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Modelling Salinity Propagation in Cikarang Bekasi Laut Channel, Bekasi Regency, West Java Province, Indonesia

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Highlights:

- Salinity intrusion will be slightly higher after dredging.
- Constructing a check dam can mitigate salinity intrusion.
- Routine maintenance dredging should be carried out.

Abstract. An inland waterway is to be constructed in an existing channel in West Java, Indonesia. The change of salinity in a river due to capital dredging was investigated using a finite element modelling system. The location of the research was the Cikarang Bekasi Laut (CBL) channel, Bekasi Regency, West Java, Indonesia. This study aimed to simulate salinity propagation in the CBL channel before and after capital dredging. Salinity modelling was carried out using Surface-water Modelling System (SMS) software. Field surveys of the topography, bathymetry, current velocity, and water level were conducted to develop the model. The model's results were validated with the current velocity and water level measured in the field. The field and model results agreed well with each other. The current and salinity results showed that the trends were correlated with river discharges. After capital dredging, the salinity in the CBL channel increased. Mitigation was carried out by constructing a check dam, which could reduce the average salinity in the upstream region by up to 0.05 ppt during the wet season and up to 0.12 ppt during the dry season.

Keywords: *check dam; dredging; inland waterway; numerical modelling; salinity.*

1 Introduction

The construction of an inland waterway in the Cikarang Bekasi Laut (CBL) channel (located in Bekasi Regency, West Java, Indonesia), as an alternative type of transportation for Jakarta and West Java, is a National Strategic Project [1], see Figure 1. The total length of the dredged channel is 19 km and it is situated along the black line shown in Figure 1. The remaining reach of the channel to the upstream remains natural. The dredged channel will allow a 5000-DWT container

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barge to be able to navigate to the dry port area at the location marked with a red pin in Figure 1.

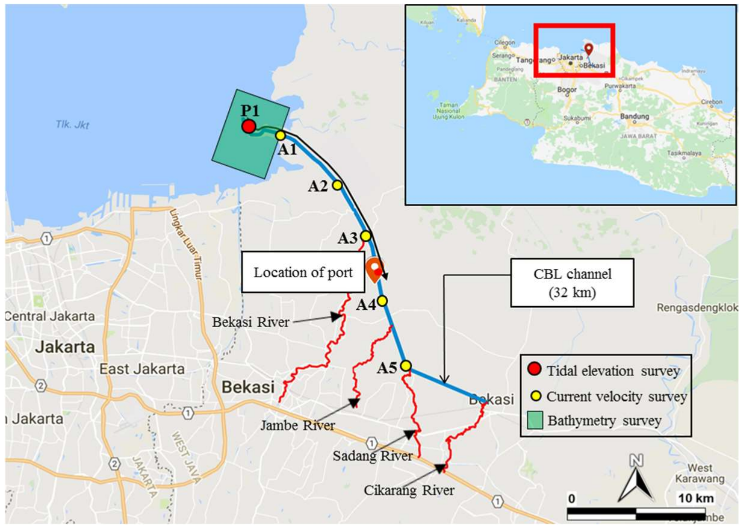


Figure 1 Overview of the CBL channel.

Hydrodynamic modelling is an approach for spatially and temporally studying natural phenomena in water bodies and is relatively cheaper than physical modelling and field investigation. This approach has been utilised in many cases in rivers, lakes, coastal environments, oceans, and, even, on a global scale. Modelling tools can be applied to one, two or three-dimensional models. For one-dimensional models, HEC-RAS [2] and MIKE11 [3] are among the most widely known tools, especially for modelling river environments. Apart from using a hydrodynamic module [4,5], the researchers also utilised a salinity module [6,7].

When a case study involves a river and a coastal environment, using a two-dimensional model has certain advantages. The complex geometry of a river outlet and the high spatial variation of hydrodynamic parameters are a problem for one-dimensional models. Three-dimensional models, meanwhile, offer an extensive representation of a vertically stratified phenomenon. However, they require considerable computational effort.

Delft3D [8], MIKE21 [9], and SMS (Surface-water Modelling Systems) [10] are among the most popular two and three-dimensional modelling tools. The hydrodynamic modules of these tools have been extensively exploited to understand the flow patterns of water bodies [11,12], study flood risk [13], and assess the potential of ocean renewable energy [14,15].

The present research focused on utilising numerical modelling to understand the hydrodynamics and salinity propagation in a river. Hariati [16] studied similar phenomena when researching salinity intrusion in the Segara Anakan Estuary, Indonesia. Their model showed that the rising sea level allows the salinity to propagate further into tributaries, where a weir/dam may reduce the severity. However, they did not consider dredging.

