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Hydraulic circulation of the tides in Lac Bay, Bonaire

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In Lac Bay, Bonaire, a part of the mangrove forest is dying partly because of reduced water circulation through the forest. Tidal waves are the main drivers of the water circulation in the forest. In this study, the tidal behaviour is analysed based on water depth measurements from earlier studies in 2012 in Lac Bay. Time series are used to determine the tidal range (difference between minimum and maximum water depth), the dominant tidal constituent (harmonic analysis) and the water circulation through the forest (difference between the timing of highest water depth).

The results show that locations close to open water in the bay have on average a large tidal range (27.8-28.1 cm) than locations in the forest (3.4-8.1 cm), with limited to no seasonal fluctuations. The dominant tide in Lac Bay is the lunisolar diurnal constituent (K1). Water depth changes from stations close to open water could be explained reasonably but in other locations they were distorted by the forest and could not be fully explained. It was found that the water moves slowly through the forest in a circular manner, moving around the islands and through the forest, thereby creating a delay in high water depths up to five-and-a-half hours.

Key words: Mangroves; Lac Bay; Water depths; Tidal range; Dominant tide; Tidal constituents

1. Introduction

Approximately 90 kilometres north of the Venezuelan coast lies the island of Bonaire (Caribbean Netherlands). The touristic island is known for its beautiful nature reserves and protected areas. An important nature reserve is Lac Bay, a lagoon in the southeast of Bonaire. The area includes a mangrove forest on the landward side, seagrass, and a coral reef located at the seaside. Lac Bay is declared a RAMSAR site and under the protection of STINAPA (MacRae & de Meyer, 2006).

For the entire year the wind comes predominantly from the east (Windfinder, 2022) and this causes higher wave energy on the east side of the island than on its west side (MacRae & de Meyer, 2006). Although the wind is coming from the same direction all year, its strength does vary over the seasons.

Waves break on the coral reef at the seaside of Lac preventing severe wave action in Lac (Vreugdenhil, 2013). At high tide there is an inflow of water into Lac over this coral reef while at low tide the water is mostly flowing out through a deep, shallow opening of Lac next to the coral reef (Meijer & van Moorsel, 1993). The inflow in Lac originates from a current starting in the Atlantic waters flowing into the Caribbean Basin (MacRae & de Meyer, 2006). Grützmacher et al. (2020) observes that in Lac there is a dominate surface current directed northeast while current in deeper layers are directed southeast. Water passes over the coral reef and flows back through the deep part of the entrance of the bay. Earlier research by Meijer & van Moorsel (1993) and Lott (2001) indicated that there is a difference in high tide throughout Lac Bay. The latter researcher reported that the high tide time difference has grown over the years.

During a tidal cycle it is not completely clear how the water propagates in the shallow areas of Lac Bay. What is clear is that the water is able to reach the back of the forest since variations in water depths are observed with some relation to the tides. This is important since the mangrove forest is slowly dying in the back due to reduced circulation of water in the backwaters and a heavy sediment load. The reduced circulation is caused by mangrove growth in the creeks present the forest (Grützmacher et al., 2020).

The 'Mangrove Maniacs' are clearing old, clogged creeks to improve the water circulation and hope to call the starvation of mangrove trees to a halt while maintaining the biodiversity. Mangroves found in Lac Bay are the Red mangrove (*Rhizophora mangle*), the Black mangrove (*Avicennia germinans*) and the White mangrove (*Laguncularia racemose*) (MacRae & de Meyer, 2006). Together the Black and Red mangrove make up 99% of the total population while the White mangrove is only found occasionally. Mangroves provide multiple services to their surroundings which makes them important to protect. They reduce flood risk, provide shelter for fish and shellfish, provide food to humans, sequestrate carbon and can also be an important source of income because of ecotourism (Gijsman et al., 2021).

