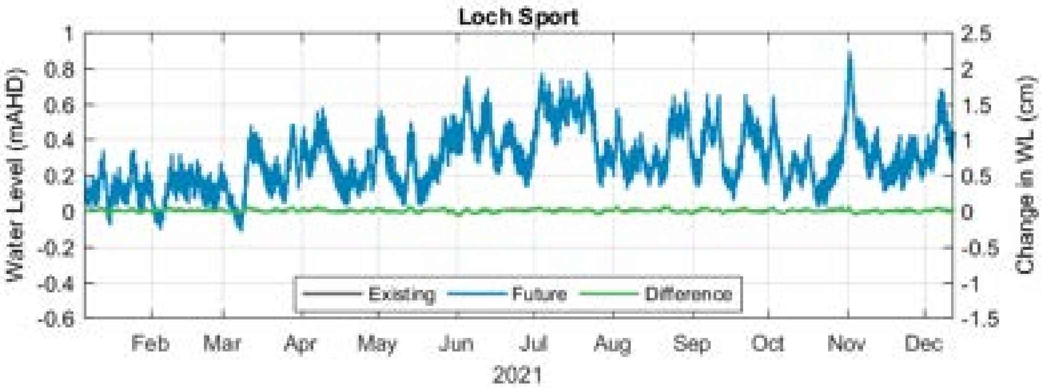

Figure 72. **Modelled water levels and change in water level at Loch Sport for the surge and freshwater forcing simulation over 12 months.**

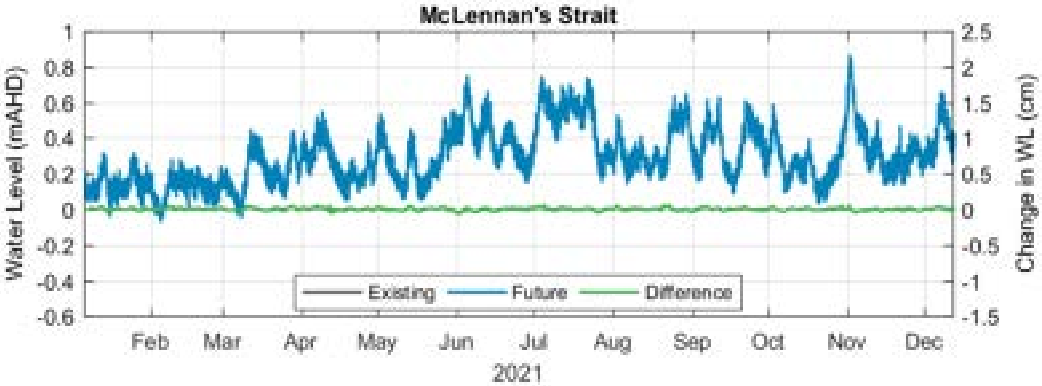

Figure 73. Modelled water levels and change in water level at McLennan's Strait for the surge and freshwater forcing simulation over 12 months.

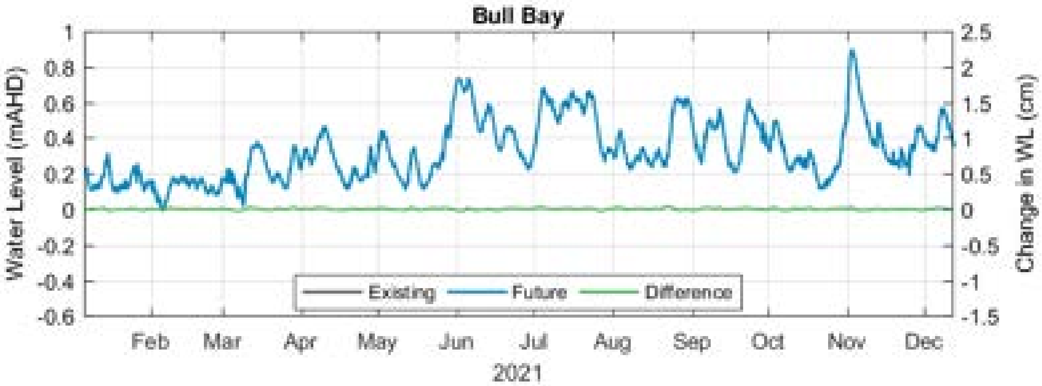

Figure 74. Modelled water levels and change in water level at Bull Bay for the surge and freshwater forcing simulation over 12 months.

5.2.2. Salinity

Results showing the change in salinity due to the future dredging are presented separately for the astronomical forcing and surge and freshwater forcing model simulations in the following sections.

The largest changes predicted to the salinity due to the future dredging are to the maximum and minimum surface salinity and the maximum salinity range over the 12 month duration. Therefore, plots showing the change in salinity for these are presented in the following sections. In addition, plots showing the change in the median (50th percentile) salinity is also presented to understand whether the future dredging impacts the typical salinity values as well as the extreme values over the 12 months. Time series plots showing changes over the entire 12 month periods at the EPA monitoring sites are also shown.

5.2.2.1. Astronomic Forcing

The change in maximum, minimum and median surface salinity over the 12 month astronomical forcing simulation are shown in Figure 75 to Figure 77, while the change in maximum salinity range over the 12 months is shown in Figure 78. The plots show the following:

- maximum salinity: there is predicted to be limited change to the maximum salinity. There are very small localised increases and decreases of less than 0.2 psu at the entrance to Lake Reeve which are likely to be a result of minor numerical instability as opposed to actual changes (these changes are not shown in the bed layer changes in Appendix B).

There is also predicted to be a small area with a reduction in salinity of up to 0.2 psu in the North Arm and within the channel to the east of Bullock Island;

- minimum salinity: there are predicted to be three small localised areas of change in Lake King of up to 0.2 psu, these changes are not predicted in the bed layer salinity and due to their localised nature are considered to be a result of minor numerical instabilities. There are predicted to be increases in salinity of up to 0.2 psu in the North Arm, within the channel to the east of Bullock Island and within Cunninghame Arm. There is also predicted to be both increases and decreases in salinity immediately offshore of the Entrance Channel. The largest change in this area is a reduction of up to 1 psu in the surface salinity immediately to the west of the Entrance Channel;
- median salinity: there is predicted to be a very small localised increase of up to 0.2 psu in surface salinity in Cunninghame Arm. There is also predicted to be a small localised increase of up to 0.2 psu in one of the narrow channels in Lake Reeve, as with the predicted change in water level in this area, the change is considered to be due to minor numerical instabilities as opposed to actual changes; and
- maximum range: there are predicted to be small localised areas with increases and decreases in the maximum surface salinity range of up to 0.2 psu in Lake King and Lake Reeve. Due to nature of these changes they are considered to be a result of minor numerical instabilities as opposed to actual changes. Around Lakes Entrance there is predicted to be spatially continuous changes within the North Arm and Cunninghame Arm and offshore of the Entrance Channel, these changes are considered to represent actual changes. The plot shows a reduction in salinity range in the North Arm and channel to the east of Bullock Island of up to 1 psu, although the change is less than 0.2 psu over the majority of the area. In Cunninghame Arm there is predicted to be a reduction in surface salinity of up to 0.2 psu in the western half of the channel, and an increase in surface salinity of up to 0.2 psu in the eastern half of the channel. Offshore of the entrance there is predicted to be a small area with a reduction in surface salinity of up to 0.02 psu, while the largest change is to the west of the Entrance Channel with an increase in salinity range of up to 1 psu.

To show how these changes to surface salinity statistics relate to changes over time, time series plots of existing and future surface and bed salinity, as well as changes in salinity due to the future dredging, at the long term salinity monitoring sites maintained by EPA are shown in Figure 79 to Figure 83. The plots show that the changes in the surface salinity are typically larger than the changes in the bed. The largest changes are predicted at Shaving Pt with short duration changes in surface salinity of up to ±0.2 psu and short duration changes in bed salinity of less than ±0.1 psu predicted. The magnitude of the changes in salinity reduce with increasing distance from Lakes Entrance, with almost no changes predicted at Lake Victoria and Lake Wellington. At all sites the plots show that the changes in salinity occur as short duration spikes, with no gradual increases or decreases in salinity predicted at any of the sites.

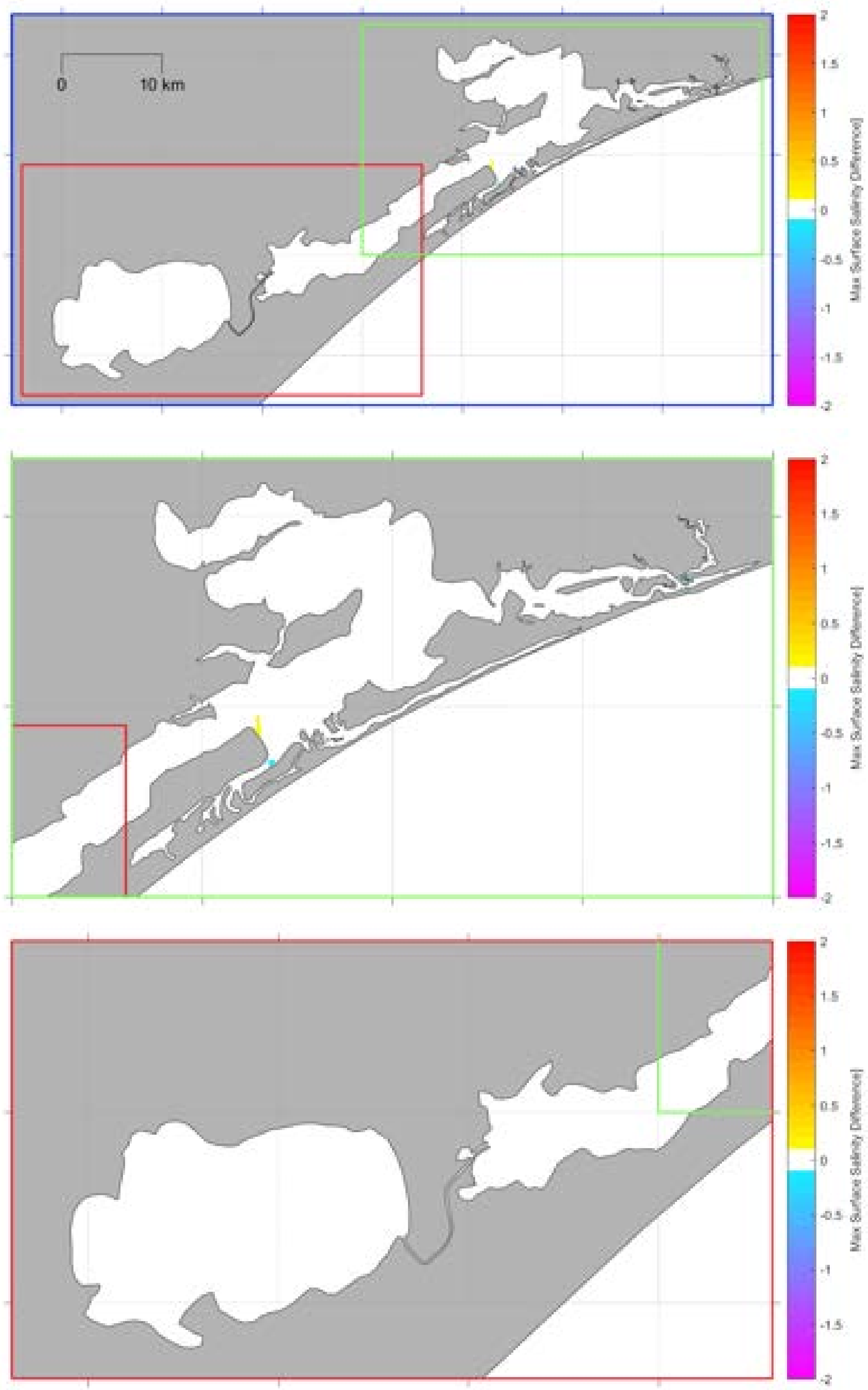

Figure 75. Modelled change in maximum surface salinity over 12 months with astronomical forcing due to the future dredging.

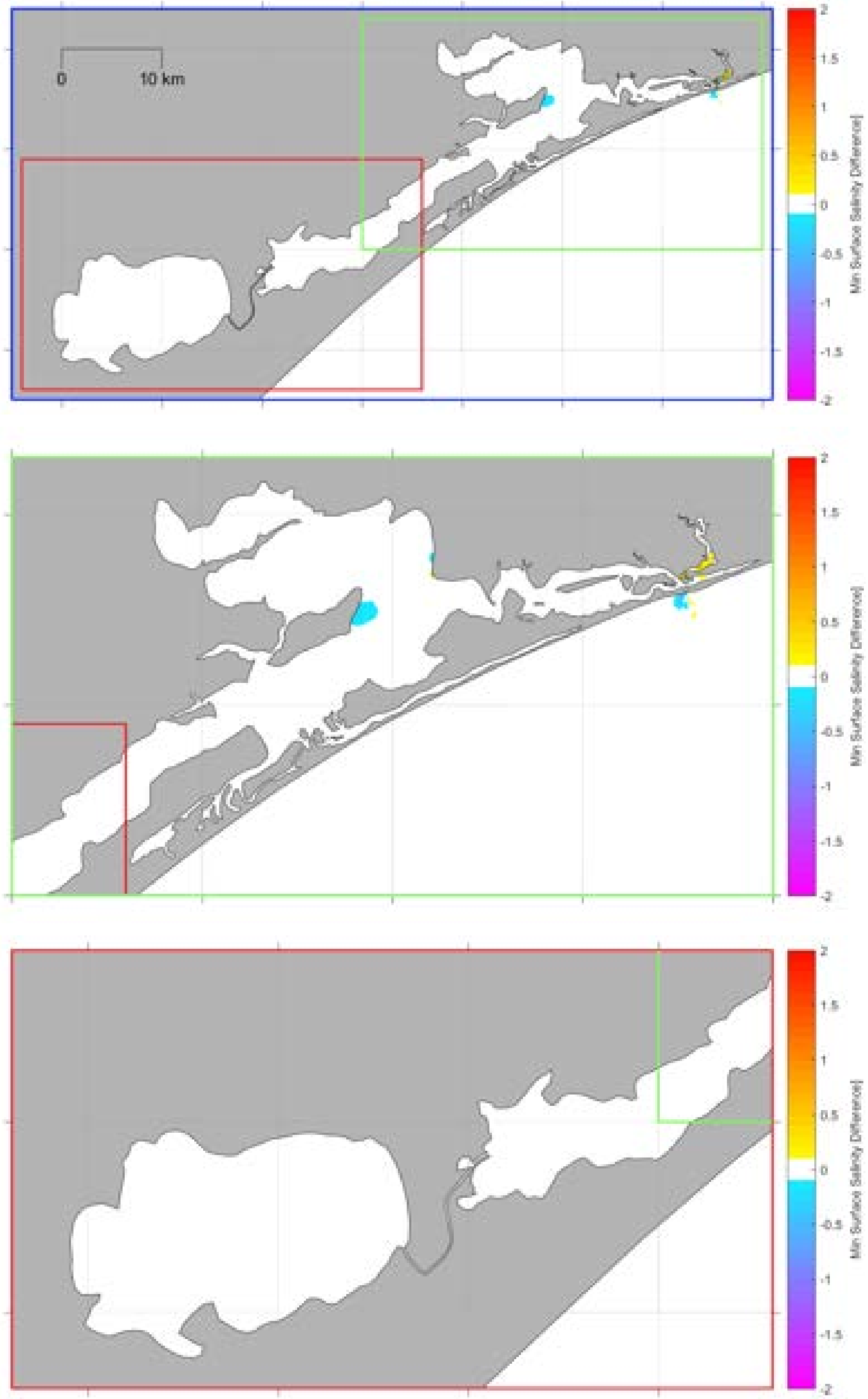

Figure 76. Modelled change in minimum surface salinity over 12 months with astronomical forcing due to the future dredging.

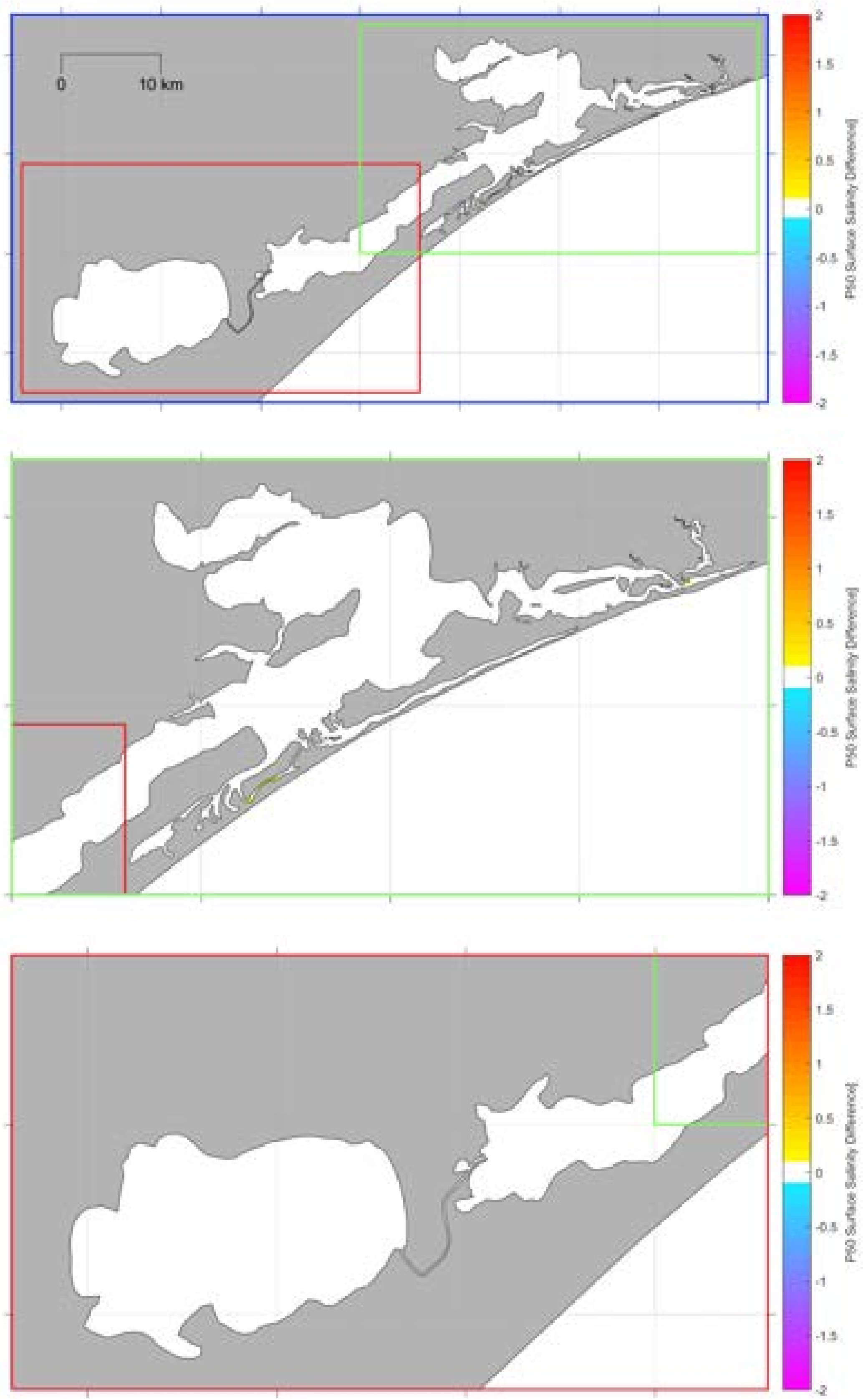

Figure 77. Modelled change in median surface salinity over 12 months with astronomical forcing due to the future dredging.

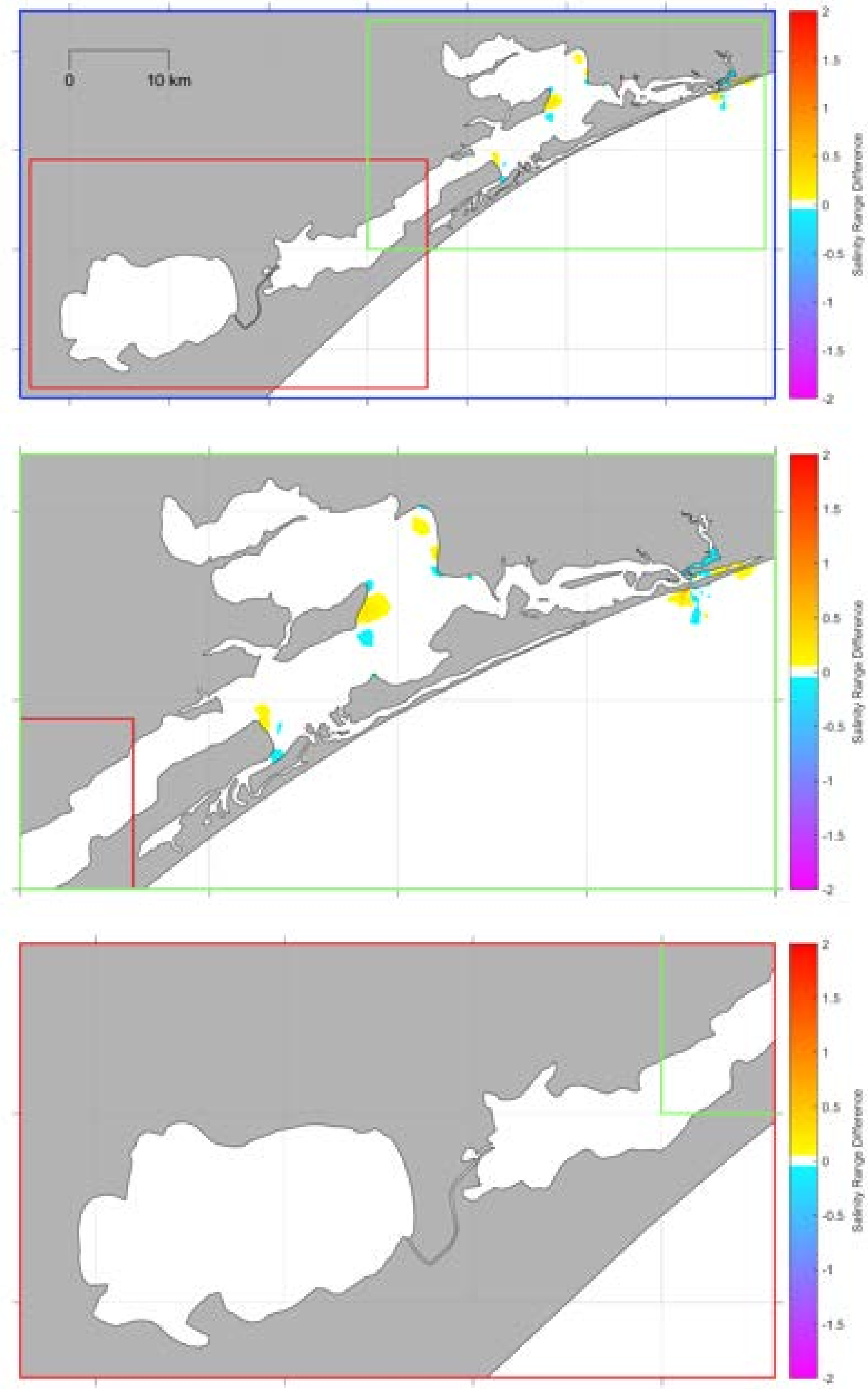

Figure 78. Modelled change in maximum surface salinity range over 12 months with astronomical forcing due to the future dredging.

Figure 79. **Modelled surface (top) and bed (bottom) salinity and change in salinity at Shaving Pt for the astronomical forcing simulation over 12 months.**

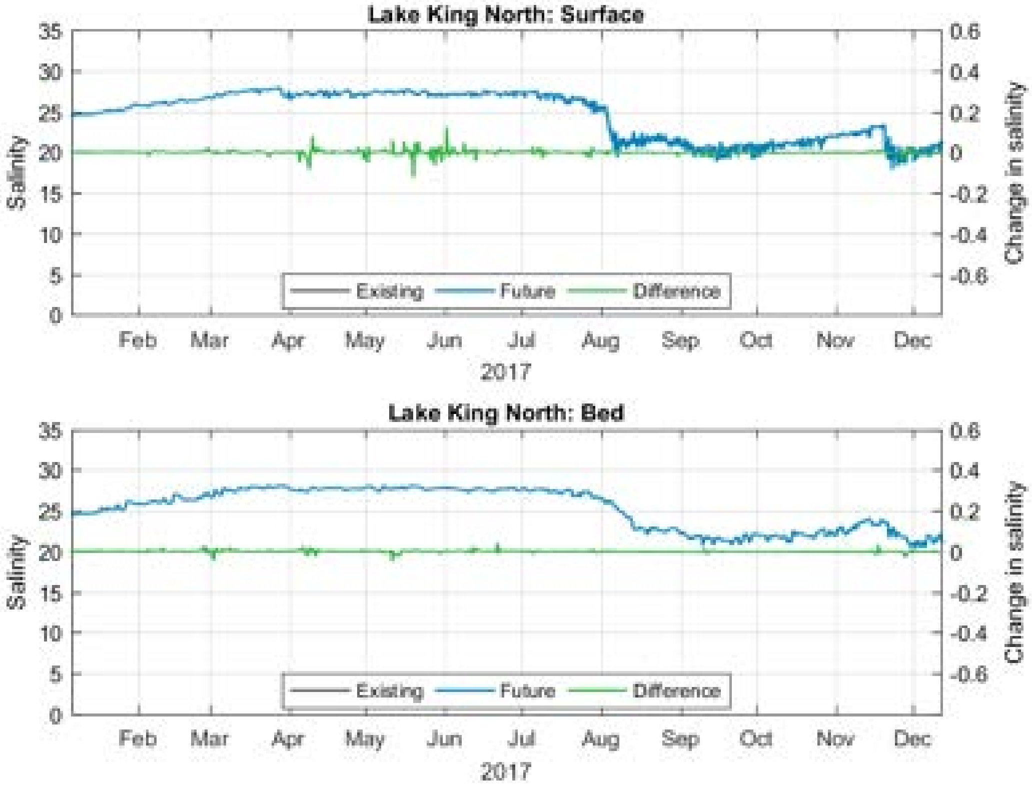

Figure 80. **Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake King North for the astronomical forcing simulation over 12 months.**

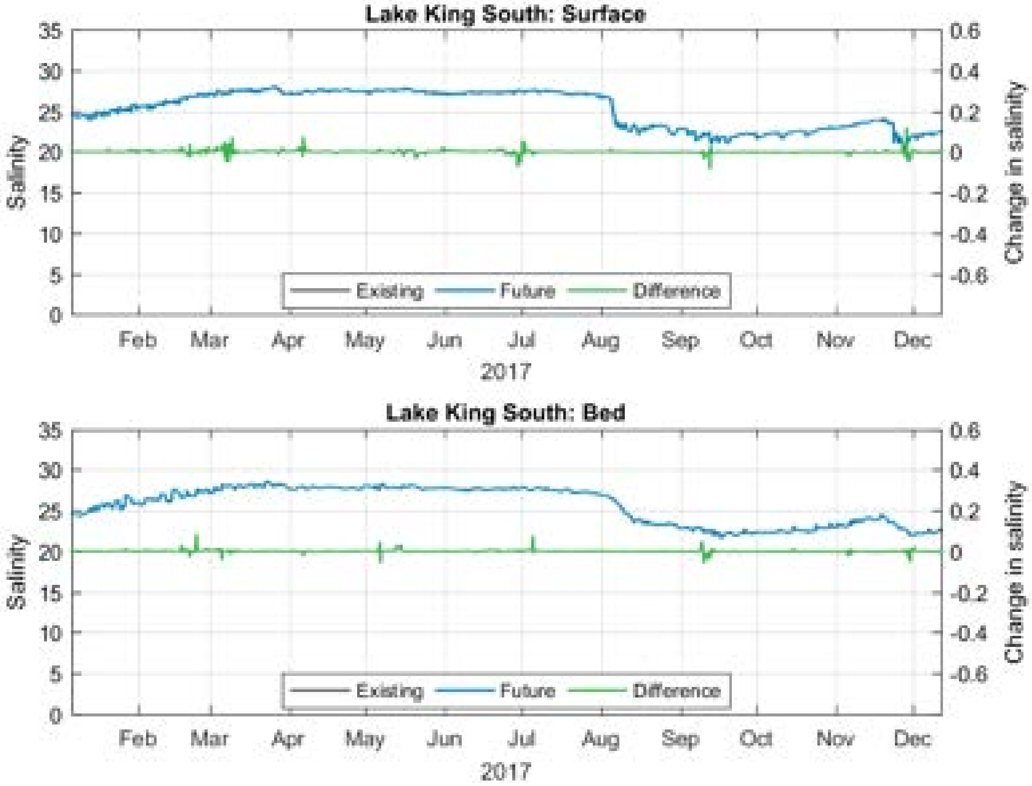

Figure 81. Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake King South for the astronomical forcing simulation over 12 months.

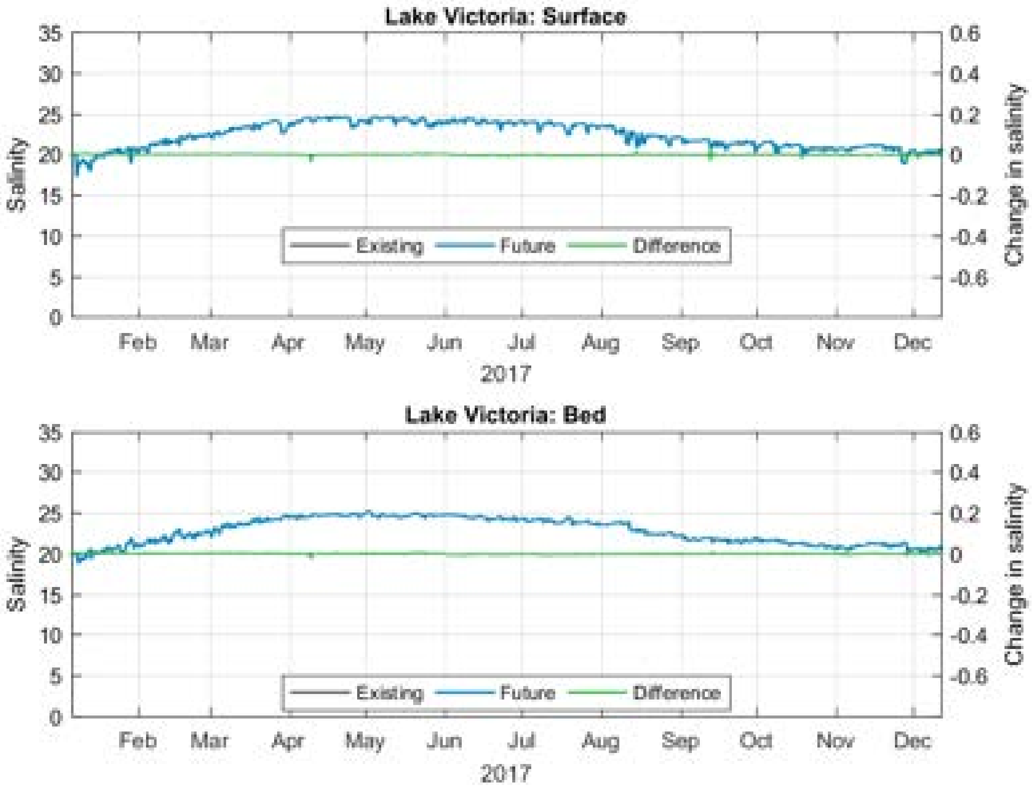

Figure 82. Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake Victoria for the astronomical forcing simulation over 12 months.

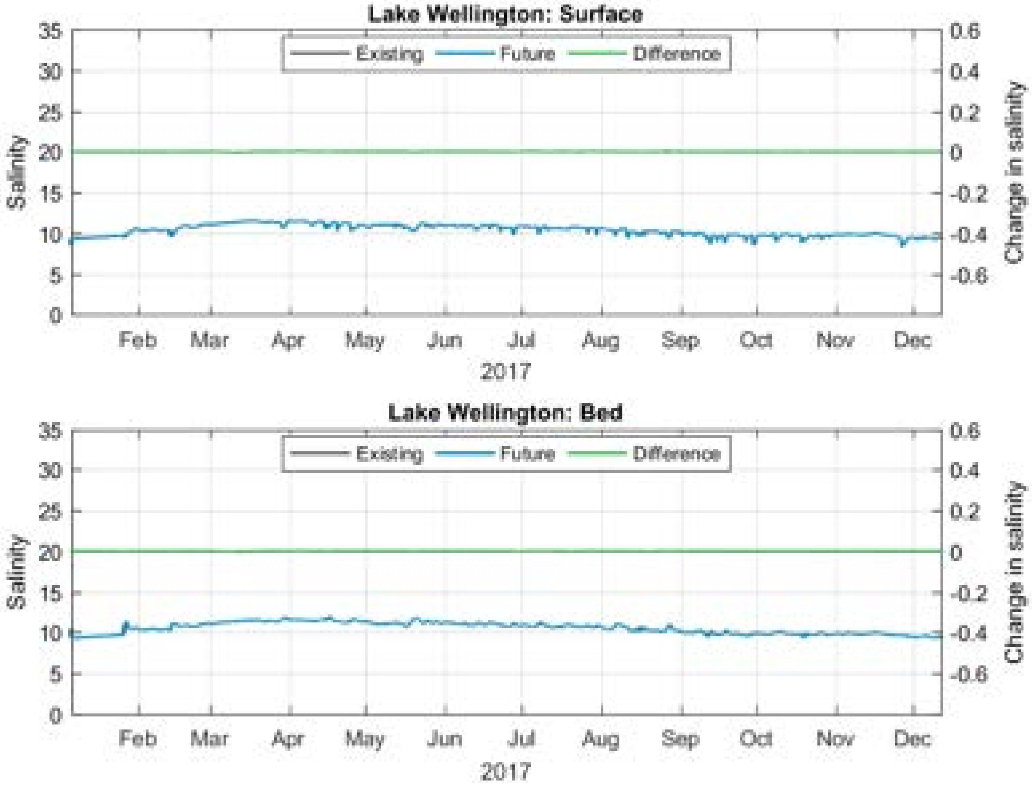

Figure 83. Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake Wellington for the astronomical forcing simulation over 12 months.

5.2.2.2. Surge and Freshwater Forcing

The change in maximum, minimum and median surface salinity over the 12 month astronomical forcing simulation are shown in Figure 84 to Figure 86, while the change in maximum salinity range over the 12 months is shown in Figure 87. The plots show the following:

- maximum salinity: there is predicted to be limited change to the maximum salinity. The only change is predicted to be a small area with a reduction in salinity of up to 0.2 psu within the channel to the east of Bullock Island;
- minimum salinity: there are predicted to be increases in salinity of up to 1 psu (predominantly less than 0.2 psu) in the North Arm, within the channel to the east of Bullock Island and within Cunninghame Arm. There are also predicted to be both increases and decreases in salinity immediately offshore of the Entrance Channel and along the offshore shoreline to the west and east of the Entrance Channel. The largest change in this area is ±1 psu in the surface salinity immediately adjacent to the western side of the Entrance Channel;
- median salinity: the only predicted changes to the median salinity are small, localised increases of up to 0.2 psu in the surface salinity in North Arm and within the channel to the east of Bullock Island; and
- maximum range: the only changes to the maximum salinity range are predicted to occur in the channels around Lakes Entrance and directly offshore of the Entrance Channel. There is predicted to be a reduction in salinity range of up to 1 psu (predominantly less than 0.2 psu) in the North Arm, within the channel to the east of Bullock Island and within Cunninghame Arm. There are also predicted to be both increases and decreases in the range of salinity immediately offshore of the Entrance Channel and along the offshore shoreline to the west and east of the Entrance Channel. The largest change in this area

are ±1 psu in the surface salinity immediately adjacent to the western side of the Entrance Channel, with increases along the shoreline and decreases directly offshore. Similar changes are also shown for the 90th percentile salinity range, although the extent and magnitude of the change is reduced.

To show how these changes to surface salinity statistics relate to changes over time, time series plots of existing and future surface and bed salinity, as well as changes in salinity due to the future dredging, at the long term salinity monitoring sites maintained by EPA are shown in Figure 88 to Figure 92. The plots show that the changes in the surface salinity are typically larger than the changes in the bed. The largest magnitude changes are predicted at Lake King South, with short duration changes in both surface and bed salinity of up to ±0.4 psu. At all sites the plots show that the changes in salinity occur as short duration spikes which only occur irregularly over the 12 month period. There are no gradual increases or decreases in salinity predicted at any of the sites as a result of the future dredging.

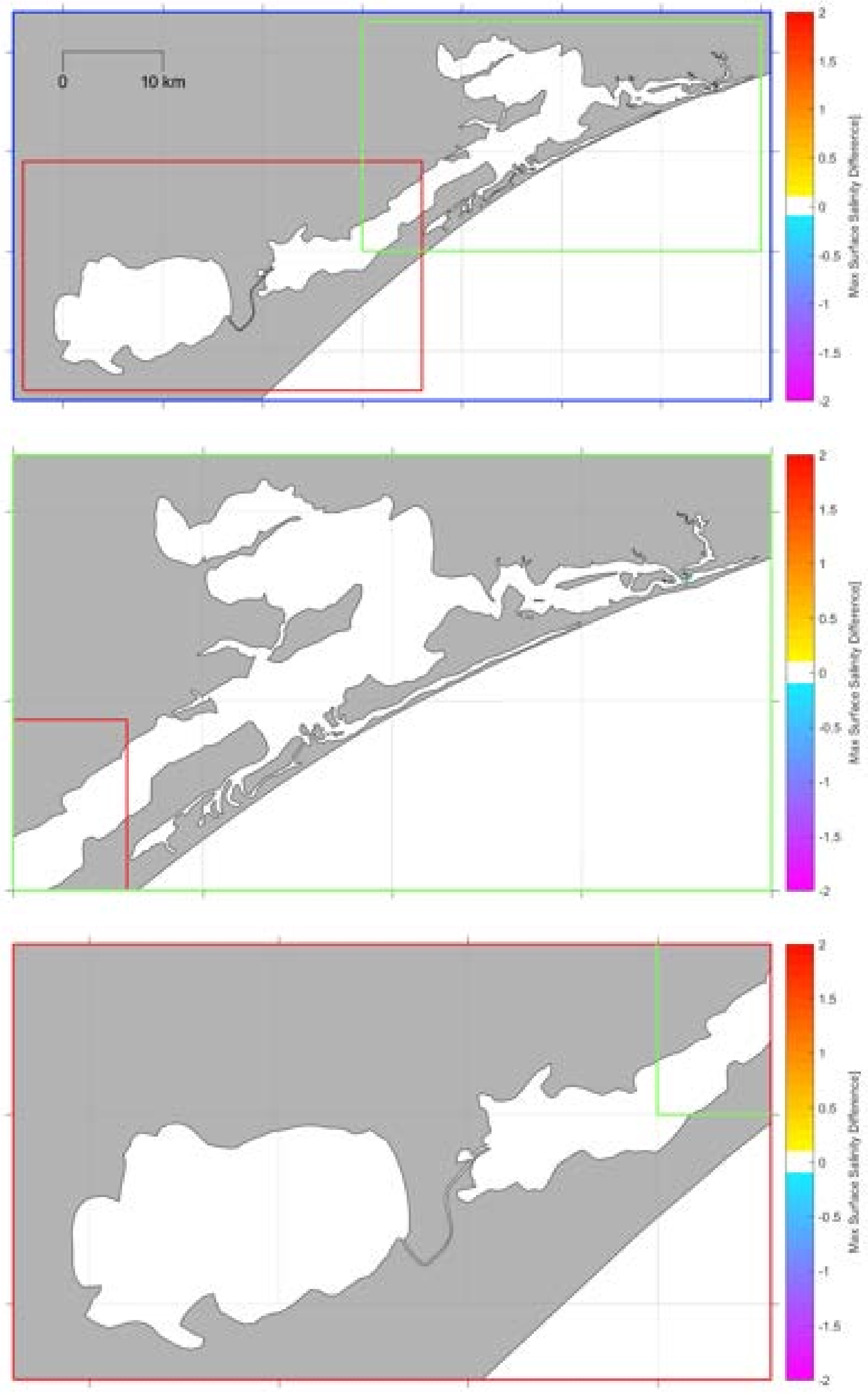

Figure 84. Modelled change in maximum surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

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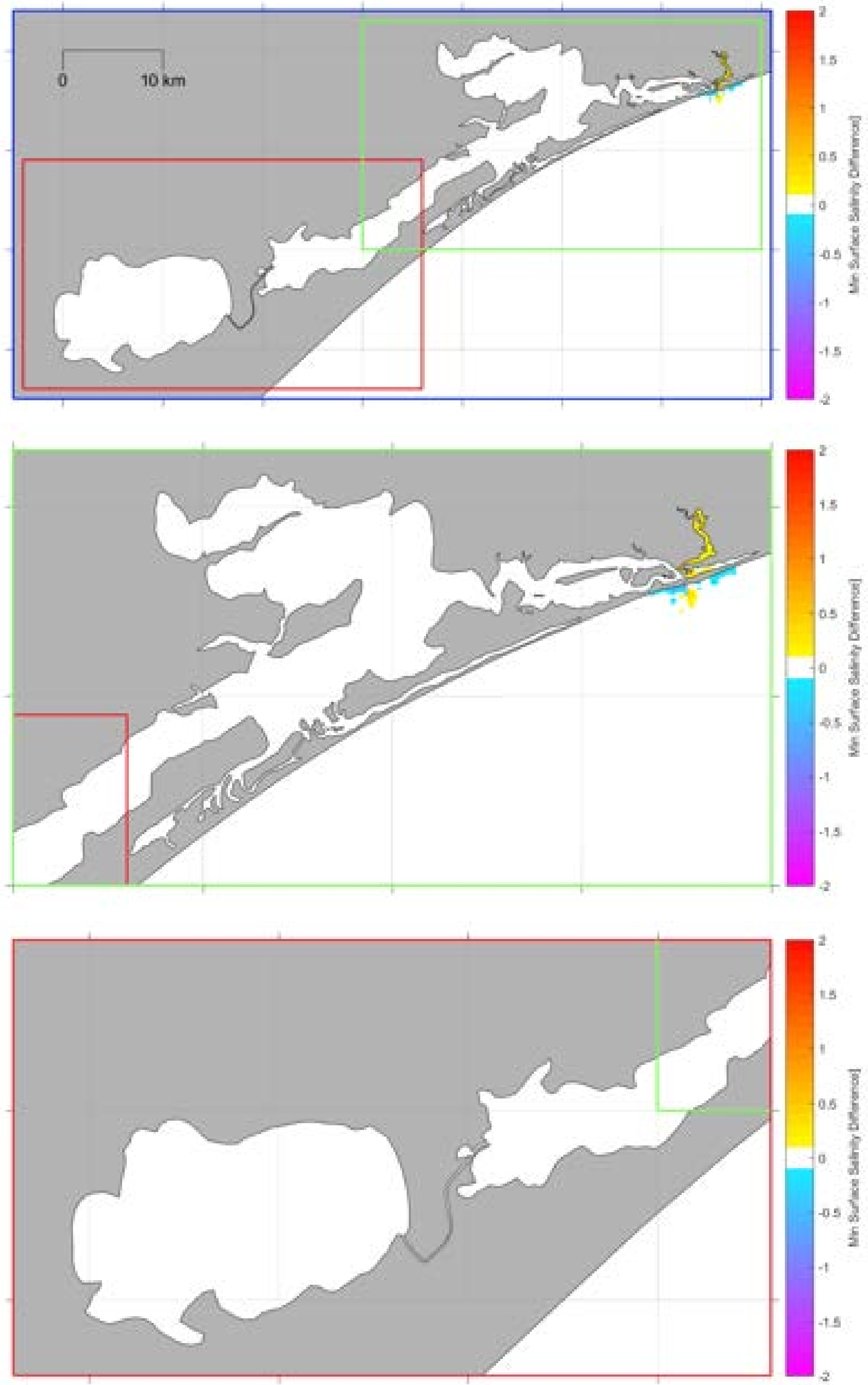

Figure 85. Modelled change in minimum surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

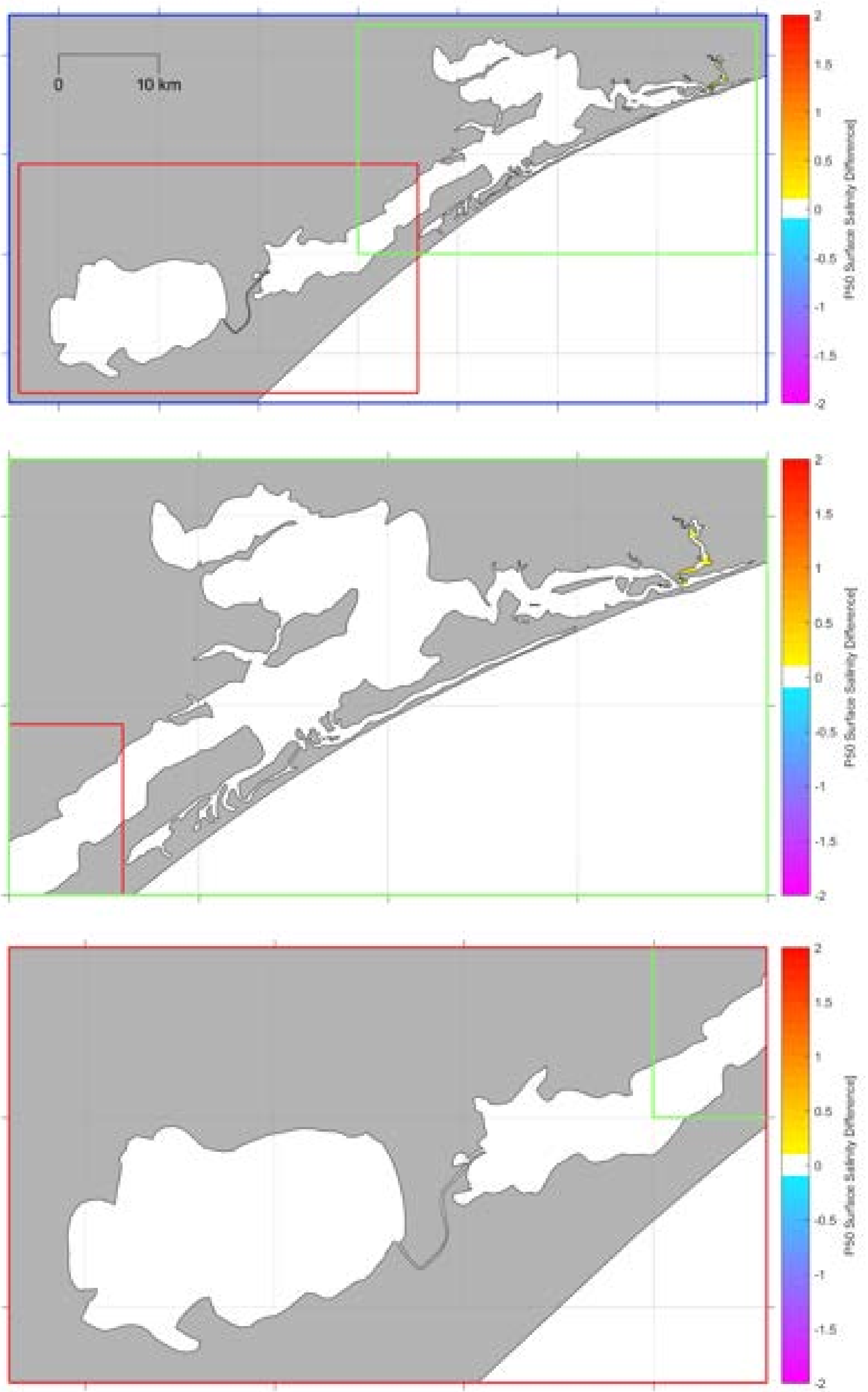

Figure 86. Modelled change in median surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

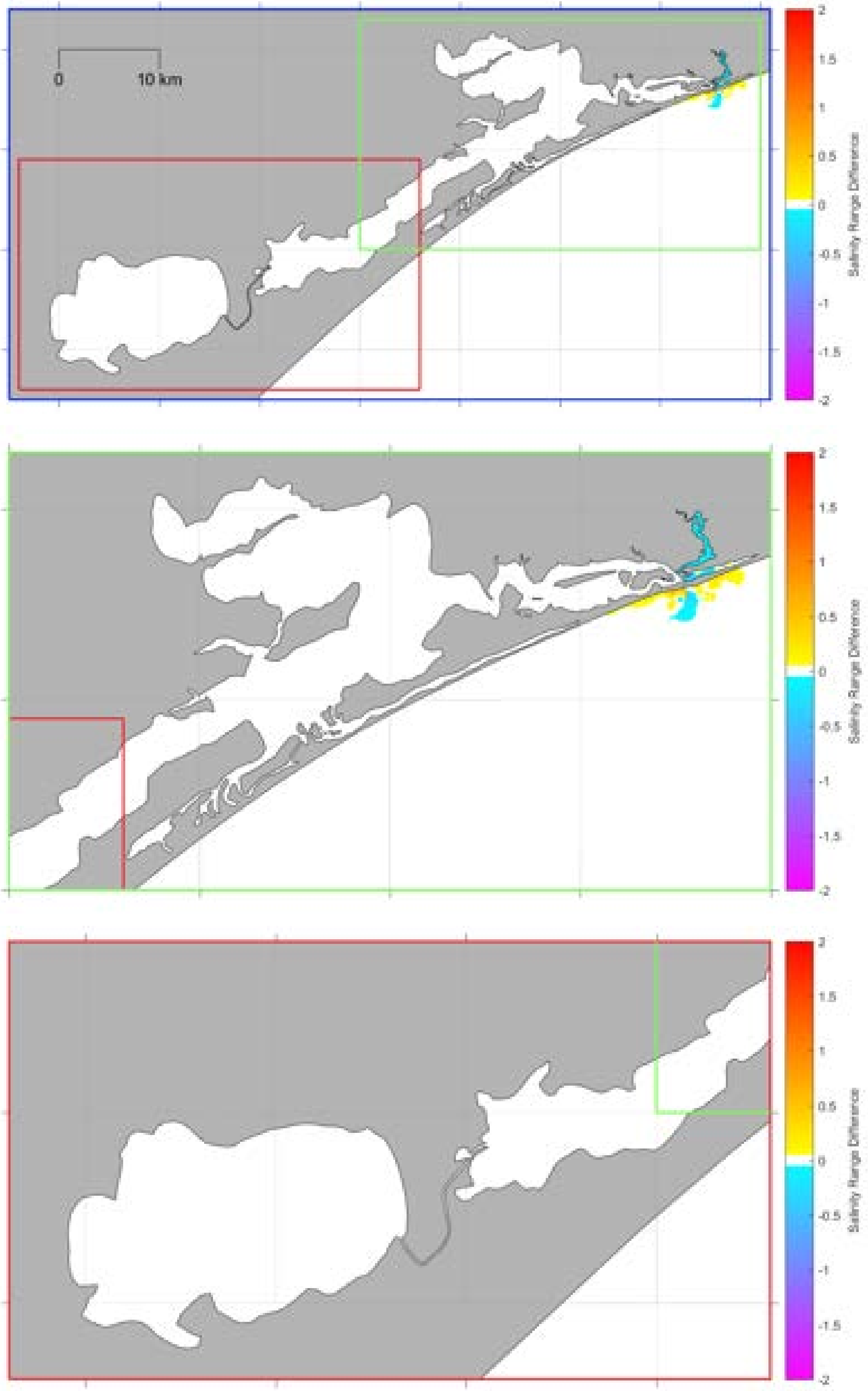

Figure 87. Modelled change in maximum surface salinity range over 12 months with surge and freshwater forcing due to the future dredging.

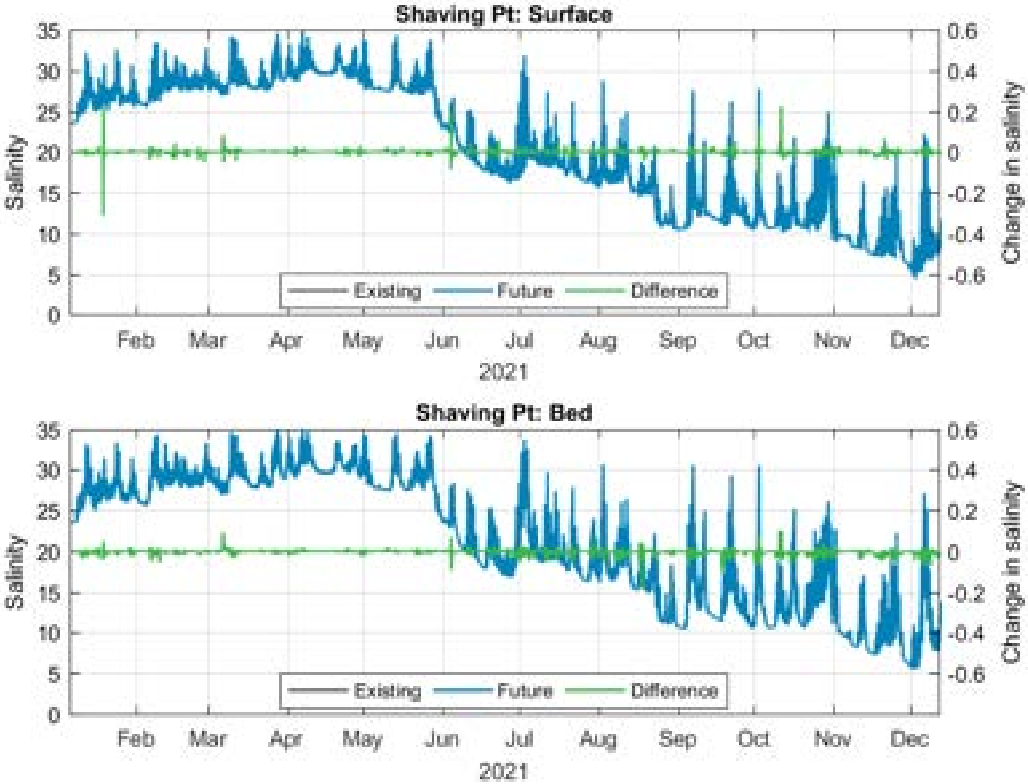

Figure 88. Modelled surface (top) and bed (bottom) salinity and change in salinity at Shaving Pt for the surge and freshwater forcing simulation over 12 months.

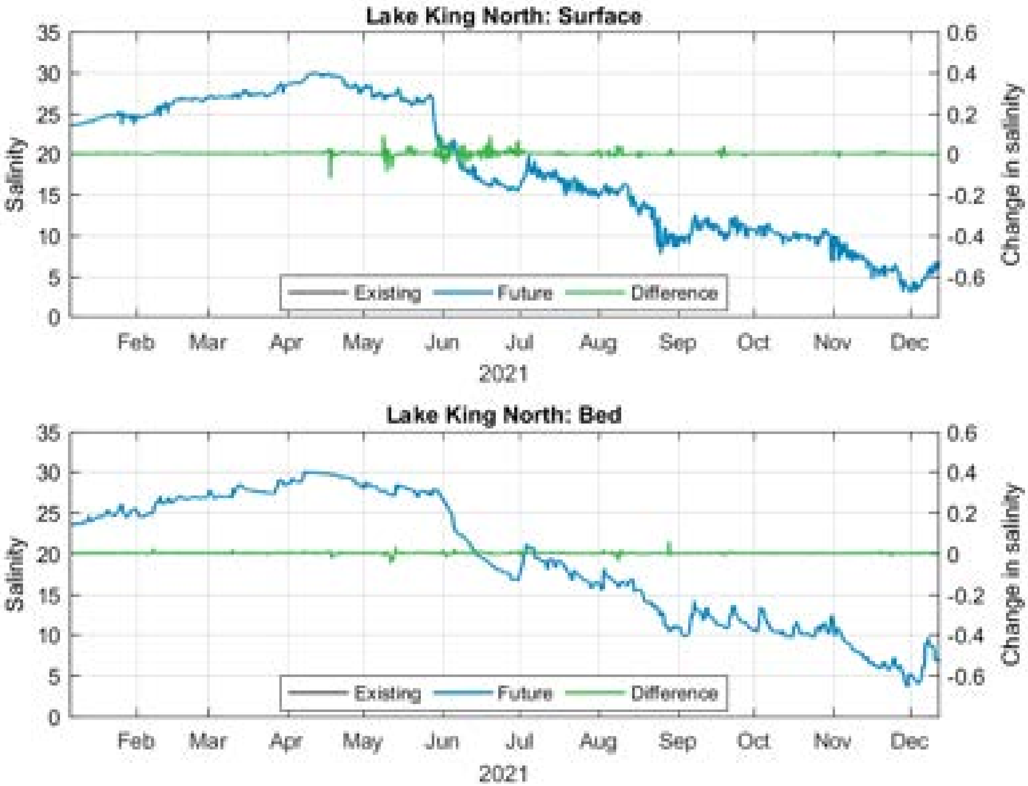

Figure 89. Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake King North for the surge and freshwater forcing simulation over 12 months.

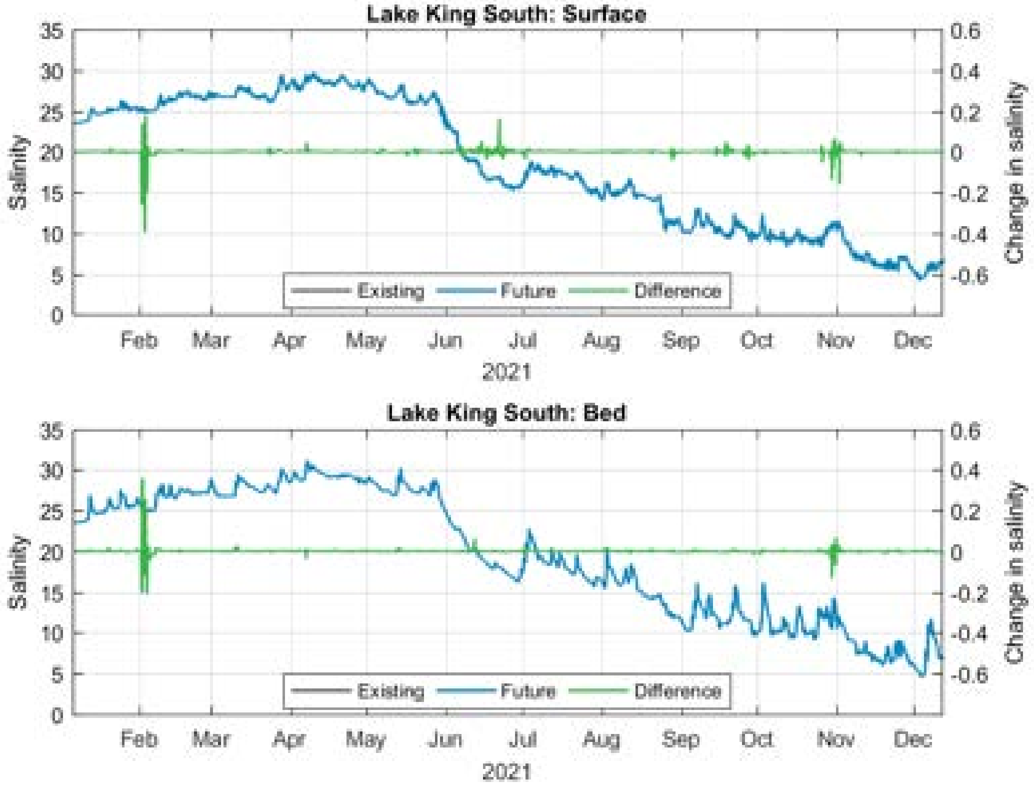

Figure 90. **Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake King South for the surge and freshwater forcing simulation over 12 months.**

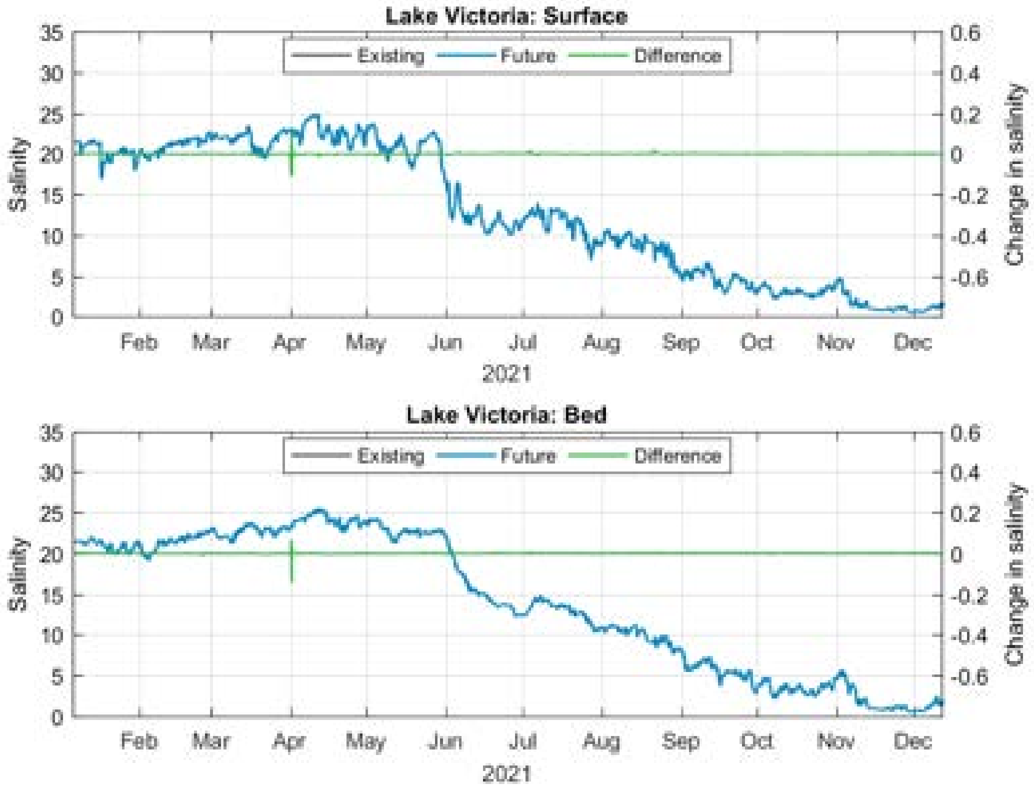

Figure 91. **Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake Victoria for the surge and freshwater forcing simulation over 12 months.**

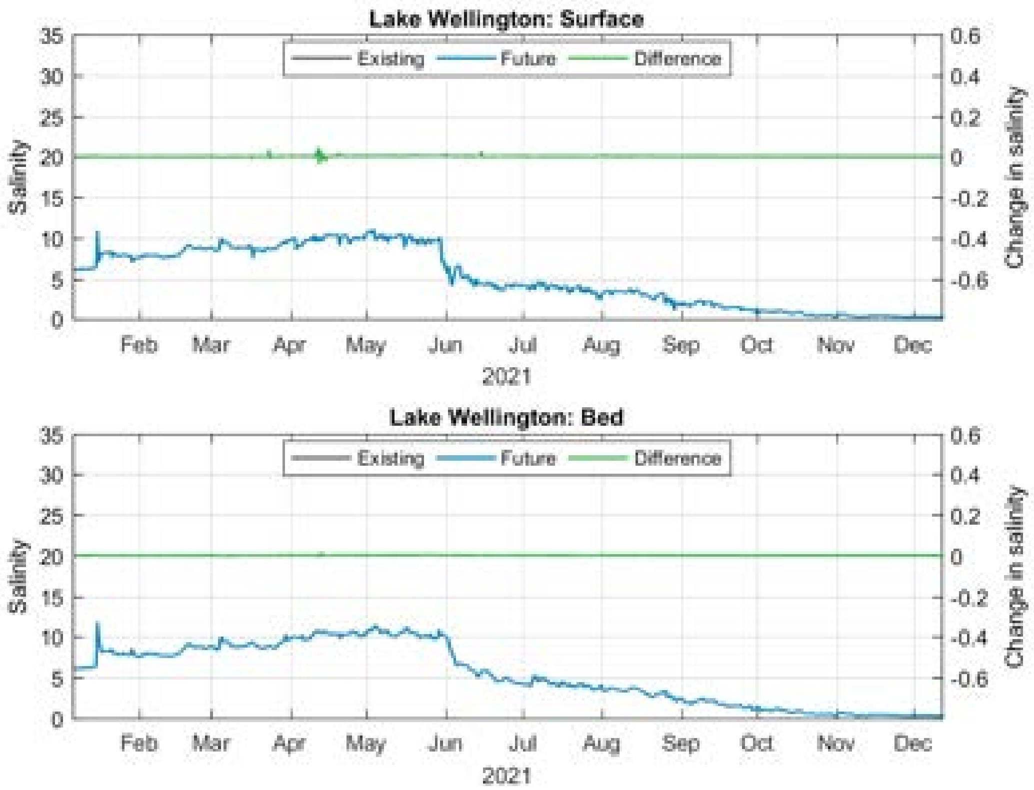

Figure 92. Modelled surface (top) and bed (bottom) salinity and change in salinity at Lake Wellington for the surge and freshwater forcing simulation over 12 months.

