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Modelling Mangrove growth and salinity: a semi-arid case study

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Master thesis

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Pictures front:
- Top left: die-off of the mangroves at the northern outer shore of Lac Bay
- Top right: Diver located at Fogon
- Down left: Pneumatophores of Avicennia Geminans
- Down right: Diver located at Cai

SUMMARY

Degradation of the mangrove forest in Lac Bay, Bonaire is an environmental issue. Mangrove forests surround Lac Bay. Lac Bay has a status as RAMSAR site (RAMSAR, 2013), providing a defined legal protected status for this wetland. The most common species in Lac are *Rhizophora mangle* (red mangrove) and *Avicennia germinans* (black mangroves). The growth of *Rhizophora mangle* have become so successful that it limits the water circulation from the open bay passage into the back shallow ponds (Lott, 2001). This has led, due to the semi-aridity, to hypersaline water quality conditions in the back shallow ponds. *Avicennia germinans* is better able to deal with these hypersaline conditions. They dominate the interior area. The salinity at the Northern-outer borders might become that high that mangrove growth is strongly limited, even impossible. Skeletons of former mangrove trees can be seen at the outer borders, which suggests a dying-off process. Nutrient limitation and frequent flooding leading to oxygen stress could also reduce the mangrove growth. The main question to be answered within this study is: What could be the cause of the degradation of the Mangroves in Lac Bay? More insight in which factors might limit the growth *Rhizophora mangle* and *Avicennia germinans* is needed in order to answer this research question.

Bonaire is an island situated in the Southern Caribbean. It has a semi-arid climate according to the Köppen classification. Average daily temperature ranges between 25 and 31 °C. Average annual precipitation is 475 mm of which 55 % occurs in the rainy season which lasts from October to December (Borst and De Haas, 2005). Lac Bay is a basin, positioned on the southeastern side of the island. Mangroves forests border the bay.

SWAP (soil, water, atmosphere, plant model) will be used to model the mangrove growth depending on the salinity. SWAP is a physical 1D-model and is able to simulate transport of water, solutes and heat in the vadose zone in interaction with vegetation development (Van Dam, 2000). A new subroutine, which simulates tree biomass growth, was added to SWAP. SWAP is unable to simulate tides. Tides were given as an irrigation gift. The sum of the daily inflow equals the irrigation gift. Biomass growth of *Avicennia germinans* and *Rhizophora mangle* was modelled with SWAP for the period of 1989 to 2009.

Tides within Lac can be classified as a mixed dominant semidiurnal type (Brown et al., 1995). Tides in Lac have a daily, two-weekly and annual tidal component. The maximum daily fluctuation within Lac equals on average approximately 30 cm. The annual fluctuation equals approximately 10 cm. The tidal fluctuation is delayed and attenuated towards the backland, given equal evapotranspiration. Salt stress will increase towards the backland. Observations show a negative relation between the abundance of *Rhizophora mangle* and salt stress. *Avicennia germinans* will occur at locations where the salt stress is too high for *Rhizophora mangle* to grow. There is a peak in the salinity stress in March. Surface runoff will reduce stress. There is a linear relation between the amount of precipitation and runoff. The decline in salt stress if surface runoff is taken into account is on average approximately 28% for *Avicennia germinans* and 30 % for *Rhizophora mangle.* Although, the exact influence of surface runoff on the salt stress is strongly dependent on the locations and the annual precipitation rate. Locations where more salt is stored within the soil will benefit more from the surface runoff. The amount of saltwater inflow is also of major importance. Simulations at different locations show that seawater flush salt out of the soil when the salt concentration increases above the salt concentration of seawater. The saltwater inflow at the backland is relatively low, which will lead to hypersaline conditions. The total seawater inflow should be increased with at least 130% so that salt stress will not limit the mangrove growth.

The modelled peak seems to be relative low compared to field measurements done in other studies. This study modelled a monthly mean of 120 mS/cm at Rooi Grandi (situated in the backland) in March. Kats (2007) measured a monthly mean of 170 mS/cm at Awa Lodo di San José in March. Regensburg (2012) measured electrical conductivities of 155 up to 160 mS/cm at this location in April. The difference between the electrical conductivity modelled within this study and the mean measured by Kats (2007) might be explained by the fact that SWAP simulate too low values for the evapotranspiration or that barriers within Lac Bay limit the water circulation. Areas might become

hydrologically isolated during the dry season. Mangrove trees might then die because of hyper salinity. SWAP is currently unable to simulate this die-off process. The model could be improved by simulating die-off of the mangrove trees, when the trees cannot transpire for a period of time.

The salinity increases towards the backland. There seems to be a negative relation between the abundance of *Rhizophora mangle* and salt stress. *Avicennia germinans* will occur at locations where the salt stress is too high for *Rhizophora mangle* to grow. Conditions at the northern outer shore (around Awa Lodo di San José) become too saline for *Avicennia germinans* and *Rhizophora mangle* to grow. The salt stress at the northern outer shore might be decreased by increasing the surface runoff or by improving the salt water circulation. Increasing the salt water circulation seems to have the most impact. The seawater inflow should increase with 60%, so that *Avicennia germinans* will not be limited by salt stress and with 130% so that *Rhizophora mangle* will not be limited by salt stress.

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1 INTRODUCTION

Mangrove forests surround Lac Bay. Lac Bay is a basin (a cross between a lagoon and a bay) situated in the southeast of Bonaire. Lac Bay has a status as RAMSAR site (RAMSAR, 2013), providing a defined legal status for this wetland. Therefor the mangroves receive protection (Debrot et al., 2010). Lac Bay is managed by STINAPA-Bonaire (Stichting Nationale Parken-Bonaire). STINAPA is a non-governmental non-profit foundation. Their mission is to protect the native flora and fauna of Bonaire for future generations (Thom 1984). STINAPA is concerned about the degradation of the mangroves, which is visible on the Northern outer borders of Lac Bay. Skeletons of mangroves can be observed at the outer borders which suggests a dying-off process (Lott, 2001). The mangroves provide habitat, nursery grounds and nutrients for many marine and terrestrial species (Nagelkerken et al., 2000). Furthermore, the mangroves also have an important socio-economic function. Tourism is one of the most important economic activities in Bonaire (Debrot et al., 2010). Lac Bay and its mangroves is an important touristic spot. Degradation of the mangroves could therefor also have negative side effects for tourism (Debrot et al., 2010). Therefor, it is necessary to make a management plant to ensure the protection of the mangroves.

The most common waterbound species in Lac are *Rhizophora mangle* (red mangrove) and *Avicennia germinans* (black mangroves). *Avicennia germinans* dominate the interior area, while *Rhizophora mangle* dominate the shoreline of Lac. The seawater salinity ranges at the shoreline are favourable for the growth of *Rhizophora mangle*, at approximately $35^{0}/_{00}$ to $45^{0}/_{00}$ (Moorsel and Meijer, 1993). The growth of *Rhizophora mangle* has become so successful that may limit the water circulation from the open bay passage into the back shallow ponds (Lott, 2001). This have led to hypersaline water quality conditions in the back shallow ponds, ranging from $45^{0}/_{00}$ to $100^{0}/_{00}$ over a year period (Moorsel and Meijer, 1993). *Rhizophora mangle* is less able to thrive under these hypersaline conditions (Roos and Hummelinck, 1969). The growth of *Rhizophora mangle* is reduced to 5% when the salinity content increase above approximately $70^{0}/_{00}$ (Chen and Twilley, 1998). *Avicennia germinans* is better able to deal with these hypersaline conditions. The growth of *Avicennia germinans* is reduced to 5% when the salinity content reaches approximately $90^{0}/_{00}$ (Chen and Twilley, 1998). This might also be the reason that *Avicennia germinans* dominates the interior area (Moorsel and Meijer, 1993). Mangrove growth becomes negligibly small if the salinity content increase above $90^{0}/_{00}$. It's unknown how the salinity fluctuates within Lac Bay. More understanding of the salinity fluctuation could help to prevent further degradation of the mangrove forest.

The die-off of mangroves inland and the accretion of the mangroves at the shoreline of the lagoon is a common phenomenon is semi-arid mangrove systems, mostly caused by high evapotranspiration rates and lack of refreshment of water inland during high tide (Moorsel and Meijer, 1993). This effect might be strengthened in Lac since the fresh water inflow on the landside is limited. Thom (1984) defines Lac as "a carbonate environment behind a mobile but protective sand or shingle barrier". This type of mangrove forest is quite rare and vulnerable (Moorsel and Meijer, 1993). Most mangrove forests are influenced by fresh water rivers. The fresh water inflow in Lac is dependent on rainfall runoff and groundwater flow. The construction of 54 dams and many (uncounted) wells in the upland area may have limited runoff and freshwater flow towards Lac (Debrot et al., 2010). The limitation of fresh water runoff might lead to a further increase in salinity, which might have a negative impact on the growth of mangroves, and accelerate the die-off process inland. In addition, the rainfall in Bonaire is not equally distributed over the year. Optimal condition for mangroves can be found in estuaries where there are high rainfall rates equally distributed through the year (Feller et al., 2011). These might also accelerate the die-off of the mangroves inland in Lac Bay. Limiting studies have been done to see whether there is an accelerated die-off of the mangroves within Lac Bay.