Lac Bay is a dynamic system driven by tidal- and wind-driven circulation, sediment dynamics and ecological processes. To protect the area the hydrodynamic processes that steer these dynamics must be understood such that appropriate measures can be taken. Several studies have been done on Lac Bay, but these studies have focused mainly on its ecological functioning (Grützmacher et al., 2020). Research is required to understand the hydrodynamic behaviour of the tides, to form new theories or models for the protection of Lac Bay. As an addition to earlier research analyses of previous water depth data are done. This will help support understanding the hydraulic circulation in the area. The basis for this research is the MSc thesis by Lodder (2013) who already calculated the average water depth and the water depth range per day but did so without smoothening the data.

The goal of this study is to describe the behaviour of the hydraulic circulation in Lac Bay. This will be done based on the following steps. First the tidal range for different locations in Lac Bay will be studied. Secondly, the dominant tide for Lac Bay and the differentiates per location will be determined. Lastly the tidal-driven circulation of the water through the bay will be investigated.

2. Methods

Water depth data measured by earlier research is the data that will be analysed (Vreugdenhil, 2013). This research will only look at the study site of Lac Bay, Bonaire. The available data covers a period from January 2012 to January 2013.

2.1. Data

Data is obtained from earlier research conducted by a team of researchers Wageningen in 2012. The study was originally planned two years earlier (Debrot et al., 2010). During the research period 10 measurement station were put in Lac Bay, namely at: Cai, Rooi Grandi, Isla Rancho, Punta Rancho, Mangrove center, Awa "D", Awa Yuwana, Awa Fogon, Awa Yanapa and Isla di Chico. These locations can be found in Figure 1.

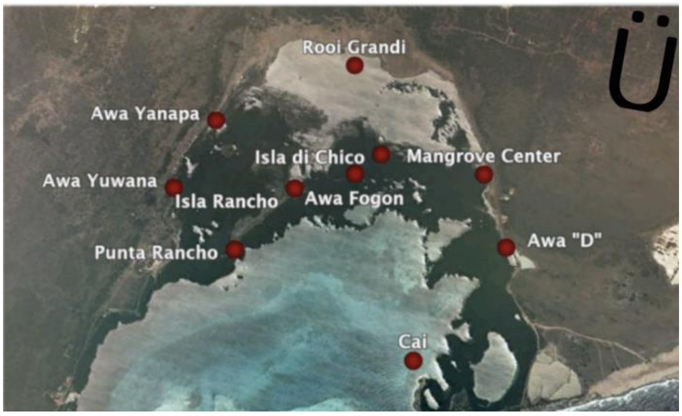

Figure 1: Locations of the measurement station in Lac Bay (Vreugdenhil, 2013)

The measurement data generated includes: date (dd-mm-yy), time (hh:mm), pressure (cm), temperature (C), air pressure (cm), water column (cm), water level above soil (cm) (referred to in this research as 'water depth') and settings of the used instruments. The sample period, for most of the data, was 15 minutes. Some measurement stations did not start with the measurements from the start of the research but started measuring later in 2012. Table 1 shows the start and end date of each measurement station including data gaps. From 18 April till 13 May there is no water depth data available which causes a gap in the overall time series.

The data contained some outliers. These are most likely errors in the measurements of the instruments since the water depth will not change 50 cm in 15 minutes at this study site. Therefore, outliers with unrealistic water depth changes in a short time period were removed from the dataset.

Many of the outliers for multiple measurements stations were found on May 31, 2012 between 22:00 and June 1st 01:00. These could be due to a storm or a software problem creating incorrect values. The same happened between July 31 22:00 and August 1st 00:00.

Table 1: Timing datasets of the measurement stations in Lac Bay

Measurement station	**Start date**	**End date**	**Gap**
Cai	01-01-2012	16-01-2013	18-04-2012 : 13-05-2012
Rooi Grandi	01-01-2012	16-01-2013	20-04-2012 : 13-05-2012
Isla Rancho	13-11-2012	16-01-2013	-
Punta Rancho	13-11-2012	16-01-2013	-
Mangrove center	01-01-2012	02-01-2013	20-04-2012 : 13-05-2012
Awa "D"	13-05-2012	02-07-2012	-
Awa Yuwana	01-01-2012	17-01-2013	18-04-2012 : 13-05-2012
Awa Fogon	13-05-2012	25-09-2012	-
Awa Yanapa	03-01-2013	17-01-2013	-
Isla di Chico	13-11-2012	16-01-2013	-

To create a dataset where the noise does not dominate, a 1-D median filtering is applied. A 10th-order (window of 10 timesteps) median was used to smoothen the signal. Figure 2 shows the effect of the smoothening at high tide for measurement station Cai. In the analysis of the dominant tide (section 2.3), the smoothening was not applied since the used program already considers another filtering method.