5.2.3. Discussion

The results from the numerical modelling have predicted similar changes due to the future dredging for the simulations with astronomical tide forcing and storm surge and freshwater input forcings. Although the results showed some localised areas with low magnitude changes in Lake King and Lake Reeve, the only changes of sufficient magnitude and extent to potentially be measured were located in the Lakes Entrance channels and directly offshore of the Entrance Channels. The predicted changes can be summarised for the different areas as follows:

- Hopetoun Channel: the largest predicted change in water level occurred at the western end of Hopetoun Channel, which is also where the largest depth change due to the future navigable channel extension is located. At the western end of Hopetoun Channel an increase in maximum water level range of up to 0.025 m was predicted due to both increases in maximum water level and reductions in minimum water level. The changes in water level in this area are not predicted to result in a change in salinity;
- West of Hopetoun Channel to Metung: this area was predicted to have a small increase in maximum water level range of up to 0.002 m, this increase was predominantly due to a predicted increase in maximum water level. The changes in water level in this area are not predicted to result in a change in salinity;
- Reeve Channel, North Arm, Cunninghame Arm and Entrance Channel: there is predicted to be a reduction in maximum water level range in these channels of typically around 0.002 m, but up to 0.01 m. This reduction in range is due to a combined reduction in maximum water level and an increase in minimum water levels. Within the North Arm and Cunninghame Arm there is also predicted to be an increase in minimum salinity, which results in a reduction in the maximum salinity range of up to 1 psu (predominantly less than 0.2 psu); and

- Offshore: changes to water levels and salinity offshore of the Entrance Channel vary between the two simulations, with the changes significantly larger during the surge and freshwater forcing simulation. Large scale changes in water level offshore are only predicted for the surge and freshwater forcing simulation, with a large area (10 km by 5 km) approximately 5 km to the south of the Entrance Channel predicted to have an increase in maximum water level of up to 0.002 m. The offshore areas with predicted changes to salinity are located closer to the Entrance Channel, with areas adjacent to the shoreline up to 3 km to the west and east of the Entrance Channel predicted to have an increase in salinity range of up to 1 psu (the majority is less than 0.1 psu), while an area adjacent to the Entrance Channel extending 2 km to the south is predicted to have a reduction in salinity range of up to 1 psu (the majority is less than 0.1 psu).

The primary driver for most of these changes is that the western extension of Hopetoun Channel as part of the future dredging acts to increase the tidal prism which flows through this channel (both on the flood and ebb flows). This, in turn results in a small reduction in the tidal prism which flows through Reeve Channel and also the channels to the east of Reeve Channel (North Arm and Cunninghame Arm). This very small change in the balance of how the tidal prism flows into and out of Gippsland Lakes results in a localised increase in water level range in Hopetoun Channel, and a small increase between Hopetoun Channel and Metung. In contrast, the change results in a reduction in water level range in the channels to the east of Hopetoun Channel. The change in tidal prism also means that slightly less of the lower salinity water from the upstream lakes is transported through Reeve Channel during the ebb stage of the tide (or during large flood events), which results in a slight increase in the minimum salinity in the North Arm and Cunninghame Arm. The predicted offshore changes in water level and salinity due to the future dredging are expected to be a result of minor changes in how the ebb tide flows out of the Entrance Channel during periods of high freshwater discharge, which results in localised changes to both water level and salinity.

6. Summary

GP commissioned PCS to undertake data analysis and numerical modelling to support the GLOA Program (2023-33). The study has included the analysis of historical measured water level data as well as hydrodynamic modelling to predict potential changes to water levels and salinity within Gippsland Lakes due to proposed future dredging.

The analysis of historical measured water level showed an increasing tidal range in Gippsland Lakes over the last 30 years, with the rate of increase reducing since 2008. The limited available data indicated that the change in tidal range which occurred from 2003 to 2008 was due to a gradual ongoing increase in tidal range over this period as opposed to a large jump which occurred over a single year. This suggests that the change was not due to the change from using a side-cast dredge in 2007 to using a TSHD in 2008. The results from the analysis could not identify a driver (or drivers) which was responsible for the gradual increase in tidal range which occurred from 1994 to 2002 and again from 2003 to 2008. It was therefore considered most likely that the gradual increase was a result of multiple factors which could include natural processes and dredging.

A detailed 3-Dimensional hydrodynamic model was setup for the Gippsland Lakes. The model was calibrated and validated using measured water level and salinity data from multiple locations within the Gippsland Lakes over two 12 month periods. The calibration and validation periods covered different conditions and have shown that the model is able to represent the changes in water level and salinity in the Gippsland Lakes resulting from astronomical tides, offshore storm surge, freshwater inputs and evaporation processes.

The 3D hydrodynamic model was setup to represent the existing bathymetry and the future dredged bathymetry. The model was then used to simulate the water level and salinity over two 12 month periods for the following cases:

- offshore forcing due to just astronomical tide, with no offshore storm surge, and with low freshwater inputs; and
- offshore forcing due to the astronomical tide and offshore storm surges along with high freshwater inputs.

The results from the numerical modelling predicted similar changes due to the future dredging for both simulations, with the largest changes to both water levels and salinity predicted to occur in the channels around Lakes Entrance and directly offshore of the Entrance Channel. The modelling did predict some localised areas with very low magnitude changes in lake King and Lake Reeve, but these changes would be too small and localised to be measurable. The predicted changes around the Lakes Entrance region are summarised below:

- Hopetoun Channel: the largest predicted change in water level occurred at the western end of Hopetoun Channel, with predicted increases in high water levels and reductions in low water levels resulting in an increase in the maximum water level range of up to 0.025 m. This is the location of the largest depth change due to the future channel extension. The changes in water level in this area were not predicted to result in a change in salinity;
- West of Hopetoun Channel to Metung: this area was predicted to have a small increase in maximum water level range of up to 0.002 m, this increase was predominantly due to a predicted increase in maximum water level. The changes in water level in this area were not predicted to result in a change in salinity;
- Reeve Channel, North Arm, Cunninghame Arm and Entrance Channel: there was predicted to be a reduction in maximum water level range in these channels of typically around 0.002 m, but up to 0.01 m. This reduction in range was due to a combined reduction in maximum water level and an increase in minimum water levels. Within the

North Arm and Cunninghame Arm there was also predicted to be an increase in minimum salinity, which resulted in a reduction in the maximum salinity range; and

- Offshore: changes to water levels and salinity offshore of the Entrance Channel was variable between the two simulations, with the changes significantly larger during the surge and freshwater forcing simulation. An offshore area of 10 km by 5 km located approximately 5 km to the south of the Entrance Channel was predicted to have an increase in maximum water level of up to 0.002 m. The offshore areas with predicted changes to salinity were located closer to the Entrance Channel, with areas adjacent to the shoreline up to 3 km to the west and east of the Entrance Channel predicted to have an increase in salinity range of up to 1 psu (the majority is less than 0.1 psu), while an area adjacent to the Entrance Channel extending 2 km to the south was predicted to have a reduction in salinity range of up to 1 psu (the majority is less than 0.1 psu).

Most of these changes occur due to the extension of the western navigable section of Hopetoun Channel as part of the future dredging acting to increase the portion of the tidal prism which flows through Hopetoun Channel (both on the flood and ebb flows). This, in turn results in a small reduction in the tidal prism which flows through Reeve Channel and also the channels to the east of Reeve Channel (North Arm and Cunninghame Arm). This small change in the balance of how the tidal prism flows into and out of Gippsland Lakes results in a localised increase in water level range in Hopetoun Channel, and a small increase between Hopetoun Channel and Metung. In contrast, the change results in a reduction in water level range in the channels to the east of Hopetoun Channel. The change in portion of the tidal prism which flows through Hopetoun Channel also means that slightly less of the lower salinity water from the upstream lakes is transported through Reeve Channel during the ebb stage of the tide (or during downstream flows in large flood events), which results in a slight increase in the minimum salinity in the North Arm and Cunninghame Arm. The predicted offshore changes in water level and salinity due to the future dredging are expected to be a result of minor changes in how the ebb tide flows out of the Entrance Channel during periods of high freshwater discharge, which results in localised changes to both water level and salinity.

The predicted changes in water level resulting from the proposed future dredging being relatively localised to the GLOA dredge areas and of small magnitudes (maximum water level range increases of up to 0.025 m) provides further evidence that the historic changes in tidal range experienced in the Gippsland Lakes is unlikely to be a result of changes in dredging approach.

7. References

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Appendices

Appendix A – Model Calibration and Validation

A1. Introduction

Model calibration is the process of specifying model parameters so that the model reproduces observed data to a suitable level of accuracy. Model validation is used to confirm that the calibrated model continues to consistently represent the natural processes to the required level of accuracy, in periods other than the calibration period, without any additional adjustment to the model parameters. The calibration and validation processes provide confidence in the model results and are essential to ensure the accurate representation of variations in water levels, currents and salinity.

This section provides details of the calibration and validation undertaken for the hydrodynamic model adopted as part of this assessment.

A1.1. Calibration and Validation Standards

To demonstrate that the HD model is capable of accurately representing the natural hydrodynamic conditions the model performance has been assessed against a set of standard guideline calibration standards based on Evans (1993). For combined coastal and estuarine waters such as at Gippsland, the following performance criteria are applicable:

- Modelled water levels (WL) should be within 15 – 20% of the tidal range over a spring neap tidal cycle, or within ± 0.1 – 0.3 m;
- Timing of high water (HW) and low water (LW) should be within 15 – 25 minutes;
- Modelled peak current speeds at the time of Peak Flood (PF) and Peak Ebb (PE) should be within 10 – 20% of measured speeds over a spring neap tidal cycle, or within ± 0.2 m/s; and
- Salinity should be ±1 practical salinity unit (PSU) at the mouth and head of an estuary (the Gippsland Lakes are considered to represent a complex estuary in terms of salinity variability) and within ±5 psu in the areas where most rapid changes occur.

These standards provide a good basis for assessing model performance, but experience has shown that sometimes they can be too prescriptive and it is also necessary for visual checks to be undertaken. Under certain conditions, models can meet statistical calibration standards but appear to perform poorly. Conversely, seemingly accurate models can fall short of the guidelines. Consequently, a combination of both statistical calibration standards and visual checks has been used to ensure that the model can simulate the hydrodynamics.

A1.2. Calibration and Validation Periods

To ensure that the hydrodynamic model accurately represents the natural conditions within the study area, measured water level, current (speed and direction) and salinity data have been compared against modelled predictions. The location of available data (referred to as calibration data) are shown in Figure A1.

Modelled water levels, currents and salinity have been compared with the measured data for the following periods:

- calibration period: January to December 2021. These 12 months represent a period with significant variability in salinity due to high river discharges into Gippsland Lakes; and
- validation period: January to December 2017. These 12 months represent a period with relatively low river discharge into Gippsland Lakes and so are representative of different conditions to the calibration period.

Measured salinity profiles through the water column were available at the EPA salinity monitoring sites up to July 2020. Therefore, it has not been possible to calibrate the model using these data, but they have been used to assess the performance of the model at predicting how salinity varies through the water column during the validation period.

Figure A1. Location of measured water level (blue) and salinity (green) data available for the model calibration and validation. *Note: salinity and water level data are available at Bull Bay and water level and current data are available at the Entrance Channel*.

A1.3. Water Levels

Time series of measured and modelled water levels at the GP measurement sites (Entrance Channel and Bullock Island) and the DEECA measurement sites (Bull Bay, McLennan's Strait, Loch Sport, McMillans Strait and Metung) are shown in Figure A2 to Figure A8 for the calibration period. The plots show the measured and modelled water levels over the entire 12 month period and for 30 day periods over the summer (February) and winter (June).

The plots at the Entrance Channel and Bullock Island demonstrate the complexity of the tidal signature at Lakes Entrance, with alternating periods of large semi-diurnal and small semi-diurnal tidal variations. The plots at the other sites (herein referred to as the sites within the Lakes) show how the tidal range reduces upstream of Lakes Entrance, with non-tidal drivers becoming responsible for the largest variations in water levels.

The time series plots demonstrate that at the Entrance Channel and Bullock Island the model replicates the measured variations in water levels that occur, capturing the magnitude and timing of peak (HW and LW) levels as well as the complex shape of the tidal curve. At the sites within the Lakes the plots demonstrate that the model is generally able to replicate the variation in mean water level at the sites, whilst also being able to replicate the magnitude and timing of the smaller tidal variations. There are periods when the model over-predicts the mean water level at the sites (e.g. mid July to early August), these are during periods of high freshwater discharge and rainfall and indicate that for some events the freshwater discharge is slightly too high. However, overall the model can be considered to be providing a good representation of the measured water levels at the sites.

To further assess the level of calibration achieved (and to ensure that the model performs within the calibration standards set out in Section A.1.1), a statistical analysis was undertaken to quantify the difference in elevation and timing between the modelled and measured water levels at the Entrance Channel and Bullock Island over the 30 day summer and winter periods. The magnitude of the tidal signal was insufficient at the sites within the Lakes to allow a quantitative comparison to be undertaken. The results of the statistical analysis are presented in Table A1. The table shows that all the guideline standards are achieved at the Entrance Channel and all guideline standards except for the phase difference during the winter period are achieved at Bullock Island. The phase difference at Bullock Island shows that the model high water is late and the model low water is early by more 30 minutes. However, the overall phase difference of all measured water levels was only 1 minute, indicating that the differences in timing of high and low water are due to small differences in the timing of these rather than an overall difference in the tidal phasing.

Time series of measured and modelled water levels over the model validation period are shown in Figure A9 to Figure A15. As for the model calibration period, the plots generally show that the model is able to represent the measured water levels at all the sites. There are periods when the model under-predicts the mean water level at the sites within the Lakes (e.g. mid November to start of December), these are during periods of low freshwater discharge and rainfall and indicate that the balance between the inputs (river discharge and rainfall) and losses (evaporation) of water in the Lakes is slightly different to what actually occurred. However, overall the model can be considered to be providing a good representation of the measured water levels at all the sites. To further assess the model validation, a statistical analysis was undertaken at the Entrance Channel and Bullock Island over the 30 day summer and winter periods. The results of the statistical analysis are presented in Table A2. The table shows that all the guideline standards are achieved at the Entrance Channel and all guideline standards except for the phase difference at low water during the winter period are achieved at Bullock Island. As for the model calibration, the overall phase difference was only 1 minute, showing that the modelled tidal signal is in phase with the measured signal, just there was a slight difference in the timing of high and low water.

Table A1. Statistics for comparison of modelled and measured water levels during the calibration period.

Site	WL difference (m)			WL difference (%)		Phase difference (minutes)		
	HW	LW	RMS	HW	LW	HW	LW	All
February 2021								
Lakes Entrance	0.01	0.02	0.03	2	5	-1	13	3
Bullock Island	-0.03	0.02	0.04	-5	3	-17	18	1
June 2021								
Lakes Entrance	0.07	0.05	0.08	16	12	22	-1	0
Bullock Island	0.07	0.03	0.09	11	5	34	-35	-1

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

*Values in **blue** are above the calibration standard*

Table A2. Statistics for comparison of modelled and measured water levels during the validation period.

Site	WL difference (m)			WL difference (%)		Phase difference (minutes)		
	HW	LW	RMS	HW	LW	HW	LW	All
February 2017								
Lakes Entrance	-0.01	0.01	0.03	-2	2	-4	15	6
Bullock Island	0	0.01	0.04	0	2	-24	19	1
June 2017								
Lakes Entrance	-0.02	0	0.03	-5	0	15	7	5
Bullock Island	0	0.02	0.03	0	3	22	-27	1

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

*Values in **blue** are above the calibration standard*

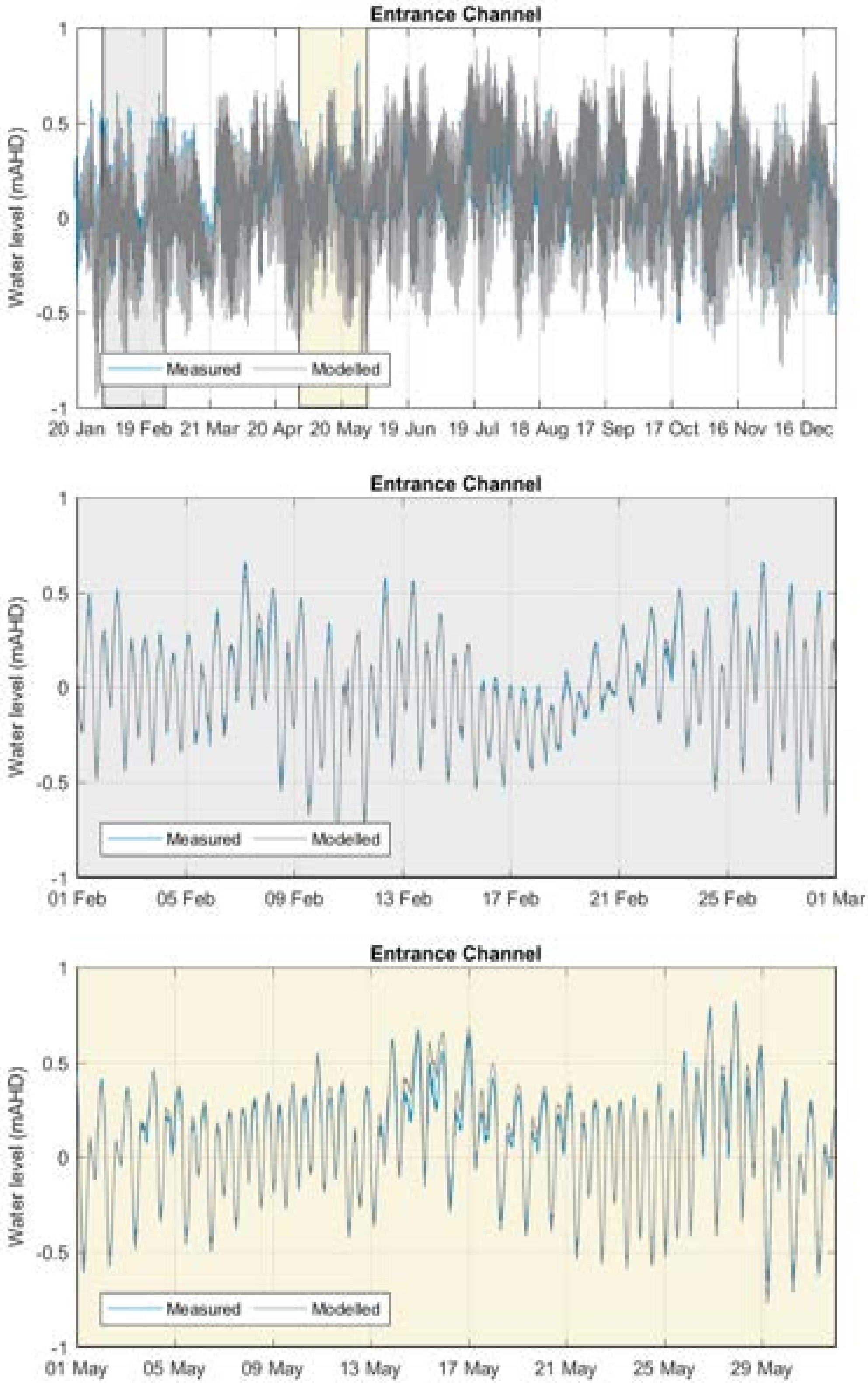

Figure A2. Measured and modelled water level at the Entrance Channel over the 2021 calibration period.

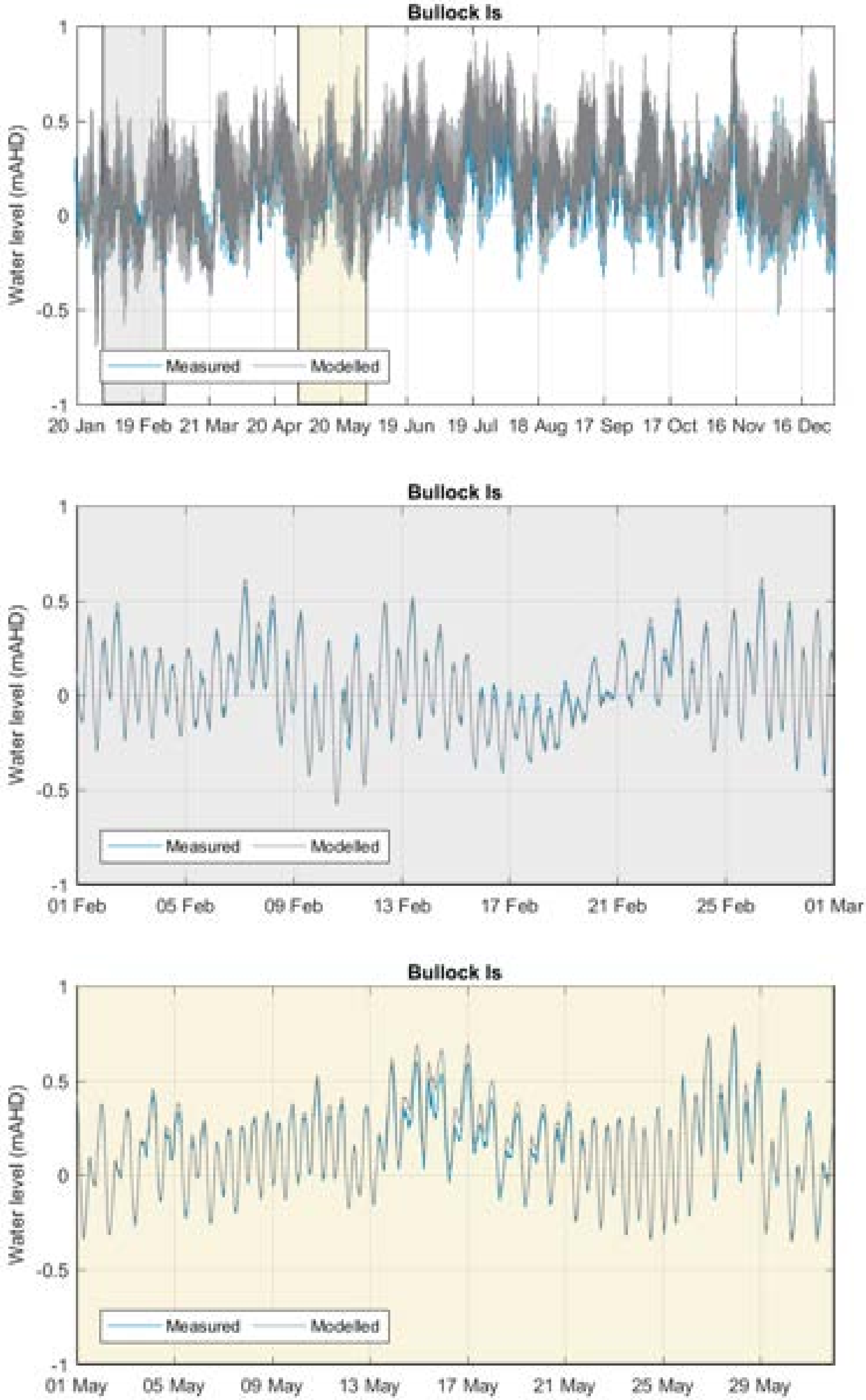

Figure A3. Measured and modelled water level at Bullock Island over the 2021 calibration period.

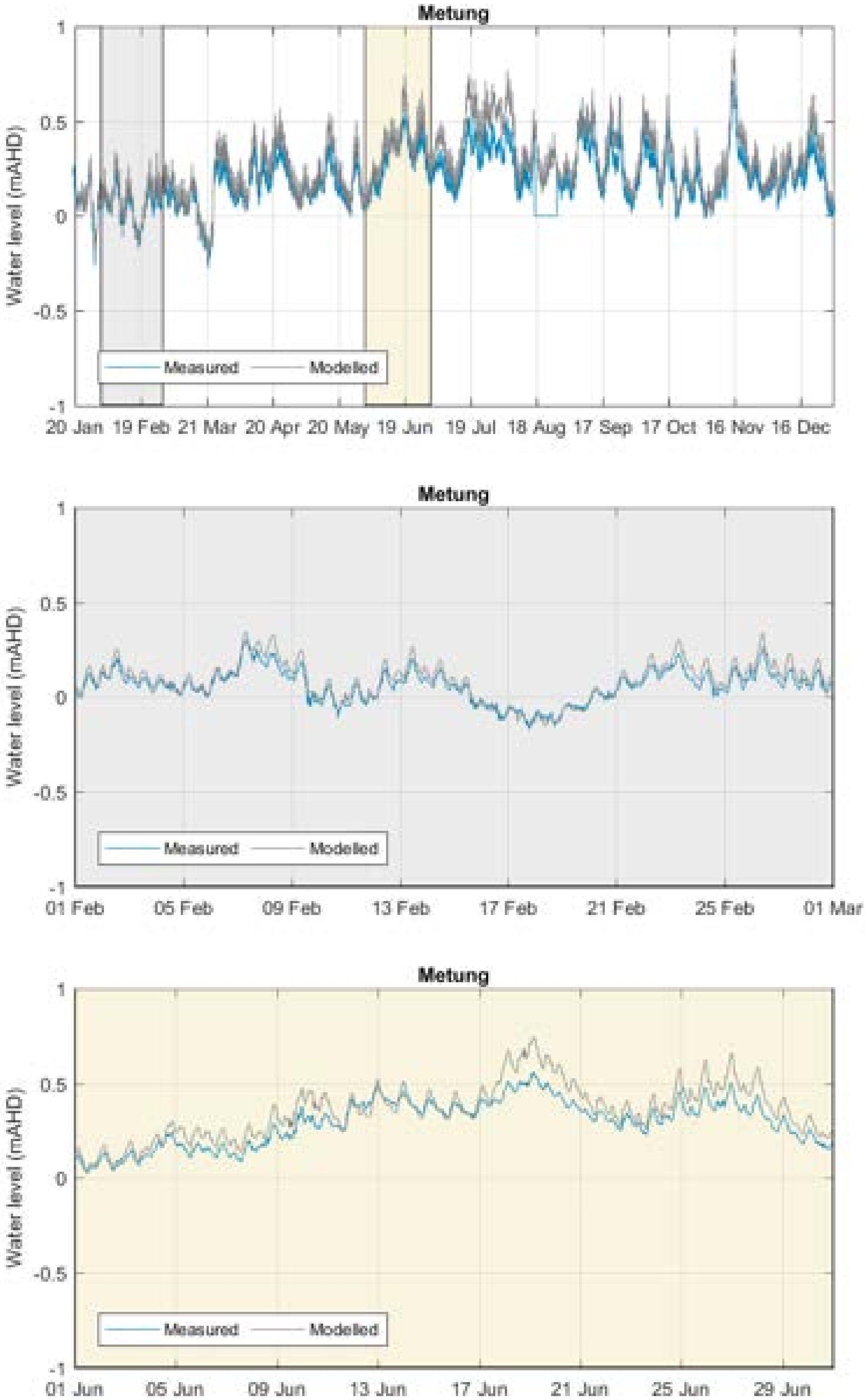

Figure A4. Measured and modelled water level at Metung over the 2021 calibration period.

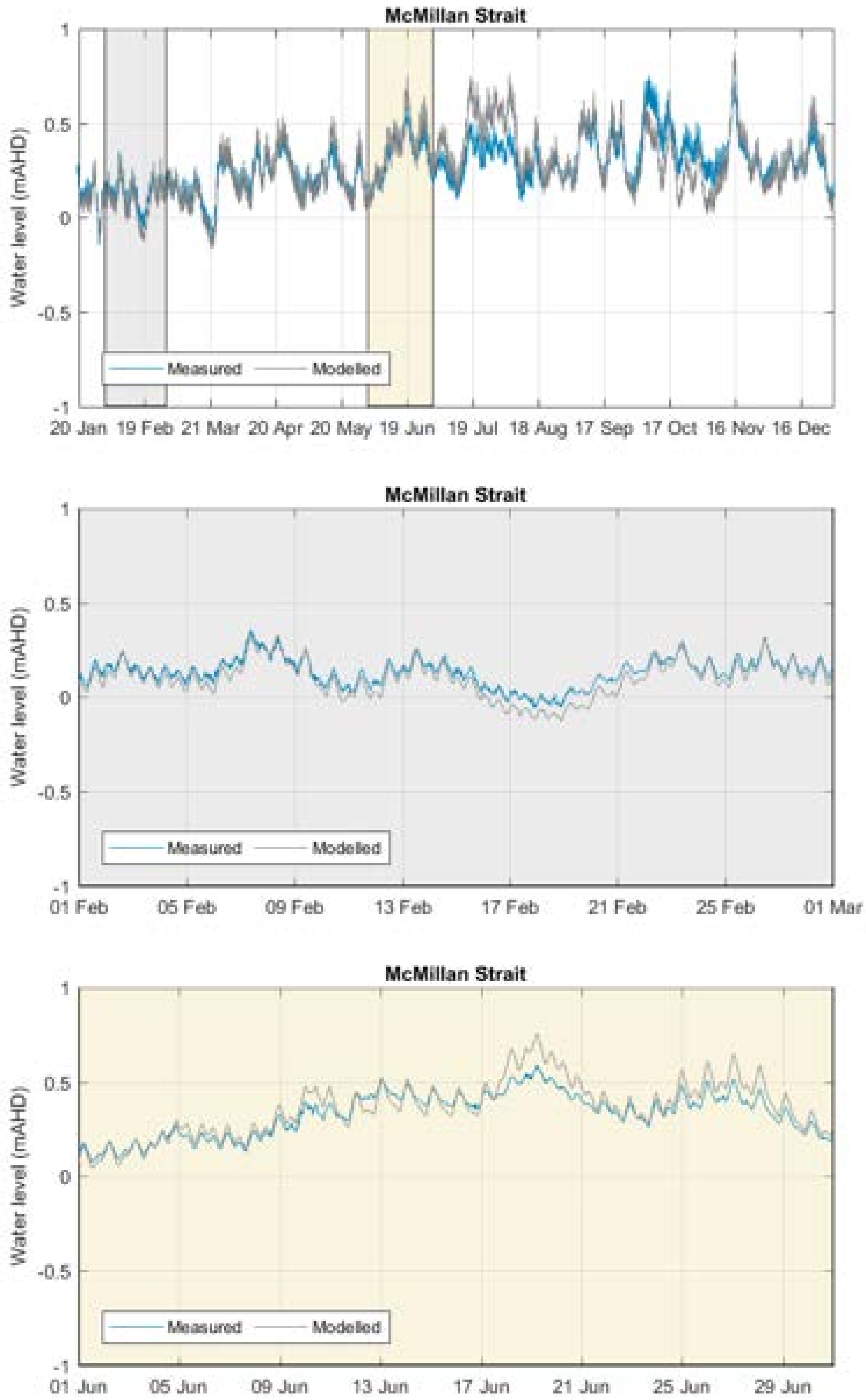

Figure A5. Measured and modelled water level at McMillan Strait over the 2021 calibration period.

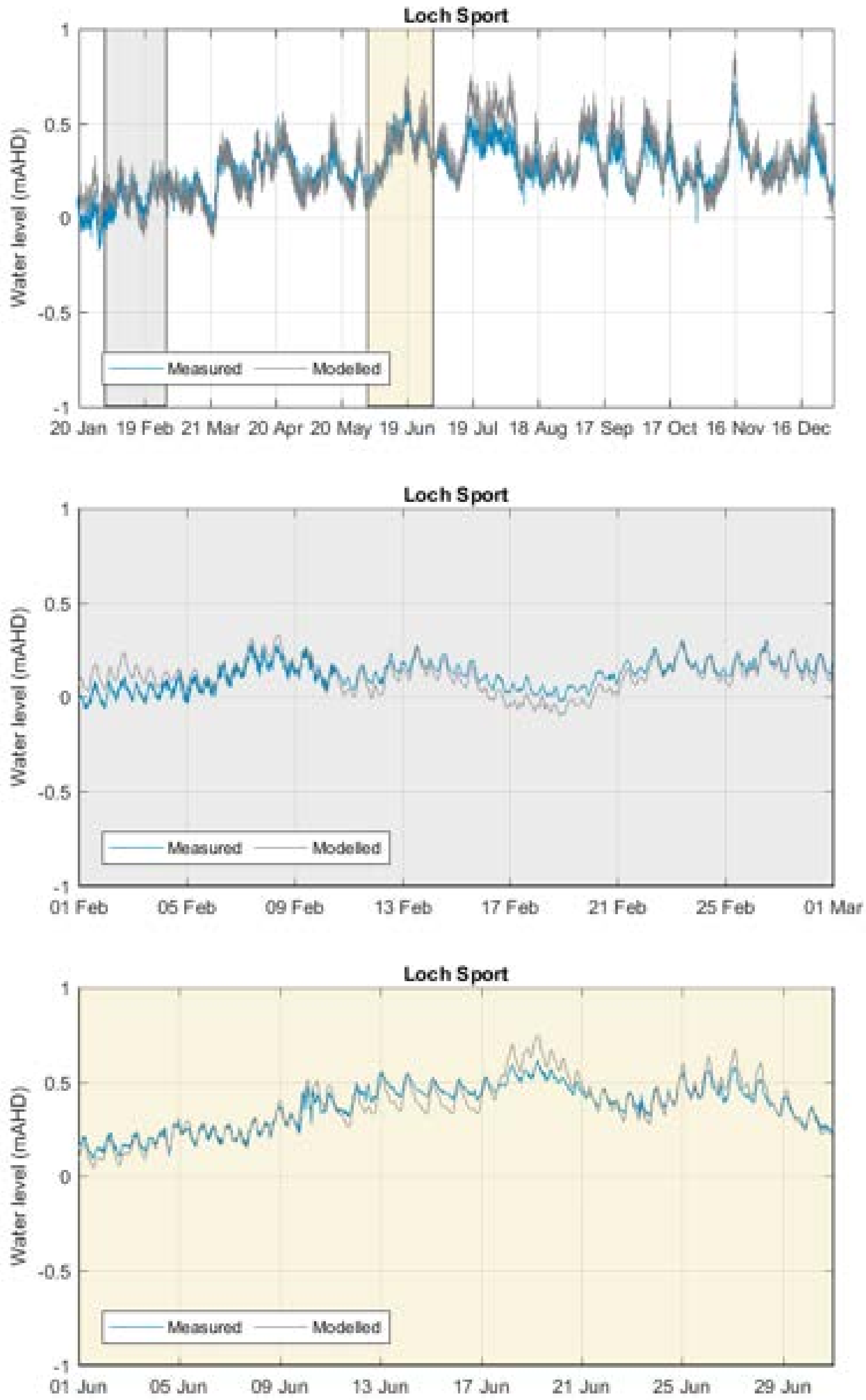

Figure A6. Measured and modelled water level at Loch Sport over the 2021 calibration period.

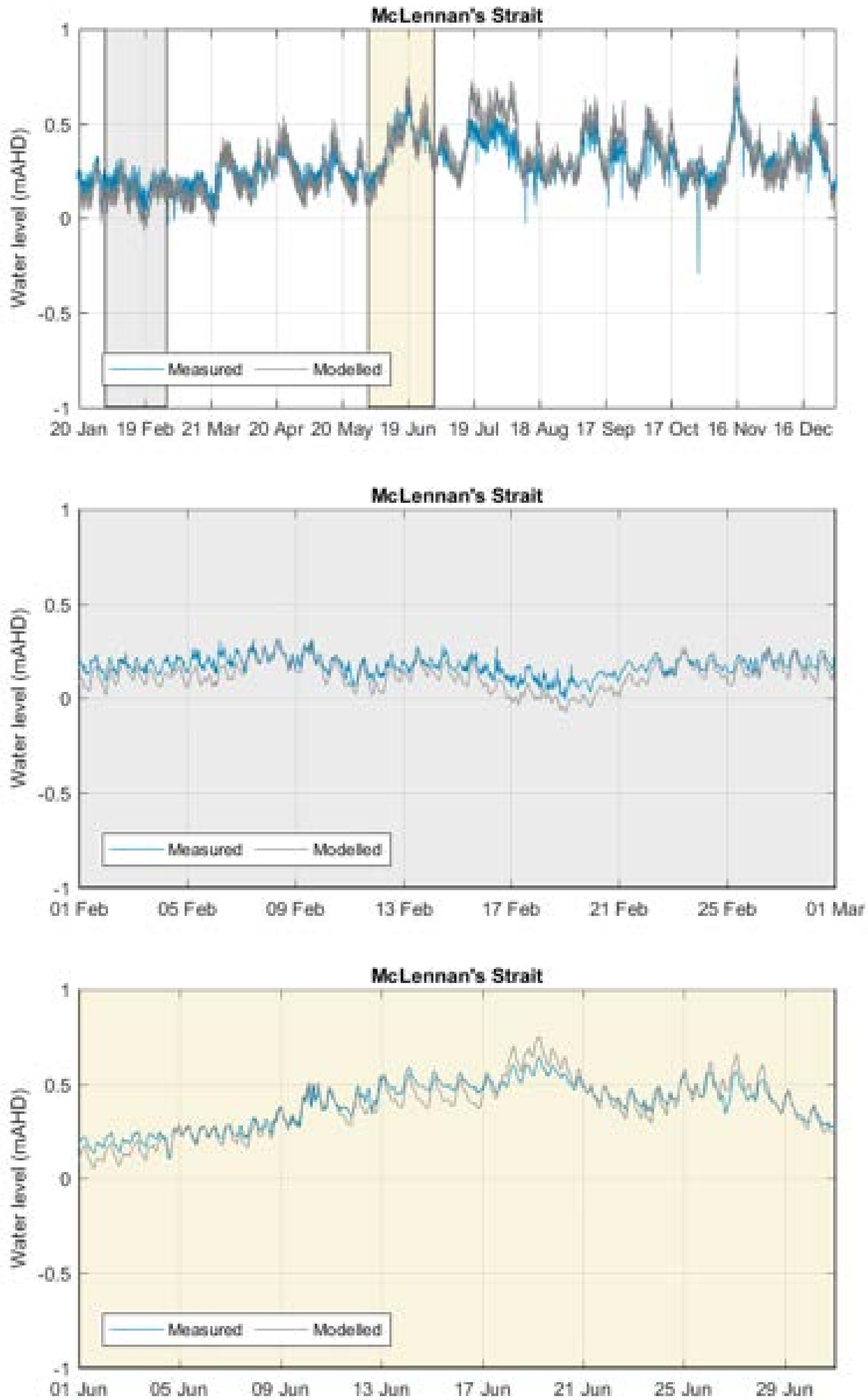

Figure A7. Measured and modelled water level at McLennan's Strait over the 2021 calibration period.

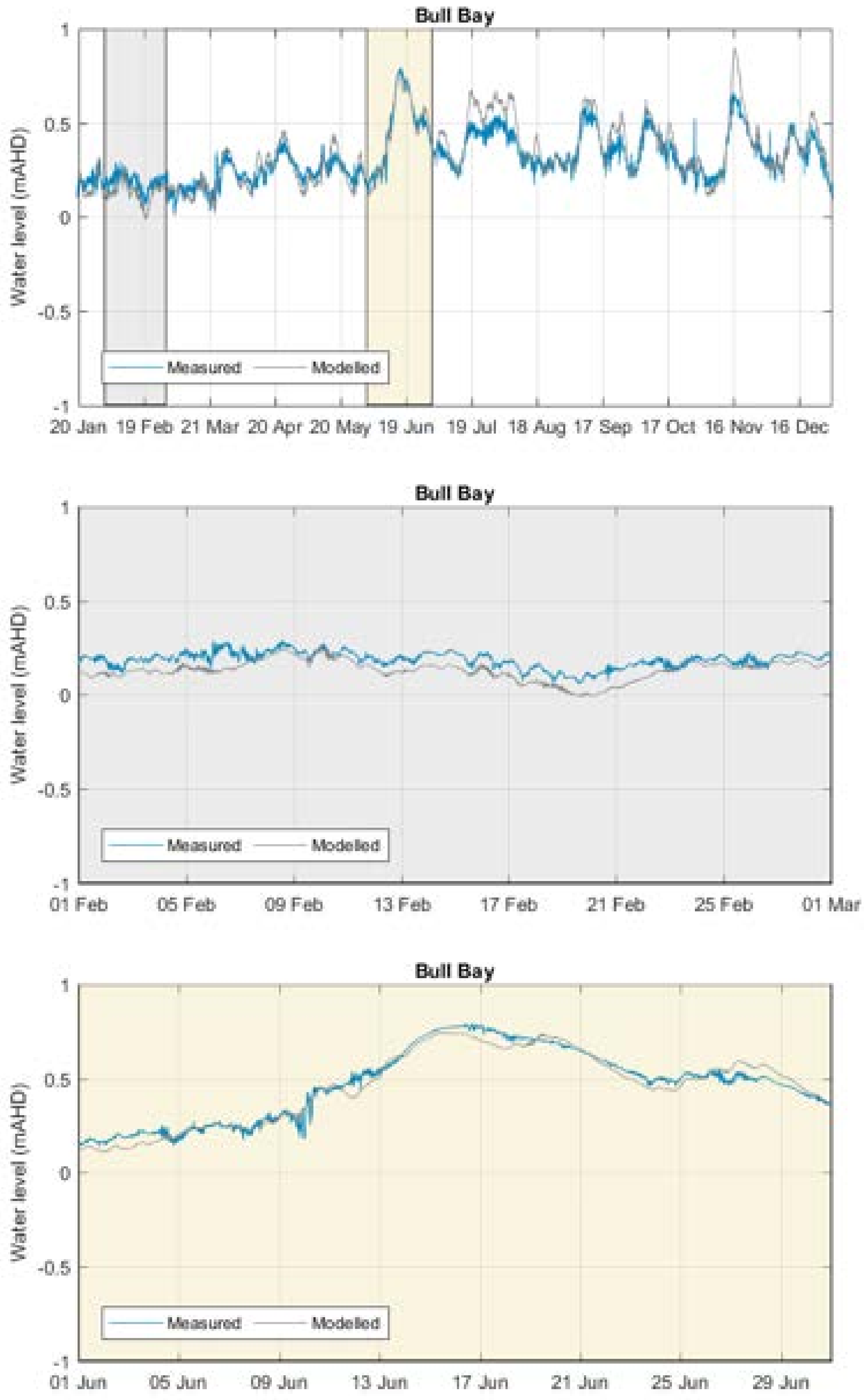

Figure A8. Measured and modelled water level at Bull Bay over the 2021 calibration period.

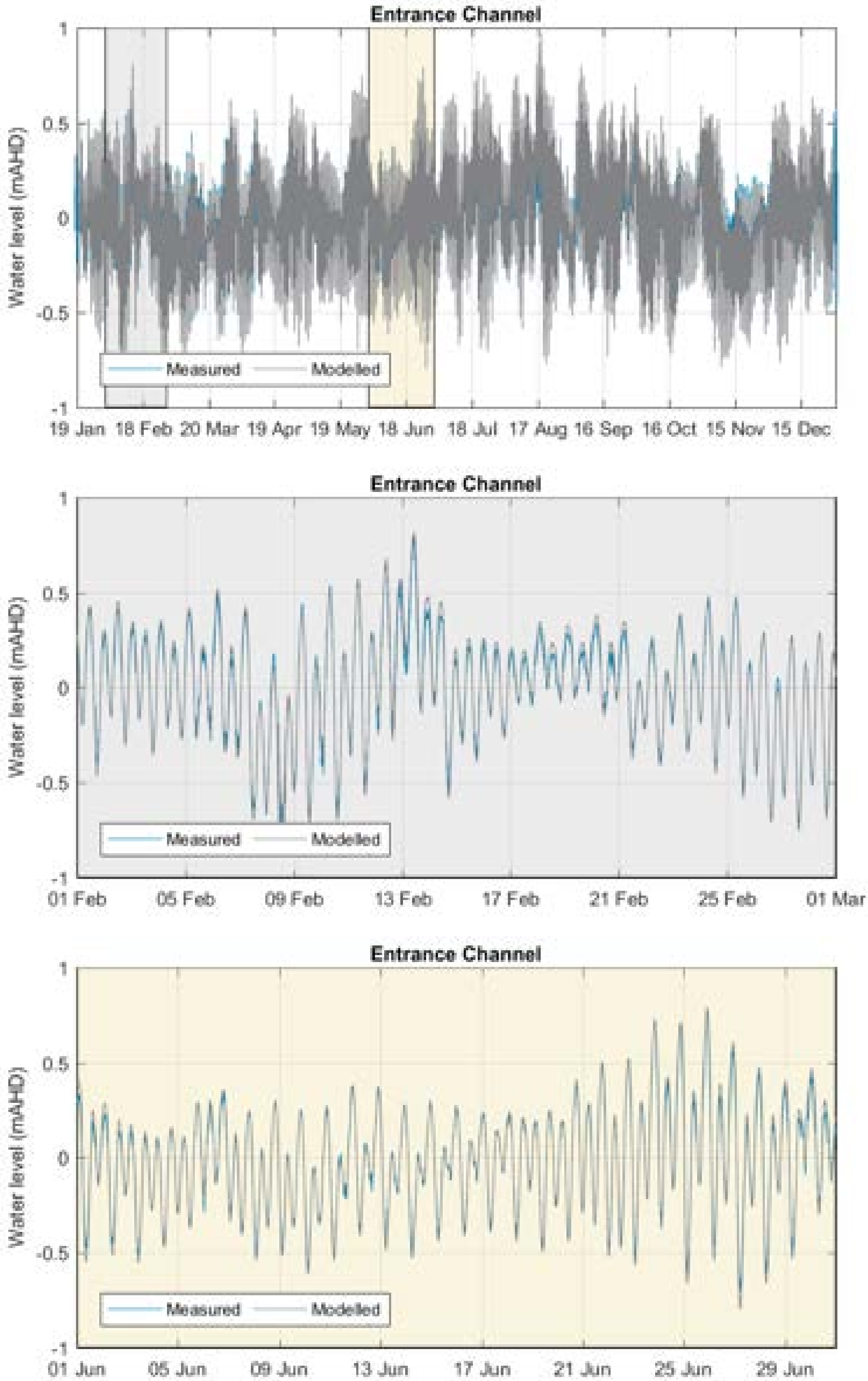

Figure A9. Measured and modelled water level at the Entrance Channel over the 2017 validation period.

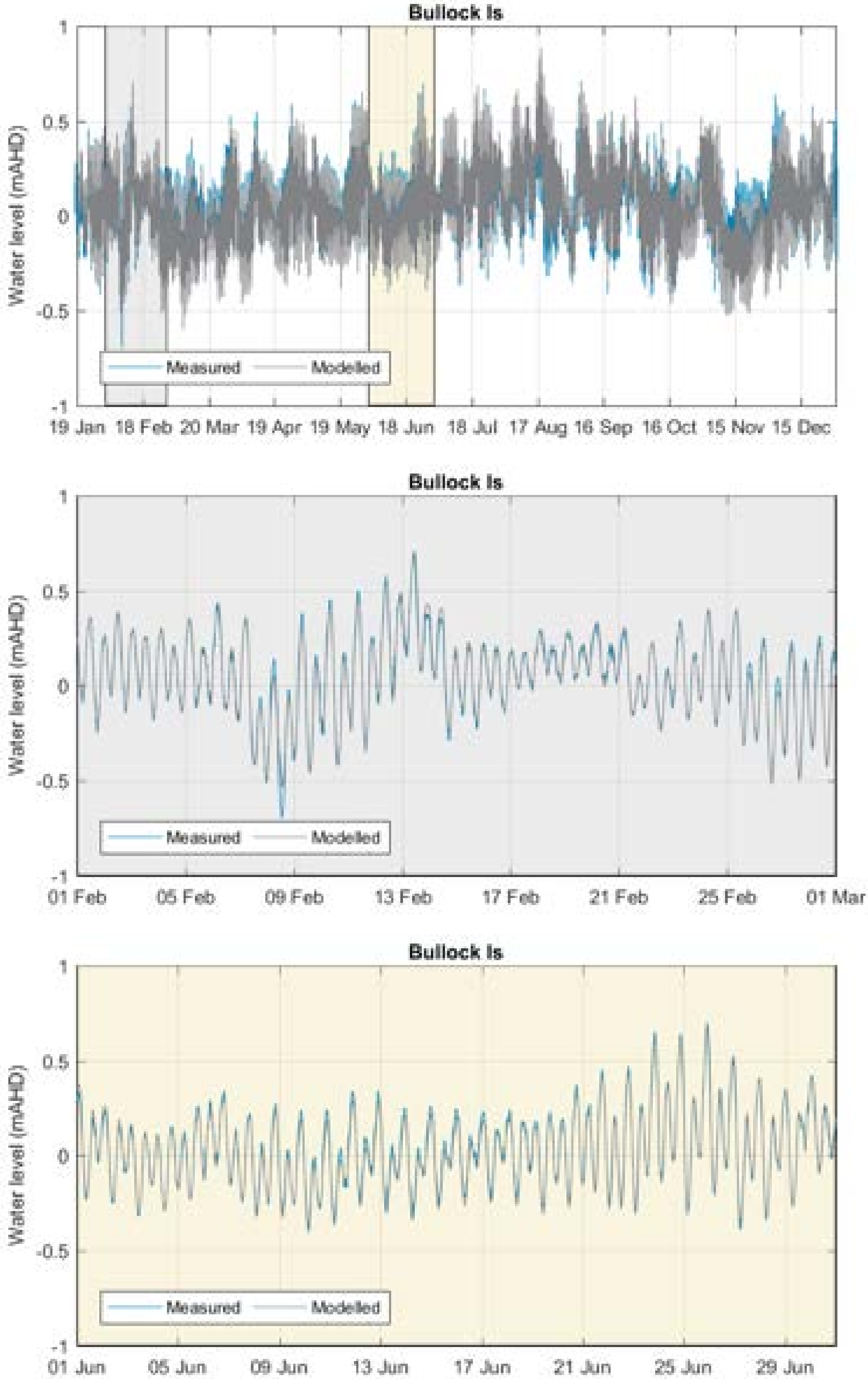

Figure A10. Measured and modelled water level at Bullock Island over the 2017 validation period.

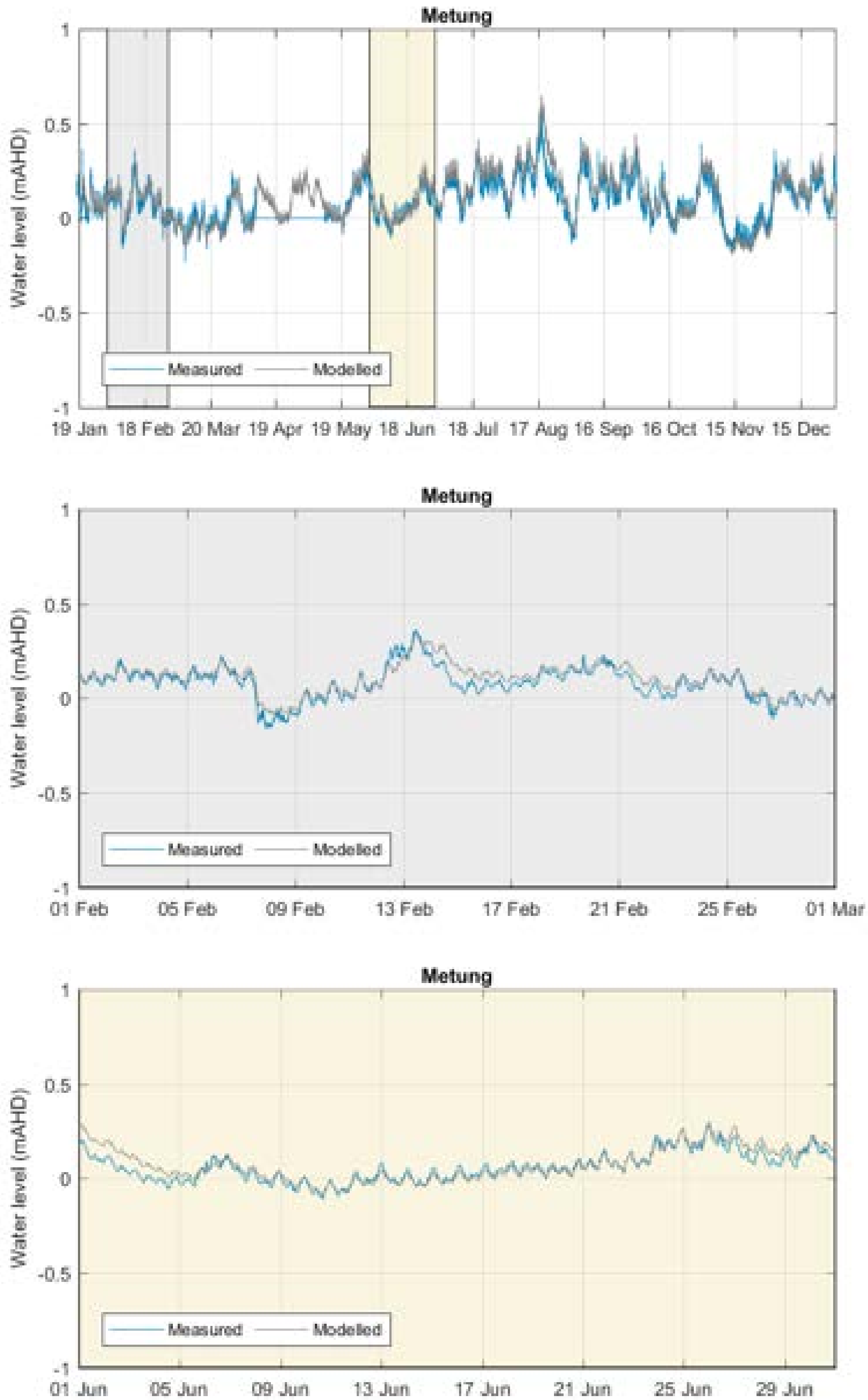

Figure A11. Measured and modelled water level at Metung over the 2017 validation period.

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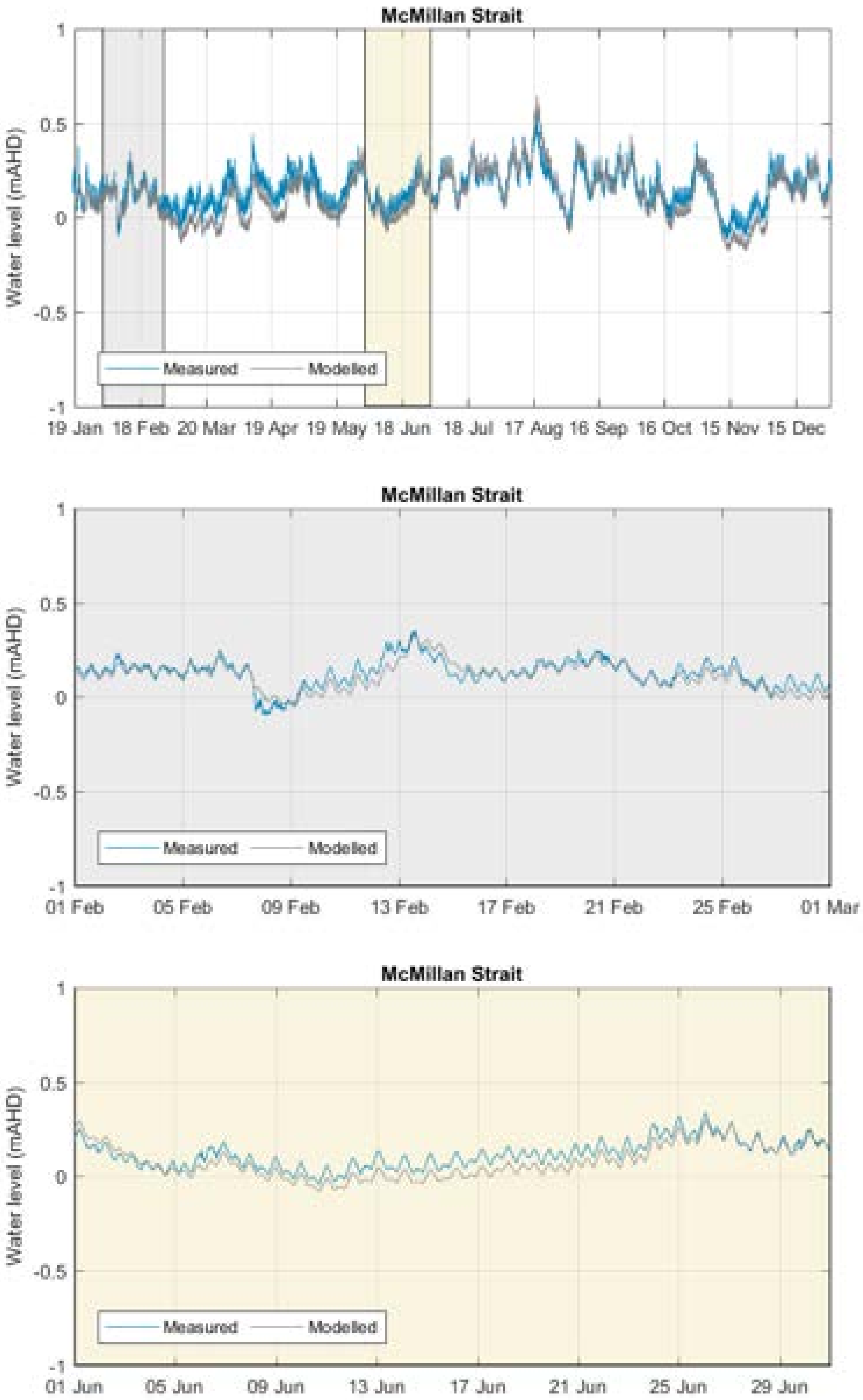


Figure A12. Measured and modelled water level at McMillan Strait over the 2017 validation period.

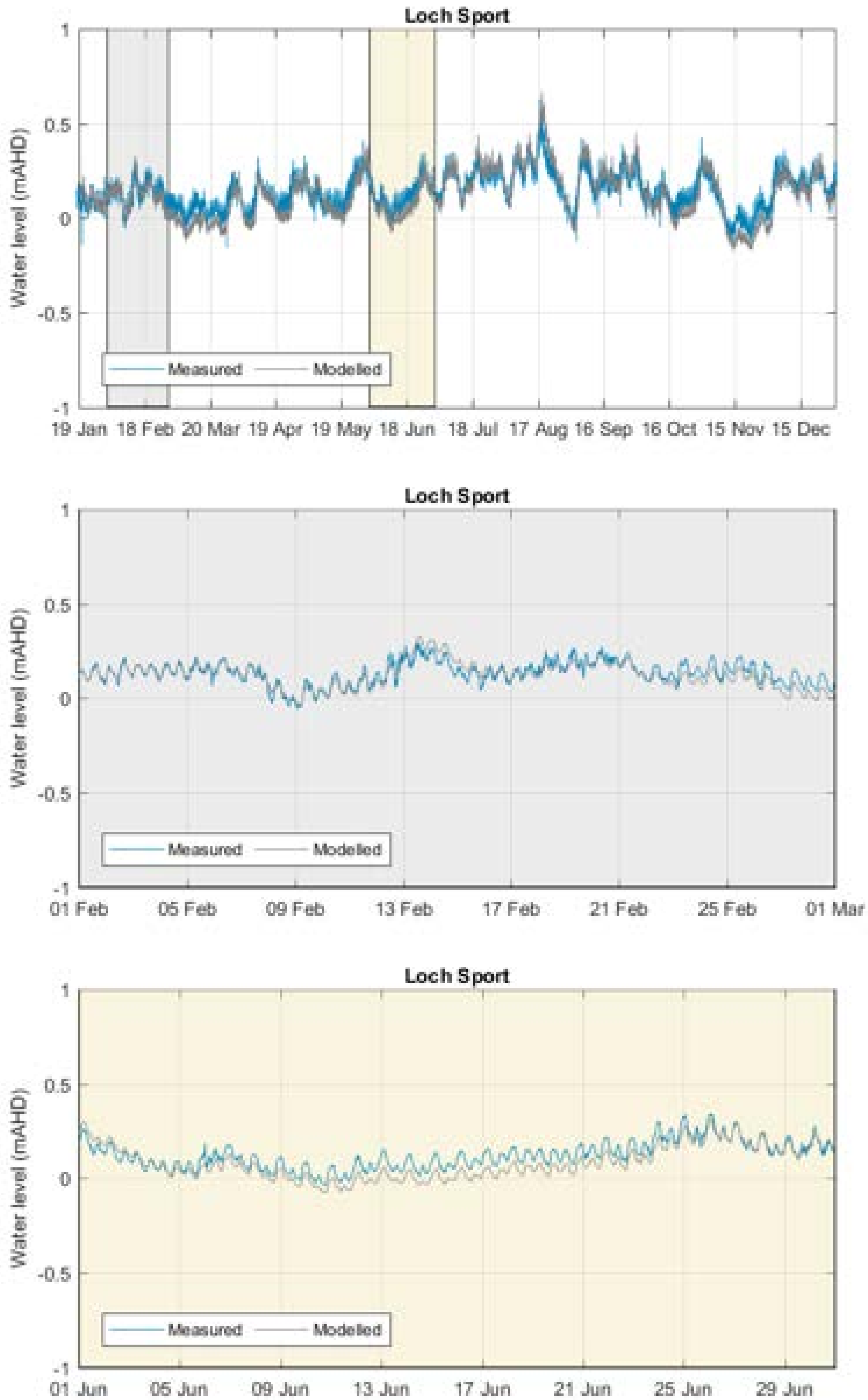


Figure A13. Measured and modelled water level at Loch Sport over the 2017 validation period.