Mangrove forests are well known for their adaption to anaerobic conditions. The exchange of oxygen between soil and ponding water is limited and leads to anaerobic conditions (Colmer et al., 2012). Mangrove trees have developed roots, which are able to cope with anaerobic conditions. The roots of

Avicennia germinans (so-called pneumatophores) protrude out of the muddy soil, enable them to take up oxygen above the ground. The roots of *Rhizophora mangle* (so-called aerial prop roots) stand above the soil surface and contain small pores. The trees are able to take up oxygen through these pores. Notwithstanding these adaptations, long periods of inundation might still harm the mangrove trees (Berger et al., 2008). Previous research has documented the general principle that mangrove forests worldwide occur on raised and sloped platforms situated above mean sea level and inundated less than 30 percentage of the time by tidal waters (Lewis, 2005). More frequent flooding can cause stress and death of the tree species (Lewis and Gilmore, 2007). Especially *Avicennia germinans* are harmed by frequent floodings. *Rhizophora mangle* is better able to deal with these conditions and can be planted in zones of greater inundation (Turner and Lewis, 1997). Some barriers in Lac Bay limit the water circulation. This could also mean that during low tide water is unable to flow back towards the Bay and so water levels remain high for a longer period. The question rises if the trees in Lac Bay are inundated for such long periods that it is harmful.

Mangrove forests are highly productive ecosystems, in terms of primary and/or of secondary production (Clough, 1992), while being relatively poor in nutrients (Koch and Madden, 2001). Especially phosphorus and nitrate concentrations play an important key role in mangrove growth. Low concentrations of nitrate or phosphorus might limit the mangrove growth. Especially the growth of the *Avicenna germinans* is sensitive to low nitrate concentration. *Rhizophora mangle* is better able to cope with low nitrate concentrations since it has a relative high nitrate reabsorption efficiency (69%) compared to *Avicenna germinans* (5%) (Feller et al., 2007; Feller et al., 2003). The conventional ecological theory shows that nitrate limits tree growth at the shoreline while phosphorus limits tree growth in the open waters (Prasad et al., 2010; Feller et al., 2003). Different studies also indicate that especially phosphorus is limiting in subtropical and tropical mangroves, in contrast with the temperate mangroves, which are mostly nitrate limited (Boto and Wellington, 1983 ; Feller et al., 2003; Feller et al., 1999). Other studies indicate that high concentrations of nitrogen, nitrate and ammonium concentrations might be a problem for the coral reef ecosystem in Lac Bay (Buurt, 2002).

STINAPA is concerned about the degradation of the mangroves within Lac Bay. This study will help to understand the degradation process of the mangroves within Lac Bay. The main focus will be on stress caused by salinity, nutrients or high water levels. To make some conclusions about which factor will be the most limiting SWAP (soil water atmosphere plant model) will be used. SWAP is a physical 1D-model and is able to simulate tree growth and tree stresses.

1.1 RESEARCH OBJECTIVES

The main question to be answered is: What could be the cause of the degradation of the Mangroves in Lac Bay? More insight in the factors limiting the growth *Rhizophora mangle* and *Avicennia germinans* is needed in order to answer this research question. Hypersaline conditions, high water levels and nutrient limitation are three important (limiting) factors in mangrove growth. The main focus of this study will also be on these three factors in relation to tree growth. The question rises whether the die-off of *Rhizophora mangle* and *Avicennia germinans* at the northern outer shore is caused by high salinity conditions, low nitrate or phosphorus concentrations or long periods of inundation. Based on this data an indication of the severity of the degradation of the mangroves within Lac Bay can be given. In addition, some insights in the tidal fluctuation and the fluctuation in salinity in a one-year period within Lac Bay will be given.

1.2 Research questions

The following questions need to be answered in order to achieve the research objectives:

1. What could be the cause of the degradation of the Mangroves in Lac Bay?
2. How does the salinity change over a one-year period and how does this influence the growth of *Rhizophora mangle* and *Avicennia germinans* in Lac Bay, Bonaire?
3. What is the tidal fluctuation over a one-year period and how does this influence the growth of *Rhizophora mangle* and *Avicennia germinans* in Lac Bay, Bonaire?
4. What is the influence of surface runoff on the growth of *Rhizophora mangle* and *Avicennia germinans* in Lac Bay, Bonaire?
5. How much does the nitrate and phosphorus concentration change in the area and how does this influence the growth of *Rhizophora mangle* and *Avicennia germinans*?

1.3 Reading guide

The next chapter (Background information) will give a description of the climate and geology of Bonaire and data on the tides in Lac Bay will be represented. Chapter 3 (Methodology) will give a description about the data compilation and the method how tidal data is measured. Also a short overview of the main processes in SWAP and the assumptions made will be given. Chapter 4 (Results) will first give an overview of the measured nutrient concentrations, secondly analyses of the tidal fluctuation will be presented and combined with the salinity fluctuation. Thirdly some insights will be given in the salinity fluctuation. At last the modelled growth of R*hizophora mangle* and *Avicennia germinans* will be given. Chapter 5 (Discussion) will discuss the methods and the assumptions made in SWAP. Chapter 6 (Conclusion) will shortly numerate the most important findings of this study and will give some recommendations for further research.

2 BACKGROUND INFORMATION

Bonaire is an island situated in the Southern Caribbean (Figure 1). The island covers a surface area of 288 km^2. The southern part is flat with maximum elevations of 25m+msl. The northern part is more hilly with elevations up to 241m+msl. Bonaire has about 16.000 inhabitants. Most people live in Kralendijk, the capital city and main port. Economic activities are mainly related to tourism and some industries. Agriculture is of less importance (Borst and De Haas, 2005).

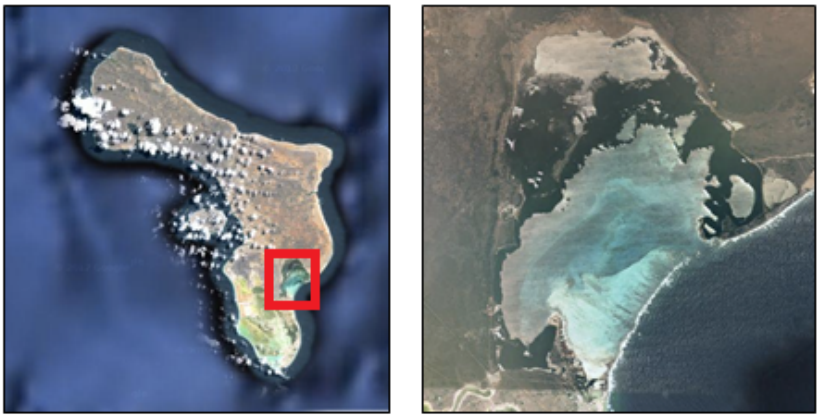

Figure 1 An overview of the island Bonaire and a snapshot of Lac (from Google Earth 2012).

Climate

Bonaire has a semi-arid climate according to the Köppen classification. Average daily temperature ranges between 25 and 31 °C with an annual mean of 28 °C. Average annual precipitation is 475 mm of which 55 % occurs in the rainy season which lasts from October to December. There is a dominant eastern trade wind with typical wind speeds of 7 m/s (Borst and De Haas, 2005). Average annual potential evaporation is about 2600 mm, but uncertain as global radiation values may be lower than expected due to cloudiness (De Bourgraaf, 2012).

Geology

Bonaire is of volcanic origin. Volcanic rocks of the Washikemba formation (of Cretaceous age) form the base and the core of the island. After the Eocene age these volcanic rocks came to the surface due to tectonic uplifting. Several (coral) limestone terraces were formed on top of the volcanic rocks, during the uplifting. While the island was stepwise uplifted, the central part eroded and thus the volcanic rocks were exposed again and eroded as well. Locally, wind blown sands were deposited on top of the volcanic rocks. These calcareous sands have been cemented together and form the so-called aeolianites (Burg et al., 2012).

Lac Bay

Lac Bay is a basin, on the southeastern coast of the island (coordinates 12°6'22"N 68°13'46"W, figure 1). It covers a total area of approximately 700 ha. A shallow sandbar partially covered by living coral extends the full length of the bay mouth to open sea. Waves coming from the sea break against the sandbar, preventing severe wave action within the bay. The lagoon bottom is primarily covered with seagrasses, macro-algae and sand mounds. Mangroves forests cover the borders of the bay. The subsoil of Lac consists of a coral calcium deposit, with a sediment deposit on top of it (Augustinus, 2005). The soil texture found at Lac Bay is clay loam and ranges from loam to clay (Van Kekem et al., 2006)

Tides in Lac

The daily tidal fluctuation in Lac is about 30 cm. The annual fluctuation is about 15 cm. The water levels reach their lowest point in February-March (Moorsel and Meijer, 1993). The tides in the rainy season are dominated by a diurnal component. High tide occurs in the early morning and shifts approximately one hour each day. Subsequently a duplication of the diurnal component occurs, while the amplitude decreases. This daily dual fluctuation dominates for one week. The tidal fluctuation is delayed and attenuated towards the backland (Moorsel and Meijer, 1993). Figure 2 gives an example of the tidal fluctuation.