Studies relevant to riverbed modification and port development are available in the literature. For instance, Rahman [17] modelled the impact of river dredging on hydrodynamics and sediment transport changes. The model was well-validated and offered flexibility in projecting future scenarios. In addition, numerical modelling offers several advantages, as seen in [18] and [19]. However, none of these models explain the potential hydrodynamic and salinity-related impact of capital dredging in port waterway development in a river.

In this research, potential changes in river hydrodynamics and salinity propagation, due to massive dredging that took place in the Cikarang Bekasi Laut channel, were studied. Two adaptation scenarios are introduced and assessed in this paper. Modelling related to salinity propagation is still limited to existing condition modelling and climate change scenarios [7,16]. The impact of massive changes in riverbed elevation has yet to be understood.

Hydrodynamic modelling of the CBL channel was carried out using the RMA2 module in SMS. The current velocity and the water level resulting from the RMA2 output were validated with field data. A hydrodynamic simulation was developed based on the water quality model, using the RMA4 module in SMS to understand the salinity propagation and evaluate the two adaptation scenarios.

2 Field Data Acquisition

Field activities included topographic, bathymetric, water level, and current velocity surveys. Figure 2 shows the documentation of the field data activities.

Figure 2 Documentation of (a) topographic, (b) bathymetric, (c) water level, and (d) current velocity surveys.

2.1 Topographic Survey

The topographic survey extended from the river's centreline to the riverbanks and along the river (from downstream to upstream). The survey results were used as the boundaries of the waterbody and topographic measurements were carried out using the terrestrial method and the total station.

The data obtained were spatial and elevation data. The survey area was 32 km in length and with a cross-section of 100 m in width. The blue curve marks the total topographic survey length in Figure 1. The topographic study used a total station survey and a water pass survey; a benchmark was used as the reference for the spatial and elevation data. Figure 2(a) shows the topographic survey documentation.

2.2 Bathymetric Survey

Bathymetric measurements were conducted along the CBL, channel starting from the estuary and extending 32 km upstream. The total survey area was ±2500 ha, measured using an Odom Hydrotrac II single beam echosounder (see Fig. 2(b)). The final results of the bathymetric survey were the seabed and riverbed elevations.

2.3 Water Level Survey

The water level fluctuation was noted by installing a tide gauge equipped with AWLR in the estuary. Data were automatically recorded hourly for fifteen days. The water level measurement location is denoted by P1 in Figure 1. Figure 2(c) shows the documentation of the water survey.

2.4 Current Velocity Survey

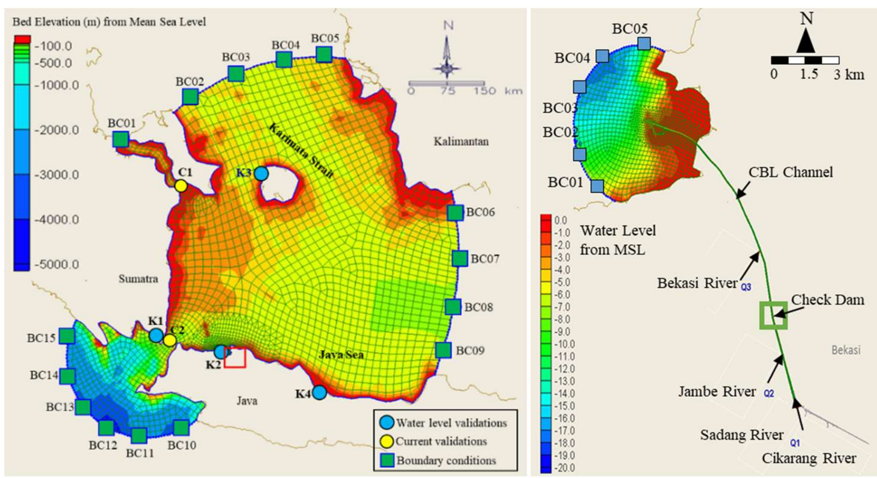
The current velocity data were obtained using an Aanderaa current meter (see Figure 2(d)). The current velocity was measured at three vertical locations, namely 0.2d, 0.5d, and 0.8d (where d is the water depth). The representative current is the average of these measured data. The output data are the current directions and magnitudes at five points, marked by yellow dots and labelled A1-A5 in Figure 1. The current data were recorded hourly for two days.