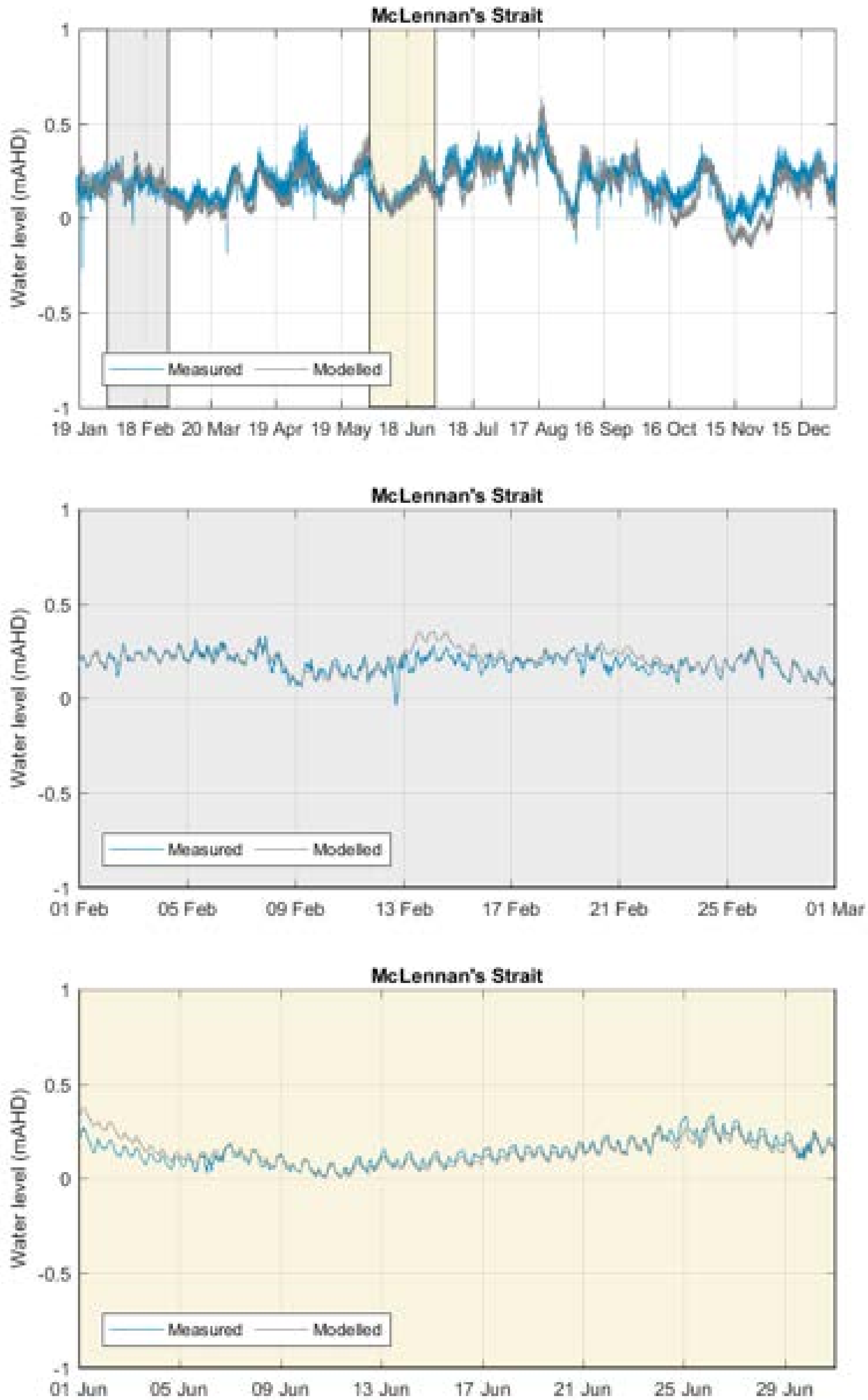


Figure A14. Measured and modelled water level at McLennans's Strait over the 2017 validation period.

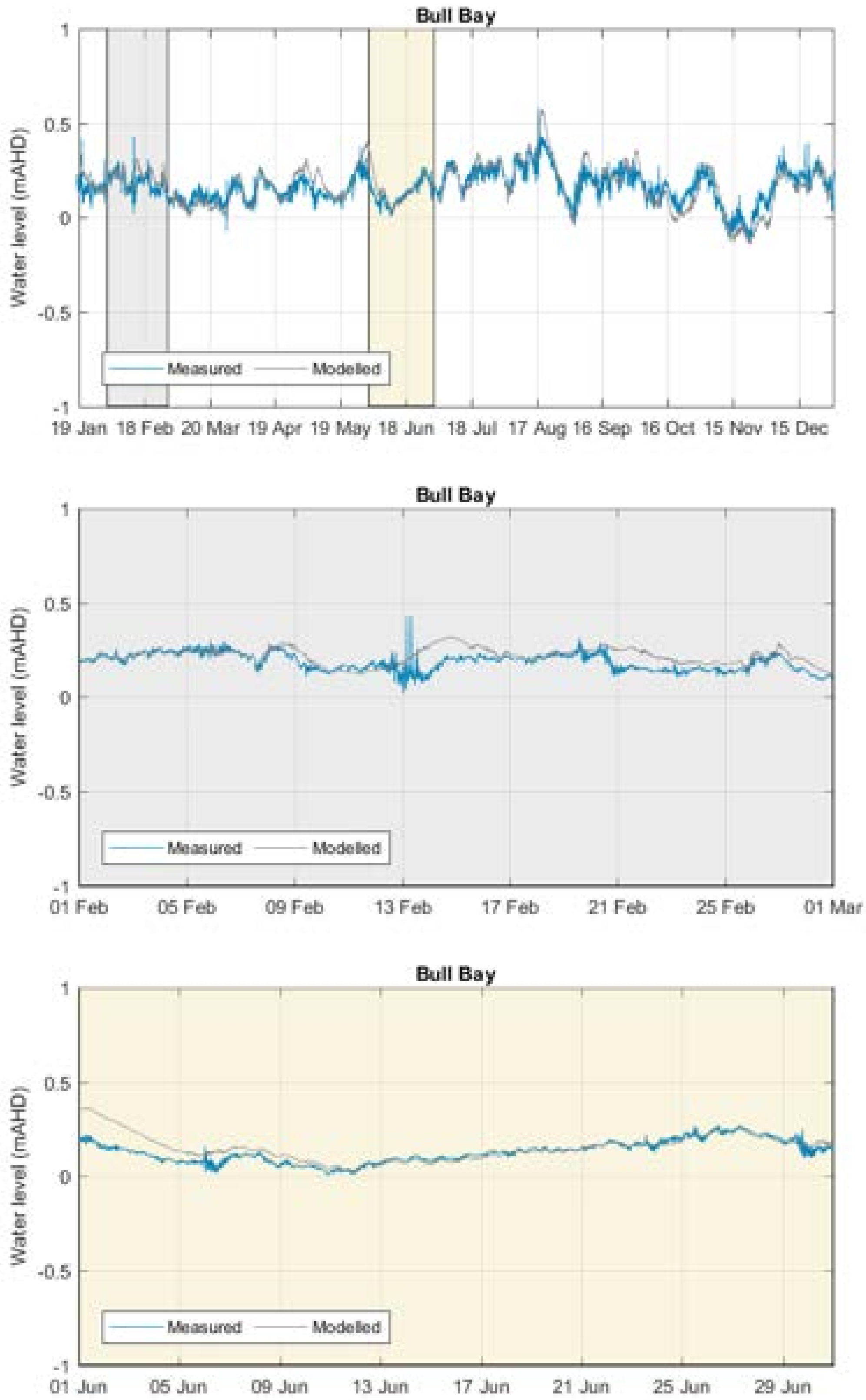


Figure A15. Measured and modelled water level at Bull Bay over the 2017 validation period.

A1.4. Currents

Time series plots of the measured and modelled current speed and direction at the Entrance Channel monitoring site are shown in Figure A16 and Figure A17 for the calibration period and in Figure A18 and Figure A19 for the validation period. The plots show that the model replicates the peaks in flows and the timing of the flow speed changes for the majority of tides.

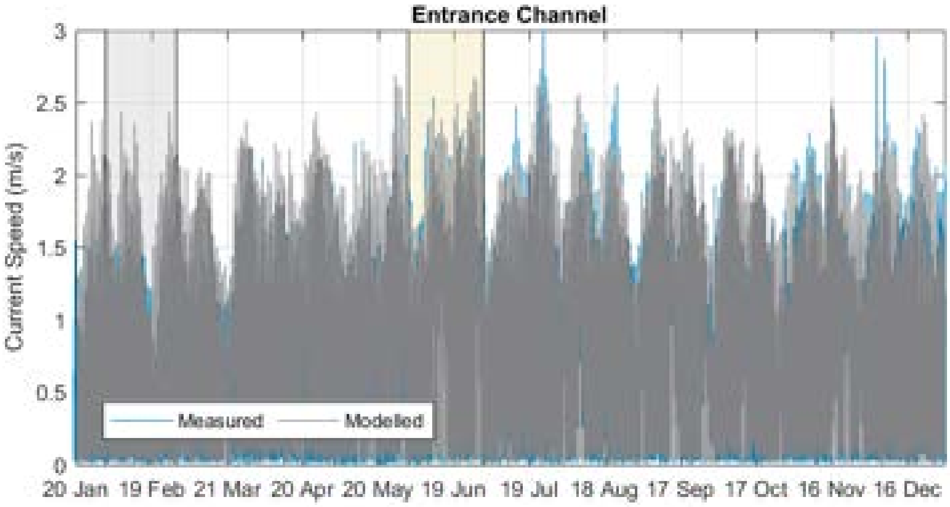
To further assess the level of calibration achieved (and to ensure that the model performs within the calibration standards set out in Section A1.1.), a statistical analysis was undertaken to quantify the difference in magnitude and phasing between the modelled and measured current speeds and directions over the two 30 day periods during the calibration and validation years. The results of the statistical analysis are presented in Table A3. The table shows that the guideline standards are achieved for all statistics during both the calibration and validation periods. The RMS error for the current speed during both periods is relatively high indicating there are times with relatively large differences between the modelled and measured current speeds. However, visual comparison between the measured and modelled data gives confidence that the model is providing a good representation of the current speed overall and the high RMS is likely to be related to the natural variability in the current speeds and the relatively high flow speeds in the channel. Overall, the calibration and validation of the currents along with the water levels provides confidence that the model is able to accurately represent the tidal prism for the Gippsland Lakes.

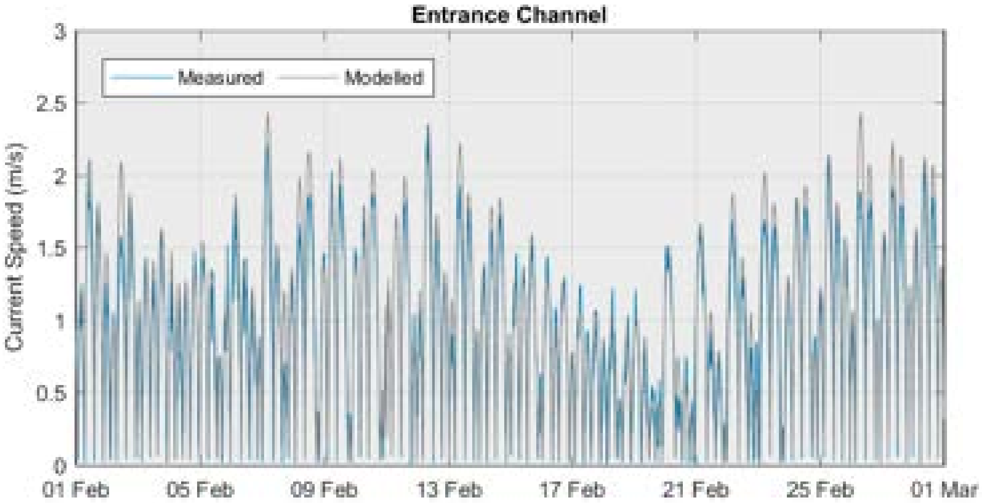
Table A3. Statistics for comparison of modelled and measured currents during the calibration and validation periods.

Period	Speed difference (m/s)			Speed difference (%)		Direction difference (°)		Phase difference (minutes)
	PF	PE	RMS	PF	PE	PF	PE	All
2021 (Calibration Period)								
February	0.04	0.00	0.22	2	0	-2	1	-2
June	0.14	0.04	0.32	5	2	7	0	-2
2017 (Validation Period)								
February	0.01	0.03	0.32	0	2	-3	1	-3
June	-0.16	-0.07	0.22	-6	-3	-2	1	-3

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

Values in bold are above the calibration standard





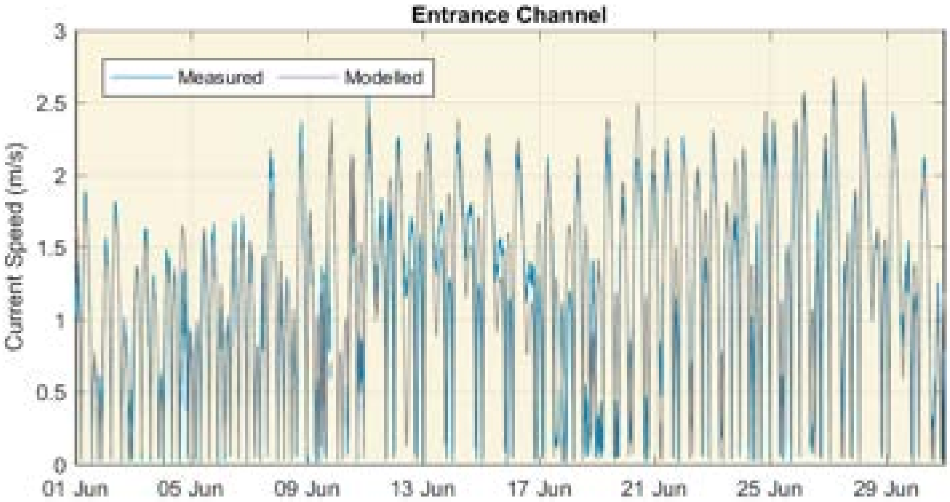


Figure A16. Measured and modelled current speed at the Entrance Channel over the 2021 calibration period.

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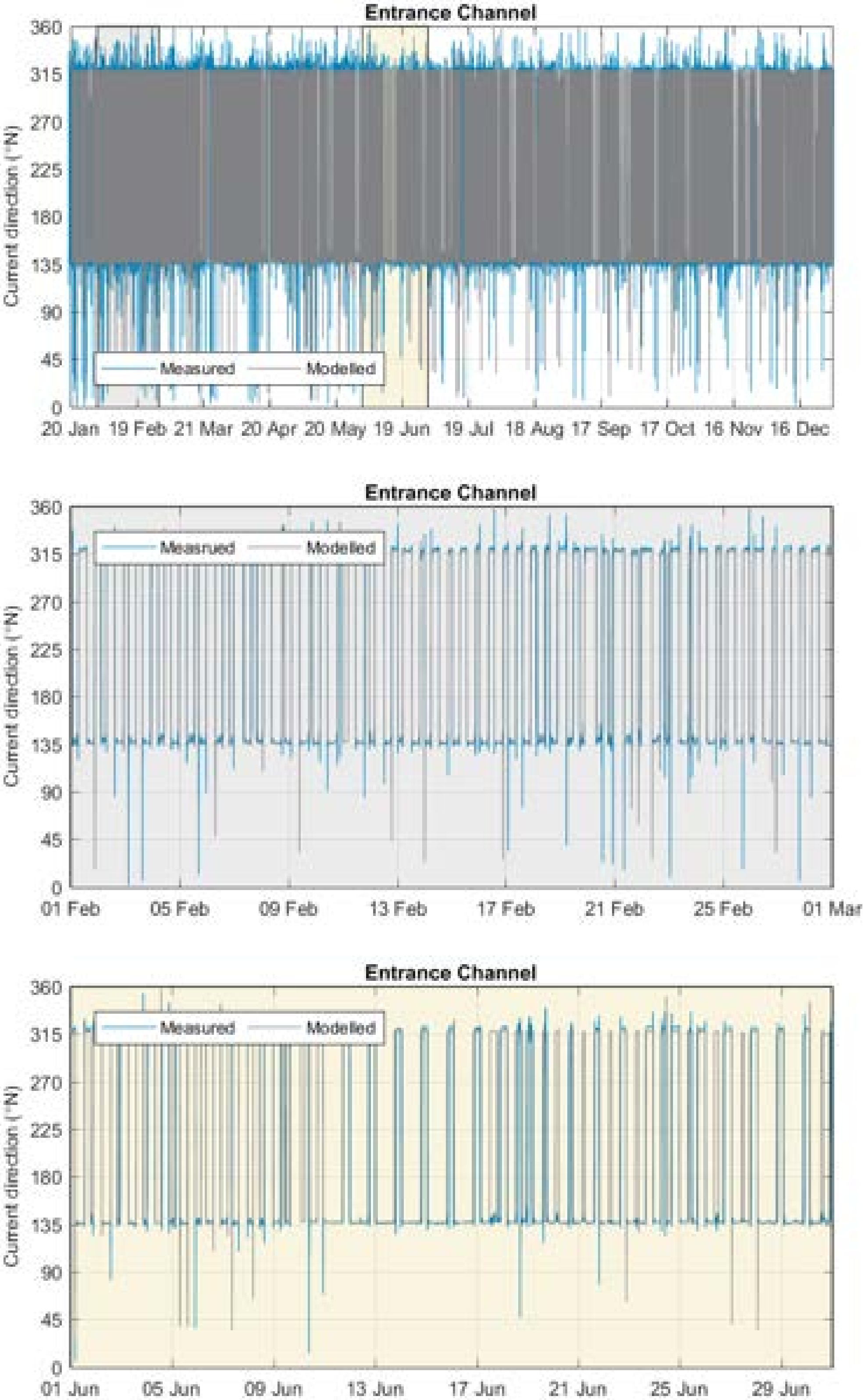


Figure A17. Measured and modelled current direction at the Entrance Channel over the 2021 calibration period.

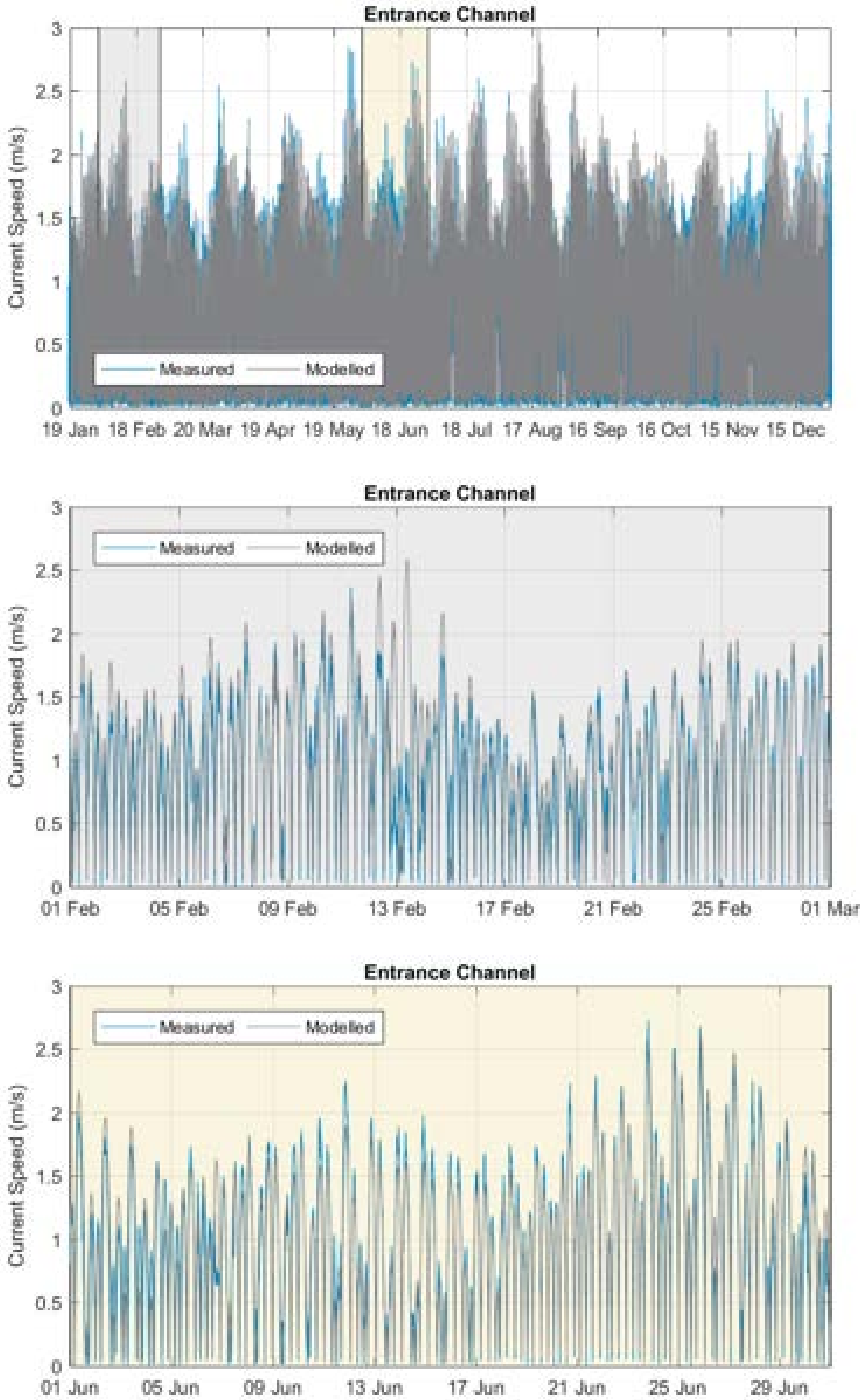
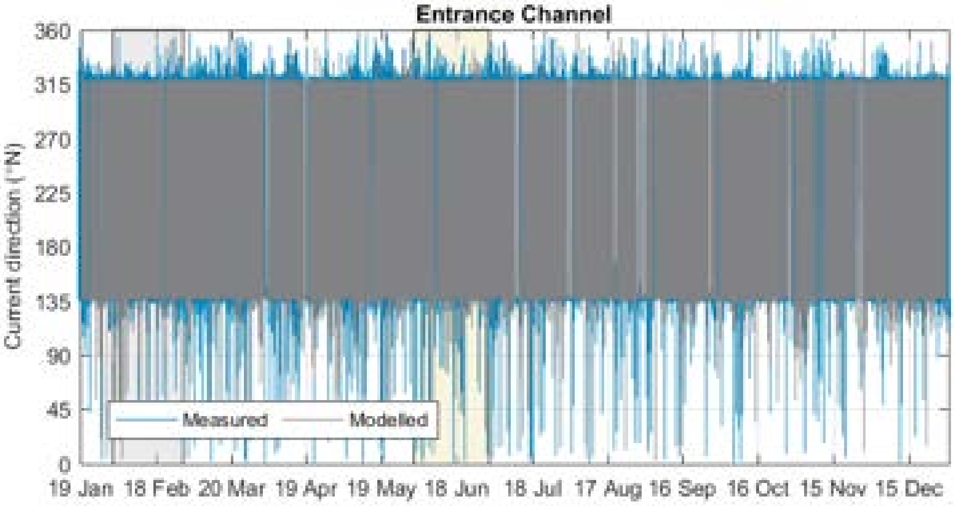
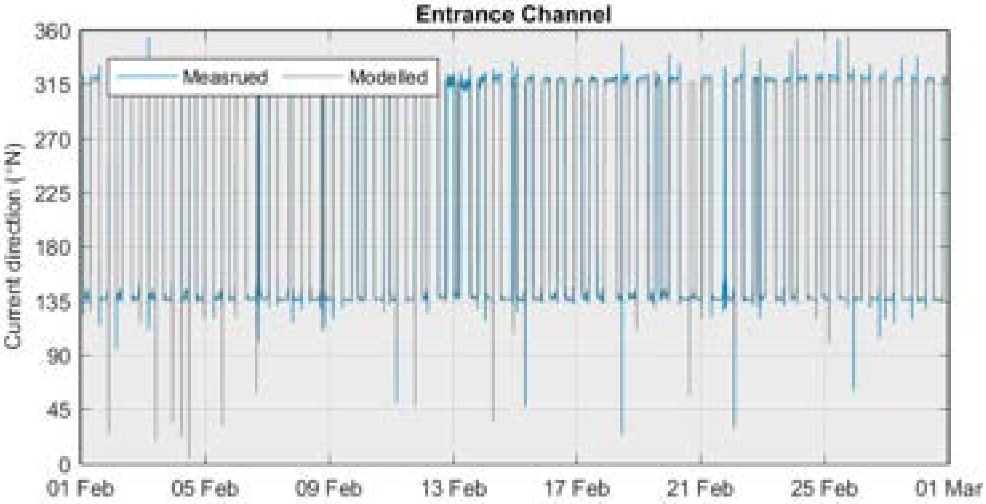


Figure A18. Measured and modelled current speed at the Entrance Channel over the 2017 validation period.





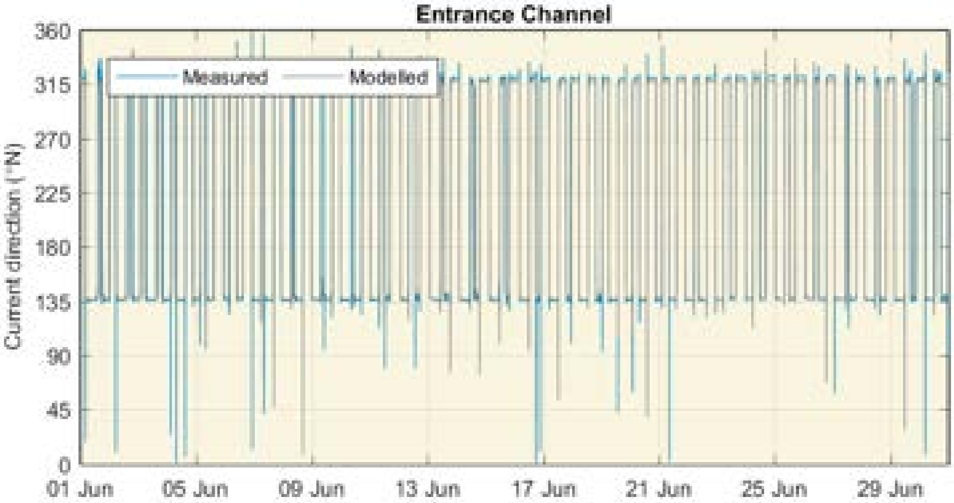


Figure A19. Measured and modelled current direction at the Entrance Channel over the 2017 validation period.

A1.5. Salinity

Time series of measured and modelled surface salinity at the EPA measurement sites (Lake Wellington, Lake Victoria, Lake King North, Lake King South and Shaving Point) and the DEECA measurement site (Bull Bay) are shown in Figure A20 and Figure A21 for the calibration period. The plots show the measured and modelled salinity over the entire 12 month period, with the measured data at the EPA sites only represented by single measurements approximately every 6 weeks while the measured data at the DEECA site is a continuous time series.

Over the duration of the 12 month calibration period there is an increase in salinity over the first four months and then a reduction in salinity over the subsequent eight months. There is significant variability in the salinity temporally and spatially, with modelled salinity varying from 5 to 35 psu at Shaving Point and from 1 to 11 psu at Lake Wellington. Comparison between the measured and modelled salinity shows that the model is able to provide a good representation of the salinity over the 12 months at all sites. The model slightly underpredicts the reduction in salinity from May to June at Shaving Point, Lake King North and Lake King South. The difference between the measured and modelled salinity remains within 5 psu over this period except at Lake King South, where it is just above this threshold. The time series comparison between the measured and modelled salinity at Bull Bay shows that the model provides a very good representation of the variability in salinity over the 12 months.

Time series of measured and modelled surface salinity at the EPA measurement sites and the DEECA measurement site are shown in Figure A22 and Figure A23 for the validation period. Compared to the calibration period, the salinity over the 12 month validation period remains relatively stable, with salinity varying by 5 to 10 psu at the measurement sites. Comparison between the measured and modelled salinity shows that the model is able to provide a good representation of the salinity over the 12 months at all the sites. The largest difference between the measured and modelled salinity was in August 2017 when two surface salinity measurements were collected which varied from 16 to 28 psu and when the modelled surface salinity was approximately mid way between the two (23 psu). This shows that the model is able to represent the average salinity which occurred at this time as opposed to the upper or lower bounds. At the other sites the modelled salinity remained within 5 psu of the measured salinity throughout the 12 month period.

To determine whether the model is able to represent any vertical variability in salinity, vertical profiles through the water column are plotted at the EPA measurement sites for two measurement periods over the model validation period in Figure A24 to Figure A28. The plots show that the model is able to consistently represent the depth varying trend in salinity shown by the measured data. The modelled salinity close to the bed is slightly lower (up to 4 psu) than the measured salinity at Shaving Point, Lake King South and Lake Victoria. Overall, the model is considered to provide a good representation of the variability in salinity through the water column.

The calibration and validation of the model to the measured salinity data has shown that the model is able to reliably represent changes in the salinity spatially, temporally and through the water column. The calibration and validation periods covered different conditions and have shown that the model is able to represent the changes in salinity resulting from river discharge, rainfall, saline intrusion through the Entrance Channel and evaporation processes.

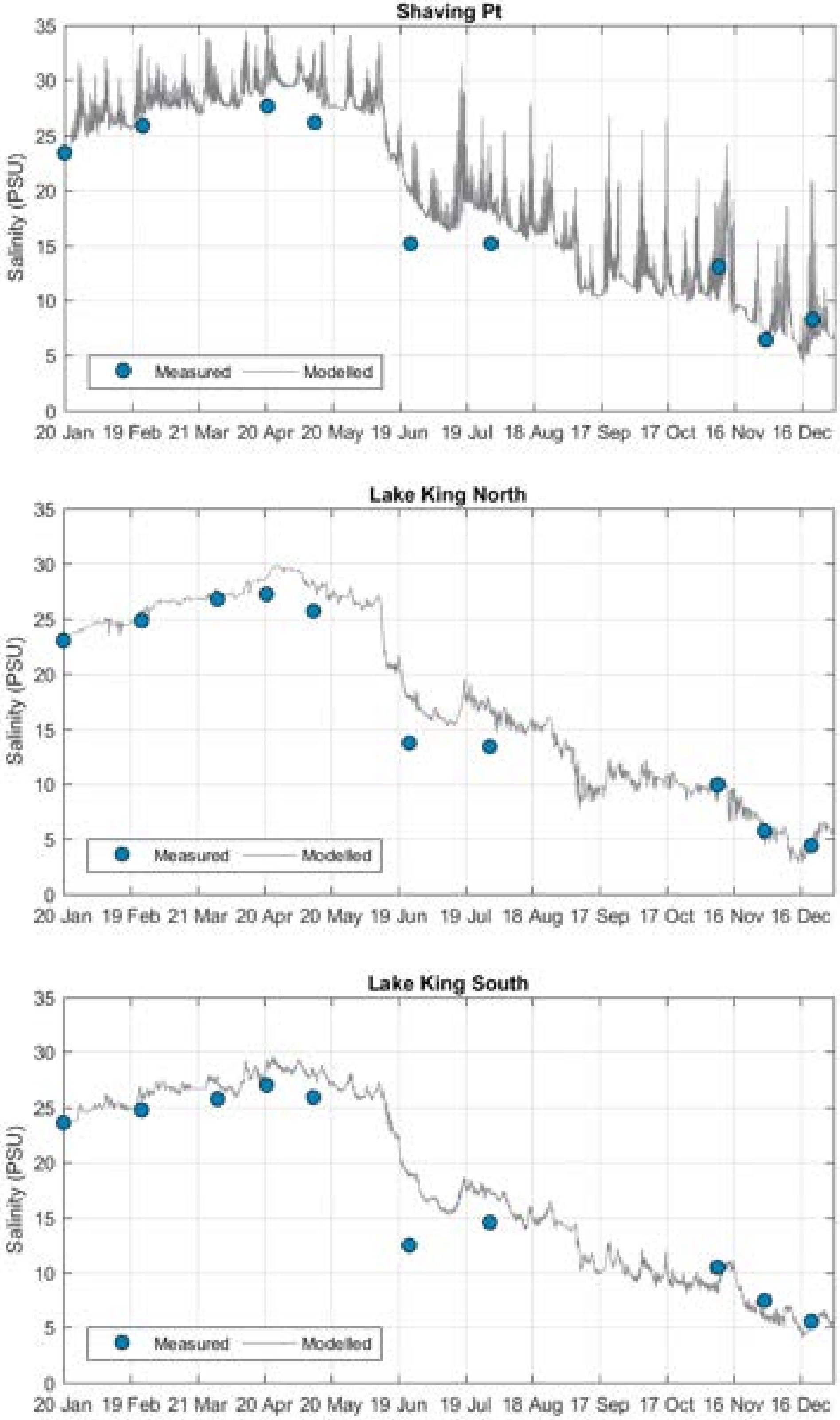


Figure A20. Measured and modelled salinity at Shaving Pt, Lake King North and Lake King South over the 2021 calibration period.

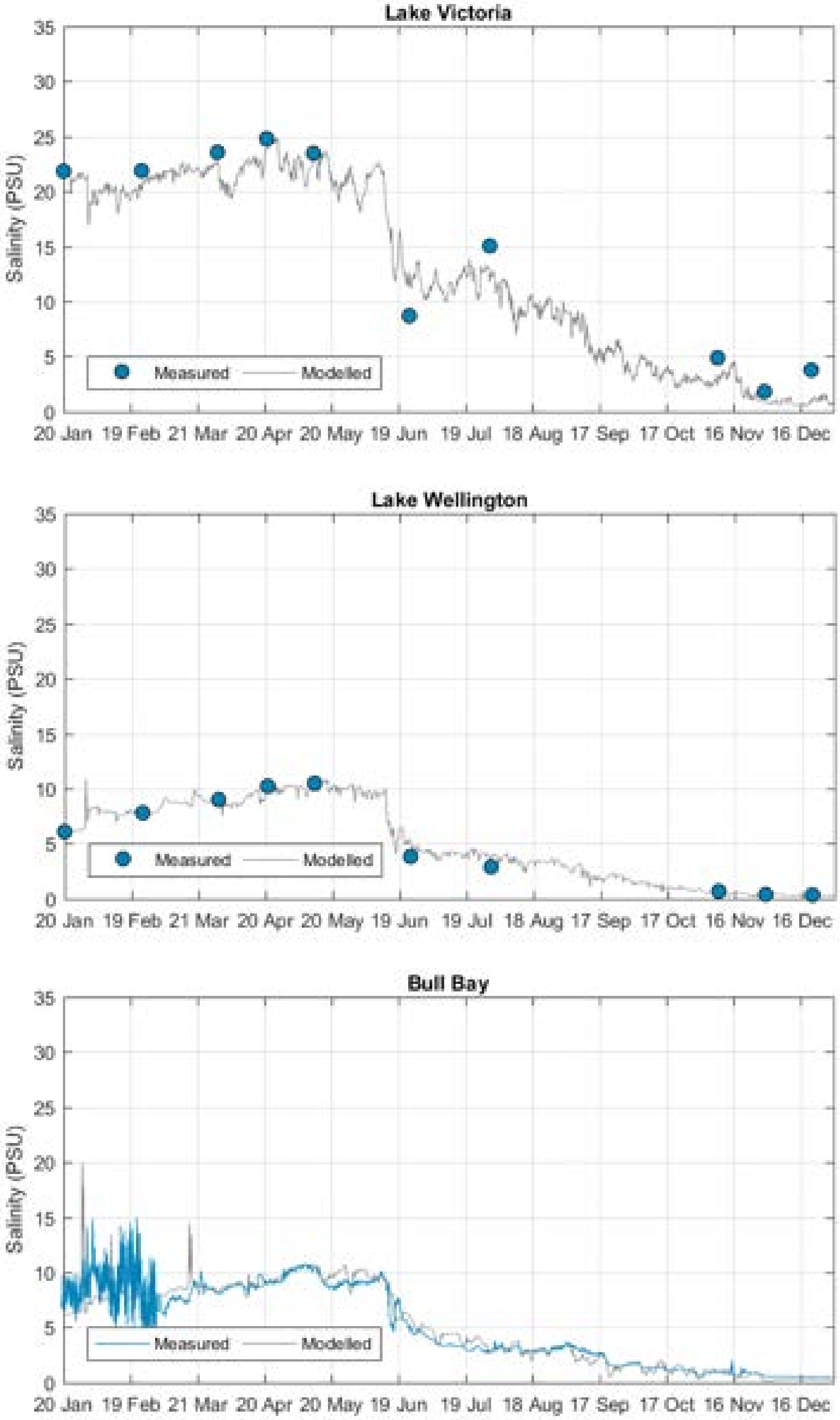


Figure A21. Measured and modelled salinity at Lake Victoria, Lake Wellington and Bull Bay over the 2021 calibration period.

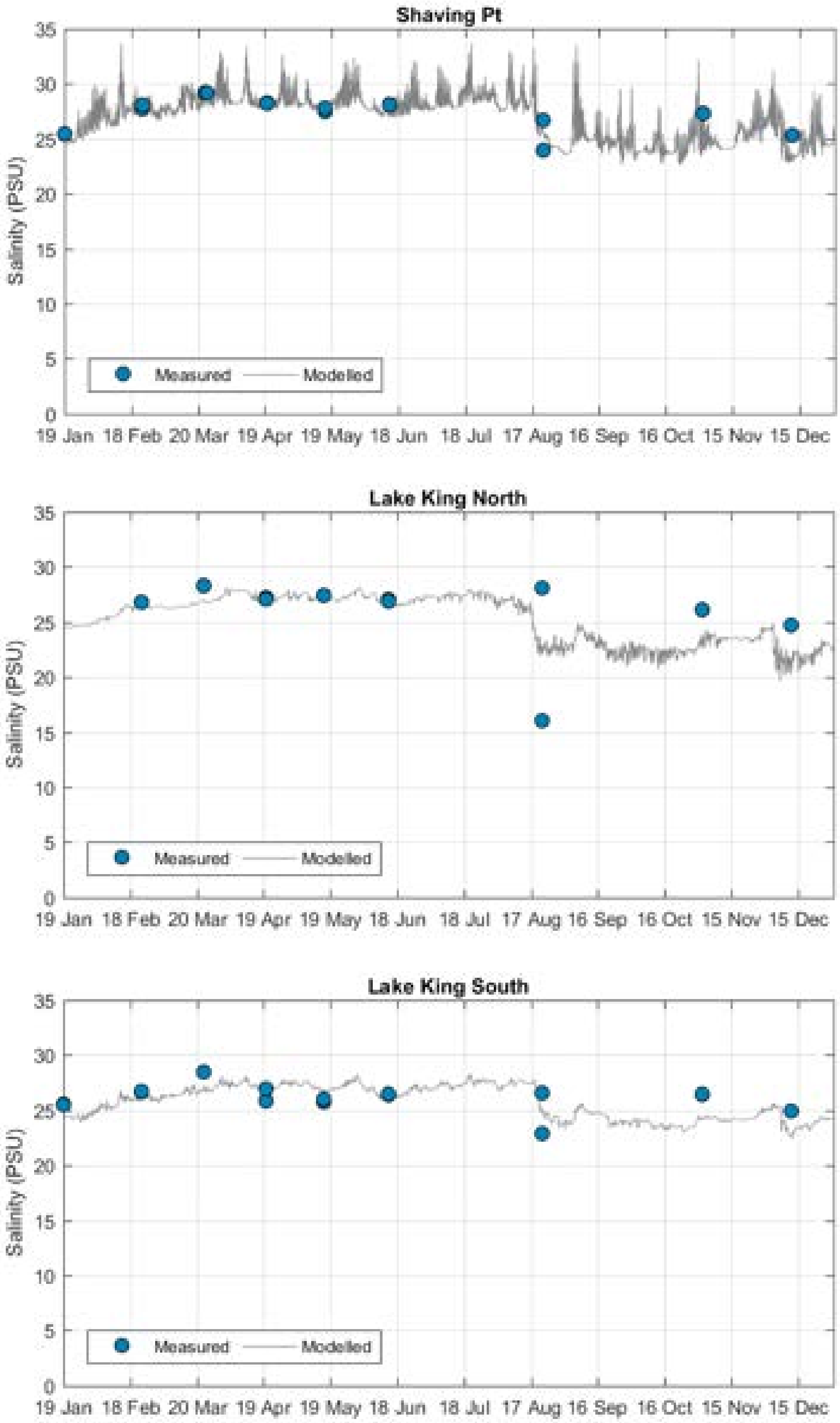


Figure A22. Measured and modelled salinity at Shaving Pt, Lake King North and Lake King South over the 2017 validation period.

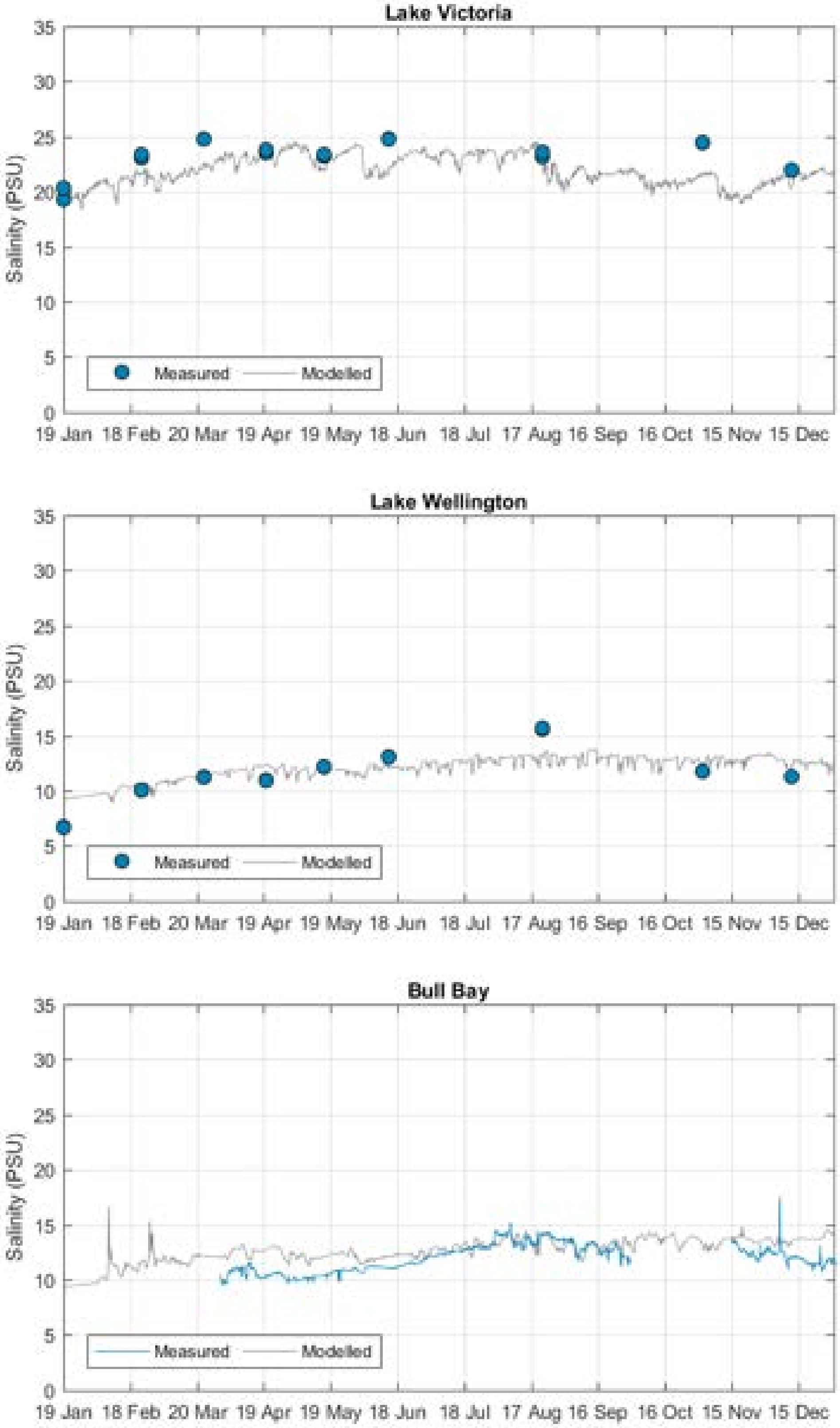
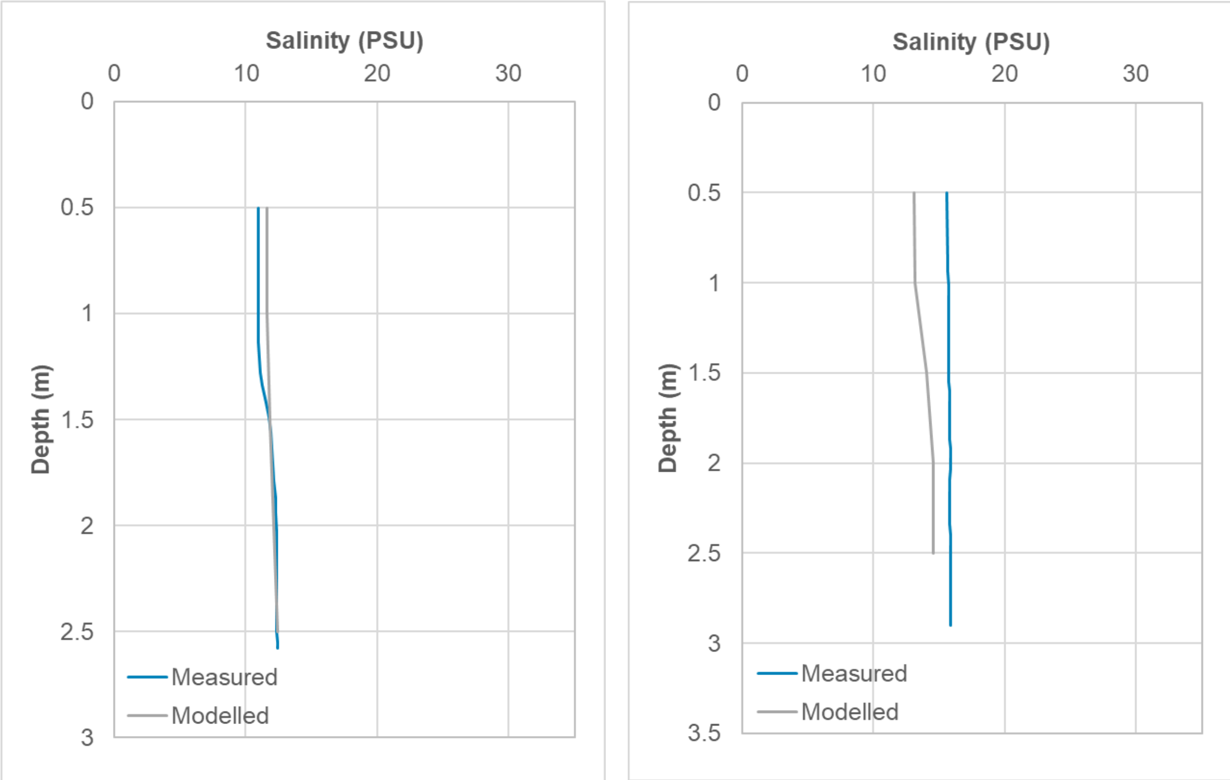
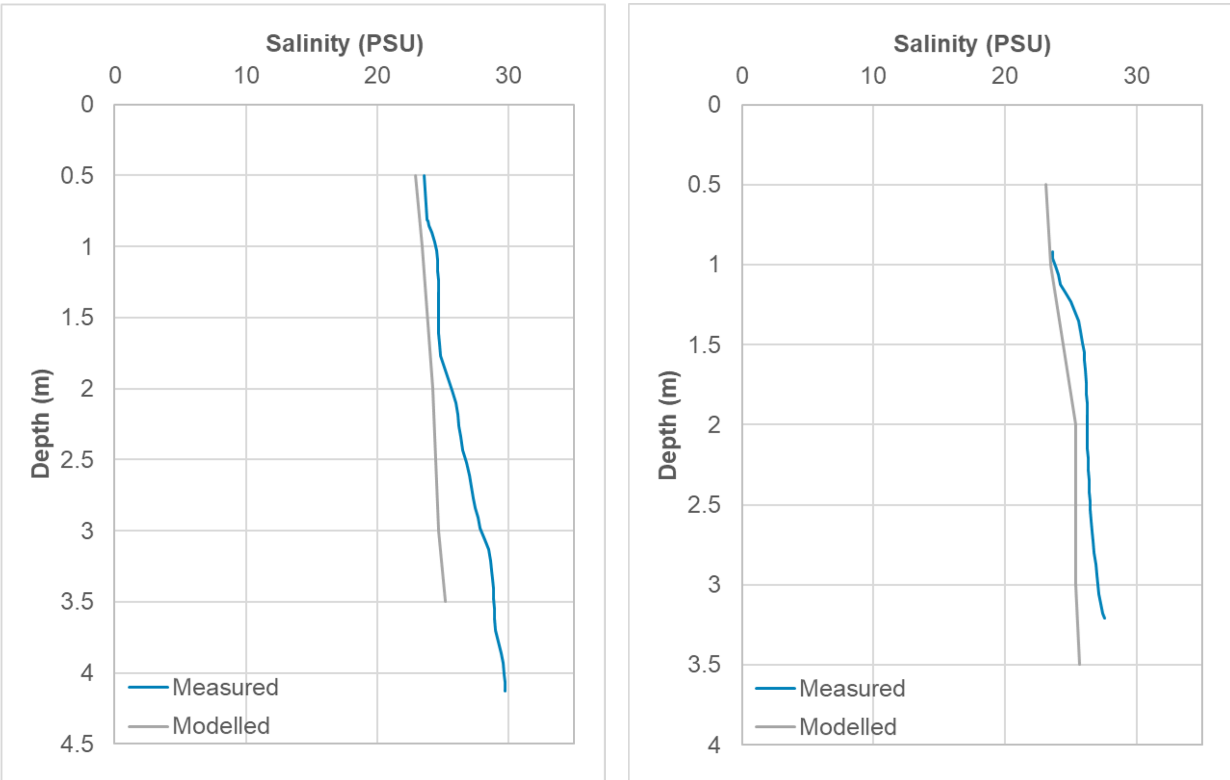


Figure A23. Measured and modelled salinity at Lake Victoria, Lake Wellington and Bull Bay over the 2017 validation period.



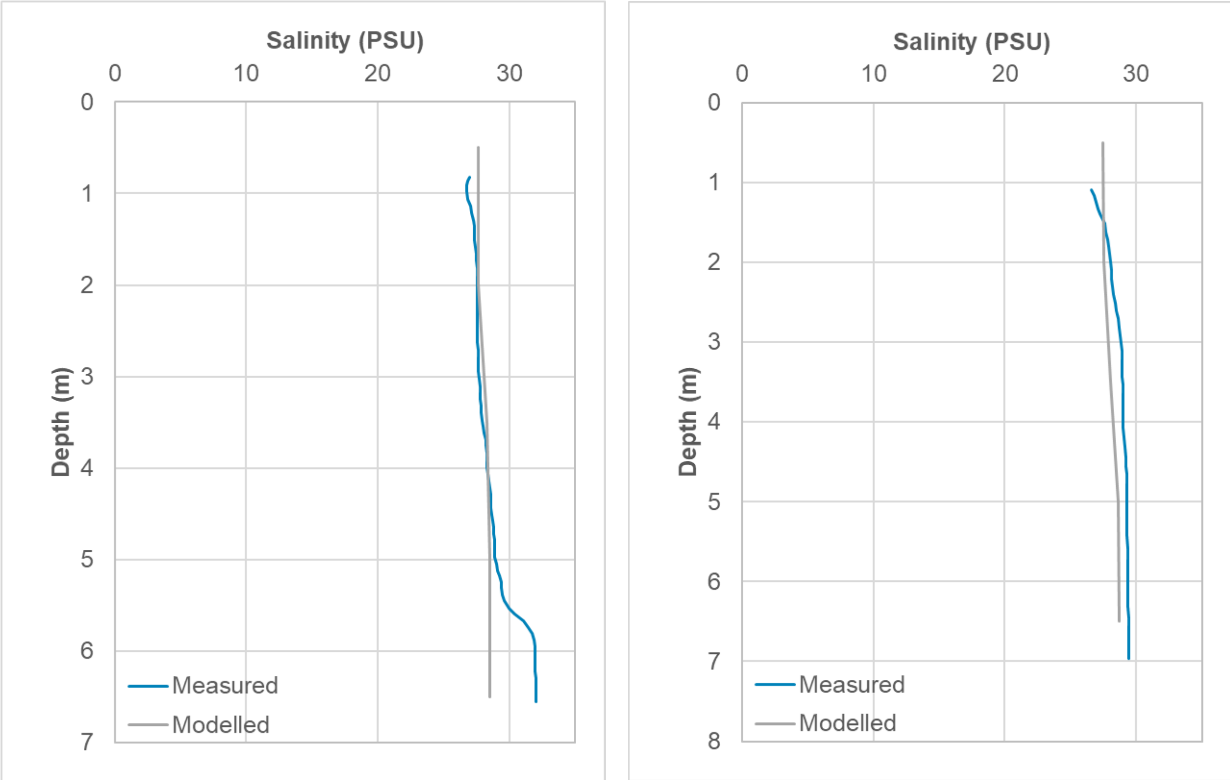
20 April 2017 *22 August 2017*

Figure A24. Measured and modelled salinity profiles at Lake Wellington in April and August 2017.



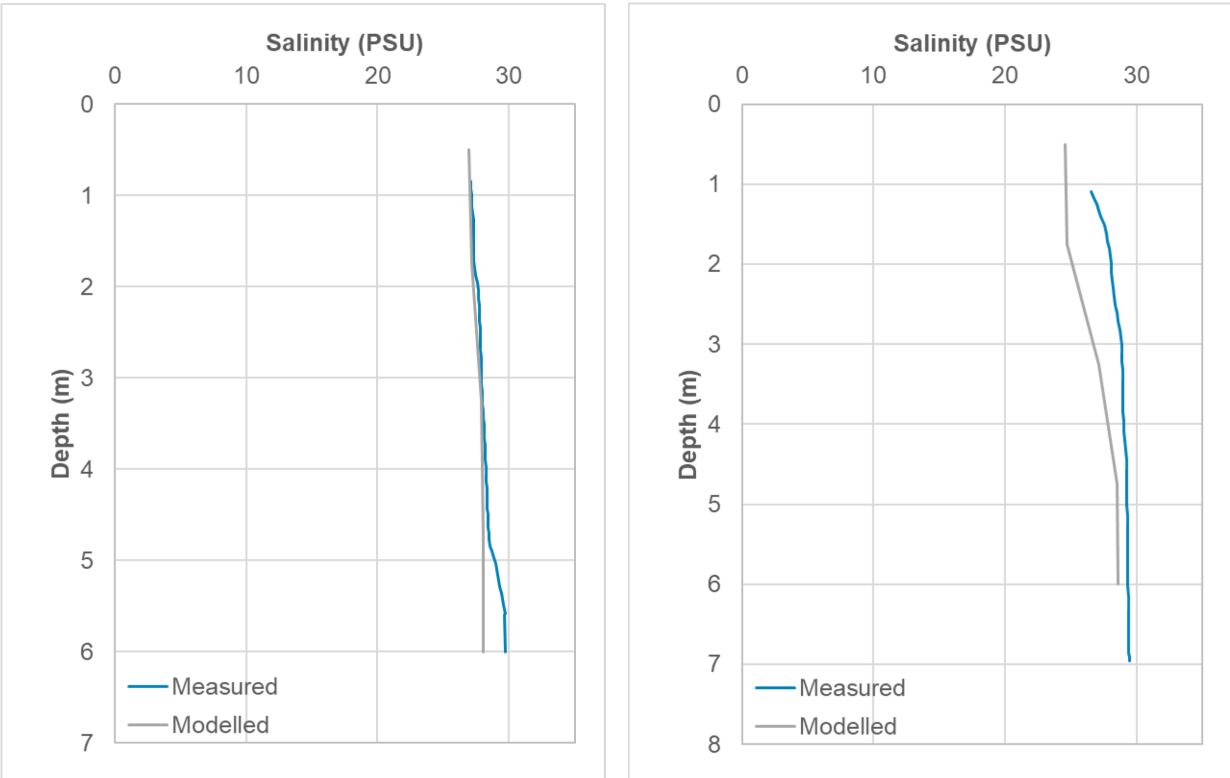
20 April 2017 *22 August 2017*

Figure A25. Measured and modelled salinity profiles at Lake Victoria in April and August 2017.



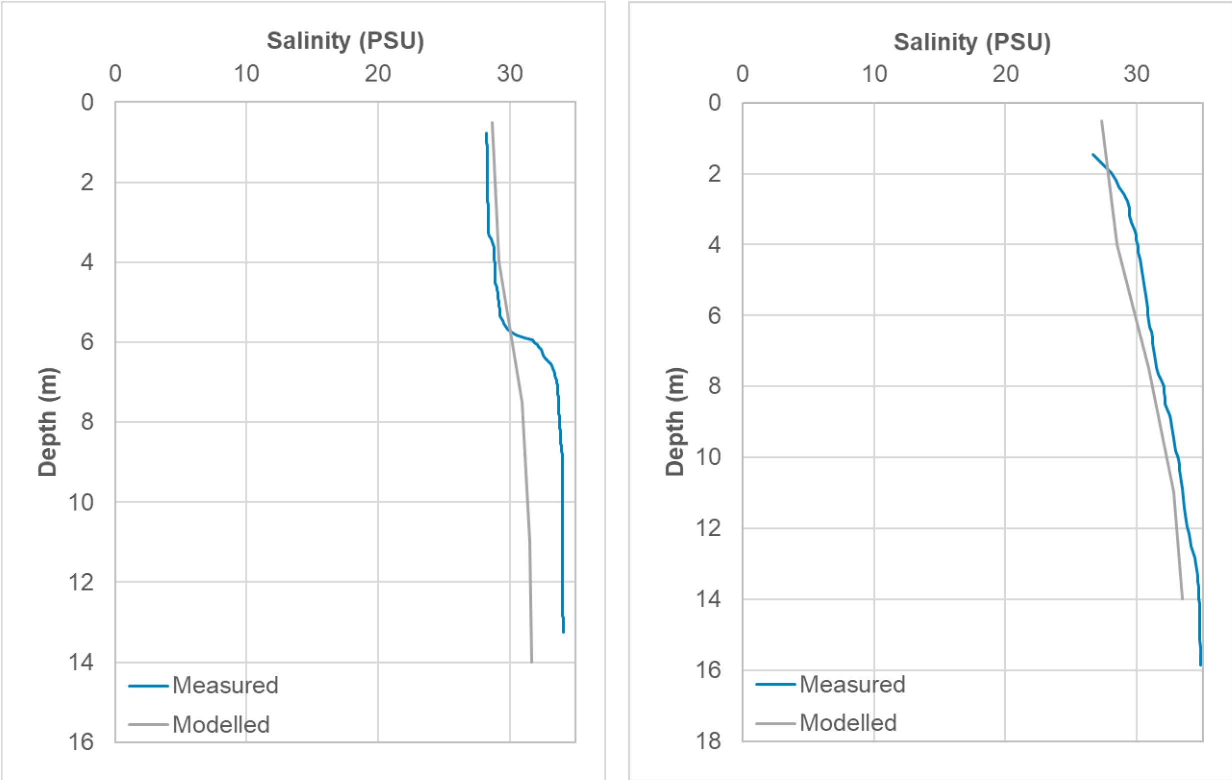
20 April 2017 *22 August 2017*

Figure A26. Measured and modelled salinity profiles at Lake King South in April and August 2017.



20 April 2017 *22 August 2017*

Figure A27. Measured and modelled salinity profiles at Lake King North in April and August 2017.



20 April 2017 *22 August 2017*

Figure A28. Measured and modelled salinity profiles at Shaving Point in April and August 2017.

Appendix B – Water Level and Salinity Model Results

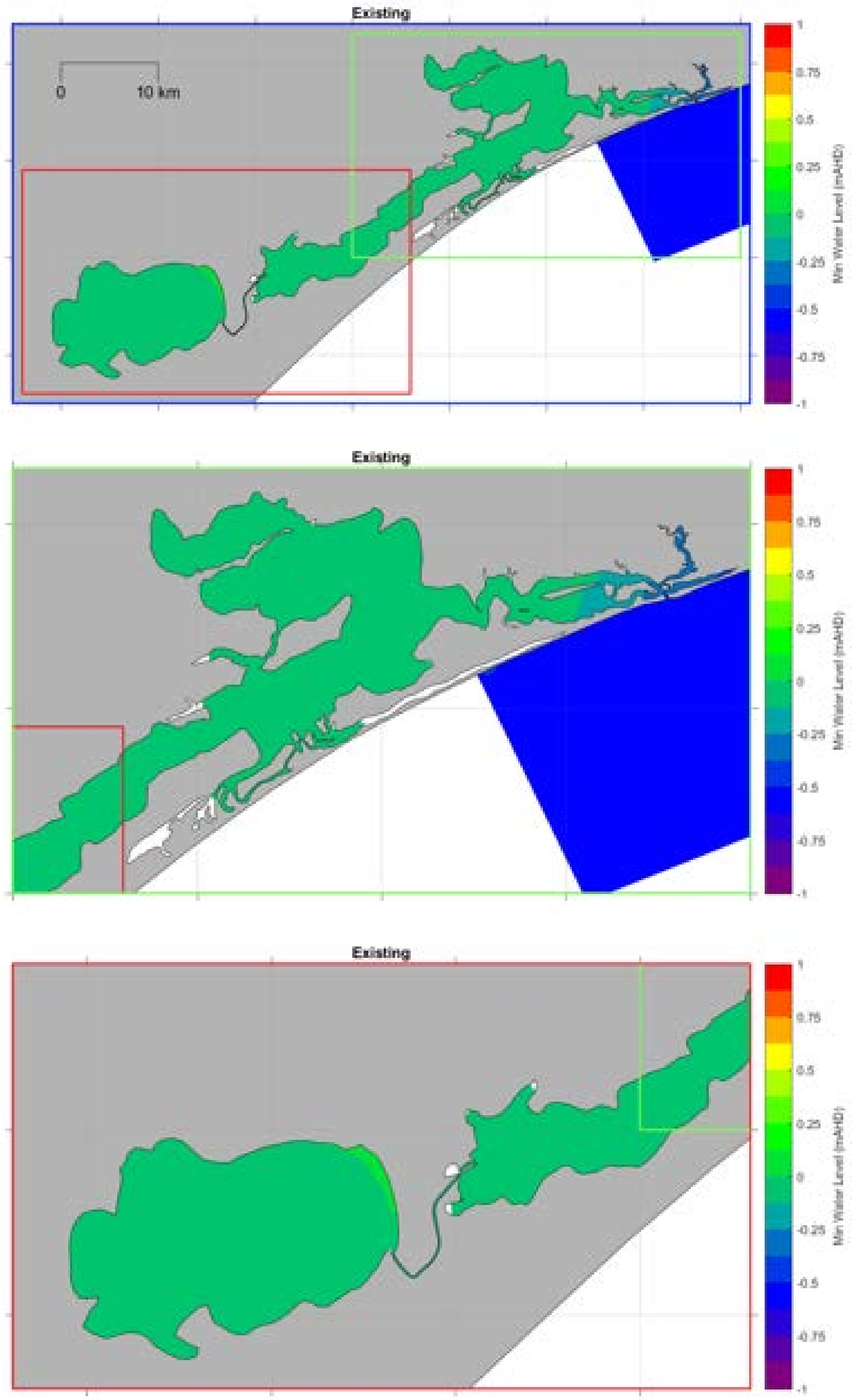


Figure B1. Existing case modelled minimum water level over 12 months with astronomical forcing.

