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Coastal Bris Wetland Hydrodynamics in Non-monsoon and Monsoon Seasons at Mengabang Telipot Terengganu, Peninsular Malaysia

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ABSTRACT

BRIS (beach ridges interspersed with swales) wetlands dominate the coastal plains of the east coast of Peninsular Malaysia. This study examined the impact of rainfall and river levels on groundwater hydrodynamics in a coastal BRIS wetland at Universiti Malaysia Terengganu during the northeast monsoon and non-monsoon seasons (July 2022 to January 2023). Six monitoring wells (WA-WF) were built, with WB, WC and WD positioned on the higher ground, whereas WA, WE and WF were on the lower ground. River levels were observed at three stations (R1–R3), rainfall data were collected using a weather station and tidal data were obtained from an existing station. Measurements at 5-minute intervals identified a strong correlation. Between tidal oscillations and river water level ($r = 0.7–0.92$, average, 0.81), typical of tidal rivers. However, the influence of tidal oscillation on groundwater level was weak (average $r = 0.22$), suggesting an indirect influence through river dynamics. Groundwater level in lower areas near rivers was more influenced by river water level changes (average $r = 0.54$, monsoon average = 0.76). In contrast, the higher section showed a weak influence in general (average $r = 0.02$, monsoon average = 0.34). During monsoon season, increased upstream flows elevated river levels, enhancing hydraulic connectivity across the wetland. Groundwater fluctuations were limited to 0.5 m below ground, with lower areas frequently saturated or inundated, limiting floodwater retention capacity. Future research could explore the impact of soil texture and porosity to refine understanding of BRIS wetland hydrodynamics.

Keywords: Coastal BRIS wetland, hydrodynamics, monsoon season, non-monsoon season

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INTRODUCTION

On the east coast of Peninsular Malaysia, the non-monsoon season occurs from May to September, while the monsoon season (northeast monsoon) occurs from November to March annually (Ariffin et al., 2019). During the northeast monsoon, heavy rainfall with an average of 2990 mm occurs, in contrast with the non-monsoon season, with only 740 mm of average rainfall (Ismail et al., 2020; Arrifin et al., 2016). Flooding often occurs when heavy rainfall coincides with high tides (Cai et al., 2022; Pirani & Najafi, 2020; Zhang & Najafi, 2020; Westra et al., 2014). In addition, the average high tide was 2.28 meters, while the average tide height was less than 0.4 meters during the southwest monsoon (Ismail et al., 2020). This indicates the differences in rainfall amount and tidal heights during the two seasons.

The coastal plains of the east coast of Peninsular Malaysia are dominated by beach ridges and swales, i.e. BRIS environment. The soil type is typically sand, silty sand and silty clay. Sandy soil promotes water movement as discharge/recharge, whereas silty-clayey layers aid groundwater accumulation (Mohamad et al., 2002; Roslan, 2010; Koh et al., 2018). Naturally, ridges are occupied by heath forests, while swales are occupied by wetland vegetation (Kamoona et al., 2023; Ikbal et al., 2023; Touchette et al., 2011; Salim et al., 2014).

The tidal activities and river flows affect groundwater in the coastal BRIS area. It depends upon hydraulic properties, the geomorphology of the area, and the topography (Moffett et al., 2012; Ensign, 2013). Hydraulic gradient governs groundwater flow direction, where groundwater flows from high hydraulic head to low hydraulic head areas (Zhang et al., 2022; Gleeson et al., 2011). Ridges have higher elevations and water tables, i.e. higher hydraulic heads. They recharge the swales that are located in lower-elevation areas. Swale groundwater is also replenished by rivers and streams (Curtis et al., 2017). As a result of such hydrologic process, swales become an important water retention area and may have a potential in flood mitigation (Revitt et al., 2017; Gao et al., 2015). Unfortunately, the BRIS study has been more focused on its agriculture potential than ecological services like flood mitigation (Bakar et al., 2023; Zakaria et al., 2023; Ishaq et al., 2019; Toriman et al., 2009; Hossain et al., 2011; Lah et al., 2011).

This study hypothesises a significant difference in groundwater levels between the non-monsoon and monsoon seasons. It suggests that the higher rainfalls during the monsoon season significantly affect groundwater dynamics compared to the non-monsoon season. Additionally, this study suggests that tidal levels affect groundwater dynamics differently across these seasons. Furthermore, the interaction between rainfall amount and tidal levels during the monsoon season substantially affects groundwater dynamics compared to the non-monsoon season.

This study focuses on analysing the behaviour of the groundwater system in response to non-monsoon and monsoon seasons to address the gap in understanding the ecosystem services in this area. The objective is to determine the impact of rainfalls and tidal levels on the hydrodynamic of groundwater in the BRIS coastal wetland during these distinct seasonal periods.

METHODOLOGY

Study Area

The study area is on the Universiti Malaysia Terengganu (UMT) campus at Mengabang Telipot. It is a coastal BRIS wetland located 15 km north of Kuala Terengganu City (UTM 48N, 287720 m N, 598526 m E) (Figure 1). This coastal area has several beach ridges with low-lying backfill areas in between. The ridges are relict beaches, indicating the coastlines' position changes as the sea level regressed after the Holocene high stand (Sathiamurthy et al., 2021). The estuary of this area is a temporarily open/closed estuary type (Sathiamurthy & Pauzi, 2020). The surrounding rivers could overflow their banks during heavy, prolonged

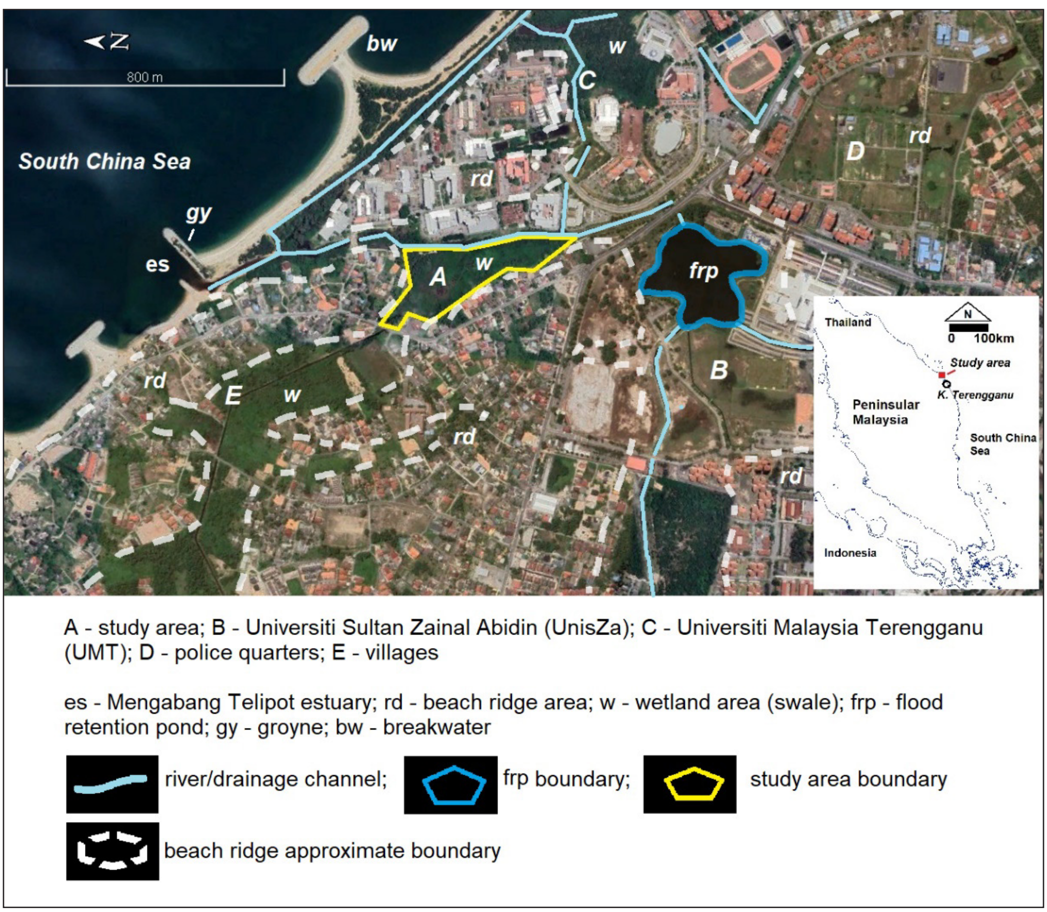

Figure 1. Study area (*Source*: Google Earth and fieldwork)

monsoonal rainfalls coinciding with high tides or when the estuary is closed. The flood flows would inundate a 5.26-ha wetland located within the UMT campus. Stations were set up to capture the hydrodynamic behaviour of the wetland under study (Figures 2 and 3). The river stations consisted of the outlet near the estuary (R1), the inlet area from the campus of Universiti Sultan Zainal Abidin (UniSZA) and the Kuala Terengganu Golf Resort drainage system (R2), and the Wakaf Tengah River (R3). The wetlands stations, WA, WB, WC, WD, WE and WF were monitoring wells.