3 Numerical Modelling

The modelling was carried out using SMS with two modules, namely RMA2 for the hydrodynamic model and RMA4 for the water quality model. RMA2 is a two-dimensional average-depth hydrodynamic module that calculates water level and horizontal velocity components for subcritical and free surface flow in the field of two-dimensional flow. RMA4 is a water quality model, where the depth concentration distribution is uniform. The U.S. Army Corps of Engineers coded RMA2 and RMA4. Both modules have been widely used in studies of water quality in water bodies [20-22].

3.1 Model Setup

The hydrodynamic modelling (RMA2) was staged in a global and local model and resulted in current velocity and surface water elevation data, which were validated using the field data. After validation, the current velocity data were used for the salinity distribution in the water quality model (RMA4). The water quality model (RMA4) used a local domain. The output data were the salinity data with time and spatial variations. The domain and meshes of the global and local models are given in Figure 3.



Global Domain Local Domain

Figure 3 Domain and mesh of the global model (left). Blue and yellow dots mark the validation locations. The red box indicates the local domain (the study area). The local domain at the CBL channel is on the right.

The global model domain included the islands of Sumatra, Java, and Kalimantan (Indonesia), with five tidal validation points and two current velocity validation points. The validation data for the global model used the secondary data obtained from the Center of Hydrography and Oceanography of the Indonesian Navy [23,24]. The global model's boundary conditions (BCs) were obtained from the same sources, as well as the web-based program Naotide of Poseidon [25], indicated by the green boxes and marked as BC01 to BC15 in Figure 3. Tidal time-series data at BC01 were obtained from the Indonesian Navy Hydrooceanography Agency at Muntok Station, while data for BC02 to BC15 were extracted from Naotide of Poseidon [25].

The local model domains are given in Figure 3. The BCs are tidal levels at the downstream points and river discharges at the upstream points. The tidal levels were extracted from the global model downstream from the channel, marked as BC01 to BC05 (see Figure 3). Four rivers coming into the CBL channel were considered in the local model: the Sadang, Cikarang, Jambe, and Bekasi Rivers. The discharges can be seen in Figure 4, they were inputted in the model as monthly values, linearly transitioning between months. These discharges were calculated to estimate the relations between rainfall and runoff, using the Mock method [26].

The Mock method makes calculations based on the water balance principle, considering evapotranspiration, soil storage, and runoff. The method uses data such as precipitation, catchment area, temperature, sunshine hours, relative humidity, and wind velocity. The catchment area is 452, 126, and 490 km^2 for the Sadang-Cikarang, Jambe, and Bekasi Rivers, respectively. The outlet of each river is located 25, 20, and 14 km from the coast.

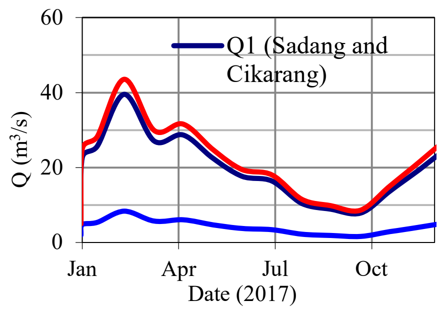


Figure 4 Monthly averaged river discharge.

3.2 Model Scenarios

After validation, the model was developed into a water quality model using the RMA4 module. The scenario was run from December 28th 2016, to January 1st 2018, covering 2017 and allowing four days of spin-up time for the model. The water quality model only ran in the local domain, with additional inputs in the form of salinity of 0 ppt in the tributaries (the black arrow in Figure 3) and 35 ppt on the coast (the blue box in Figure 3). This salinity input followed the setting of a previous study in the exact same location [16].

The water quality model in the local domain included three scenarios: the conditions before dredging (called the existing scenario), conditions after capital dredging (to –4 m below the lowest low water level, called scenario 1), and conditions after capital dredging (with the additional construction of a check dam, called scenario 2). The check dam was located upstream of the port to accommodate the dramatic bed slope changes due to waterway dredging, placed between the Bekasi and Jambe River outlets (see Figure 3). The model was simulated for one year. An illustration of the check dam is given in Figure 5. The check dam was incorporated into the model by modifying the bed elevation. In detail, the bed elevation at the check dam location was elevated locally, working like a weir. It is important to note that all models used the same roughness coefficient since the riverbed sediment is expected not to change after dredging. The roughness change due to capital dredging has yet to be included in the model.

