



## Exposure of coastal ecosystems to river plume spreading across a near-equatorial continental shelf



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### ABSTRACT

The Berau Continental Shelf (BCS) in East Kalimantan, Indonesia, harbours various tropical marine ecosystems, including mangroves, seagrass meadows and coral reefs. These ecosystem are located partly within reach of the Berau River plume, which may affect ecosystem health through exposure to land-derived sediments, nutrients and pollutants carried by the plume. This study aims (1) to assess the exposure risk of the BCS coastal ecosystems to river plume water, measured as exposure time to three different salinity levels, (2) to identify the relationships between these salinity levels and the abundance and diversity of coral and seagrass ecosystems, and (3) to determine a suitable indicator for the impacts of salinity on coral reef and seagrass health. We analysed hydrodynamic models, classified salinity levels, and quantified the correlations between the salinity model parameters and ecological metrics for the BCS systems. An Empirical Orthogonal Functions (EOF) analysis revealed three modes of river plume dispersal patterns, which strongly reflect monsoon seasonality. The first mode, explaining 39% of the variability, was associated with the southward movement of the plume due to northerly winds, while the second and third modes (explaining 29% and 26% of the variability, respectively) were associated with the northeastward migration of the plume related to southwesterly and southerly winds. Exposure to low salinity showed higher correlations with biological indicators than mean salinity, indicating that low salinity is a more suitable indicator for coastal ecosystem health. Significant correlations ( $R^2$ ) were found between exposure time to low salinity (days with salinity values below 25 PSU) with coral cover, coral species richness, seagrass cover, the number of seagrass species, seagrass leaf phosphorus, nitrogen, C:N ratio and iron content. By comparing the correlation coefficients and the slopes of the regression lines, our study suggests that coral reefs are more susceptible to low salinity levels exposure than seagrass meadows. Regarding the risk of corals being exposed to low salinity, nearshore and northern barrier reefs were classified as “high risk”, the middle barrier reef as “medium to high risk” and southern barrier reefs as “medium risk”. Further offshore, the oceanic reefs were classified as “low risk”. Regarding the seagrass meadows, the nearshore region was categorized as “high risk”, the barrier reef as “medium to low risk” and oceanic reefs as “low risk”. This study contributes to assessing the potential impacts of salinity on the BCS ecosystems, and further provides a knowledge base for marine conservation planning.

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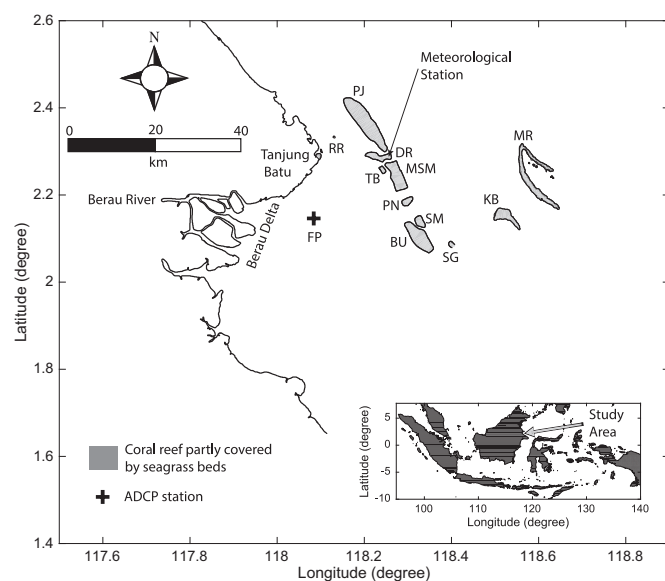
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**Fig. 1.** Map of the Berau Continental Shelf and adjacent waters. Gray colours denote coral reefs partly covered by seagrass. RR denotes Rabu Rabu; PJ, Pulau Panjang; DR, Derawan; TB, Tababinga; MSM, Masimbung; PI, Pinaka; SM, Samama; BU, Buliulin; and SG, Sangalaki. The plus sign locates ADCP station at the Fishing Platform (FP). The insert in the bottom right panel displays a map of Indonesia.

## 1. Introduction

River plume dynamics play an important role in the transport processes that control salinity, sediment concentrations, nutrient loads, and pollutant dispersal in coastal waters. Furnas et al. (1997) found that nutrient inputs in the central Great Barrier Reef ecosystems are dominated by river runoff, which contributes on average 30% of the total nutrient load and 39% of the phosphorus load. Devlin et al. (2001) showed that water quality parameters such as dissolved inorganic nutrients, dissolved inorganic phosphorus, sediments, particulate phosphorus and silicate, are significantly correlated to salinity levels, with coefficients of determination ( $R^2$ ) exceeding 0.7. The mean photic depth can also be strongly related to river plume properties (Fabricius et al., 2014). Generally, coastal water quality is highly dependent on river plume dynamics. The impact of water quality deterioration on coral reef ecosystems, initiated by the input of sediments, nutrients, pollutants and fresh water, has been widely studied and linked to decreases in coral cover, coral species richness and survival, and coral growth, photosynthesis and respiration (Coles and Jokiel, 1992; Van Woessik et al., 1995; Moberg et al., 1997; Nakano et al., 1997; Fabricius, 2005; Burke, 2011; Berkemans et al., 2012; Erftemeijer et al., 2012). For example, van Katwijk et al. (1993) found a clear link between terrigenous sediment concentrations and the stress response in Kenyan coral reefs. In Indonesia, river discharge is recognised as an important factor limiting coral species diversity on nearshore reefs (Cleary et al., 2006; Hoeksema, 2012a), and this may explain the clear decline in the number of coral species in northern Jakarta over a span of more than 80 years (van der Meij et al., 2010).

Seagrass communities are also considered to be severely threatened by increased loads of sediments, nutrients and pollutants (Waycott

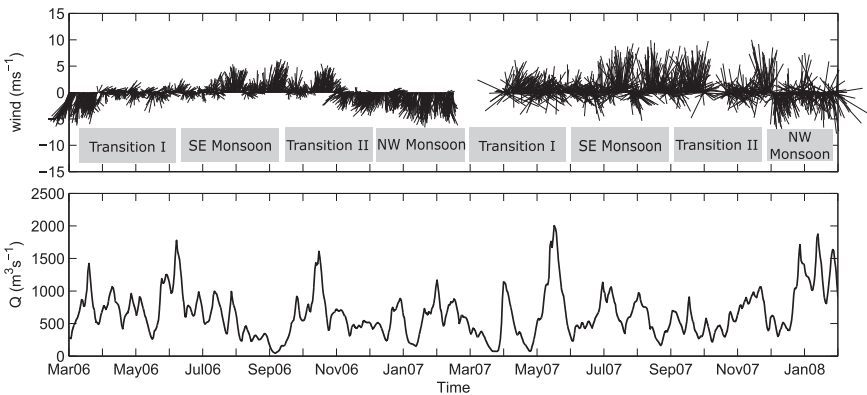
et al., 2005; Erftemeijer and Lewis, 2006; Orth et al., 2006; van Katwijk et al., 2011; Petus et al., 2016). Terrestrially sourced nutrients reduce seagrass abundance and the extent of meadows, decrease reproductive efforts, and lead to limited or absent seed production (McKenzie et al., 2012). Coral reef and seagrass properties have been used as bioindicators of water quality (Van Woessik et al., 1999; van Katwijk et al., 1993; De'ath et al., 2008; Reopanichkul et al., 2009; Gittenberger et al., 2015; Petus et al., 2016). In the Great Barrier Reef area, water quality parameters including particulate nitrogen, particulate phosphorus, suspended particulate matter and total organic matter, are strongly related to biotic metrics, such as coral cover, coral species richness and macroalgae indices (Van Woessik et al., 1999; De'ath et al., 2008). For seagrass communities, Collier et al. (2012) identified a linear relationship between seagrass abundance and reduced light levels in the northern Great Barrier Reef. Roca et al. (2015) reported that seagrass abundance was strongly related to nutrient loads by measuring seagrass tissue (nitrogen, phosphorus and total nonstructural carbohydrates) for the Catalan coast of Spain.

Most of the attention has been focused on bioindicators for sediments and nutrients in coastal ecosystems, whereas the direct effect of low salinity as a result of riverine discharge has not been addressed as an additional stressor (Humphrey et al., 2008; Haapkyla et al., 2011; Ban et al., 2014). Low salinity has been found to cause severe mortality in corals in many near-shore coral reefs throughout the world (Jokiel et al., 1993; Van Woessik et al., 1995; Berkemans et al., 2012; Jones and Berkemans, 2014; Huang et al., 2014) and dramatically decrease growth rates of seagrasses (Lirman, 2003). Salinity is a likely candidate for being a good indicator of nutrient and sediment loads (Furnas et al., 1997; Devlin et al., 2001; Devlin and Brodie, 2005) and thus can be considered as an important parameter for assessing coastal ecosystem health.

