How channel dimensions relate to the erosivity of tidal flows in mangrove channels of Lac Bay, Bonaire

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1 **Figure: Runoff into the northern sub-basins of Lac after a shower, 19 May 2012 (Taco Regensburg).**

Table of Contents

1. Introduction

Almost the entire shoreline of Bonaire belongs to the Bonaire National Marine Park (BNMP), from the high water line to 60m depth. The marine park also includes a shallow lagoon called Lac, which is positioned on the windward site of Bonaire (van Moorsel & Meijer 1993, STINAPA 2003-2012). A sandbar extends almost the full length of the bay mouth to open sea. Waves break against this shallow bar, preventing severe wave action within the bay. An island arc in the middle of the lagoon encloses sub-basins in the northern landward edge, which is covered by an actively growing mangrove forest (Lott 2001).

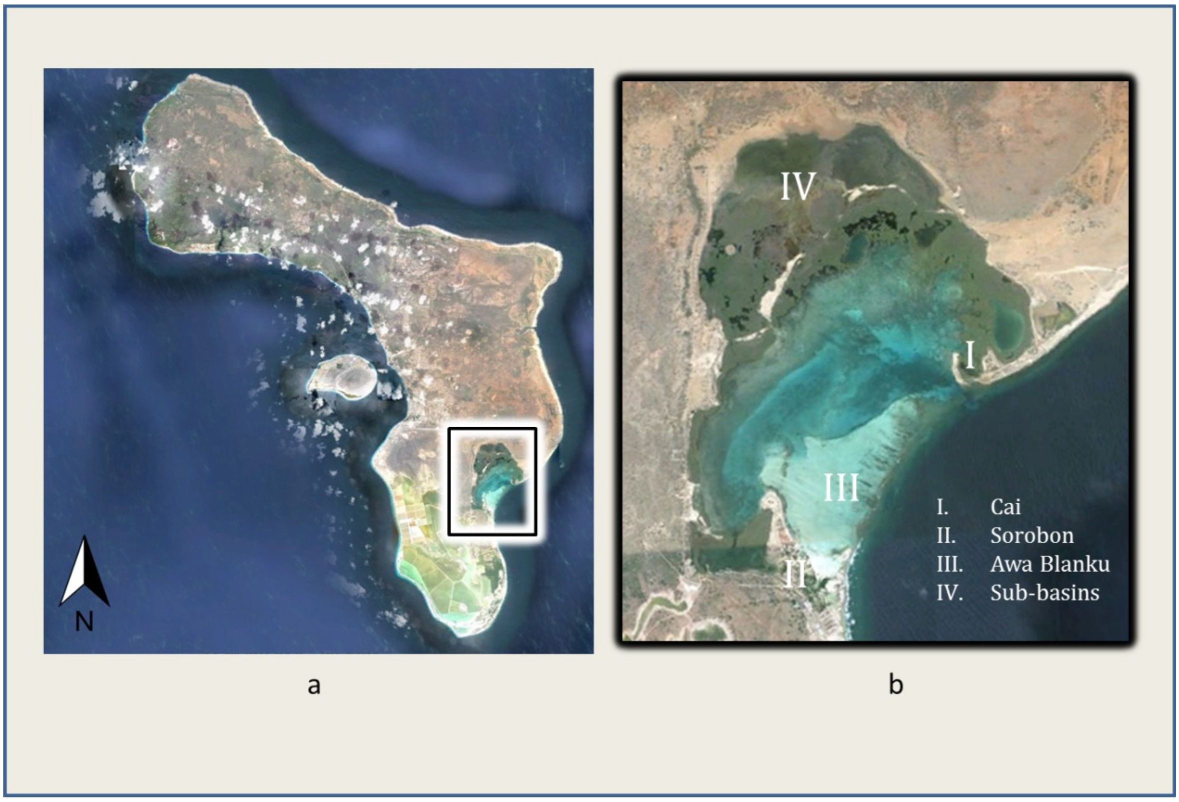


Figure 1: a. an overview of the island Bonaire; b. a snapshot of Lac (from Google Earth).

In the last few decades researchers noticed a decline of the forest area in Lac. Due to construction of roads and dams in the northern catchment, runoff deposited terrestrial sediments in the sub-basins, and hence became shallower over time (Wagenaar Hummelinck & Roos 1969, van Moorsel & Meijer 1993, Kats 2007, Lott 2001). Forest patches with dead mangroves started dominating the mudflats in the rear of Lac. Moreover, at the vernal equinox the shallow sub-basins get isolated temporarily from the main seawater circulation in the lagoon due to smaller tidal prisms. Inconsistent inundation of the tidal flats leads to desiccated soils and temporary highly saline waters. These conditions contrast with the favourable hydrology for mangrove growth (Clough 1992, Kathiresan & Bingham 2001, Berger *et al*. 2004, Kats 2007, Parida & Jha 2010).

The BNMP started a monitoring program to understand the hydrology of Lac and provide sustainable solutions to restore the extent of the mangrove forest. The actual program has included pro-active maintenance of mangrove channels that connect the sub-basins to the main seawater circulation in the lagoon. Two main channels have been identified which feed the rear of the forest. A current theory is held that the cross-sectional area of these feeder channels affects the in- and outflow of sea water to the sub-basins (Wagenaar

Hummelinck & Roos 1969, van Moorsel & Meijer 1993, Lott 2001, Kats 2007, Debrot *et al.* 2010).
Over the years the channels were overgrown by red mangroves and become silted again. Although the sedimentation process is identified as stressor for the continuity of the ecosystem, still little is known about the actual rates of sediment deposition and how this process interacts and possibly affects the growth mechanism of the mangrove forest. Hence, I wanted to study the dimensions of the feeder channels in relation to the tidal prism in this mangrove ecosystem. The objective of this study is to explain how erosivity of intertidal flows in mangrove channels relate to channel design.
Different researchers emphasize the importance of a good understanding about the sedimentation process, as it is an important precondition for improving the growth potential of mangroves on tidal flats (Ellison 2000, Ellison 1999, Furukawa & Wolanski 1996, Kamali & Hashim 2011). Studying the relation between channel dimensions and erosivity of intertidal flow may help to develop future risk analyses for maintenance strategies of the actual mangrove channels.

2. The mangrove forest of Lac

1. Location

Bonaire is an island located in the Southern Caribbean, 80 kilometres off the coast from Venezuela. The island has an overall area of 290 km^2. The island's population increased over the years. Especially in the last decade, a high population growth was noted: in the period 2001-2011 the population expanded with 50%. In 2011 the total population of Bonaire was 15666 (CBS 2012). The Bonairian climate is defined as semi-arid according to the Köppen classification. The geographical position of the island at 10°N contributes to an average daily temperature ranging between 25 and 31 °C and an annual mean temperature of 28 °C. Average annual precipitation -(climate normal)- is 470 mm of which 55 % occurs in the rainy season which lasts from October to December (Borst & de Haas 2005).