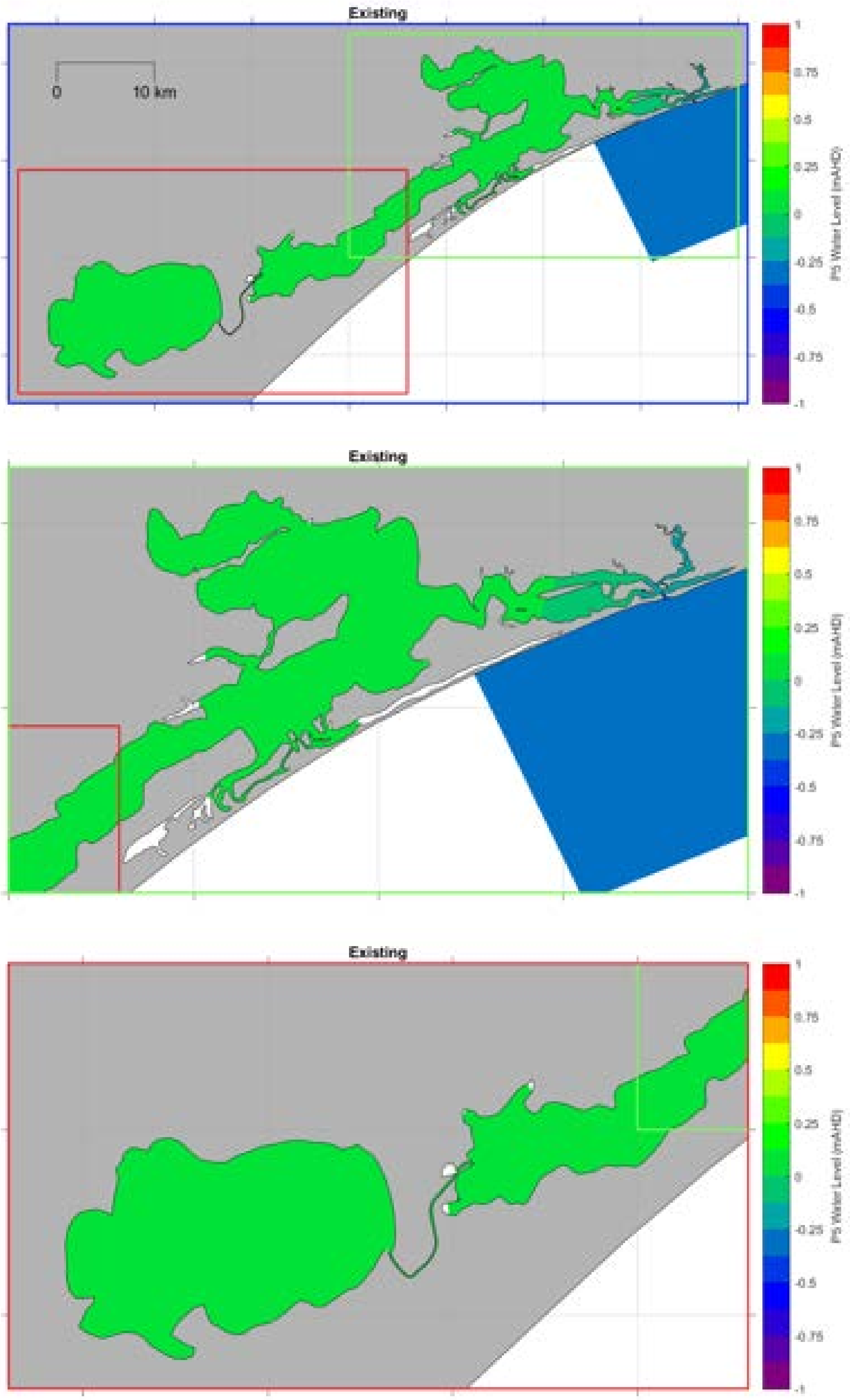


Figure B2. Existing case modelled 5th percentile water level over 12 months with astronomical forcing.

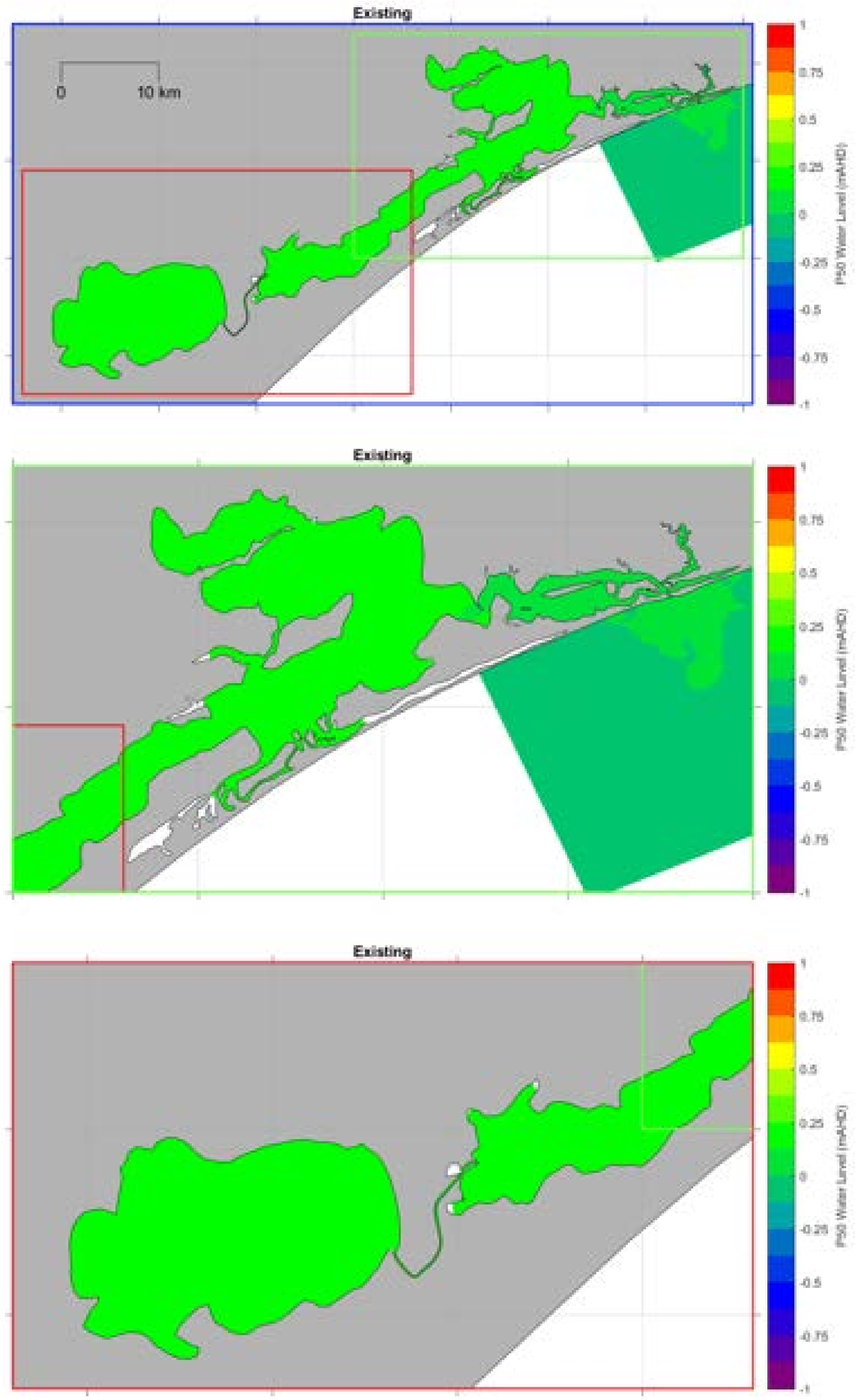


Figure B3. Existing case modelled median water level over 12 months with astronomical forcing.

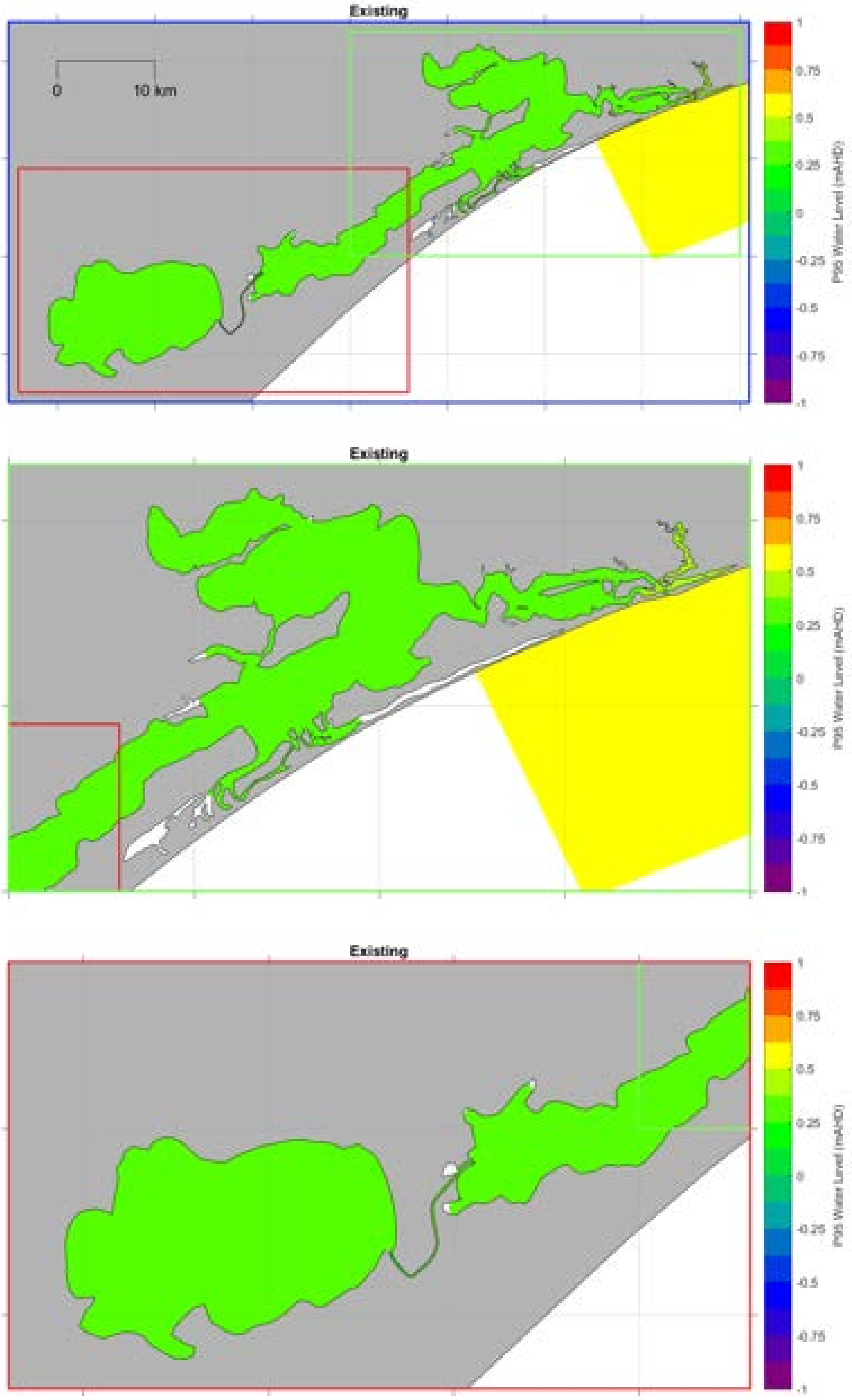


Figure B4. Existing case modelled 95th percentile water level over 12 months with astronomical forcing.

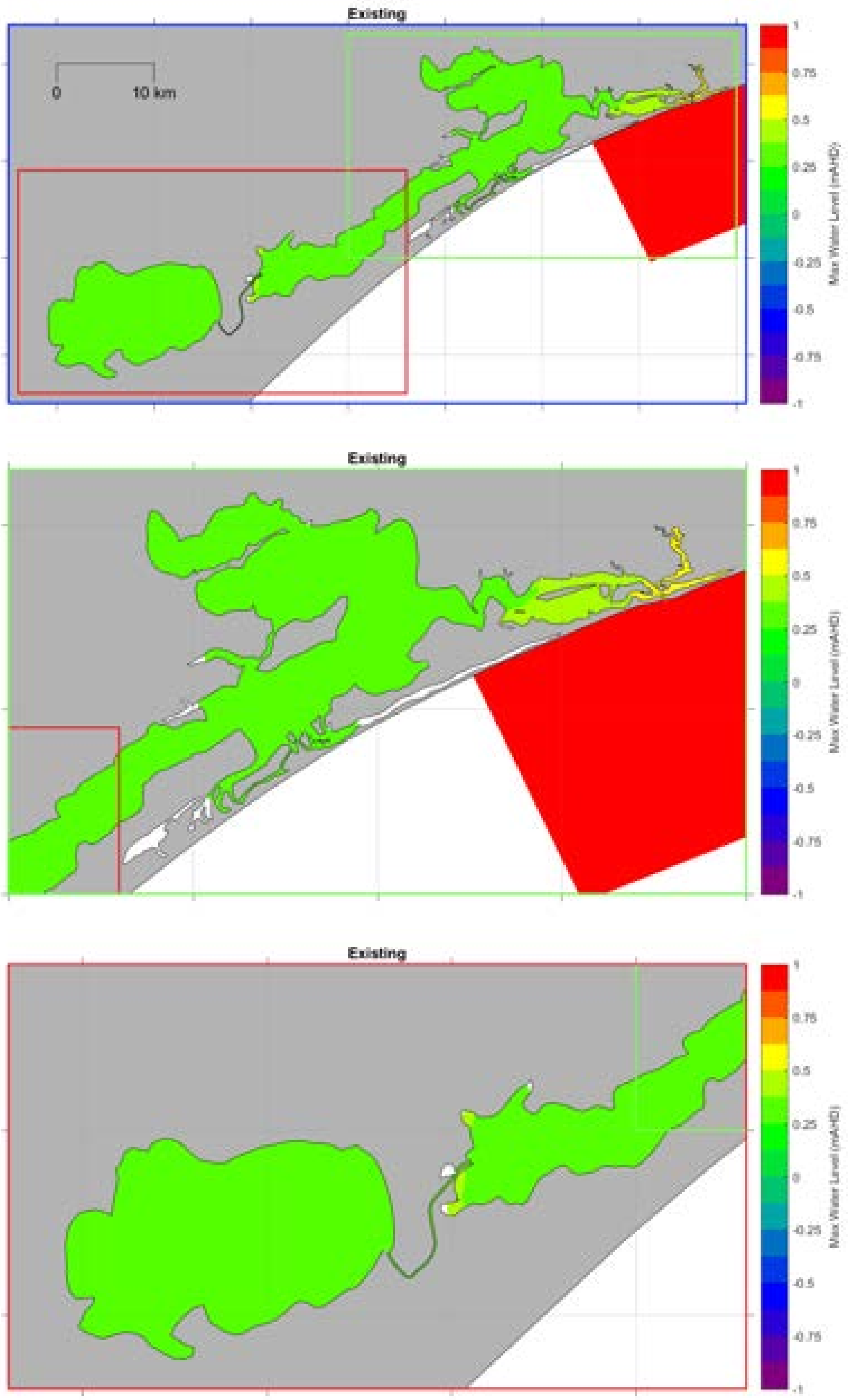


Figure B5. Existing case modelled maximum water level over 12 months with astronomical forcing.

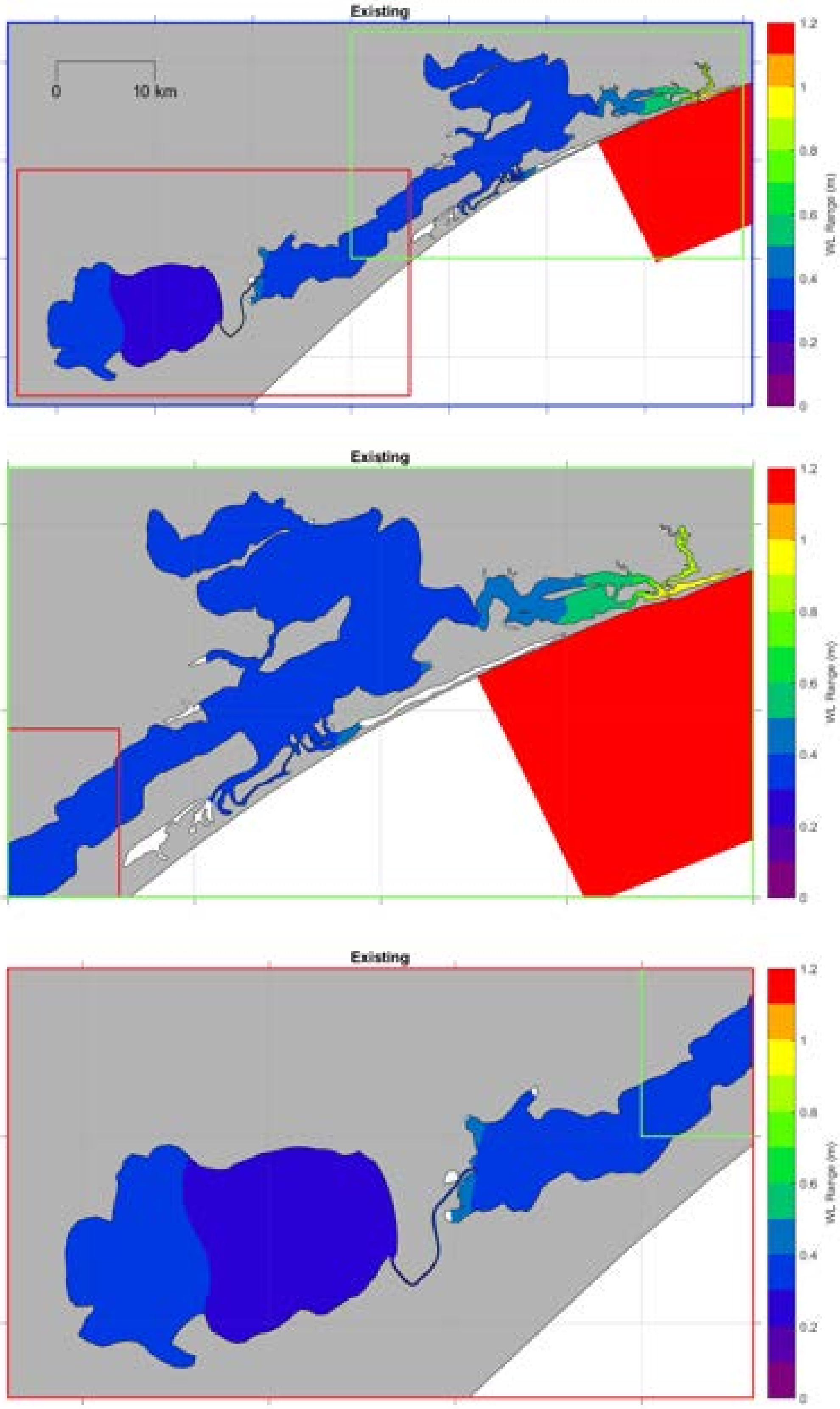


Figure B6. Existing case modelled maximum range in water level over 12 months with astronomical forcing.

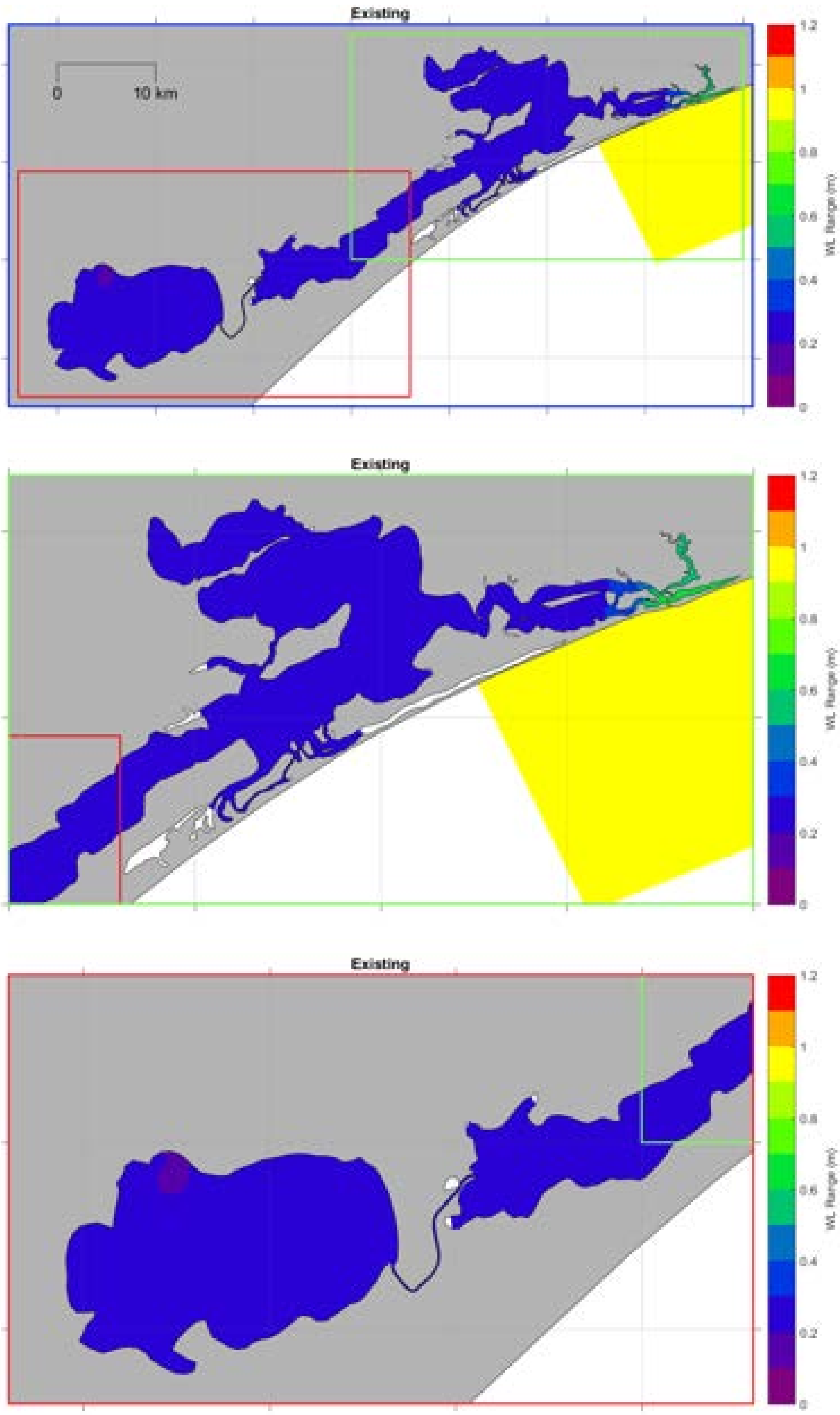


Figure B7. Existing case modelled 90th percentile range in water level over 12 months with astronomical forcing.

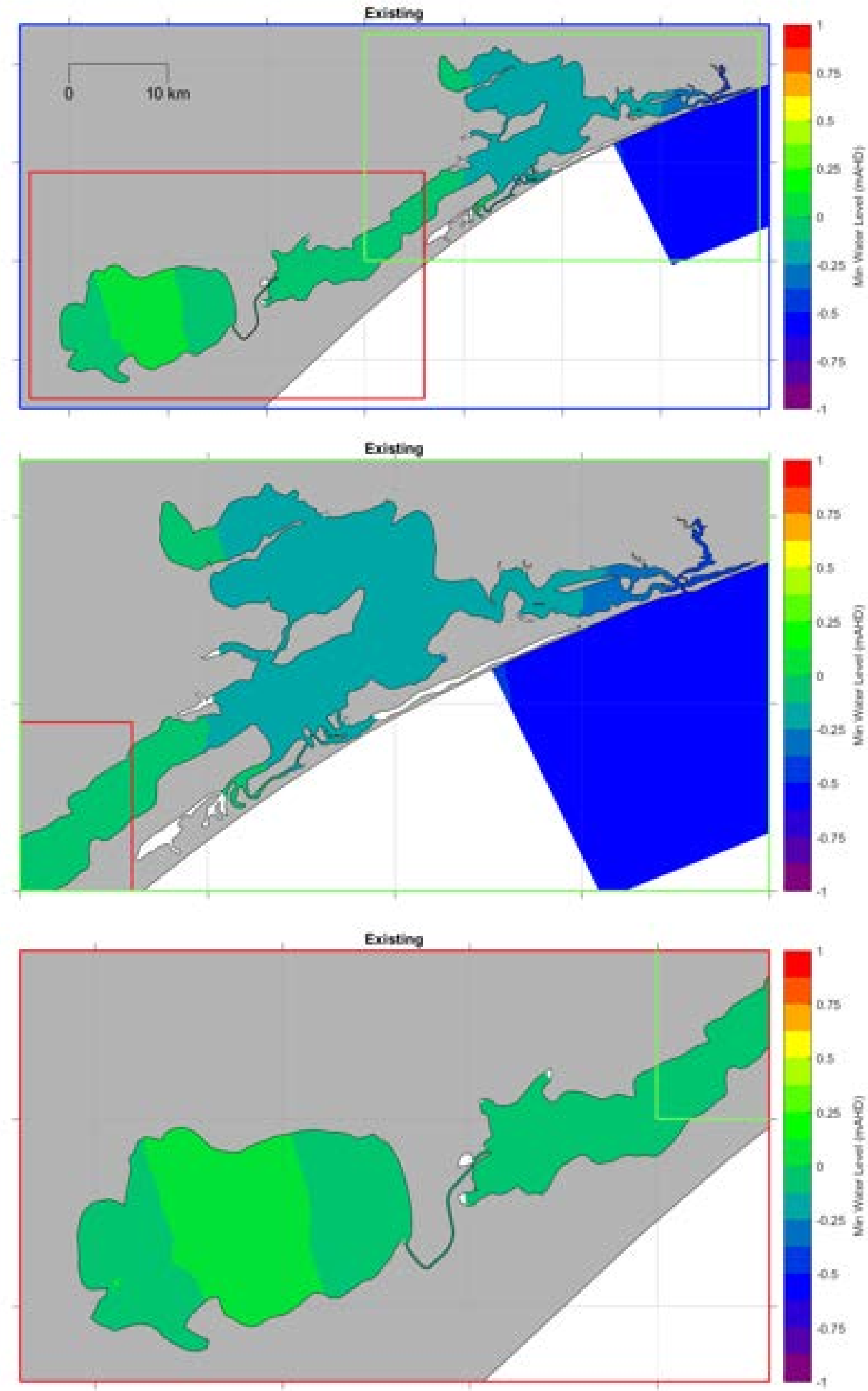


Figure B8. Existing case modelled minimum water level over 12 months with surge and freshwater forcing.

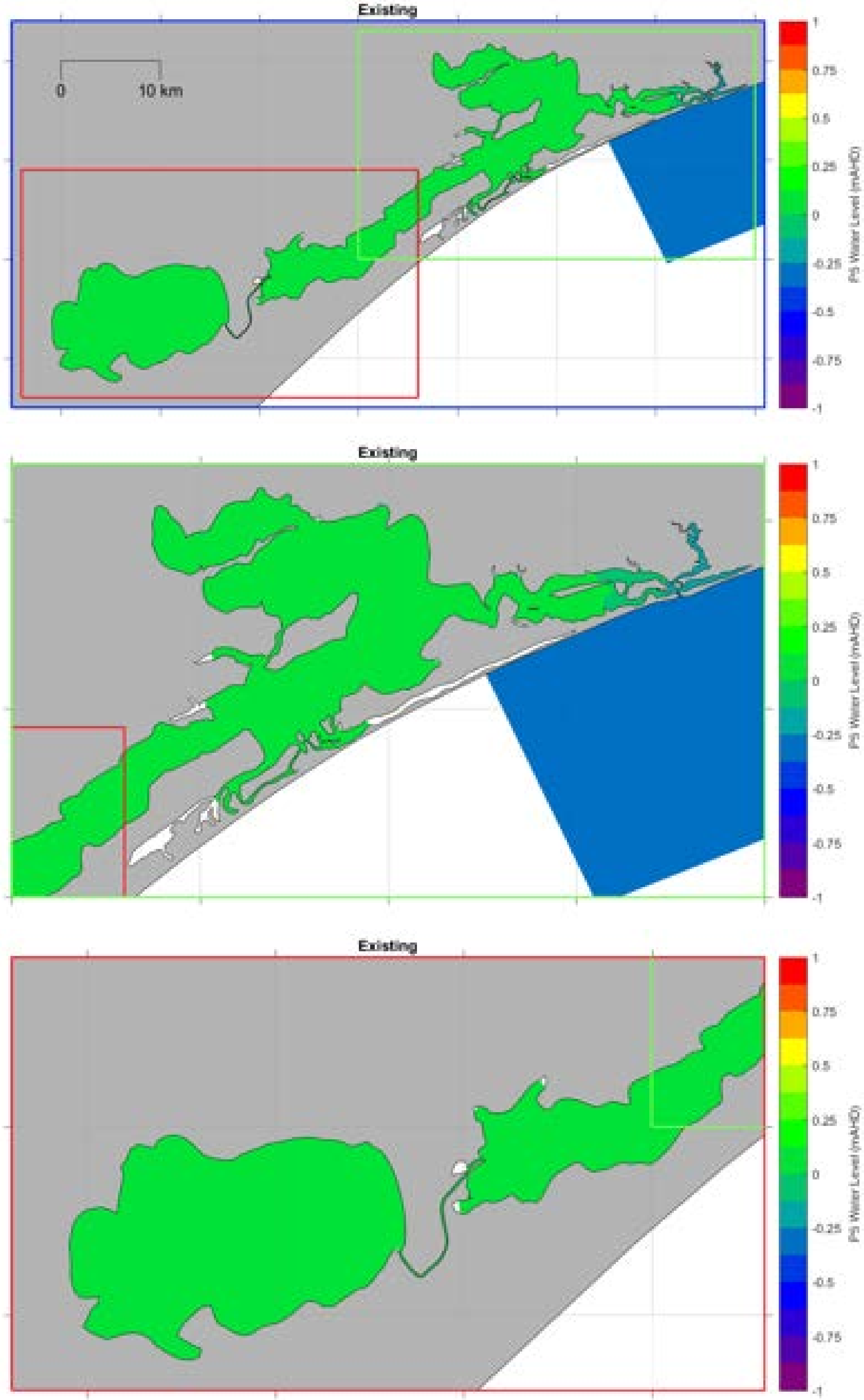


Figure B9. Existing case modelled 5th percentile water level over 12 months with surge and freshwater forcing.

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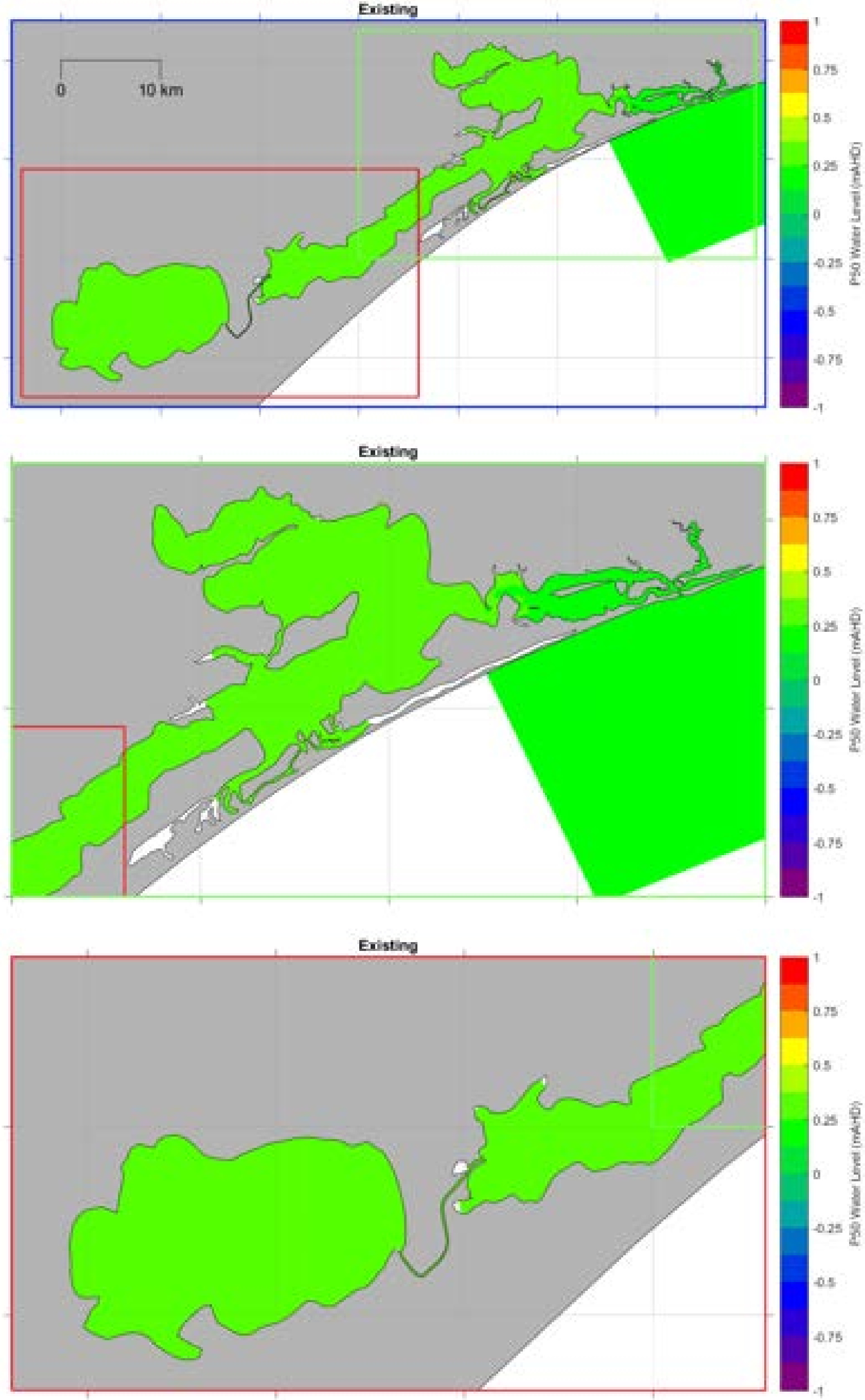


Figure B10. Existing case modelled median water level over 12 months with surge and freshwater forcing.

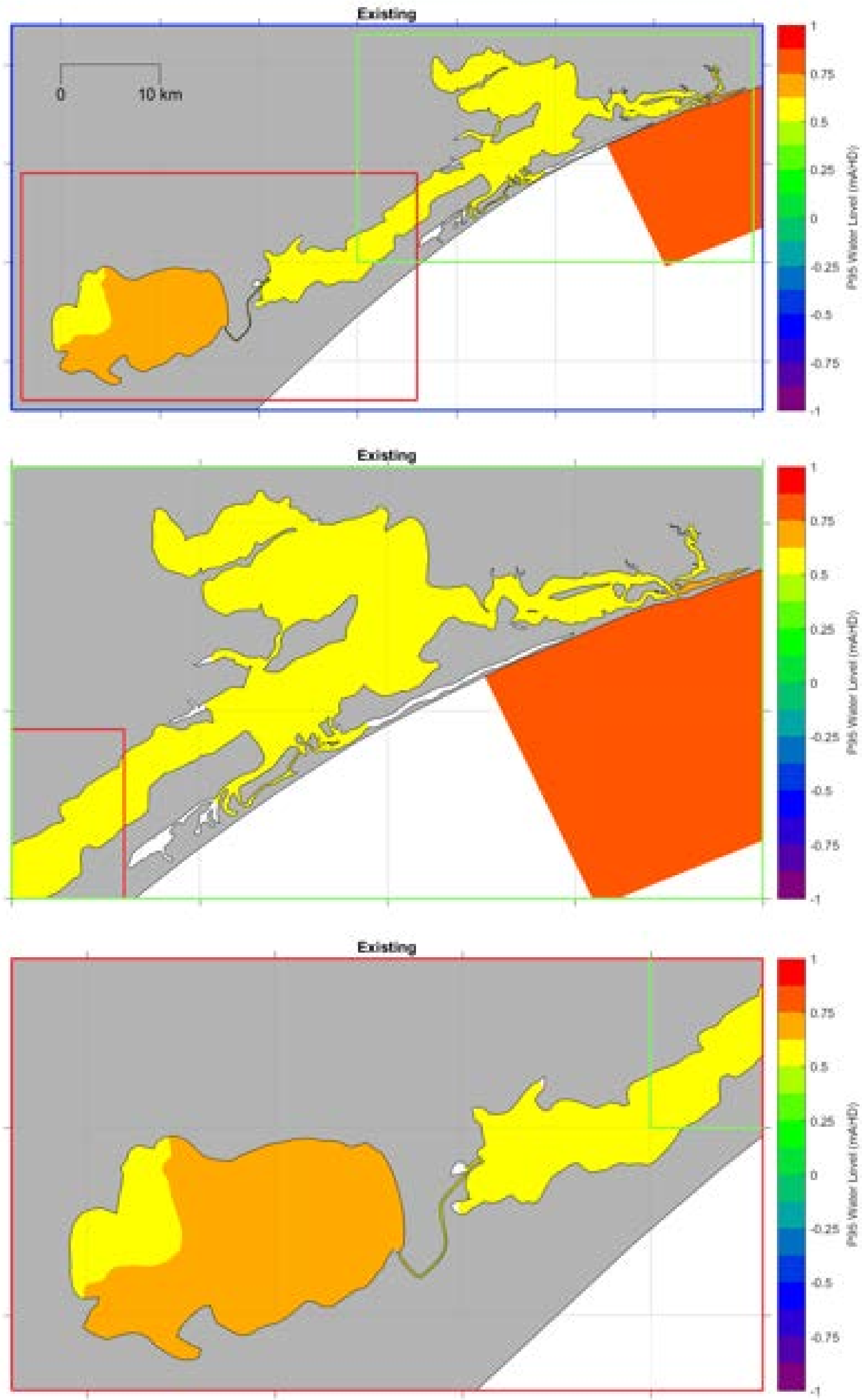


Figure B11. Existing case modelled 95th percentile water level over 12 months with surge and freshwater forcing.

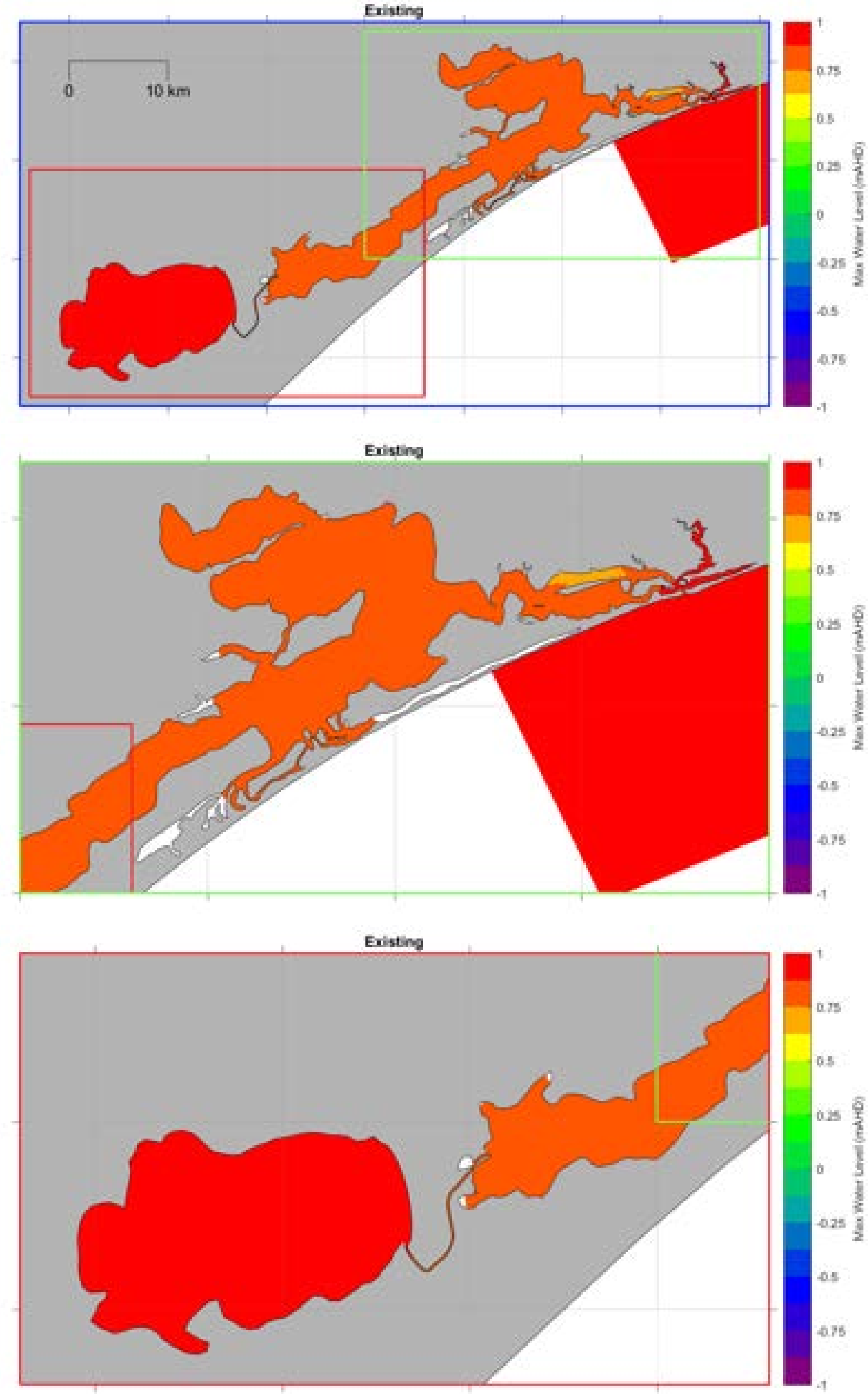


Figure B12. Existing case modelled maximum water level over 12 months with surge and freshwater forcing.

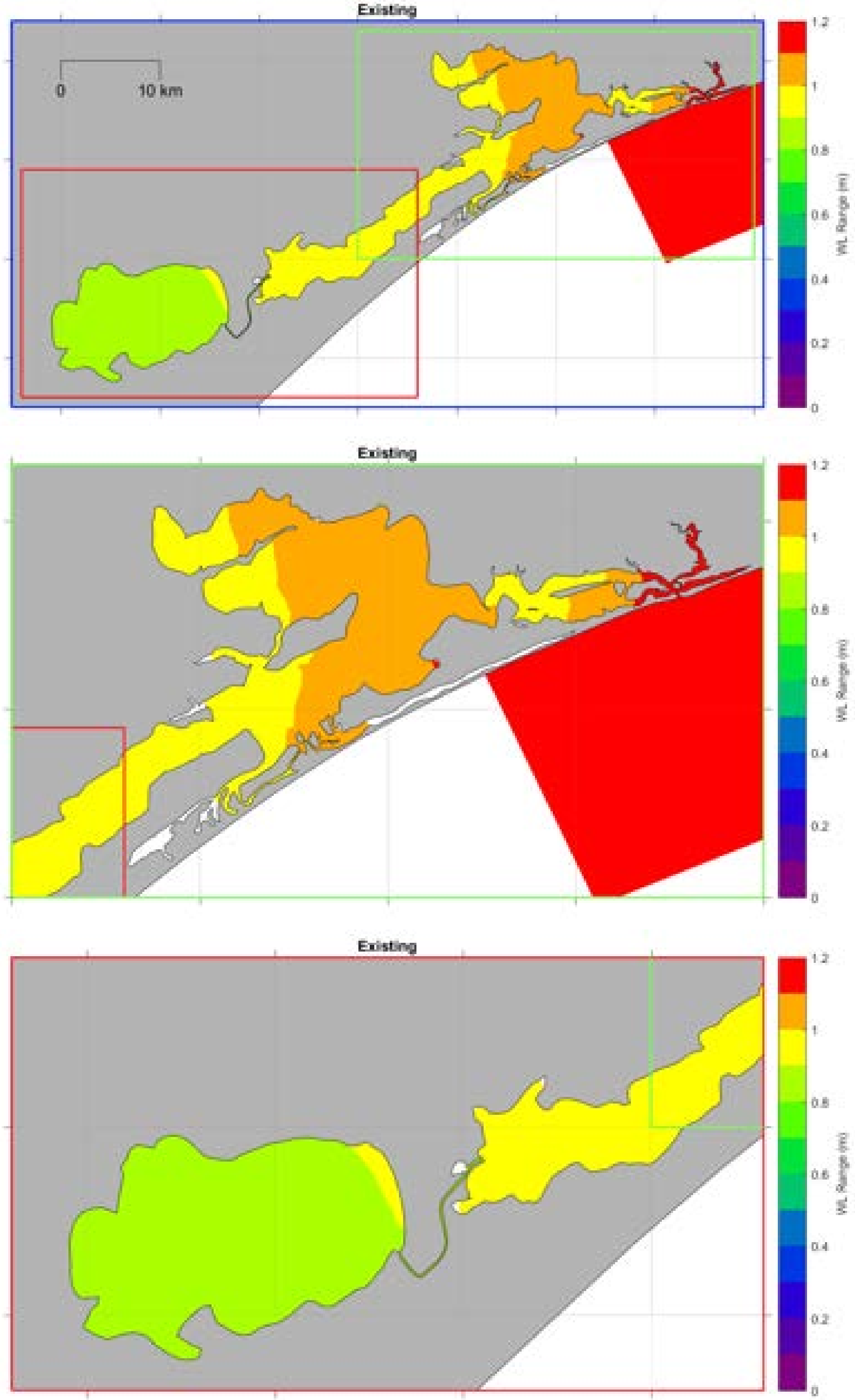


Figure B13. Existing case modelled maximum range in water level over 12 months with surge and freshwater forcing.

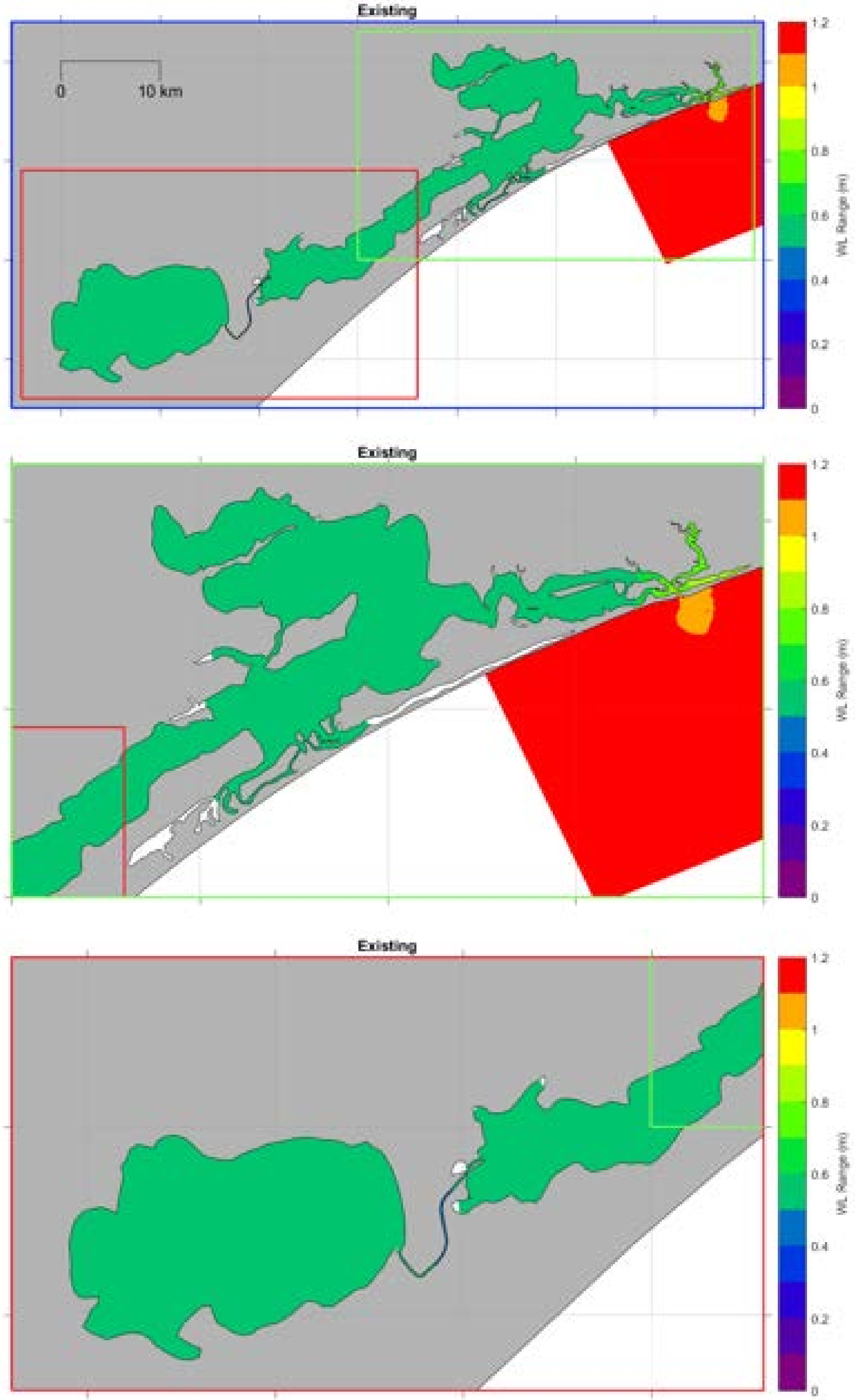


Figure B14. **Existing case modelled 90th percentile range in water level over 12 months with astronomical forcing.**

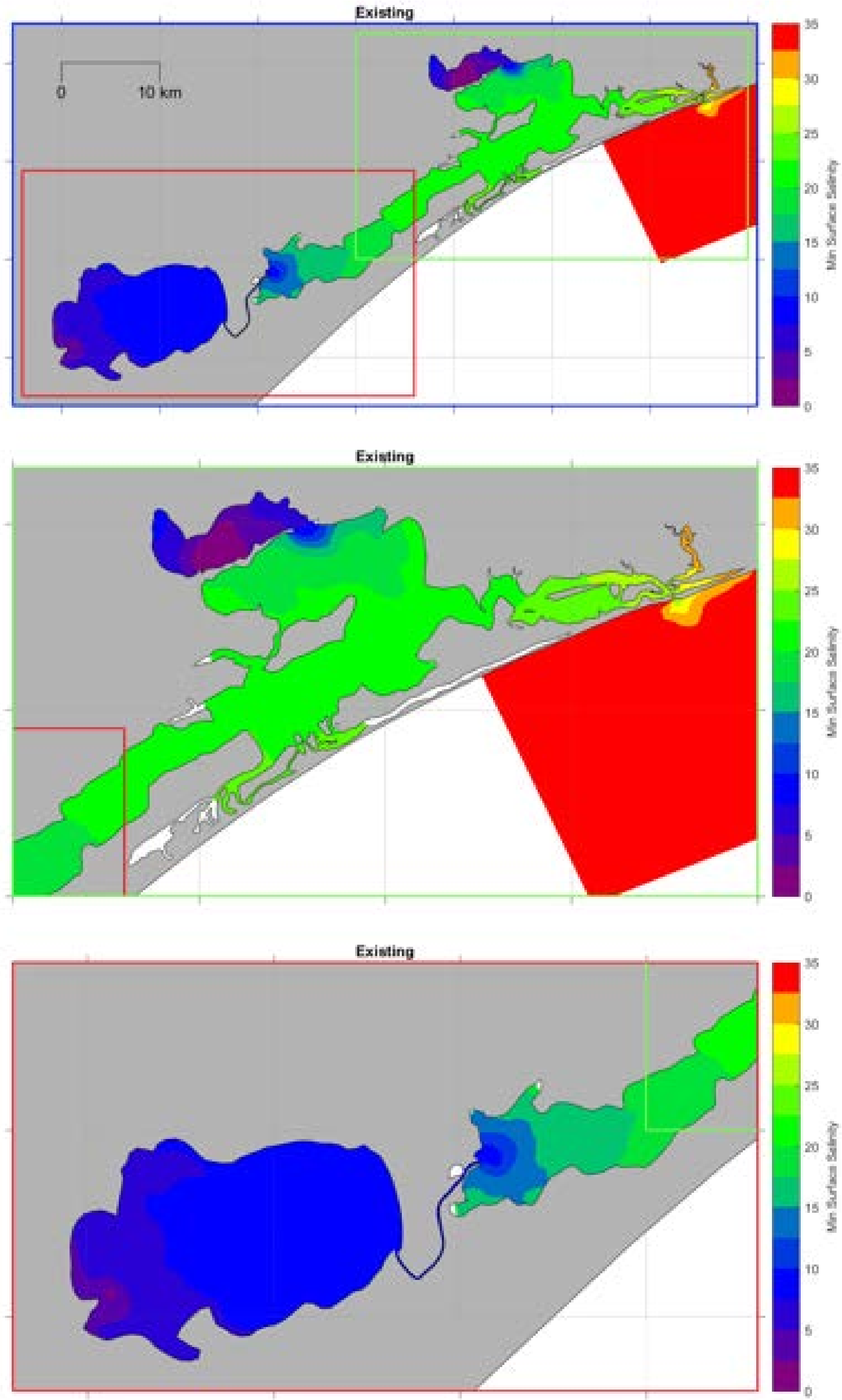


Figure B15. Existing case modelled minimum surface salinity over 12 months with astronomical forcing.

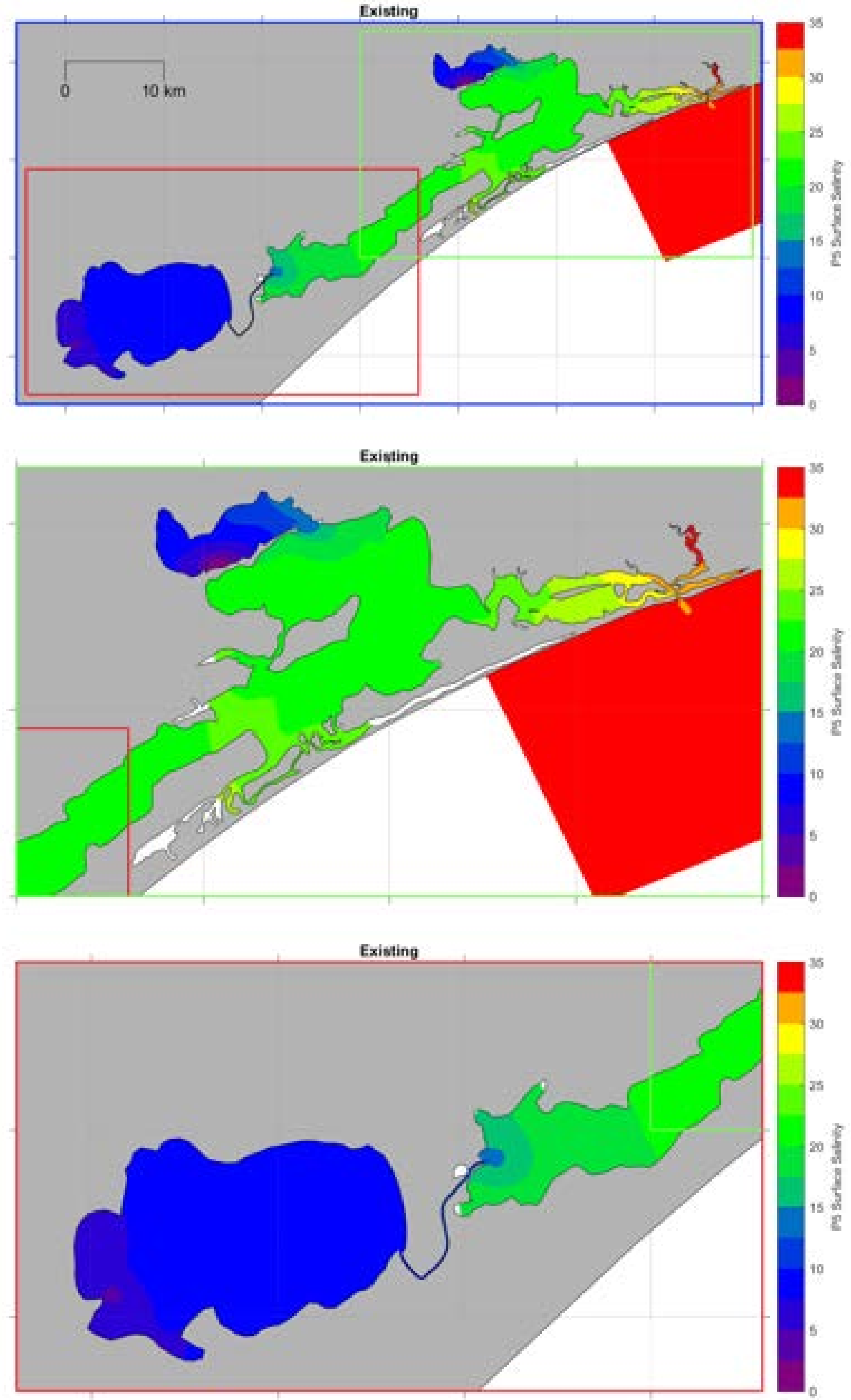


Figure B16. **Existing case modelled 5th percentile surface salinity over 12 months with astronomical forcing.**

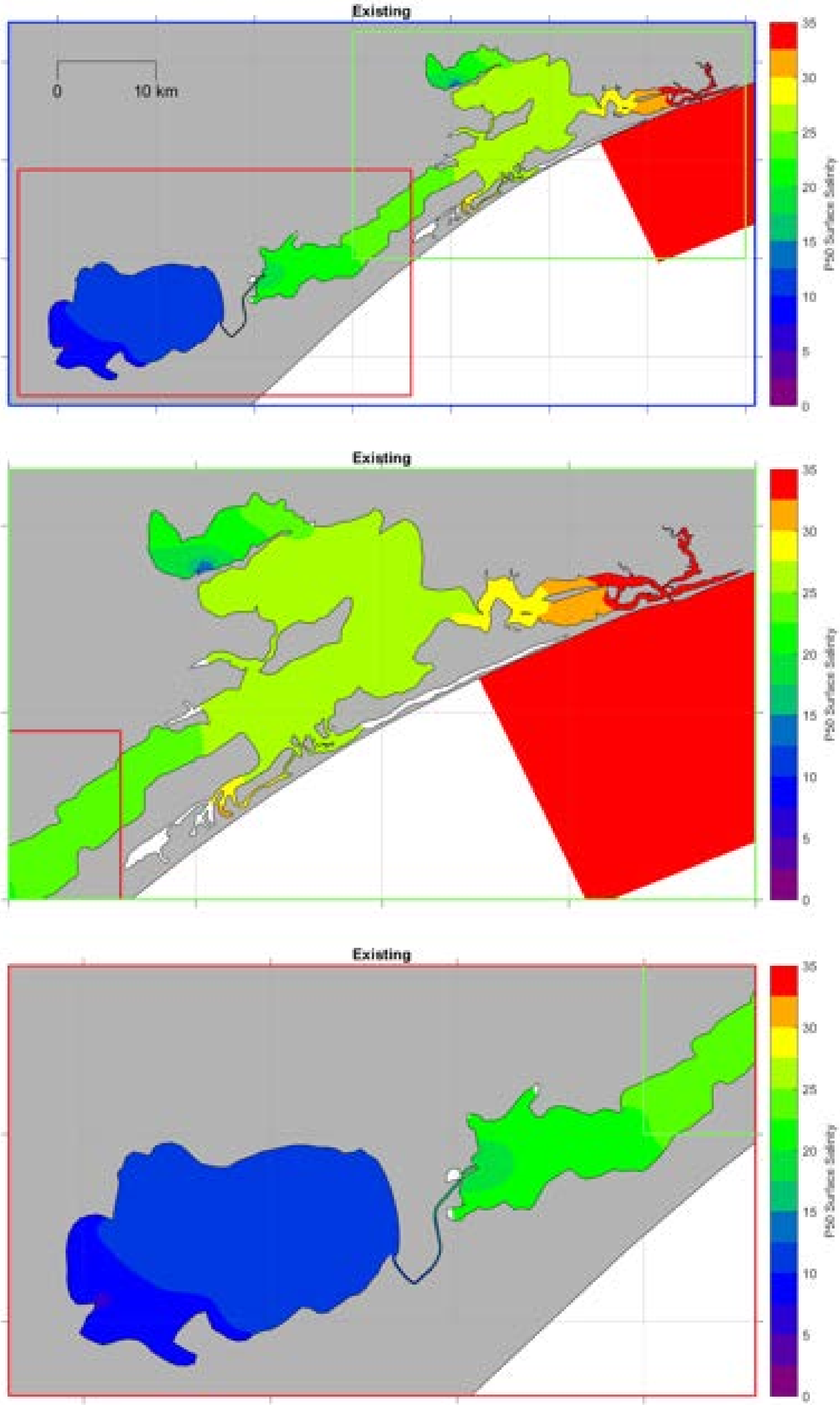


Figure B17. Existing case modelled median surface salinity over 12 months with astronomical forcing.

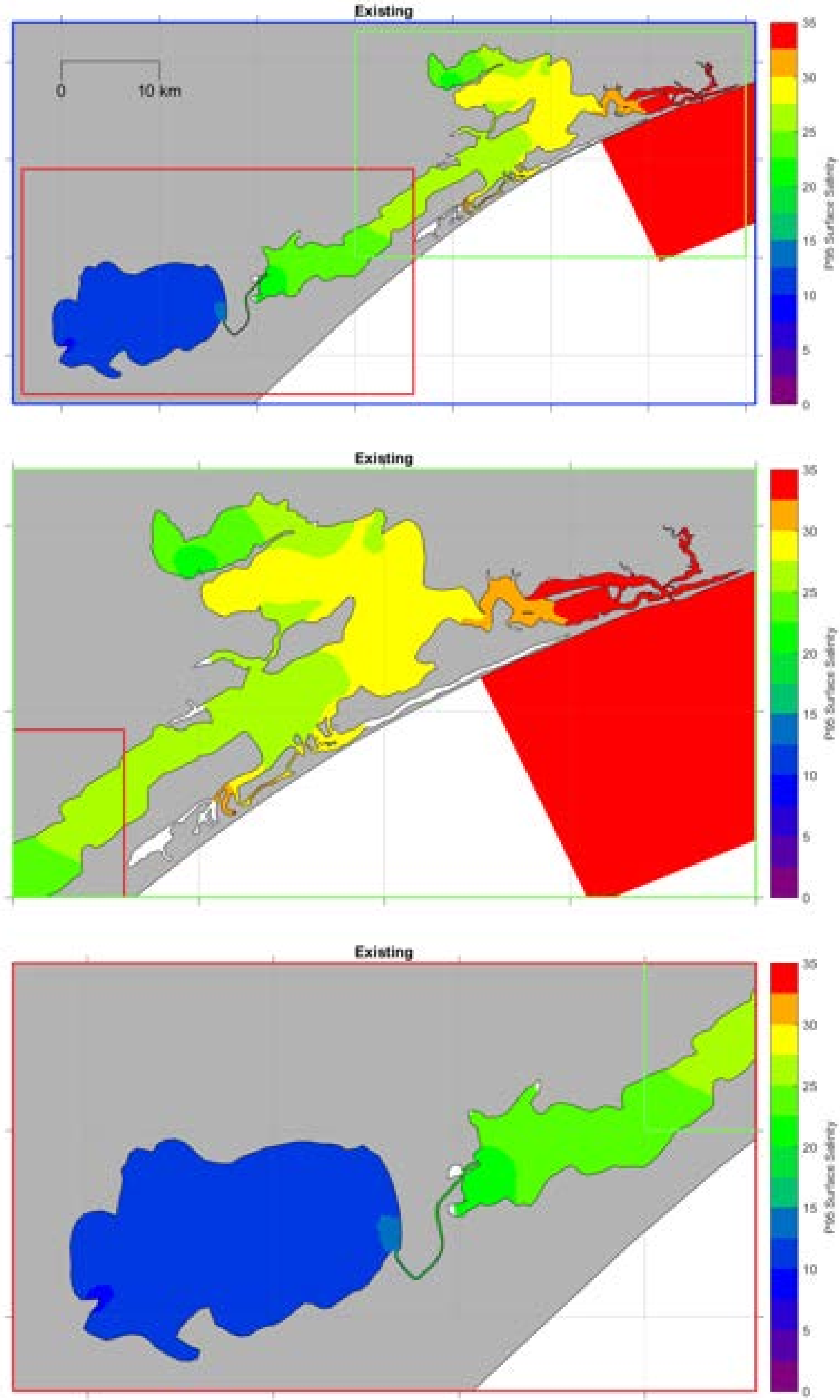


Figure B18. Existing case modelled 95th percentile surface salinity over 12 months with astronomical forcing.