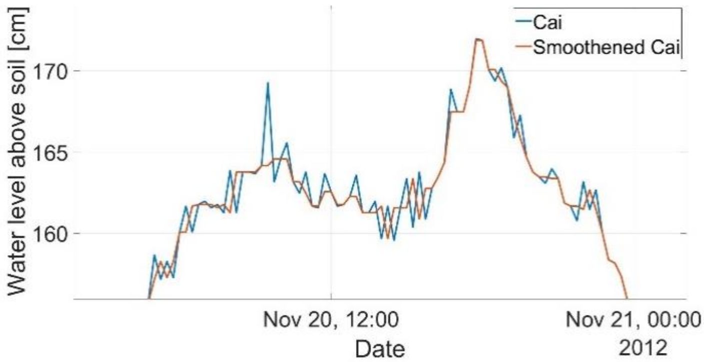

Figure 2: Smoothened water depths at measurement location Cai on November 20th

2.2. Tidal range

Daily maximum and minimum water depth will be extracted from the data. When this is subtracted from each other the tidal range per day will become clear. Since it is known that the tides are linked to the seasons (Meijer & van Moorsel, 1993) a tidal range per month will be estimated to see if there are differences over the year. For the calculations of the monthly tidal range only the measurement locations 'Cai', 'Rooi Grandi', 'Mangrove center' and 'Awa Yuwana' are used since these data covered the entire year (with gaps not exceeding 1 month).

2.3. Tidal dominance

The program 't_tide.m' (Pawlowicz, 2021) was used to do a harmonic analysis of the time series, to determine what the dominant tidal component was. Suitable data was selected because the program tries to explain the variance. Outliers or gaps could not be explained and the timeseries must be continuous. All measurement locations were checked but measurement station 'Cai' was taken as main data set because it is closest to the open sea. This means that the data is less distorted by possible dynamics inside Lac. A latitude of 12.1 degrees was used.

Earlier research indicates that the island has a diurnal tide, but that Lac Bay is slightly different leaning towards a semi-diurnal tide (Lodder, 2013; MacRae & de Meyer, 2006).

A certain tidal constituent (for example M2) must have a signal to noise ratio (snr) of at least 50 to be included in the results. This value is chosen based on the decrease of the explained variance by changing the snr value. Values lower than 50 have an insignificant effect on the observed tidal fluctuations. Some of the datasets have different measurement frequencies for one location. Since this cannot be handled by the program an interval is chosen based on the measurement frequency, either hourly of quarterly. In the results this can be found back as for example 'Cai 1' and 'Cai 2'.

2.4. Tidal-driven circulation through Lac Bay

This research will look into the timing of high tide among different water stations. The timing of largest water depth of each tidal cycle at each measurement station location will be compared between the different measurement stations. High tide at Cai is the reference location/time since the tide will be felt first at that location since it is closest to the sea. To create a timing in relation to Cai, the average time it takes to reach the highest water of a measurement station after the high tide of Cai will be taken. For a certain measurement period the measurement stations need the same number of high tides, otherwise unrealistic gaps appear between the high tides of each location. Also, representative periods for each measurement location must be chosen because an analysis over the entire period would give false results since not all peaks are easy to distinguish. Earlier research focused mainly on the lagoon (Grützmacher et al., 2020; Meijer & van Moorsel, 1993) where in this research also the tides in the mangrove forest will be investigated.

3. Results

3.1. Tidal range and its seasonal component

Table 2 displays the average water level above soil, the water depth range and the average tidal range per location. In Lac Bay, the tidal range is comparable, only at Awa Fogon and Cai the tidal ranges are much higher.