The island is well known for its diverse and colourful underwater scenery and well-preserved nature. In 1979, the Bonaire National Marine Park (BNMP) was declared, to preserve this scenery for future generations. Almost the entire shoreline of Bonaire and Klein Bonaire belongs to the BNMP, from the high water line to 60m depth. The marine park is managed by Stichting Nationale Parken-Bonaire (STINAPA-Bonaire). Their mission is to protect and manage the island's natural, cultural and historical resources. In 1991, new regulations were published for protection of a shallow lagoon, called Lac. They introduced an annual nature fee for all users of the park to finance maintenance, education- and research projects. The regulations include restrictions on access to certain areas of Lac and prescribe rules about prohibited activities, like removal of (mangrove) vegetation, construction of dams and sand mining (van Moorsel & Meijer 1993, STINAPA 2003-2012).

2. Geomorphology

The interior of Lac is protected against severe wave action by a shallow bar, which extends almost the full length of the bay mouth to open sea (Lott 2001). The presence of the bar reveals a part of the geographic history of Lac. Throughout the Quarternary, the island of Bonaire was subject to discontinuous vertical uplift. Then, glacial and interglacial periods caused the sea levels to drop and rise, which caused erosion and inundation. At a high sea level coral terraces were formed. At a succeeding low sea level the terrace eroded (Borst & de Haas 2005). Wagenaar Hummelinck and Roos (1969) state that during these ages the limestone plateau of South Bonaire drained into the north-east part of Lac, collecting weathering products of the island's interior. When the sea level rose to its actual level, the outlet area submerged slowly (Wagenaar Hummelinck & Roos 1969). The submerged outlet had at least one large opening at the present location of Boca Fogon (see figure 2). It is supposed that on the both peninsulas slowly fall apart. The new passages provided access to the waters in the outlet area, allowing development of a vast mangrove forest. The original access to the hinterland silted over time due to invasive mangroves, changing the peninsulas into an island arc. Over time, deposition of terrestrial runoff and deposition of aeolian particles caused the sub-basins to become gradually shallower (Wagenaar Hummelinck & Roos 1969).

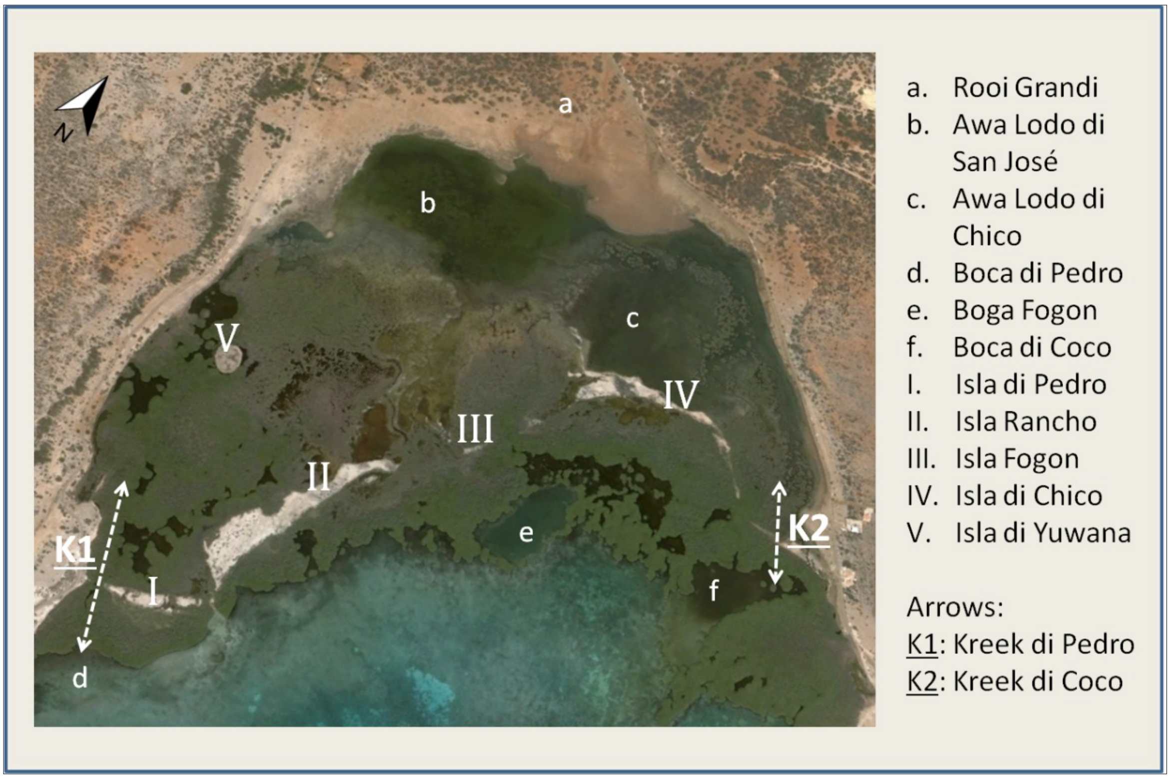


Figure 2: Detailed snapshot of Lac (altered to Google Earth, 2012)

Nowadays, the sub-basins in northern part of Lac are insulated by the island arc in the middle of the lagoon (see figure 2). Water flows to the sub-basins through channels between the islands. In former times fishermen, living at the islands, used these channels for transport to open sea and to go fishing. The wood of the mangrove was used for making coal and for weaving baskets. Fireplaces of the charcoal production can still be found on the islands. Over time, fishermen moved and settled at the peninsulas Cai and Sorobon, selling fresh caught fish to the open market. Hence, the original purpose for which the channels were used, does not longer apply (Kats 2007, STINAPA 2003-2012), and they started to grow over by mangroves (see appendix A).
The decreased use of the channels allowed mangrove colonization of channel areas. Ever since the mangrove forest functions as nesting and roosting areas for bird species. In the lagoon, fields of sea grass form nursery grounds for reef fish, queen conch (*Strombusgigas)* and the green turtle (*Cheloniamydas)*. The mangrove ecosystem is home to a unique flora and fauna. For this reason Lac is registered as a Ramsar site since May 1980 (van Moorsel & Meijer 1993, Lott 2001, STINAPA 2003-2012, Kats 2007).
At present, Lac is generally influenced by a diurnal tide, with two highs and two lows in a 24 hour period. The average daily tidal range is approximately 21cm – that is the vertical difference between a low tide and a succeeding high tide or vice versa. In the mangrove sub-basin the tidal range is very small (Kats 2007). Apart from the daily tidal range, an annual component in the tidal cycle can be observed with a range of about 15cm. In this annual component the water level is at its lowest in February-March. During this season parts of the area behind the island arc become isolated from the open water, water temperatures rise and locally water salinity can become high (van Moorsel & Meijer 1993).The diurnal tidal wave movement initiates flow through the mangrove channels and feeds the waters behind the island arc. Since the area of Lac became under consistent management in 1991 by STINAPA-Bonaire, annual maintenance to the mangrove channels prevents these flows to become obstructed by actively growing red mangroves (Kats 2007, STINAPA 2003-2012, Oleana 2012).