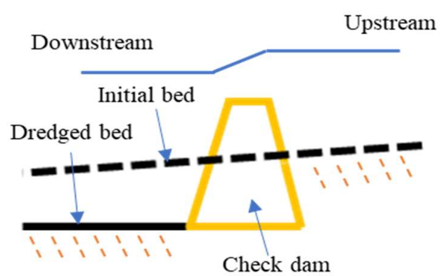


Figure 5 Illustration of check dam.

4 Results and Discussion

4.1 Model Validation

To ensure the validity of the model's results, they were compared with the field data. The validation model was run over the same time frame as the observation date. The data to be validated were the water level and the current magnitude. The locations of the validation points can be seen in Figure 3. The global data results were validated at four locations for the water level data (marked as blue circles) using secondary data [23] and two locations for the current data (marked as yellow circles), also using secondary data [24]. The list of the validation locations is given in Table 1. Statistical parameters, such as the correlation coefficient (r), root means square error (rmse), mean absolute error (mae), and Nash-Sutcliffe efficiency (nse) were used to characterise the reliability of the water level and current magnitude validation. The results are given in Table 1. The r and nse-values were close to 1 and the rmse and mae approached 0, indicating a decent match between the model result and the field data. A time-series display of the water level validation at points K1, K2, K3, and K4 is given in Figure 6.

Table 1 Details of validation locations and statistical parameters between the field and model output. The water level and current magnitude data were obtained from [23] and [24].

Point	Data Type	Locations	r	rmse	mae	nse
K1	Water level	Bakauheni	0.835	0.127	0.103	0.512
K2	Water level	Tj. Priok	0.922	0.098	0.078	0.849
K3	Water level	Tj. Pandan	0.983	0.133	0.106	0.957
K4	Water level	Cirebon	0.911	0.084	0.144	0.828
C1	Current	Selat Sunda	0.956	0.163	0.130	0.908
C2	Current	Bt. Nemesis	0.971	0.128	0.107	0.877

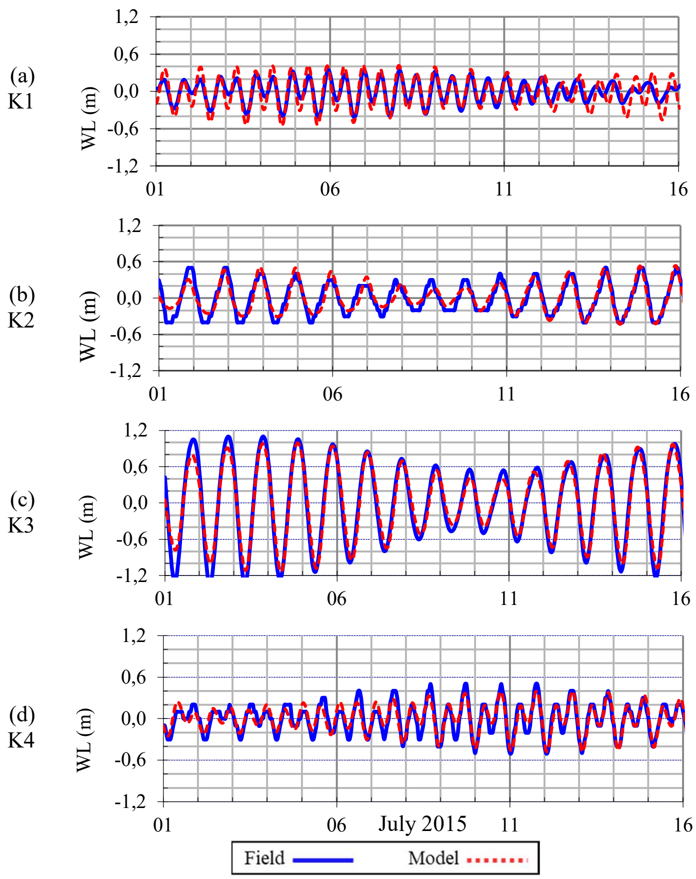


Figure 6
Comparison of water level between the global model and the field data at points K1 to K4. The blue and red dotted lines indicate the field and model data, respectively.

Meanwhile, time-series displays of the current velocity validation are shown in Figure 7(a) for location C1 and 7(b) for location C2, also presenting a good agreement between the field data and the model output.