River Water Level Measurements

The hydrodynamic behaviour of the wetland corresponding to the rivers was examined by measuring water levels in all stations simultaneously under high temporal resolution, i.e. 5-minute intervals. Every station had a data logger for this purpose (Table 1). Measurements

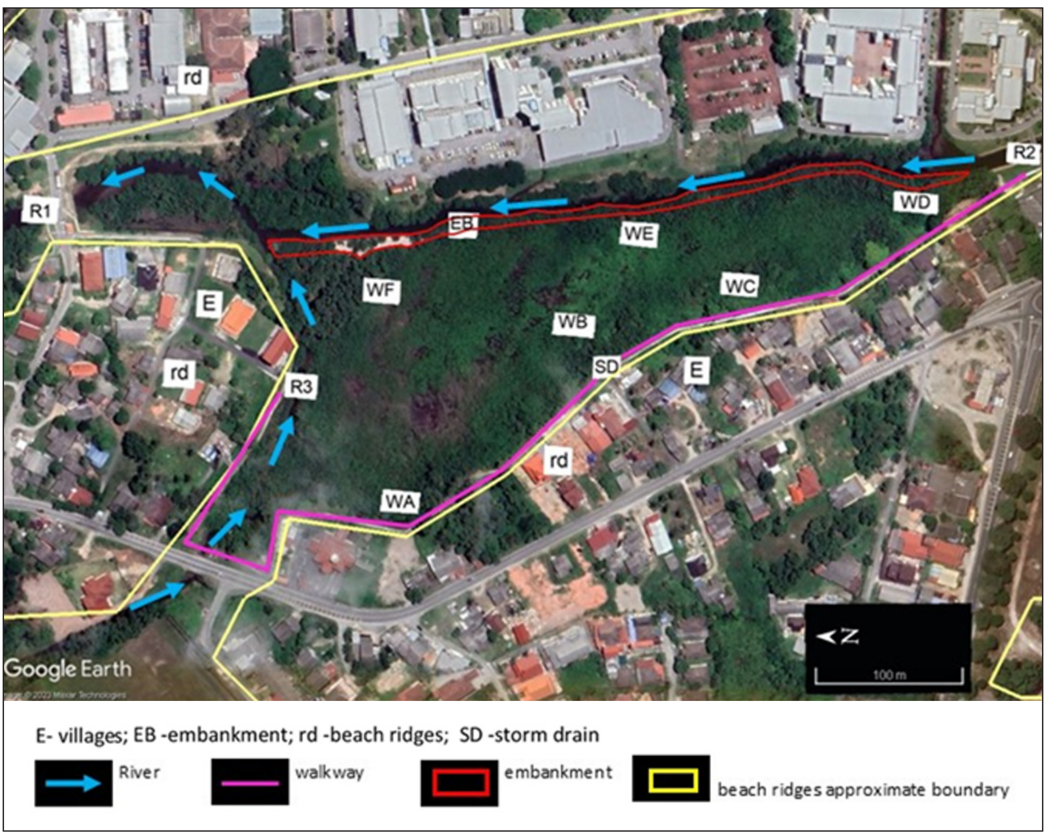

Figure 2. River and wetland station in the study site, Universiti Malaysia Terengganu (*Source*: Google Earth and fieldwork)

Note. The middle section is inaccessible; no stations were assigned. All stations were scattered across the wetland area, so the sampling work was unaffected as all stations covered the wetland area. R1 is the nearest station to the estuary, about 525 m downstream, whereas R2 is upstream of the same main channel, and R3 is in the main tributary that flows from the west

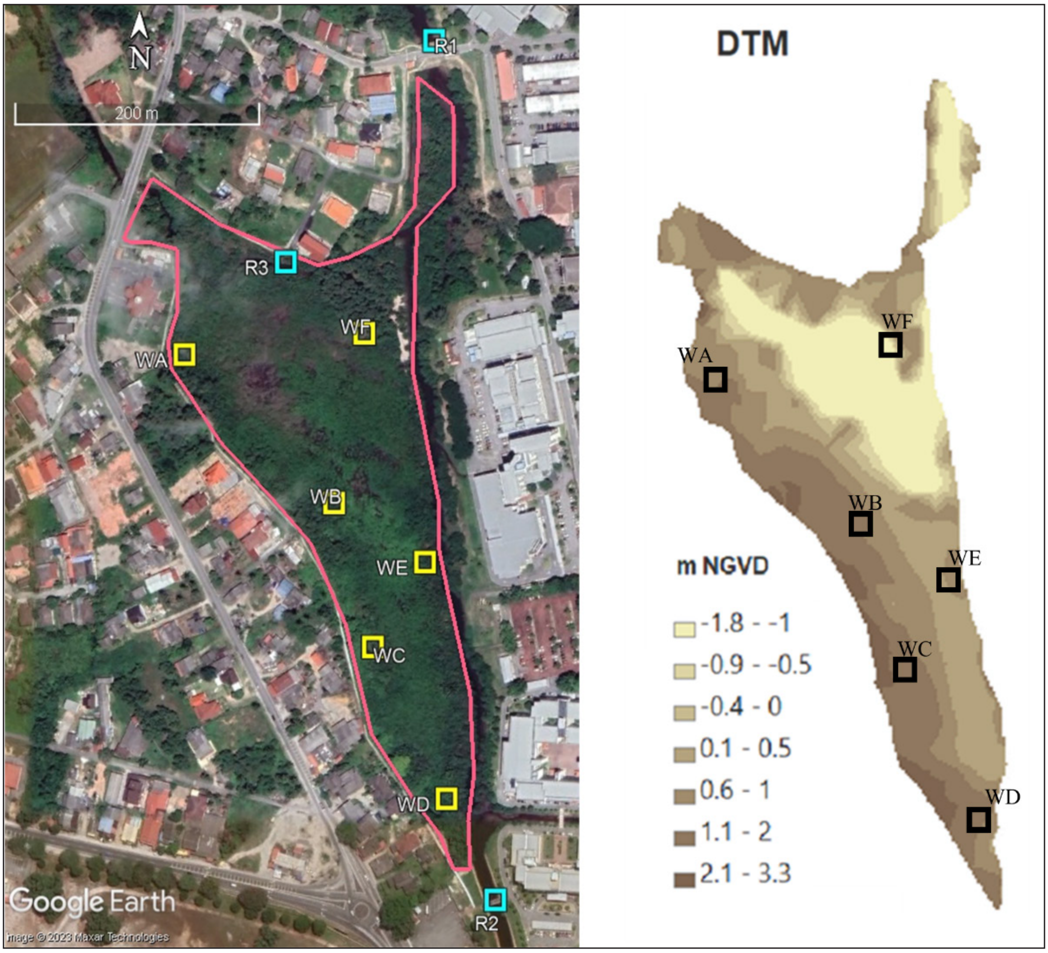

Figure 3. Satellite and digital terrain model (DTM) image of the Universiti Malaysia Terengganu campus study site
Note. The DTM image was analysed using ArcMap software to indicate the ground elevation in this study area. The dark colour shows the high ground level. WB, WC, and WD were high-ground-level wetland stations, while WA, WE, and WF were low-ground-level wetland stations

were done from 10 to 21 July 2022 (non-monsoon season), 22 October to 7 November 2022 (early monsoon season), and 4 December 2022 to 1 January 2023 (middle-monsoon season). It should be noted that the monsoon season here refers to the northeast monsoon, whereas the non-monsoon season refers to the season outside of the northeast monsoon season. These monitoring wells were made from perforated PVC pipes (Figure 4). They reached the marine clay layer in the wetland area at roughly 0.6 m to 2.4 m, with an average depth of 1.9 m.

The marine clay layer is the first confining layer that marks the bottom boundary of the unconfined aquifer. The unconfined layer is only relevant for this study as the focus was surface and upper subsurface hydrodynamics. River stations were equipped with stick gauges and perforated PVC pipes as well. However, the pipes were set up primarily to

Table 1
Basic information on wetland and river stations

The coordinates, the depth and the ground level of the wetland stations			
Station	Coordinates (UTM 48N)	Well Depth (m)	Ground Level (m NGVD)
WA	287600 m N, 598599 m E	3.4	1.31
WB	287724 m N, 598485 m E	3	1.60
WC	287758 m N, 598373 m E	2.6	2.03
WD	287820 m N, 598255 m E	3	1.63
WE	287799 m N, 598440 m E	3.2	1.21
WF	287747 m N, 598618 m E	3	1.09
The coordinates, the bed level and the ground level of the river stations			
Station	Coordinates (UTM 48N)	Bed Level (m NGVD)	Ground Level (m NGVD)
R1	287799 m N, 598849 m E	-0.262	2.744
R2	287861 m N, 598176 m E	0.345	3.312
R3	287681 m N, 598673 m E	-0.139	1.891

Note. WA: Well A, WB: Well B, WC: Well C, WD: Well D, WE: Well E, WD: Well D; R1: River 1, R2: River 2, R3: River 3

gauges and perforated PVC pipes as well. However, the pipes were set up primarily to protect data loggers from debris damage. PVC pipes were chosen because they are inert and stable, lowering the contamination risk. A filter layer made of cloth was used to keep fine soil particles from entering the monitoring wells.

The elevation of each data logger was determined based on the crown elevation of the wells and the elevation points on the stable structures where the river stations were set up. Elevations were determined via ground levelling work based on the National Geodetic Vertical Datum (NGVD) with reference to an existing land survey benchmark. This work was vital to ensure comparable water levels, and hence, their differences and changes through time and space indicate hydrodynamic behaviour.