3. Forest composition!

Worldwide, mangroves comprise 55 species in 20 genera, belonging to 16 families. Most families are represented by a small number of mangrove species. However, the majority of the species belong to two families, the *Avicenniaceae* and *Rhizophoraceae*. These families dominate mangrove communities worldwide (Hogarth 2007).
Mangrove species tend to occur in zones according to micro-elevation and frequency of inundation (Ellison 1999). *Rhizophora ssp.* can be found mainly in the seaward, while *Avicennia ssp.* often have a bimodal distribution and are abundant near the seaward fringe and also some way onshore. Close to the shore, salt concentrations are equal to that of the ocean. But more landward, in shallow waters salinity can rise to hypersaline conditions (Kathiresan & Bingham 2001, Hogarth 2007). Mangroves have a natural ability to adapt to extreme conditions to survive. Lac represents one of those communities. The adaptation mechanism of mangroves to saline substrates is further explained in Appendix C. Table 1 gives an overview of the species common to the mangrove forest of Lac and shows the nomenclature used in the analyzed literature.

Table : Selection of principle mangrove species common to Lac (altered to table p. 21 (Hogarth 2007)).

Family	Subspecies	English	Papiamento
Avicenniaceae	*Avicennia germinans*	Black mangrove	Mangel blanku
Combretaceae	*Laguncularia racemocae*	White mangrove	?
Rhizophoraceae	*Rhizophora mangle*	Red mangrove	Mangel tam

Black mangrove is often found in its native range with the red mangrove and the white mangrove. Although they have different inundation preferences, they stabilize the shoreline. The root system of *Rhizophoraceae* forms an important buffer for storm surges, since it slows down tidal inflow. At the landward edge *Avicennia ssp.* provide sediment buffering by shallow rooting (Ellison 1999, Kamali & Hashim 2011, Ellison 2000, Alleman & Hester 2011, Furukawa & Wolanski 1996). The dense mangrove root system also provide nursery habitats for reef fish and birds.

4. Hydrology

Historical data of the island do not clarify whether the mudflats of Lac already existed before mangroves colonized the bay. In case of Lac, the sediment found in the sub-basins is both marine and terrestrial of origin. Sediment transport mechanisms have received little attention in studies of Lac so far. To be able to understand sedimentation process in the described mangrove ecosystem, the hydrodynamics in the mangrove forest of Lac need to be studied in more detail.

4.1. Status quo

In case of Lac, oceanic sands are carried in with currents crossing Awa Blanku. The circulation of water in the bay is believed to move in clockwise rotation (van Moorsel & Meijer 1993). Channels between the island arc provide access to the sub-basins (Lott 2001, van Moorsel & Meijer 1993). These sub-basins formed mudflats over time, due to terrestrial runoff in the rainy season and disposal of oceanic sediments. In the dry season, elevated shallow ponds will only be refreshed when very high tides occur (neap tides). In general, when tide induced streams reach the sub-basins, e.g. Awa di San José, the flow velocity is severely lower than in the tidal creeks (Kats 2007). The sediments found in the sub-basins reflect an extensive history of carbonate sediment disposal and are overlain by fine mangrove litter (Pers. Obs. 2012). In an ecosystems such as Lac, the severity of sediment disposal is reflected by the seasonal variability of discharges stimulated by ocean swells.

4.2. Flow resistance

While studies of van Moorsel & Meijer (1993), Kats (2007), Debrot et al. (2010) lacked detailed data on flow dynamics in the mangrove forest of Lac, in the same period of research, this phenomenon have been studied successfully at similar sites with mangroves in the Caribbean (Debrot et al. 2010, Kats 2007, Urish *et al.* 2009, van Moorsel & Meijer 1993).

Since 1972 the Twin Cays Archipelago, 22 km off coast of Belize, has been the location for scientific ecosystem studies by the Smithsonian Institute (Urish et al. 2009). The pristine conditions and relative isolated location of the archipelago were favoured for detailed scientific research of oceanic mangroves and associated marine ecosystems. Field studies of the dynamic hydrology of the Twin Cays mangrove ecosystem started in 1986 and have continued since. In recent research, Urish et al. focused on the surface hydrology of West Island of Twin Cays, a 21.5ha kidney-shaped landmass approximately 900m long and 400 wide (Urish et al. 2009). The West Island forests compose the same mangrove species as in Lac and the interior is a semi-closed ecosystem, seasonally flooded by the tides and with high organic export (leaf drop). This overwashed mangrove island reveals close similarities to the mangrove vegetated sub-basins of Lac.

Urish et al. determined water flow direction and velocities during various positions of the tide cycle using stream gauging techniques along channel cross sections. Using fluorescent dye flow patterns were determined in the interior lakes over a period of subsequent tide cycles (Urish et al. 2009).

The researchers showed that the combined frictional resistance of the bottom and associated mangrove roots is characterized by a Manning's roughness coefficient, n. Urish et al. found values ranged from 0.084 to 0.445 (Urish et al. 2009). The gross of the values found were about 10 times the normal value for sandy channels with weed cover, approximately 0.035 (Chow 1959). Repeated hydrologic research in mangrove swamps showed that Manning's roughness coefficient should be in the order of 0.2-0.4 (Wolanski 1992).

Apparently, peat soil formation in the measured transacts at West Island played a key role in determining the resistance values Urish et al. came up with. Hence, it might be useful to enhance our view on processes which affect the Manning's roughness coefficient.

Research underlines that the type of bottom and wall cover in mangrove channels contribute to a frictional force in the stream flow (Furukawa & Wolanski 1996, Inman & Jenkins 2005, Mazda *et al.* 1995, Urish et al. 2009, Wolanski 1992).

4.3. Risks of sedimentation

Most mangrove estuaries have a tidal asymmetry (Mazda et al. 1995). In case of Lac it is believed that flood flows are dominant. This means that the tide induced inflow velocities are higher than the retreating velocities at ebb. The expected result is accumulation of oceanic sediments; other studies show that 80% of suspended sediment brought in from coastal waters is trapped in mangroves in this way (Hogarth 2007, Kamali & Hashim 2011, Furukawa & Wolanski 1996). Appendix B shows an overview of sedimentation rates obtained in different researches on mangrove forests.

Moreover, the consequent changing flow direction, but with flood dominance, affects sediment transport and thus the geomorphology of the Lac and that of its sub-basins. The actual state of sedimentation might be affected due to redistribution of sediments by currents or local detritus deposition and subsidence from peat compaction (Urish et al. 2009). It is believed that these processes in mangrove swamps are often irreversible (Augustinus 1995, Ellison 1999, Furukawa & Wolanski 1996, Hogarth 2007).

The filling rate of the mudflats in Lac has increased last decades and is compromised with recent dieback of dwarf sized red mangroves (Debrot et al. 2010, Kats 2007). The vegetation cover that is still intact, affects actively the forming of peat soil. Root resistance to flow slows down flow velocities and facilitates opportunity to sediment deposition (Urish et al. 2009). Sediment deposition rates depend on transport load, type of flow dominance and seasonal inertia, e.g. runoff or sewage disposal. The sediment transport appears to be a seasonal phenomenon, going either land inward or seaward, but the net sediment transport moves along a long-term equilibrium (Urish et al. 2009).