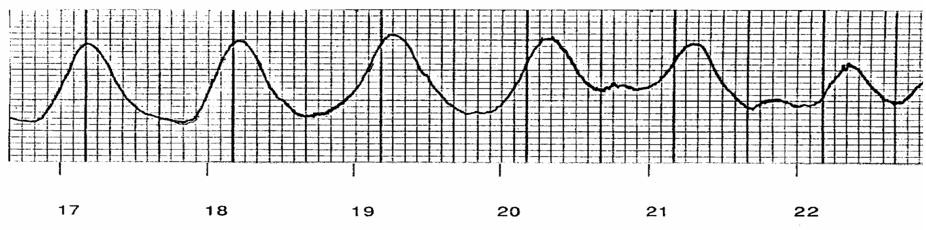

Figure 2 Tidal fluctuation in the period of 17th to 23th of January 1992 (Moorsel and Meijer, 1993)

Figure 3 shows the time when the water level reaches their highest point and the maximum amplitude at different location within Lac Bay. Visible is that the tidal component is delayed and attenuated towards the backland (Roos and Hummelinck, 1969).

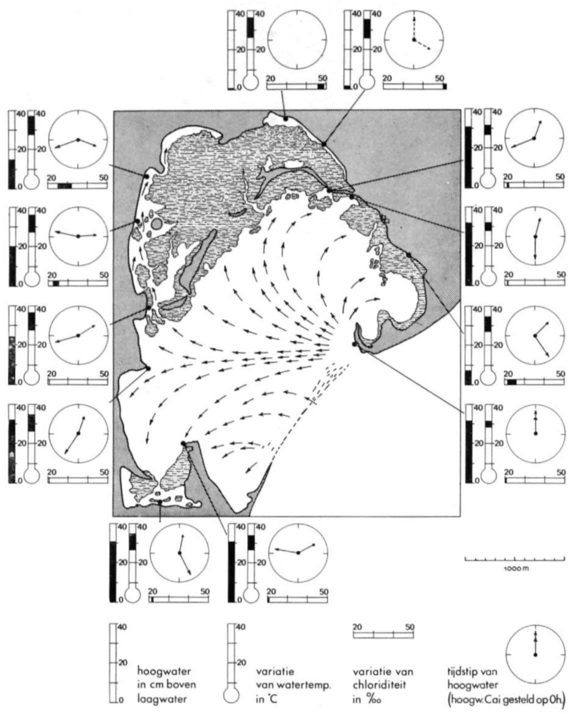

Figure 3 the time when the water level reaches their highest point and the maximum amplitude at twelve different location within Lac Bay measured within 24 hours at 15 and 16 September 1967 (Roos and Hummelinck, 1969)

Mangroves of Lac

Mangrove forest surrounds Lac Bay. The most common species are *Rhizophora mangle* (red mangroves) and *Avicennia germinans* (black mangroves). *Rhizophora mangle* is dominant at the shoreline, while the *Avicennia germinans* is the dominant species more inland. Dead mangroves can be found at the northern shallow shores of the lagoon. In addition to *Rhizophora mangle* and *Avicennia germinans*, *Laguncularia racemosa* (white mangroves) and *Conocarpus erectus* (grey mangroves) can be found in Lac Bay (Augustinus, 2005).

3 METHODOLOGY

In this section the methodology will be discussed. First an overview of the data compilation will be given. Secondly a description is given on how tidal data is measured and analysed. Finally SWAP (soil, water, atmosphere and plant model) will be presented. SWAP is used in this study to simulate mangrove growth depending on different abiotic factors. SWAP is a physical 1D-model and is able to simulate transport of water, solutes and heat in the vadose zone in interaction with vegetation development. Also an overview of the assumptions made in this model is included in this section.

3.1 DATA COMPILATION

Meteorological input data comes from the meteorological department Bonaire (2013). Evapotranspiration data and global radiation are calculated using FAO 56 (Allen et al., 2006); missing values were replaced by long term averages for that specific day. Ten logging saltwater proof divers and one baro-diver measured the tidal fluctuation. The salinity is measured with an electrical conductivity (EC) meter. The oxygen content of the water is measured with an OxyGuard (Handy Polaris). For both (oxygen and salinity) time series are measured in order to cover one tidal range. Soil samples were taken in order to determine the saturated water content, porosity and dry bulk density. The saturated hydraulic conductivity is determined following the method described by Dirksen (1999). The unsaturated hydraulic conductivity of the soil is determined using a mini disk infiltrometer (Tue et al., 2012). At each diver two water samples were taken and analysed on nitrate and phosphorus. Nitrate is measured photometrically with a cell test. Phosphorus is measured colometric with a colour card.

Leaf area index (LAI) is measured, using a fisheye photograph. The fraction intercepted light is measured using a light meter. The difference between the light above and underneath the leaves allows estimating the extinction coefficient. Using equation 1 the LAI can be calculated.

$$\frac{I}{I_0} = e^{-K*LAI} \qquad (1)$$

Where I_0 is the light above the leaves (nm), I is the light underneath the leaves (nm), LAI is the leaf area index (-) and K is a constant value (-).

Furthermore the tree density is determined, by counting the number of *Avicennia germinans* and *Rhizophora mangle* on a 10*10 m^2 plot. The rooting density of the *Avicennia Germinans* will be determined. The tree diameter at breast height is measured (of ten trees). The average crop height is measured with a telescopic measurement pole or a range finder.

3.2 TIDAL DATA

Ten saltwater proof logging divers were installed in Lac Bay (

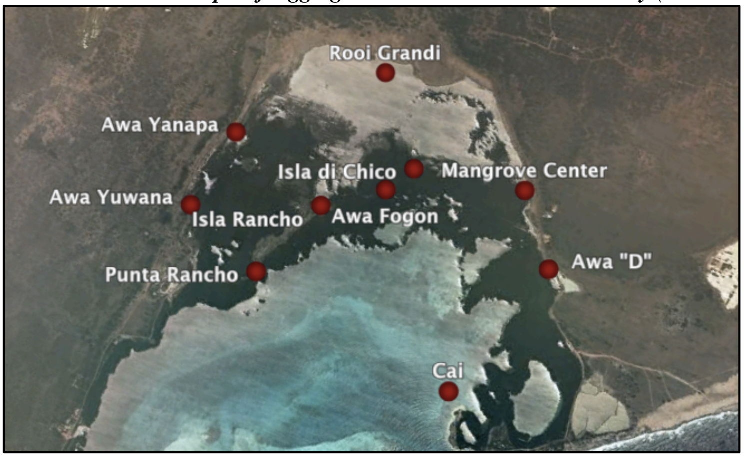

Figure 4). These divers measure the pressure exerted by the water column and the atmospheric pressure. To measure the variations in atmospheric pressure a baro-diver is installed. By using equation 2 the height of the water column can be established (Eijkelkamp, 2011)

$$WC = 9806.65 * \frac{P_{diver} - P_{baro}}{\rho * g} \quad (2)$$

Where P_{diver} is the pressure (cm) measured by the diver, P_{baro} is the barometric pressure (cm), ρ is the density of the water (g/cm^3) and g is the gravity (cm/s^2).

In total ten divers have been measuring water levels at different locations within Lac Bay. Five divers have been measuring for approximately 18 months (May 2011 to January 2013). Five other divers were installed at the beginning of November 2012 and have been measuring for three months (until the end of January 2013).

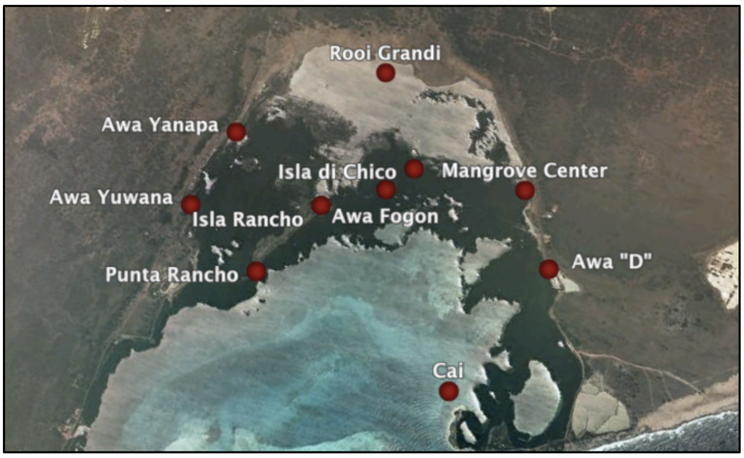

Figure 4 Locations and the names of the divers installed in Lac Bay.

One baro-diver has been measuring atmospheric pressure in the period January until September 2012. The pressure was inexplicably high and could not be used to calculate water levels. The atmospheric pressure was used to correct data for this period. The data from the baro-diver however did give an indication of the fluctuation in atmospheric pressure (Figure 5). A diurnal fluctuation is visible in the atmospheric pressure (Turk, 1975). Based on the baro-diver data the assumption is made that the atmospheric pressure is at its maximum at 4 o'clock PM and at its minimum at 10 o'clock PM. The function has a twelve-hour period. The wavelength is approximately half as large in the morning than in the afternoon. Data used for the daily minimum and maximum values for the atmospheric pressure are measured by the Meteorological Department Bonaire (1993). Figure 6 gives a schematic overview on how the atmospheric pressure is modelled.