During the middle monsoon season, on 9 December 2022 at 12:30 pm, monitoring

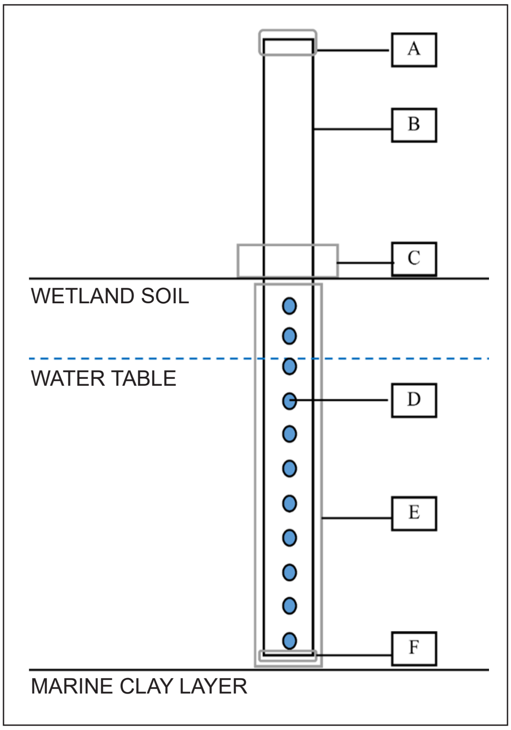

Figure 4. Schematic diagram of wetland monitoring station
Note. A: PVC cap, B: PVC pipe, C: Concrete cement, D: Perforated PVC Pipe, E: Filter layer, F: PVC bottom cap

protect data loggers from debris damage. PVC pipes were chosen because they are inert and stable, lowering the contamination risk. A filter layer made of cloth was used to keep fine soil particles from entering the monitoring wells.

The elevation of each data logger was determined based on the crown elevation of the wells and the elevation points on the stable structures where the river stations were set up. Elevations were determined via ground levelling work based on the National Geodetic Vertical Datum (NGVD) with reference to an existing land survey benchmark. This work was vital to ensure comparable water levels, and hence, their differences and changes through time and space indicate hydrodynamic behaviour.

During the middle monsoon season, on 9 December 2022 at 12:30 pm, monitoring well R2 sustained structural damage due to the rapid water flow through the pipe. As a result, a new station was installed on 11 December 2022 at 3:15 pm. However, the damage has prevented data collection, resulting in an 8.22% absence of recorded data. Nonetheless, the collected data remains suitable for analysis.

Salinity

The salinity in the river and wetland stations was recorded using the same data loggers at 5-minute intervals. Salinity measurements were taken to detect saltwater intrusion. A saltwater intrusion would indicate seawater infiltration into the wetland soil until it reaches the groundwater, which would mean the tidal event influenced the stations. However, the rainfall-runoff process appeared to be the main factor influencing groundwater levels when salinity was low.

Tidal and Rainfall Data

The Department of Survey and Mapping Malaysia provided tidal data, while the Drainage and Irrigation Department provided rainfall data as supplementary data. The data were recorded at 5-minute intervals from 10 to 21 July 2022 (10:50 pm and 11:05 pm, respectively), 22 October (2:00 pm) to 7 November 2022 (8:00 am), and 4 December 2022 (1:25 pm) to 1 January 2023 (10:55 am). Rainfall data primarily came from a portable weather station (RainWise Portlog) set up adjacent to the study area, and rain data were recorded every 5 minutes as well. Hence, the rainfall and tidal data match the water level data. Hence, the cause-and-effect relationship can be examined. They demonstrated how the river and groundwater systems responded to non-monsoon, early monsoon, and mid-monsoon seasons.

Data Analysis

Pearson correlation and X-Y scatter graphs were used to analyse the collected data. Pearson correlation, together with significance tests, was conducted between stations. This was to determine their correlations (corresponding or inverse), strengths, and significance (with a p-value lower than 0.05). These analyses indicated which stations influence water level changes in other stations. The graphs gave a visual relation between them. For example, a weak positive correlation (r near 0) between two stations would indicate that the rise and fall of water levels of both wells had a very weak influence on each other hydrodynamically. However, if the correlation is strong but the 'p' value is higher than 0.05, it would mean the relation is not significant and could result from randomness, error, or lack of data.

The study area groundwater stations (wells) were divided into high-ground and low-ground stations based on ground elevation (Figure 3). The groundwater levels of these wells were compared because high-ground wells are more likely to be affected by rainfall recharges from the adjacent sand ridge. In contrast, the low-ground wells would be more affected by river water changes caused by tidal intrusions, recessions, and river upstream outflows. Such comparisons also enable the examination of the cause-effect relationship between them. Thus, the factors that affect hydrodynamic behaviour could be determined from these comparisons.

The graph plots helped visually compare the high and low-ground-level wetland stations during the non-monsoon, early-monsoon, and mid-monsoon seasons. The graphs demonstrated the relationship between rainfall intensities, tidal levels, river water levels and groundwater levels in a cause-and-effect manner. They showed the wetland's response patterns or behaviour as the groundwater level fluctuated due to parameter changes.

RESULTS AND DISCUSSION

High Ground-level Wetland Stations During Non-monsoon Season

Groundwater stations (monitoring wells) WB (ground level: 1.60 m NGVD), WC (2.02 m NGVD), and WD (1.63 m NGVD) are located on higher grounds, i.e., close to the middle of the beach ridges (Figure 3). Unlike the other wells and river stations, these WB stations were unaffected by tidal changes during the non-monsoon season, as the salinity range was 0.375 ppt to 0.391 ppt (Figure 3). The WB station has a weak connection with R1 ($r=0.04$, $p=0.02$) and R3 ($r=0.08$, $p< 0.001$), as indicated by their almost zero correlation values. On the other hand, the WB station and the R2 station do not have a statistically significant relationship ($r= 0.01$, $p= 0.64$). This station's water level range was from 1.475 m to 1.658 m NGVD. Nonetheless, when it rained, the water level in WB increased. Water from the nearby village storm drain flowed into the wetland when it rained (Figure 2).

Moreover, it was found that R1 ($r= 0.13$, $p< 0.001$), R2 ($r= 0.09$, $p< 0.001$), and R3 ($r= 0.15$, $p< 0.001$) had a weak positive relation with WC station. That showed WC essentially was not influenced by river water fluctuations. WC was in the upper part of the wetlands and near the middle of the beach ridge. Its water level ranged from 1.967 m to 2.091 m NGVD during the non-monsoon season. The ground level of the WC was higher than other stations, and generally, it had a higher hydraulic head.

There were weak negative relationships between the WD station and R1 ($r = -0.12$, $p < 0.001$), R2 ($r = -0.12$, $p < 0.001$), and R3 ($r = -0.08$, $p < 0.001$). The salinity ranges from 0.122 ppt to 0.136 ppt. It should be noted that in the natural environment, freshwater would show some values for conductivity because of dissolved minerals. Hence, very low values do not necessarily indicate minor seawater intrusions (McCleskey et al., 2011). In addition, although tidal events cause changes in river water levels, it showed a limited susceptibility to these changes, as evidenced by its very low salinity values (Xu et al., 2022). The water level at WD ranges between 1.554 m and 1.638 m NGVD, demonstrating minor fluctuations (less than 10 cm) compared to the large fluctuations in the river (Figure 5). As a result of tidal intrusions and recessions in the river, river water levels showed changes, while groundwater levels at WD displayed a minor drop trend. This indicated that river water level changes had little effect on WD, even though WD was just 15 m away. The natural process of groundwater recharge/discharge relation with the river was most probably impeded by an embankment of compacted clay soil that reduced hydraulic conductivity. Such impeded exchange could harm the ecosystem (Wilopo & Putra, 2021; Aish, 2010; Pang et al., 2009).

During the non-monsoon season, all high-ground level wetland stations were unaffected by the river water fluctuations, as indicated by their weak correlations (average r was only 0.02). The higher groundwater levels prevented river water from reaching this area as it was against the hydraulic gradient. It showed that ground elevation has a significant effect on groundwater flow. In addition, in the case of WD, the embankment impeded the subsurface intrusion of river water into the wetland. This also retarded the recharge/discharge of the groundwater. The total rainfall recorded was 113.2 mm from 10 to 22 July 2022 (10:50 pm and 1:50 am, respectively), indicating no significant groundwater recharge from adjacent ridges. The rainfall amount was classified as type 1 with no runoff occurrence (Othman et al., 2020).

Low Ground-level Wetland Stations During Non-monsoon Season

Changes in river water levels and rain influenced the lower-ground wetland stations. This can be seen in the observations made at WA (ground level: 1:30 m NGVD), WE (1:21 m NGVD) and WF (1:09 m NGVD). The groundwater water level generally ranged from 0.589 m NGVD to 1.431 m NGVD (Figure 6) - the area with lower elevations experienced flooding during spring high tides.