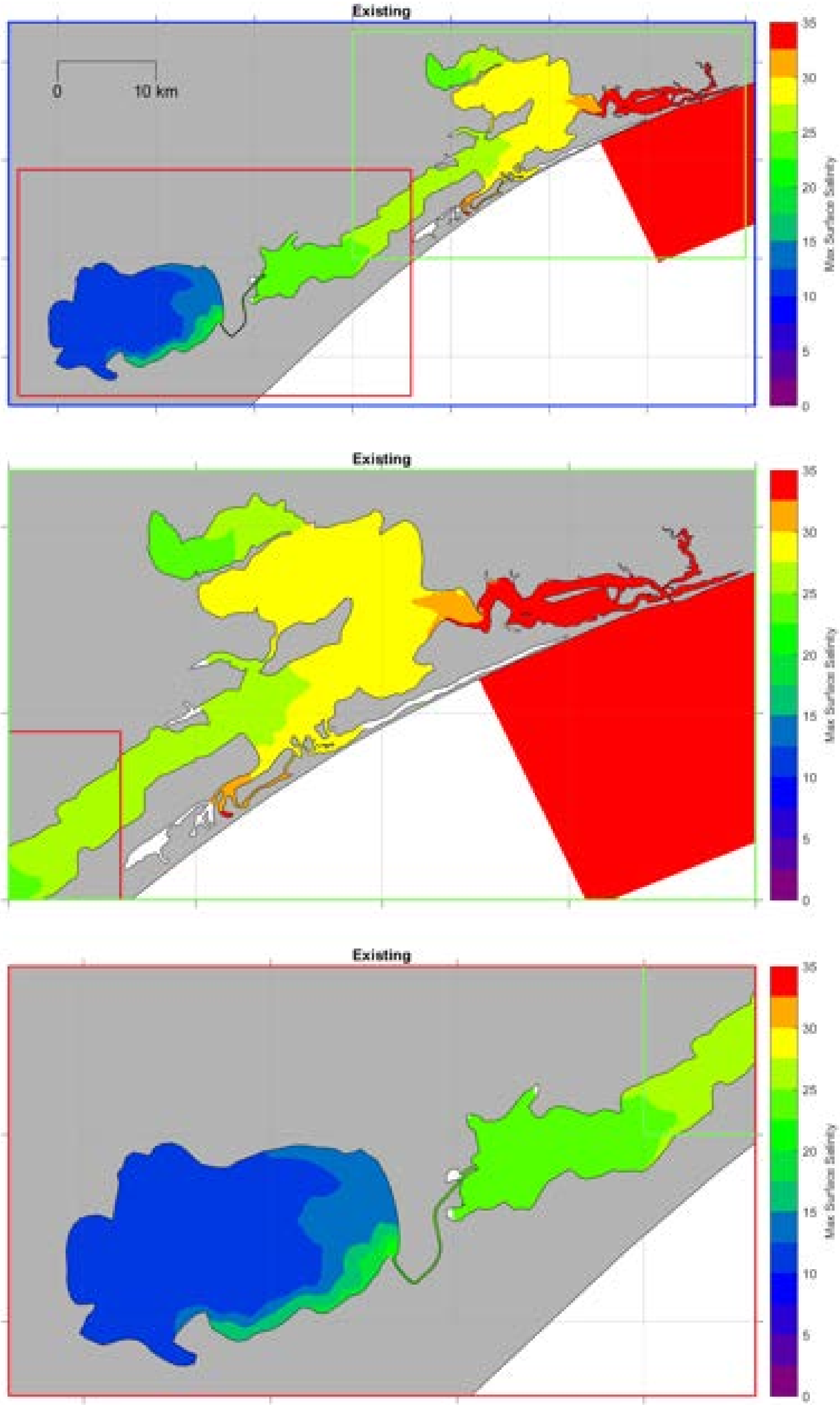


Figure B19. Existing case modelled maximum surface salinity over 12 months with astronomical forcing.

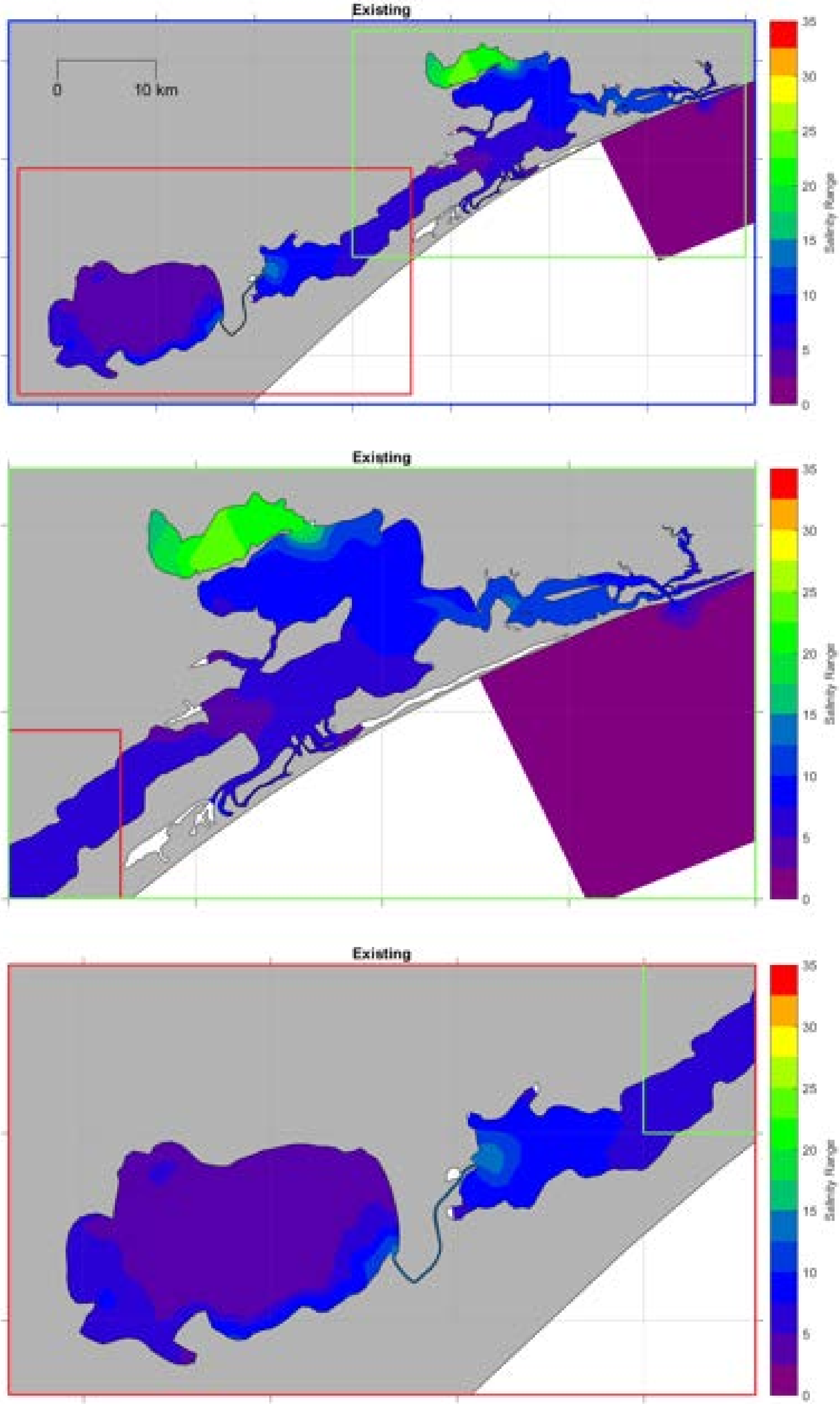


Figure B20. Existing case modelled maximum range in surface salinity over 12 months with astronomical forcing.

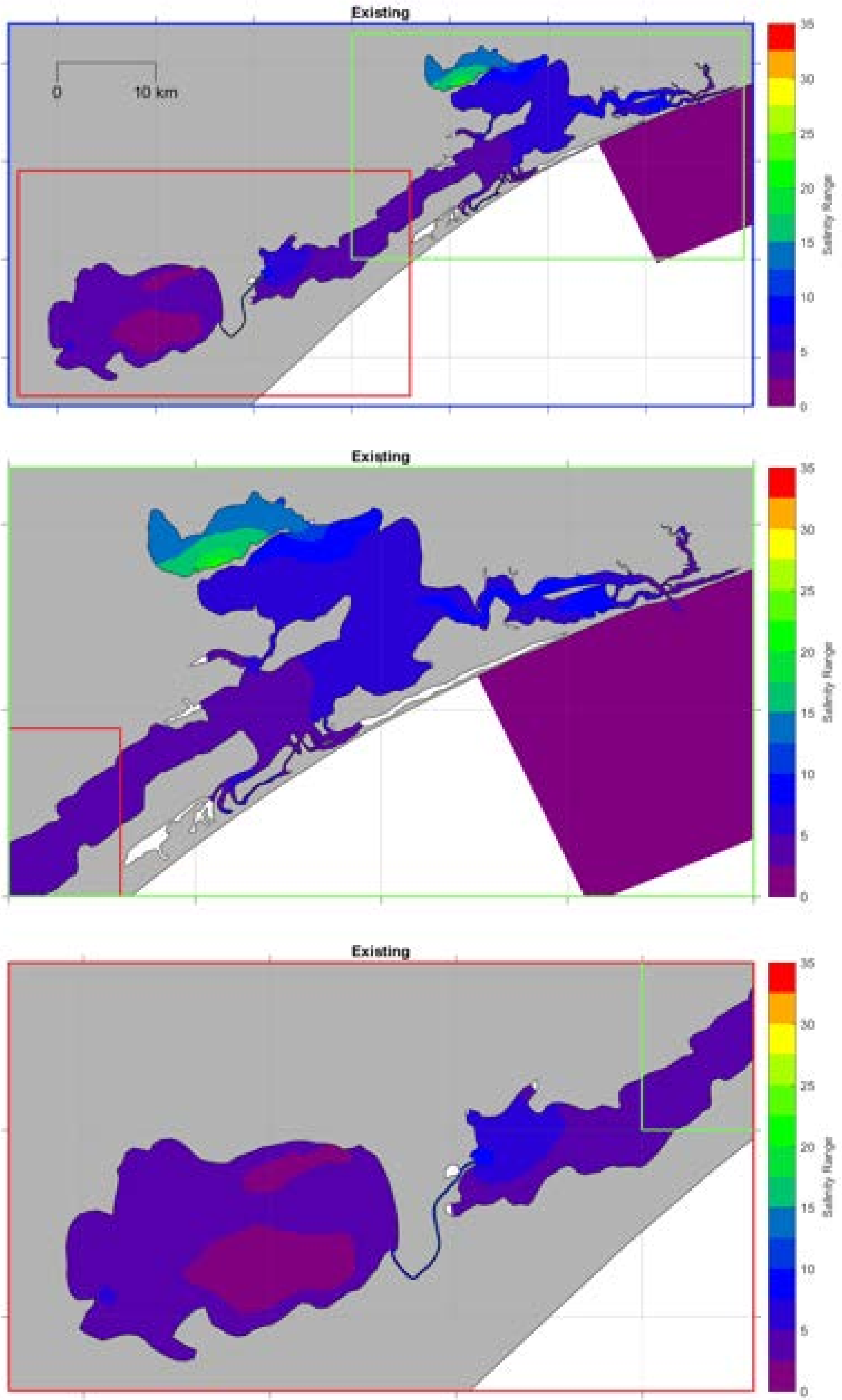


Figure B21. Existing case modelled 90th percentile range in surface salinity over 12 months with astronomical forcing.

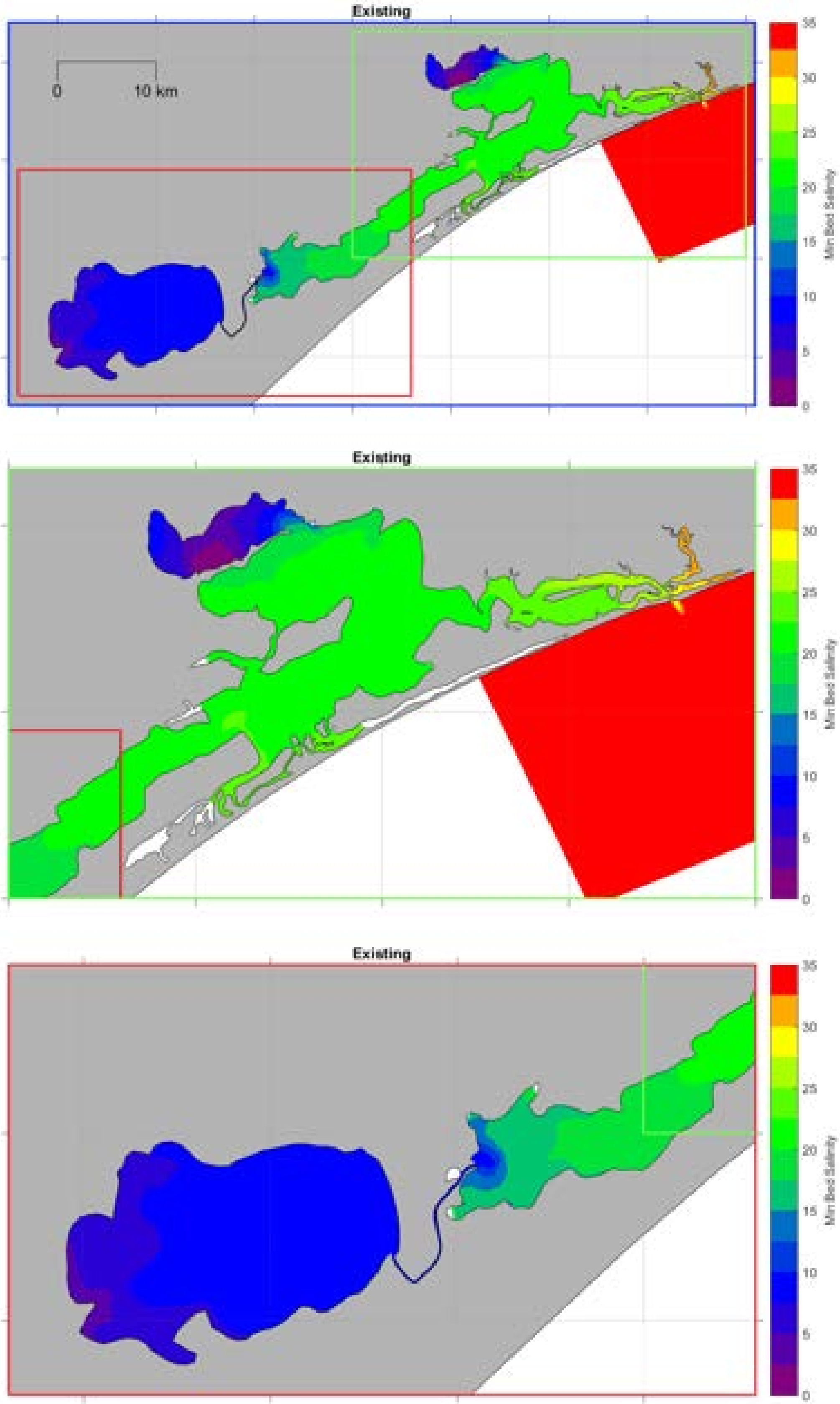


Figure B22. Existing case modelled minimum bed salinity over 12 months with astronomical forcing.

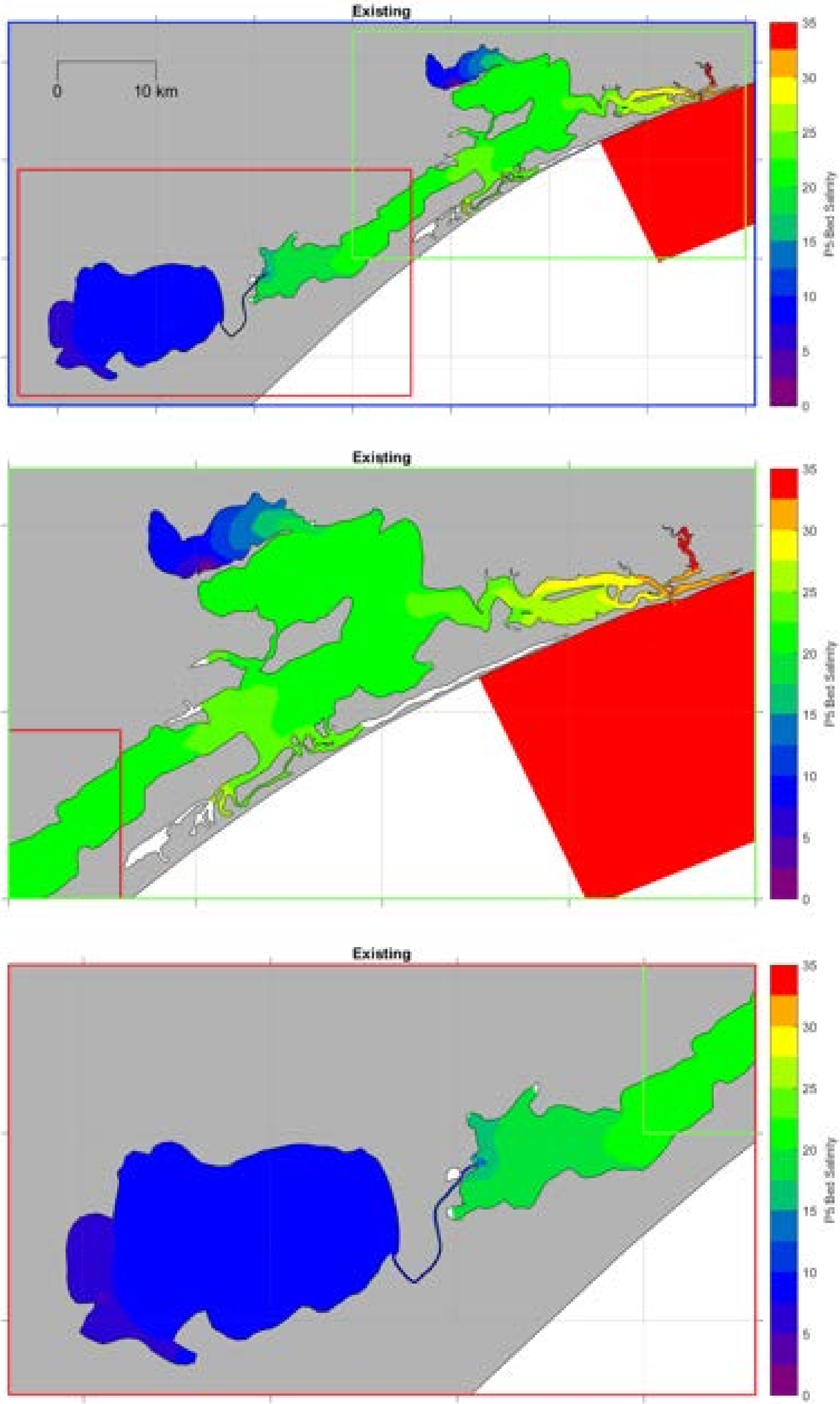


Figure B23. Existing case modelled 5th percentile bed salinity over 12 months with astronomical forcing.

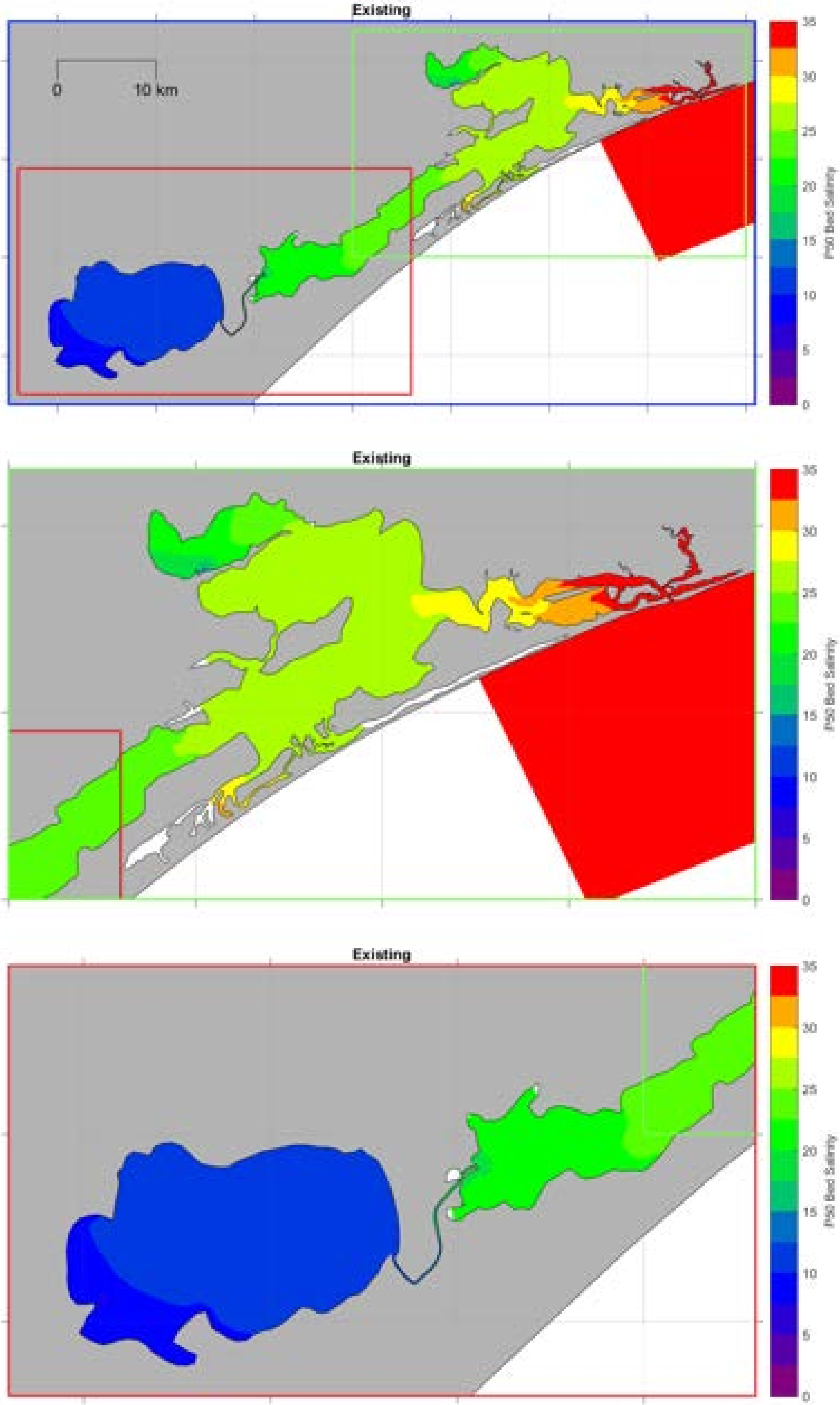


Figure B24. Existing case modelled median bed salinity over 12 months with astronomical forcing.

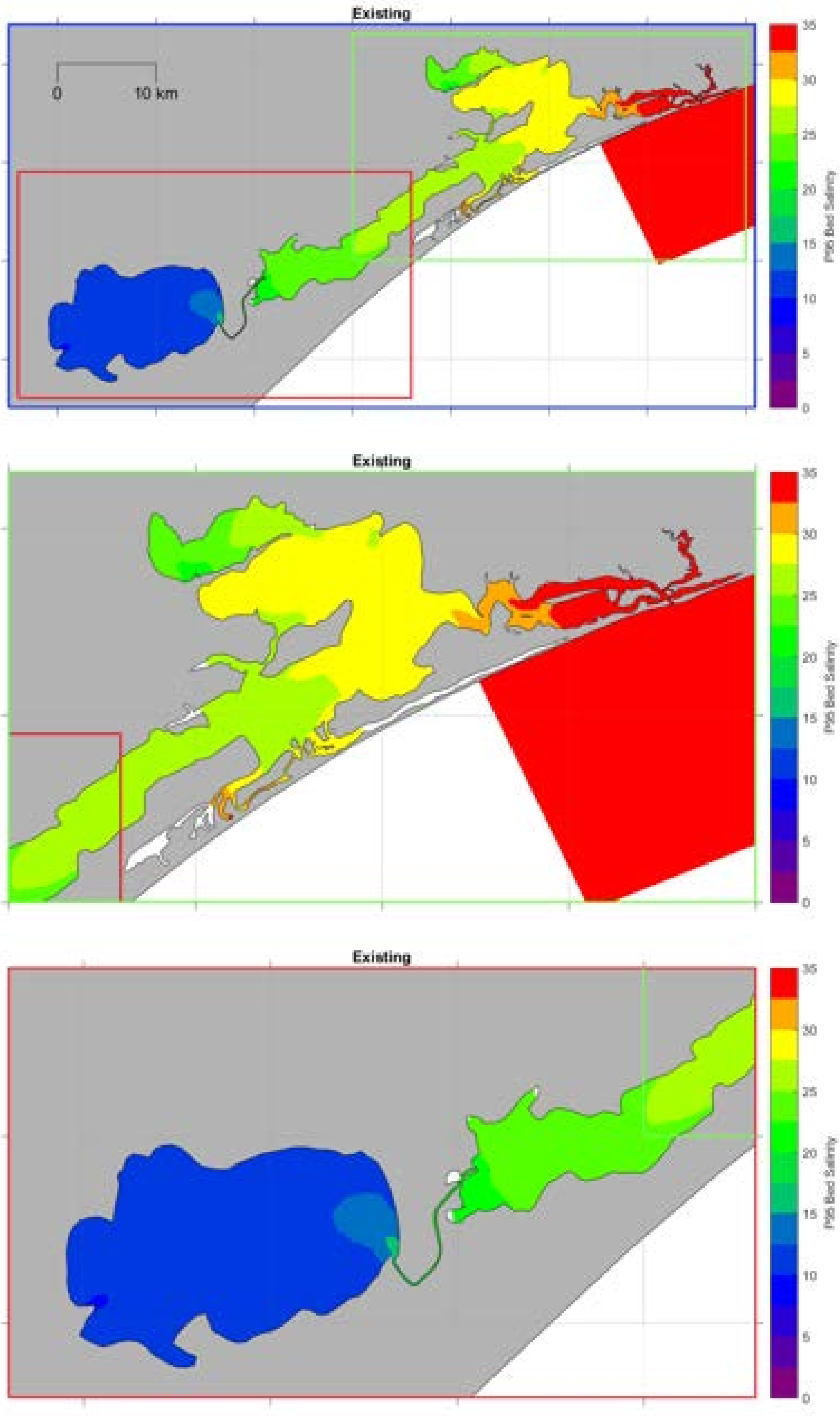


Figure B25. Existing case modelled 95th percentile bed salinity over 12 months with astronomical forcing.

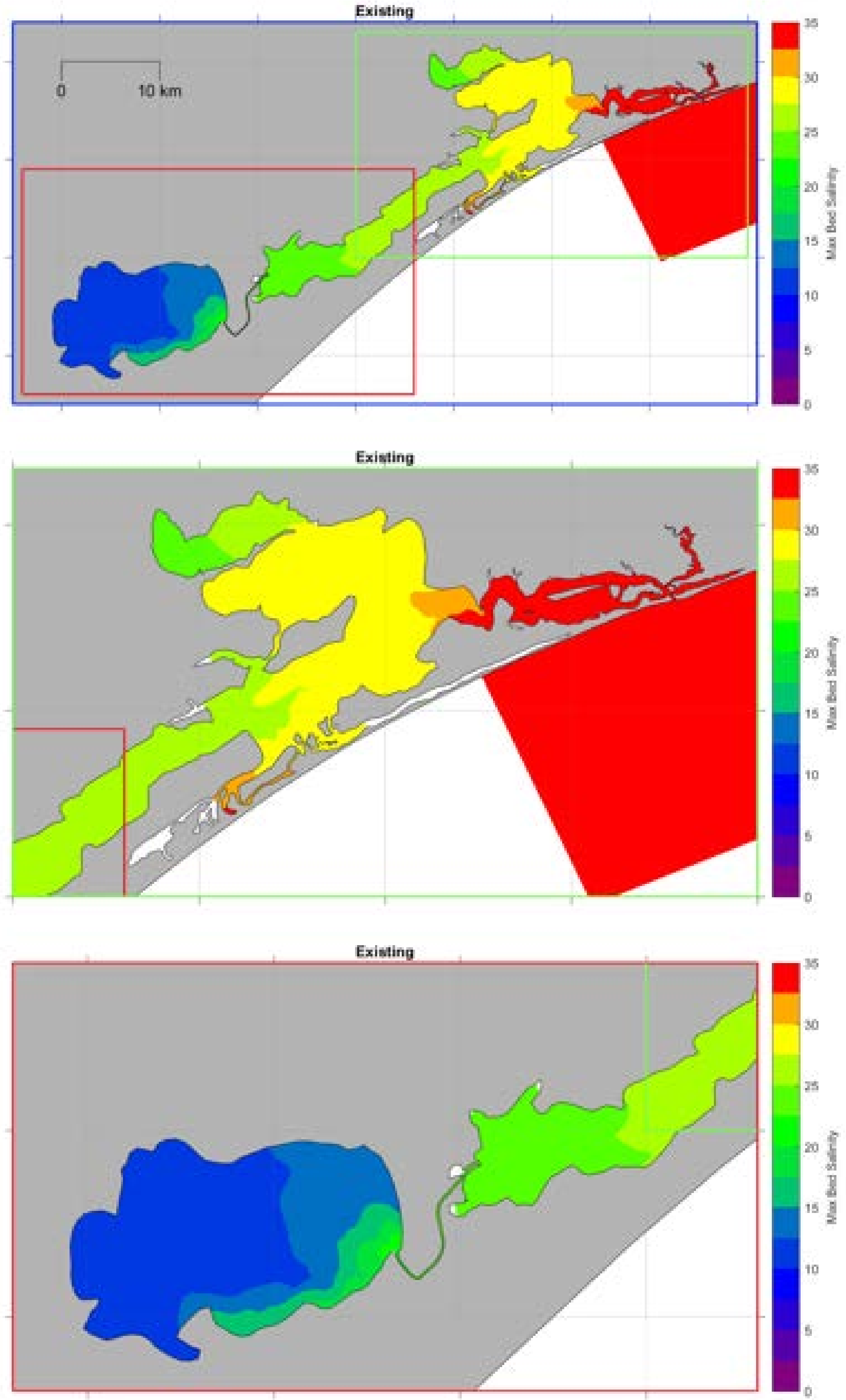


Figure B26. Existing case modelled maximum bed salinity over 12 months with astronomical forcing.

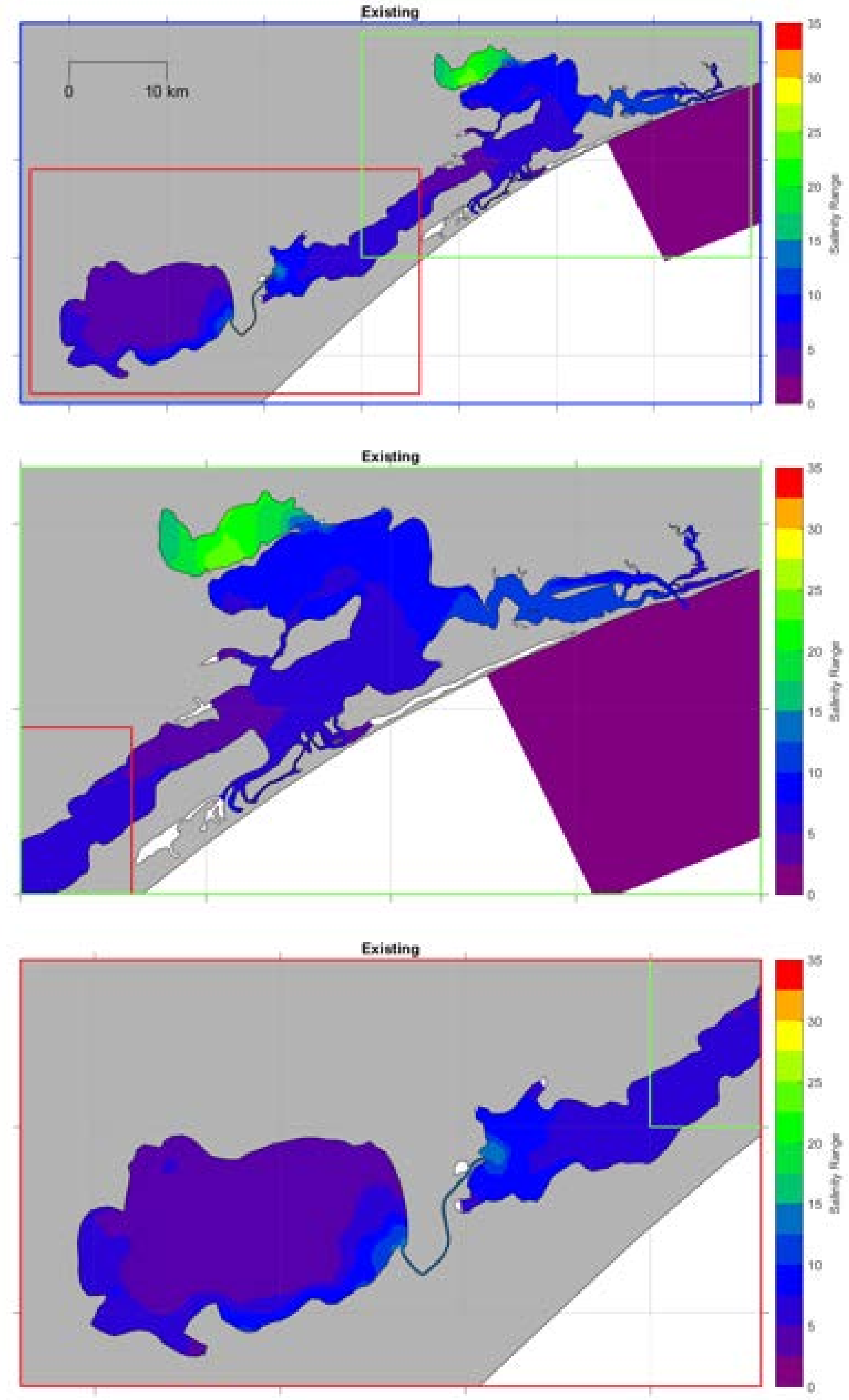


Figure B27. **Existing case modelled maximum range in bed salinity over 12 months with astronomical forcing.**

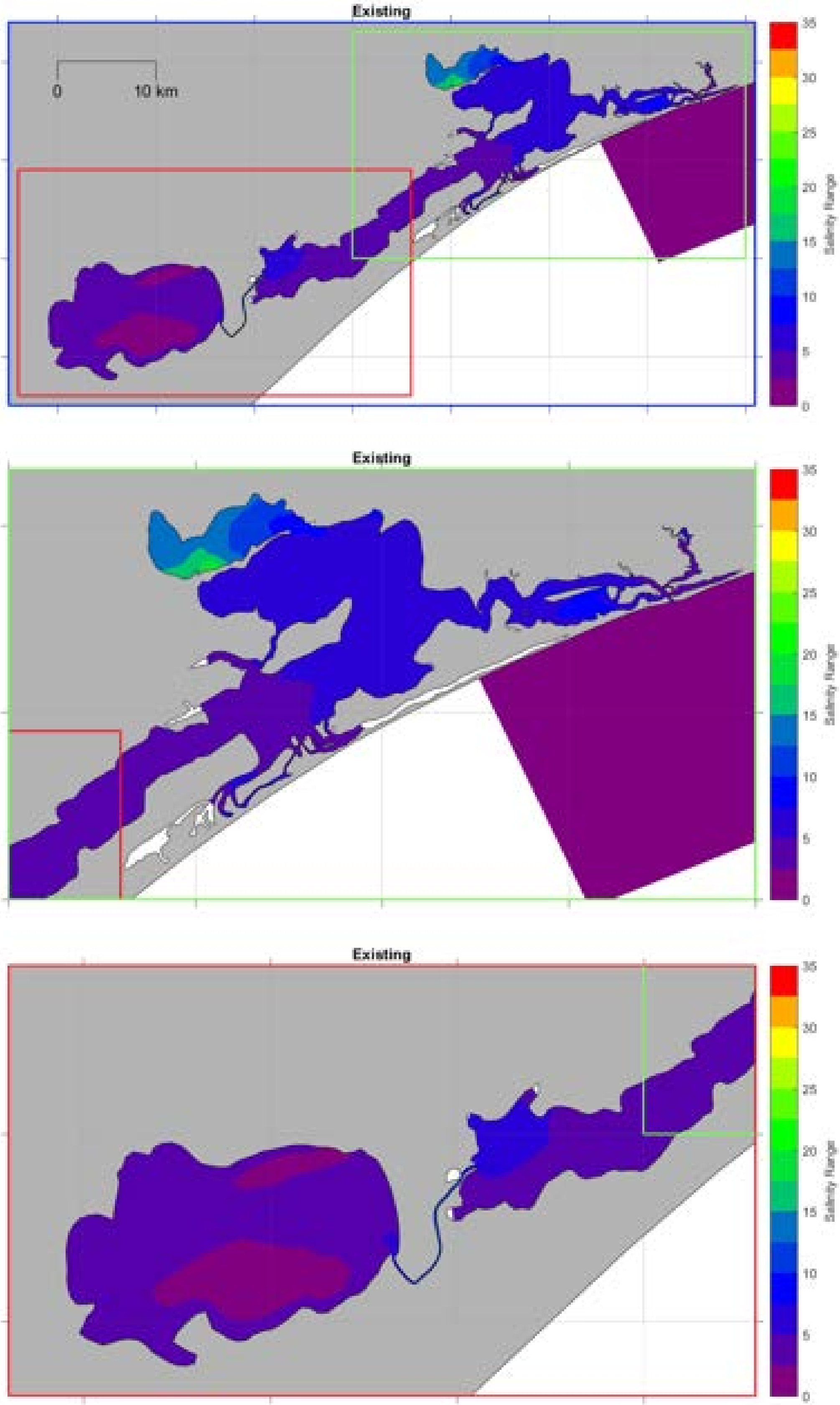


Figure B28. Existing case modelled 90th percentile range in bed salinity over 12 months with astronomical forcing.

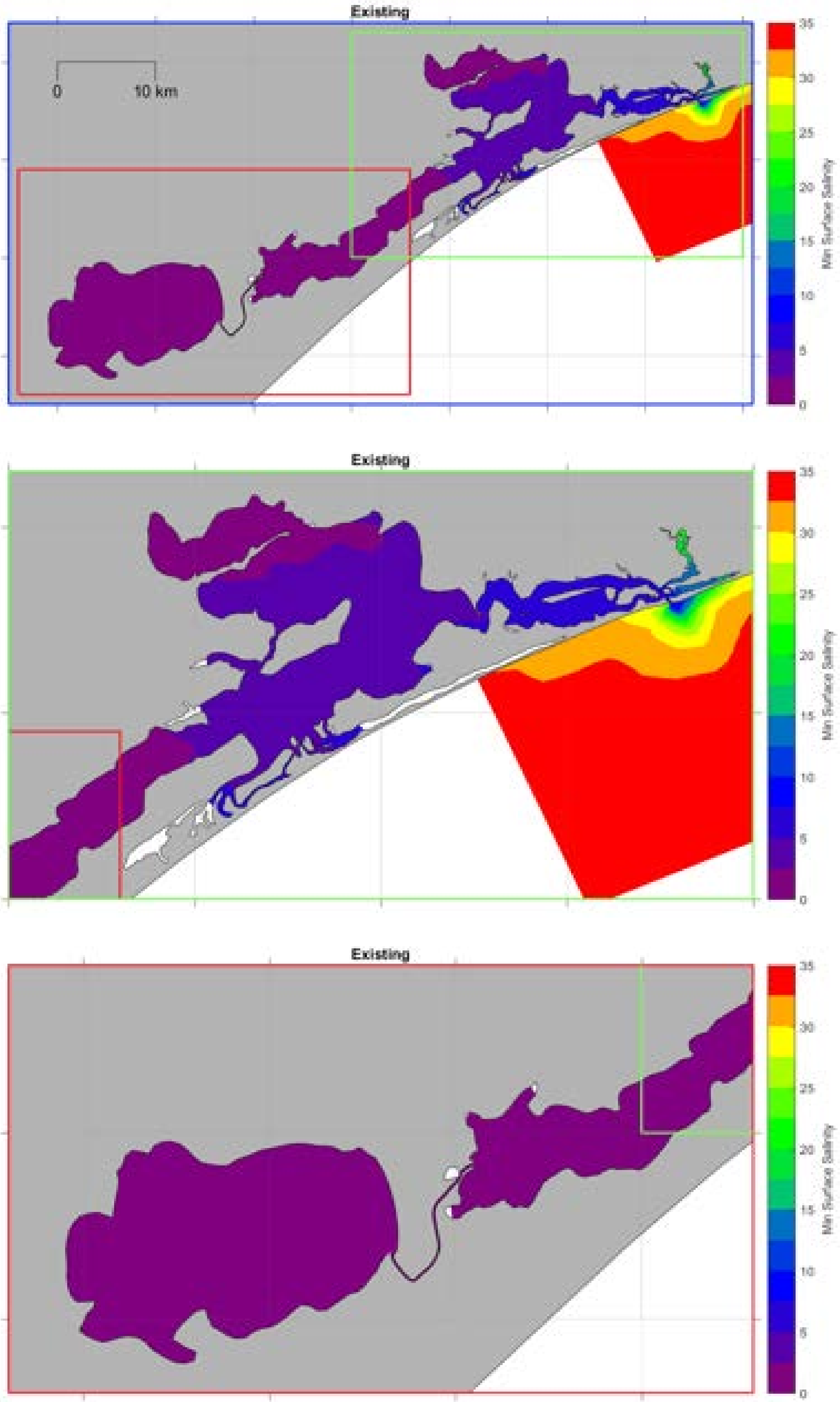


Figure B29. Existing case modelled minimum surface salinity over 12 months with surge and freshwater forcing.

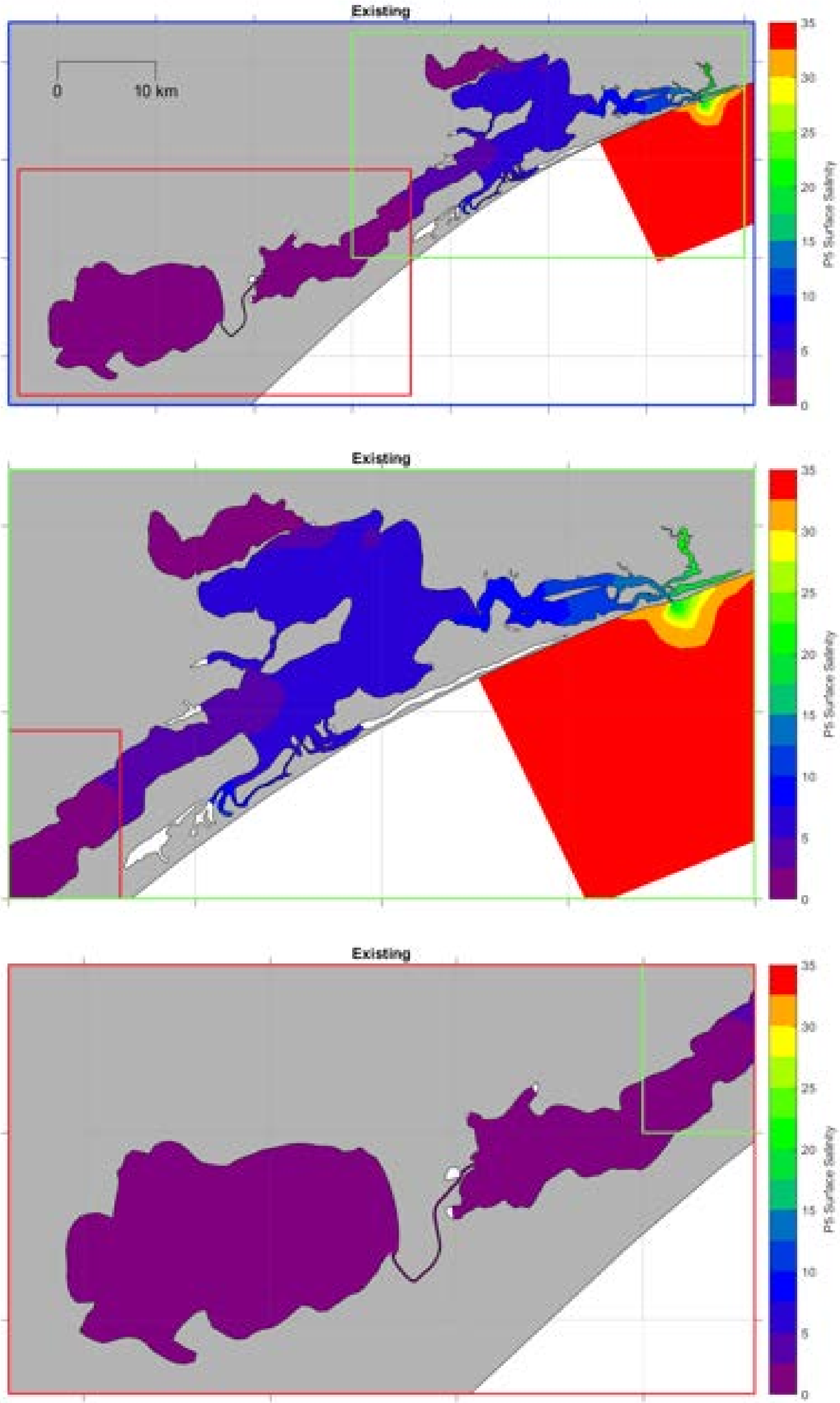


Figure B30. **Existing case modelled 5th percentile surface salinity over 12 months with surge and freshwater forcing.**

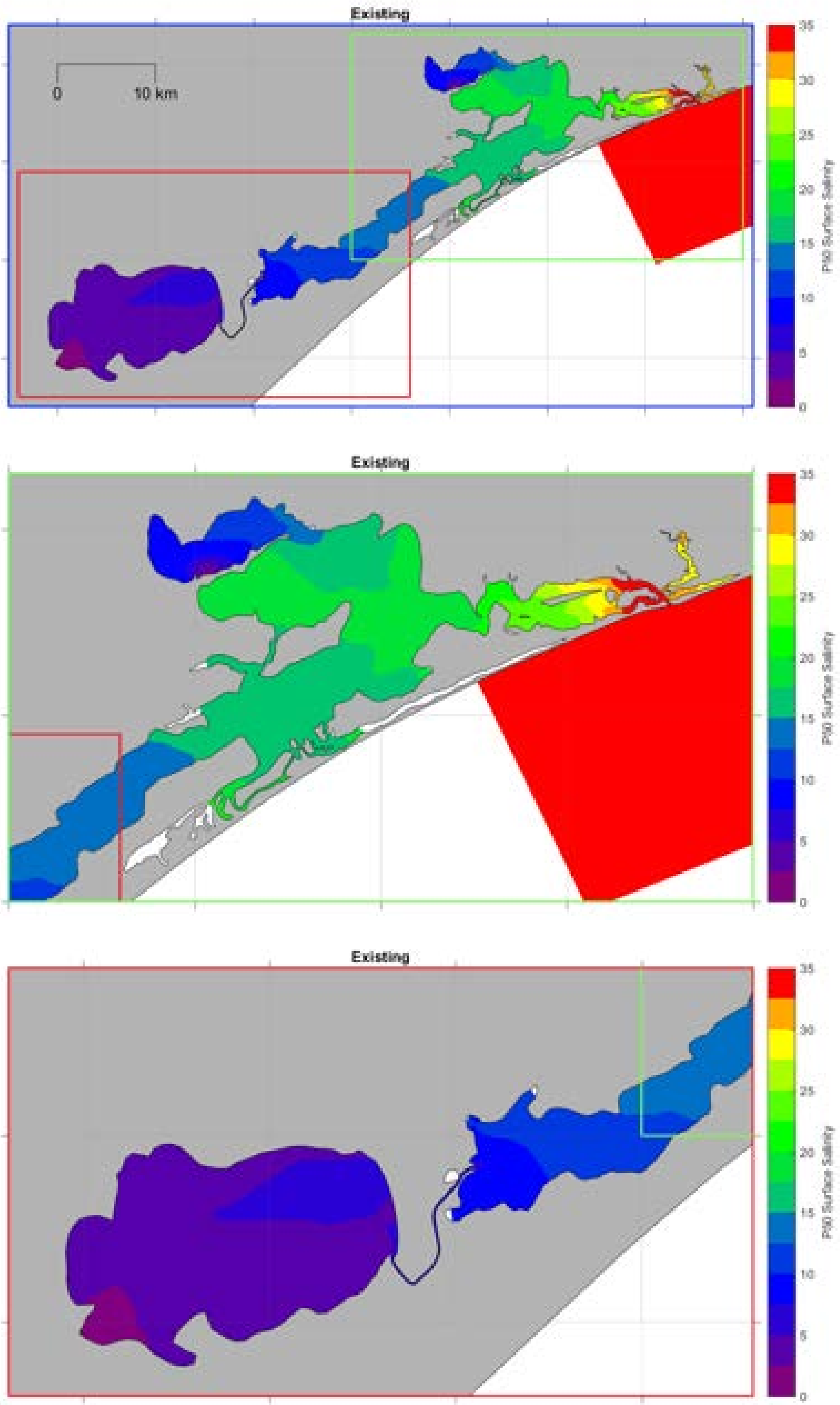


Figure B31. Existing case modelled median surface salinity over 12 months with surge and freshwater forcing.

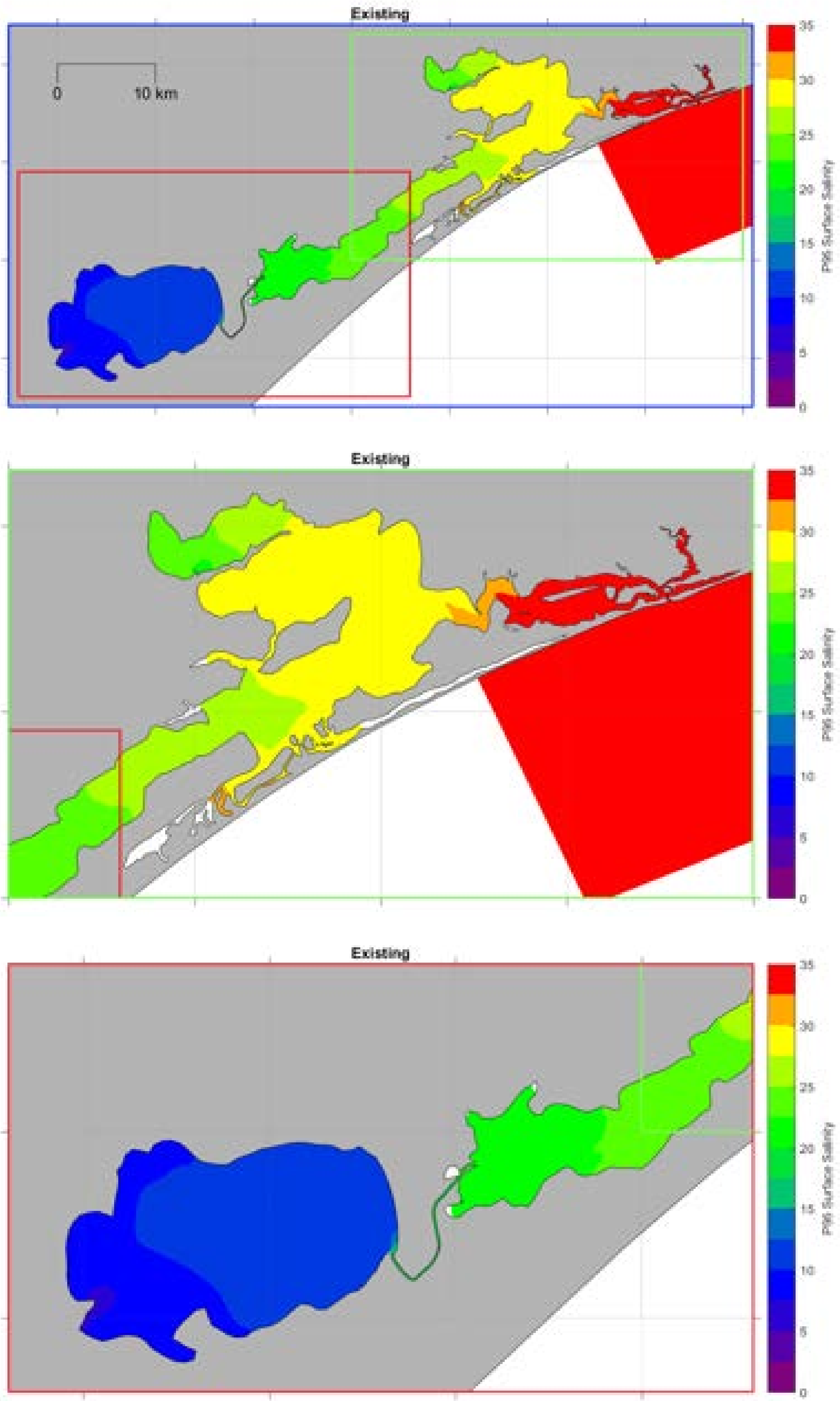


Figure B32. Existing case modelled 95th percentile surface salinity over 12 months with surge and freshwater forcing.

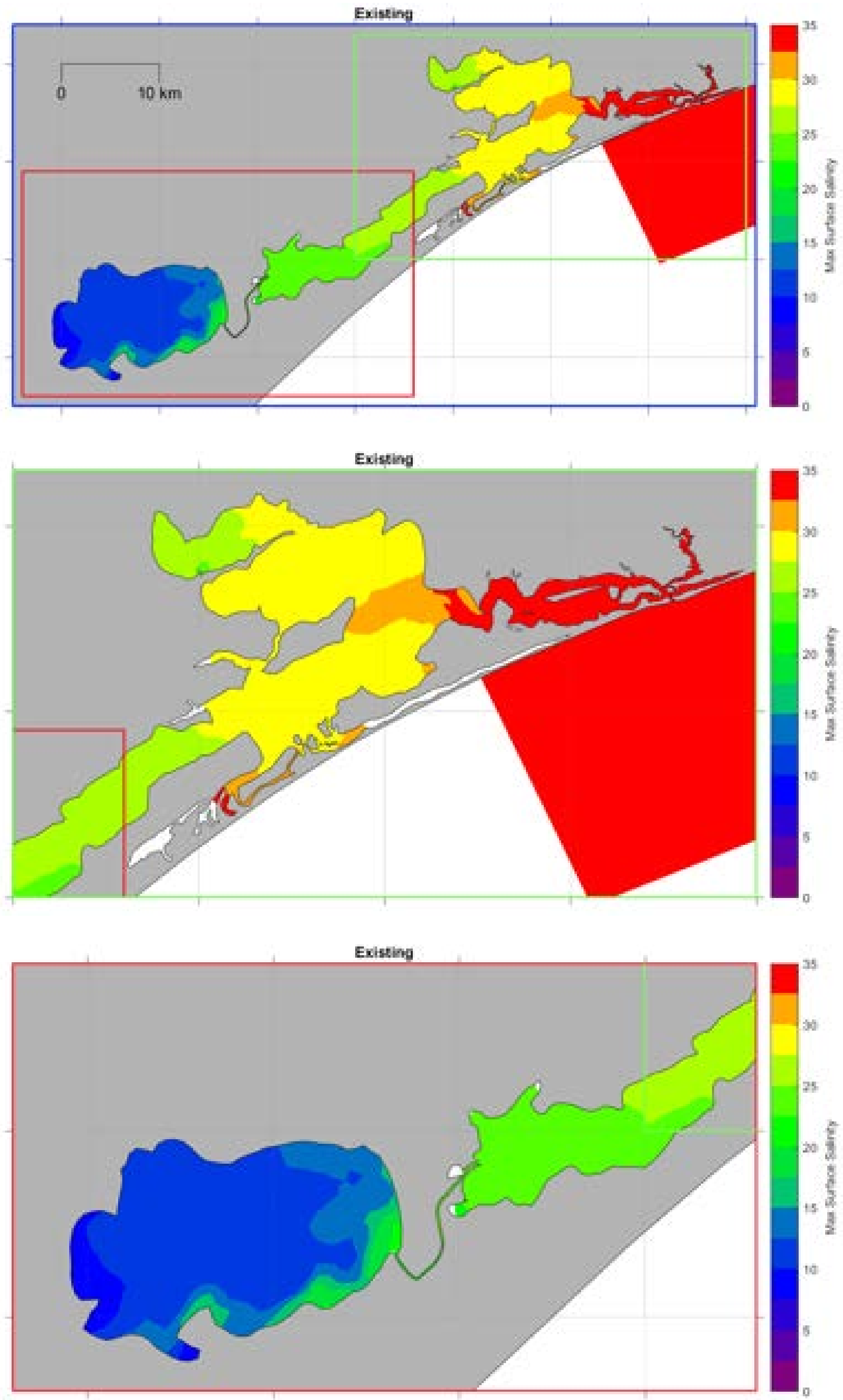


Figure B33. Existing case modelled maximum surface salinity over 12 months with surge and freshwater forcing.

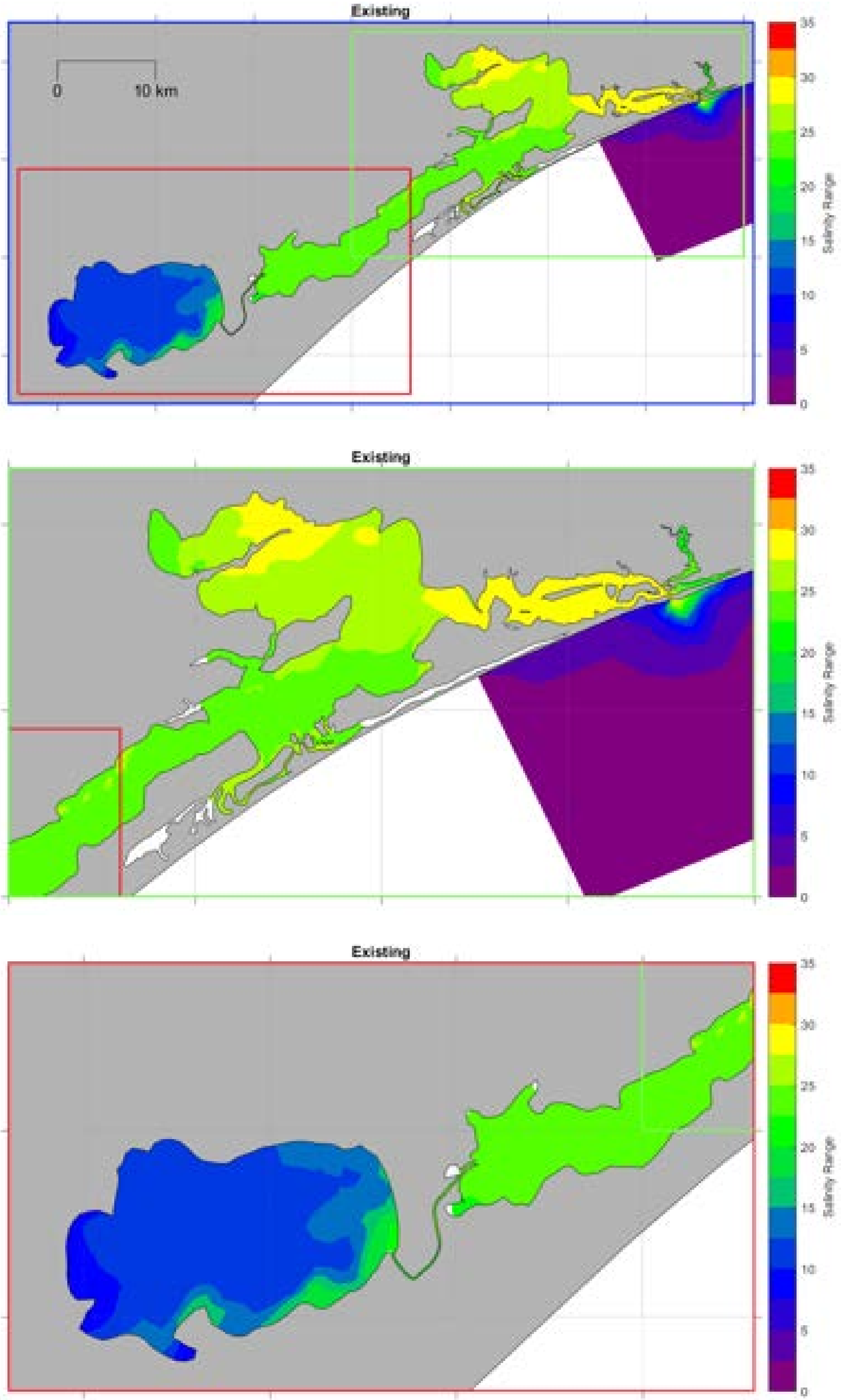


Figure B34. Existing case modelled maximum range in surface salinity over 12 months with surge and freshwater forcing.