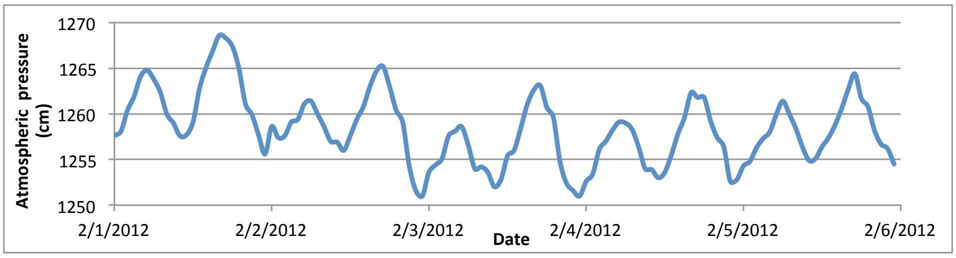

Figure 5 The measured atmospheric pressure by the baro-diver.

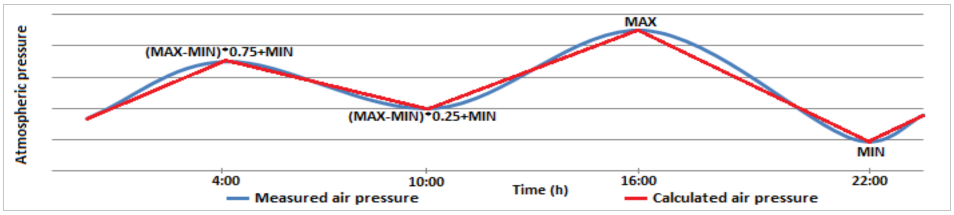

Figure 6 Schematic view on how the atmospheric pressure is modelled based on the measured minimum and maximum atmospheric pressure coming (Meteorological department Bonaire, 2013).

3.3 SWAP

SWAP (soil, water, atmosphere, plant model) (Van Dam, 2008) will be used to model the mangrove growth depending on the salinity. SWAP is a physical 1D-model and is able to simulate transport of water, solutes and heat in the vadose zone in interaction with vegetation development. Meteorological data, such as daily temperature, wind speed, radiation, precipitation and wind speed is given as input. Potential evapotranspiration is calculated using Penman-Monteith. Actual transpiration depends on moisture and salinity conditions. Actual evaporation depends on different soil factors. Irrigations with fixed date, depth and quality can be given as input. Runoff will occur when the rainfall intensity exceeds the maximum matrix infiltration rate. Interflow will occur when the groundwater level becomes higher than the interflow drainage level. Drainage is calculated with the Hooghoudt or Ernst equation or the user might define an input table. The module WOFOST 6.0 can simulate crop growth and leaf photosynthesis. Crop growth is affected by external stress factors such as salinity, drought, wetness and frost. Soil water flow is calculated with the Richards' equation. Concepts are added to account for macroporous flow and water repellency. Soil physical relations are based on the Mualem-Van Genuchten function. For solute transport SWAP considers: convection, diffusion, dispersion, adsorption and decomposition. Soil water fluxes are generated as PEARL for pesticides and ANIMO for nutrients. SWAP simulates soil heat flow taking into account actual heat capacities and thermal conductivities. Figure 7 gives a schematic overview of the processes incorporated in SWAP. Van Dam (2000) gives a complete description of the SWAP model.

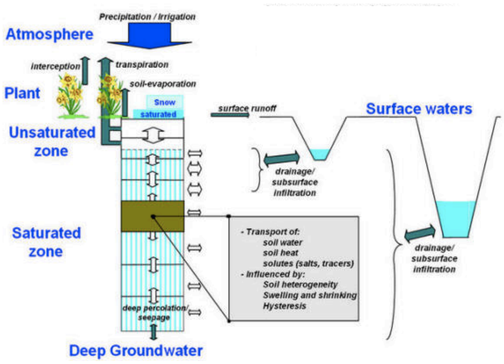

Figure 7 schematic overview of the processes incorporated in SWAP (Van Dam, 2000)

The following assumptions have been made in this study relating to SWAP;

- Run-on and runoff processes are disregarded. The water will leave the system by evapotranspiration or drainage. There is free drainage within the system. The bottom of the soil column is assumed to be impermeable. It's unknown whether there is any fresh water seepage or infiltration. Possible seepage or infiltration is included in the tidal fluctuation and so within the irrigation gift. The total drainage is as high that ponding on a daily basis will not occur.
- The pressure head of each compartment is in hydrostatic equilibrium with initial groundwater level.
- The salt concentration of the irrigation water equals 35 mg/cm^3. The ECmax equals 72 mS/cm for *Avicennia germinans* and 59 mS/cm for *Rhizophora mangle* (Chen and Twilley, 1998). The ECslope equals 11 %/mS/cm for *Avicennia germinans* and 14 %/mS/cm *Rhizophora mangle* (Chen and Twilley, 1998).
- A new subroutine, which simulates tree biomass growth, is added to SWAP. For modelling the tree biomass growth a minimal set of non-linear differential equations is used (Keesman et al., 2007). Appendix II gives an overview of these equations.
- SWAP is unable to simulate tides. To implement the tidal effect within SWAP an irrigation file is made. The (daily) amount of irrigation is based on the daily tidal inflow. The assumption is made that the difference between high and low tide equals the inflow volume. The sum of the daily inflow equals the irrigation gift (Figure 8). There is no tidal data available in the period of 1989 to 2009. The irrigation gift will be modelled for this period. The daily irrigation gift based on the tidal chart of Kralendijk (Flater, 2012) is modelled for these years. Based on the relation between the daily irrigation gift in Kralendijk and the daily irrigation gift of the different divers, the daily irrigation gift for the period of 1989 to 2009 can be calculated. Also gaps in the tidal data in 2012 can be filled using this method.

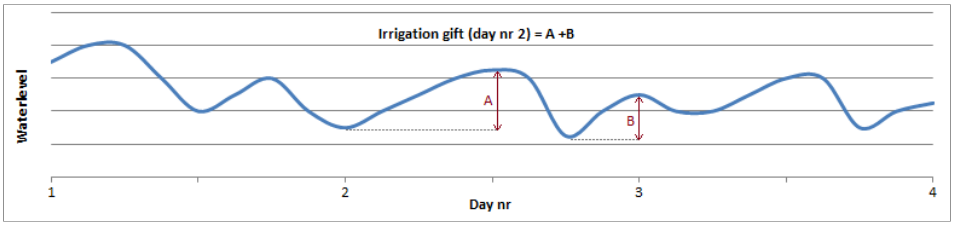

Figure 8 Schematic view on how to calculate the daily irrigation gift.

- Using equation 3 the amount of surface runoff can be calculated:

$$Concentrated\ local\ inflow = \begin{cases} \left(\frac{A_1}{A_2} * frac\right) * (Prec - 5) & if \quad Prec > 5 \\ 0 & if \quad Prec < 5 \end{cases} \tag{3}$$

Where A_1 is the surface area of the runoff catchment (22.6 km^2), A_2 is the surface area of Lac Bay (0.634 km^2). Frac equals the fraction of precipitation that will come to runoff. Following Grontmij (1968) will this fraction be in between 10 until 14% if the precipitation exceeds a minimum of 5 until 10 mm per day. For this study the assumption is made that if the precipitation exceeds a minimum of 5 mm per day 12 % will come to runoff. The amount of runoff is given as extra precipitation within SWAP. The assumption is made that the amount of surface runoff is equally distributed within Lac and that the entire catchment generates runoff.

- Meteorological data, the observed vertical discretization of the soil profile, measured soil hydraulic functions are input for SWAP. The tree biomass (gr) in SWAP is based on tree height and the tree diameter at breast height. The tree biomass, measured LAI and observed tree density are given as the start point for simulating tree growth.
- The modelled output for salt stress is in the same range as the measured electrical conductivity.
- Finally the biomass growth of *Avicennia germinans* and *Rhizophora mangle* will be simulated with SWAP for the period of 1989 to 2009 at ten different locations.

4 RESULTS

In this section an overview of the results will be given. First an overview will be given of the nitrate and phosphate concentrations at different locations within Lac Bay. Secondly the water-level fluctuation at different locations within Lac Bay will be given. Afterwards the modelled salinity fluctuation of a one-year period, the salinity in relation with the growth of *Rhizophora mangle* and *Avicennia germinans* and the influence of surface runoff on the salinity will be given. Finally the tree growth in a one-year period at different locations in Lac will be given.

4.1 NUTRIENTS

The nitrate concentration within Lac Bay differs from an average of 1.5 mg/l in the west until an average maximum of 4 mg/l in the west. There is no clear pattern in the nitrate concentration at the different locations. At all locations duplicates have been taken. The difference in concentration between the duplicates is maximum 0.9 mg/l. The phosphorus concentration is in between 0 and 0.25 mg/l at all locations. The used method was unable to give a more precise indication of the phosphate concentration.