There was a stronger positive relationship between WF with all three river stations, R1 ($r=0.59$, $p< 0.001$), as well as R2 ($r=0.66$, $p< 0.001$) and R3 ($r=0.61$, $p< 0.001$) compared to WA and WE. The moderate correlation coefficients for WA with R1 ($r=0.48$, $p< 0.001$), R2 ($r=0.52$, $p< 0.001$), and R3 ($r=0.52$, $p< 0.001$) river stations indicated a slightly weaker link by comparison. WE station showed a similar moderate relation, indicated by correlation

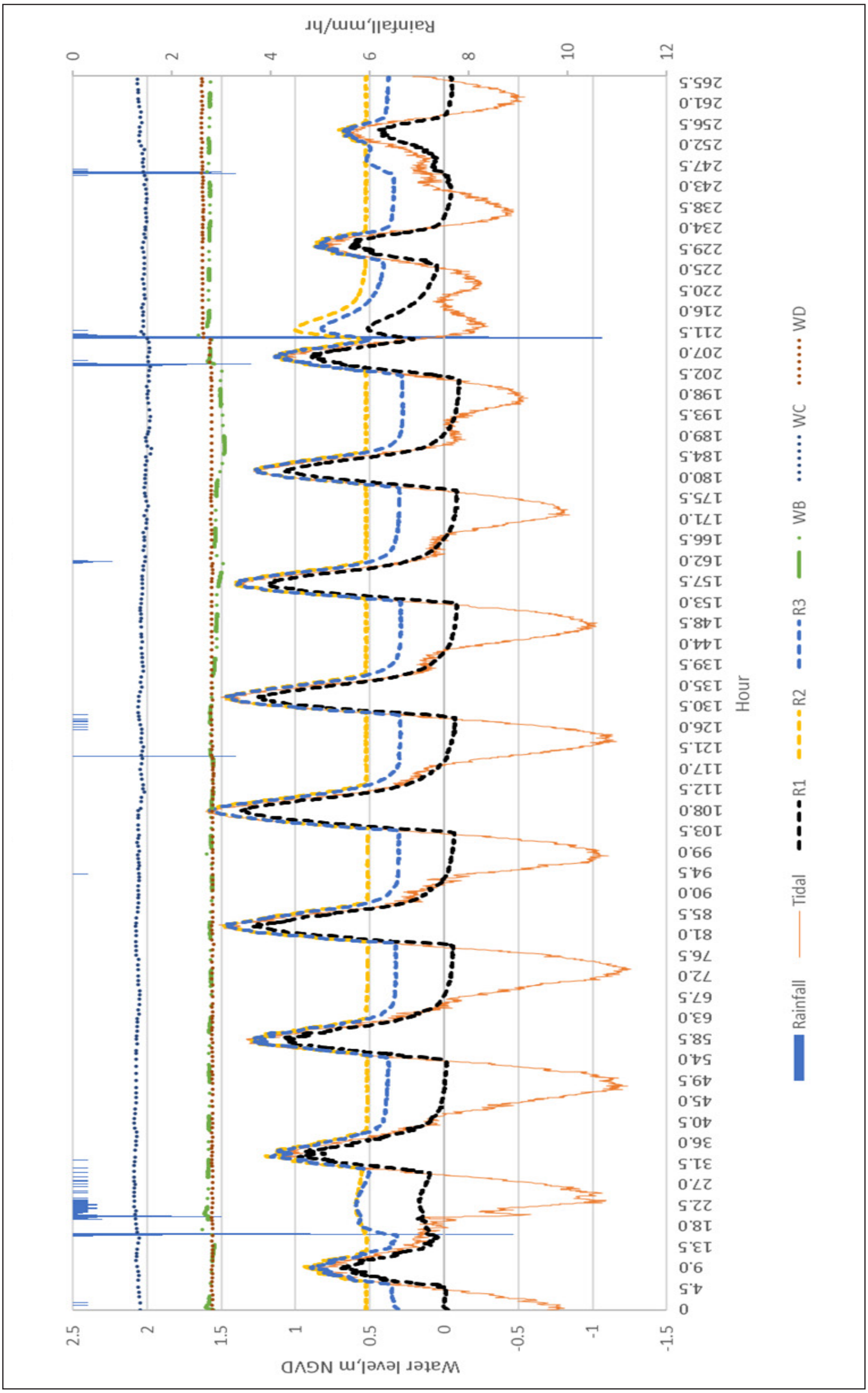

Figure 5. Water levels of high-ground wetland stations (WB, WC, and WD) and river stations (R1, R2 and R3) during non-monsoon season
Notes. The 0 hour starts at 10:50 pm on 10 July 2022, and the 264.3 hour ends at 11:05 pm on 21 July 2022

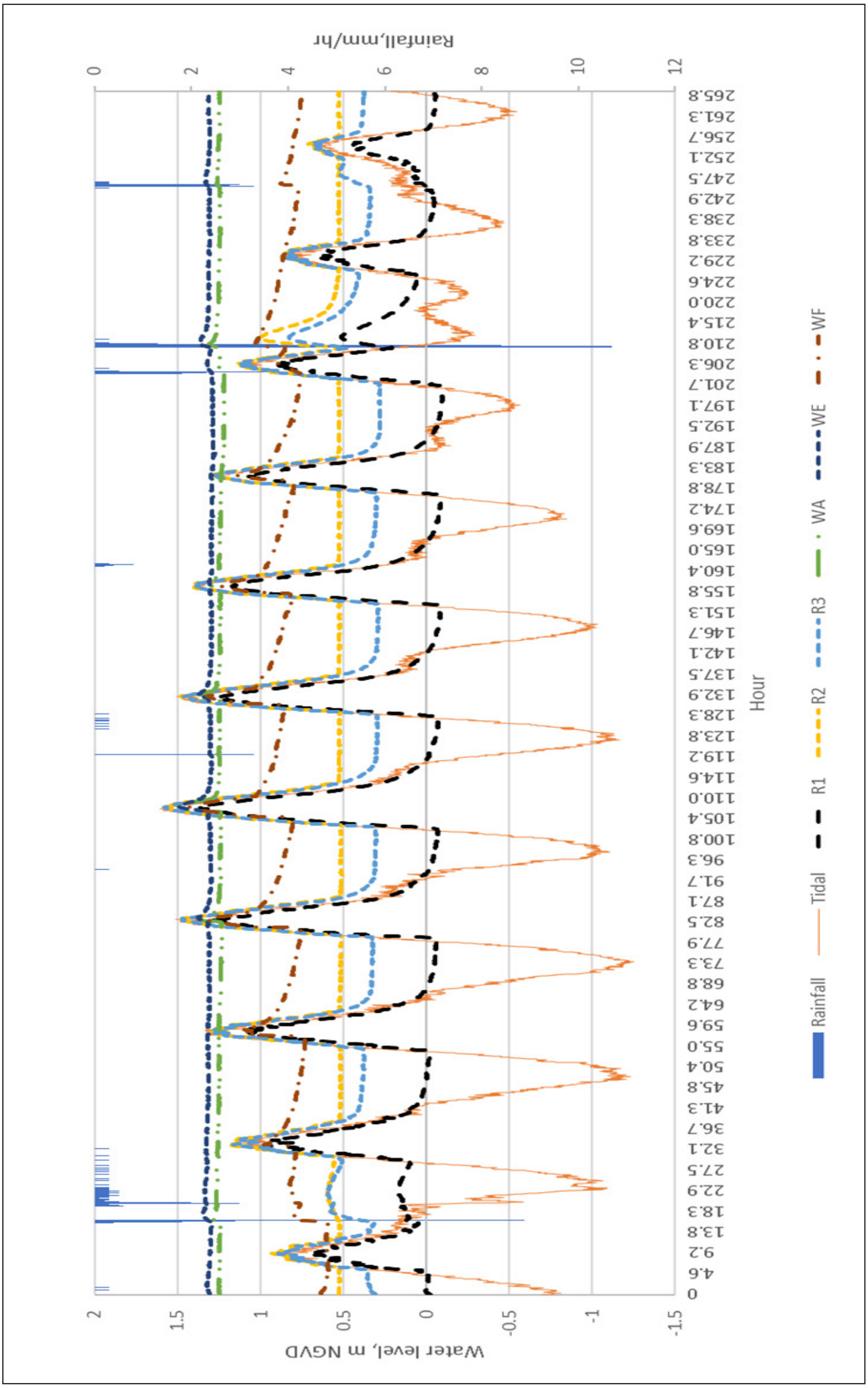

Figure 6. Water levels of low-ground wetland stations (WA, WE, and WF) and river stations (R1, R2 and R3) during non-monsoon season
Notes. The 0-hour starts at 10:50 pm on 10 July 2022. The 264.3 hours period ends at 11:05 pm on 21 July 2022

coefficients of 0.45 ($p< 0.001$), 0.49 ($p< 0.001$), and 0.52 ($p< 0.001$) for R1, R2 and R3. In comparison, these correlation values were significantly higher than those of WB, WC, and WD, indicating that river water fluctuations influenced the lower area of the wetland more.