The mangrove population in Lac develops its root system in instable, water logged substrates. Their rhizosphere forms a physical barrier for mass transport. Restricted mass transport enhances sedimentation around roots and may end in burial of the mangrove pneumaphores. Research on aerial root architecture reveals specific tolerance thresholds of mangrove species to sediment burial. In the studied cases, excessive sedimentation leads to death of mangroves, especially under *Avicennia germinans* (Ellison 1999). Due to the combination of waterlogged substrates and accumulated litter, anaerobic conditions may occur. Then, root respiration is restricted and gas exchange inhibited (Hogarth 2007, Ellison 1999). Ellison concluded that excess input of sediment to mangroves can cause death of trees owing to root smothering. In addition, in these wet, anaerobe conditions decomposition rates of organic matter are often low, enhancing the forming of peat soils (Reef *et al.* 2010). Different studies on mangrove reforestation support this theory and identify sediment burial as a risk for mangrove ecosystems or restoration potential (Ellison 2000, Ellison 1999, Furukawa & Wolanski 1996, Inman & Jenkins 2005).

3. Material and Methods

4.

1. Data collection

In March 2012, two mangrove channels in Lac were considered to be most important for supply of sea water to the sub-basins. Actually, the whole mangrove forest area consists of a matrix of poorly defined channels that vary greatly in depth and width. The cross-sectional areas of three identified channels, respectively channel A, B and C (see figure 3), have been measured, a selection can be found in appendix D. Cross-section measurements revealed a high rate of asymmetry due to a complex setup of vegetated wall structures. The channel walls mainly consisted of mangrove roots (pers. obs. 2012). Given the day to day variation in tides and the complexity of the mangrove ecosystem, the observations carried out could not cover the full range of factors that affect tide induced flow or channel dimensions. Since June 2011 automated pressure transducer water level loggers were employed at 5 different locations in Lac (see figure 3), respectively Awa Yuwana, Rooi Grandi, Isla Fogon, Mangrove Center and Cai. The Cera Divers in Awa di Lodo and Isla Rancho were installed in late December 2011. I also installed three divers gauges at the lagoon sited entrance of each identified channel and record wave movements for 7 days in the period of 3 May-10 May 2012. It is believed that an asymmetrical distribution of the water in the lagoon contributes to a water surface gradient, which drives the flow circulation in Lac (Wagenaar Hummelinck & Roos 1969).

Figure 3: an overview of installed divers in Lac and channels studied (picture altered after Google Earth).

Channel A represents Kreek di Pedro, former used as gateway by fishermen (see appendix A). It forms a junction between the lagoon and waters around Isla di Yuwana and connects presumably the waters of Awa di Lodo with those of the lagoon. Channel B represents Kreek di Coco, which forms a junction between Boca di Coco and the waters at the north east side of Lac, up to Rooi Grandi. Channel C is a junction channel between Boca di Coco and an interior sited pond at the east point of Isla di Chico (see appendix A, figure 9). Channel C could provide control information about the mixing effect of water in the feeder channels and about the connectivity to the main flow circulation, since both channels A and B are believed to be the main drivers of the flow circulation in the sub-basins.

2. Design criteria

Channel design can be performed by different methods and is a consensus between different approaches to set the criteria for this design. One of those criteria is the volume of water which discharges through the channel in time. In the next section two different approaches will be discussed to calculate channel discharges.

2.1. Effective discharge

The flow in a mangrove forest is driven by the ever-changing hydraulic gradient induced by the tides (Urish et al. 2009). The distribution of these flows depends on the topography of the forest, the extent and stem density. This diversity of shape allows certain flows to occur more frequently. Sediment yield by these flows highly depend on the sediment transport capacity, grain-size of the sediments and above all, the flow velocity. In this way, the flow which discharges the most sediment – allocation of sediments from location A to location B – is considered to have the most effective discharge (Doyle *et al.* 2005). The effective discharge depends thus on the statistical representation of stream flows and .
The flow velocity at which the effective discharge occurs should contain a certain amount of energy to erode the substrate and suspend sediment particles. These energy conditions are hard to estimate, unless flow velocities and sediment suspension data are available. In the case of Lac, these values are not measured yet. So I used the Reynolds number as proxy for the energetic conditions wherein the effective discharge could occur. Osborne Reynolds discovered that when a fluid is scouring a surface, the viscosity of the fluid affects the kinematic properties of its flow along that surface. Determination of the Reynolds number can point out at which flow velocity this energy condition occurs. Hence, the dimensionless Reynolds number, Re, represents the energy level of stream flow in open channels and can be subdivided in three categories (Hamill 2001).

Table 2: Overview of flow categories based on the Reynolds number for open channel flow (from (Hamill 2001)).

Reynolds Number	Flow type	Flow description
Re <500	Laminar flow	A relative deep, slow flow
500 < Re <2,000	Transitional flow	In between
Re > 2,000	Turbulent flow	A relative shallow, fast flow

Laminar flow occurs in deep basins, where the water processes slowly through the channel. Turbulent flow is a very fast flow in shallow waters, but will only occur on micro scale. Turbulence is the type of flow that keeps sediment particles in suspension (Hamill 2001).

In my approach, I assume transitional flow to be sufficient enough to suspend deposited sediments. I also assume that the flow velocity at transitional flow is constant over time. Thus, the effective discharge is to be found in the range of 500-2000.

$$Re = \frac{\rho}{\mu} \cdot v \cdot d \qquad \text{(eq. 1)}$$

Where:
d = the depth of the channel (m)
ρ = the density of the fluid (kgm^{-3})
μ = the viscosity of the fluid ($kgm^{-1}s^{-1}$)
v = averaged velocity in the channel (ms^{-1})

The water level is assumed to be uniform over the whole channel body. Rewriting the equation of Reynolds under the stated assumptions results in the flow velocity, veff, at which the effective discharge may occur. Assuming the dimensions of the cross-sectional area of the channel, a value for the effective discharge can be calculated.

$$Q_{eff} \equiv v_{eff} \cdot A_{total} \quad m^3 s \qquad \text{(eq. 2)}$$

Where:

Q_{eff} = the effective discharge

v_{eff} = the flow velocity for chosen Reynolds number

A_{total} = the total cross-sectional area of a channel body

At this moment, detailed calculation of channel dimensions for a channel design based on the approach of effective discharge, is only possible when the discharge component in this formula is known. In order to make this approach work well, first the values for the fluid viscosity, the density of the fluid and the statistical occurrence of stream flow events need to be determined. Moreover, the energy conditions at which erosion starts must be defined well.