Table 2: Water depth related data per measurement station

Measurement station	Average water level (cm above soil)	Water depth range (cm)	Average tidal range (cm)
Cai	157.3	118.7 - 190.1	28.1
Rooi Grandi	51.2	21.4 - 81.8	5.9
Isla Rancho	32.5	23.1 - 47.1	3.4
Punta Rancho	18.5	2.0 – 33.7	6.9
Mangrove center	43.7	0.0 – 65.2	7.7
Awa "D"	15.7	7.2 – 33.1	8.1
Awa Yuwana	31.2	17.9 – 50.7	6.6
Awa Fogon	61.3	34.9 – 88.9	27.8
Awa Yanapa	52.0	41.1 - 62.5	4.3
Isla di Chico	3.5	0.0 - 16.0	5.2

It is expected that Awa Fogon and Cai have a much larger tidal range since they have a closer link to the open sea than most other locations, which are more in the back of the forest. Meijer & van Moorsel (1993) show similar results: higher tidal ranges at stations near the open water of Lac Bay and smaller tidal ranges to the back of the forest. Punta Rancho would have gotten larger tidal ranges in this dataset based on this theory. However, the measurement location of Punta Rancho is located on the island and is not directly connected to the open water. Therefore, is does not have these larger tidal ranges.

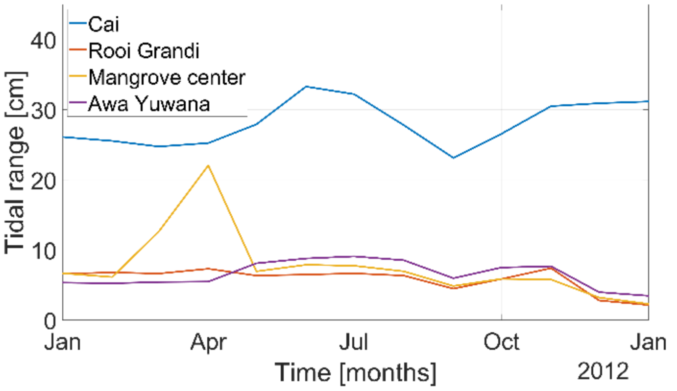

Figure 3: Tidal range per month for measurement stations with data sets longer than four months

The results displayed in Table 2 slightly differ from the results by Lodder (2013) due to smoothening of the dataset but there are no major differences. The water depth range as well as the average tidal range are smaller compared to Lodder (2013).

No clear seasonal change in tidal range is visible (Figure 3). A slight decrease in tidal range in August and January can be seen while in June, July and November the tidal ranges were higher. If these values are not caused by random noise in the data, it suggests that the tidal range increases in the dry season and decreases in the raining season.

3.2. Dominant tide

The results of the harmonic analysis are presented in Table 3. Not the entire table is filled because some datasets were not fit for the data processing of the program. The values for 'snr' and 'Amplitudes' are ordered according to the tides in the column 'Dominant tidal component'. For example, at measurement Cai 1, K1 has a snr value of 11 and an amplitude of 10.1, since they are all the third object in the cell.