Table 1 Measured nitrate and phosphate concentration at the different locations.

	Nitrate concentration (mg/l)		Phosphate concentration (mg/l)	
	1	2	1	2
Awa Yuwana	1.9	1.0	0-0.25	0-0.25
Mangrove Center	3.7	4.2	0-0.25	0-0.25
Cai	2.3	2.8	0-0.25	0-0.25
Rooi Grandi	3.6	4.2	0-0.25	0-0.25
Awa Fogon	2.8	3.6	0-0.25	0-0.25
Isla di Chico	2.9	2.5	0-0.25	0-0.25
Isla Rancho	2.3	1.8	0-0.25	0-0.25
Punta Rancho	2.9	3.5	0-0.25	0-0.25
Awa "D"	3.7	3.5	0-0.25	0-0.25
Awa Yanapa	3.5	4.2	0-0.25	0-0.25

4.2 WATER LEVELS

Tides within Lac can be classified as a mixed dominant semidiurnal type (Brown et al., 1995). The maximum daily fluctuation within Lac equals on average approximately 30 cm. The annual fluctuation equals approximately 10 cm. The tidal fluctuation is delayed and attenuated towards the backland (Appendix III). The water levels reach their highest point in January (after the rain season). Afterwards the water levels declines again until it reaches their lowest point by the end of March/beginning of April. Afterwards the water levels fluctuate around a stable average (Appendix IV).

Figure 9 gives an overview of the tidal fluctuation in Cai. Visible is a two-week tidal component. There is a diurnal tidal fluctuation at the beginning of December. After approximately one week a duplication of the diurnal component occurs, while the amplitude decreases. This daily dual fluctuation dominates until the diurnal fluctuation constitutes one week later. This two-week tidal component can be seen during the entire year. Also an annual tidal component is visible.

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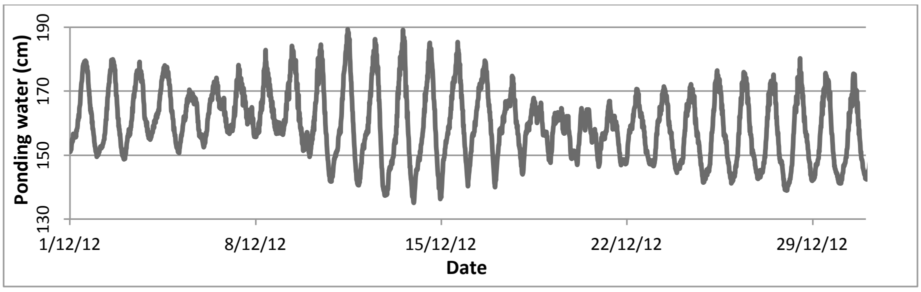

Figure 9 Water-level fluctuations at Cai in December 2012.

Figure 10 shows the tidal fluctuation of Awa Yuwana, Rooi Grandi and Mangrove Center in December. Awa Yuwana is located in the west, Rooi Grandi is located in the north and Mangrove Center is located in the east. Visible is an attenuation compared to the tidal fluctuation in Cai (Figure 9). Also in this case a two-week tidal component is visible. The tidal fluctuation in the beginning of December equals the attenuated tidal fluctuation in Cai. Afterwards the tidal amplitude in Cai decreases. At the some point the tidal fluctuation at Awa Yuwana, Rooi Grandi and Mangrove Center is almost completely attenuated and a decreasing trend in the water level becomes visible.

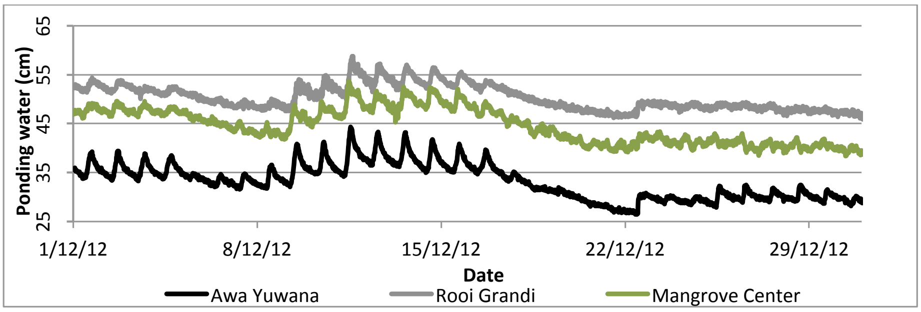

Figure 10 Water-level fluctuations at Awa Yuwana, Rooi Grandi and Mangrove Center in December 2012.

4.3 Salinity

Table 2 gives an overview of the abundance *Avicennia germinans and Rhizophora mangle* and the salt stress at different locations. Visible is an increase in modelled salt stress towards the backland. The lowest salt stress values can be found at Cai, highest salinity values can be found at Rooi Grandi. The annual salt stress for *Rhizophora mangle* is at the most location between 0.7 and 0.8, the annual salt stress for *Avicennia germinans* is in between 0.2 and 0.3. There seems to be a negative relation between the abundance of *Rhizophora mangle* and salt stress. *Avicennia germinans* will occur at locations where the salt stress is too high for *Rhizophora mangle* to grow.

Table 2 Abundance of Avicennia germinans (Av) and Rhizophora mangle (Rh) and the modelled salt stresses at different locations within Lac Bay in 2012.

	Abundance (%)		Salt stress ($1-T_{act}/T_{pot}$)	
	Av	**Rh**	**Av**	**Rh**
Awa Yuwana	20	80	0.22	0.69
Mangrove Center	60	40	0.26	0.73
Cai	0	100	0.00	0.16
Rooi Grandi	100	0	0.30	0.80
Awa Fogon	0	100	0.24	0.73
Isla di Chico	100	0	0.24	0.76
Isla Rancho	90	10	0.26	0.74
Punta Rancho	50	50	0.29	0.77
Awa "D"	30	70	0.24	0.73
Awa Yanapa	10	90	0.28	0.74

Figure 11 gives the relation between the measured range of electrical conductivity in the period of November 2012 until January 2013 and the abundance of *Avicennia germinans* (Av) and *Rhizophora mangle* (Rh). Figure 12 gives an overview of the observed abundance of *Avicennia germinans* and *Rhizophora mangle* in relation with the modelled salt storage of the soil at the end of 2009 after 20 years of simulations. This relation will be the same through the entire year. In both cases dominate *Avicennia germinans* in areas where the salt storage is relatively high. In comparison with *Rhizophora mangle* that is dominant in areas where the salt storage is relatively low.

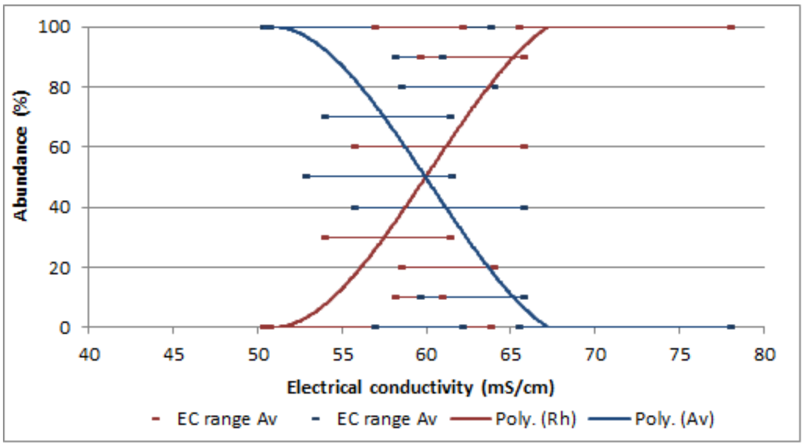

Figure 11 the relation between the measured range of electrical conductivity in the period of November 2012 until January 2013 and the abundance of Avicennia germinans (Av) and Rhizophora mangle (Rh).

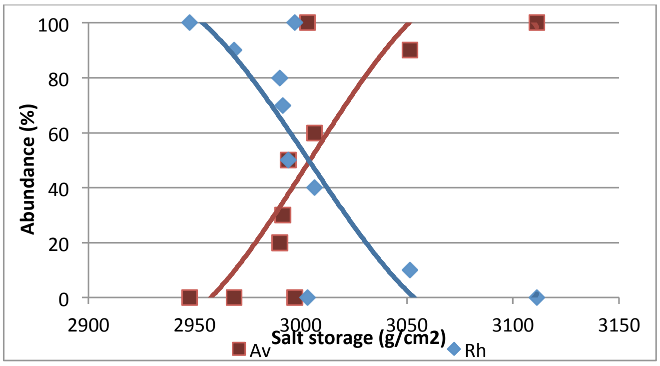

Figure 12 The relation between the modelled salt storage in the soil and the observed abundance of Avicennia germinans (Av) and Rhizophora mangle (Rh) by the end of 2009 after 20 years simulation.