WE water level ranged from 1.282 m to 1.493 m NGVD and WA, 1.216 m to 1.514 m NGVD in response to the spring tide event in mid-July that reached 1.510 m NGVD. Their water levels showed very little change over time throughout the observation period. In contrast, the WF groundwater level showed fluctuations that corresponded closely to river water level changes, as indicated by its stronger correlations. WF was located on lower ground compared to WE and WA. Unlike WE, it was beside the river, and there was no embankment to impede river overflow. Thus, WF was very susceptible to inundation through direct overflow from the river, and this emphasised the effect of topography and man-made structures like an embankment. The recorded amount of rainfall was just 113.2 mm starting from 10 to 21 July 2022 (10:50 pm and 11:05 pm, respectively), which could not have generated high upstream flows that would have elevated river levels hence high tides were the essential cause of groundwater rise and even inundations (Hsieh et al., 2020). Rainfalls did not have a significant effect.

High Ground-level Stations During Early Monsoon Season

During the monsoon season, changes in river water levels caused slight changes in the water level at three high-ground wetland stations (WB, WC, and WD), just like the non-monsoon season. The average correlation between groundwater and river levels was 0.22. It was stronger than the non-monsoon condition but still a weak one. Figure 7 shows small changes in groundwater water levels during rainfalls, but they were generally insignificant, just like in the non-monsoon conditions.

WB groundwater level rose from 1.578 m to 1.669 m NGVD, showing a bigger change compared to WC and WD. Notably, the salinity range found at this station was in the freshwater category, with a reading of 0.28 ppt. This low salinity was due to the area being closed to a nearby drain that discharged stormwater from the beach ridge and sub-surface flow from the ridge (Figure 2). These were freshwater recharges. The study showed that there was a weak relationship between the station in the wetland and the river stations, with R1 ($r=0.26$, $p< 0.001$), R2 ($r=0.28$, $p< 0.001$), and R3 ($r=0.37$, $p< 0.001$). This discovery suggests that variations in river water levels have a minor influence on the water level of the WB, and the fact that the wells remained fresh indicated no significant saline intrusion into this area.

The correlation coefficients for R1 ($r=0.21$, $p< 0.001$), R2 ($r=0.22$, $p< 0.001$), and R3 ($r=0.25$, $p< 0.001$) with WC showed that the WC station had a weak hydraulic connection to the river station. The high-water levels in WC range from 2.068 m to 2.10 m NGVD compared to the other wells, suggesting that it was a recharge area receiving groundwater

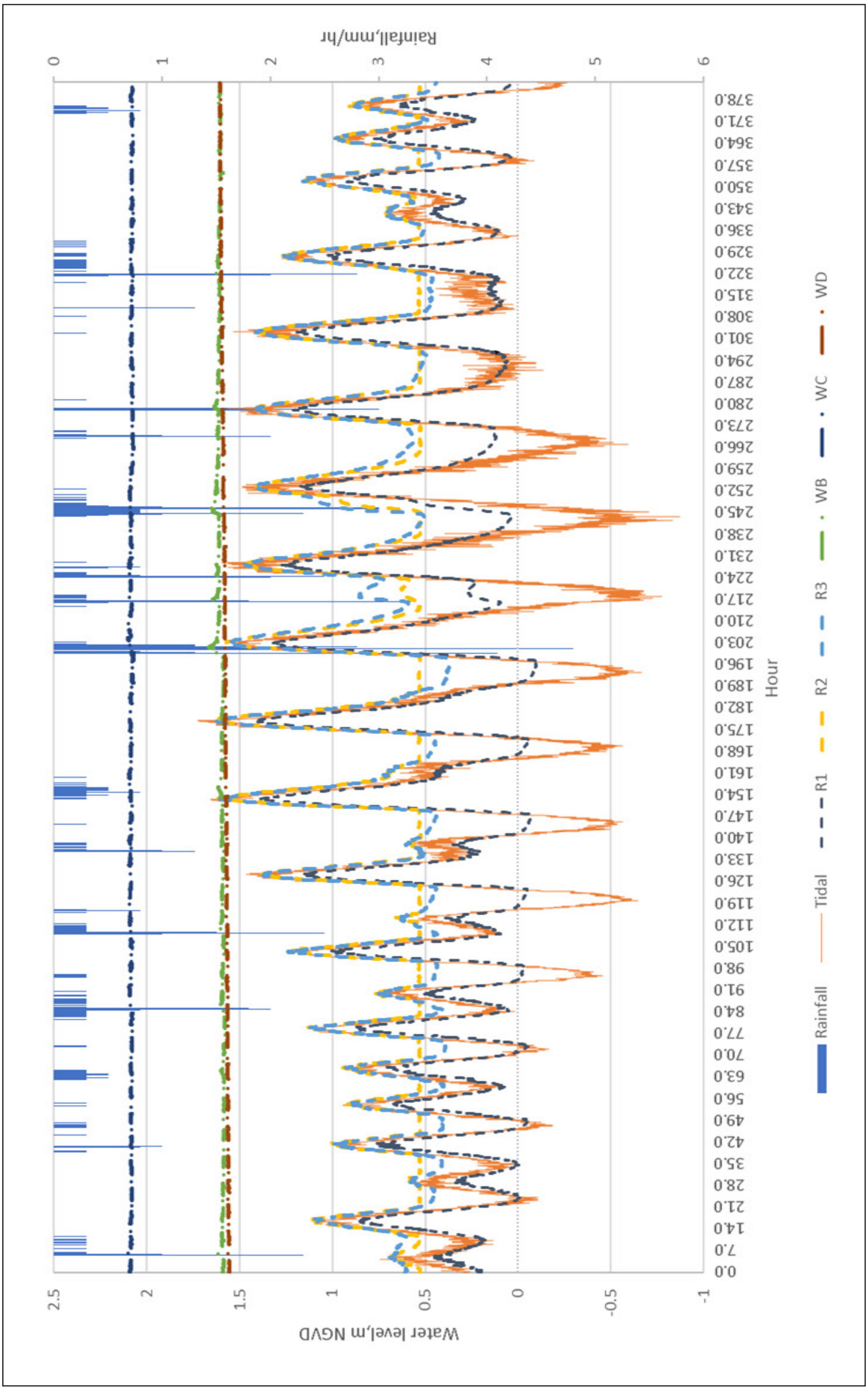

Figure 7. Water levels of high-ground wetland stations (WB, WC, and WD) and river stations (R1, R2 and R3) during the monsoon season
Note. The 0-hour period starts at 2:00 pm on 22 October 2022, and the 378-hour period ends at 8:00 am on 7 November 2022

from the beach ridge. WC was the closest well to the ridge. Ridges are active rainfall recharge areas with high hydraulic conductivity that could transfer sub-surface water downslope since they are made of sand (Sathiamurthy et al., 2021).

The WD station water level ranges from 1.551 m to 1.610 m NGVD, which also results from ridge recharge. The relation of WD to R1, R2, and R3 were positive just like WC but weaker (i.e. $r=0.12$, $p< 0.001$, $r=0.10$, $p< 0.001$, and $r=0.13$, $p < 0.001$, respectively). Also, the salinity of the groundwater ranged between 0.126 ppt to 0.115 ppt, which means it was not affected by the tidal intrusion but received freshwater from rainfalls and ridge sub-surface input (Abdullahi & Garba, 2016).

Early in the monsoon season, the study area received moderate rainfalls of 245.3 mm (22 October 2022, 2:00 pm to 7 November 2022, 1:50 pm). The WD station indicated no influence from the fluctuation of the river water, which means tidal activity had little impact. Meanwhile, WC and WB stations fluctuated after rainfall (total rainfall: 42.4 mm, 30 to 31 October 2022, 9:35 pm and 1:20 am, respectively) (Figure 6). The WB station was exposed to the storm drain, which accumulated rainfall surface runoffs in the wetland station and increased the water level. Meanwhile, the WC received sub-surface water from the ridges.

Low Ground-level Wetland Stations During the Early Monsoon Season

All stations were affected by river water level changes and rainfall events, especially WF. They had an average correlation of 0.54 with river water levels. The water level range of WF was 1.551 m to 1.610 m NGVD and had a strong positive correlation with river stations, i.e. R1 ($r= 0.66$, $p < 0.001$), R2 ($r=0.72$, $p < 0.001$), and R3 ($r= 0.75$, $p < 0.001$). High tides caused increases in the water levels of R3 and led to an overflow into the WF area when the water level exceeded the ground level (Meng et al., 2022). The water level of R3 needed to reach 1.2 m NGVD for this overflow to occur, as shown in Figure 8.

There was a moderately strong positive link between WA and R1 ($r=0.55$, $p< 0.001$), R2 ($r=0.62$, $p< 0.001$), and R3 ($r=0.61$, $p< 0.001$). Its water levels rose during the spring tide. This observed rise in water levels coincided with increased salinity ranging from 2.759 ppt to 3.368 ppt, indicating saline intrusions. Outside the monsoon season, the water level ranged from 1.216 m to 1.514 m NGVD. Water levels during the early monsoon season ranged from 1.237 m to 1.553 m NGVD, showing small changes. The water table in the area affected by the flooding remained high, causing saturation (Mitsch & Gosselink, 2015).

WE had a stronger positive relation to R1 ($r=0.60$, $p< 0.001$), R2 ($r=0.65$, $p< 0.001$), and R3 ($r=0.66$, $p< 0.001$). Water levels at this station varied from 1.276 m to 1.535m NGVD, depending on the effect of tidal fluctuations in the river. When the river flow increased, the water level rose. Its salinity rose from 5.543 ppt to 6.461 ppt during spring tides, indicating saline intrusion. Low ground level and a high-water table near WE caused the area to flood often, hence lacking storage for extra flood water. (Jolly et al., 2008).