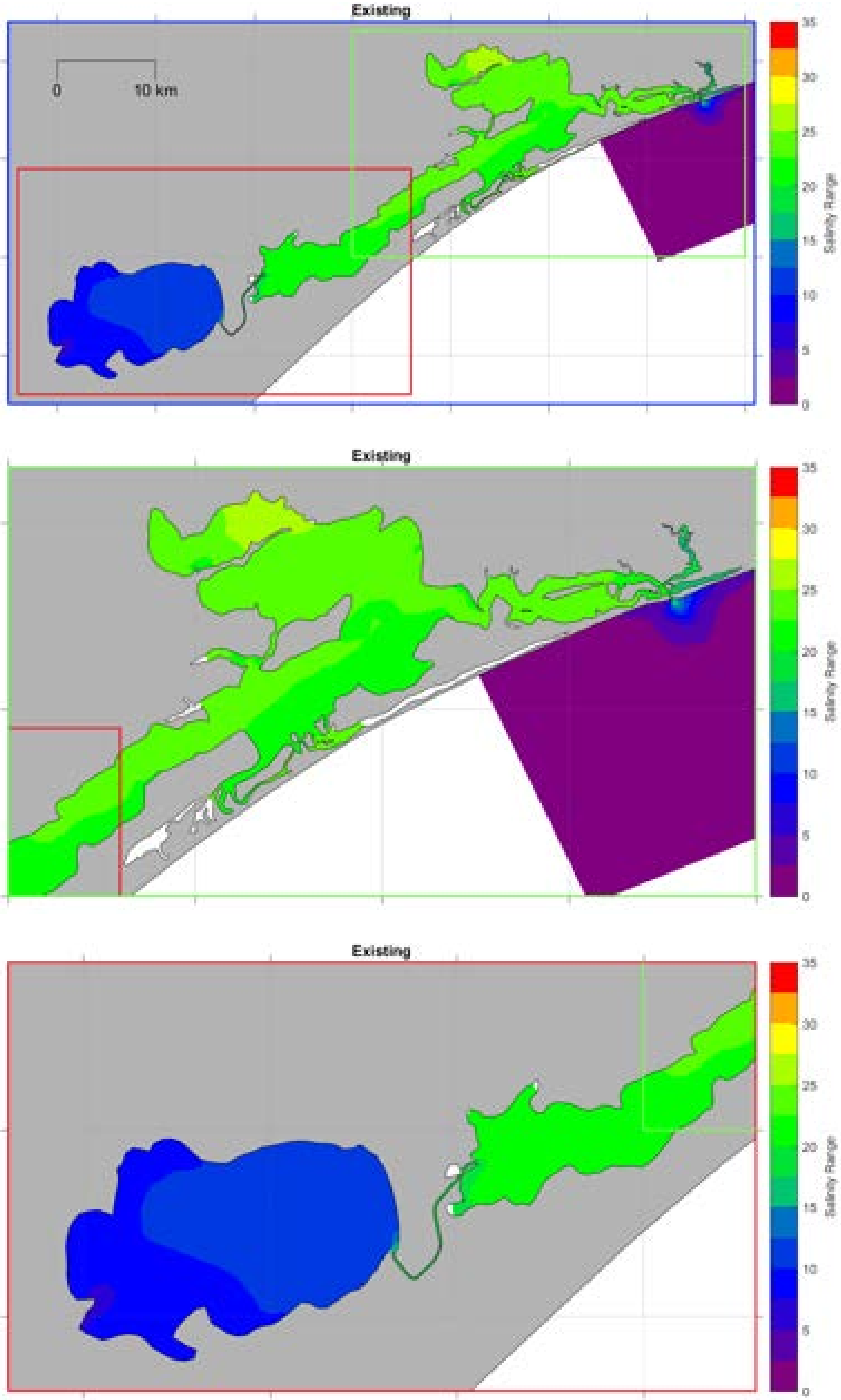


Figure B35. Existing case modelled 90th percentile range in surface salinity over 12 months with surge and freshwater forcing.

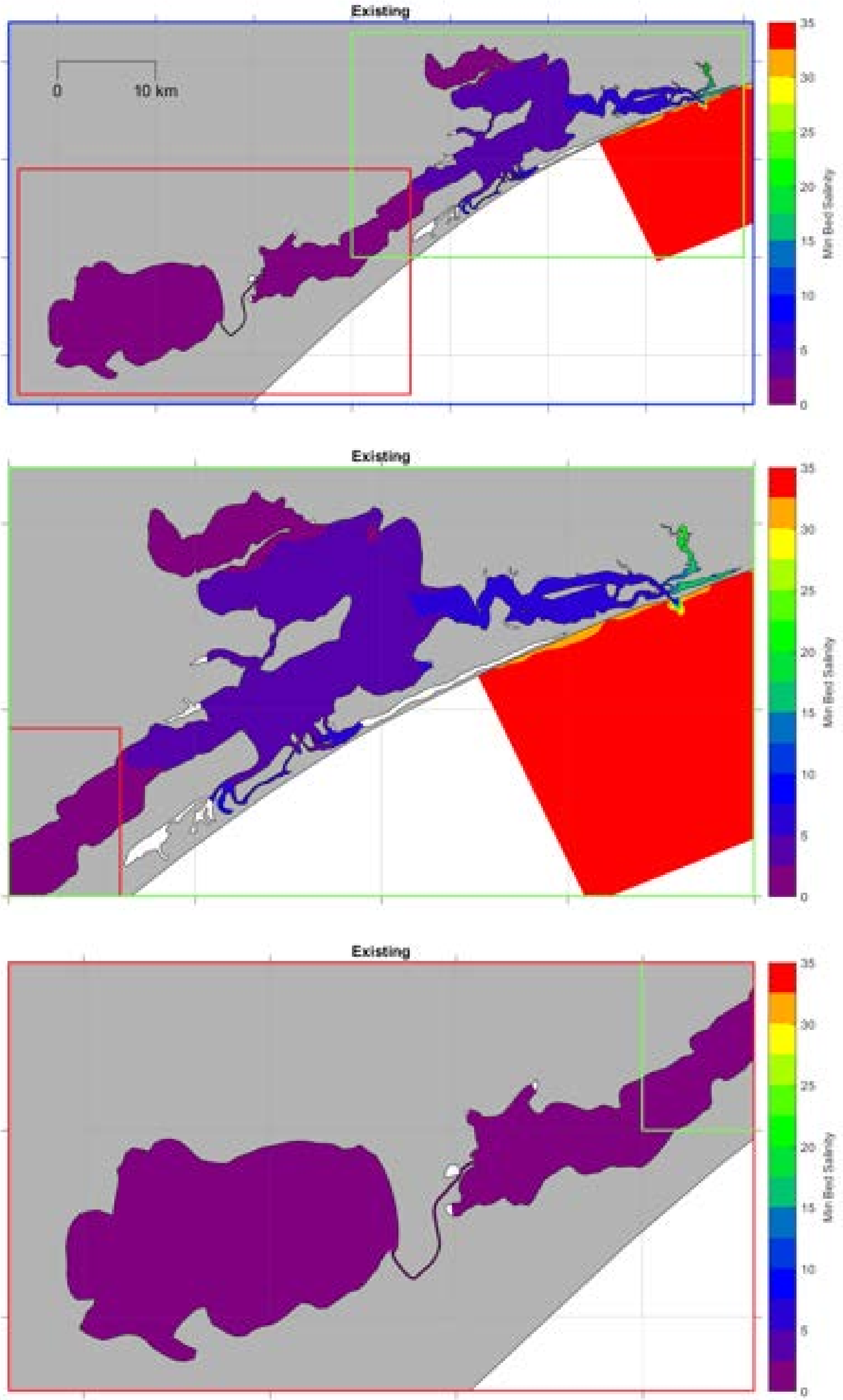


Figure B36. **Existing case modelled minimum bed salinity over 12 months with surge and freshwater forcing.**

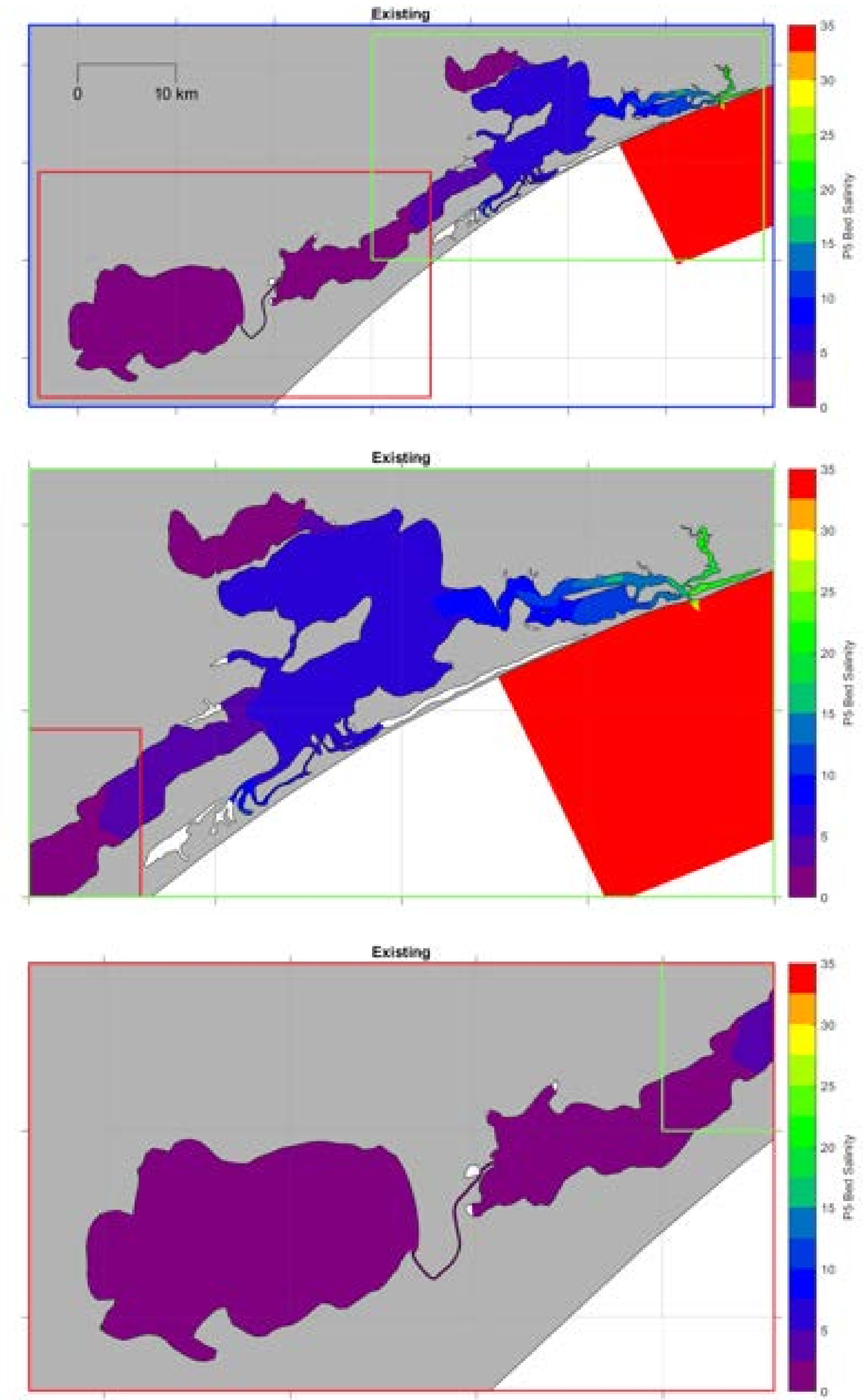


Figure B37. Existing case modelled 5th percentile bed salinity over 12 months with surge and freshwater forcing.

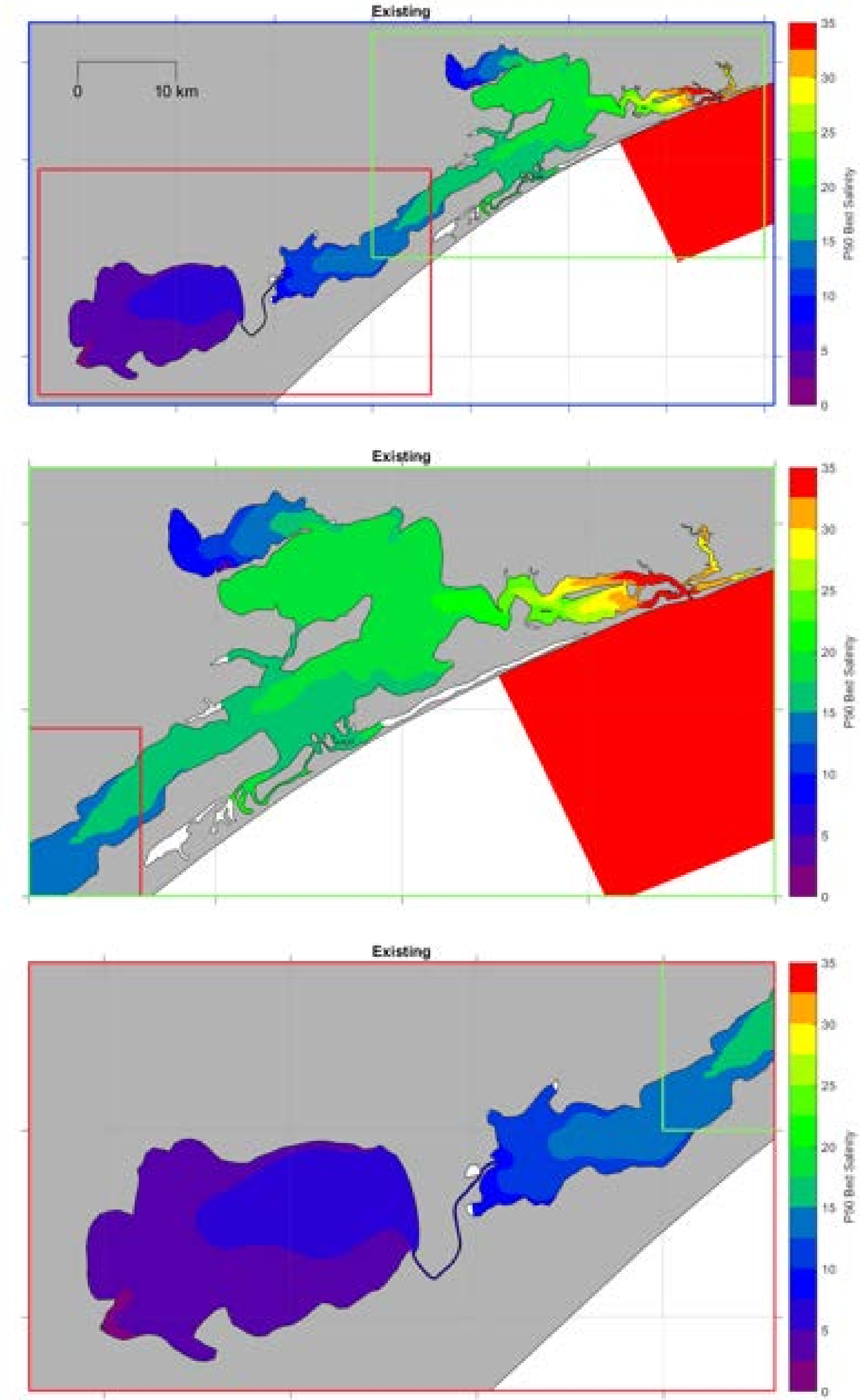


Figure B38. Existing case modelled median bed salinity over 12 months with surge and freshwater forcing.

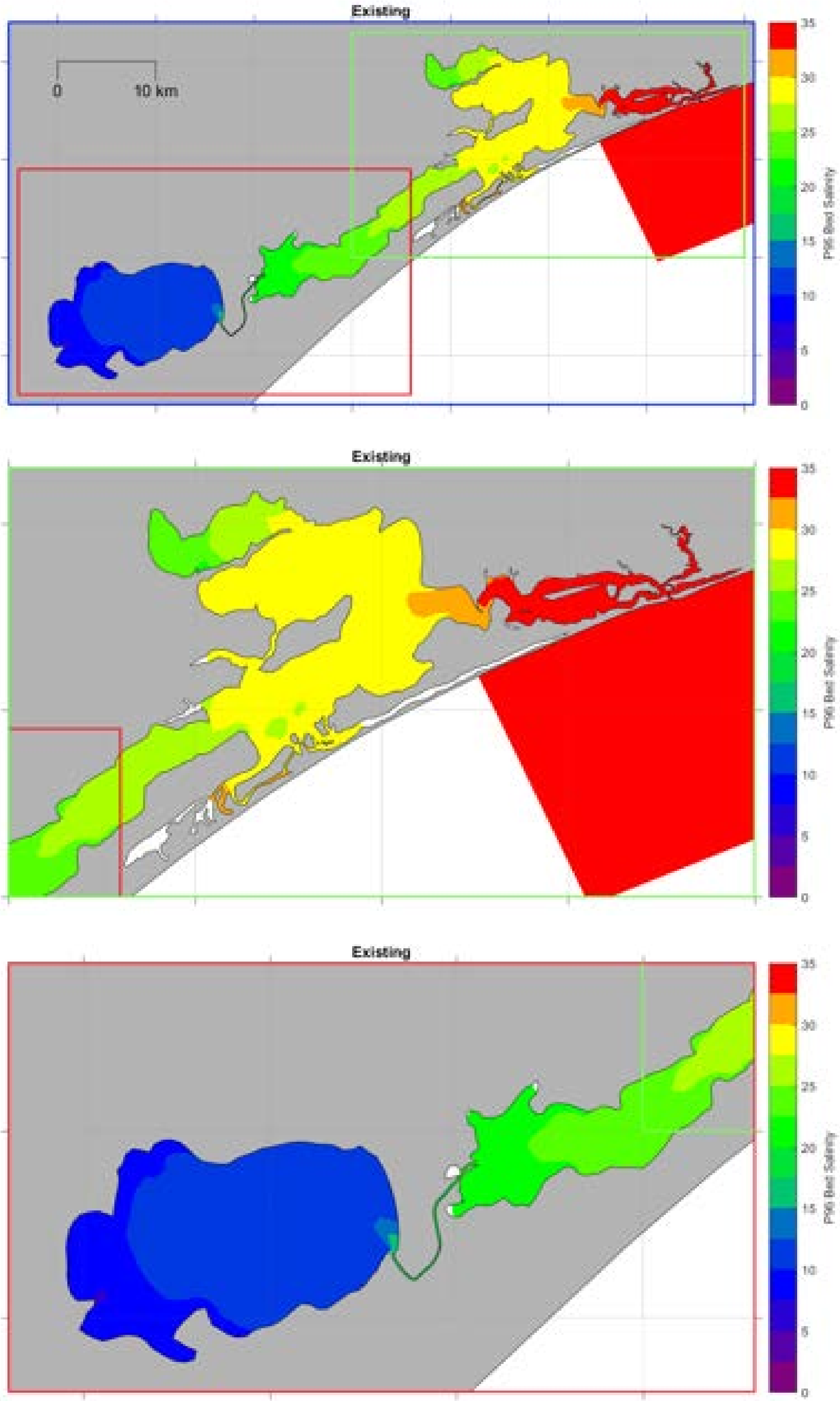


Figure B39. Existing case modelled 95th percentile bed salinity over 12 months with surge and freshwater forcing.

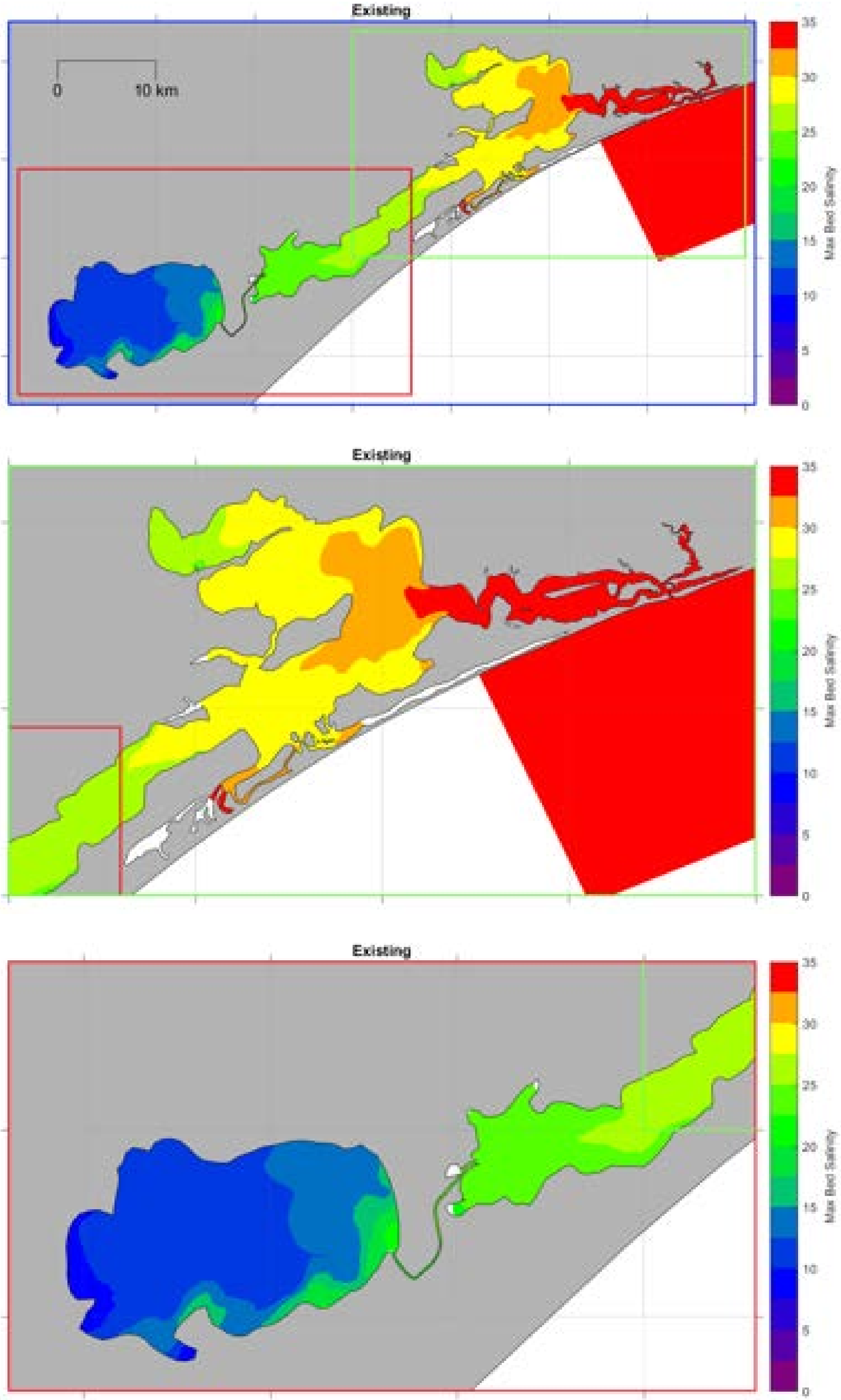


Figure B40. Existing case modelled maximum bed salinity over 12 months with surge and freshwater forcing.

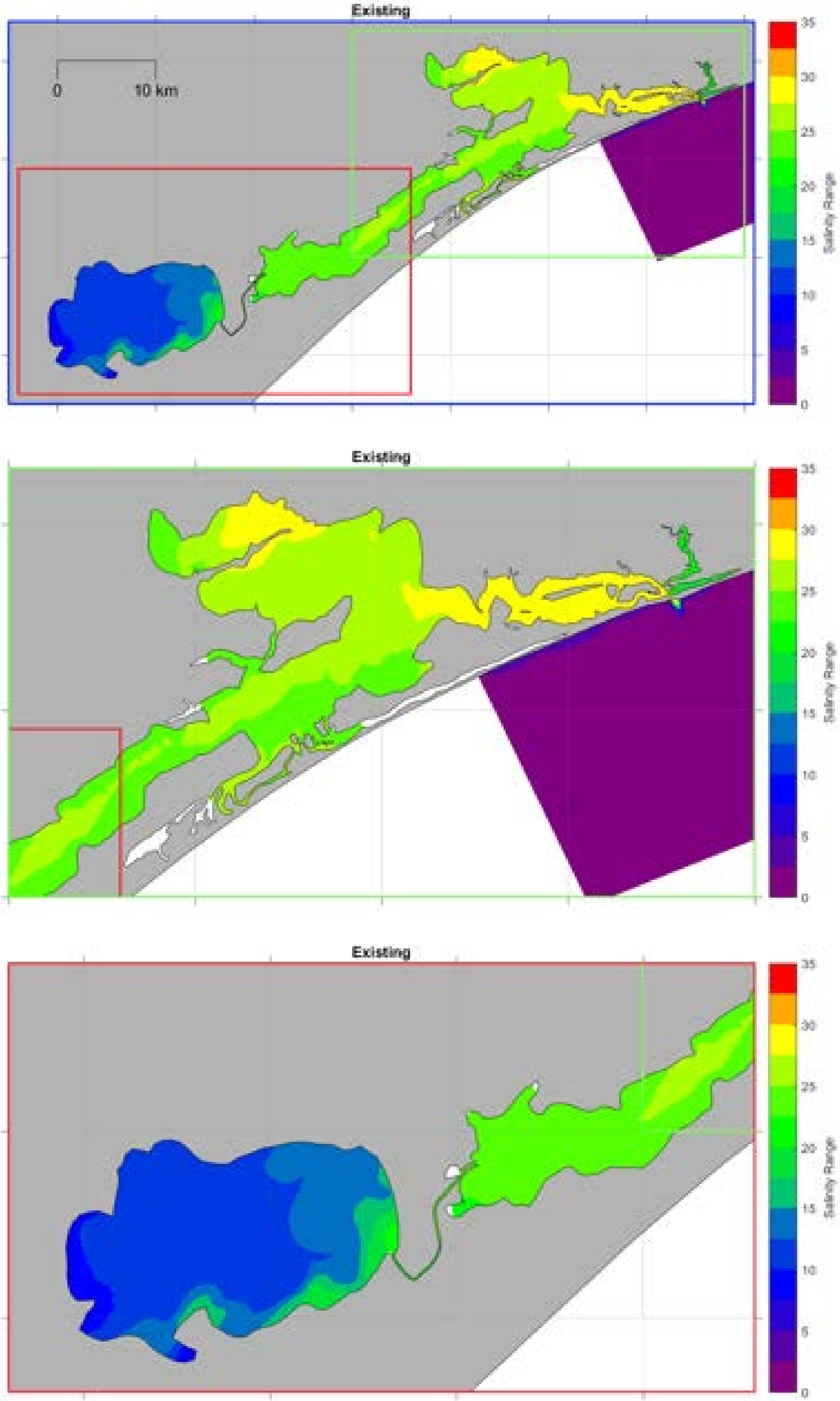


Figure B41. Existing case modelled maximum range in bed salinity over 12 months with surge and freshwater forcing.

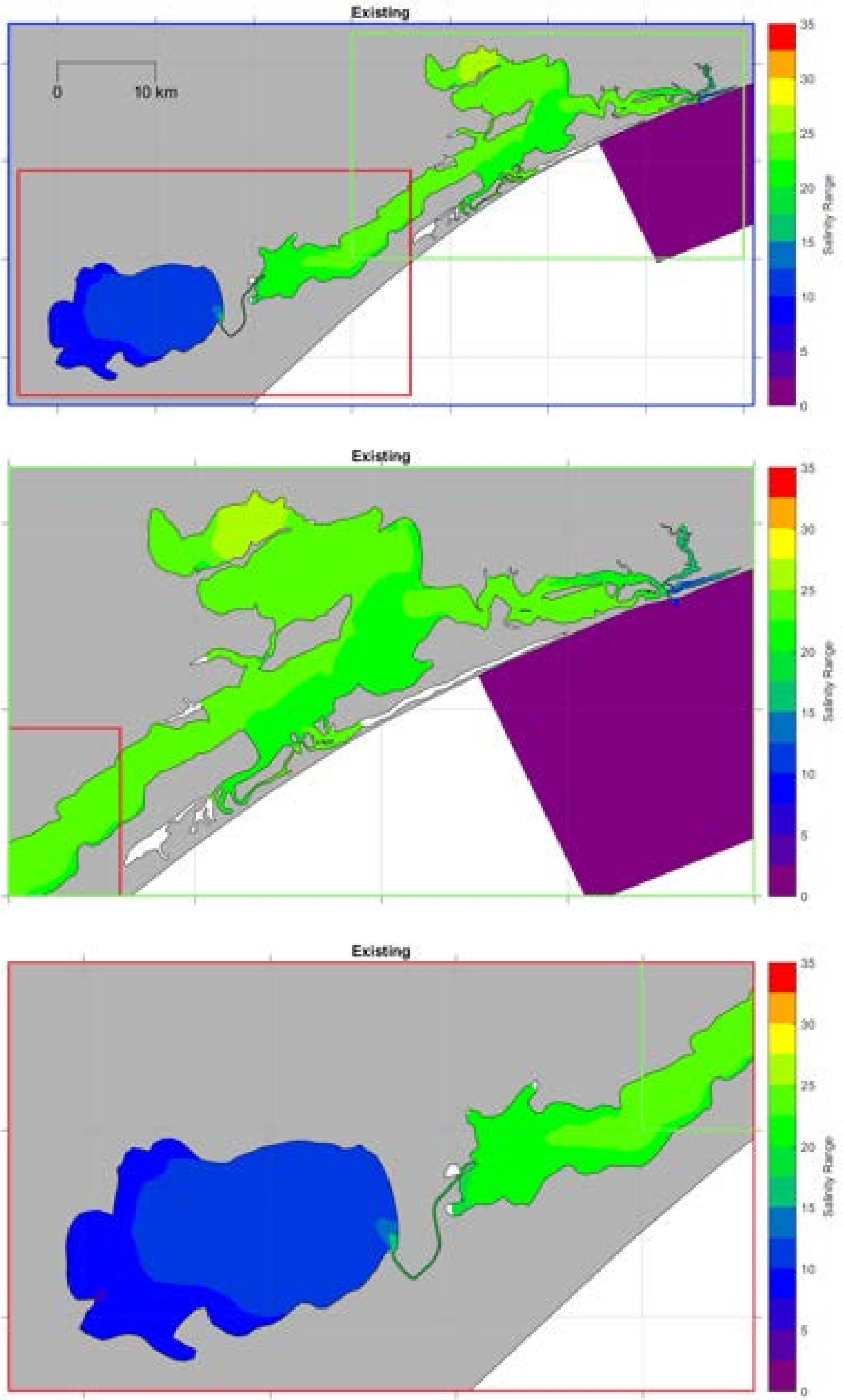


Figure B42. Existing case modelled 90th percentile range in bed salinity over 12 months with surge and freshwater forcing.

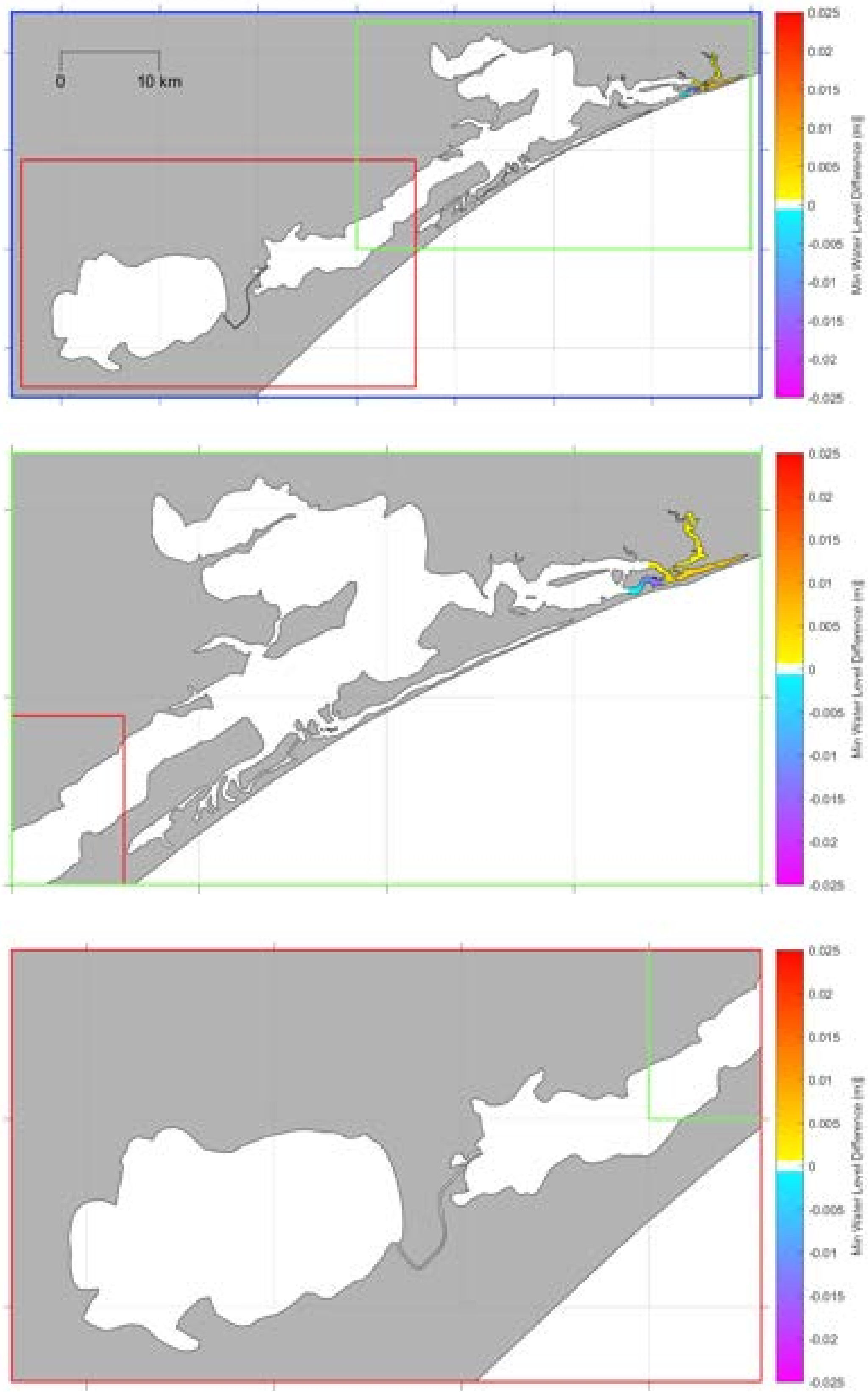


Figure B43. Modelled change in minimum water level over 12 months with astronomical forcing due to the future dredging.

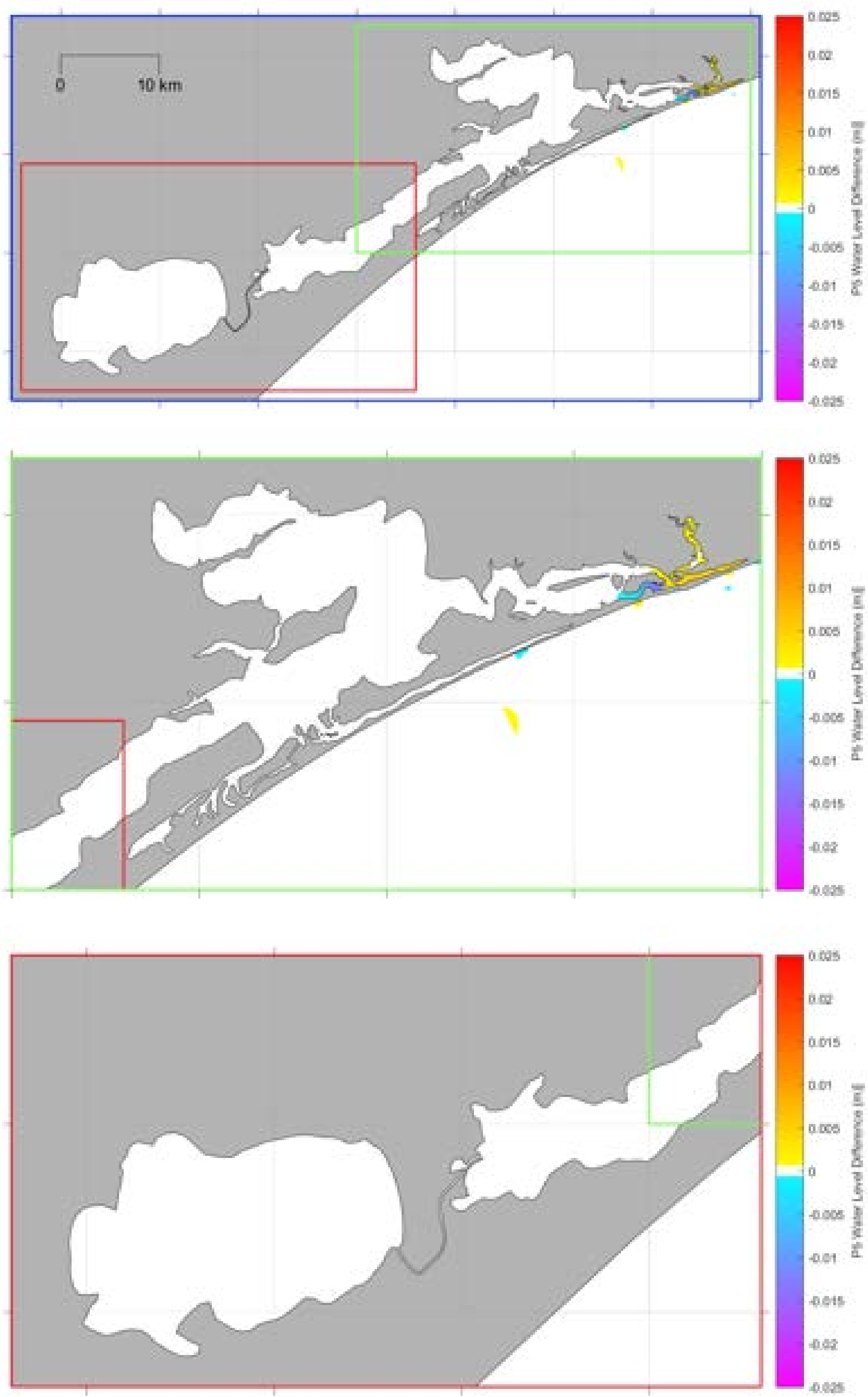


Figure B44. Modelled change in 5th percentile water level over 12 months with astronomical forcing due to the future dredging.

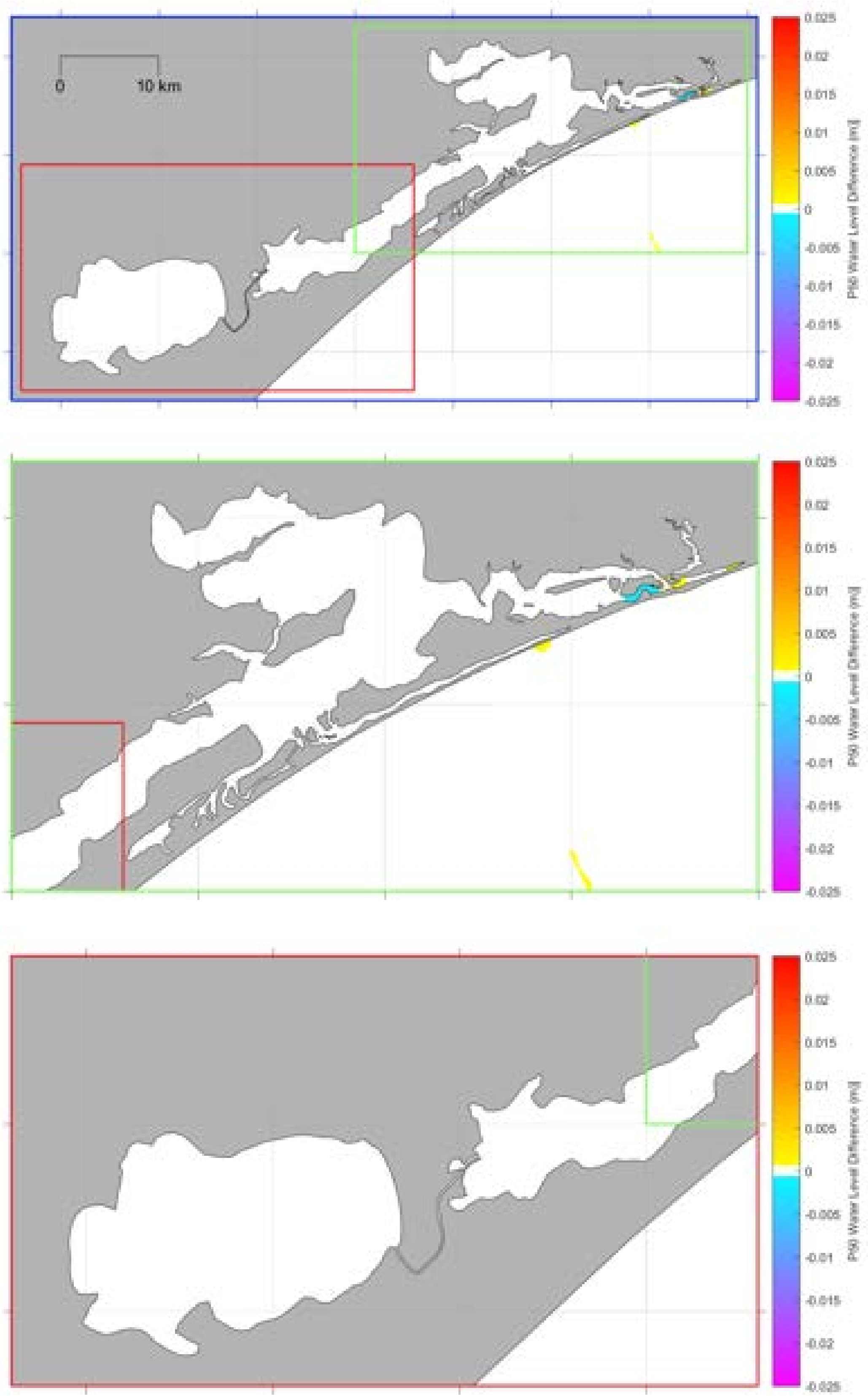


Figure B45. Modelled change in median water level over 12 months with astronomical forcing due to the future dredging.

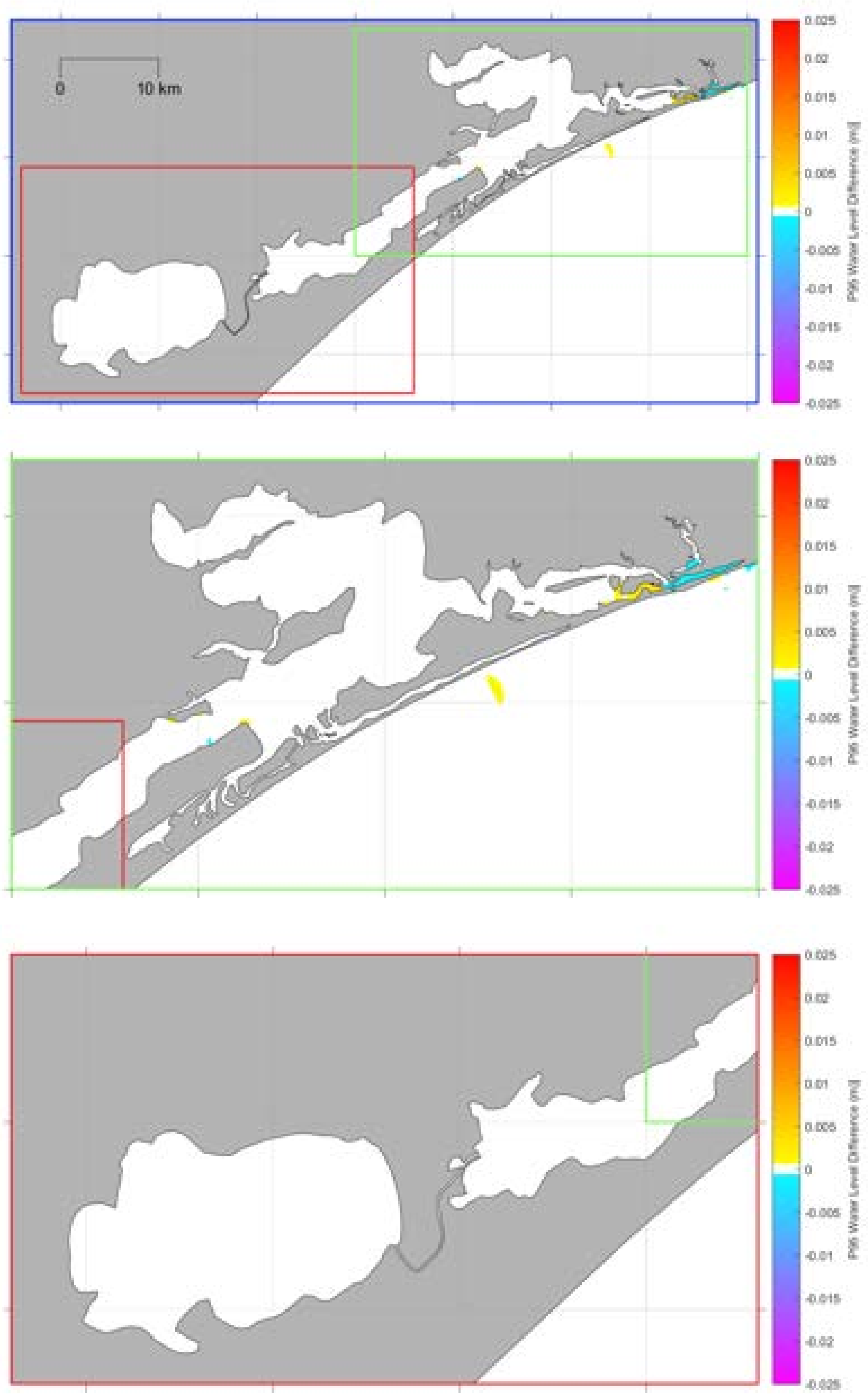


Figure B46. Modelled change in 95th percentile water level over 12 months with astronomical forcing due to the future dredging.

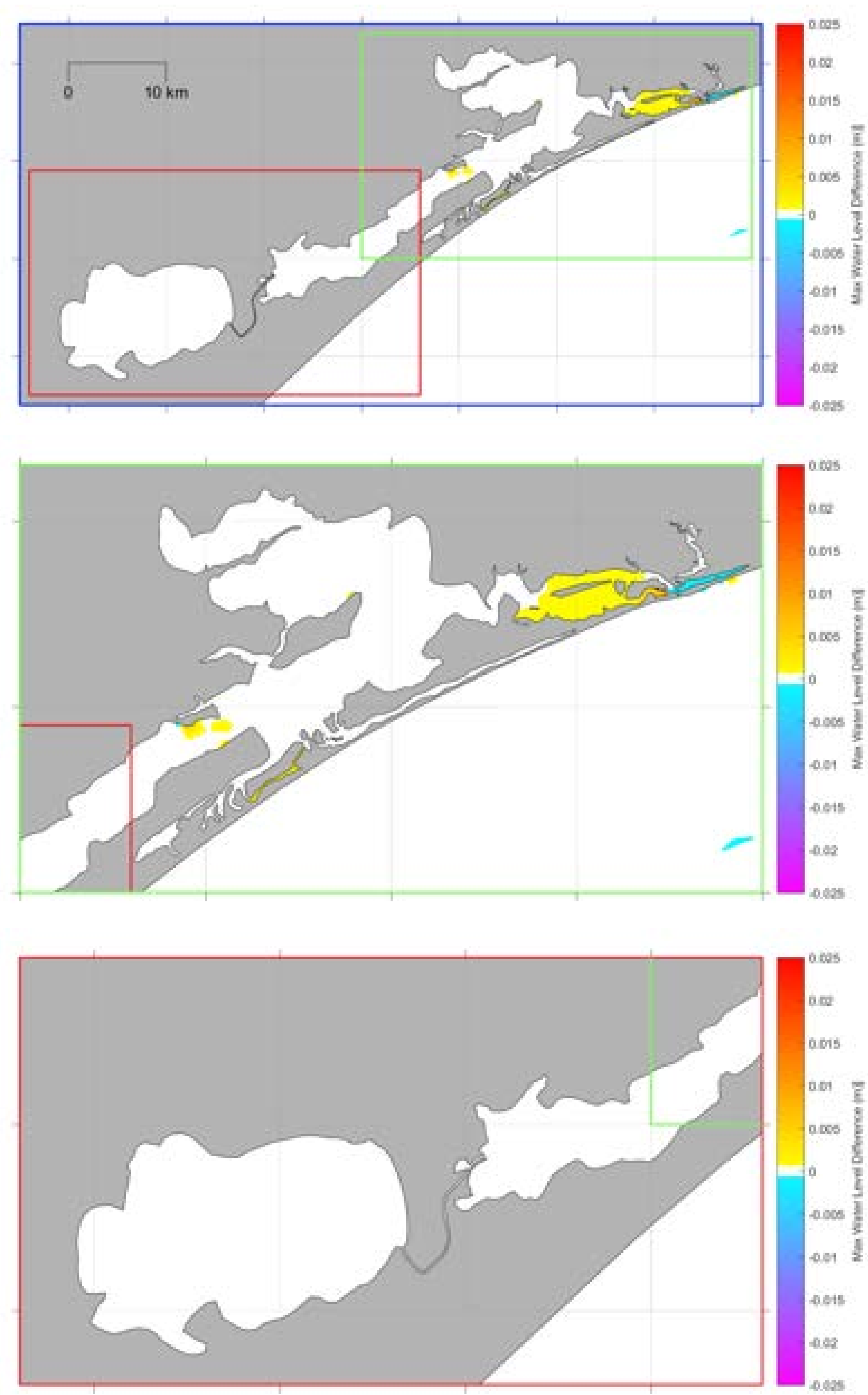
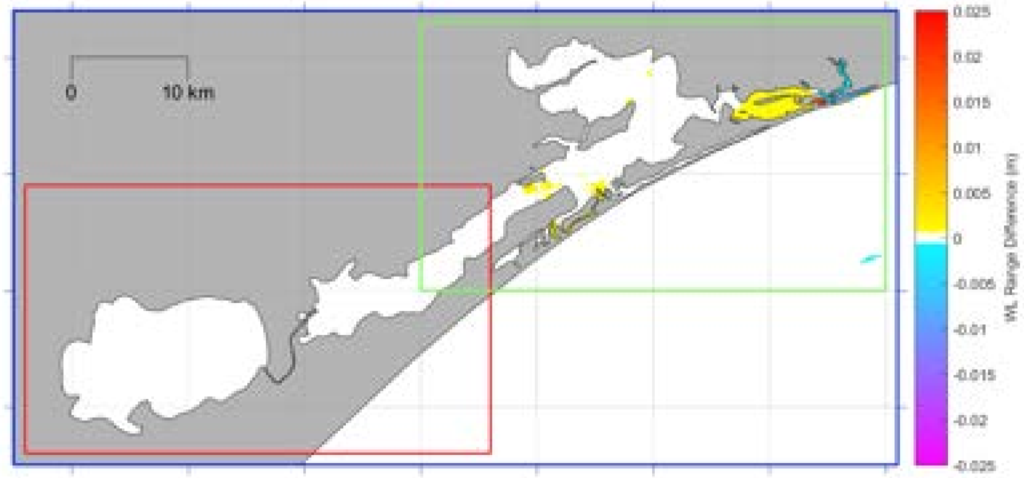


Figure B47. Modelled change in maximum water level over 12 months with astronomical forcing due to the future dredging.



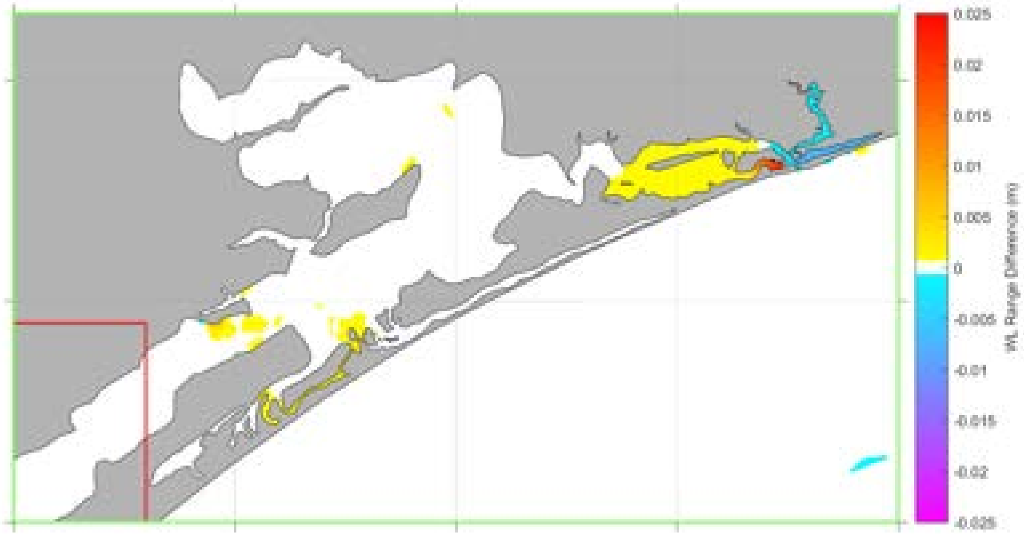


Figure B48. Modelled change in maximum range in water level over 12 months with astronomical forcing due to the future dredging.

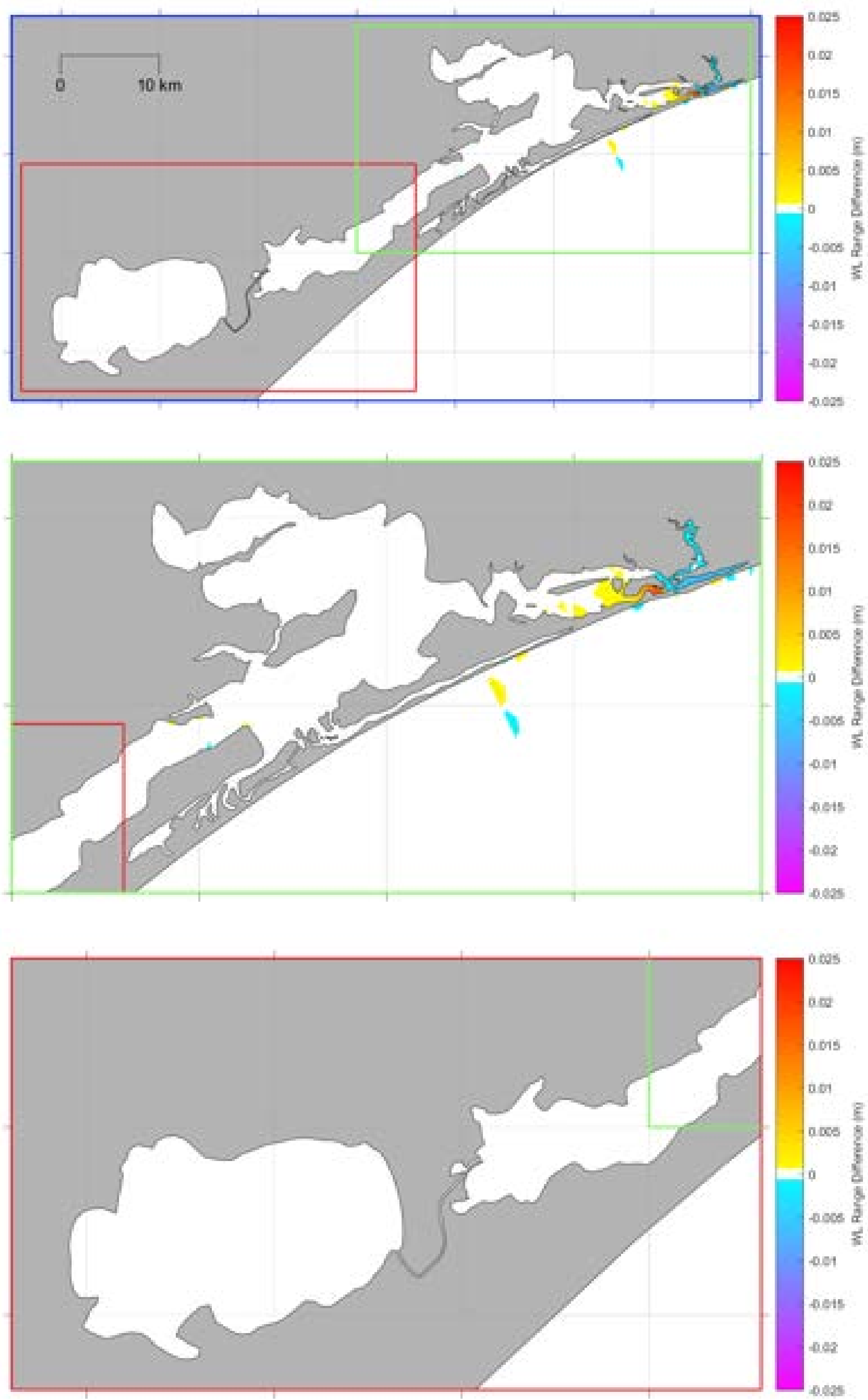


Figure B49. Modelled change in 90th percentile range in water level over 12 months with astronomical forcing due to the future dredging.

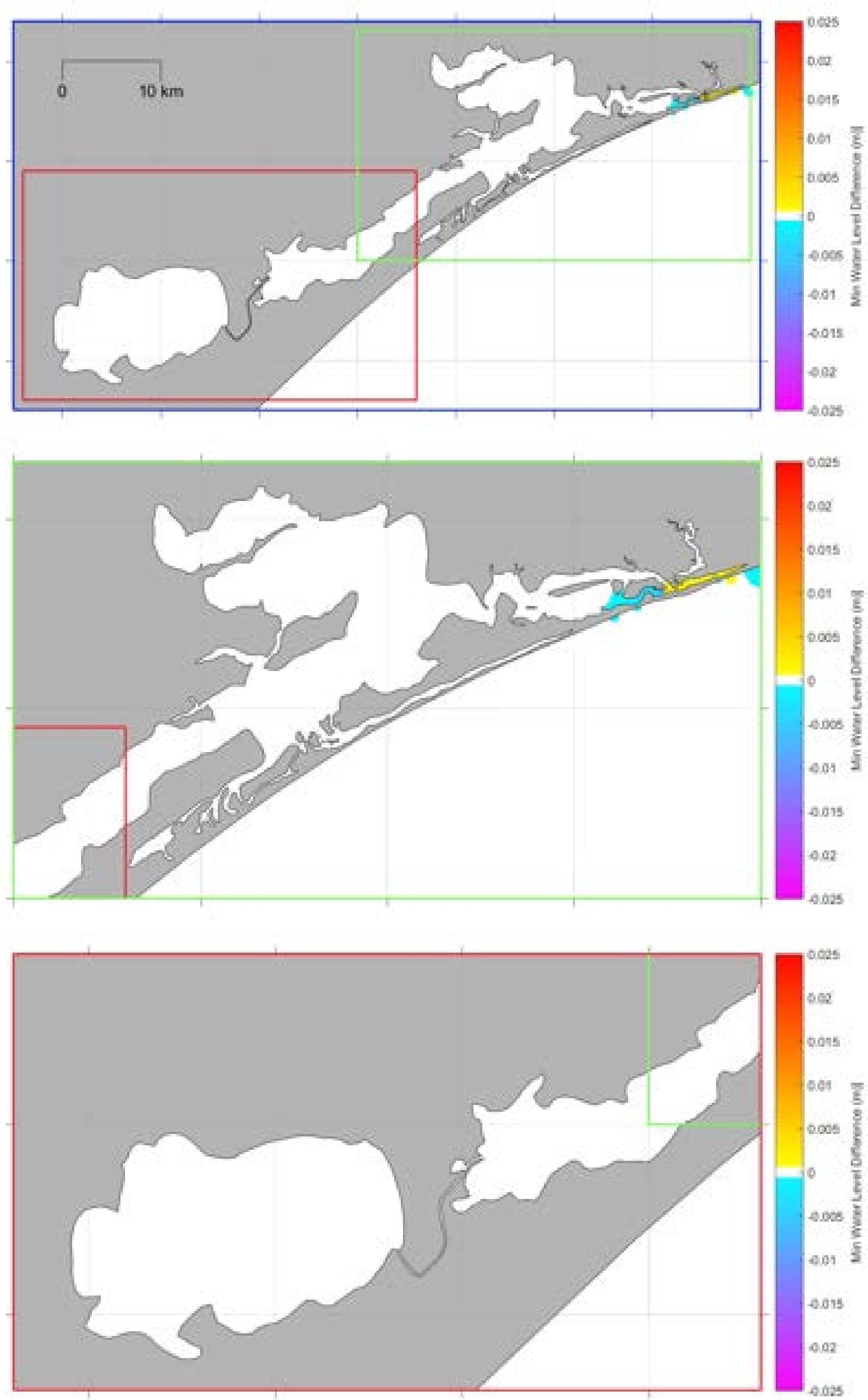


Figure B50. Modelled change in minimum water level over 12 months with surge and freshwater forcing due to the future dredging.

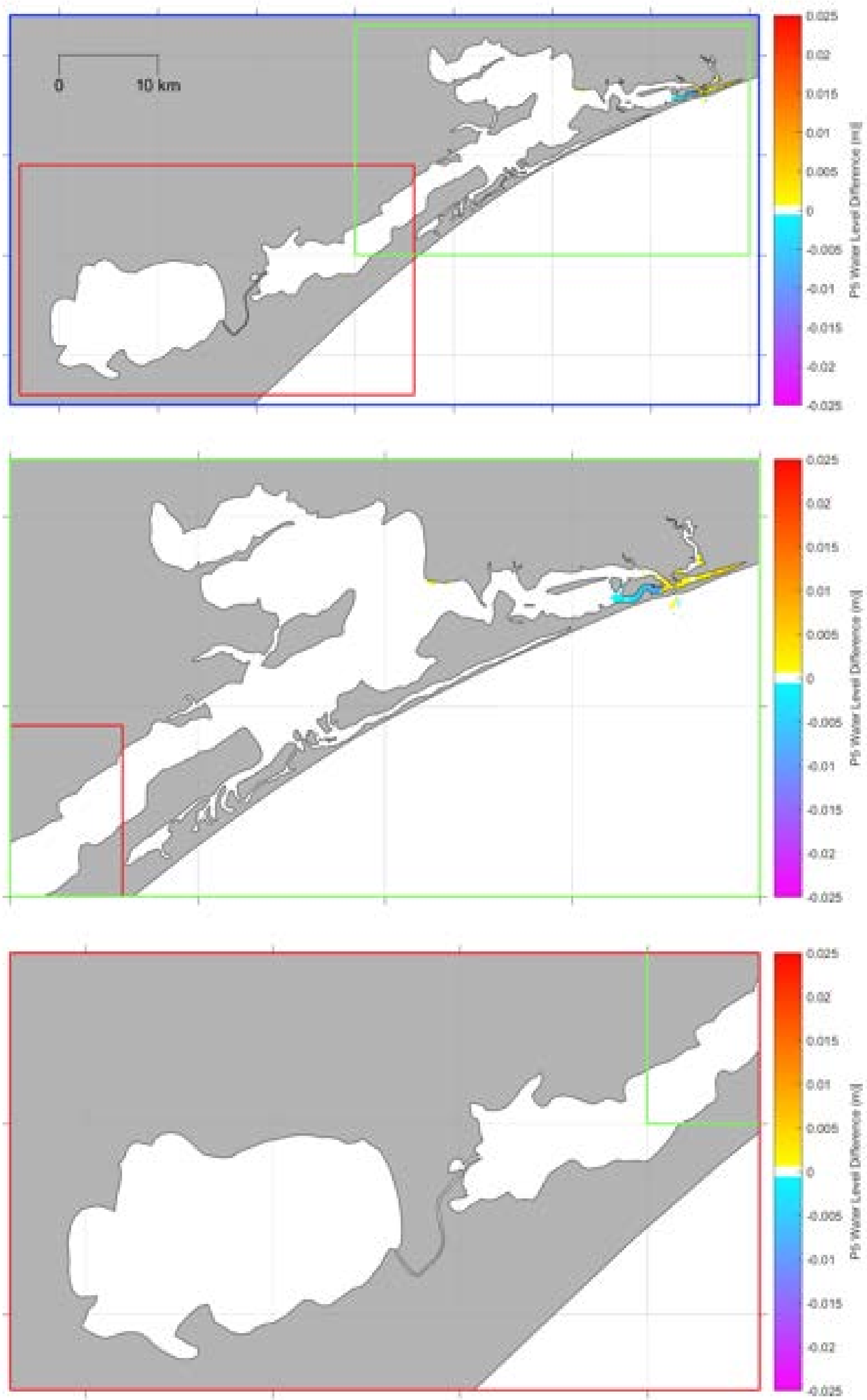


Figure B51. Modelled change in 5th percentile water level over 12 months with surge and freshwater forcing due to the future dredging.