2.2. Prism discharge

Tidal flow moves in and out of the mangrove forest with the tide. As a result the seawater regularly changes in direction (Urish et al. 2009). To get an indication of the amount of water that actually flows into the forest by the tides, the tidal prism can be calculated. A tidal prism is the total volume of water that has been exchanged between relatively two sequential mean high-water levels and two sequential mean low-water levels. The tidal prism can be calculated by multiplication of the cumulative tidal level between two sequential dead tides with the average surface area of the sub-basin/tidal flat. Dividing this volume by the time it takes to move it in or out the mangrove ecosystem, results an average discharge that may be of use to channel design.
To determine the tidal induced discharge during flood I took data from three different diver gauges, located on the lagoon site entrance of the channels, respectively channel A, B and C (see figure 3).
The water elevation can be measured by diver gauges installed in the water column. The change in height of the water column equals a change in water pressure on the diver gauge and can be denoted in cm water pressure. I assume that the water lifts uniformly in time over the whole area. The change in elevation of the water column over a certain time can be expressed in a parabolic function, $h(t)$.

$$h = at^2 + bt - c \quad m \qquad \text{(eq. 3)}$$

The volume brought in by one flood represents half of the prism. A_b represents the area of the sub-basins that drains into a channel. A value for the area is to be assumed. The area of the channels themselves is negligible small and thus not included in A_b.

$$\text{Half Prism} = A_b \cdot \int_0^{t_{top}} h \, dt \quad (m^3) \qquad \text{(eq. 4)}$$

Then, the daily prism is the sum of two half prisms, respectively two sequential flood waves. In this case the function of the other flood wave is expressed in $g(t)$.

$$\text{Daily prism} = A_b \cdot \int_0^{t_{top}} h \, dt + \int_0^{t_{top}} g \, dt \, (m^3) \qquad \text{(eq. 5)}$$

The time boundary, referring to t_{top}, has been defined as the point in time at which the maximum water level has been reached. The average prism discharge, Q, can be calculated by dividing the daily prism by the time needed to exchange the volume of both flood waves.

Q=Ab 0ttoph dt+0ttopg dtttop-t0h+ttop-t0g (m3/s)! ! ! (eq. 6)! !

2.3. Channel design

To calculate channel dimensions, single channels should be identified. However, at the moment only two channels have been identified in Lac as contributors to the exchange of water to the sub-basins.

To come to a design for a single channel using the average discharge, I assume that the average discharge can be subdivided over multiple mangrove channels. The intertidal conditions of the diffuse mangrove forest make it difficult to visualize flow during a flood. Assuming that all the water flows only through channels with defined boundaries, calculation of channel dimensions become possible. In this way, I assume that all channels have similar properties to a river, hence discharges specific to the mangrove channels can be determined using the Manning equation (see equation 7).

Q=S12n·R23 ·Atotal m3s ! ! ! (eq. 7)! !

Where:
Q! = the average discharge
R! = the hydraulic radius
n! = Manning's roughness coefficient
S! = the water surface slope

To simplify the calculation, I assume that per flood event a virtual box is filled. The a half tidal prism is divided over multiple taps, which fill the box gradually in time. If all taps are by assumption identical in design and properties and contribute equally to the average discharge, dividing the average discharge by the number of taps result in the discharge per tap (see equation 8). In this way, I only need to focus on the design of one tap at the time.

Q=Q1+Q2+..+Qn=vch ·Ach·N m3s! ! (eq. 8)! !
!
vch=S12n·B·dB+2d23! ! ! ! (eq. 9)! !

Where:
vch! = the average flow velocity in a channel (m/s)
Ach! = the cross-sectional area of a channel
B! = the width of a channel
d! = the depth of a channel

To find the number of channels needed to support the average discharge, different values of the equation must be known at forehand. Estimating those numbers may lead to better insights how channel dimensions affect the discharge setup and provide information about the proportional distribution of flow in the mangrove channel area.

N=n·QS0.5·B·d·B·dB+2d-2/3! ! ! (eq. 10)! !

Surface water slope, S, is defined as constant and will be estimated to approximate N. The surface water slope is assumed to be parallel to the bed slope. The value for the bed slope is to be assumed.

5. Results

6.

1. Effective discharge

In theory, different flow resistance factors can be attributed to sediment transport and sediment distribution in channels such as in a complex mangrove forest. However, calculations on the effective discharge could not be performed due to lack of valid input data. It seemed unrealistic to perform this method in more detail, since all input variables had to be chosen manually. To proceed with this method, a well-defined dataset is required on sediment transport to determine at which velocity sedimentation begins or erosion starts. As well, trend studies need to be performed to determine the discharge frequency in the specific channels.

2. Prism discharge

The obtained data from the installed pressure gauges differed a lot per location and thus trend studies for the whole area seemed impossible to perform. With this in mind, I only used the three divers installed at the entrance of the channels to study the interaction between tidal movement and flow properties in the channels. Because the diver gauges were not installed with a geographical reference, correlation research could not be performed for the three locations. Moreover, the values measured could not be corrected to absolute values due to malfunctioning of the barometric pressure gauge. Despite this, the data provided valuable information about the relative movements of the water line at a certain diver location. To calculate the daily prisms I selected a period (May 7 to May 8) in the end of experiment run (see figure 4a). In this selection I highlighted two sequential floods for each channel. For each channel I fitted the flood movements into a parabolic function, to calculate the maximum elevation per flood (see figure 4b). The average elevation for each channel could be drawn from these functions (see figure 4c).

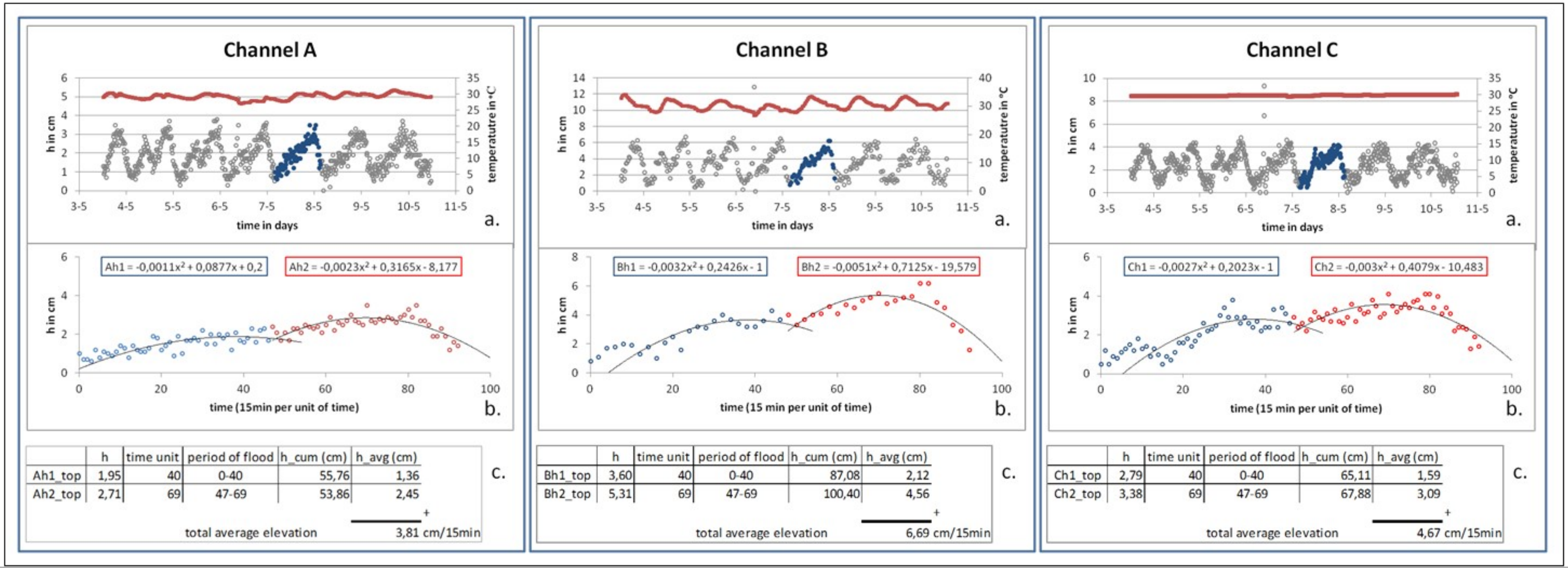
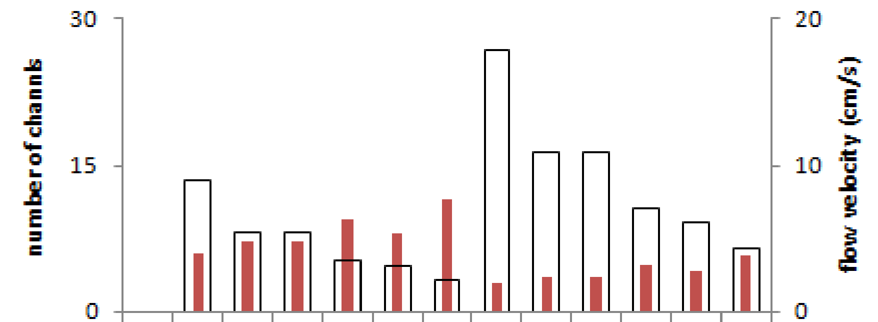