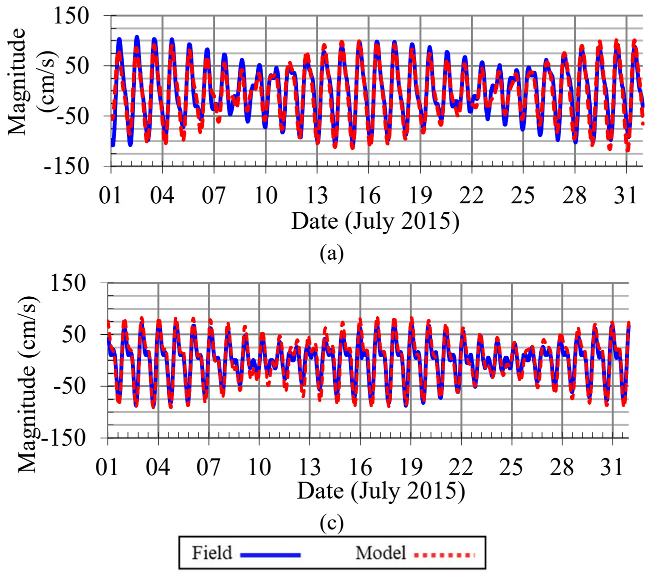


Figure 7 Comparison of current velocity in the global model and the field data at (a) C1 and (b) C2. The blue and red dotted lines indicate the field and model data, respectively.

Model validation in the local domain involved the water level elevation and current velocity obtained from the field survey. The water level elevation was validated at point P1, located at the outlet of the CBL channel (see Figure 1). The similarity between the surveyed and the modelled data can be seen, where the statistical errors were in the same range as those in the global model validation.

The current velocity validations were carried out at the yellow points A1-A5, as shown in Figure 1, where both the measured and the modelled velocities are averaged values. Figure 8 compares the water level elevation between the survey and the simulation. Both amplitude and phase had the same tendency in the field (survey) data and the model. The current velocity data measured in the field are shown in Table 2. The current velocity in the CBL channel had its highest value (71.13 cm/s) at point A5 and its lowest value (0.30 cm/s) at point A1. Figure 9 shows the validations of the current velocity. The comparison between the survey data and model simulation show good agreement.

Table 2 Summary of the statistical characteristics and errors for the current velocity validation of the local model.

	A1	A2	A3	A4	A5
Statistical characteristics (cm/s)					
Maximum	41.65	45.46	55.74	68.21	71.13
Minimum	0.30	8.80	15.75	37.79	61.83
Average	22.76	29.14	31.48	57.16	65.50
Errors between survey and model data (cm/s)					
rmse	16.47	12.80	9.60	7.19	45.03
mae	13.49	10.69	7.78	5.37	43.17

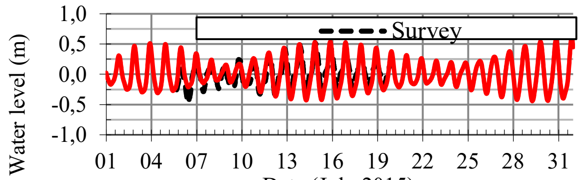


Figure 8 Water level validation at the local domain. The r, rmse, mae, and nse values were 0.850, 0.128, 0.108, and 0.606, respectively.

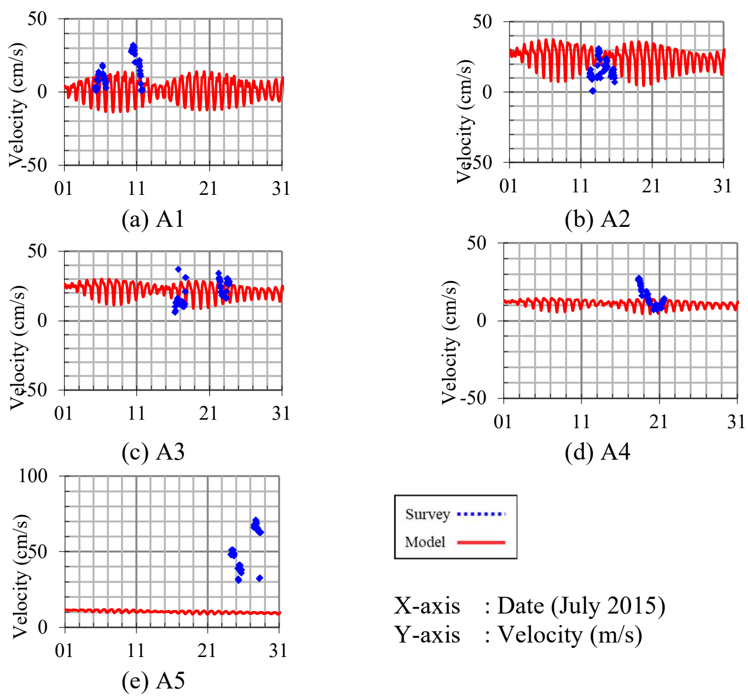


Figure 9 Current velocity validation of local domain at five locations.