The Berau Continental Shelf (BCS) is located in East Kalimantan, Indonesia (Fig. 1). It features extremely high biodiversity and unique species assemblages, which are apparent in the high diversity of coral, reef fish species, a large population of green turtles (*Chelonia mydas*), manta rays (*Manta* spp.) and extensive seagrass meadows (Hoeksema, 2004; Hoeksema et al., 2004; de Voogd et al., 2009; van Katwijk et al., 2011; Christianen et al., 2012). Furthermore, some of its offshore islands contain anchialine lakes, which are rare and vulnerable ecosystems that house rare and endemic species (Tomascik et al., 1997; Becking et al., 2011; Hoeksema et al., 2014). Like many other coastal ecosystems around the world, the BCS is under pressure from human activities. Land-use changes in the catchment area of the Berau River have led to increased loads of sediment, nutrients and pollutants in the river discharge as a result of mining, logging, and agriculture development (Buschman et al., 2012). Based on a hydrodynamic modelling study, Tarya et al. (2015) demonstrated that the river plume moves northeast during southwesterly and southerly winds towards a complex of coral reefs with very high biodiversity. These conditions may affect water quality, indicating a number of potentially negative impacts on the BCS reef ecosystems. While de Voogd et al. (2009) reported that BCS reef corals are found across a water gradient ranging from turbid water to oceanic conditions, they did not observe a clear relationship between live coral cover and river discharge because there was interference from other factors, such as blast fishing. Seagrass cover and diversity, however were found to decrease from offshore locations

**Table 1**  
Fieldwork design and method for coral reef and seagrass monitoring.

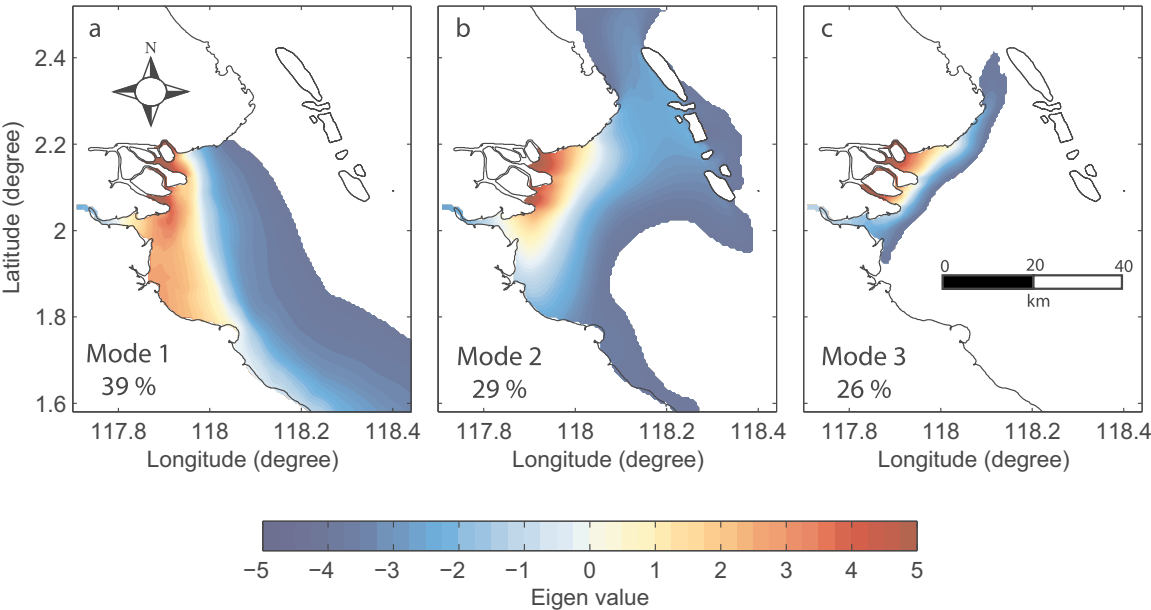
Time	Habitat	Station	Method
October 2003	Coral reef	25 (43 samples)	1 m <sup>2</sup> quadrats every 2 m along a linear transect of 20 m at three different depths (10, 6 and 2 m) Three parameters of coral reefs analysed: live coral cover, dead coral cover and the number of mushroom coral species
October 2003	Seagrass	15	Snorkelling over an area of 500 × 50 m <sup>2</sup> Nine seagrass properties are analysed: seagrass cover, number of seagrass species, seagrass biomass DW, benthic macrofauna FW, leaf tissue P, leaf tissue N, N:P ratio, C:N ratio and leaf tissue Fe



**Fig. 2.** Time-series of wind stick vectors (a) and river discharge (b) for the period from February 2006 up to and including January 2008.

**Table 2**  
Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and Correlation Coefficient (CC) scores for modelled east and north velocity, and salinity during spring tide and salinity during neap tide for simulations with constant discharge (Tarya et al., 2015) and variable discharge (present study) at the Fishing Platform station.

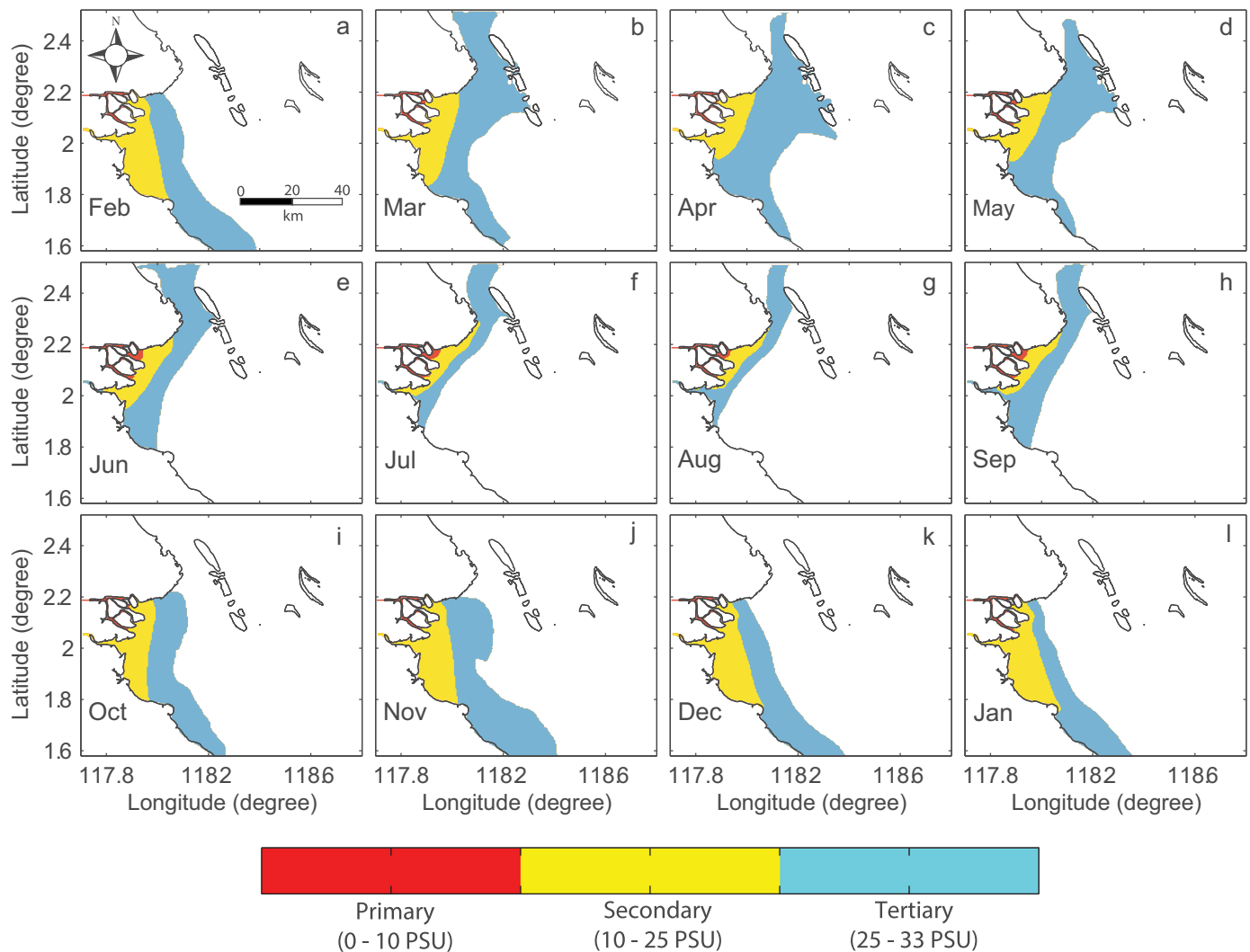
Parameter	Layer	MAE		RMAE		CC	
		Q <sub>constant</sub>	Q <sub>variable</sub>	Q <sub>constant</sub>	Q <sub>variable</sub>	Q <sub>constant</sub>	Q <sub>variable</sub>
East velocity	Surface	0.14	0.12	0.17	0.13	0.68	0.74
	Middle	0.11	0.09	0.14	0.12	0.67	0.69
	Bottom	0.08	0.08	0.10	0.10	0.74	0.75
North velocity	Surface	0.04	0.03	0.04	0.03	0.80	0.82
	Middle	0.02	0.02	0.03	0.02	0.85	0.85
	Bottom	0.01	0.01	0.02	0.02	0.89	0.89
Salinity at Spring	Surface	0.58	0.55	0.73	0.70	0.85	0.88
	Middle	0.27	0.26	0.35	0.34	0.37	0.43
	Bottom	0.12	0.12	0.15	0.15	0.30	0.39
Salinity at Neap	Surface	1.09	1.01	1.19	1.10	0.91	0.93
	Middle	0.18	0.14	0.24	0.21	0.86	0.88
	Bottom	0.06	0.06	0.07	0.06	0.97	0.99



**Fig. 3.** Three leading Empirical Orthogonal Functions (EOFs) of surface salinity: Mode 1, a; Mode 2, b; and Mode 3, c. The percentage of the variance explained by each mode is shown in each respective panel. Mode 1 corresponds to the northwest monsoon. Mode 2 corresponds to the Transition II monsoon. Mode 3 corresponds to the southeast monsoon.

towards the river mouth at the BCS (van Katwijk et al., 2011). Despite the position of the BCS at the global center of marine biodiversity (Hoeksema, 2007), there is still limited knowledge about the effects of exposure time to multiple salinity levels and subsequent impacts on the health of coastal ecosystems at the BCS. Specifically, little is known about the degree to which the BCS ecosystems are exposed to

low salinity waters, which may be affected by catchment runoff processes related to deforestation and the construction of oil palm plantations. The present study extends the three-dimensional hydrodynamic model described in Tarya et al. (2015) by adding a river discharge that varied throughout the year. The improved model results were linked to coral reef metrics and seagrass patterns. The objectives are (1) to assess



**Fig. 4.** Water type classification for the surface layer in the period covering February 2006 through January 2007. Water types were mapped following the study of [Devlin and Schaffelke \(2009\)](#). Water types are characterised by varying salinity levels: the primary water type is 0–10 PSU, the secondary water type is 10–25 PSU and the tertiary water type is 25–33 PSU. December to February corresponds to the northwest monsoon (a, k and l), March to June to the Transition I period (b, c, d and e), July to September to the southeast monsoon (f, g and h) and October to November to the Transition II period (i and j). PSU is practical salinity unit.

the risk of possible exposure of BCS coastal ecosystems to water from the river plume, measured as exposure time to three different salinity levels, (2) to identify the relationships between salinity levels and abundance and diversity of coral and seagrass ecosystems, and (3) to identify a suitable indicator for assessing salinity impacts on coral reef and seagrass health. This study is the first step towards constructing a river plume risk map for the area. The field site is further described in the next section. [Section 3](#) describes the materials and methods, and [Section 4](#) describes the model validation, river plume dynamics and the river plume properties versus ecological data. Interpretations of the results are discussed in [Section 5](#) and in [Section 6](#) conclusions are drawn.