Table 3: Dominant tides of all datasets

Dataset	Measurement time	Variance explained (%)	Dominant tidal component	snr values (x10²)	Amplitudes (cm)
Cai 1	01-01-2012 18-04-2012	67.1	O1, P1, K1, M2, S2	5.3, 1.2, 11, 1.2, 0.6	7.0, 3.4, 10.1, 3.8, 2.5
Cai 2	13-05-2012 16-01-2013	82.9	O1, P1, K1, M2	9.5, 1.9, 16, 1.2	6.6, 2.9, 8.7, 3.3
Rooi Grandi 1	01-01-2012 20-04-2012	3.4	S2, K2	23, 1.7	2.4, 0.7
Rooi Grandi 2	13-05-2012 16-01-2013	1.9	K1	0.9	1.5
Isla Rancho	13-11-2012 16-01-2013	-	-	-	-
Punta Rancho	13-11-2012 16-01-2013	-	-	-	-
Mangrove center 1	01-01-2012 20-04-2012	2.5	S2	89	2.6
Mangrove center 2	13-05-2012 02-01-2013	10.0	O1, K1, M2	0.6, 1.2, 0.9	1.2, 1.6, 0.6
Awa "D"	13-05-2012 02-07-2012	-	-	-	-
Awa Yuwana 1	01-01-2012 18-04-2012	6.2	S2, K2	22, 1.6	2.3, 0.6
Awa Yuwana 2	13-05-2012 17-01-2013	15.4	O1, K1, M2, MK3	1.0, 2.2, 1.8, 0.7	1.3, 2.0, 0.8, 0.3
Awa Fogon	13-05-2012 25-09-2012	78.5	O1, P1, K1, M2	10, 2.4, 22, 2.8	6.8, 3.3, 9.9, 3.7
Awa Yanapa	03-01-2013 17-01-2013	-	-	-	-
Isla di Chico	13-11-2012 16-01-2013	-	-	-	-

Starting with answering the research question, K1 (Lunisolar diurnal constituent) seems to be the dominant tidal component. K1 stands out in multiple harmonic analyses and explains a significant part of the variance. This can be seen by the high corresponding values for the snr and amplitude. Other diurnal tidal constituents (O1 and P1) are also important and the only semi-diurnal tidal constituent showing up in the measurements is the M2 tide. Therefore, can be concluded that the tide is diurnal. The M2 tide also has some influence, as can be seen in Figure 4. At spring tide, the diurnal tidal component is dominant but during neap tide the influence of the semi-diurnal tidal component can be seen. The findings that diurnal tides are the dominant tide is not in line with earlier findings by Lodder (2013)and MacRae & de Meyer (2006). They stated that Lac Bay has semi-diurnal tides.

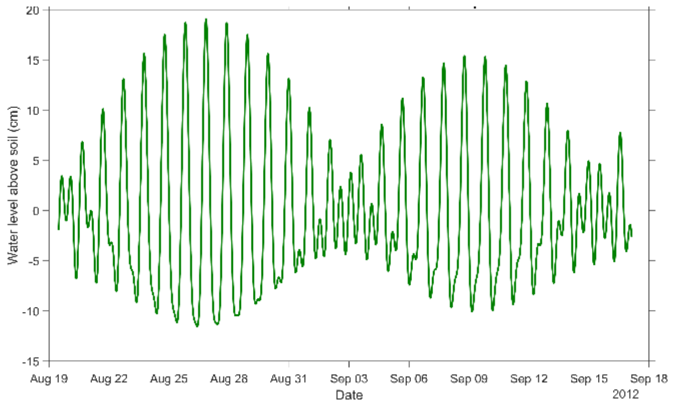

Figure 4: Reconstructed tide of the second time period of Cai by t_tide.m

Only a few measurement stations have an explained variance higher than 50, meaning that more than half of the variance could be explained. It seems that deeper into the forest the signal of the tide becomes weaker. Cai is close to the entrance of the Lac and is therefore expected to have a clearer signal. Awa Fogon is connected to Lac Bay by a creek and is therefore has a good connection with the open water, which causes the high explained variance. Lower explained variance is found by stations at locations on the outer edge of Lac Bay, which do not have a good connection to the open water. This does not mean that those locations are not influenced by the tide, but they are not explained well by the harmonic analysis. Figure 5 shows that Rooi Grandi clearly is influenced by the tides in the bay while the location has a very low explained variance (table 3).

Another reason for the explained variance being low is the low quality of the data in relation to the demands of the software. There are sudden jumps in water depth and sometimes there seems to be a minimum water depth in the data: during a tidal cycle the decreasing water depth does not follow its expected decrease. It stops decreasing before reaching the expected minimum water depth and becomes constant. Both are characteristics of the dataset which a harmonic analysis cannot explain resulting in low explained variances.

3.3. Tidal-driven circulation in between the mangrove trees

Figure 5 shows a clear delay in the moment of the highest water depth per tidal cycle. At Cai (close to sea) the highest water depth is reached about 3 hours and 45 minutes earlier than at Rooi Grandi (the back of the forest). This also shows that the influence of the tides can be seen throughout Lac Bay.