4.2 Model Results

The modelling results for 26 observation points are presented in Figure 10. Points 1 and 26 are located upstream and in the estuary, respectively.

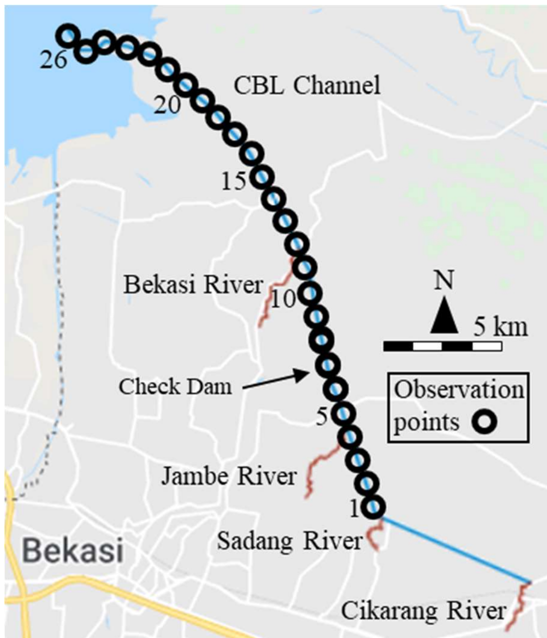


Figure 10 Observation points for salinity model.

Time-series salinity graphs are presented in Figures 11 and 12 for points 7, 13, 16, and 21, respectively. Figures 11(a)-(d) show a comparison of the salinity between the existing condition and after capital dredging in scenario 1. Figures 12(e)-(h) show a comparison of the salinity for the existing condition and scenario 2 (with the additional check dam to mitigate salinity intrusion). The salinity at point 7 (upstream area), shown in Figures 11(a) and 12(e), was low. The value was close to 0 in the existing conditions, as well as scenarios 1 and 2. At point 13, which is in the middle of the channel (see Figures 11(b) and 12(f)), the salinity was influenced by the river discharges (or rainfall season). The dry season is from August to September. During those months, the salinity values increased due to the lack of fresh water supply upstream. Point 16 (see Figures 11(c) and 12(g)) and point 21 (see Figures 11(d) and 12(h)) show that the check dam stabilised the salinity in the upstream area. In this model, the check dam was capable of reducing the volume or percentage of saline water propagating further into the downstream and upstream areas.