## 2. Field site

The BCS features species-rich shallow coastal ecosystems, such as mangroves, seagrasses and coral reefs ([Hoeksema et al., 2004](#); [Renema, 2006a, 2006b](#); [de Voogd et al., 2009](#)). The area is part of the Coral Triangle in the central Indo-West Pacific ([Tomascik et al., 1997](#); [Hoeksema, 2007](#)) ([Fig. 1](#)). The shelf-based reefs and the seagrass meadows that occupy the reef flats are located up to 30 km from the river mouth on the edge of the continental shelf, facing the Berau Delta in the west. On its eastern boundary, the reef is flanked by a deep

trench, the Strait of Makassar, whereas reefs fringing the offshore islands Kakaban and Maratua are located up to 50 km away from the river mouth. The typical depth of the seafloor is between 20 and 50 m at the landward side of the barrier reef, while in the offshore direction, water depths increase rapidly to more than 3000 m in the Makassar Strait. The mainland adjacent to the BCS hosts one of the largest watersheds in Kalimantan, drained by the Berau River. The Berau River discharge varies between 200 and 2000 m<sup>3</sup> s<sup>−1</sup> with an average of 605 m<sup>3</sup> s<sup>−1</sup> ([Buschman et al., 2010, 2012](#)).

Water circulation on the BCS is primarily driven by tides, wind and density differences. The tidal regime is mixed and predominantly semidiurnal. The tidal range is about 1 m during neap tide and 2.5 m during spring tide ([Tarya et al., 2010](#)). The subtidal circulation is dominated by a southward flow close to the coast, while between the 10–20 m isobaths the mean velocities are directed northward ([Tarya et al., 2010](#)). Monsoons have a strong effect on river plume dynamics on the BCS ([Tarya et al., 2015](#)). During the southeast monsoon (July to September, dry season conditions), the river plume moves northeast and may expose the coral reef environment to river-derived waters ([Tarya et al., 2015](#)). The prevailing northerly winds during the northwest monsoon (December to February, wet season) act to drive river plumes to the south, affecting ecosystems in the southern BCS ([Tarya et al., 2015](#)). The seasons are separated by two transition periods,

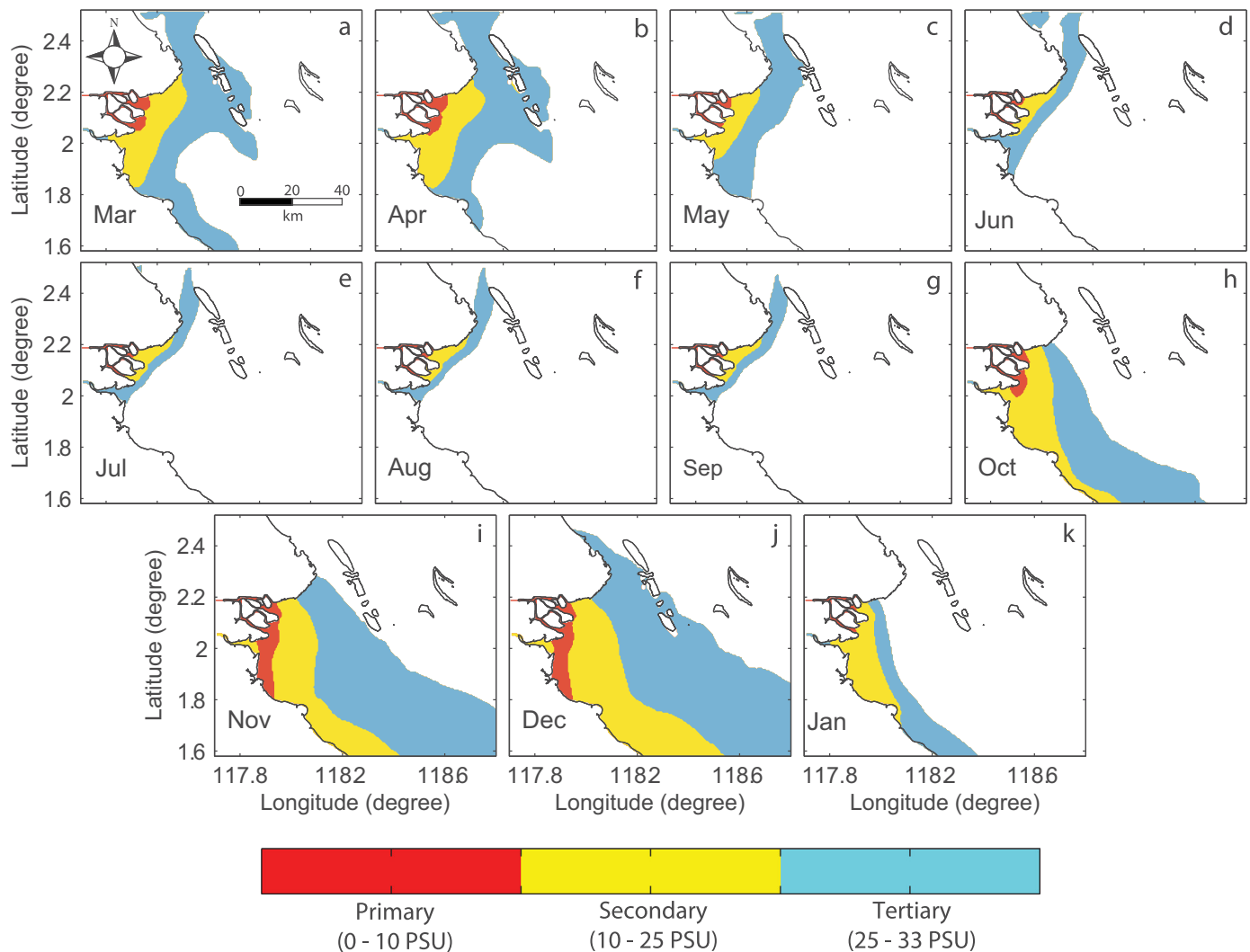


Fig. 5. Similar to Fig. 4 but for period covering March 2007 to January 2008.

Transition I (March to June) and Transition II (October to November). During the transitional periods, winds are weak and more variable (Tarya et al., 2015).

### 3. Materials and methods

#### 3.1. Field sampling and data acquisition

Coral reef data were obtained within the monitoring programme of the BCS in 2003 (Escalante, 2004; Hoeksema et al., 2004) (Table 1). The health status of the coral reefs was surveyed by taking digital pictures at a distance of 2 m from the bottom (Escalante, 2004). The surveys were conducted at 25 stations using 1 m<sup>2</sup> quadrats every 2 m along a linear transect of 20 m at three different depths (10, 6 and 2 m). Coral biodiversity was assessed by collecting distribution data on 40 mushroom corals species from 43 samples in October 2003 (Table S1 Hoeksema et al., 2004). Mushroom coral species (*Scleractinia: Fungiidae*) are suitable as a model group because they can be found along environmental gradients across shelves from nearshore to offshore reefs and from shallow reef flats to deep, sandy reef bases, as demonstrated in other areas in northern Borneo (Waheed and Hoeksema, 2012, 2014; Waheed et al., 2016) and in the Makassar Strait (Hoeksema, 2012a, 2012b).

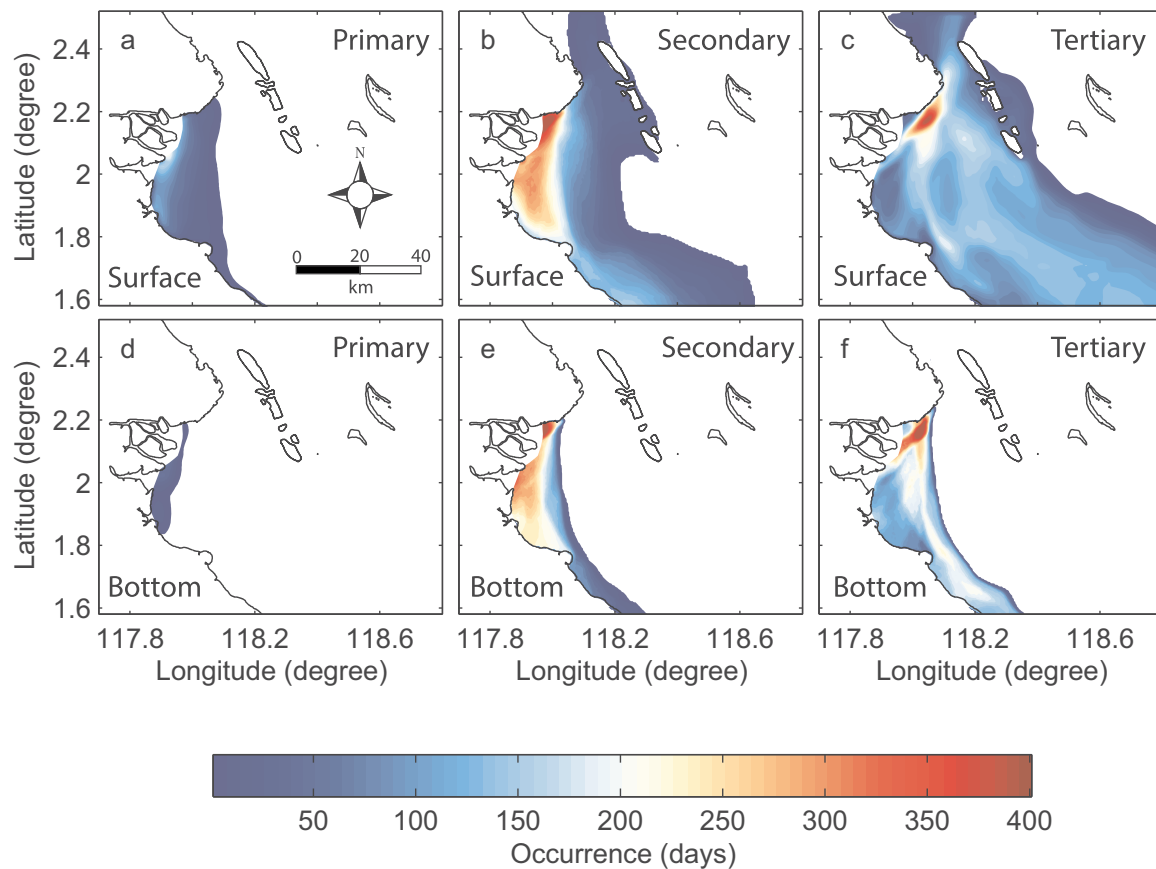
The field survey was conducted within the BCS seagrass monitoring programme during October 2003 at 15 seagrass sites, covering an area