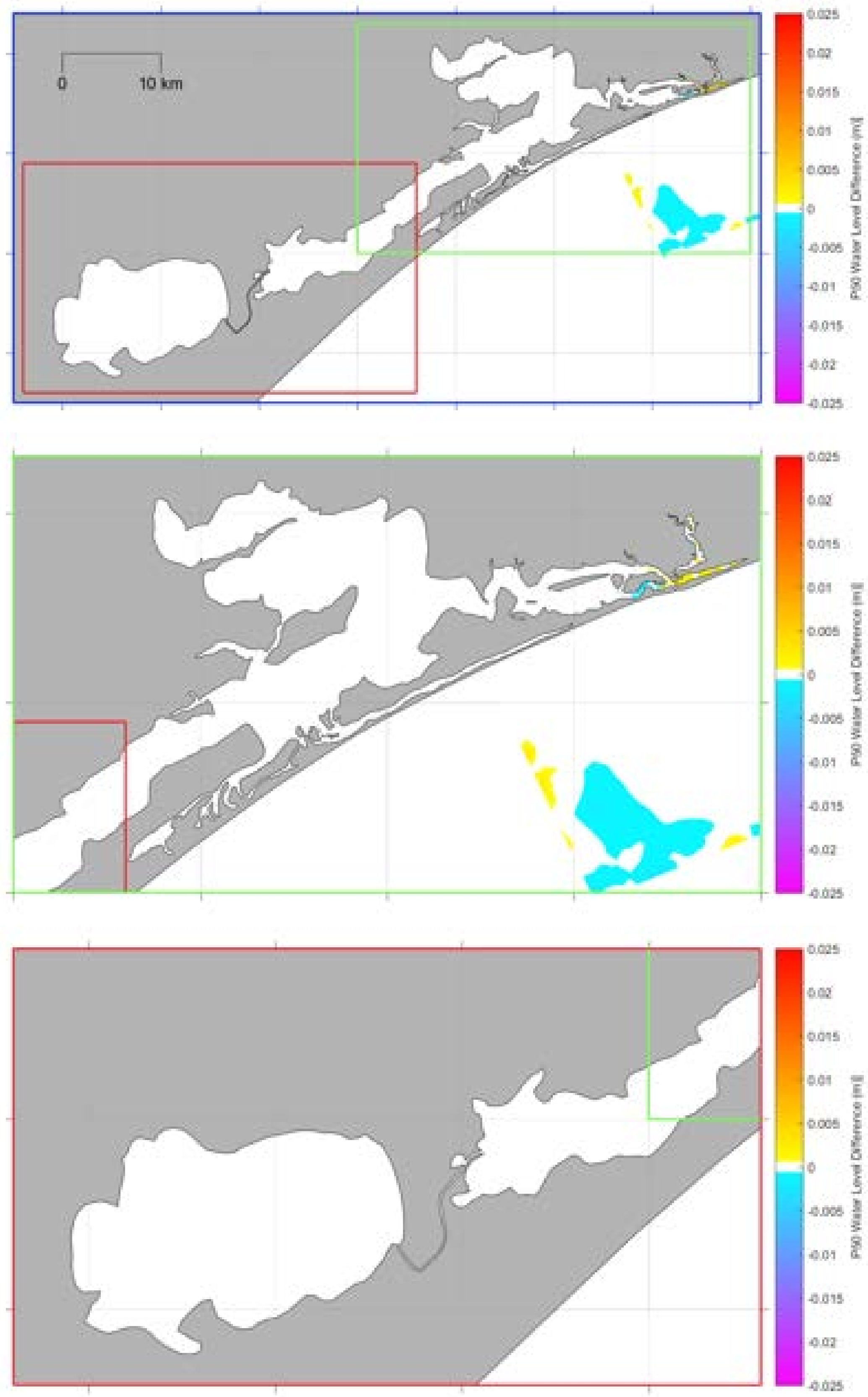


Figure B52. Modelled change in median water level over 12 months with surge and freshwater forcing due to the future dredging.

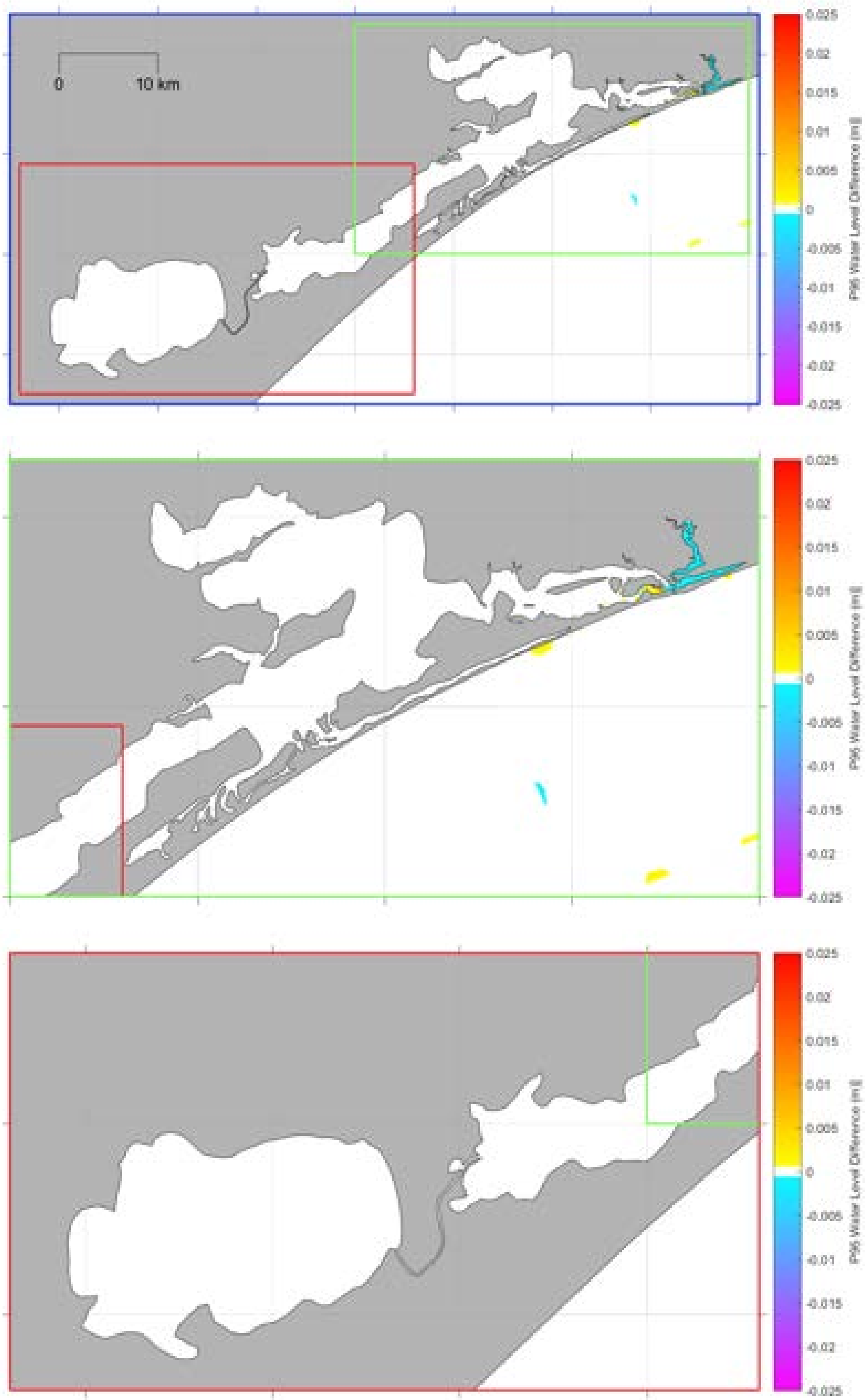


Figure B53. **Modelled change in 95th percentile water level over 12 months with surge and freshwater forcing due to the future dredging.**

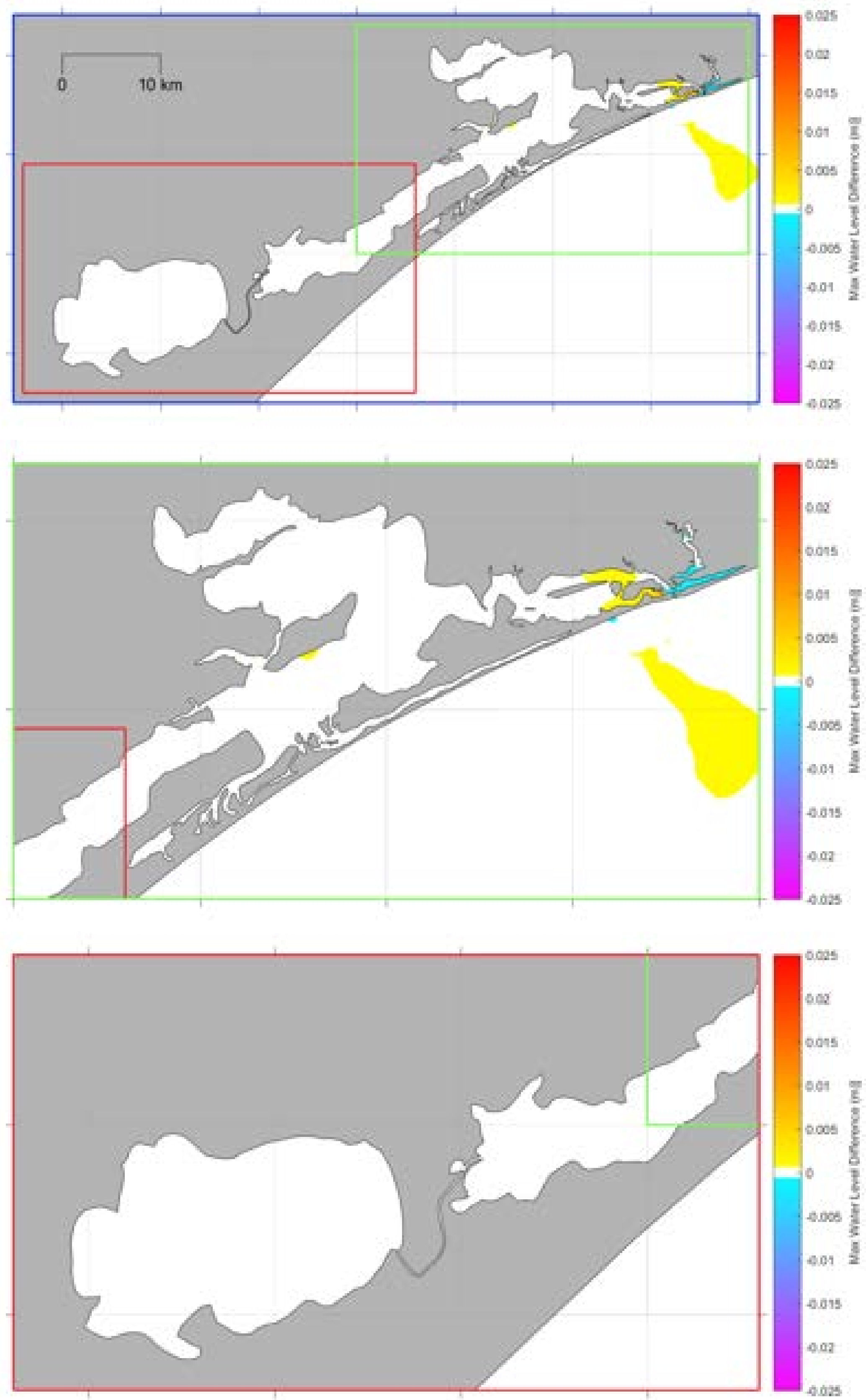


Figure B54. Modelled change in maximum water level over 12 months with surge and freshwater forcing due to the future dredging.

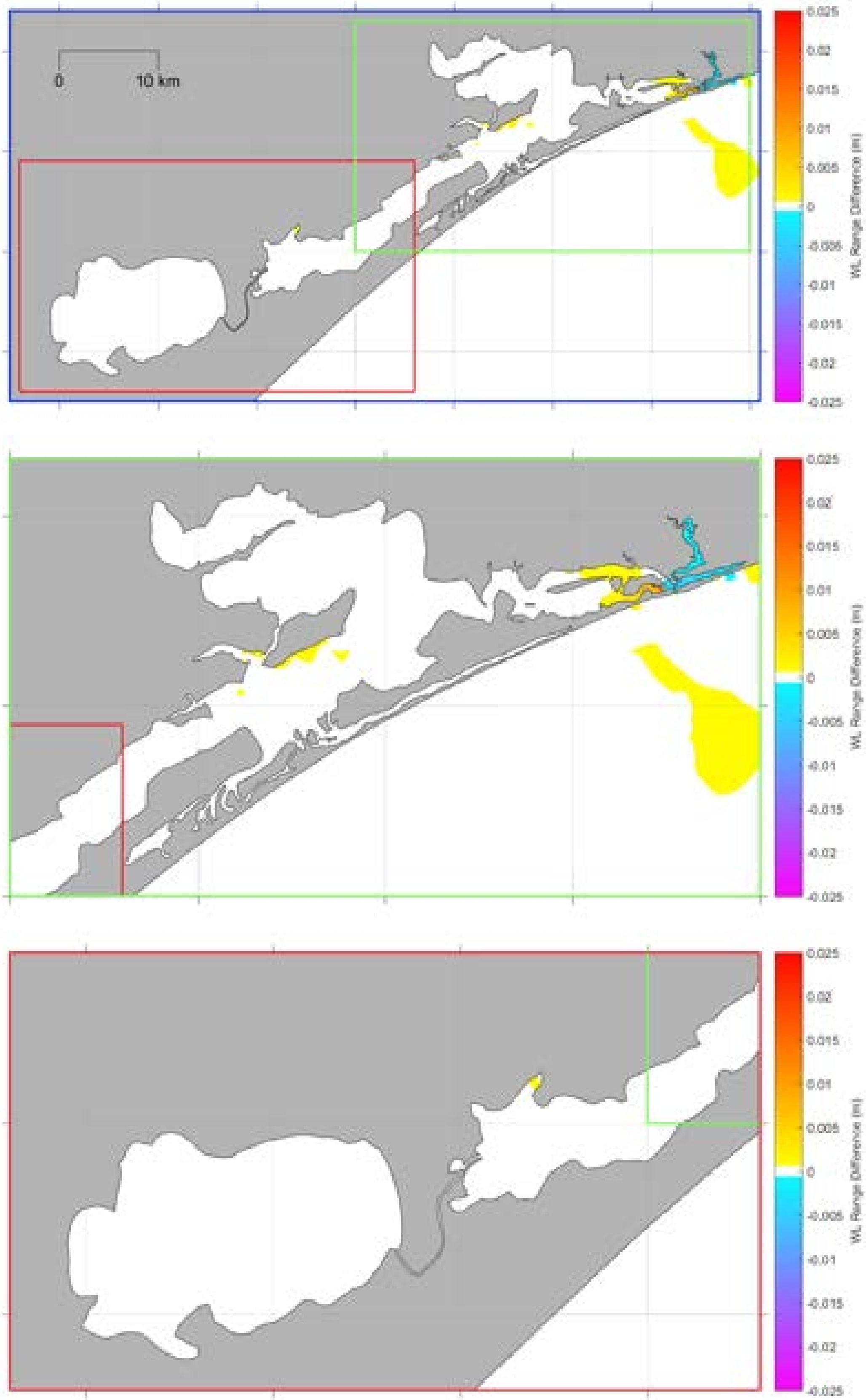


Figure B55. Modelled change in maximum range in water level over 12 months with surge and freshwater forcing due to the future dredging.

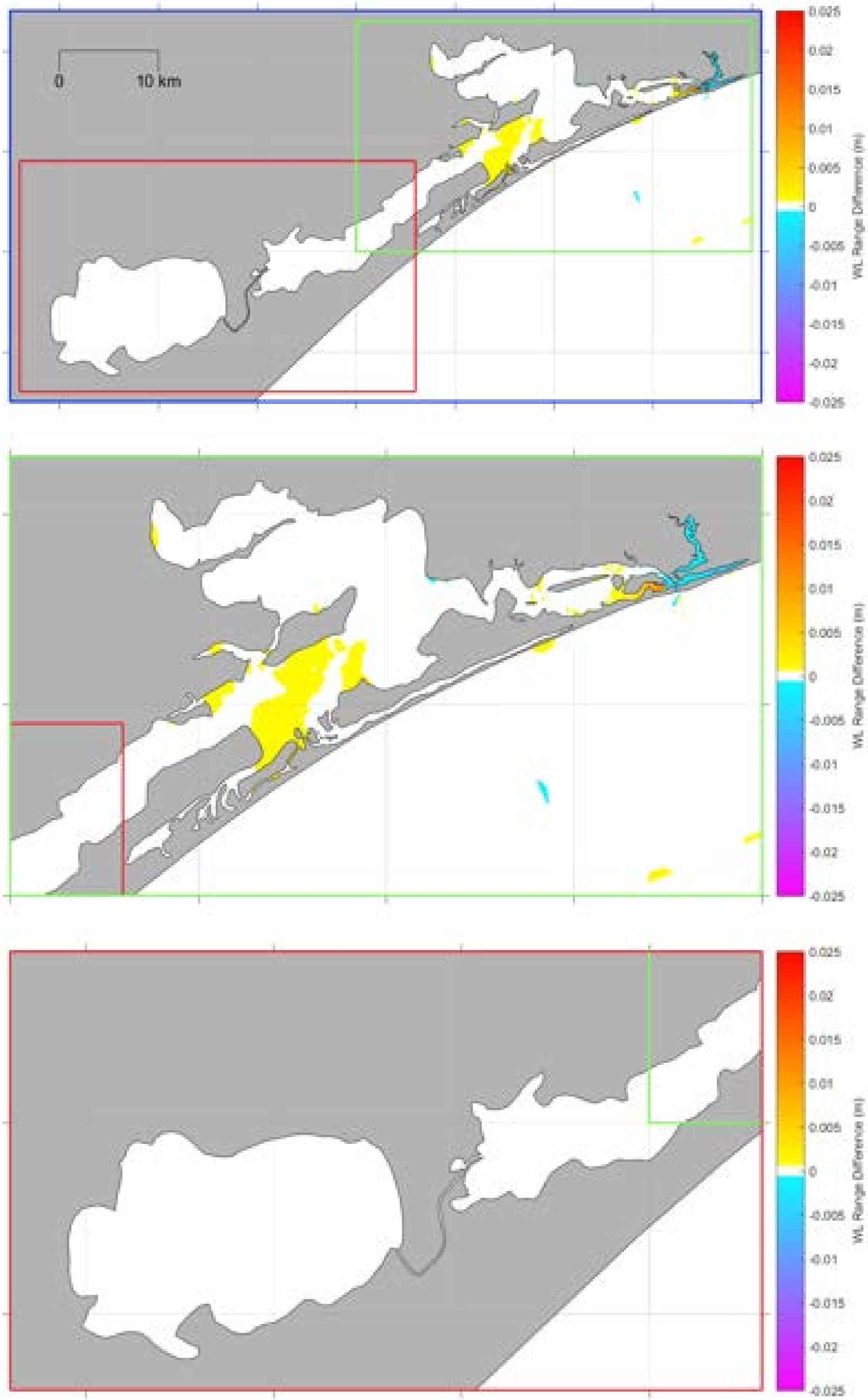


Figure B56. Modelled change in 90th percentile range in water level over 12 months with astronomical forcing due to the future dredging.

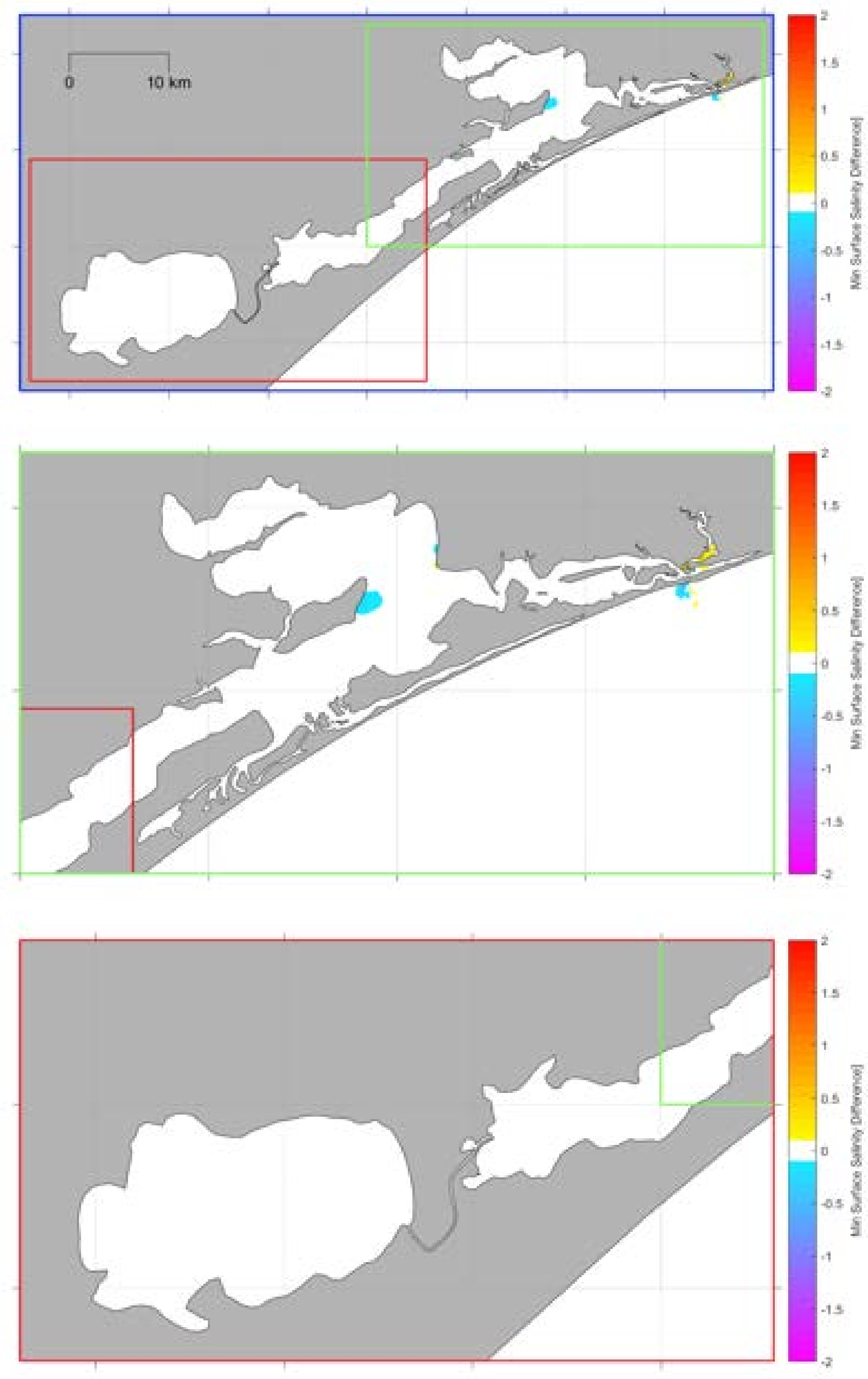


Figure B57. **Modelled change in minimum surface salinity over 12 months with astronomical forcing due to the future dredging.**

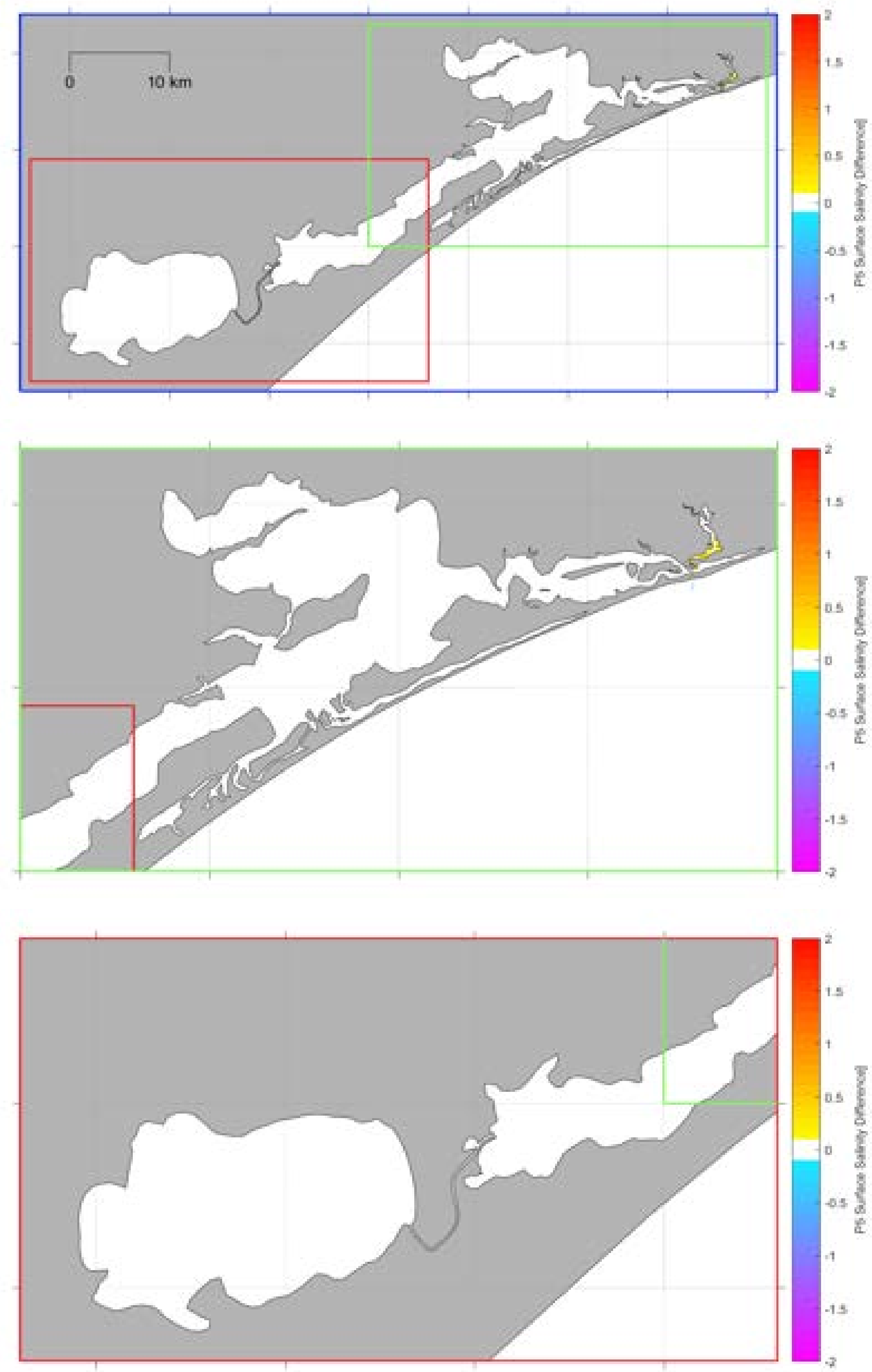


Figure B58. Modelled change in 5th percentile surface salinity over 12 months with astronomical forcing due to the future dredging.

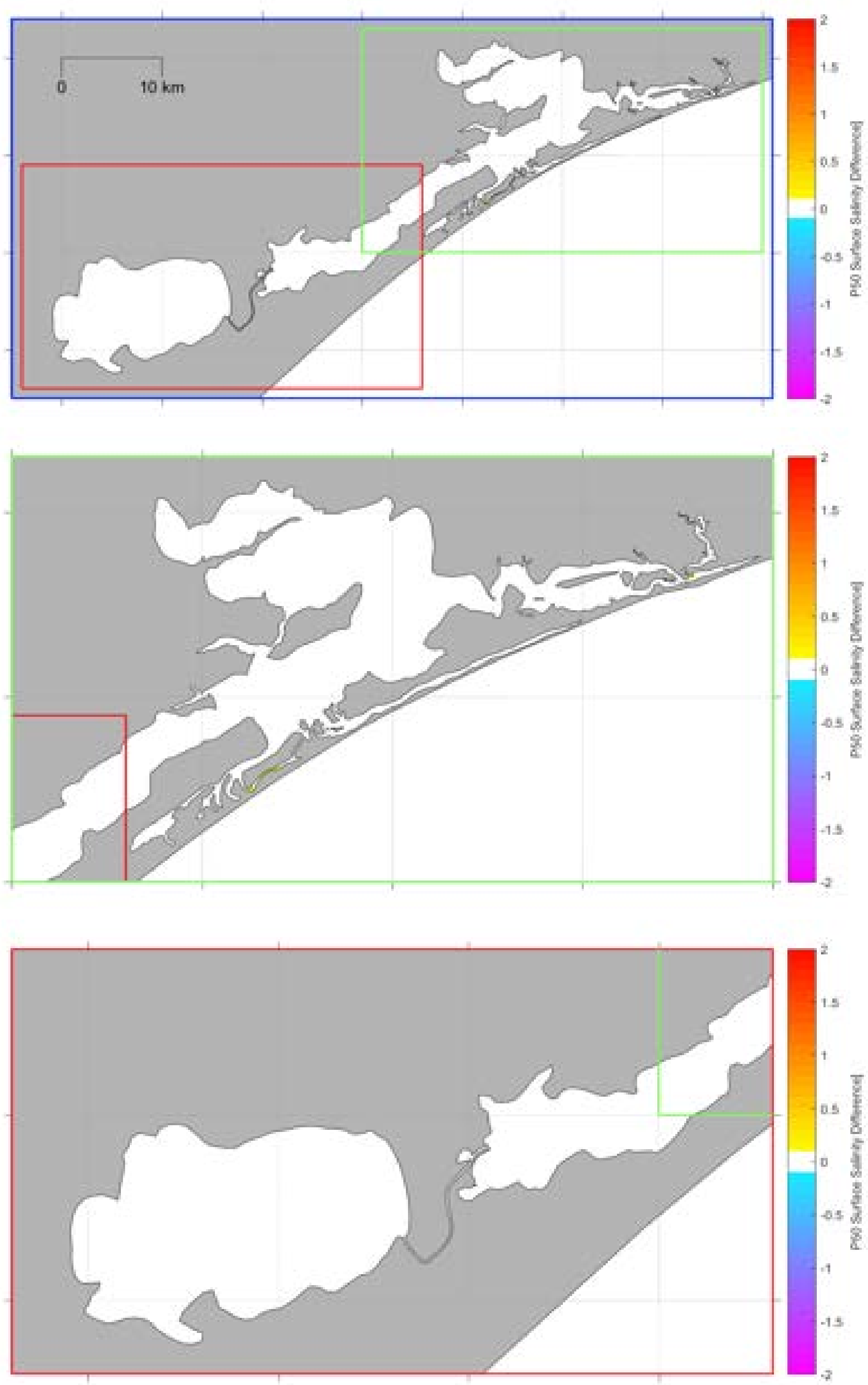


Figure B59. Modelled change in median surface salinity over 12 months with astronomical forcing due to the future dredging.

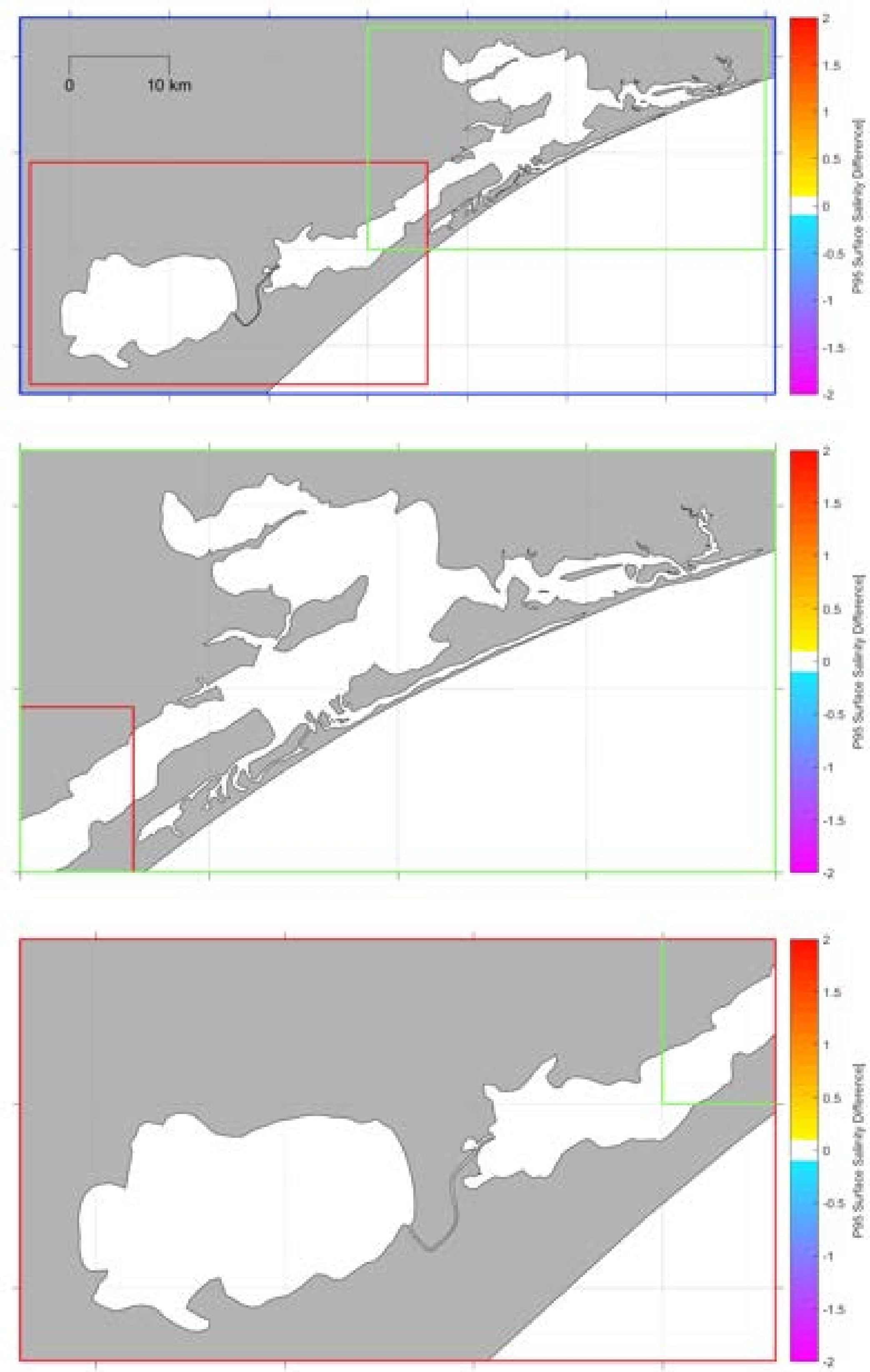


Figure B60. Modelled change in 95th percentile surface salinity over 12 months with astronomical forcing due to the future dredging.

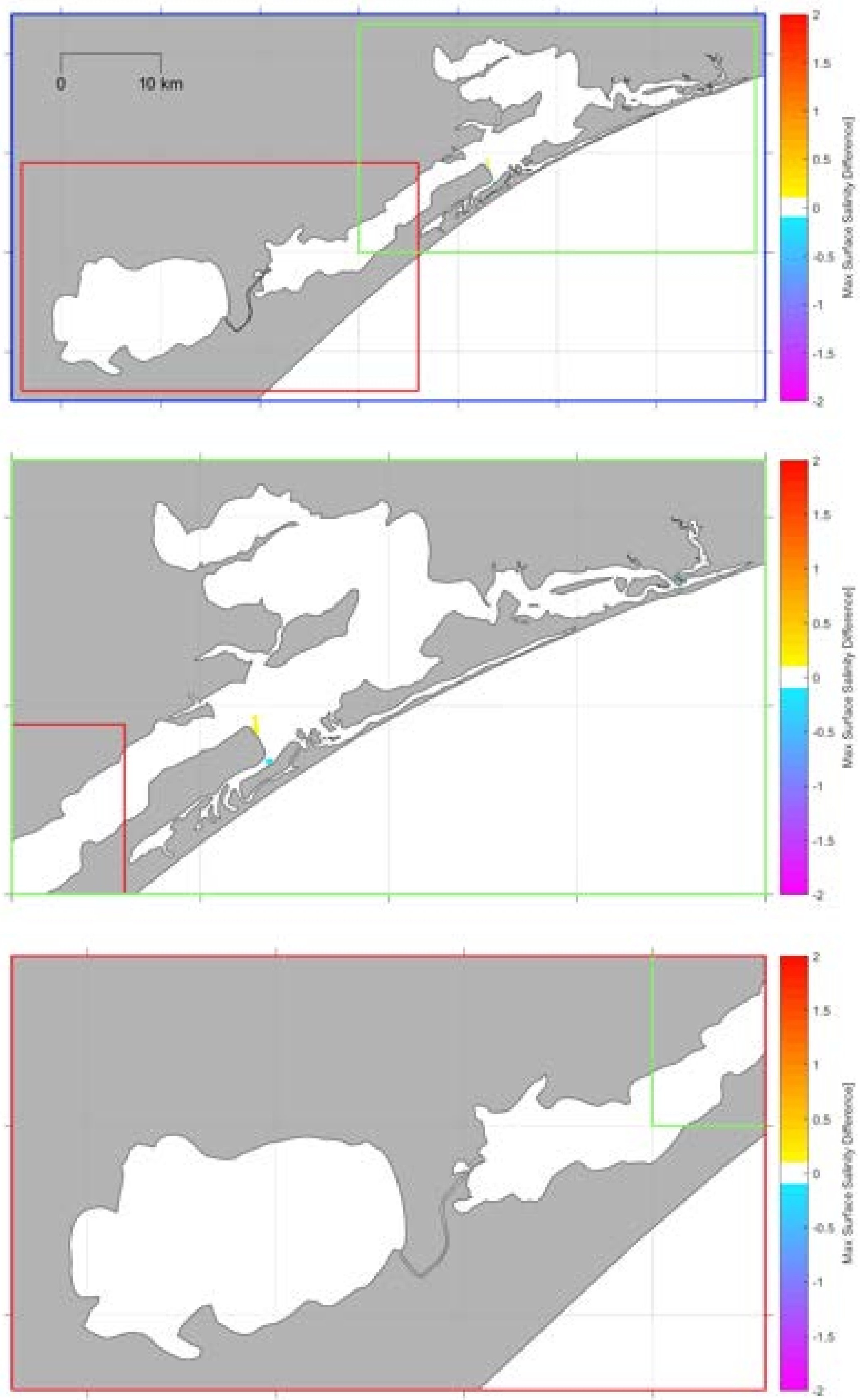


Figure B61. Modelled change in maximum surface salinity over 12 months with astronomical forcing due to the future dredging.

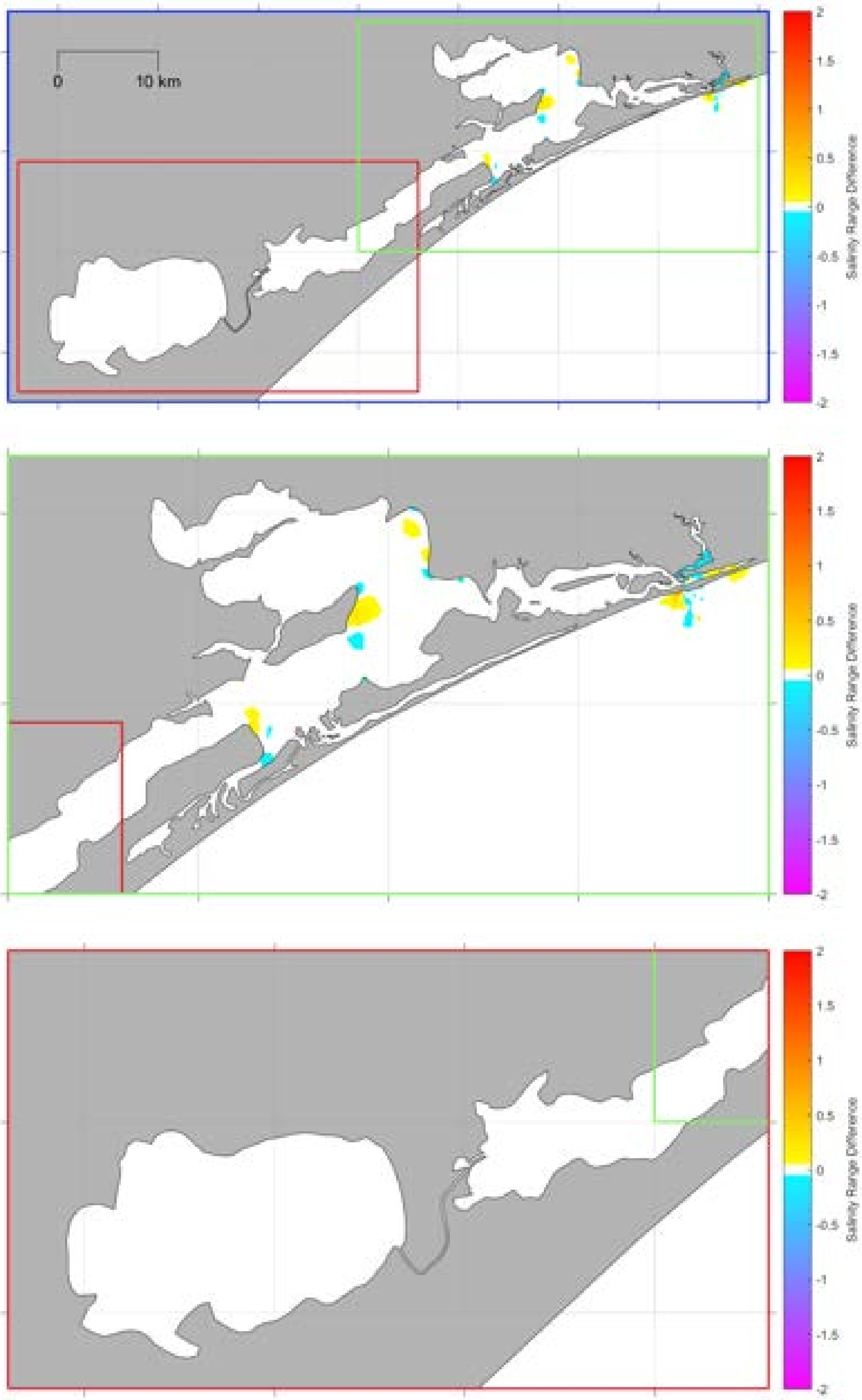


Figure B62. Modelled change in maximum range in surface salinity over 12 months with astronomical forcing due to the future dredging.

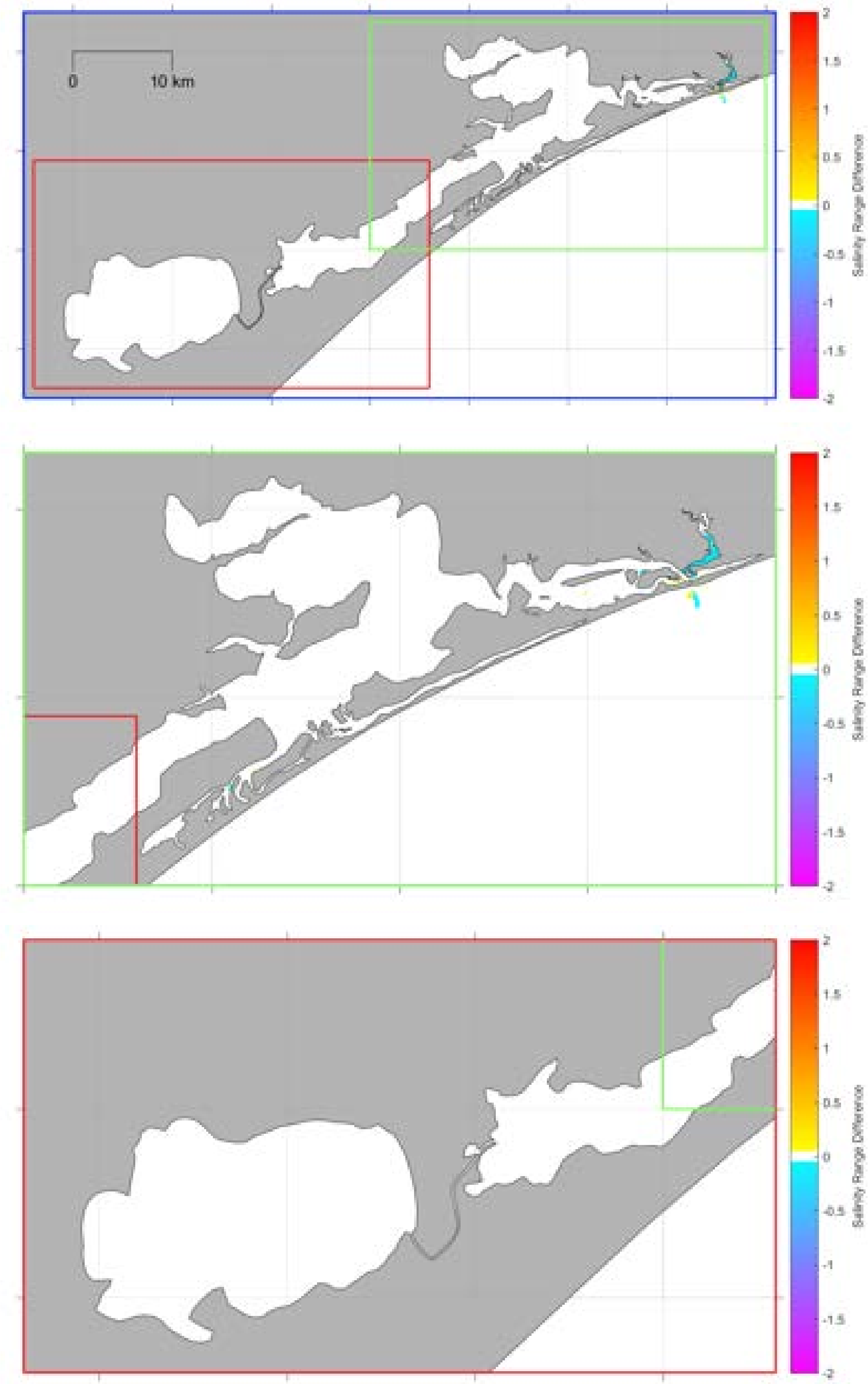


Figure B63. Modelled change in 90th percentile range in surface salinity over 12 months with astronomical forcing due to the future dredging.

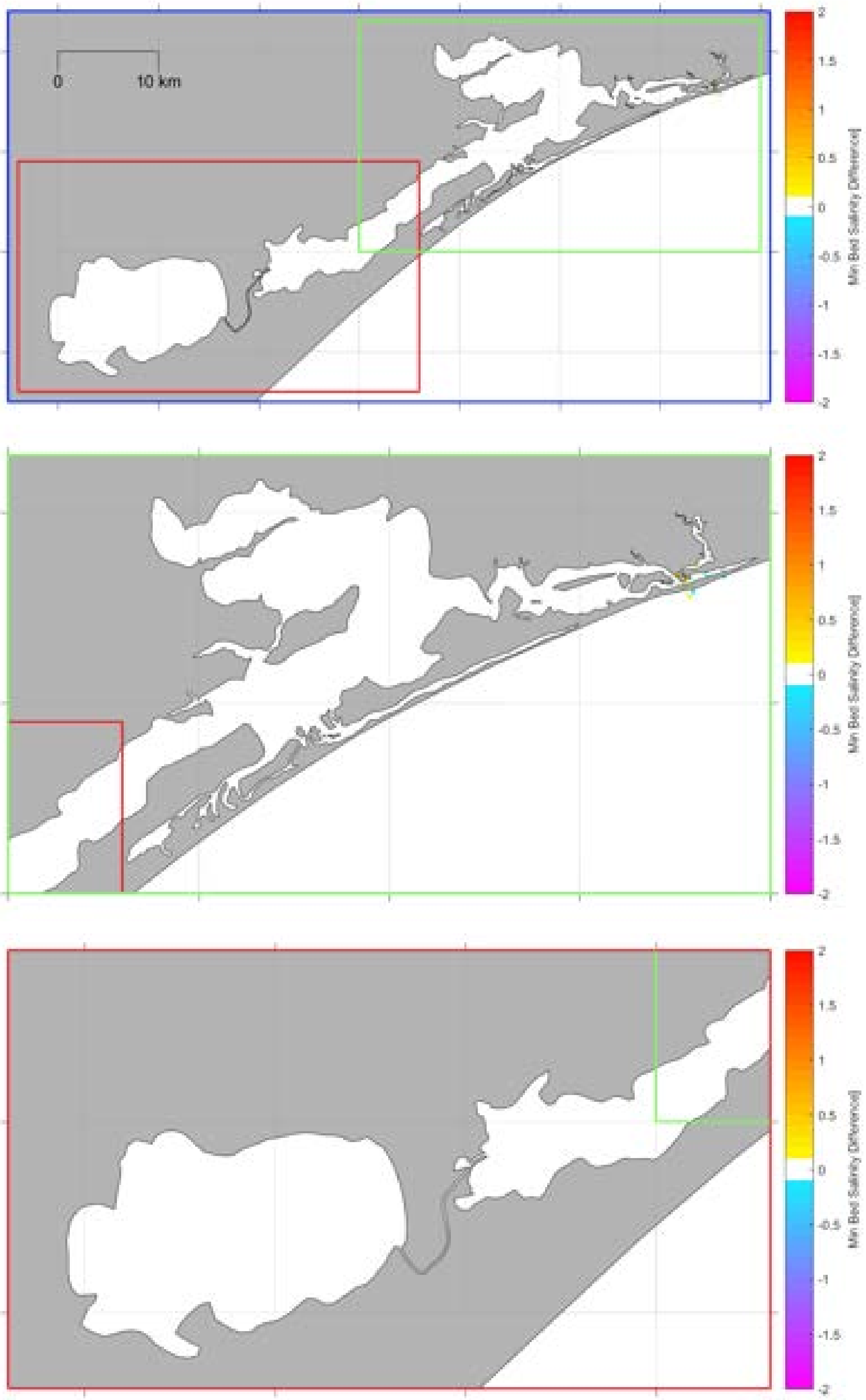


Figure B64. Modelled change in minimum bed salinity over 12 months with astronomical forcing due to the future dredging.

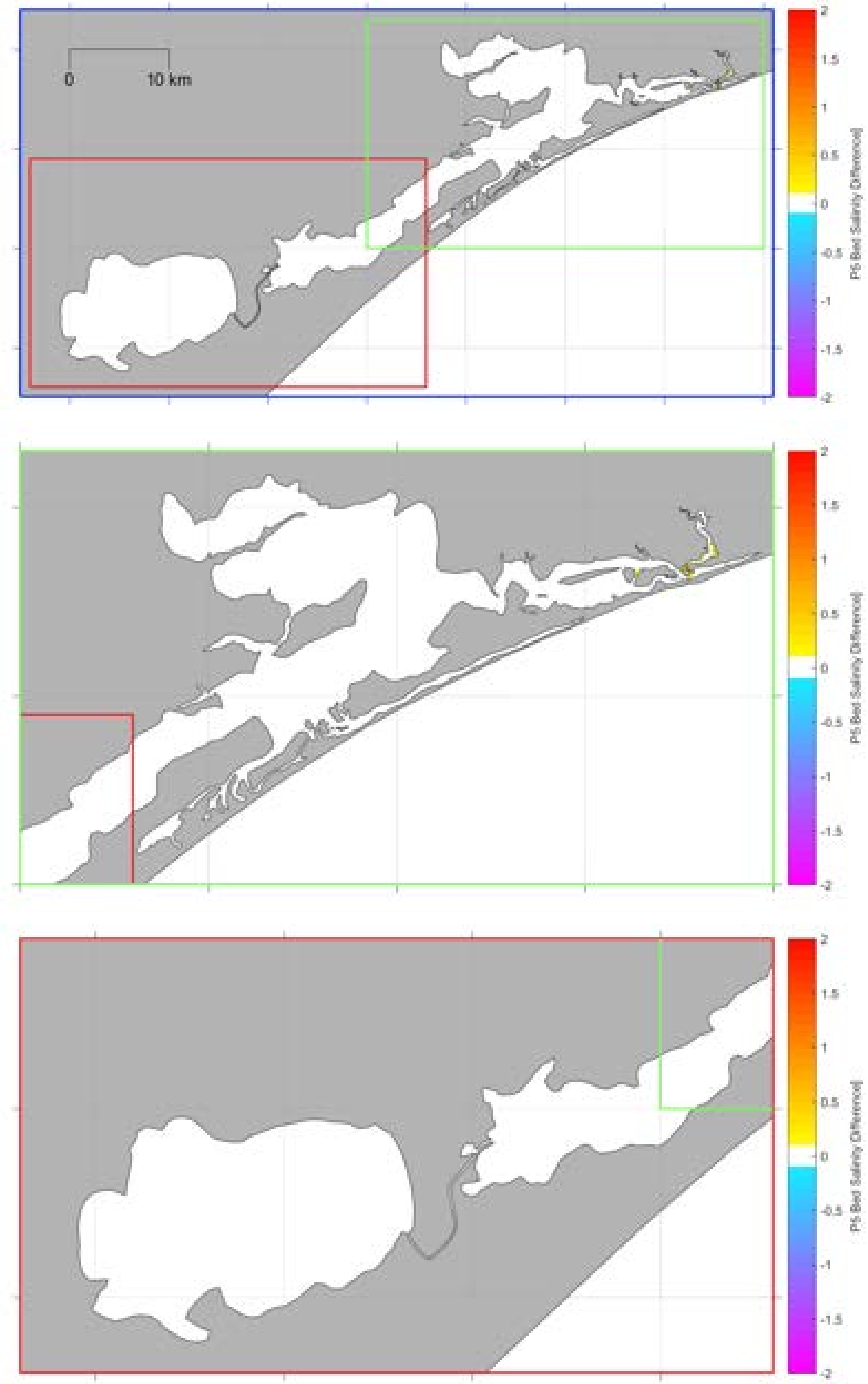


Figure B65. Modelled change in 5th percentile bed salinity over 12 months with astronomical forcing due to the future dredging.

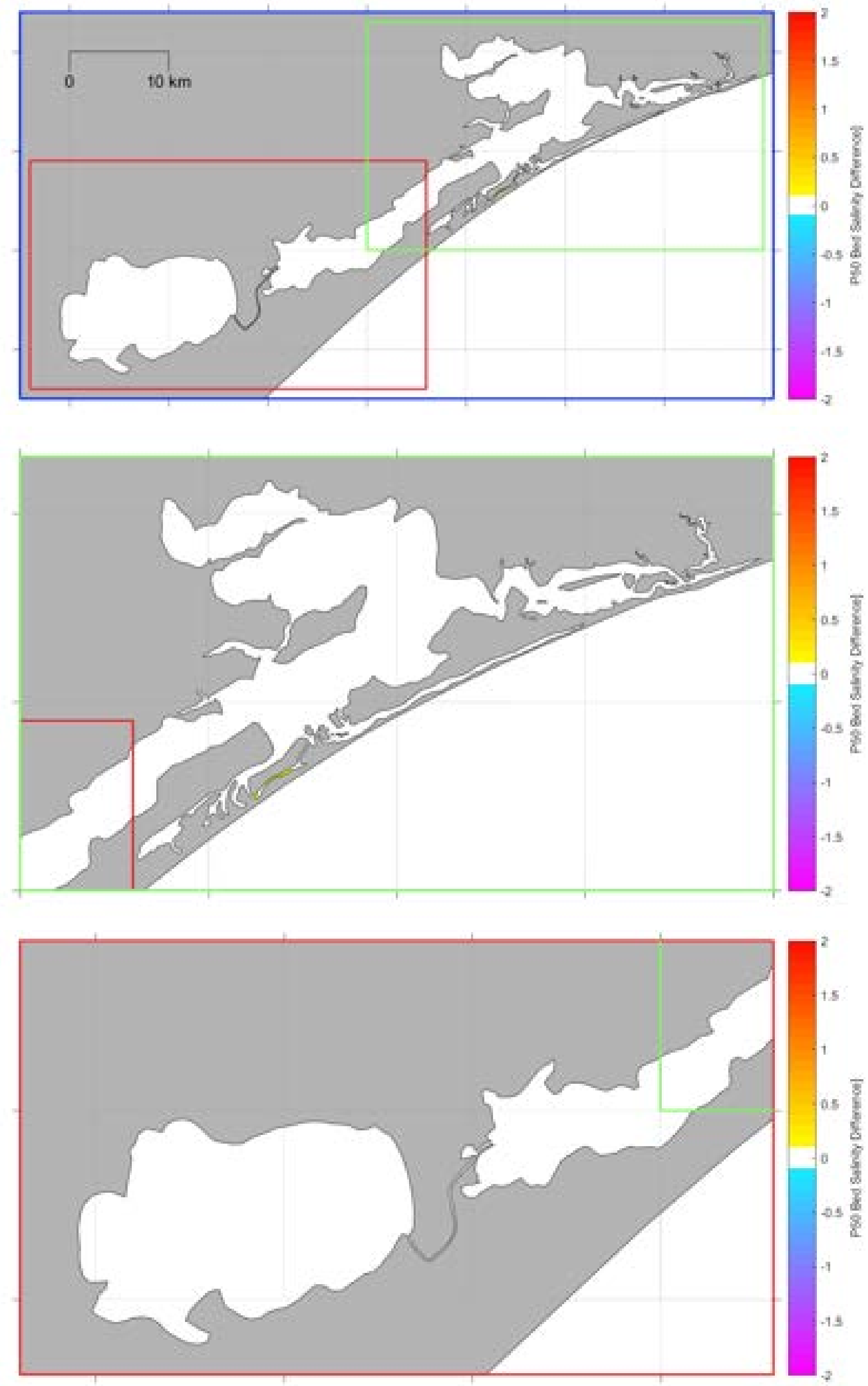


Figure B66. Modelled change in median bed salinity over 12 months with astronomical forcing due to the future dredging.

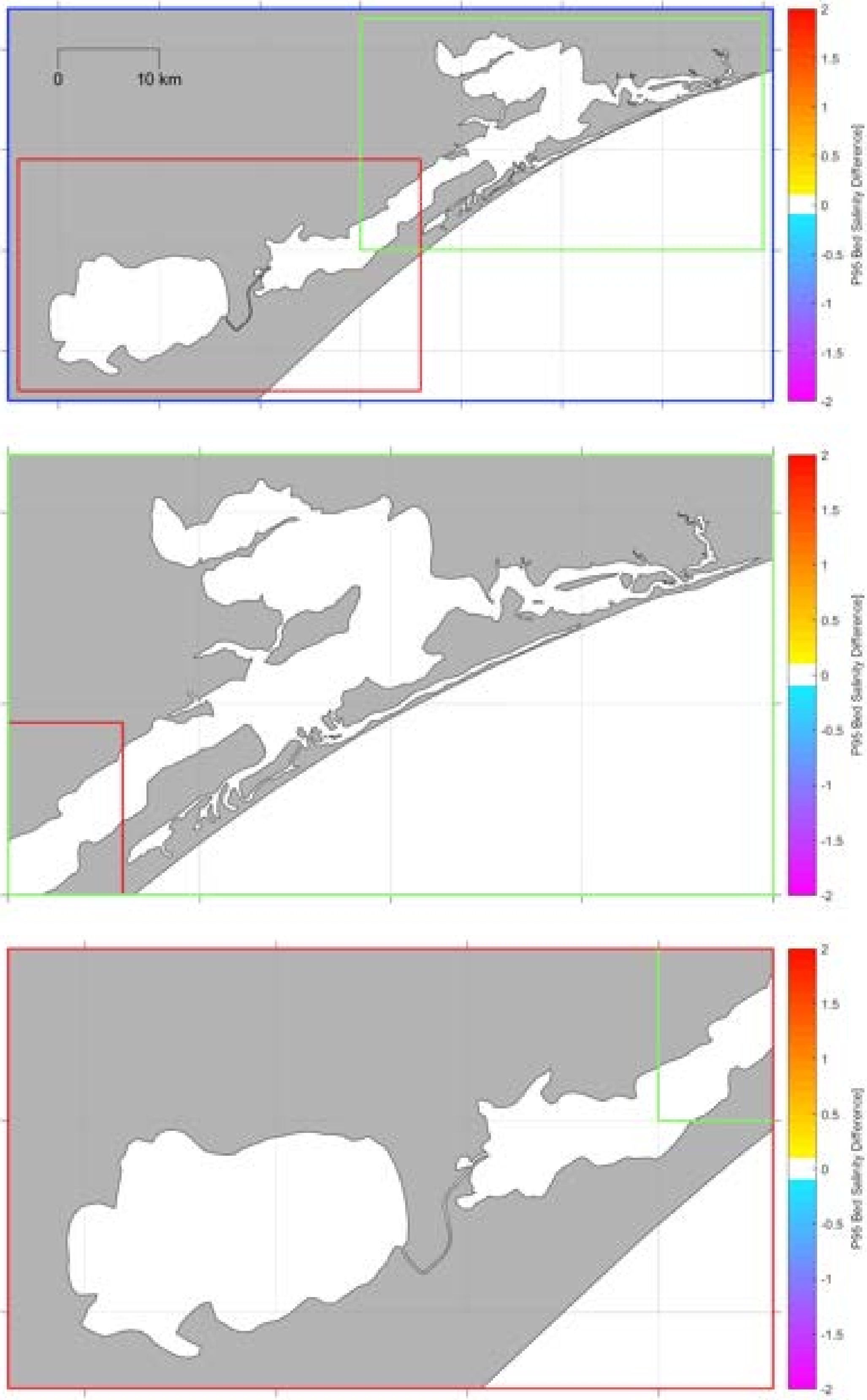


Figure B67. Modelled change in 95th percentile bed salinity over 12 months with astronomical forcing due to the future dredging.