Looking at the yearly salinity fluctuation a peak in salt stress in March becomes visible. This peak is caused by a lack of precipitation and high evapotranspiration rates. This peek will become more extreme in the backland (Appendix V). There is a dip in the salt stress in the months October, November and December, caused by high precipitation rates. Figure 13 gives an example of the salt stress fluctuation and amount of precipitation for *Avicennia germinans* and *Rhizophora mangle* in the year 2012.

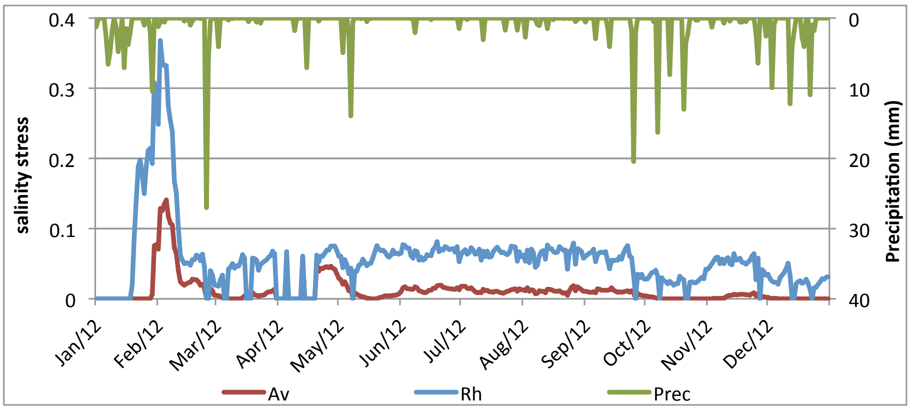

Figure 13 The salinity stress (1-T_{act}/T_{pot}) and precipitation for Avicennia germinans (Av) and Rhizophora mangle (Rh) at Mangrove Center in the year 2012.

4.3.1 FRESH WATER INFLOW

Annual average precipitation rates vary strongly. The average amount of precipitation measured in the period of 1989 to 2009 equals 388 mm. The standard deviation equals 168 mm. The amount of annual precipitation is important for the salinity. High precipitation rates might dilute the salinity and so decrease the salt stress for the mangrove trees. This effect is strengthened by surface runoff as described in methods (chapter 3). The founded relation between the modelled surface runoff and the amount of precipitation is linear. High precipitation peaks will also lead to high amounts of surface runoff. The total annual average amount of surface runoff is about 990 mm, with a standard deviation of 780 mm (measured in the period of 1989 to 2009). Figure 14 gives an example of the fluctuation in salt stress for *Avicennia germinans* at Isla di Chico in the period 1989 to 2009. The fresh water inflow depends on precipitation or precipitation and surface runoff. The salt stress is declines if surface runoff is also taken into account combined runoff peaks and precipitation peaks will lead to a decrease in salt stress.

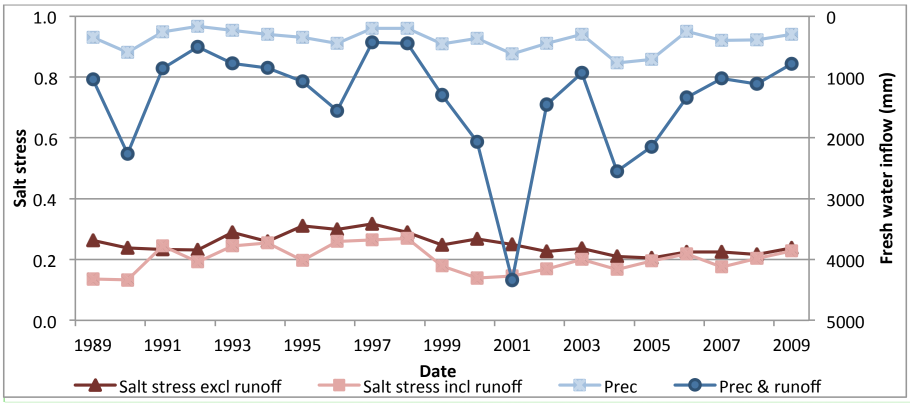

Figure 14 The modelled salt stress (1-T_{act}/T_{pot}) for Rhizophora mangle at Isla di Chico in a situation with and without surface runoff and the yearly amount of precipitation and the calculated annual amount of surface runoff in the period of 1989 to 2009.

Figure 15 show the salt stress for *Avicennia germinans and Rhizophora mangle* depending on the amount of precipitation and surface runoff at Isla di Chico. *Avicennia germinans* is in general better able to cope with hypersaline conditions and experiences less salt stress compared to *Rhizophora mangle* (Table 2). Trees at Isla di Chico have to deal with relative salt conditions. This might be the reason why *Avicennia germinans* is the dominant species at Isla di Chico. *Rhizophora mangle* will be dominant in areas were the salt conditions are relatively low. The decline in salt stress if surface runoff is taken into account is on average approximately 28% for *Avicennia germinans* and 30% for *Rhizophora mangle.* Although, the exact influence of surface runoff on the salt stress is strongly dependent on the locations and the annual precipitation rate. Locations were more salt is stored within the soil will more benefit from the surface runoff. The intensity of the rainfall events is also of importance for the salt stress. Only rainfall events with a high intensity will contribute to runoff and so decline the salt stress.

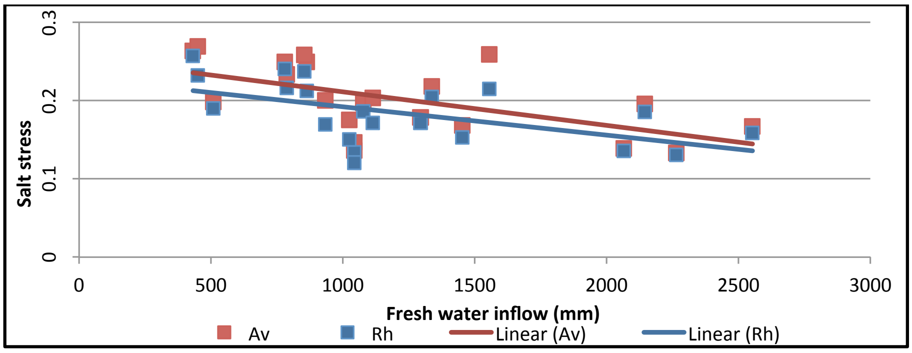

Figure 15 The relation between the annual amount of fresh water inflow (precipitation and surface runoff) and salt stress (1-Tact/Tpot) for Avicennia germinans (Av) and Rhizophora Mangle (Rh) at Isla di Chico and Fogon.

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Figure 16 shows the relation between the modelled salt stress stress for *Avicennia germinans* and *Rhizophora Mangle* at Rooi Grandi by the end of 2009 and the percentage of the calculated runoff within this study. The runoff calculated within this study might overestimate the actual runoff. If the actual runoff will be lower the salt stress will be higher.

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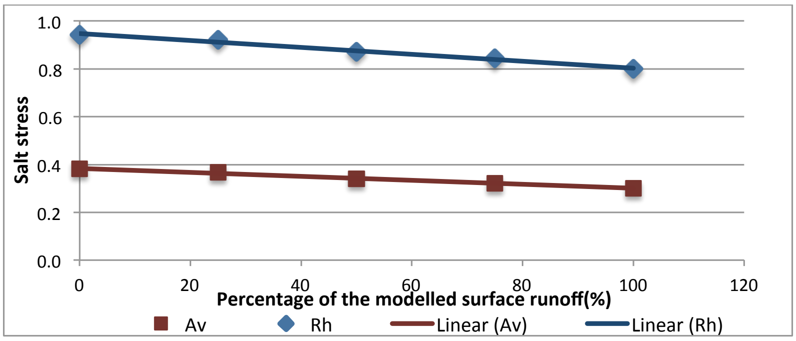

Figure 16 The relation between the modelled salt stress stress for Avicennia germinans and Rhizophora Mangle at Rooi Grandi by the end of 2009 after a simulation period of 20 years and percentage of the modelled runoff within this study.

4.3.2 Saltwater inflow

The amount of saltwater inflow is also of major importance. Seawater might flush salts out of the soil when the salt concentration increases above the salt concentration of seawater. Figure 16 shows the relation between the modelled salt stress for *Avicennia germinans* and *Rhizophora Mangle* at the end of 2009 after a simulation period of 20 years and the increase in tidal amplitude (mm) at Isla di Chico. There is a negative relation between the tidal amplitude and the salt stress. *Rhizophora mangle* is more influenced by an increase in tidal amplitude compared to *Avicennia germinans*. No salt stress occur when the tidal amplitude increase with approximately 11 mm. This will mean that the salt water inflow should be increased with 130%. *Avicennia germinans* will not be limited with salt stress if the tidal amplitude increases with approximately 5 mm. This equals an increase of approximately 60% in the salt water inflow.