of 200 km<sup>2</sup> (van Katwijk et al., 2011) (Table 1). Plant characteristics were described by van Katwijk et al. (2011) and they also sampled and analysed seagrass plants, macrofauna, sediments, sediment pore water and the overlying water. Seagrass cover and species composition were estimated by visual inspection while snorkelling over an area of 500 × 50 m<sup>2</sup>. Plants were collected at each site for free amino acid analysis and vitality measurements. Five vegetated and five un-vegetated plots were selected within each site for sampling pore water, sediment, macrofauna and plant properties. Seagrass plants and macrofauna were sampled to a sediment depth of 20 cm once per plot, using a core of 16.5 cm diameter. Plants were cleaned and dried before biomass measurements and tissue nutrient analysis. Nine seagrass properties were analysed, namely seagrass cover, number of species, seagrass biomass dry weight (DW), benthic macrofauna fresh weight (FW), leaf tissue phosphorus (P), leaf tissue nitrogen (N), leaf tissue N:P ratio, leaf tissue C:N ratio and leaf tissue iron (Fe). Details of the sampling design, data analysis and statistical data analysis are described in van Katwijk et al. (2011).

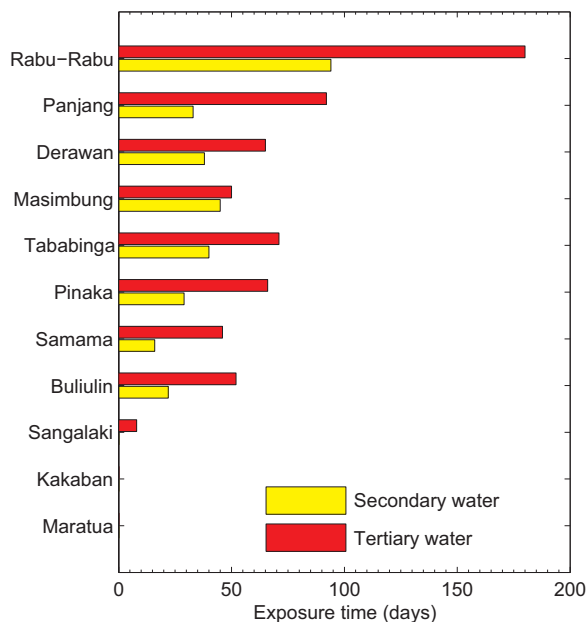
#### 3.2. Hydrodynamic model

We used the ECOMSED model (Estuarine and Coastal Ocean Model with SEDiment) (Blumberg and Mellor, 1987), which is a three-dimensional, primitive equation hydrodynamic model used in numerous previous studies on river plumes (e.g., Garvine, 1999; Fong and Geyer,





**Fig. 6.** Length of exposure time to a water type category (in days during the period February 2006 to January 2008) in the surface layer for primary (a), secondary (b) and tertiary (c) waters and in the bottom layer for primary (d), secondary (e) and tertiary (f) waters. Blue colours denote lower occurrence of plumes, while red colours denote higher occurrence of a specified water type in that area.

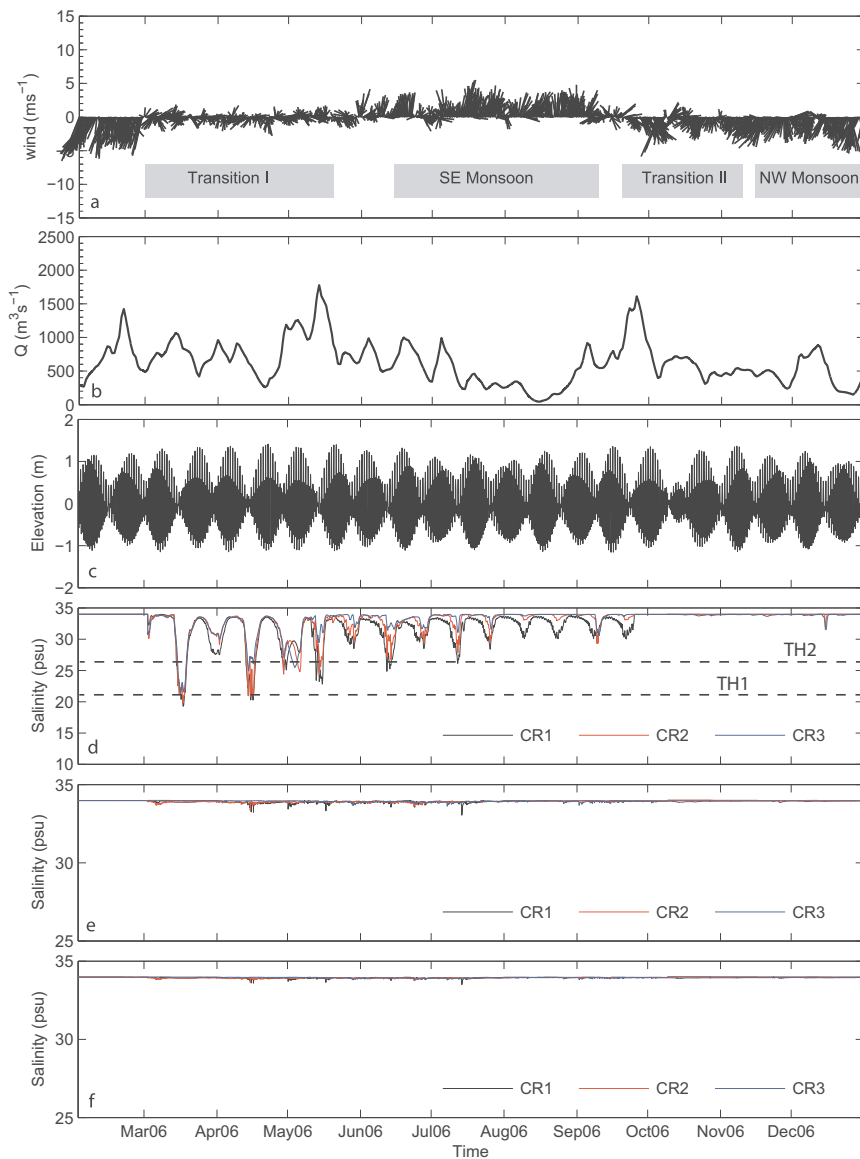


**Fig. 7.** Length of exposure time to river plume waters at the nearshore reef (Rabu-Rabu), the barrier reef (Panjang, Derawan, Tababinga, Masimbung, Pinaka, Buliulin and Sangalaki) and the oceanic reefs (Maratua and Kakaban).

2002; Whitney and Garvine, 2006; Tilburg et al., 2007). Further details on this model are presented in Blumberg and Mellor (1987). The rectangular model grid consists of  $253 \times 196$  cells covering the 136 km by 109 km domain. The horizontal grid size was 536 m along the x-axis

and 556 m along the y-axis. The vertical resolution was provided by 15 sigma levels, respectively at 2%, 4%, 6%, 8%, 10%, 15%, 25%, 40%, 50%, 60%, 70%, 80%, 90%, 95% and 100% of the water depth (Tarya et al., 2015). A barotropic time step of 2 s and baroclinic time step of 20 s were used to avoid numerical instabilities (Tarya et al., 2015). Bottom friction follows the quadratic drag law (Blumberg and Mellor, 1987). The bottom friction coefficient ( $C_D$ ) was set to 0.0035 (Tarya et al., 2010). Details of the model set-up, boundary condition, initial conditions and forcing mechanisms are discussed in Tarya et al. (2015).

In previous model simulations, Tarya et al. (2015) used a constant river discharge. To further improve the model, the present study uses the daily river discharge as observed by Buschman et al. (2010). The time-series of river discharge covered the period between February 2006 and January 2008. Variable winds over time were imposed in a spatially uniform manner over the model domain. Hourly observations were obtained from a meteorological station (see Fig. 1) for the period from March 2007 to February 2008, while wind data for the period from February 2006 to January 2007 were extracted from the NCEP reanalysis database, provided by the National Oceanic Atmospheric Administration (NOAA) ([www.esrl.noaa.gov/psd](http://www.esrl.noaa.gov/psd)). The time series for the wind vector field and the river discharge are shown in Fig. 2. In general, the wind speeds obtained from global wind data (February 2006 to January 2007) are lower than locally measured wind speeds (March 2007 to February 2008). To capture the seasonal variability of the river plume driven by the tides, winds and river discharge, the model was run from February 2006 to January 2008. These results were used for the comparative analysis.



**Fig. 8.** Time-series of wind vectors (a), river discharge (b), elevation (c), salinity in the surface layer (d), salinity in the middle layer (e) and salinity in the bottom layer for the period covering February 2006 to January 2007 in the northern barrier reef (CR1, Panjang), the middle barrier reef (CR2, Masimbung) and the southern barrier reef (CR3, Buliulin). TH1 indicates the salinity threshold identified by [Berkelmans et al. \(2012\)](#) and TH2 indicates the salinity threshold identified by [Edmondson \(1928\)](#).