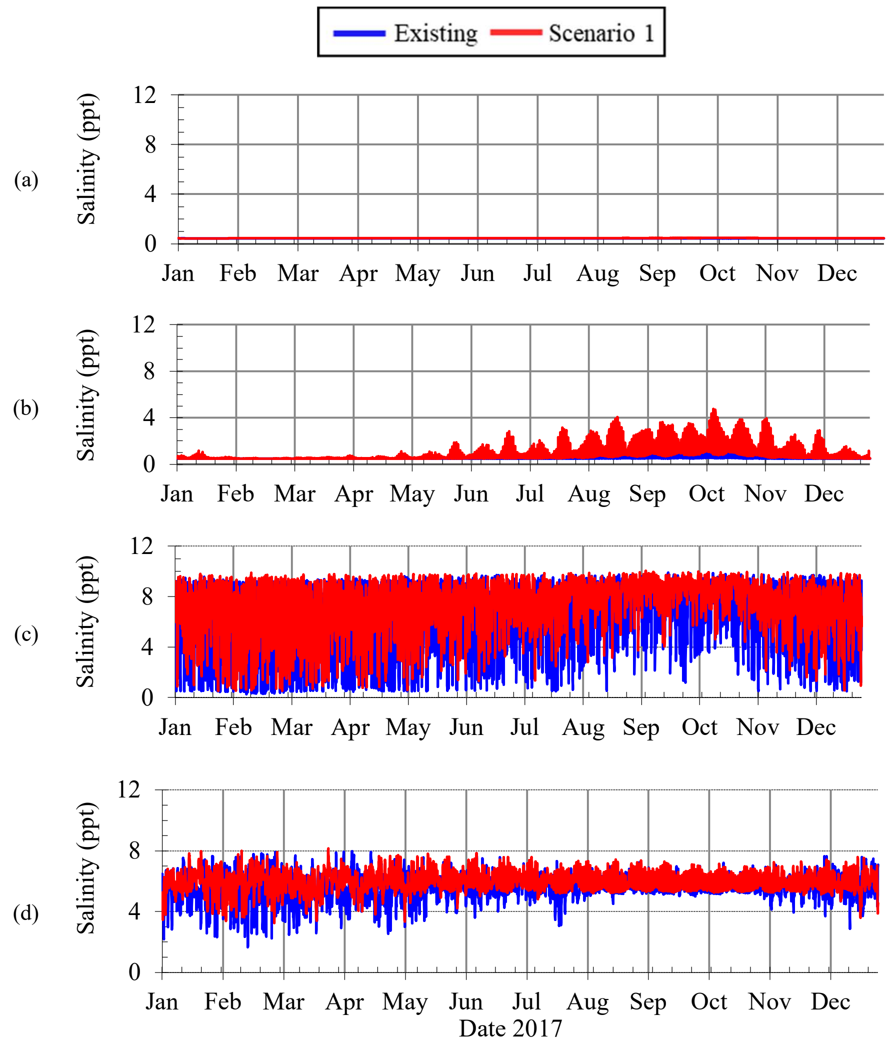


Figure 11 Time series of salinity at points 7, 13, 16, and 21, respectively, for the existing scenario (blue lines) and scenario 1, after capital dredging (red lines).

The time-series graph shows that the salinity fluctuated periodically, indicating that the sea tides still influence the river hydrodynamics at this location. Overall, with the dredging of the CBL channel, the salinity became higher. This is because a larger volume of seawater entered the CBL channel. However, with the construction of a check dam, the salinity upstream of the CBL channel can be reduced and stabilised.

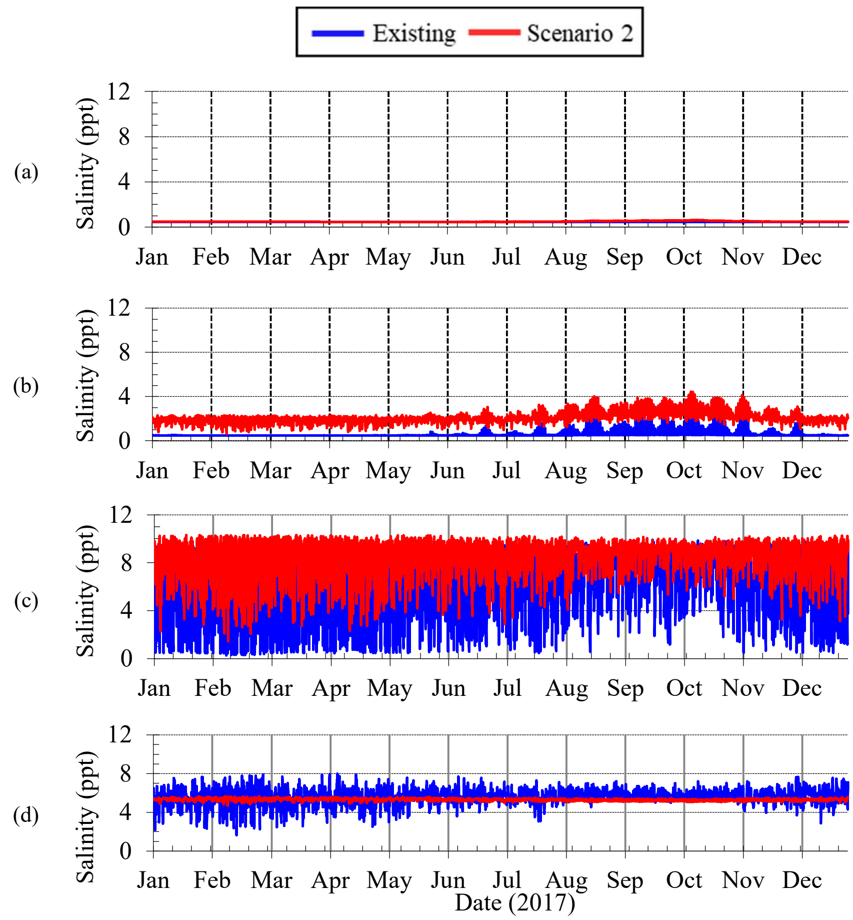


Figure 12 Time-series graph of salinity at points 7, 13, 16, and 21, respectively, for the existing scenario (blue lines) and scenario 2, after capital dredging (red lines).