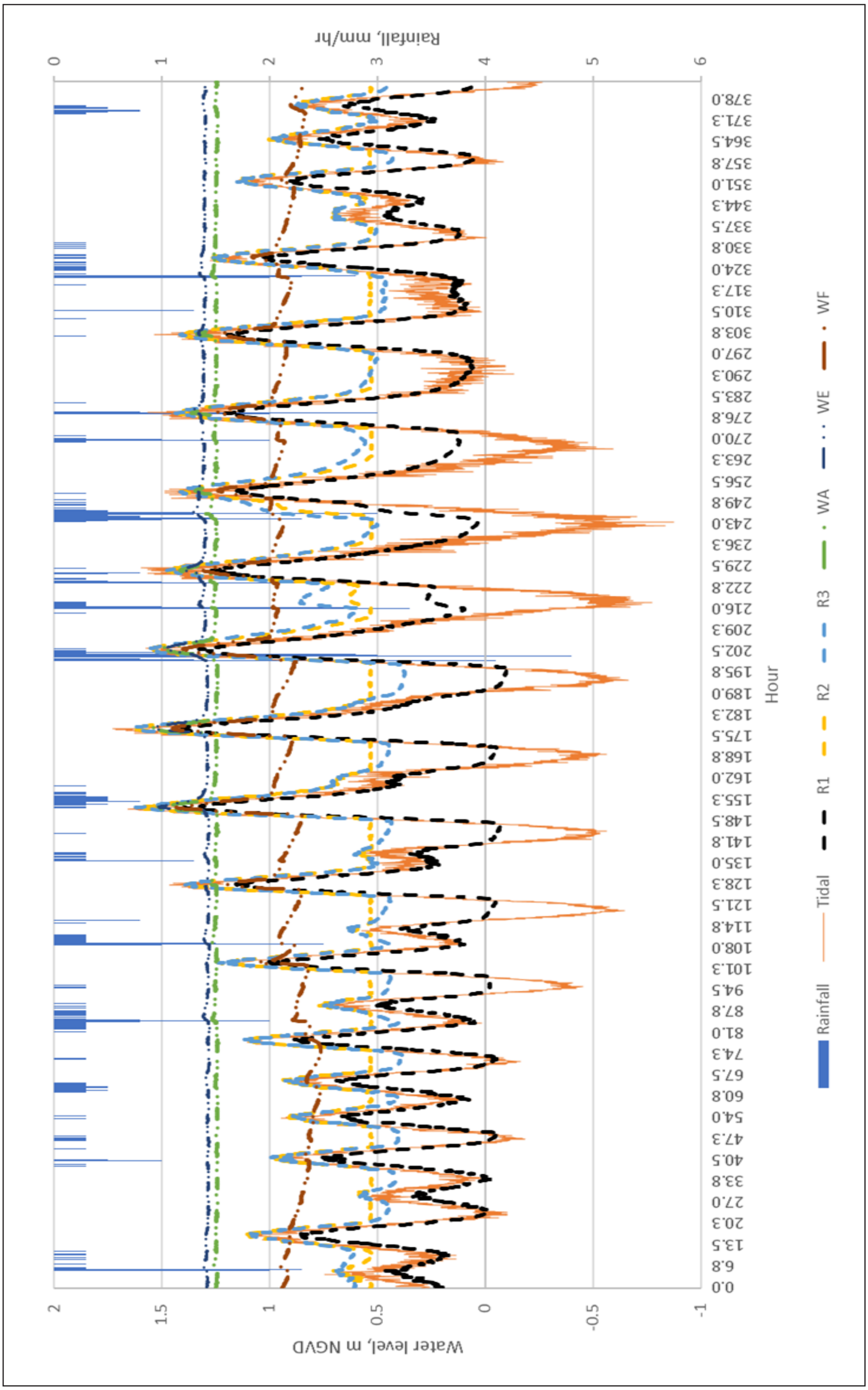

Figure 8. Water levels of low-ground wetland stations (WA, WE, and WF) and river stations (R1, R2 and R3) during the early monsoon season

Note. The 0-hour period starts at 2:00 pm on 22 October 2022, and the 378-hour period ends at 8:00 am on 7 November 2022

Rainfalls amounting to 245.3 mm, 22 October 2022, 2:00 pm to 7 November 2022, 1:50 pm, coinciding with high spring tides elevated river levels affecting all low-ground wetland stations. The river level fluctuation affected the WF station, indicating a corresponding oscillation. In comparison, the WA and WE stations were affected only during spring tides with several inundation episodes.

High Ground-level Wetland Stations During Mid-monsoon Season

A flood event occurred during the mid-monsoon season and reached this wetland section. It was during neap tide; hence, it was not the result of high tidal levels but of river flood flows (Figure 9). Notably, the salinity found at this station was in the freshwater category, with a reading of 0.288 ppt. The higher section of the wetland received river surface overflows. The WB station recorded a water level range of 1.521 m to 2.341 m NGVD (flood event). The WB station showed strong significant correlations with R1 ($r=0.50$, $p< 0.001$), R2 ($r=0.66$, $p<0.001$), and R3 ($r=0.63$, $p< 0.001$). The R2 station was destroyed during this season due to very strong water flow (refer to Water Level Measurement). As this station was near the storm drain, this area received high stormwater discharge from the beach ridge, and sub-surface flow from the ridge entered the wetland, which was separated from the river overflows.

At the WC station, the water level ranged from 2.041 m to 2.314 m NGVD. This station had a moderately weak positive correlation with R1 ($r=0.30$, $p< 0.001$), R2 ($r=0.44$, $p<0.001$), and R3 ($r=0.41$, $p< 0.001$), showing that WC had a weak hydraulic connection to the river station. During this season, high rainfall amounts (1056.1 mm) from 4 December 2022 (1:25 pm) to 1 January 2023 (10:55 pm) recharged the beach ridge near the WC station, creating excessive subsurface water from the beach ridges.

The water level in the WD station ranged from 1.639 m to 2.379 m NGVD. This station showed weak correlations with R1 ($r= -0.02$, $p = 0.135$), R2 ($r = 0.10$, p 0.001), and R3 ($r = -0.06$, p 0.001). Also, the salinity ranged between 0.07 ppt and 0.10 ppt, which means it was not affected by tidal intrusion despite receiving river flood overflows from R2 and subsurface input.

As recorded during the middle monsoon season, the water level in high-ground-level wetland stations was affected by the water level from the R2 station (Figure 9). The high rainfall amount (668.9 mm) from 4 to 19 December 2022 (1:25 pm and 12:00 pm, respectively) led to the flood event. However, the rainfall amount from 19 to 23 December 2022 was 387.2 mm, which did not increase the groundwater level stations. However, WB and WC station water levels decreased right after the flood event receded, while WD remained with high water levels. WD station was behind an embankment composed of low hydraulic conductivity material (i.e. clay), which slowly discharged water back into the river. This indicated that ground elevation was not solely responsible for retaining water