### 3.3. Water type classification

Water types in the BCS domain were classified following [Devlin and Schaffelke \(2009\)](#), who proposed a subdivision of three water types to describe 11 events (1994–2008) in response to the Tully River floods affecting the Great Barrier Reef. They argued for the existence of distinct water types inside a river plume region, characterised by specific salinity and water quality concentrations (Total Suspended Solids (TSS), Coloured Dissolved Organic Matter (CDOM) and chlorophyll). The primary water type is characterised by low salinity, ranging from 0 to 10 PSU, which corresponds to a highly turbid river plume region with high concentrations of TSS and CDOM. The secondary water type features intermediate salinity, ranging between 10 and 25 PSU, and lower TSS and CDOM concentrations. The tertiary water type is characterised by salinity levels greater than 25 PSU. This water type exhibits reduced TSS and CDOM compared with the other two water types.

According to experimental results and field studies, changes in salinity are likely to be lethal to corals after moderate exposure (periods of days to weeks) to levels less than 25 PSU, with upper salinity tolerances being around 40–41 PSU ([Coles and Jokiel, 1992](#)). However, the exact responses depend on the coral species, the magnitude of salinity change compared with background levels and the exposure

time ([Berkelmans et al., 2012](#)). For *Acropora species*, field observations revealed a salinity tolerance ranging from 22 to 28 PSU and an exposure time of 3–16 days at the lowest and highest salinities, respectively ([Berkelmans et al., 2012](#)). For three tropical seagrass species, a decrease in growth rate was observed below 10–15 PSU and above 30–40 PSU ([Berkelmans et al., 2012](#)). Thresholds for both corals and seagrasses correspond to the secondary water type. Moreover, experiments by [Edmondson \(1928\)](#) revealed that for sensitive coral species, the lower limit is between 26 and 30 PSU for exposure periods of 1 or more days. For example, *Pocillopora species*, *Porites species* and *Montipora patula* all died within 2 days of exposure to 26 PSU. The salinity threshold of [Edmondson \(1928\)](#) falls within the range of the tertiary classification.

A variety of regression techniques was tested to determine whether ecological variables are correlated to salinity levels. The regression equations tested include (1) linear, (2) power, (3) exponential and (4) logarithmic functions. The lines of best fit represent the regression equation between biological data and salinity with the highest  $R^2$  value (using Pearson's correlation coefficients) and statistical significance set at  $p < 0.05$ .

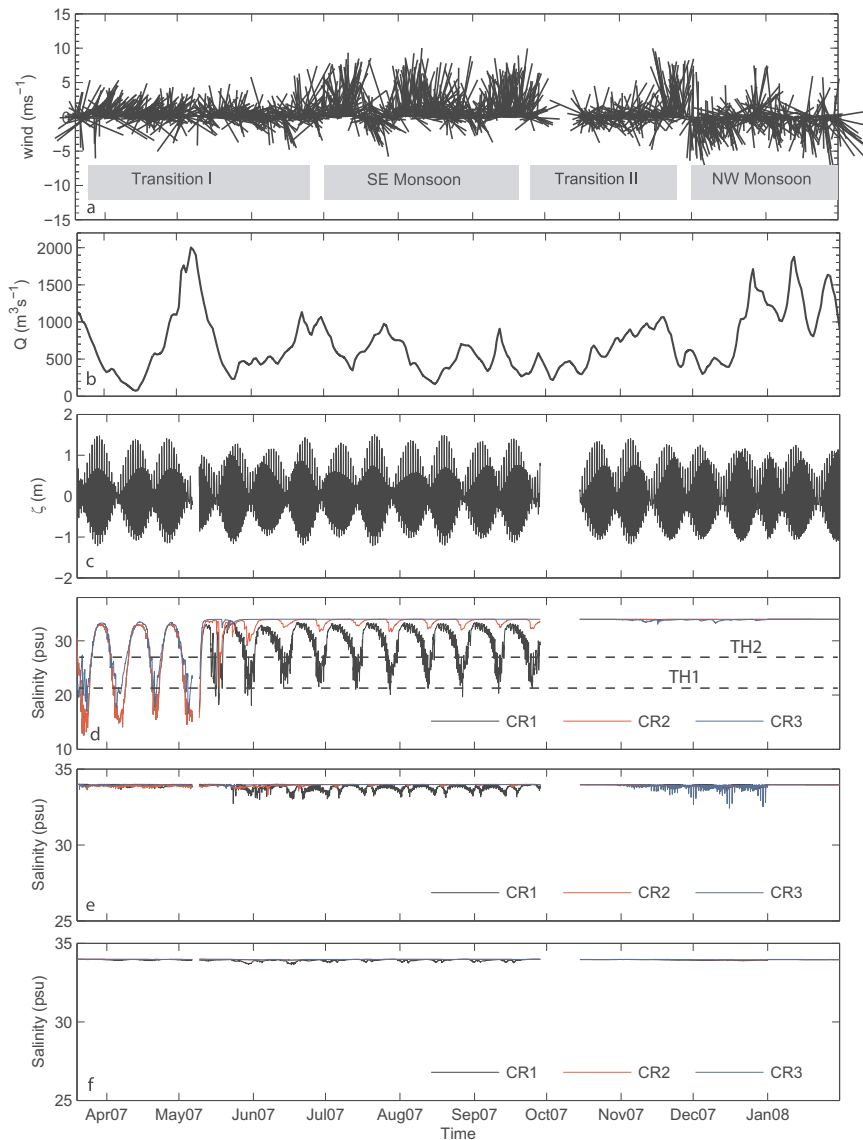


Fig. 9. Similar to Fig. 4 but for the period covering March 2007 to January 2008.

## 4. Results

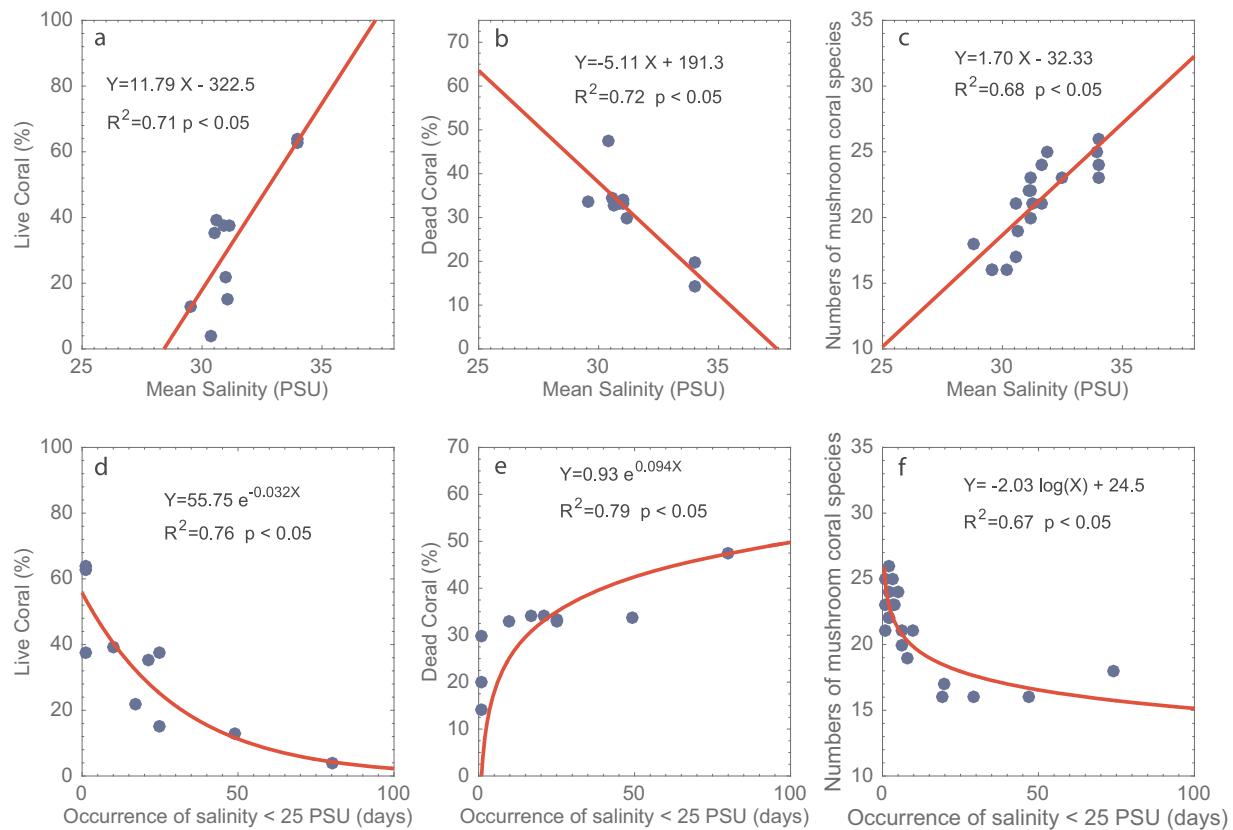
### 4.1. Model skill

Results presented by Tarya et al. (2015) showed a high degree of agreement between model results and observations, based on time-series of velocity and vertical profile of salinity at the Fishing Platform station (see Fig. 1). Discrepancies in simulated east and north velocity were about  $0.14$  and  $0.05 \text{ m s}^{-1}$ , respectively (Fig. S1b). For salinity, the calculated error was  $0.6$  and  $1 \text{ PSU}$  at spring and neap tides, respectively. Compared with the model using constant river discharge (Tarya et al., 2015), the result of the present model with variable river discharge exhibited an even better fit to the observations (Fig. S1c). This is reflected in the statistical evaluation of the performance for the constant vs. variable river discharge models, as presented in Table 2. For the velocity components, the Mean Absolute Error (MAE) was reduced by  $10\%$  and the Root Mean Square Error (RMSE) by  $16\%$  when river discharge was variable. For salinity, the MAE and RMSE decreased by  $7\%$  and  $8\%$ , respectively. Furthermore, the coefficient of determination increased by  $5\%$ .