Figure 4: a. the output plot of diver gauge information for the period between 3 May-10 May 2012; b. the water elevation during the two sequential tides from the highlighted period of 7 May; c. calculation sheet of the total average elevation per time unit.

The water temperatures, shown in figure 4a, are fluctuating in both channel A and B, which could mean that there is mixing of different water layers over time. The water temperature in channel C lack this fluctuation, while it has the same tidal elevation trend as can be seen at channel A and B. For all channels an artefact can be spotted just after 6 May, this could have been a rain event, causing temporal changes in the air pressure on the water surface. Both channel B and C show higher total average elevations. This could mean that more water is pushed into Boca Coco than is pushed up to Boca di Pedro (see figure 2). The total average elevation indicate the vertical rise of water in the channels. The drainage area for each channel was not measured. Hence, an output value for equation 6, the average prism discharge, cannot be provided yet.

3. Channel design

The output values of equation 10 provide an indication of the number of taps/channels needed to fill the virtual box at the average discharge. To show the power distribution of the different parameters in the Manning's equation (see equation 6), the total average elevation of the selected period for channel A was used. Different options for the input parameters in equation 10 are displayed is an example output (Figure 5). The drainage area of the mangrove channel was estimated to be around 40 hectares and the water surface slope in the channels was held constant at 0,0004m/m.



	d	0,5	1	0,5	1	0,5	1	0,5	1	0,5	1	0,5	1
	B	1	1	2	2	4	4	1	1	2	2	4	4
	n	0,2	0,2	0,2	0,2	0,2	0,2	0,4	0,4	0,4	0,4	0,4	0,4
Flow velocity (cm/s)		4	5	5	6	5	8	2	2	2	3	3	4
Number of channels		13	8	8	5	5	3	27	16	16	11	9	6

Figure 5: example output of the calculation of number of channels and flow velocity for different values of depth, width and Manning's roughness coefficient n.

The cross-sectional area of a channel does not relate linearly to the flow velocity trough it. For the same depth, but with a larger width, the flow velocity is larger. A duplication of the Manning's roughness coefficient resulted logically for all combinations in decreased flow velocities and increased numbers of channels needed. A higher number for the roughness coefficient represents more vegetation in the channel, which obstruct a clear flow through. At a higher roughness coefficient lower flow velocities are obtained and relative more channels are needed to contribute to the average prism discharge.

7. Discussion

The input values of the dataset for this thesis was collected during a field trip in a period of only three month. This period did not allow enough time to focus on multiple factors that play a role in the ecosystem of Lac. Hence, only the hydrology of the sub-basins was marked as stressor for mangroves growth and has been of interest to develop the two approaches of discharge calculation. Also, the presented approach to design channels is a simplification of the reality. In reality substrate of the mangrove forest in the sub-basins is geomorphology complex. The effect of inertia of ground water and runoff as contribution to the hydrodynamics of Lac are still not well understood. Thus, I assumed the sub-basins to be shaped like a virtual box. The variables used to calculate the volume of the box were only the surface area and the tidal elevation range. The change in volume along the curve of the tidal elevation should be applied through a perfect rectangular shaped channel. But in reality, the shape of the wetted perimeter in mangrove channels is highly dependent on the shape of mangrove root zone.

In fact, most of the channels are cut manually through the forest, hence irregular wall- and floor shapes are present. Also larger cross-sectional areas have been measured in the mangrove channels, while the model only shows estimated widths and depths randomly chosen as example. The outcome should be interpreted only to get a better theoretical perspective on the design dimensions of the described mangrove channels.

To avoid the complex calculation on the channel bed structure, I assumed the depth of the channel to be smooth and uniform over the length of the channel. In reality, soil erosion changes the shape of the channel continuously. The volume of virtual box, representing the sub-basins, was by assumption only filled by water brought in by the tides. I assumed no losses occurred in the system. However, the ecosystem in reality acts in a complex environment, where multiple factors interact and affect each other. The approaches shown do not include important factors that can change the box volume, such as inertia from runoff, precipitation, evapotranspiration and subterraneous groundwater activity. Some of these parameters are difficult to estimate without proper datasets available. In this way, I neglected the annual change in tidal elevation. The tidal elevation in Lac processes along a complex curve over time. Local morphology of the landscape and synoptic meteorological factors affect the shape of this curve. Due to Earth's obliquity, the latitude at which the Sun is directly overhead varies continuously throughout the year. At two days in the year the Sun is directly overhead at the equator: the vernal equinox at March 20 and the autumnal equinox at September 22. Because Bonaire is situated at approximately 10°N, the effects of the equinoxes are noticed just before vernal equinox and before autumnal equinox, resulting in the highest water events of the year (Kats 2007, Krump *et al*. 2011). Since only measurements were collected in May, the outcome of the experiment does not cover the full range of tidal elevation in Lac. A good channel design should include at least discharges of the lowest possible water elevation and the highest water elevation.

When the Sun is directly overhead, the greatest heating occurs as well. Then, water that reaches the hinterland may evaporate more rapidly and become highly saline in a short time. Apart from Earth's position towards the Sun, also the position of the Moon towards the Earth affects the tidal elevation. The largest spring tides occur shortly after the New and Full moon closest to the equinoxes. The tidal forces due to the sun reinforce those of the moon optimally. The reinforcements of tidal elevation are also the result of differences in barometric pressures in the Caribbean between these two equinoxes (Kats 2007, Krump et al. 2011). In the field, the barometric pressure was measured for the same period as the Cera divers installed in Lac. The absolute values appeared to be higher than the pressures measured under the water surface. This measurement error is not clarified yet. Hence, the tidal elevation data, originated from the Cera diver installed in Lac, could not be corrected for changes in barometric pressure.