An analysis of the average salinity concentration for one year in the existing condition for scenarios 1 and 2 (at each point) is shown in Figure 13. Seawater intrusion occurred in the existing condition, about 10 km into the CBL channel. Then the salinity fell to close to 0, upstream of the river. In scenario 1, where dredging was conducted, the salinity value increased by an average of 0.42 ppt, compared to the existing condition. In scenario 2, where the dredging and construction of a check dam were carried out, the salinity value increased by an average of 0.37 ppt, compared to the existing condition.

The average salinity concentrations in dry months (such as October) in the existing condition, for scenarios 1 and 2, at each point, are shown in Figure 13(b). In dry season months, there were increases in the average salinity of 0.80 and 0.68 ppt under scenarios 1 and 2, respectively. This salinity increment occurred because of the low freshwater supply to the channel. The average salinity concentrations in wet season months (such as February) at each point, are shown in Figure 13(c). After dredging, the average salinity increased by 0.23 ppt under both plans, compared to the existing condition. Again, the average salinity was lower due to the freshwater supply in the channel.

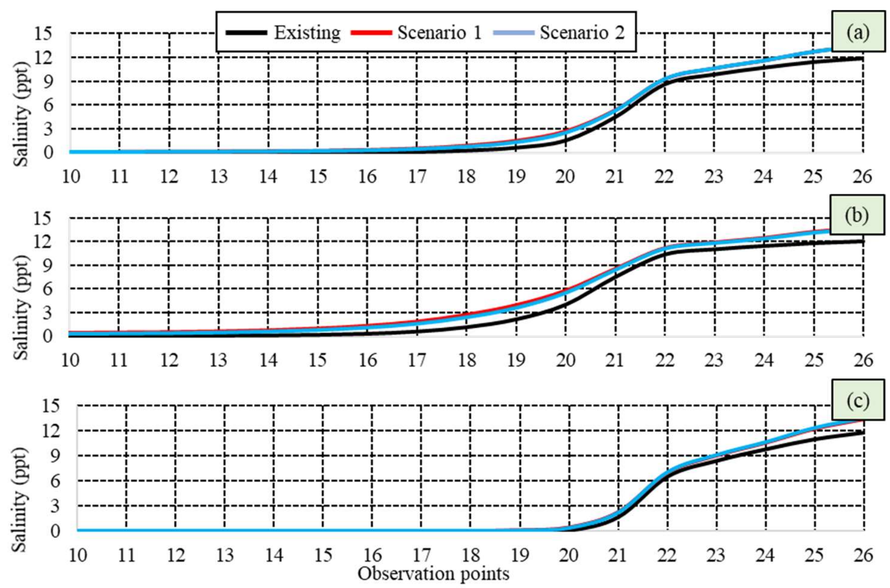


Figure 13 The average salinity concentration at 26 observation points (a) in one year, (b) around October (dry season month), and (c) February (peak of wet season).

The behaviour of the salinity observed in the presented model was in line with findings from other studies on cases in Indonesia [16], Vietnam [27], and Portugal [28]. Salinity highly depends on the monsoonal season, where the wet season significantly reduces the salinity reached in the river. This increment may lead to an increase in the sediment transport rate due to salinity-driven circulation [29], which was not demonstrated in the presented model.

The presented model provided a projection of salinity propagation in three scenarios where a massive riverbed modification was imposed. First, the model showed that capital dredging allows extra room for seawater to propagate into the river, increasing the salinity. The model also demonstrated that a check dam, a volume control-like structure, is promising as an adaptation effort.

Nevertheless, more effort into model calibration is required in future research. The advanced utilisation of numerical models in mimicking actual processes was demonstrated in [30], where the salinity was nicely reproduced vertically, spatially, and temporally. Vertical discretisation, turbulence parameterisation and diffusion are expected to bring the model closer to the actual phenomena [31].

5 Conclusion

Our numerical model showed good agreement with the field data. The CBL channel's hydrodynamics are strongly influenced by the freshwater supply upstream of the river. Furthermore, the salinity in the CBL channel increased after capital dredging. The salinity increment after dredging was approximately 0.23 ppt during the wet season and 0.8 ppt during the dry season. The construction of a check dam can decrease the salinity value to 0.68 ppt during the dry season.

This paper presented a preliminary assessment of hydrodynamic and salinity changes due to waterway development in the CBL channel. In the future, a three-dimensional approach, coupled with a groundwater model, is needed to investigate its impact on the surrounding farms and crops. The effects of the dredging and check dam construction on the tributaries should be studied in subsequent research. The long-term bed changes after dredging should also be observed during the waterway operation.

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