### 4.2. Spatiotemporal dynamic of plumes

The spatiotemporal dynamics of surface salinity at the BCS simulated with variable discharge are very similar to the constant discharge results of Tarya et al. (2015). The surface salinity patterns illustrate the marked seasonal variation following monsoon dynamics. To identify the dominant modes of salinity variability in the period from February 2006 to January 2008, an Empirical Orthogonal Function (EOF) analysis was applied following Von Storch and Zwiers (2001). EOF analysis is a common multivariate analysis technique used to derive the dominant patterns in the spatiotemporal dynamics of a scalar field, and is a widely used method in studies on sea surface salinity field and suspended sediment concentration (e.g. Lihan et al., 2008; Marques et al., 2009; Falcieri et al., 2014). The three leading EOF modes of the river plume are shown in Fig. 3. Mode 1 explained  $39\%$  of the variance, representing the spreading of the coastal plume along the southern coast as it covers a large extent of the shoreline. This mode captured the river plume patterns during the northwest monsoon during wet season. Mode 2 explained about  $29\%$  of the spatiotemporal variability, reflecting the dominantly northeastward migration of the plume during southwesterly winds. The third mode explained  $26\%$  of the variation, representing a plume that is pushed to the coastline and transported northward. Mode 3 corresponded to river plume patterns during





**Fig. 10.** The relationship between the modelled river plume parameters (mean salinity and exposure period to salinity below 25 PSU) and coral reef data of Escalante (2004) and Hoeksema et al. (2004). Red solid lines represent regressions.

southerly winds (southeast monsoon during the dry season).

#### 4.3. Water type classes

Exposure to the different water types varied between inshore and offshore areas (Figs. 4 and 5). The primary water type 0–10 PSU) remained predominantly concentrated near the river mouth throughout the simulation periods, but it occasionally spread south, extending over a distance of 40 km in November and December of 2007. The secondary water type 10–25 PSU) showed seasonal variation, owing to the prevailing monsoon climate. From March to June, the offshore extent of secondary water incursion decreased from about 20 to 2 km. During the southeast monsoon, secondary waters remained concentrated near the estuary, due to southerly winds, in a small band along the shoreline. During the Transition II period, secondary waters developed to the south in October, as a result of the shifted wind direction to the north. From November to December, spreading of secondary waters extended further offshore and southward. The entire barrier reef was exposed to the tertiary water type (> 25 PSU) brought by the plume during Transition I. During the southeast monsoon, the northern barrier reef tended to be exposed to tertiary waters. Northerly winds during the northwest monsoon drove tertiary waters to the south. Hence, the reefs were mostly safeguarded from river plume exposure during this period.

#### 4.4. Exposure periods

The exposure periods to primary, secondary and tertiary water types on the BCS are presented in Fig. 6, with the surface and bottom layers shown in separate panels. The estuary of the north channel was the region most exposed to the secondary and tertiary water types, with exposure times exceeding 200 and 150 days, respectively. Likewise, the coastal area of Tanjung Batu was found to be an area with a long period

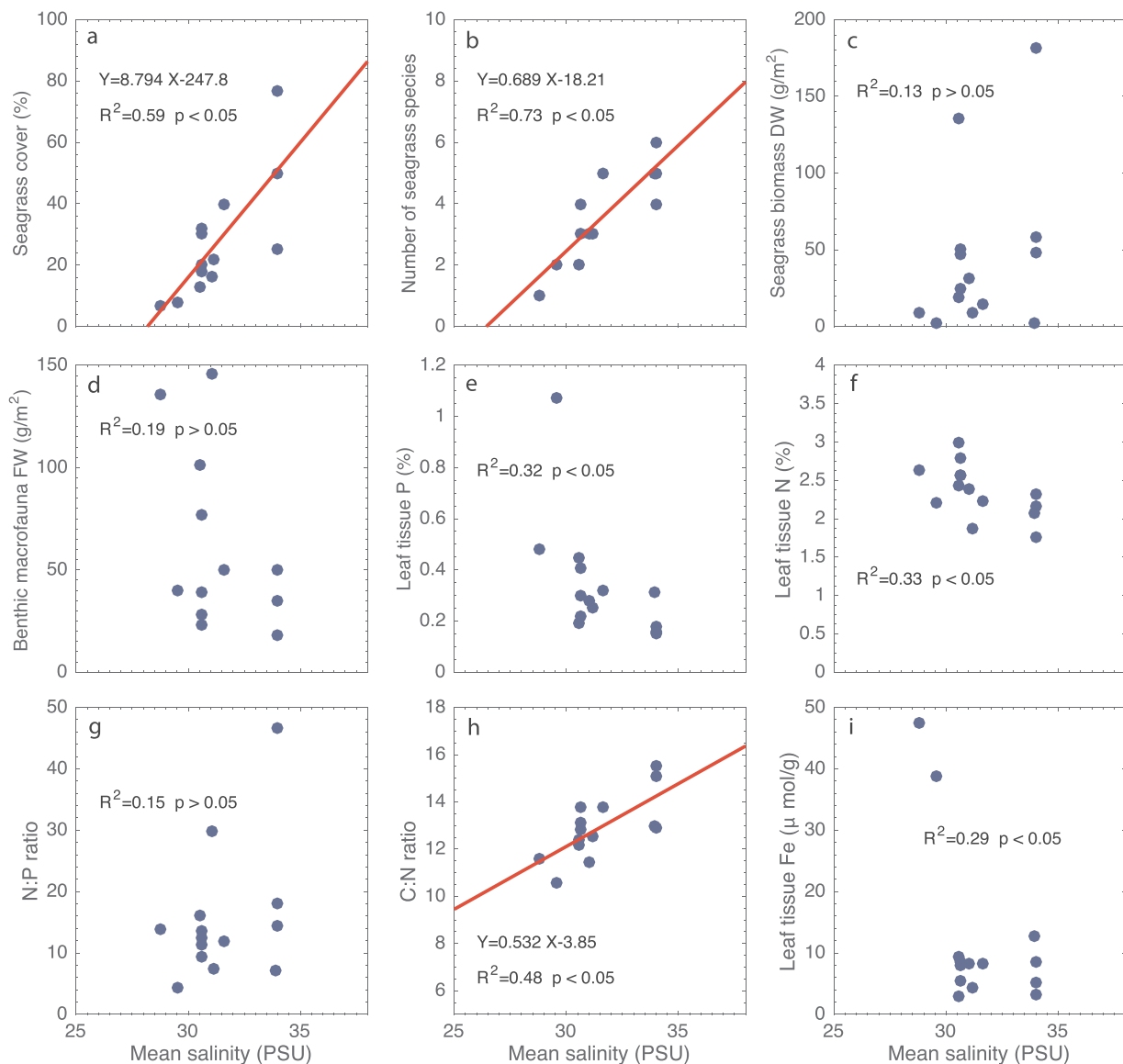
of exposure to tertiary waters, exceeding 100 days. The region in front of the south channel, near the shoreline, experienced an exposure period to secondary and tertiary waters of 125 and 50 days, respectively.

Regarding the coral reef region (Fig. 7), Panjang and Derawan in the northern barrier reef were exposed to the tertiary water type, with exposure times over 92 and 65 days, respectively. These reefs were also exposed to secondary waters, with exposure times of 33 and 38 days, respectively. The exposure periods to the tertiary water type at Masimbung, Tababinga and Pinaka in the middle barrier reef area were 50, 71 and 66 days, respectively, and exposure periods to the secondary water type for these areas were 45, 40 and 29 days, respectively. For the southernmost barrier reefs referred to as Samama, Buliulin and Sangalaki, exposure periods to the tertiary water type were 46, 52 and 8 days, respectively. Moving further offshore to the oceanic reefs, Maratua and Kakaban were not exposed to the secondary or tertiary water types.

The temporal dynamics of salinity in the reef area are visualized in Figs. 8 and 9, focussing on three locations along the barrier reef. Fig. 8 shows that the plume water can remain restricted to the surface layer throughout the year (February 2006 to January 2007). This holds even for the northern reef location (CR1, Panjang). Fig. 9 shows that even in a year with relatively strong winds (March 2007 to January 2008), salinity near the bottom showed only a very minor response to wind and tidal forcing.

#### 4.5. Salinity level model versus ecological data

First, we compared our plume model results with observed coral reef data collected in 2003 by Escalante (2004) and Hoeksema et al. (2004), as presented in Fig. 10 and summarised in Table 6. The observed coral reef datasets include three parameters: percentage live



**Fig. 11.** The relationship between modelled mean salinity and the seagrass data series described in van Katwijk et al. (2011). The red solid lines represent regressions. The correlations between mean salinity and seagrass biomass DW, benthic macrofauna FW and N:P ratio are insignificant ( $p > 0.05$ ). DW is dry weight, FW is fresh weight, P is phosphorus and N is nitrogen.