8. Conclusion

The complex water circulation in the mangrove forest of Lac cannot be caught in one single model. Consulted literature showes that mangroves are positive related to sediment accumulation. The calculations performed provide an indication which parameters are important when redesigning channel dimensions. From the example calculation it could be concluded that there is a relation between the roughness coefficient and the flow velocity. An increased roughness coefficient, using no other changes, resulted in a lower flow velocity. Increasing the channel width without changing the channel depth, increases the flow velocity in that channel. However, this is only true when the discharge component in the equation was already known, as in this case. Whether and how the flow velocities, found in the example calculation, relate to the erosivity of the flow is still unclear.

9. Recommendations

To find a balanced solution for the sedimentation problems in Lac, completion of the two described approaches is necessary. Despite the qualitative focus on the water circulation in Lac so far, detailed quantitative datasets on flow dynamics are still not available. In order to fully understand the sediment transport dynamics in mangrove forest of Lac, the focus in future research must be drawn on collection of quantitative data. To perform the calculations on discharges and channel numbers in more detail, trend studies must be performed on sediment disposal and sediment transport in relation with growth mechanisms of the mangrove forest. Studies as performed at Twin Cays might provide insights to those processes characterizing the mangrove ecosystem in Lac.
STINAPA-Bonaire is dealing with variety of stakeholders in Lac. Hence, to avoid biased products, future research should be performed by researchers that are accepted by the actual stakeholders in Lac. At last, the results of new research should be validated to all stakeholders to produce widely supported resolutions and a healthy financial balance, in order to commit to the proposed resolutions and sustain continuity of all measures.

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List of acronyms

Tidal prism can be defined as the total volume of water that has been exchanged between relatively two sequential mean high-water levels of two sequential mean low-water levels. The tidal prism can be calculated by multiplication of the cumulative tidal level between two sequential dead tides with the average surface area of the sub-basin/tidal flat.

Tidal flats or sub-basins are low-gradient headlands alternately covered and uncovered by the tide and consisting of unconsolidated sediment (Inman & Jenkins 2005). The tidal flats in Lac are sandy, covered in shell pavements and compositionally underlain by carbonate sediments. The area is covered by patches of mangroves forest. This forest composes mainly red mangroves (*Rhizophora mangle*) and black mangroves (*Avicennia germinans*). Red mangroves can be found mainly in the seaward, while black mangroves often have a bimodal distribution (Hogarth 2007, Inman & Jenkins 2005, Kathiresan & Bingham 2001).

Erosivity is the potential ability of physical dynamic agents such as water, wind or ice to cause erosion (FAO 1997).This ability to erode is dependent on the tidal prism and geomorphology of the flow path through the mangrove forest. Friction along the wetted perimeter of the mangrove channel may result a natural, but non-uniform distribution of flow velocities in the channel cross-sectional area. The flow velocity in the channel is related to the potential energy level of the flow (Chow 1959, Hamill 2001, Inman & Jenkins 2005). Categorization of this potential energy level per velocity allows to determine the conditions in which erosion begins. For practical reasons I assume that transitional flow is to be required to erode the channel floor substrates and transitional flow exceeds velocities which allow sedimentation to occur.

11. Appendix A: Aerial photos of the mangrove forest of Lac

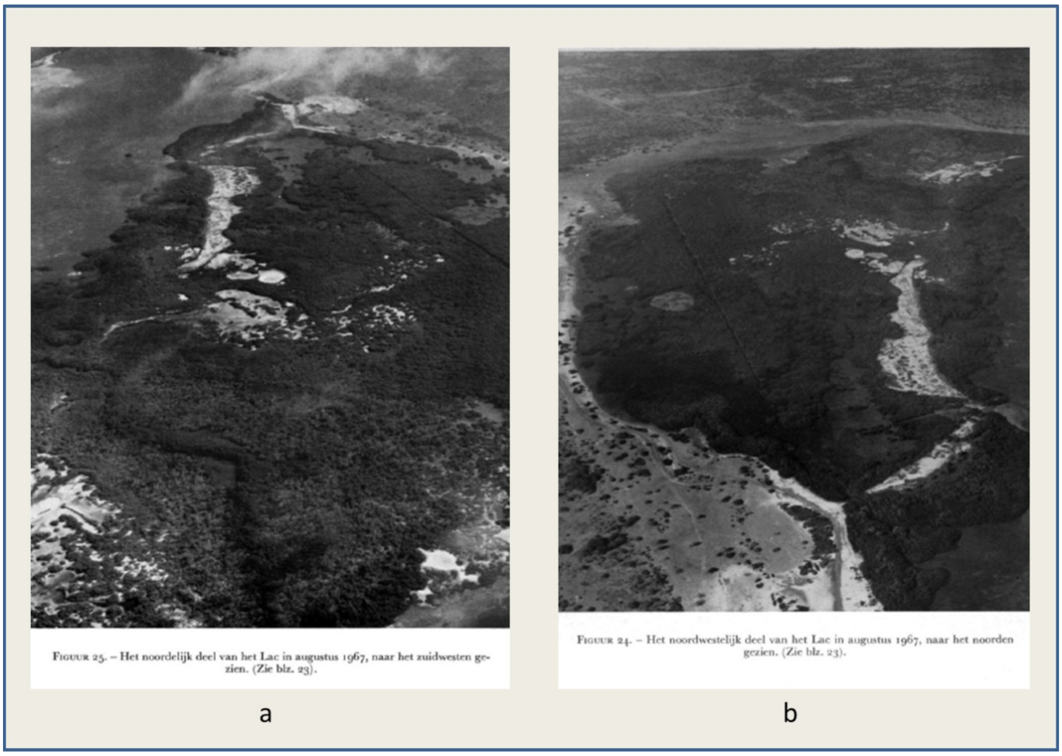

Figure 6: a. a snapshot of the northern part of Lac, in south-west view; b. a snapshot of the northern part of Lac, in northern view. The arrow in picture b indicates the hand-cut mangrove channel used by presumably fishermen. Both pictures dated August 1967 (altered from (Wagenaar Hummelinck & Roos 1969)).

Figure 7: a. and b. show Awa Lodo di San José and Awa Lodo di Chico, the main sub-basins consist of dwarf mangrove in moribund state; snapshots made in south-west view; c. Lac Bay overview; snapshot in west view. All three photos dated May 2012 (Taco Regensburg).

Figure 8: Boca Fogon in the foreground, with Boca Coco in the upper left corner; snapshot made in south-east view. Photo dated May 2011 (photo courtesy to Wietze Koopman).

Figure 9: Boca Coco in the foreground, with the entrance of channel C in middle of the picture. The interior pond channel C runs to is visible in the lower right corner. On the upper left corner the beach of Cai is visible; snapshot made in south view. Photo dated May 2011 (photo courtesy to Wietze Koopman).