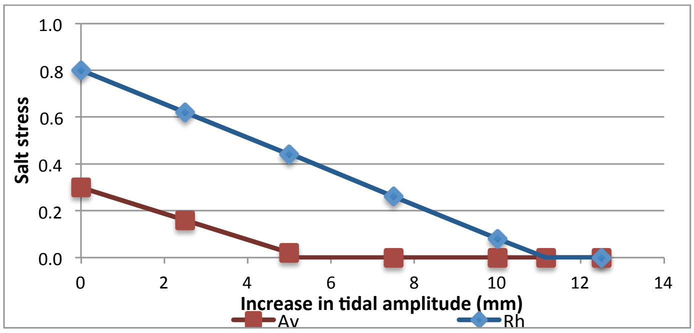

Figure 16 The relation between the modelled salt stress for Avicennia germinans and Rhizophora Mangle at the end of 2009 after a simulation period of 20 years and the increase in tidal amplitude (mm) at Rooi Grandi.

4.4 TREE GROWTH

Table 3 gives an overview of the salt storage within the soil, biomass growth within one year when not limited by salts stress and the biomass growth within one year limited by salt stress. Visible is a high increase in biomass at Rooi Grandi if salt stress is not taken into account. This can be explained by the fact that the tree density and tree biomass is relatively low at this location, so the growth will be relatively high. The decline in biomass growth however is largest at Rooi Grandi, if salt stress is taken into account.

Table 3 The abundance (%), biomass growth within one year with no stress (%) and the biomass growth within one year limited by salt stress (%) of Avicennia germinans and Rhizophora mangle at different location within Lac Bay at the end of 2012.

	Salt storage soil (g/cm^2)		**Biomass growth (%/yr)**		**Biomass growth limited by stress (%/yr)**	
	Av	**Rh**	**Av**	**Rh**	**Av**	**Rh**
Awa Yuwana	3036.6	2990.2	2.6	6.6	2.2	3.0
Mangrove Center	3056.9	3006.5	5.1	3.2	3.9	1.3
Cai	3000.0	2947.6	-	-	-	-
Rooi Grandi	3154.3	3111.3	10.6	10.6	5.9	3.3
Awa Fogon	3051.3	2997.2	-	1.2	-	0,8
Isla di Chico	3074.6	3003.2	2.8	-	2.1	-
Isla Rancho	3046.2	3051.5	2.5	6.7	2.1	2.9
Punta Rancho	3033.4	2994.2	3.1	5.1	2.5	2.0
Awa "D"	3045.3	2991.6	3.4	2.9	2.6	1.0
Awa Yanapa	2999.6	2968.7	4.7	3.1	2.9	1.3

Figure 17 and Figure 18 gives an overview of the biomass growth of *Rhizophora mangle* and *Avicennia germinans* including salt stress and the biomass growth excluding salt stress at Isla di Chico and Fogon. As *Avicennia germinans* will not occur at Fogon and *Rhizophora mangle* will not occur at Isla di Chico the assumption is made that the tree density and biomass at the beginning is the same for *Avicennia germinans* as for *Rhizophora mangle.* Since the increase in tree biomass is only dependent on radiation, tree density, tree height and LAI, the biomass growth without stress will be equal for *Avicennia germinans* and *Rhizophora mangle*. The biomass growth is larger at Isla di Chico; the tree density and biomass at start is lower compared to Fogon. The biomass growth becomes very small after approximately 18 years. The biomass growth at Isla di Chico is more limited by salt stress compared to Fogon. For example the biomass growth for *Rhizophora Mangle* is limited with 42% at Fogon and with 50% at Isla di Chico.

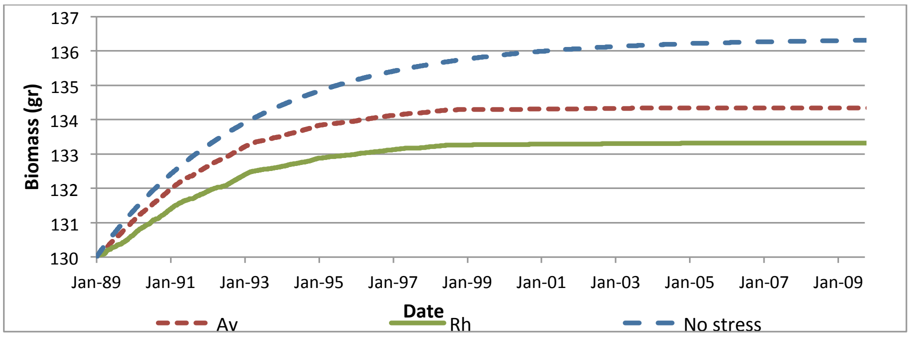

Figure 17 The increase in biomass (gr) pertaining to January 1989 for Avicennia germinans (Av), Rhizophora mangle (Rh) with salt stress and the biomass growth if salt stress is not taken into account at Fogon in the period January 1989 to December 2009.

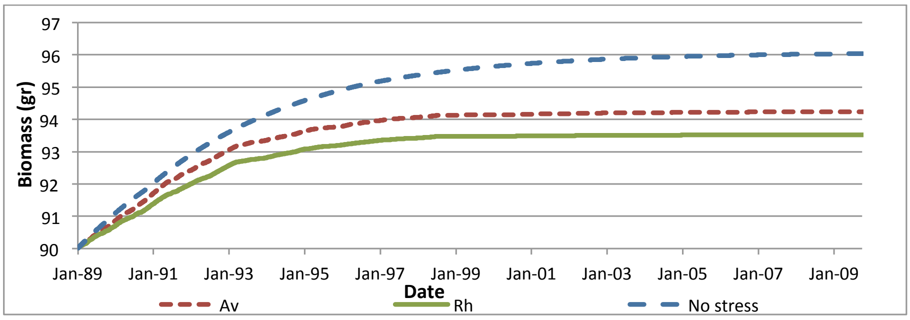

Figure 18 The increase in biomass (gr) pertaining to January 1989 for Avicennia germinans (Av), Rhizophora mangle (Rh) with salt stress and the biomass growth if salt stress is not taken into account at Isla di Chico in the period January 1989 to December 2009.

5 DISCUSSION

SWAP has been used in order to model salinity fluctuation and the growth of *Avicennia germinans* and *Rhizophora mangle*. These results are shown in the previous chapter (Results). This chapter will discuss these results. First the salinity fluctuation will be discussed. Secondly tree growth and the possible causes for the degradation of the mangrove forest will be discussed. Thirdly the consequences for management purposes will be discussed.

5.1 SALINITY

SWAP has been used in order to simulate the salinity fluctuation. The electrical conductivity has been measured in the field in the period November 2012 to January 2013. The measured values seem to be relatively high if you would compare it with the monthly averages that have been measured by Kats (2007). The reason for this might be the relatively low amount of precipitation in this year. The annual average rainfall amount is about 460 mm (World weather and climate information, 2012-2013). The amount of rainfall in 2012 was only 260 mm. High precipitation rates might dilute the salinity. The modelled electrical conductivity values are consistent with the values given by Kats (2007). Visible is an increase in salinity stress towards the backland. The diver data show decrease in tidal fluctuation towards the backland; the amount of inflowing water will decrease. So less salt will be flushed out of the soil and the salinity increases. Evapotranspiration will also have more impact on the salinity when the seawater inflow is lower.

5.1.1 SALTWATER INFLOW

SWAP has modelled the annual salinity fluctuation in the period 1989 to 2009. Noteworthy is the salinity peak around March. The modelled peak seems to be relatively low compared to field measurements done in other studies. Especially the soil salt storage in the period around March in the backland seems to be underestimated. This study modelled a monthly mean of 120 mS/cm at Rooi Grandi (situated in the backland) in March. Kats (2007) has measured a monthly mean of 170 mS/cm at Awa Lodo di San José in March. Regensburg (2012) has measured electrical conductivities of 155 up to 160 mS/cm at this location in April. The difference between the electrical conductivity modelled within this study and the measured mean by Kats (2007) might be explained by the fact that barriers within Lac Bay limit the water circulation. Normally the water flows from the Kreek di Coco towards Awa Lodo di San José (Figure 19). This area might become isolated when the water level drops during the dry season. This can be seen at the measured tidal fluctuation (Appendix III). The tidal fluctuation seems to be cut off at a certain minimum. High evapotranspiration rates might now lead to hypersaline conditions. Furthermore the assumption is made that the salt concentration of the inflowing water will be 35 g/l (equals the salt concentration of seawater), although inflowing water will probably have a higher salt concentration in the backland caused by evapotranspiration. This might lead to an underestimation of the salinity.

Figure 19 Flow pattern (Kats, 2007)

5.1.2 FRESH WATER INFLOW

Precipitation and surface runoff are two sources of fresh water for Lac Bay. The amount of precipitation varies strongly within the area. Within this study the assumption is made that the precipitation measured by the Meteorological department Bonaire (2013) at flamingo airport equals the precipitation at Lac Bay and the runoff catchment. The actual amount of precipitation varies strongly within the area. The measured precipitation might be different at the measuring location compared to Lac Bay. The same holds for runoff, which is dependent on the precipitation. The amount of runoff calculated within this study might be overestimated. The assumption has been made that runoff occurs when the total daily precipitation exceeds a minimum of 5 mm. Grontmij (1986) describes that this minimum should be between 5 until 10 mm per day and the fraction runoff in between 10 until 14%. In addition the assumption is made that no runoff is trapped and the total amount of runoff is equally distributed in the area. The actual influence of the runoff will be larger on the shore of Lac Bay and smaller onshore and part of the runoff will be lost. So the given amounts of runoff might overestimate the actual runoff. Although, based on these results the conclusion can be made that runoff is of significant influence and more research should be done towards this subject.