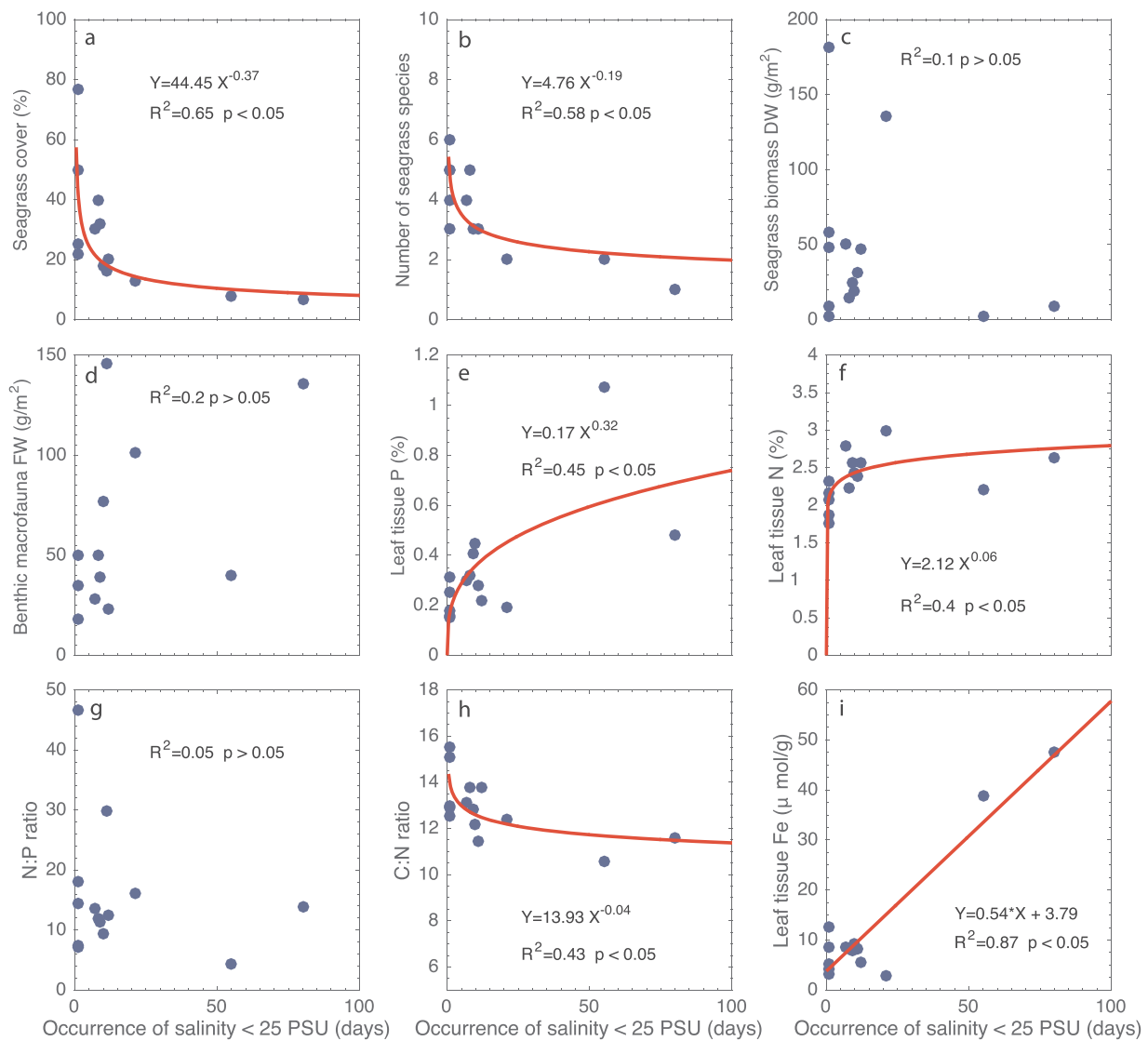
coral cover, percentage dead coral cover and the number of mushroom coral species. The salinity model results aligned well with observed coral reef data, as indicated by significant correlations for mean salinity with the percentage live coral ( $R^2 = 0.71$ ,  $p < 0.05$ ), mean salinity with percentage dead coral cover ( $R^2 = 0.72$ ,  $p < 0.05$ ) and mean salinity with the numbers of mushroom coral species ( $R^2 = 0.68$ ,  $p < 0.05$ ), as shown in Fig. 10a, b and c. The frequency of salinity values below 25 PSU was also well-correlated with the percentage of live coral cover ( $R^2 = 0.76$ ,  $p < 0.05$ ), dead coral ( $R^2 = 0.79$ ,  $p < 0.05$ ) and numbers of mushroom coral species ( $R^2 = 0.67$ ,  $p < 0.05$ ) (Fig. 10d–f).

Second, the model results were compared with observed seagrass data collected in 2003 (van Katwijk et al., 2011), as presented in Figs. 11, 12 and in Table 6. In general, the correlations between exposure to low salinity and the biological indicators were more often significant than correlations between mean salinity and the biological indicators. The exposure period to salinity below 25 PSU showed significant correlations with seagrass cover and the number of seagrass species ( $R^2 = 0.65$ ;  $p < 0.05$  and  $R^2 = 0.58$ ;  $p < 0.05$ , respectively) (Figs. 12a and b), as well as with leaf tissue Fe ( $R^2 = 0.87$ ,  $p < 0.05$ ) (Fig. 12i). Moderate correlations were obtained between the exposure period to salinity below

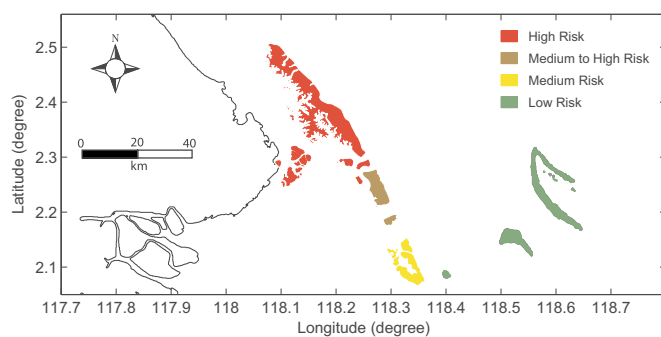
25 PSU and leaf tissue P ( $R^2 = 0.45$ ,  $p < 0.05$ ), leaf tissue N ( $R^2 = 0.40$ ,  $p < 0.05$ ) and leaf tissue C:N ratio ( $R^2 = 0.43$ ,  $p < 0.05$ ). Low values of the salinity index were not significantly correlated with seagrass biomass DW, benthic macrofauna FW and leaf tissue N:P ratio. The strongest relationships with mean salinity were found for seagrass cover ( $R^2 = 0.59$ ,  $p < 0.05$ ) and the number of seagrass species ( $R^2 = 0.73$ ,  $p < 0.05$ ) (Fig. 11a and b). Weak to moderate relationships were found between mean salinity and leaf tissue P ( $R^2 = 0.32$ ,  $p < 0.05$ ), leaf tissue N ( $R^2 = 0.33$ ,  $p < 0.05$ ), leaf tissue C:N ratio ( $R^2 = 0.48$ ,  $p < 0.05$ ) and leaf tissue Fe ( $R^2 = 0.29$ ,  $p < 0.05$ ). The correlations between mean salinity with other biotic parameters (i.e., seagrass biomass DW, benthic macrofauna FW, and leaf tissue N:P ratio) were not significant.

## 5. Discussion

In equatorial regions, river plumes are not deflected by coastal currents, as found at higher latitudes, due to weak Coriolis forcing (Chao and Boicourt, 1986; Garvine, 1995). Thus, tropical river plumes develop in the offshore direction (Garvine, 1995, 1999) and often form



**Fig. 12.** The relationship between modelled length of exposure time to salinity below 25 PSU and the seagrass data series described in [van Katwijk et al. \(2011\)](#). The red solid lines represent regressions. The correlations between exposure time to salinity below 25 PSU and seagrass biomass DW, benthic macrofauna FW and N:P ratio are insignificant ( $p > 0.05$ ). DW is dry weight, FW is fresh weight, P is phosphorus and N is nitrogen.



**Fig. 13.** Spatial distribution of risk classification in the BCS ecosystem.

surface-connected plumes ([Yankovsky and Chapman, 1997](#)). Surface-connected river plumes have a strong response to changes in the speed and direction of the wind ([Xia et al., 2010](#); [Tarya et al., 2015](#)). Here, we investigated the river plume on the Berau Continental Shelf and show that EOF modes are suitable for summarising the river plume patterns imposed by monsoons, showing clear patterns corresponding to conditions during wet and dry season.

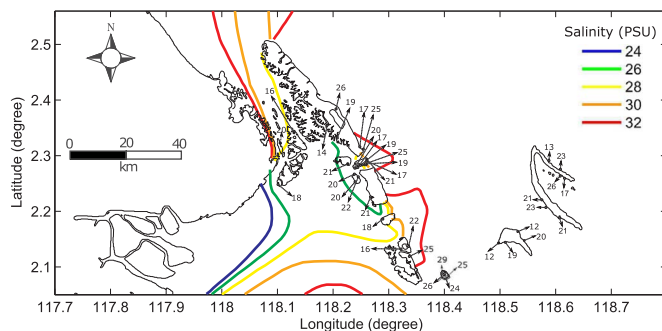
By analysing the effects of three different water types of variable salinity, i.e. primary, secondary, and tertiary waters, we were able to calculate the river plume exposure risk for ecosystems on the BCS ([Fig. 13](#)). [Bryant et al. \(1998\)](#) have argued for risk levels being grouped into three classes: low risk, medium risk, and high risk. We classified the risk level for coral reef and seagrass systems accordingly, based on the length of exposure periods to the three water types ([Table 3](#)). The nearshore reef Rabu-Rabu and the northern barrier reefs Panjang, Derawan and Tababinga were classified as “high risk”, the middle barrier reefs Masimbung and Pinaka as “medium to high risk” and the southern barrier reefs Buliulin and Samama as medium risk. Further offshore, the oceanic reefs Sangalaki, Kakaban and Maratua were classified as “low risk” ([Table 4](#)). When comparing the risk classification to coral biodiversity at the BCS ([Hoeksema et al., 2004](#)), the assessed risk levels of the coral reefs are consistent with the decreasing numbers of coral species towards the oceanic reefs ([Fig. 14](#)). Additionally, the highest numbers of species per site coincide with the lowest risk levels, i.e. typical salinities over 32 PSU ([Table 5](#)). The nearshore reefs are subject to the highest risk ([Table 4](#)). The barrier reef is subject to decreasing risk towards the south. The low risk level for offshore sites are in line with the findings by [van Katwijk et al. \(2011\)](#), which showed that

**Table 3**  
River plume risk classification based on exposure time (days) to salinity stress.

Variable	Risk type	Secondary water type	Tertiary water type
Coral reef	Low risk	0–15	0–30
	Medium risk	15–30	30–60
	High risk	>30	>60
Seagrass	Low risk	0–25	0–50
	Medium risk	25–50	50–100
	High risk	>50	>100

**Table 4**  
Risk assessment of Berau coral reefs based on exposure time to salinity stress.

Coral reef island	Coral	Seagrass
Rabu-Rabu	High risk	High risk
Panjang	High risk	Medium risk
Derawan	High risk	Medium risk
Tababinga	High risk	Medium risk
Masimbung	Medium to high risk	Medium risk
Pinaka	Medium to high risk	Medium risk
Samama	Medium risk	Low risk
Buliulin	Medium risk	Low risk
Sangalaki	Low risk	Low risk
Kakaban	Low risk	Low risk
Maratua	Low risk	Low risk



**Fig. 14.** Spatial distribution of the numbers of mushroom species (indicated by numbers) overlaid by modelled surface salinity in April 2007 (after Hoeksema et al., 2004).