12. Appendix B: Sedimentation rates

Table 3: Summary of short-term natural sedimentation rates found in mangrove swamps (from (Ellison 1999))

Location	Rate (mm/y)	Reference
Magnetic Island	−11.0 to 9.0	Spenceley, 1977, 1982
Cairns	1.0	Furukawa *et al*., 1997
Cairns	3.0 to 10.0	Bird and Barson, 1977
Melbourne	8.0	Bird and Barson, 1977
Auckland, NZ	1.7	Chapman and Ronaldson, 1958
Florida	1.4 to 1.7	Lynch *et al*., 1989
Florida	0.6 to 3.7	Cahoon and Lynch, 1997
Mexico (Fluvial)	3.2 to 4.4	Lynch *et al*., 1989
Mexico (Tidal)	1.0 to 2.0	Lynch *et al*., 1989

13. Appendix C: Understanding saline substrates

Mangroves are woody plants that usually grow at the interface between land and sea in tropical and sub-tropical latitudes. They can grow in high saline conditions, extreme tides, strong winds, high temperatures and muddy, anaerobic soils (Kathiresan & Bingham 2001).
Mangroves have adapted to cope with these extreme conditions. One of those adaptations is the tolerance of salt, defined by the ability to grow and complete their life cycle on a substrate that contains high concentrations of soluble salt. Plants that can survive and grow well on saline substrates are called halophytes (Parida & Jha 2010).
Because mangroves usually grow in an environment with variable salinities due to tidal inundation, a variety of survival techniques can be recognized in mangroves and hence all species have different optimum growing conditions. Scientists recognized in the last few decades two growth conditions for halophytes, respectively, (1) facultative halophytes and (2) obligate halophytes; but they cannot yet agree on one for mangroves in general. Facultative halophytes can grow in saline environments, but their optimum growth usually occurs in salt-free or low-salinity environment. They do not require salt water to survive. However, for reasons of survival, they can tolerate high salinity conditions. Obligate halophytes can grow optimal at moderate or high salinity and those are incapable of growth at low salinity or in freshwater (Wang *et al*. 2011). Parida and Jha (2010), however, point out that salinity plays a key role in regulating the growth and distribution of mangroves. Hence, for better understanding the salinization of the waters in the sub-basins, factors that are of influence on salinity must be analyzed. Some factors are widely recognized to be of major influence on mangroves' metabolism, respectively ambient temperature, wind and availability of salt water (Parida & Jha 2010). Although mangroves occur in environments that often have an ample supply of water, it is costly for plants to extract water of low ionic content from highly saline soils. Consequently, mangroves must limit water loss. Thus, mangroves have evolved in a setting where the rates of photosynthesis and growth are restricted by the capacity to maintain a favourable water balance with minimum salt uptake (Lovelock *et al*. 2006). This favourable water balance in the tree is put to the test by extreme conditions. Firstly, when for instance the tide is low, potential pressure on the cortical cells of the roots is less. In this way, the tree must spend more energy to get water transported to its canopy. Inefficient use of its energy may lead to overheating and desiccation. Secondly, through evapotranspiration, any water that remains in its surroundings may become even more saline. Hence, high salinity makes it more difficult for mangroves to extract water from the soil. Summarizing, mangrove species must have metabolic and morphologic adaptations to survive saline waters (Parida & Jha 2010). Three main adaptations recognized in mangroves species are exclusion of salt by the roots, tolerance of high tissue salt concentrations and elimination of excess salt by secretion (Hogarth 2007). In general, the three species recognized in the mangrove forest of Lac, have different mechanisms for salt elimination (Table 3). Depending on their salt eliminating mechanism mangroves can be classified into three groups: (1) salt excluders, (2) salt secretors and (3) salt accumulators. There are species that combine more than one mechanism to protect against adverse effects of salinity (Parida & Jha 2010).

Table 4: Selection of protection mechanism of species common to the Lac Bay area (from (Hogarth 2007)).

	exclusion	secretion	accumulation
Avicennia germinans	+	+	+
Laguncalaria racemosa		+	
Rhizophora mangle	+		+

Salt excluders eliminate excess salt by an ultrafiltration mechanism occurring at the cortex of root cell membranes. Salt secretors regulate internal salt levels by secreting excess salt through foliar glands in leafs. Salt accumulators tolerate high concentration of salts in their cells and tissues. (Parida & Jha 2010). Wang et al. supposed that salt is also accumulated in leaves from salt spray (Wang et al. 2011).

14. Appendix D: Channel dimensions measured

The cross-section measurements were used to analyse the statistical occurrence of width and depth in mangrove channels profiles.

Table 5: selection of random chosen channel cross-sections measured in channel A, B and C.

ID	Width (m)	Davg (m)	P (m)	R (m)	A (m2)
1	3,35	0,63	4,61	0,46	2,11
2	3,75	0,64	5,03	0,48	2,39
3	2,2	0,66	3,53	0,41	1,46
4	2,15	1,00	4,14	0,52	2,14
5	3,3	0,71	4,72	0,50	2,34
6	3,3	0,78	4,87	0,53	2,59
7	2,05	0,79	3,63	0,45	1,62
8	3,2	0,82	4,85	0,54	2,64
9	4,1	0,82	5,75	0,59	3,38
10	5,1	0,77	6,64	0,59	3,93
11	3,6	0,88	5,35	0,59	3,16
12	4,25	0,78	5,82	0,57	3,33
13	3,45	1,06	5,57	0,66	3,66
14	4,25	1,05	6,34	0,70	4,45
15	4,5	0,67	5,83	0,51	3,00
16	4,05	0,81	5,68	0,58	3,30
17	3,7	0,82	5,33	0,57	3,02
18	2,6	0,55	3,70	0,39	1,43
19	3,65	0,39	4,43	0,32	1,43
20	4,75	0,57	5,89	0,46	2,70
21	5,3	1,15	7,60	0,80	6,09
22	4,8	0,89	6,58	0,65	4,27
23	2,5	0,96	4,43	0,54	2,41
24	3,8	1,16	6,12	0,72	4,41
25	3,3	0,90	5,10	0,58	2,96
26	5,4	0,39	6,17	0,34	2,09
27	5,6	0,46	6,52	0,40	2,59
28	3,6	0,61	4,82	0,45	2,19
29	2,94	0,67	4,28	0,46	1,96
30	2,64	0,82	4,29	0,51	2,17
31	2,08	0,56	3,20	0,36	1,16
32	2,86	0,69	4,24	0,46	1,97
33	3,19	0,78	4,75	0,52	2,48
34	2,5	0,64	3,79	0,42	1,61
35	2,66	0,69	4,03	0,45	1,82
36	2,81	0,65	4,12	0,45	1,84
37	2,46	0,70	3,86	0,45	1,72
38	2,91	0,69	4,29	0,47	2,01
39	3,22	0,52	4,26	0,39	1,67
40	2,53	0,62	3,77	0,42	1,57
41	2,74	0,57	3,88	0,40	1,55
42	2,63	0,51	3,66	0,37	1,35
43	2,57	0,52	3,61	0,37	1,33
44	2,9	0,39	3,68	0,31	1,13
45	4,1	0,34	4,78	0,29	1,39
46	3,67	0,27	4,22	0,24	1,00
47	2,67	0,42	3,51	0,32	1,12
48	2,57	0,42	3,41	0,32	1,08

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