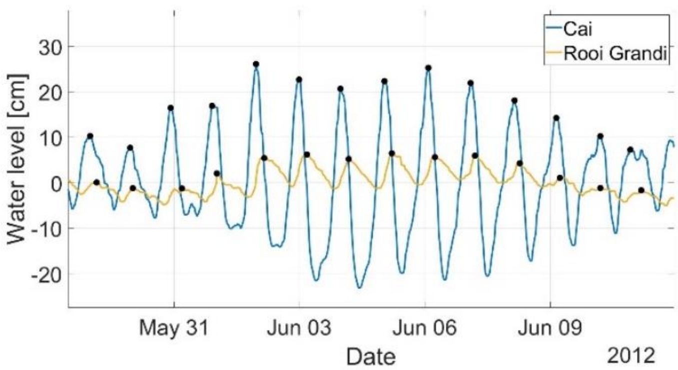

Figure 5: Tides of Cai and Rooi Grandi with black dots indicating the moment of highest tide

Table 4 shows the considered periods for each measurement station. Some stations have a short period (<1 month) due to lack of sufficient data or because the tide stopped having influence for a certain time period. The lag in high tide in relation to Cai (Table 4) is therefore an indication of what it could be and no definitive truth. As an example: Awa Fogon reaches its high tide on average 15 minutes earlier than Cai which is highly unlikely due to the nature of a travelling wave. This difference could be explained by the random noise that accidentally creates this time difference. Awa 'D's data are considered insufficient since no good period for this analysis is found in the data.

Table 4: Timing of the high water (averaged) in relation to measurement station Cai and corresponding time period

Measurement station	Period considered	Timing of high tide in relation to Cai
Rooi Grandi	14-05-2012 : 04-08-2012	-03:45:00
Isla Rancho	13-11-2012 : 03-12-2012	-03:30:00
Punta Rancho	13-11-2012 : 16-12-2012	-00:45:00
Mangrove center	14-05-2012 : 04-08-2012	-01:37:30
Awa "D"	-	-
Awa Yuwana	14-05-2012 : 04-08-2012	-02:00:00
Awa Fogon	14-05-2012 : 04-08-2012	+00:15:00
Awa Yanapa	03-01-2013 : 14-01-2012	-05:30:00
Isla di Chico	13-11-2012 : 03-12-2012	-00:30:00

Figure 6 combines the spatial and temporal differences between the stations. A relation is found by looking at the stations and their orientation in relation to the island and how far back they are in the forest. In front of the islands (Isla di Chico, Awa Fogon, Punta Rancho) there is little to no delay in the moment of highest water depth in relation to Cai. To the sides of the islands (Mangrove center, Awa Yuwana) the delay starts to increase to two hours and behind the islands (Isla Rancho, Awa Yanapa, Rooi Grandi) the delay is in the order of several hours. This indicates that the tide is slowed down by the mangrove forest and that it is travelling around the islands. In Figure 6 the tidal-driven circulation of the water is depicted by the blue lines.

Figure 6: Timing of the high water (averaged) in relation to measurement station Cai including probable paths of the tide (blue lines)

4. Discussion

As stated earlier in this paper: there is a dominant diurnal tide. This contrasts with earlier literature (Lodder, 2013; MacRae & de Meyer, 2006) who found a semi-diurnal tide. Although a dominant semi-diurnal tidal component does not arise from the analysis in this paper, at neap tide the semi-diurnal component influence can be seen. In the reconstruction of the tides for Cai (Figure 4) can be seen that during neap tide the M2 tide is peeking through. So, for a period of a few days there is a semi-diurnal pattern. Despite this short semi-diurnal pattern, the dominant tide in Lac Bay is still diurnal.