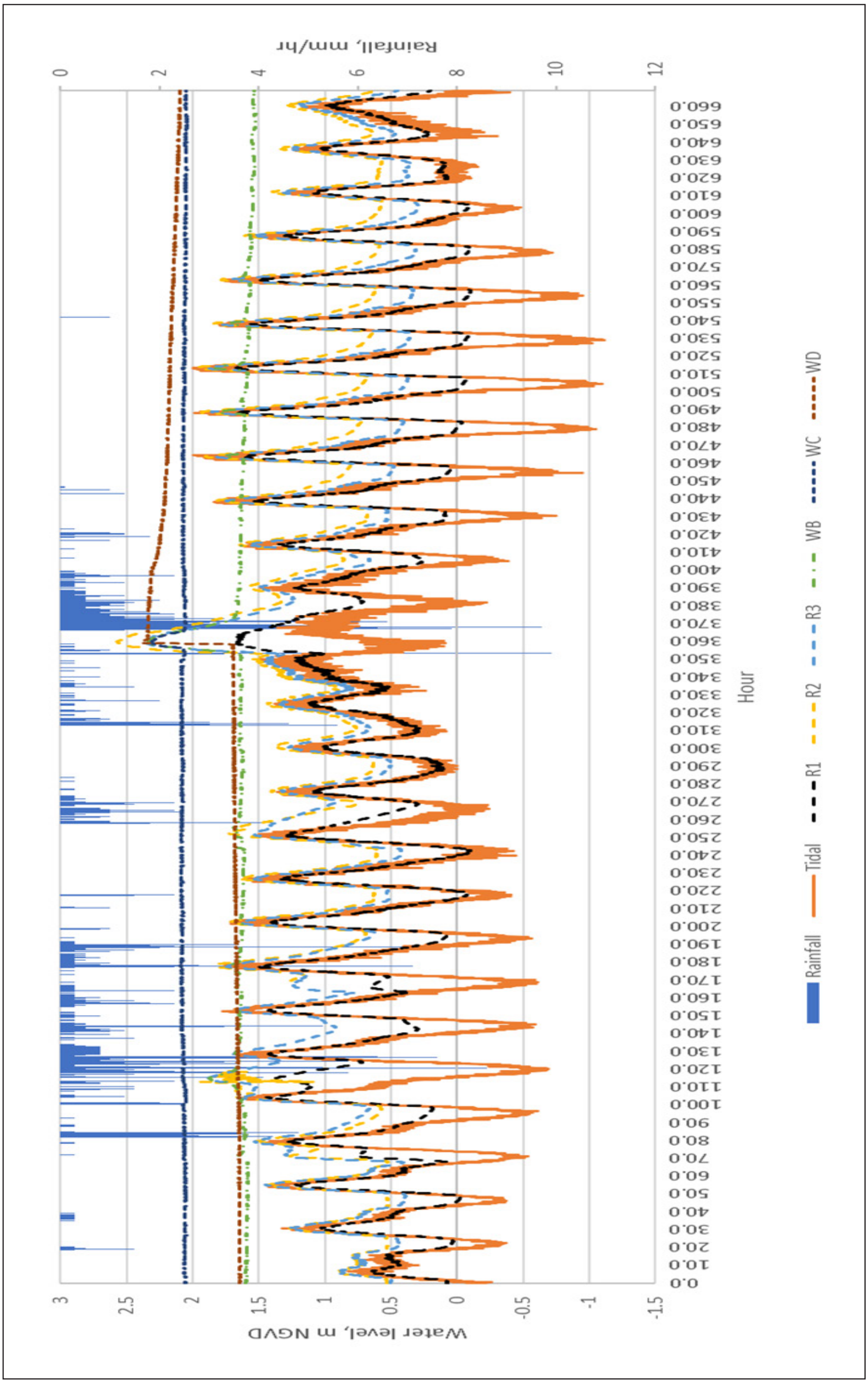

Figure 9. Water levels of high-ground wetland stations (WB, WC, and WD) and river stations (R1, R2 and R3) during the middle monsoon season
Note. The 0-hour starts at 1:25 pm on 4 December 2022, and the 660-hour ends at 1:25 am on 1 January 2023

within the wetland, but the soil texture also influenced it. Moreover, the embankment demonstrated the anthropogenic effect on the natural ecosystem.

Low Ground-level Wetland Stations During the Mid-monsoon Season

Both high tides and rainfall events impacted all stations. The water level of WA ranged from 1.234 m to 2.315 m NGVD during the flood event (Figure 10). WA stations got excess water from R3, as the R3 water level was at 2.360 m NGVD, making the water flow from R3 to WA. There was a strong correlation between this station and R1 ($r = 0.67$, $p < 0.001$), R2 ($r = 0.79$, $p<0.001$), and R3 ($r = 0.75$, $p < 0.001$). The salinity range at this site varied from 2.924 ppt to 4.113 ppt due to dissolved minerals in the natural environment of freshwater.

The WE station's initial water level measurement was 1.863 m NGVD. However, the water level rose to 2.304 m NGVD during the flood. This station exhibited a positive correlation with R1 ($r=0.64$, p 0.001), R2 ($r=0.77$, p 0.001), and R3 ($r=0.73$, p 0.001). The salinity at this site ranged from 8.126 ppt to 10.186 ppt, indicating some saline intrusions.

The correlation coefficients between WF and R1 ($r=0.79$, $p< 0.001$), R2 ($r=0.88$, $P<0.001$), R3 ($r=0.85$, $p < 0.001$) were all strong positive. During flood events, the WF water level ranged from 1.737 m to 2.171 m NGVD. The rise in river water levels during the flood increased groundwater levels at low ground-level stations.

During the middle monsoon season, the low ground-level wetland stations were affected by river overflows. The high rainfall amount (668.9 mm) from 4 to 19 December 2022 (1:25 pm and 12:00 pm, respectively) led to the flood event (Figure 10). However, the water levels of WA, WE, and WF stations decreased after the flood, following the decrease in river water levels. This showed that the low ground-level stations discharged excess water quickly and had a short flood retention time. From 19 to 23 December 2022, rainfalls (387.2 mm in total) and a transition from neap to spring tides caused the groundwater level to increase. These low ground-level wetland stations were affected by spring high tides primarily after that, as there was essentially no rainfall event (Figure 10).

There are no previous studies on coastal BRIS wetland hydrodynamics for direct comparison. Nonetheless, an indirect comparison can be made with peatlands. Peatlands are rain-fed, and coastal BRIS wetlands are essentially river-fed, as demonstrated by the results of these studies. Research on peatlands in Kuantan, Pahang, and West Kalimantan, Indonesia, demonstrated a clear seasonal water retention pattern during the northeast monsoon (Wetland International, 2010; Marwanto et al., 2018). In contrast, in this study area, wetland groundwater level changes coincided with changes in river water levels caused by tidal intrusions/recessions and upstream river flow. Hence, coastal BRIS wetlands might not be able to retain water for prolonged periods like peatlands.

Table 2 summarises water level measurements across the non-monsoon, early monsoon, and mid-monsoon seasons for wells on higher and lower wetland grounds. Table 3 shows

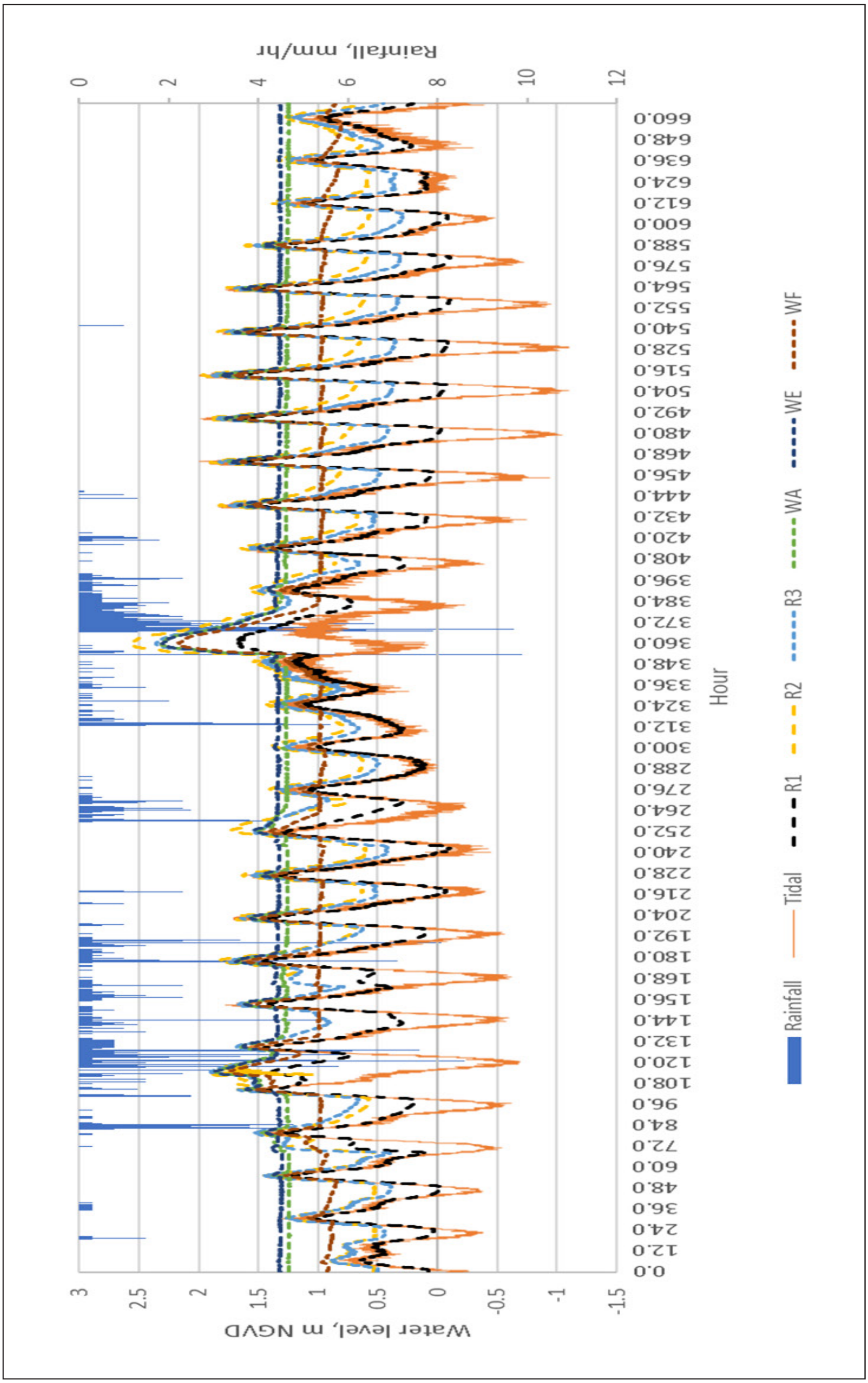

Figure 10. Water levels of low-ground wetland stations (WA, WE, and WF) and river stations (R1, R2 and R3) during the middle monsoon season
Note. The 0-hour starts at 1:25 pm on 4 December 2022, and the 660-hour ends at 1:25 am on 1 January 2023

the correlations between wells, river stations and tidal data. The elevated ground locations were near the ridge line of the beach ridge, whereas the lower ground sites were positioned adjacent to the river. This investigation revealed that the quantity of rainfall significantly influenced high-ground-level stations. These stations received rainfall recharge via sub-surface flow from the ridge area. The ridge consisted of sand sediments; hence, it has a high infiltration rate and hydraulic conductivity, creating higher sub-surface flow compared to surface runoffs. In comparison, river water levels primarily influenced low-ground level stations, which correlated with tidal fluctuations. Table 2 also indicates the percentage change in water level by comparing average levels during the mid-monsoon season with those observed during the non-monsoon season.