**Table 5**  
Distribution of 43 sites of mushroom coral species in the Berau region over salinity classes based on model results.

Salinity (PSU)	Number of species per site (range 12–29)			Total
	<20	20–24	>24	
24–26	1	5	0	6
26–28	6	2	0	8
28–30	0	2	1	3
30–32	4	4	2	10
>32	5	6	5	16

seagrass abundance and the number of seagrass species increased 5 and 3-fold, respectively, along a transect stretching from the coastal zone to offshore.

For the coral reef data, the relationships between river plume parameters and biological data demonstrate that the correlation scores of salinity frequency below 25 PSU were about 5% higher than the scores based on mean salinity. Likewise, salinity below 25 PSU was more strongly related to seagrass properties than mean salinity. Six out of nine parameters used to represent the seagrass data had a significant correlation with exposure period to salinity below 25 PSU, whereas only three out of nine seagrass parameters were significantly correlated with mean salinity. Exposure time to salinity below 25 PSU is therefore more suitable as an indicator for salinity impacts on coral reef and

seagrass health.

The length of exposure time to low salinity has previously been established as an important factor controlling coral reef health (Muthiga and Szmant, 1987; Kerswell and Jones, 2003). Short-term (i.e. hour scale) salinity stress can induce a decreased rate of photosynthesis in corals (Muthiga and Szmant, 1987; Kerswell and Jones, 2003). If the exposure is prolonged (days or more) it can affect growth and reproduction, and may eventually lead to mortality (Coles and Jokiel, 1992). Longer periods of low salinity stress also lead to a decrease in the respiration rate of corals (Moberg et al., 1997; Ferrier-Pages et al., 1999). For example, a 3-week experimental study by Ferrier-Pages et al. (1999) demonstrated reduced respiration rates even after minor changes in salinity. Based on experimental results and field studies, changes in salinity are likely to be lethal to corals after moderate exposure (periods of days to weeks) to less than 25 PSU, with upper salinity tolerances around 40–41 PSU (Coles and Jokiel, 1992).

The exact responses of coral to salinity stress will depend on the species, the magnitude of change in salinity compared with background levels, and also on exposure time (Berkelmans et al., 2012). Field observations on *Acropora* corals revealed that salinity tolerance ranges between 22 and 28 PSU for exposure times of 3 and 16 days at the lowest and highest salinities, respectively (Berkelmans et al., 2012). Experimental results by Edmondson (1928) have demonstrated that for sensitive coral species, the lower limit is between 26 and 30 PSU for exposure periods of one or more days. For example, corals of *Montipora*, *Pocillopora* and *Porites* all died within 2 days at 26 PSU. Corals in the near-surface layer of the Berau barrier reef are exposed to low salinities ranging between 15 and 25 PSU for a period of seven days (during neap tide), from March to May (Figs. 8 and 9). These values are below the salinity thresholds found by Edmondson (1928) and Berkelmans et al. (2012), and within the range of salinity thresholds observed by Coles and Jokiel (1992) and Van Woessik et al. (1995). The exposure occurs at intervals that are harmful according to Berkelmans et al. (2012). Hence, the salinity stress in the Berau barrier reef area can have serious impacts on the occurrence of several coral species.

In our study area, the dominant seagrass species that were found at sites close to the Berau River mouth belong to the genera *Halodule* spp. and *Halophila* spp. (van Katwijk et al., 2011). The seagrass species of these two genera can grow in areas that are frequently exposed to river plumes, as shown for the Great Barrier Reef, Australia (Long et al., 1993). *Halophila ovilis* can survive in salinity levels between 10 and 40 PSU, and can survive two weeks of exposure to salinity <10 PSU (Hillman et al., 1995; Benjamin et al., 1999). The salinity range for *Halodule uninervis* has been recorded to be as low as 3.5, and as high as 62 PSU (Masini et al., 2001). Recently, Collier et al. (2014) reported that severe mortality can occur for *H. uninervis* and *H. ovalis* at salinity less than 9 PSU, after a 10-week exposure period. When considering these salinity threshold studies, the BCS plume salinity, which ranges between 15 and 25 PSU, falls between the upper and lower thresholds established in the literature. Thus, based on the salinity exposure, *H. uninervis* and *H. ovalis* seagrasses in the BCS are predicted to survive and experience less impact from variations in salinity. However, seagrasses may be under pressure from multiple stressors, including river-derived pollutants, nutrients and sediments. This is likely since seagrass cover has been shown to decrease over a gradient from oceanic reefs toward the Berau River mouth (van Katwijk et al., 2011). Under increased exposure of seagrasses to salinity below 25 PSU, we found increased leaf tissue phosphorus, nitrogen and iron, and lower C:N ratios. This supports the use of these seagrass parameters as bioindicators for the impact of river discharge on other seagrass ecosystems.

The environmental stress induced by longer exposure to the river plume seems to be higher for corals than for seagrasses. This is evident from both the correlation coefficients and the slopes of the regression lines for mean salinity with coral cover (11.79 in Fig. 10a) and seagrass cover (8.79 in Fig. 11a). Corals may thus be more sensitive to river plume exposure than seagrasses. This confirms previous circumstantial

**Table 6**

Results of statistical analysis comparing salinity model results and observed ecological data. Bold font highlights the significant correlations.

Habitat	Parameter	Salinity	Statistical value	
			R <sup>2</sup>	p
Coral reef	Live coral	Mean salinity	0.71	<b>&lt;0.05</b>
	Dead coral		0.72	<b>&lt;0.05</b>
	Mushroom coral species		0.68	<b>&lt;0.05</b>
Coral reef	Live coral	Occurrence of salinity <25 PSU	0.76	<b>&lt;0.05</b>
	Dead coral		0.79	<b>&lt;0.05</b>
	Mushroom coral species		0.67	<b>&lt;0.05</b>
Seagrass	Seagrass cover	Mean salinity	0.59	<b>&lt;0.05</b>
	Number of species		0.73	<b>&lt;0.05</b>
	Seagrass biomass DW		0.13	>0.05
	Benthic macrofauna FW		0.19	>0.05
	leaf tissue P		0.32	<b>&lt;0.05</b>
	leaf tissue N		0.33	<b>&lt;0.05</b>
	N:P ratio		0.15	>0.05
	C:N ratio		0.48	<b>&lt;0.05</b>
	leaf tissue Fe		0.29	<b>&lt;0.05</b>
	Seagrass cover		0.65	<b>&lt;0.05</b>
	Number of seagrass species		0.58	<b>&lt;0.05</b>
	Seagrass biomass DW		0.10	>0.05
	Benthic macrofauna FW		0.20	>0.05
	leaf tissue P	Occurrence of salinity <25 PSU	0.45	<b>&lt;0.05</b>
	leaf tissue N		0.40	<b>&lt;0.05</b>
	N:P ratio		0.05	>0.05
	C:N ratio		0.43	<b>&lt;0.05</b>
	leaf tissue Fe		0.87	<b>&lt;0.05</b>

evidence that seagrasses have a relatively higher degree of tolerance to small changes in salinity (Hillman et al., 1995; Collier et al., 2014). Moreover, it confirms a global review indicating that seagrasses are less sensitive than coral reefs to high nutrient loads (Gillis et al., 2014). However, this global review was substantiated comparing seagrass and coral tolerances at separate locations, whereas our study is, to our knowledge, the first to compare these ecosystems within an area potentially subject to the same river plume system.

The river plume model developed for the BCS proved to be a suitable tool to investigate the ecological risk to coral and seagrass ecosystems and this was also supported by a similar study in the Great Barrier Reef (Petus et al., 2016). “Exposure to the river plume” should therefore be interpreted in an indirect manner. An increased resolution of the model in the reef environment would be needed to investigate whether three-dimensional flow structures in the reef gaps may transport plume water downward. In other words, our model resolution is too low to firmly conclude that only near-surface reefs and seagrasses are exposed. Further work is required to improve our understanding on how sediments are transported by river plumes, as these sediments may settle prior to reaching the reefs, and residence times in relation to decay processes. Measurements of water quality parameters are needed to further investigate the environmental stressors posing risks to the survival of coral and the flourishing of seagrasses in the BCS region. Finally, we plan to apply our model to longer time scales and at higher spatial resolutions to provide more complete information for policy makers and stakeholders concerned with risks imposed by river plumes on coastal ecosystems.

## 6. Conclusion

River plume dynamics of the BCS are strongly controlled by variations in monsoon activity. Variation in river discharge over the year had

limited impact on the plume extension. Coastal ecosystem communities at the BCS are exposed to seasonal episodes of low salinity. Mean salinity and the time of exposure to salinity below 25 PSU are strongly linked to ecosystem health, quantified by coral cover, coral species richness, seagrass abundance and the number of seagrass species. Under increased exposure of seagrasses to salinity below 25 PSU, we found increased leaf tissue phosphorus, nitrogen and iron, and lower C:N ratio. This supports using these seagrass parameters as bioindicators for assessing the impact of river discharge on other seagrass ecosystems. Considering the coral risk level with respect to the river plume exposure time, the nearshore area and the northern barrier reefs were classified as “high risk”, the central and southern barrier reefs as “medium to high risk” and “low to medium risk”, respectively. The oceanic reefs were classified as “low risk”. Overall, seagrass meadows appear to be less affected by river plume exposure. The nearshore seagrass meadows were categorised as “high risk”. The barrier reef region was categorised as “medium to low risk” and the oceanic reefs as “low risk”. The lowest salinity values in the barrier reef region occur in the dry season during neap tide, when salinity ranges from 15 to 25 PSU. Considering the tolerances established in previous experiments and field studies, this salinity variation could have a serious impacts on several coral reef species. This study also demonstrates that when environmental in-situ data is limited, buoyancy spreading based on model results can be used to estimate ecological change.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.csr.2017.12.003>.

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