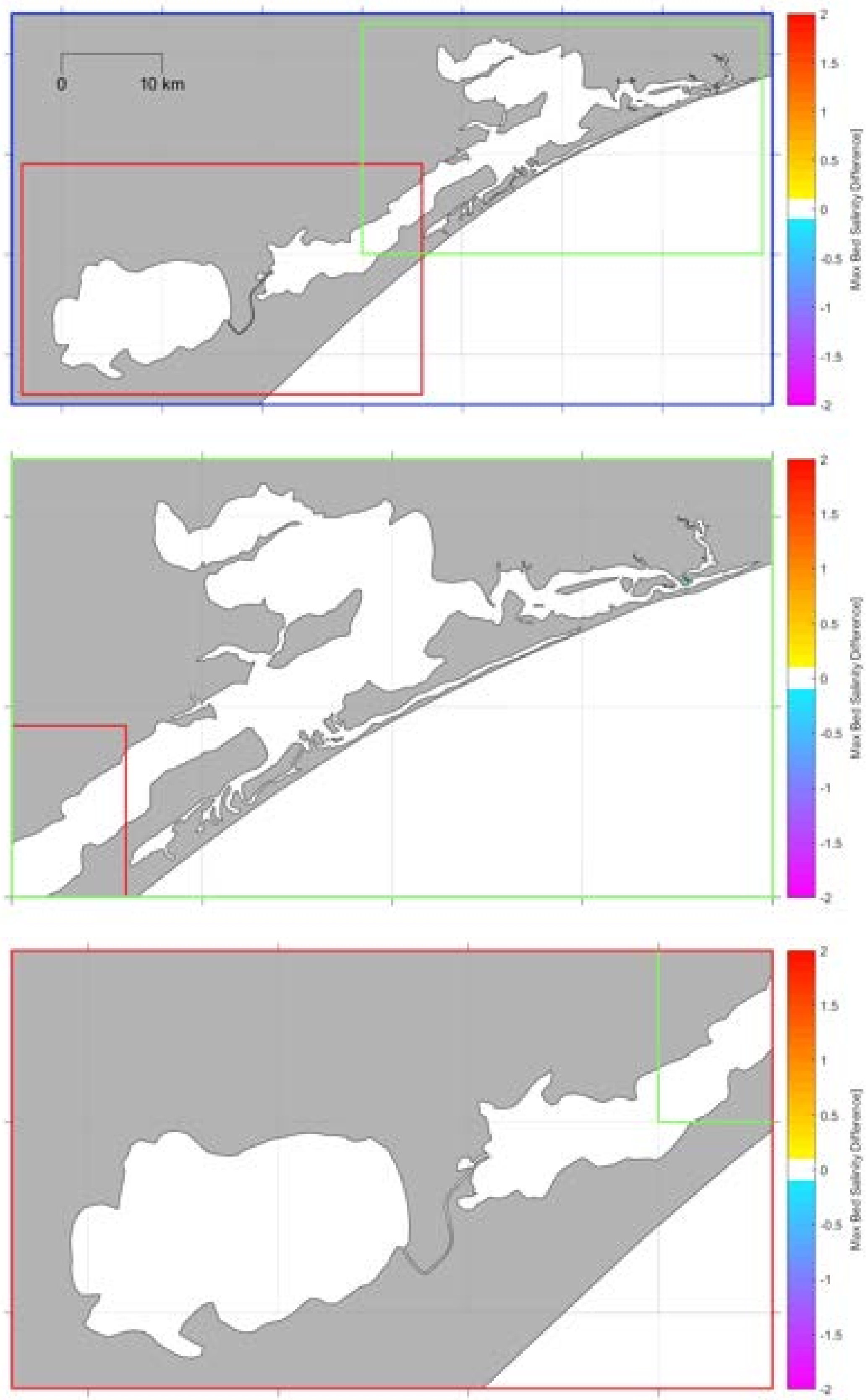


Figure B68. Modelled change in maximum bed salinity over 12 months with astronomical forcing due to the future dredging.

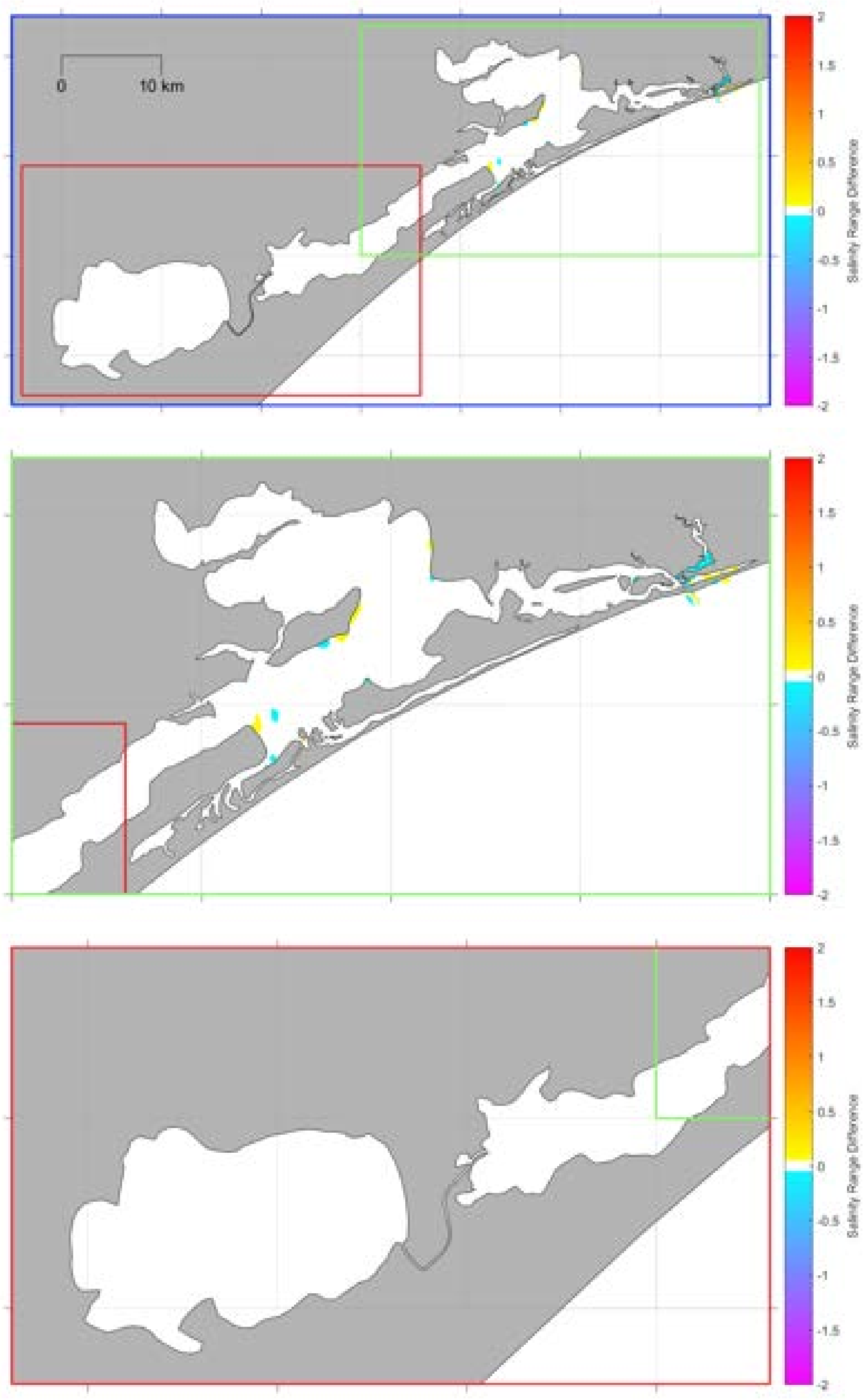


Figure B69. **Modelled change in maximum range in bed salinity over 12 months with astronomical forcing due to the future dredging.**

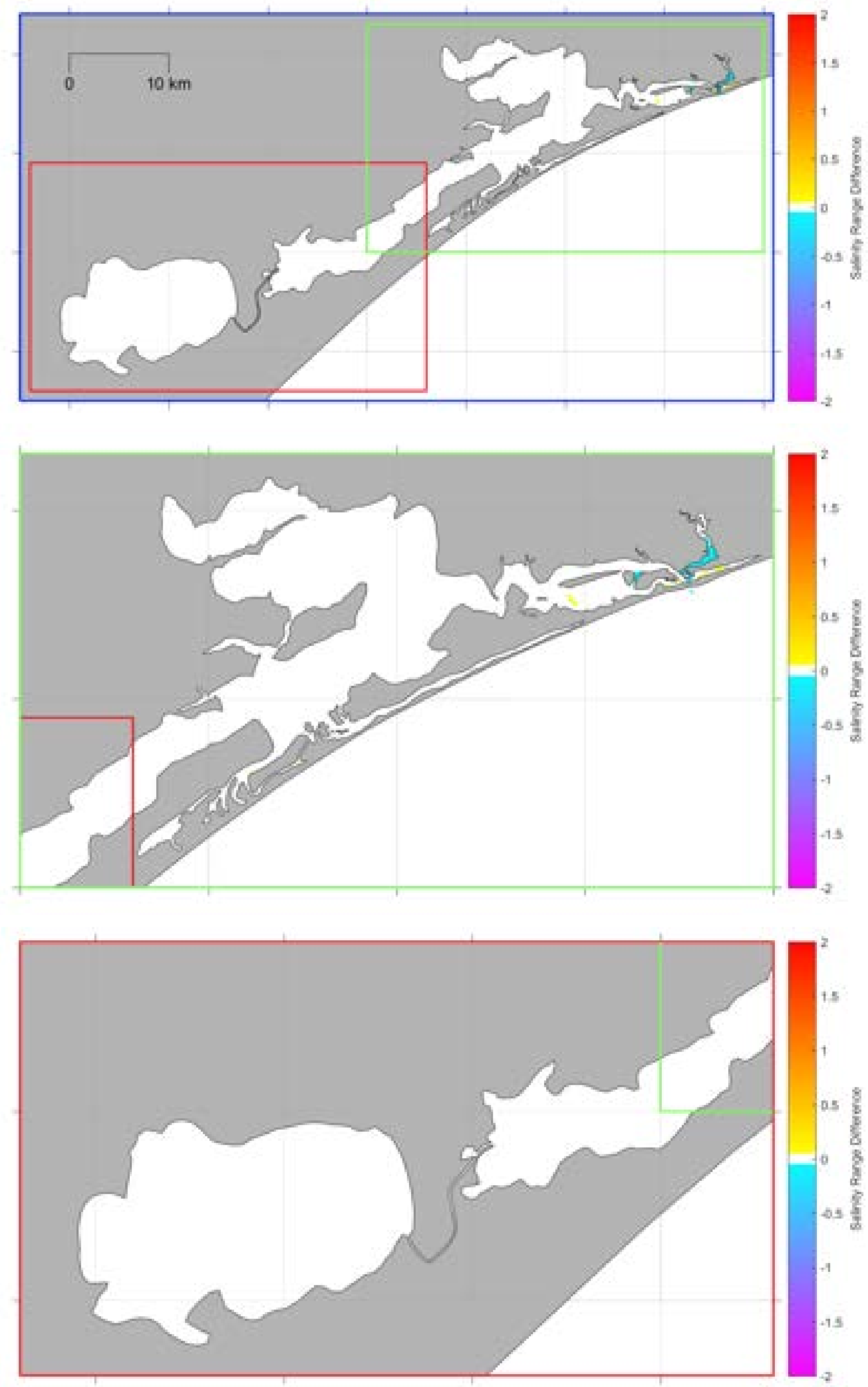


Figure B70. Modelled change in 90th percentile range in bed salinity over 12 months with astronomical forcing due to the future dredging.

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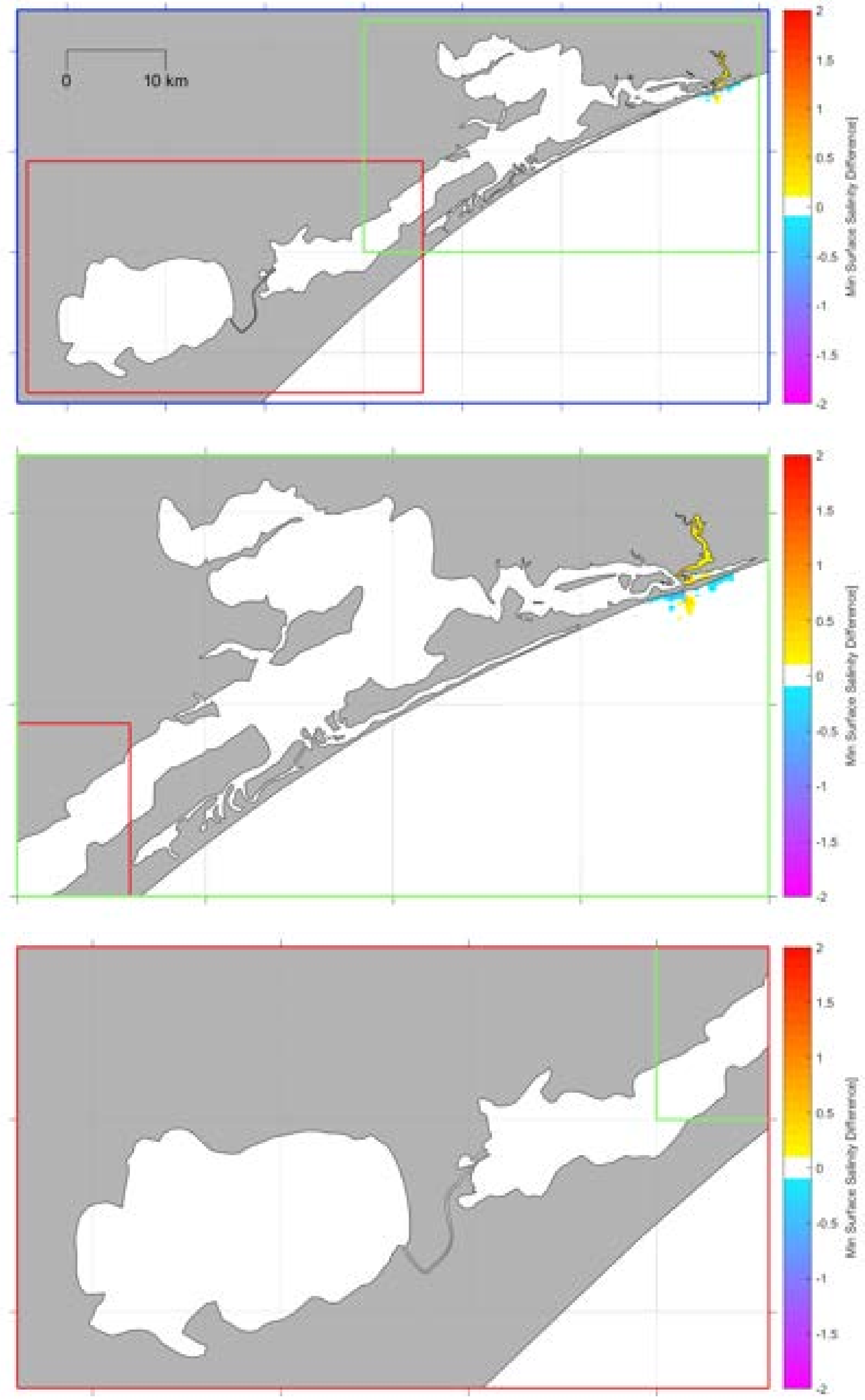

Figure B71. Modelled change in minimum surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

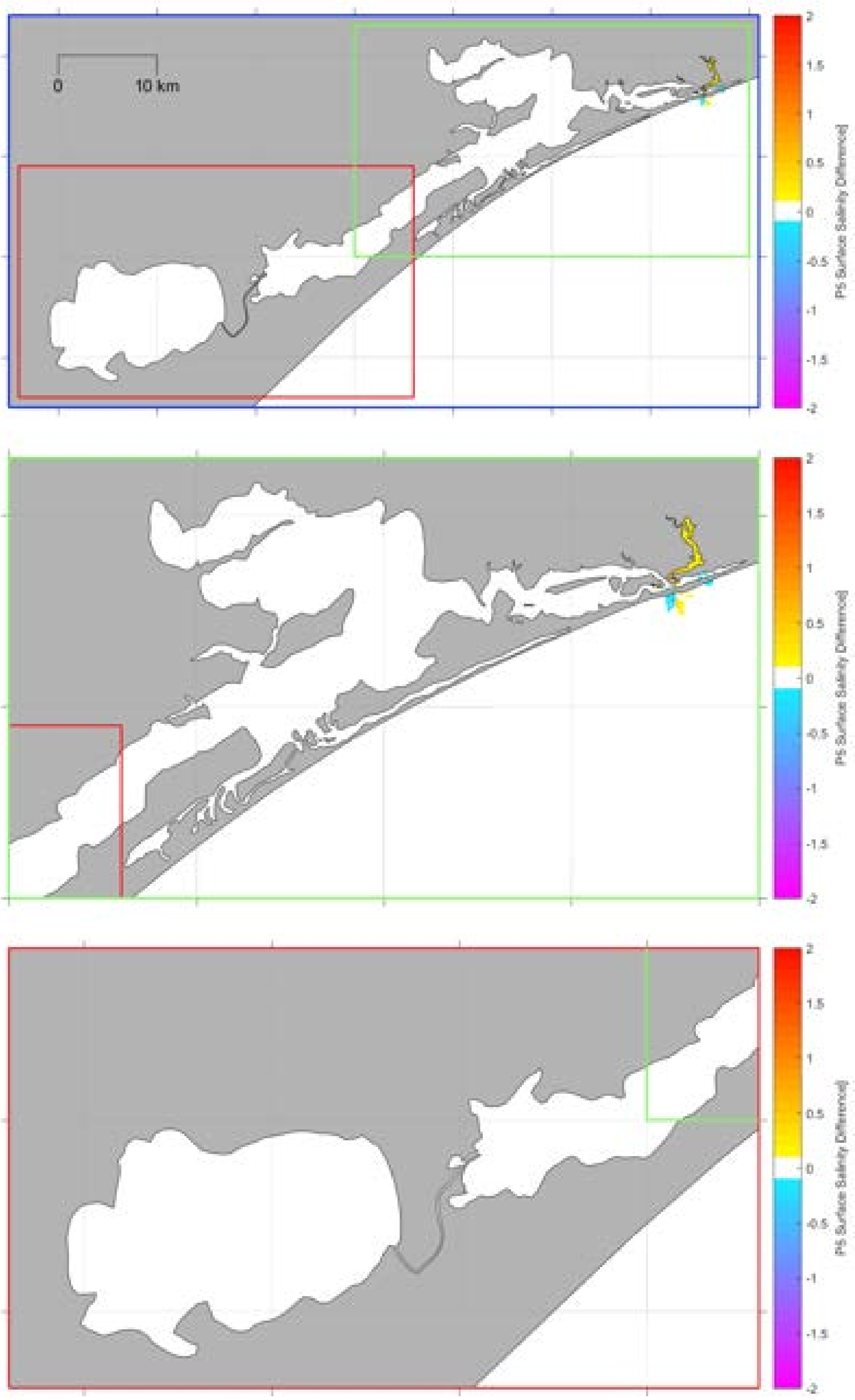

Figure B72. Modelled change in 5th percentile surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

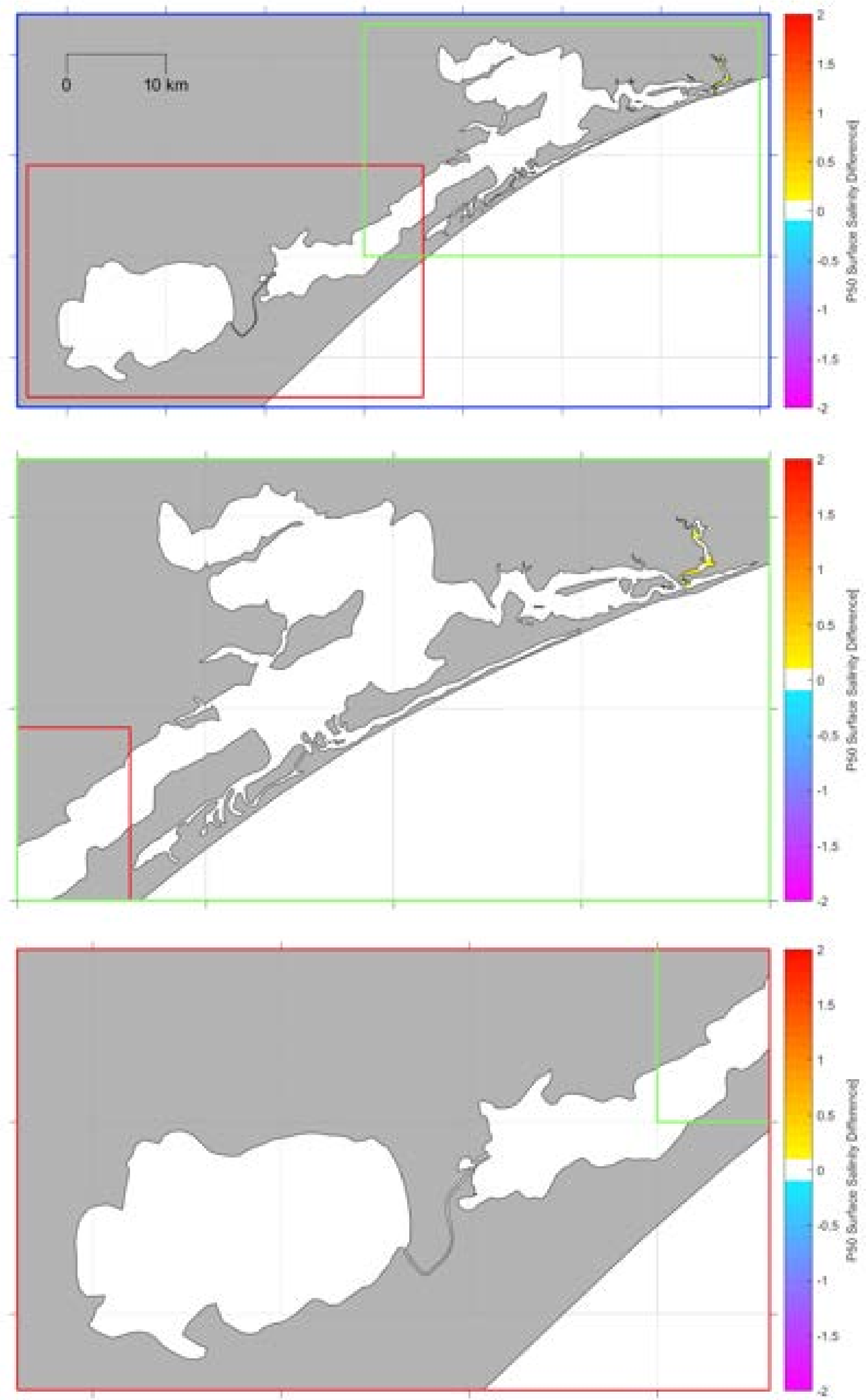

Figure B73. Modelled change in median surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

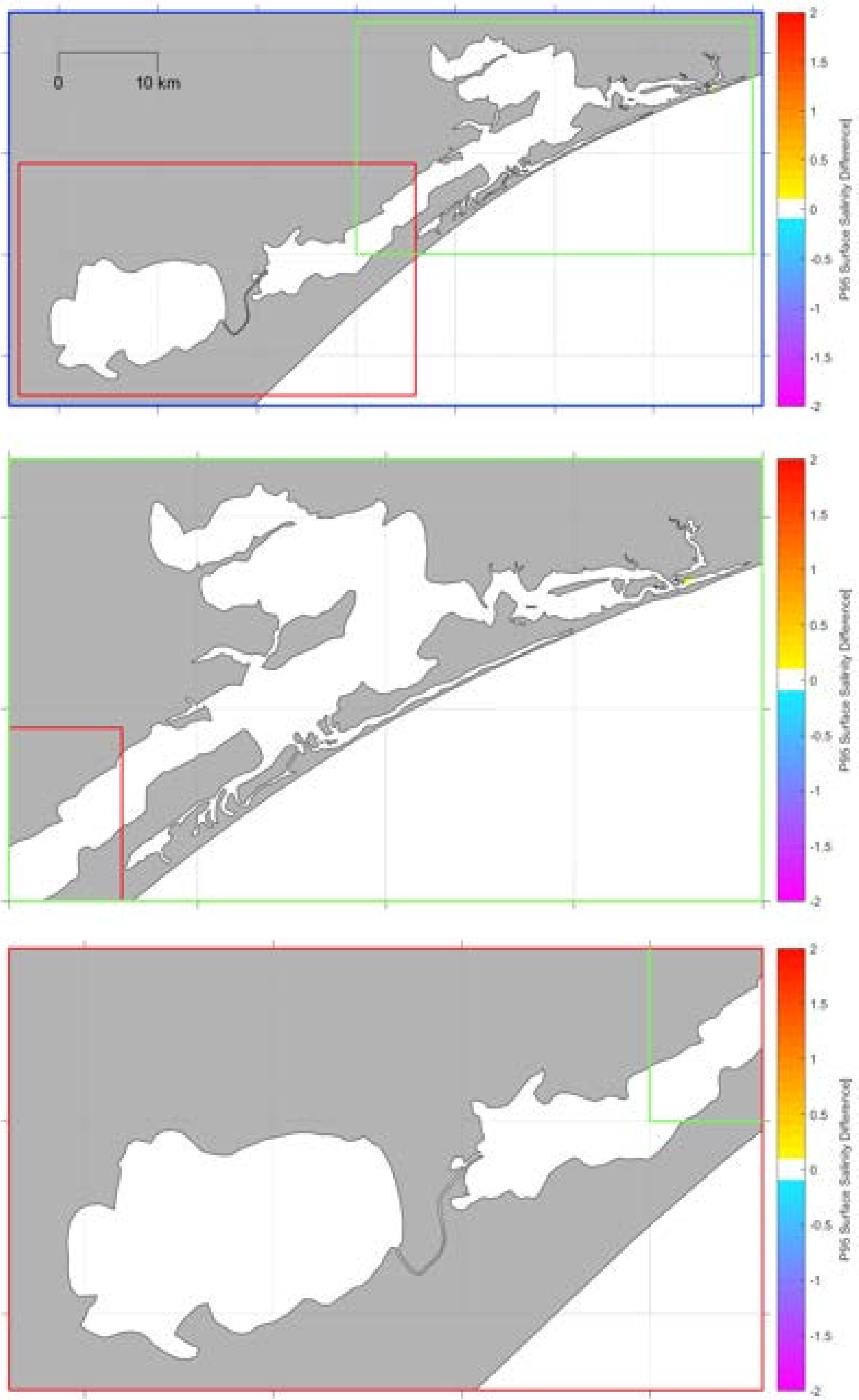

Figure B74. Modelled change in 95th percentile surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

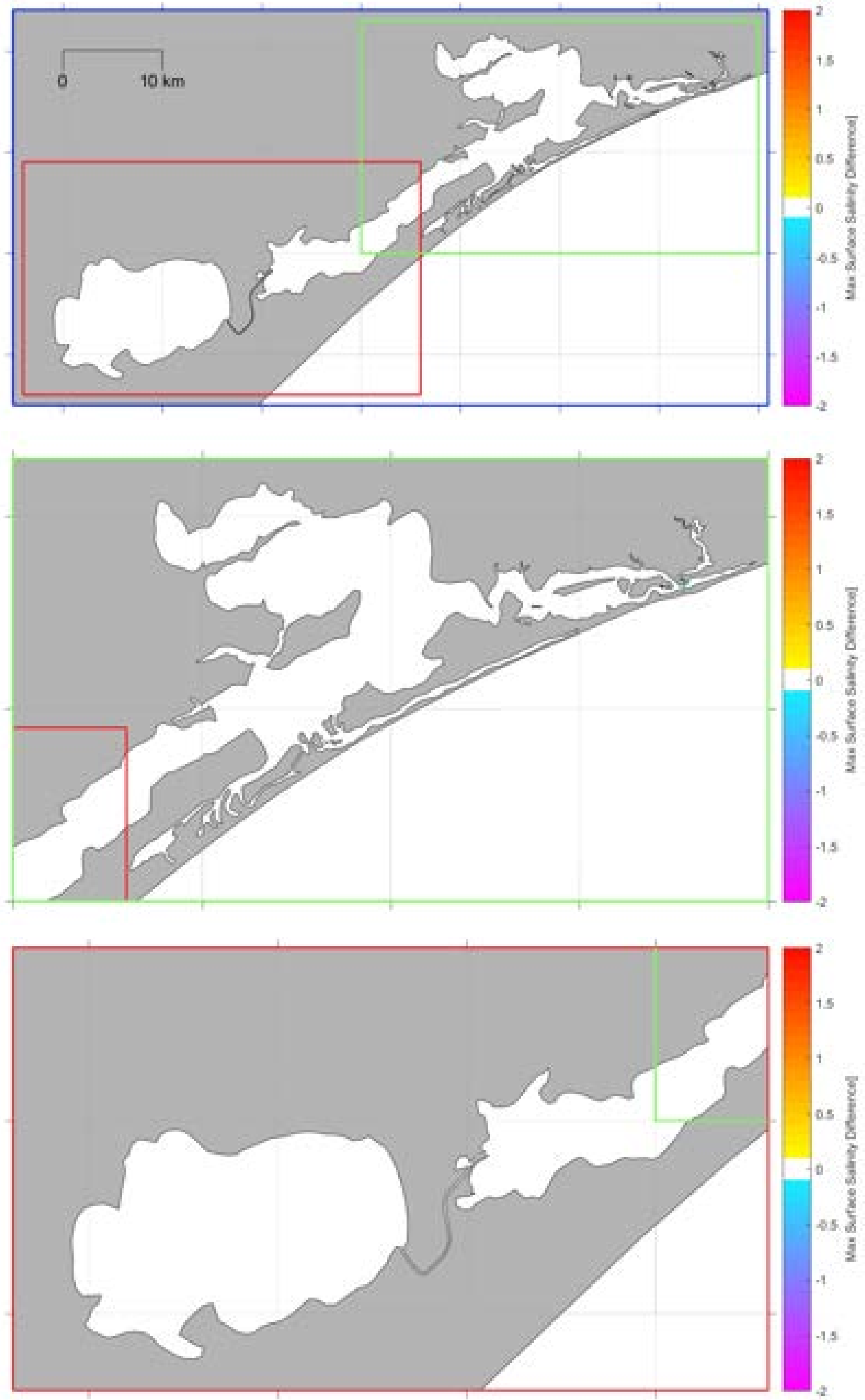

Figure B75. Modelled change in maximum surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

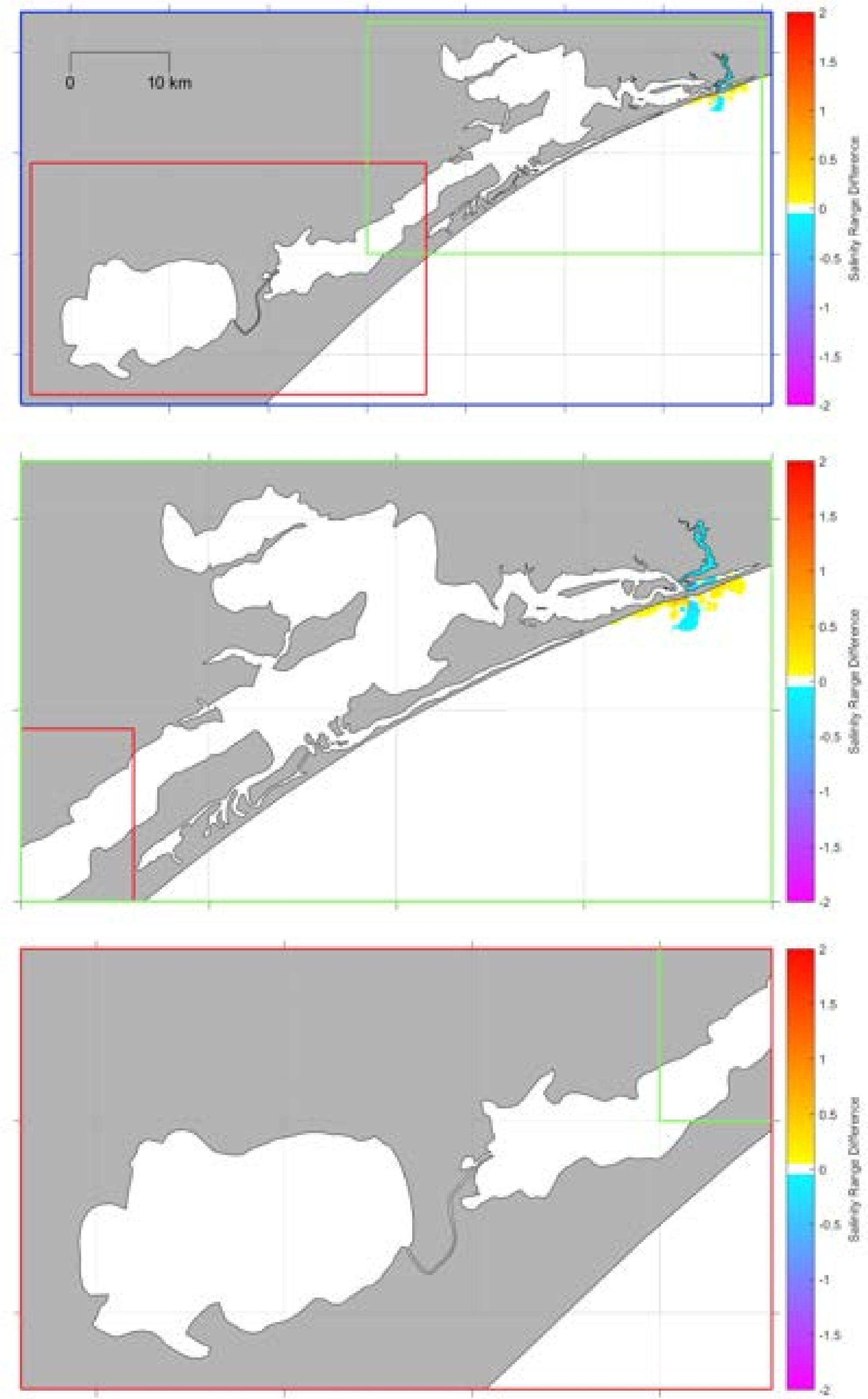

Figure B76. Modelled change in maximum range in surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

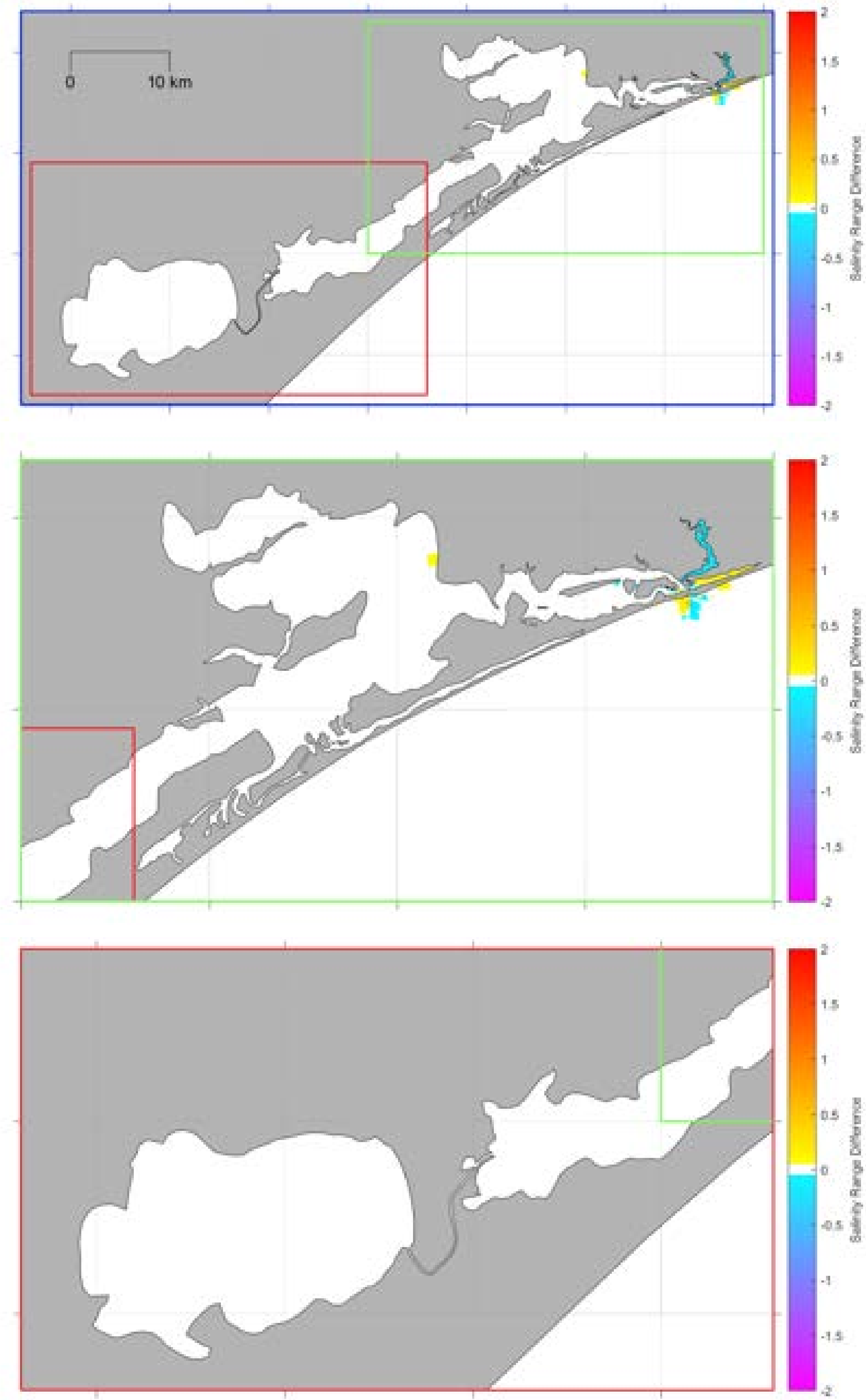

Figure B77. Modelled change in 90th percentile range in surface salinity over 12 months with surge and freshwater forcing due to the future dredging.

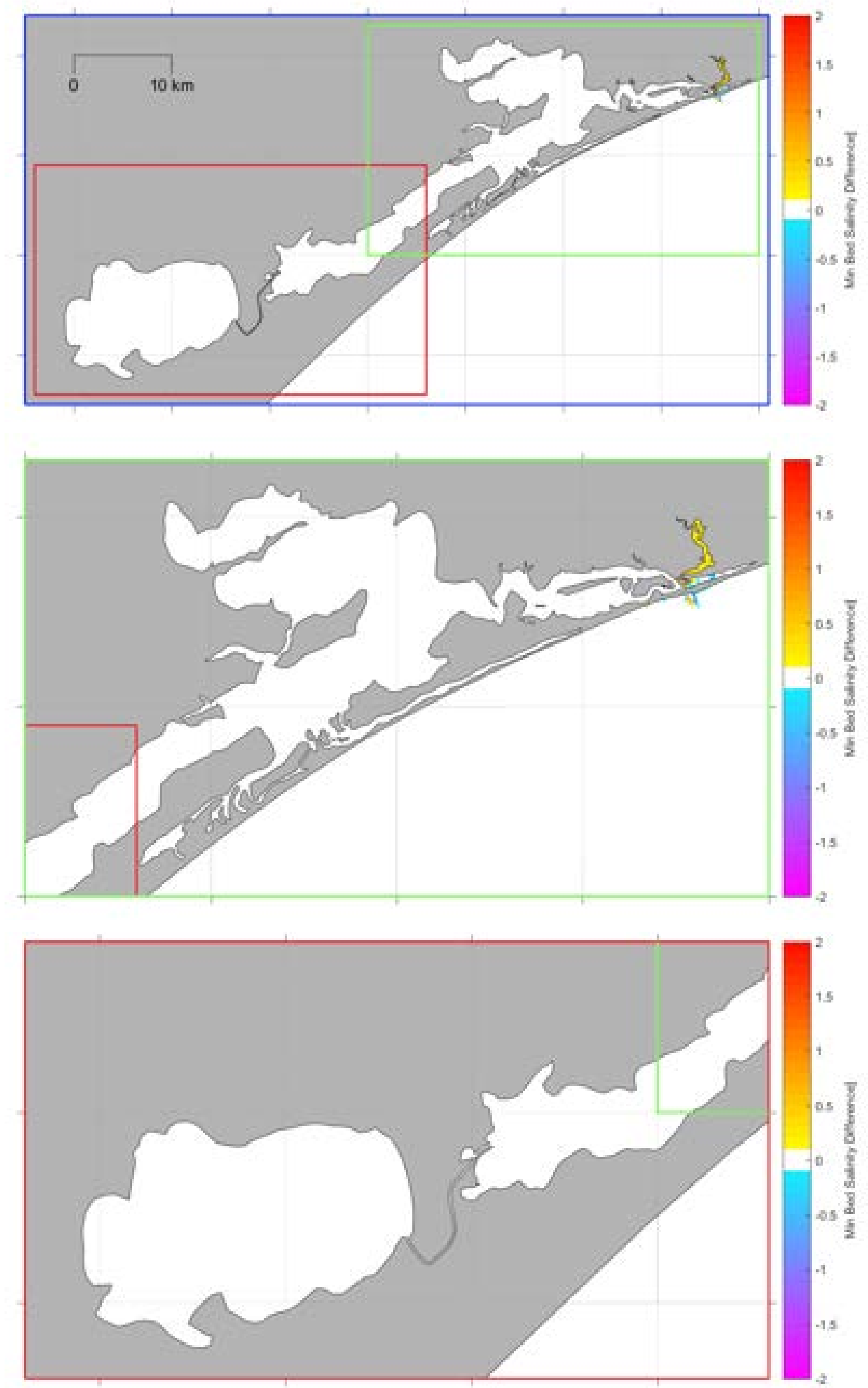

Figure B78. **Modelled change in minimum bed salinity over 12 months with surge and freshwater forcing due to the future dredging.**

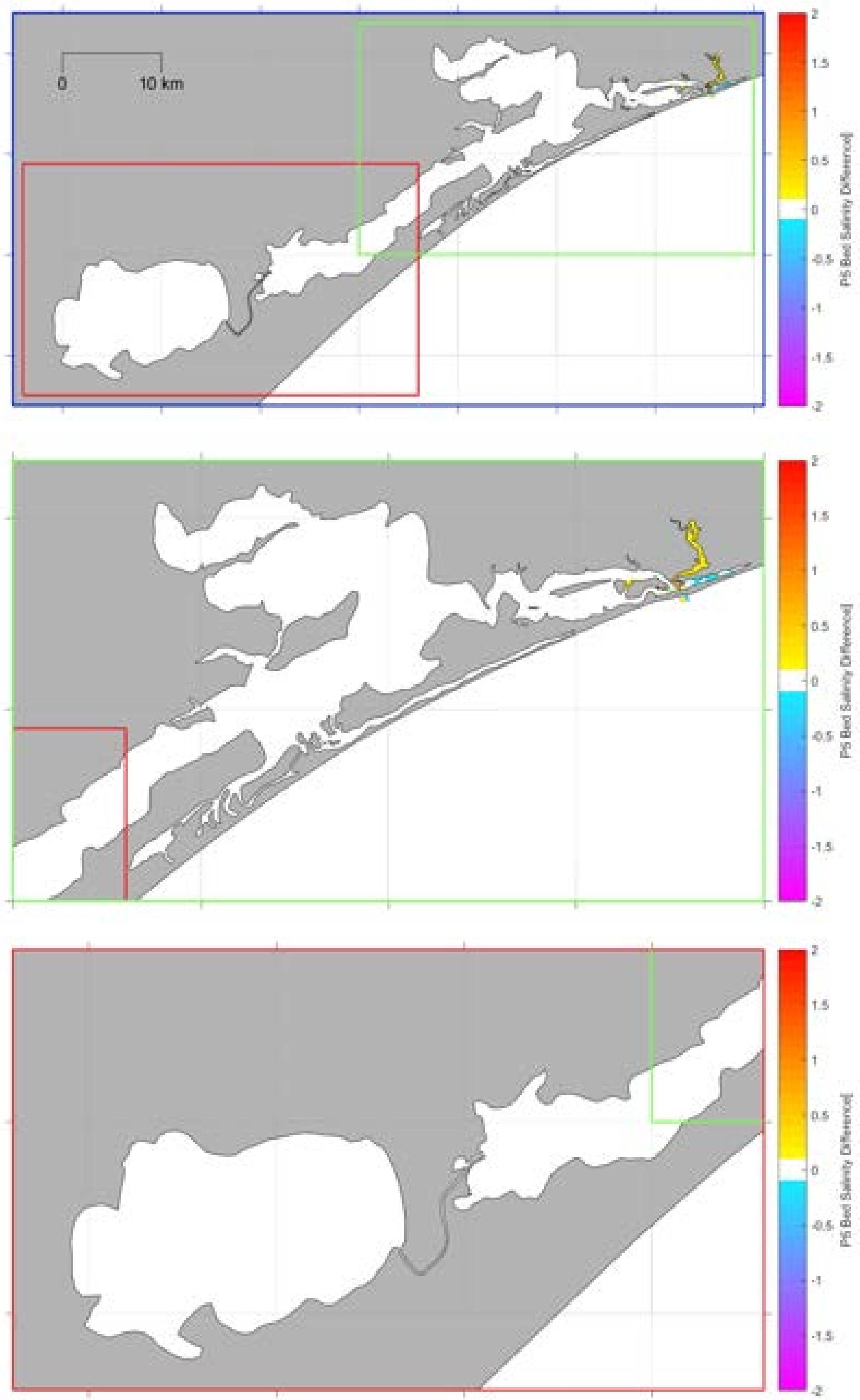

Figure B79. Modelled change in 5th percentile bed salinity over 12 months with surge and freshwater forcing due to the future dredging.

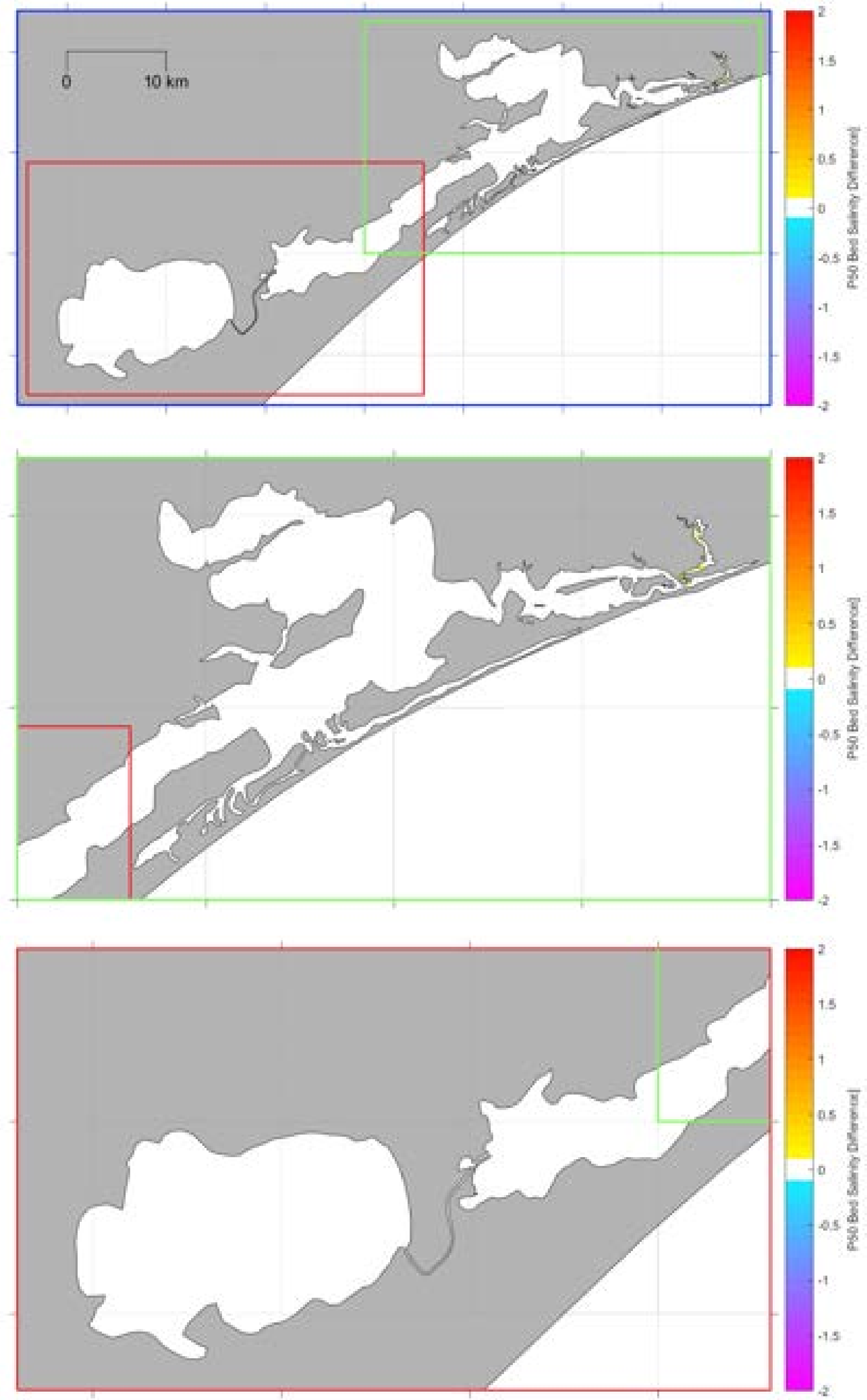

Figure B80. Modelled change in median bed salinity over 12 months with surge and freshwater forcing due to the future dredging.

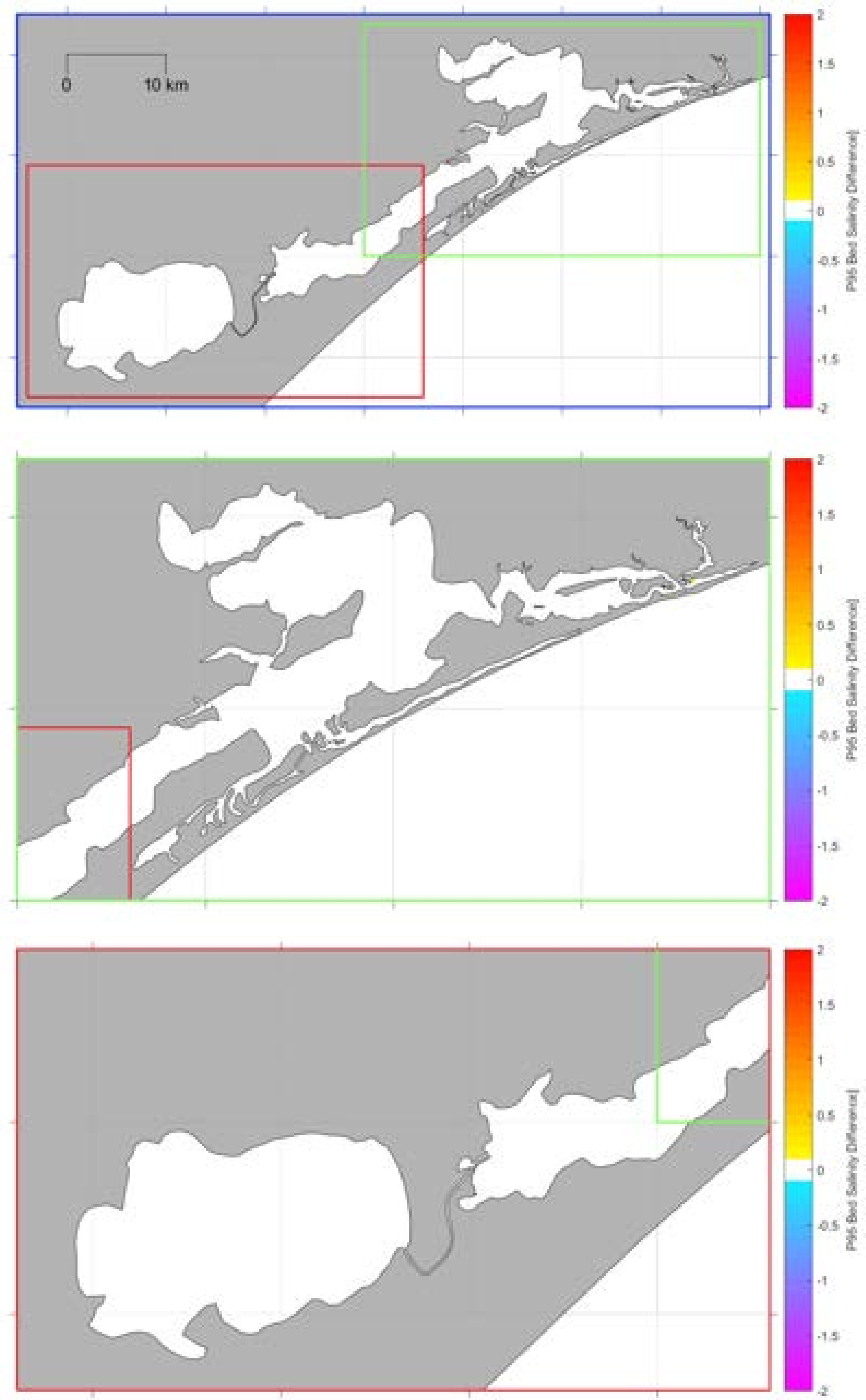

Figure B81. Modelled change in 95th percentile bed salinity over 12 months with surge and freshwater forcing due to the future dredging.

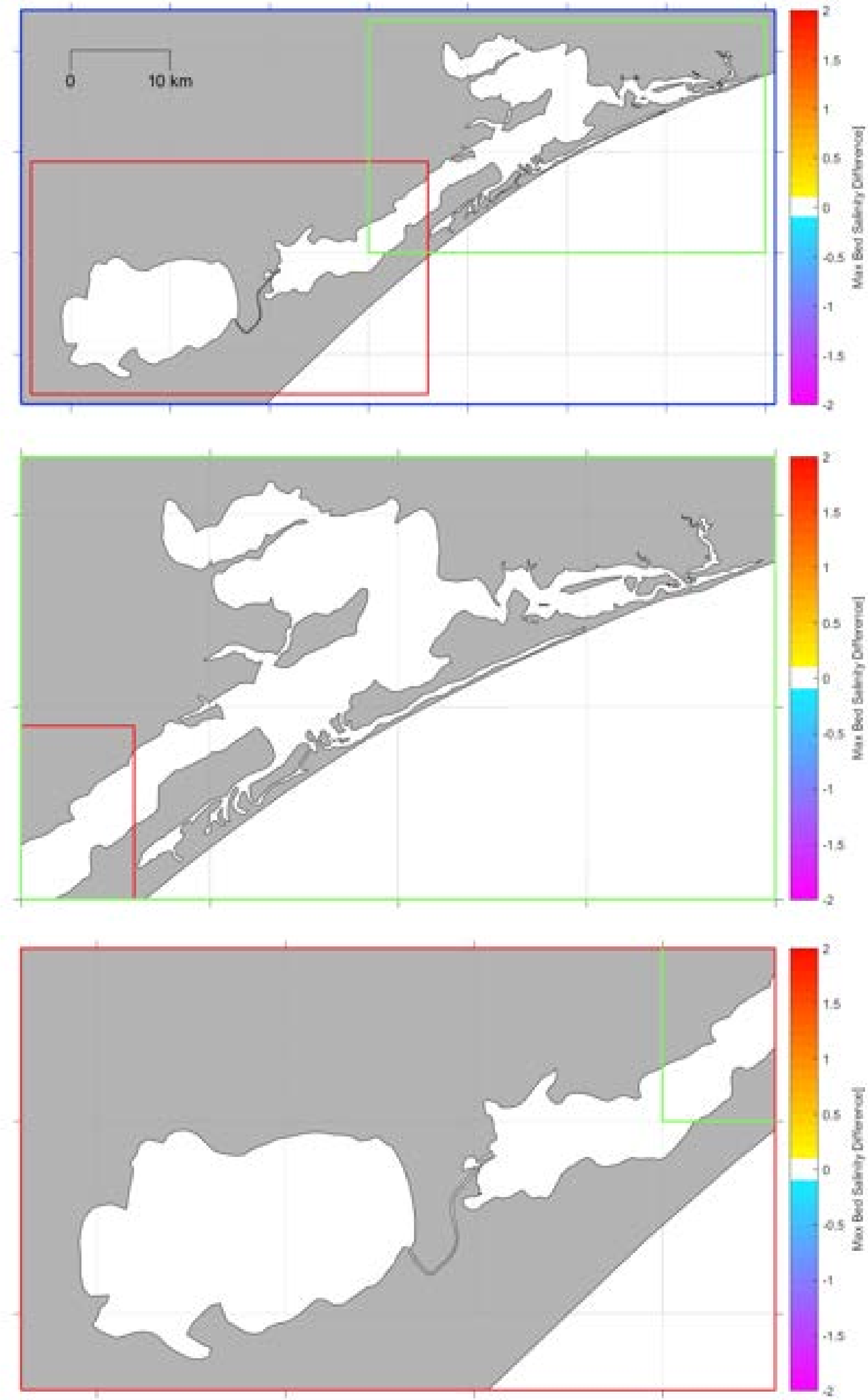

Figure B82. Modelled change in maximum bed salinity over 12 months with surge and freshwater forcing due to the future dredging.

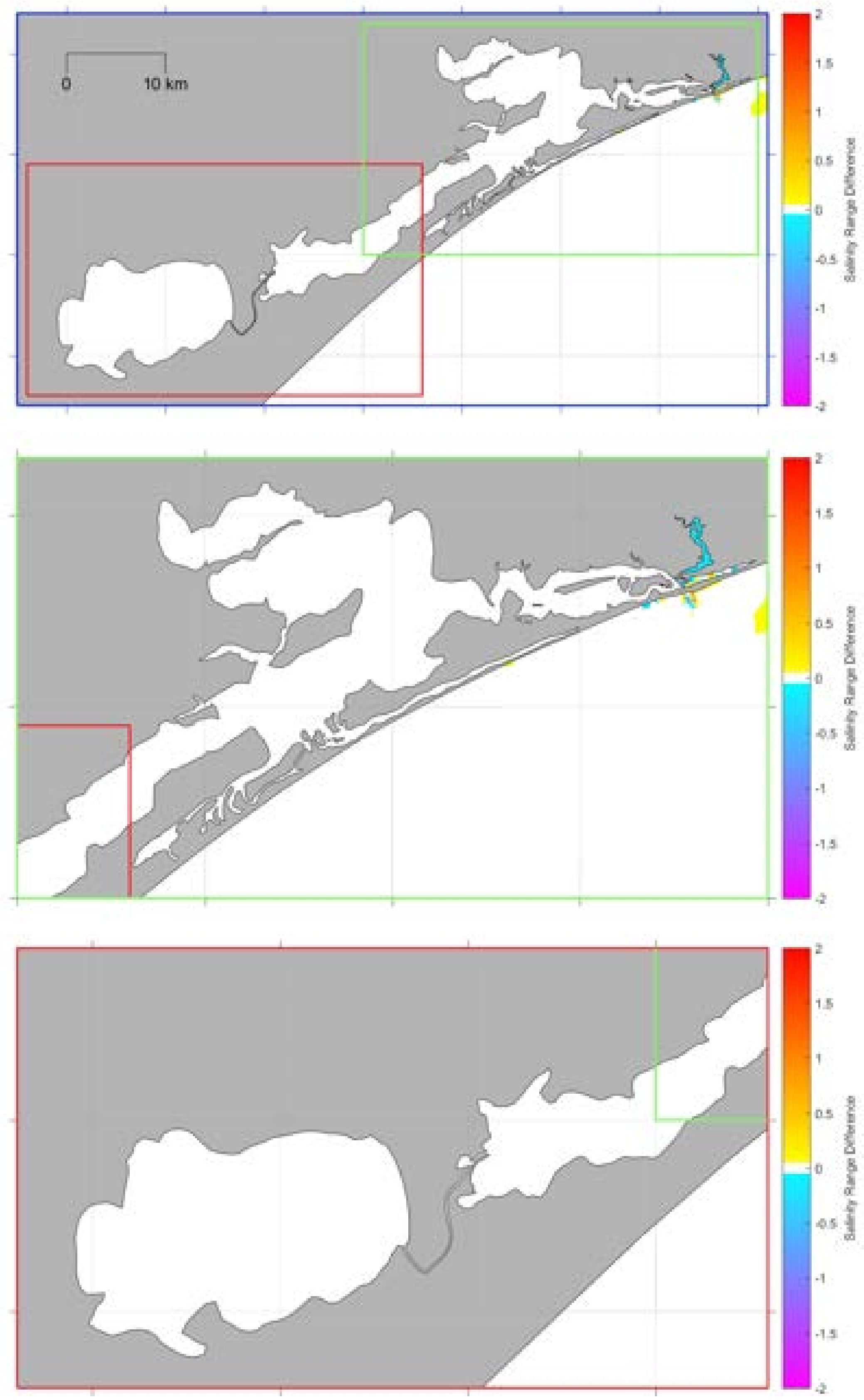

Figure B83. Modelled change in maximum range in bed salinity over 12 months with surge and freshwater forcing due to the future dredging.

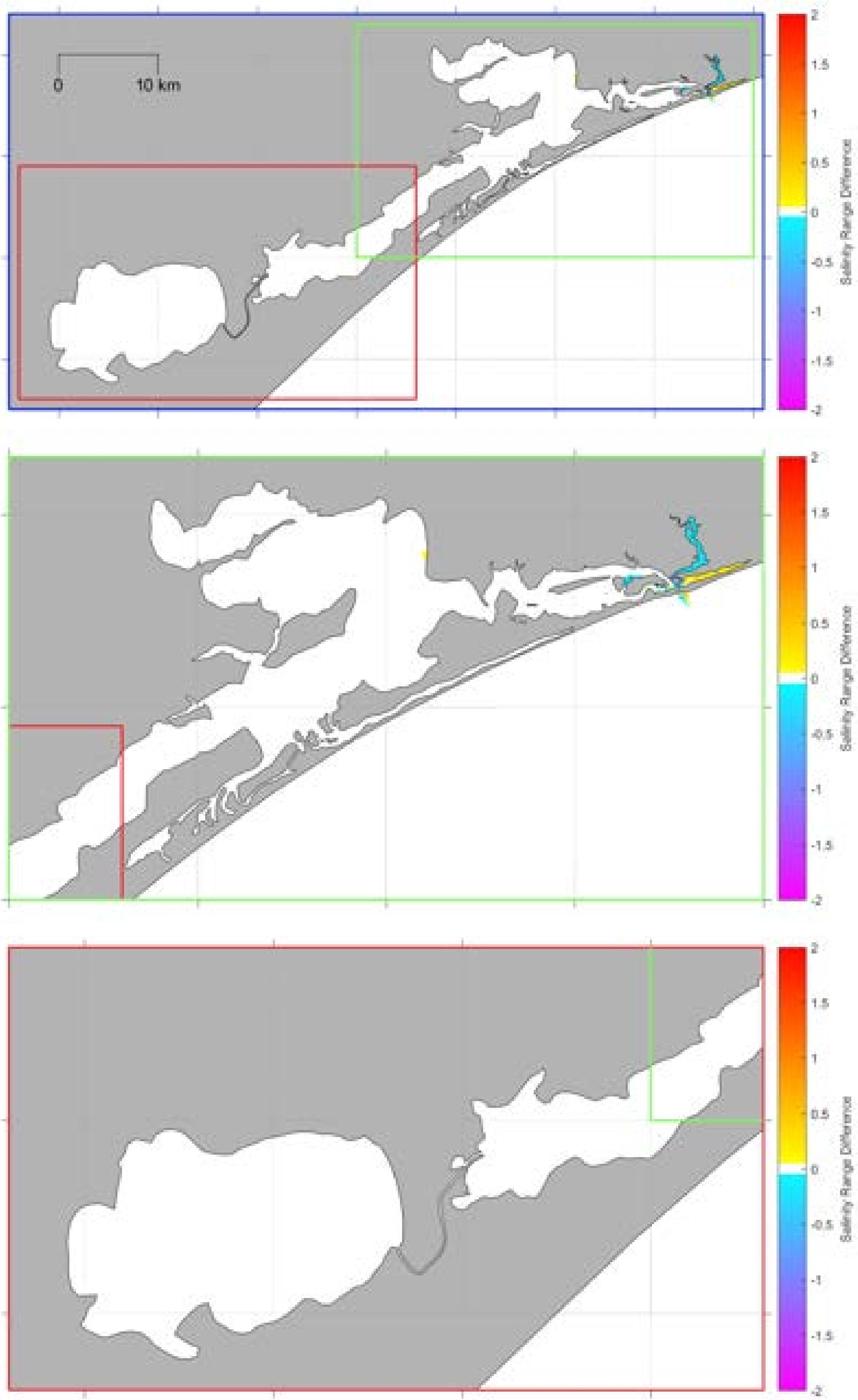

Figure B84. Modelled change in 90th percentile range in bed salinity over 12 months with surge and freshwater forcing.