The program t_tide.m was not able to do a harmonic analysis on the data of some of the stations. Because of this it was not possible to see if at the other stations the dominant tidal component would be different. If the harmonic analysis succeeded on those stations the semi-diurnal tide that is described in literature might show up. However, it is unlikely that it will because of the tidal-driven circulation through Lac Bay and just by looking at Figure 5. It is expected that further analysis of the stations that did not work in t_tide.m will not bring new insights because the variance explained is already starting to decrease when the tidal wave reaches the forest. The method and results stated in this paper are therefore seen as sufficient to determine the dominant tide in Lac Bay. Possible reasons why the harmonic analysis did not work further into the forest are that the tidal signal is too distorted to be analysed and that the data is not suitable for a harmonic analysis. The data can be 'not suitable' in terms of the dataset having jumps in water depths and having a 'minimum water depth' as described in section 3.2.

Data showed that stations placed further into the forest showed signs of a minimum water depth: the water depth would not drop below a certain value or decrease very slowly afterwards. This can be explained by imagining those areas as buckets with a hole on the side. Creeks can be seen as the holes which are located at a certain height. As long as the water depth is above that hole it will flow out fast, but when it reaches the hole the water depth will stop declining. Water flows that can still be present are groundwater flows and evaporation which are able to decrease the water depth.

Stations near open water experience higher tidal ranges than stations towards the back of the forest. Based on this observation, in combination with the lag in high water depth between measurement stations, the mangrove forest can be described as a damped system. Oscillations forced on the front of the forest are dampened by the mangrove trees and the signal gets lagged and becomes smaller.

Most of the data is collected with a frequency of 15 minutes. With the amount of noise present in the data it will create the possibility to create significant errors in the moment of high water. It is likely that this is what happened at Awa Fogon where the largest water depth per tide is on average later than that of Cai. The collection of data with a higher frequency may yield more detailed insights in the tidal circulation of Lac Bay.

All measurement stations only have water levels relative to their environment (for example water level above soil) but no absolute water levels: there is no reference water level. A reference water level could be helpful to for example see the effect of the wind and to see at what height the lagoons are situated.

Smoothening of the data makes it possible to filter out some of the noise but the possibility to miss important points increases. Therefore, it is debatable to use the smoothening at tidal range calculations since the highest point and lowest point of a tidal cycle are likely to come closer. In this paper the inclusion of a filtering decreases the tidal range between 5 and 20 percent. This percentage is also depending on the n^{th}-order of the median filter used. Because the noise also could create higher values than actually present the filtering is still valid.

While no sufficient evidence is found that there is seasonal variance in the tidal range there could be some in the hydraulic circulation through Lac Bay. Wind may be an important factor in the water depths of Lac Bay and the force of the wind varies over the seasons. Taking this into account could change the timing of the high tides through the forest since the wind force is increasing the force which the water is pushed to the back with.

Over nine years have passed since the water depth data is gathered. During these nine years the Mangrove Maniacs have been busy clearing creeks to improve the hydrodynamic circulation through the forest. Not only did this improve the water quality in former isolated lagoons, but it will also likely have a positive effect on the water level response to the tides. By clearing creeks, the hydrodynamic circulation experiences less resistance resulting in larger tidal ranges and a faster propagating tidal wave through the forest.

5. Conclusion

The tidal behaviour in Lac Bay is investigated based on an analysis of the tidal range, the dominant tidal constituent and the hydrodynamic circulation throughout the mangrove forest. The parameters were determined from water depth data collected in 2012. The dominant tide of Lac Bay is the lunisolar diurnal constituent, also known as the K1-tide. At neap tide the principal lunar semi-diurnal tide, also known as M2-tide, is also present in the measurement. Since for most of the time the M2-tide has little influence, Lac Bay can be categorized as a diurnal tidal system.

Tidal ranges are larger in areas that have a better connection to the sea. At the seaside of Lac Bay the tidal range is on average 28.1 cm. Further into the forest the tidal range reaches the lowest value of 3.4 cm. No evidence is found of change in tidal range over the seasons.

The tidal wave shows a clear circulating pattern through Lac Bay, starting in the lagoon and ending in the back of the forest. The locations are a few kilometres apart, but the moment of highest water depth can differ a few hours. During the tidal circulation through the mangrove forest, the tide goes around the central islands in Lac Bay.

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