These variations indicated the water level retained during the mid-monsoon period at each station. WF stations demonstrated a notably higher percentage change, followed by WD stations. WF station was located at a low ground level adjacent to the river. While the WD station was located at a high ground level, the groundwater level was affected by sub-surface flow from the adjacent ridges. This suggests that water from the ridges moves downwards through the subsurface, recharging the groundwater at the WD station. The river`s tidal fluctuation influenced the groundwater level indirectly, as indicated by a weaker correlation between tidal and groundwater levels, with an average of r = 0.22. In contrast, tidal and river water levels showed a strong average of r = 0.81 (Table 3). River water levels generally rose during high tide and fell during low tide, except for flooding caused by upstream outflows resulting from heavy rainfalls. This phenomenon is

Table 2
Water level ranges, averages and changes during non-monsoon, early monsoon, and middle monsoon seasons at high ground level wetland stations and low ground level wetland stations

Station / Ground level	**WC 2.02**	**WD 1.63**	**WB 1.60**	**WA 1.30**	**WE 1.21**	**WF 1.09**
	High-ground-level wetland stations			**Low ground-level wetland stations**		
Water level Non-monsoon season	1.967–2.091 (2.042)	1.554–1.638 (1.577)	1.475–1.658 (1.563)	1.216–1.514 (1.251)	1.282–1.493 (1.310)	0.589–1.431 (0.861)
Water level Early monsoon season	2.068–2.10 (2.084)	1.551–1.610 (1.580)	1.578–1.669 (1.602)	1.237–1.553 (1.257)	1.276–1.535 (1.302)	0.761–1.451 (0.937)
Water level Middle monsoon season	2.041–2.314 (2.070)	1.639–2.379 (1.908)	1.521–2.341 (1.628)	1.234–2.315 (1.327)	1.296–2.304 (1.381)	0.804–2.171 (1.072)
Water level changes	0.028	0.331	0.065	0.076	0.071	0.211
Water level changes (%)	1.37	20.98	4.15	6.07	5.41	24.50

Notes. Values in brackets are average water levels. All water levels and ground levels are in meter NGVD. Water level changes in meters were determined by subtracting the average water level during the non-monsoon season from the average of the middle monsoon season.

Table 3
Water level correlation analysis of river station (R1–R3) wetland station (WA–WF) and tide station during three different seasons: (A) the non-monsoon season, (B) early monsoon season and (C) middle monsoon season

A	**Tidal**	**R1**	**R2**	**R3**	**WA**	**WB**	**WC**	**WD**	**WE**	**WF**
Tidal	NR									
R1	0.86	NR								
R2	0.76	0.96	NR							
R3	0.81	0.99	0.97	NR						
WA	0.32	0.48	0.52	0.52	NR					
WB	-0.06	0.04	0.01	0.09	0.32	NR				
WC	-0.01	0.13	0.09	0.15	0.26	0.58	NR			
WD	-0.01	-0.12	-0.12	-0.08	0.01	0.33	-0.31	NR		
WE	0.27	0.45	0.49	0.52	0.87	0.56	0.39	0.10	NR	
WF	0.44	0.59	0.66	0.61	0.54	-0.11	-0.13	-0.05	0.38	NR
B	**Tidal**	**R1**	**R2**	**R3**	**WA**	**WB**	**WC**	**WD**	**WE**	**WF**
Tidal	NR									
R1	0.92	NR								
R2	0.85	0.97	NR							
R3	0.83	0.97	0.98	NR						
WA	0.44	0.55	0.62	0.61	NR					
WB	0.10	0.26	0.28	0.37	0.27	NR				
WC	0.15	0.21	0.22	0.25	0.28	0.06	NR			
WD	0.08	0.12	0.10	0.13	0.02	0.63	-0.35	NR		
WE	0.46	0.60	0.65	0.66	0.93	0.45	0.20	0.23	NR	
WF	0.50	0.66	0.72	0.75	0.78	0.51	0.24	0.22	0.81	NR
C	**Tidal**	**R1**	**R2**	**R3**	**WA**	**WB**	**WC**	**WD**	**WE**	**WF**
Tidal	NR									
R1	0.84	NR								
R2	0.70	0.94	NR							
R3	0.70	0.96	0.97	NR						
WA	0.32	0.67	0.79	0.75	NR					
WB	0.17	0.50	0.67	0.63	0.87	NR				
WC	0.09	0.30	0.45	0.41	0.58	0.81	NR			
WD	-0.02	-0.02	0.14	-0.06	0.12	0.02	-0.11	NR		
WE	0.31	0.64	0.77	0.73	0.99	0.89	0.62	0.11	NR	
WF	0.47	0.79	0.88	0.85	0.95	0.80	0.53	0.06	0.93	NR

Notes. Underscored numbers have a p-value equal to or greater than 0.05, indicating an insignificant correlation. The rest of the results are significant because the p-values are less than 0.05. If the r value is near +0.5, it means a moderate corresponding relationship. If the r value is near -0.5, it means a moderate inverse relationship. If the r value is near +1, it means a strong corresponding relationship. If the r value is near -1, it means a strong inverse relationship. If the positive r value is near 0, it means a weak corresponding relationship. If the negative r value is near 0, it means a weak inverse relationship understandable as the rivers are connected to the sea as open channels and hence exposed to daily tidal intrusions and recessions. In contrast, wetland groundwater was flowing through the wetland's sediment layer. In comparison, the lower section of the wetland was more influenced by river water level changes than the higher section. During the non-monsoon season, the average correlation between the low-ground wells (WA, WE and WF) with river water levels was 0.54 (r ranged from 0.45 to 0.66). In contrast, the high ground stations (WB, WC and WD) were just 0.02 (r ranged from -0.12 to 0.15) and showed negative correlations. During monsoon season, the lower section was even more influenced, with an average strong r of 0.76. The higher section also experienced greater hydraulic connectivity, as demonstrated by a higher average r of 0.34.

CONCLUSION

Rainfalls and river water levels influenced the behaviour of BRIS coastal wetland groundwater levels during both non-monsoon and northeast monsoon seasons. The study's results indicated that tidal oscillations had a strong correlation with river water level changes, with correlation coefficients (r) ranging from 0.7 to 0.92 and an average of 0.81. This strong relationship is characteristic of tidal rivers, where tidal oscillation significantly modulates river water levels. However, the effect of tidal oscillations on groundwater level changes was found to be relatively weak, with an average correlation coefficient of 0.22. This weak correlation suggests that tidal oscillations partially influence groundwater levels, primarily through their effects on river water levels, which propagate into the subsurface hydrological system. River water levels, although strongly influenced by tidal oscillations, were also found to be dependent on upstream flows, particularly during periods of increased rainfall. This dual dependence highlights the role of upstream discharge in modulating river hydrodynamics and, consequently, their influence on the surrounding wetland.

The lower section of the wetland, as evidenced by data from monitoring wells (WA, WE, and WF), exhibited a stronger response to river water level changes, with an average correlation coefficient of 0.54. During the monsoon season, this influence became even more pronounced, with the average correlation increasing to 0.76. This heightened connectivity during monsoon conditions was likely due to elevated river water levels caused by increased upstream discharge from heavy monsoonal rainfall, which enhanced hydraulic connectivity between the river and the wetland. In contrast, the higher section of the wetland, located nearer to the ridge, showed a much weaker influence from river water levels, with an average correlation coefficient of 0.18. However, even in this elevated region, the influence of river water levels increased during the monsoon season, with the average correlation rising to 0.34. This suggests that during periods of high rainfall and elevated river levels, the hydraulic connectivity between the river and the higher section of the wetland increases, allowing for greater interaction between surface and subsurface water systems. The study also revealed that fluctuations in river water levels, largely driven by tidal oscillations, are crucial in regulating the wetland's groundwater dynamics, irrespective of the season.

However, the overall groundwater level changes in the wetland were generally limited to approximately 0.5 m below ground level. This limited fluctuation indicates that the wetland system is relatively shallow and constrained in its capacity to store or regulate large volumes of water. Furthermore, low-lying areas adjacent to the rivers were frequently observed to be either saturated or inundated, particularly during high river levels or flood events. This persistent saturation of the wetland soil reduced its ability to act as a prolonged floodwater retention system, further highlighting its limitations as a natural flood mitigation mechanism. Given these findings, the BRIS wetland's effectiveness in retaining flood waters and controlling floods might be significantly constrained by its shallow groundwater table and high degree of soil saturation. These limitations were particularly evident during periods of heavy rainfall and flooding when the capacity for water storage in the vadose zone exceeded. Future research could investigate the impact of soil texture, porosity, and infiltration rates on the hydrodynamic behaviour of BRIS wetlands. Such studies would provide valuable insights into the physical properties of the wetland soil and their influence on water retention capacity, potentially contributing to developing strategies to enhance the flood control functionality of BRIS wetlands.

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