Groundwater flow might be another source of fresh water. Groundwater flow is not included in this model. The assumption is made that the bottom flux equals zero. Eventual infiltration or seepage is measured within the tidal fluctuation, and so included within the irrigation gift. The salt concentration of the irrigation gift equals 35 g/l. The groundwater consist of fresh water inflow (Rønde, 2013). This means that groundwater might flush salt out of the soil and so decrease the salinity. The exact amount of inflowing fresh water inflow is unknown, more research should be done towards this subject.

5.2 TREE GROWTH

This study mainly focuses on the growth of *Avicennia germinans* and *Rhizophora mangle* limited by high salinity, low nutrients concentrations and high water levels. These three factors seem to be the most important limiting factors for mangrove growth (Berger et al., 2008). *Rhizophora mangle* will grow on location where the salt concentration within the soil is relatively low. *Avicennia germinans* grow on locations where the salt concentration of the soil is too high for *Rhizophora mangle* to grow.

5.2.1 NUTRIENTS

Nitrate and Phosphate are the most important limited nutrients in mangrove growth (Lapointe et al., 1987). Phosphate was measured colometric with a colour card. All the location did have a phosphorus concentration in between 0 and 0.25 mg/l, this method could not give a more precise result. It is difficult to say whether phosphate is limited or not based on these results. Nitrate concentrations were relatively high. Moorsel and Meijer (1993) have measured silicum, ammonium, nitrate, nitrite and phosphate concentrations at different locations within Lac Bay in 1993. They also measured relatively high nitrate and low phosphate concentrations. It is unclear how the nitrate concentration fluctuates through the year. Although the expectation is that nitrogen will not be limiting for the growth of *Avicennia germinans* or *Rhizophora mangle*. Different studies also indicate that high sulphide concentrations might limit mangrove growth (Lin and Sternberg, 1992; Craighead, 1971; Davis, 1940). Until now no research have been done towards the sulphide concentration within Lac Bay and it is not yet clear how this might influence the mangrove growth within Lac Bay.

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5.2.2 WATER LEVELS

Hydroperiod, the duration, frequency and depth on inundation is another important limiting factor for mangrove growth (Berger et al., 2008). The tidal fluctuation at, for example, Punta Rancho, Awa "D" and Isla di Chico, is cut off at a minimum (appendix V). The water level at these locations stays constant, even when the water level at Cai decreases further. This might suggest that barriers limit the water circulation within Lac Bay. If this is the case the low-laying mangrove trees might be harmed by too long periods of inundation since water is unable to flow out of the system (Wolanski, 1992). More research is necessarily towards the duration, frequency and depth on inundation of the mangrove trees within Lac Bay in order to determine whether this harms the mangrove trees.

Tidal fluctuation is given as an irrigation gift within SWAP. The sum of the daily inflowing water equals the irrigation gift. The relation between the irrigation gift at Kralendijk and the irrigation gift of the different divers has been used to calculate the irrigation gift in the period of 1989 until 2009 and to fill gaps in the irrigation file of the year 2012. The gaps in the irrigation file of 2012 might differ from three until six months. A deviation might exist between the modelled daily irrigation gift and actual daily irrigation gift, caused by barriers within the area. Barriers might limit the water inflow and outflow towards a certain area (Lott, 2001). By linking the irrigation gift of Kralendijk towards the irrigation gift of the different divers the effect of barriers is neglected.

Within SWAP the assumption is made that the daily irrigation gift will have left the system by the end of the day, so no ponding will occur. The water will leave the system by drainage or evapotranspiration. This might lead to an increase in the salt stress within the soil since in reality some salt will also leave the system in runoff.

5.2.3 SEDIMENTATION

During heavy rainfall events eroded material might be transported from the backland towards Lac Bay. Also some sands that are carried in from currents crossing over the coral 'dam' that naturally separates the Lac from the coastal oceans, will be deposited in Lac Bay (Moorsel and Meijer, 1993). This might have a negative impact on the water circulation and so on the salinity stress. Kats (2007) noticed that the depth of the open water has decreased since the 1900s. Further research is necessary to find out where the sediment is coming from and going to and how this will influence the tidal fluctuation.

5.2.4 DEGRADATION OF THE MANGROVE

A massive die-off process of the mangroves is visible at the Northern-outer borders of Lac Bay. Based on this study it is most likely that high salinity values are the cause for the degradation of the mangroves at the Northern-outer borders. The salt concentration within the soil and so the salt stress for *Avicennia germinans* and *Rhizophora mangle* is the highest at this location. If the salt stress is too high the potential transpiration becomes zero. The tree will die when it is unable to transpire for a longer period of time. This die-off process is not included in SWAP. The degradation of the mangroves is only dependent of the relative biomass loss, which is a constant percentage of the total biomass. The model could be improved by implementing a process, which simulates die-off of the mangrove trees when the trees cannot transpire for a period of time.

Mangrove growth is impossible if the electrical conductivity exceeds 90 mS/cm (Cintron and Schaeffer-Novelli, 1983; Odgen and Gladfelter, 1980). Kats (2007) has measured the yearly average fluctuation in salinity. By comparing both studies the conclusion can be made that salinity values are too high for *Avicennia* germinans to thrive during five months of the year at the northern outer shore (Awa Lodo di San José). *Rhizophora mangle* is unable to thrive for eight months of the year at the same location. This will cause a die-off process.

5.3 CONSEQUENCES FOR MANAGEMENT PURPOSES

The salinity increases towards the backland. There seems to be a negative relation between the abundance of *Rhizophora mangle* and salt stress. *Avicennia germinans* will occur at locations where the salt stress is too high for *Rhizophora mangle* to grow. Conditions at the northern outer shore (around Awa Lodo di San José) become too saline for *Avicennia germinans* and *Rhizophora mangle* to grow. The salt stress at the northern outer shore might be decreased by increasing the surface runoff or by improving the salt water circulation. Increasing the salt water circulation seems to have the most impact. The seawater inflow should increase with 60%, so that *Avicennia germinans* will not be limited by salt stress and with 130% so that *Rhizophora mangle* will not be limited by salt stress. The salinity stress will decline with

The water flows from Kreek di Coco towards the hinterland (Figure 19). Salinity levels are already relatively high in Kreek di Coco. Salinity values measured in the west are lower. It would be useful to improve the water flow from the west (Awa Yuwana), in order to improve the conditions for mangrove growth.

There is also a die-off process going on at the mangrove trees located nearby Awa “D”. No clear reason for this die-off process could be found within this study.

6 CONCLUSION

This study focusses on the growth of *Avicennia germinans* and *Rhizophora mangle* in Lac Bay. Some insights are given on the tidal fluctuation and salinity fluctuation through the year. In addition to possible causes for the degradation of the mangrove forest at the northern outer shore are given. The most important conclusion that came forward from this study are:

- Salt stress seems to be the most limiting factor for mangrove growth. There seems to be a negative relation between the abundance of *Rhizophora mangle* and salt stress. *Avicennia germinans* will occur at locations where the salt stress is too high for *Rhizophora mangle* to grow. Conditions at the northern outer shore (around Awa Lodo di San José) become to saline; nor *Avicennia germinans* nor *Rhizophora mangle* is able to thrive at this location. The salt stress at the northern outer shore might be decreased by increasing the surface runoff or by improving the salt water circulation. Increasing the salt water circulation seems to have the most impact. The seawater inflow should increase with 60%, so that *Avicennia germinans* will not be limited by salt stress and with 130% so that *Rhizophora mangle* will not be limited by salt stress.
- The salinity is on average lower in the west compared to the east. To improve the mangrove growth at the backland, the water inflow from the west towards the hinterland should be improved.
- Annual average precipitation rates vary strongly. The average amount of precipitation measured in the period of 1989 to 2009 equals 388 mm. High precipitation rates might dilute the salinity and so decrease the salt stress for the mangrove trees. This effect is strengthened by surface runoff. There is a positive linear relation between the amount of surface runoff and the amount of precipitation. High precipitation peaks will also lead to high amounts of surface runoff. The total annual average amount of surface runoff is about 990 mm, with a standard deviation of 780 mm The decline in salt stress if surface runoff is taken into account is on average approximately 28% for *Avicennia germinans* and 30 % for *Rhizophora mangle.* Locations were more salt is stored within the soil will more benefit from the surface runoff.
- High water levels might harm trees, when they are inundated for long periods of time. The tidal fluctuation at different locations is cut off at minimum. This might suggest that barriers limit the water circulation within Lac Bay. If this is the case the low-laying mangrove trees might be harmed by too long periods of inundation. More research should be done towards this subject.
- All the location did have a phosphorus concentration in between 0 and 0.25 mg/l. The nitrate concentrations within the soil were relatively high. The expectation is that nitrate will not be a limiting factor. More research should be done towards phosphorus limitation.
- Tides within Lac can be classified as a mixed dominant semidiurnal type (Brown et al., 1995). The maximum daily fluctuation within Lac equals on average approximately 30 cm. The annual fluctuation equals approximately 10 cm.

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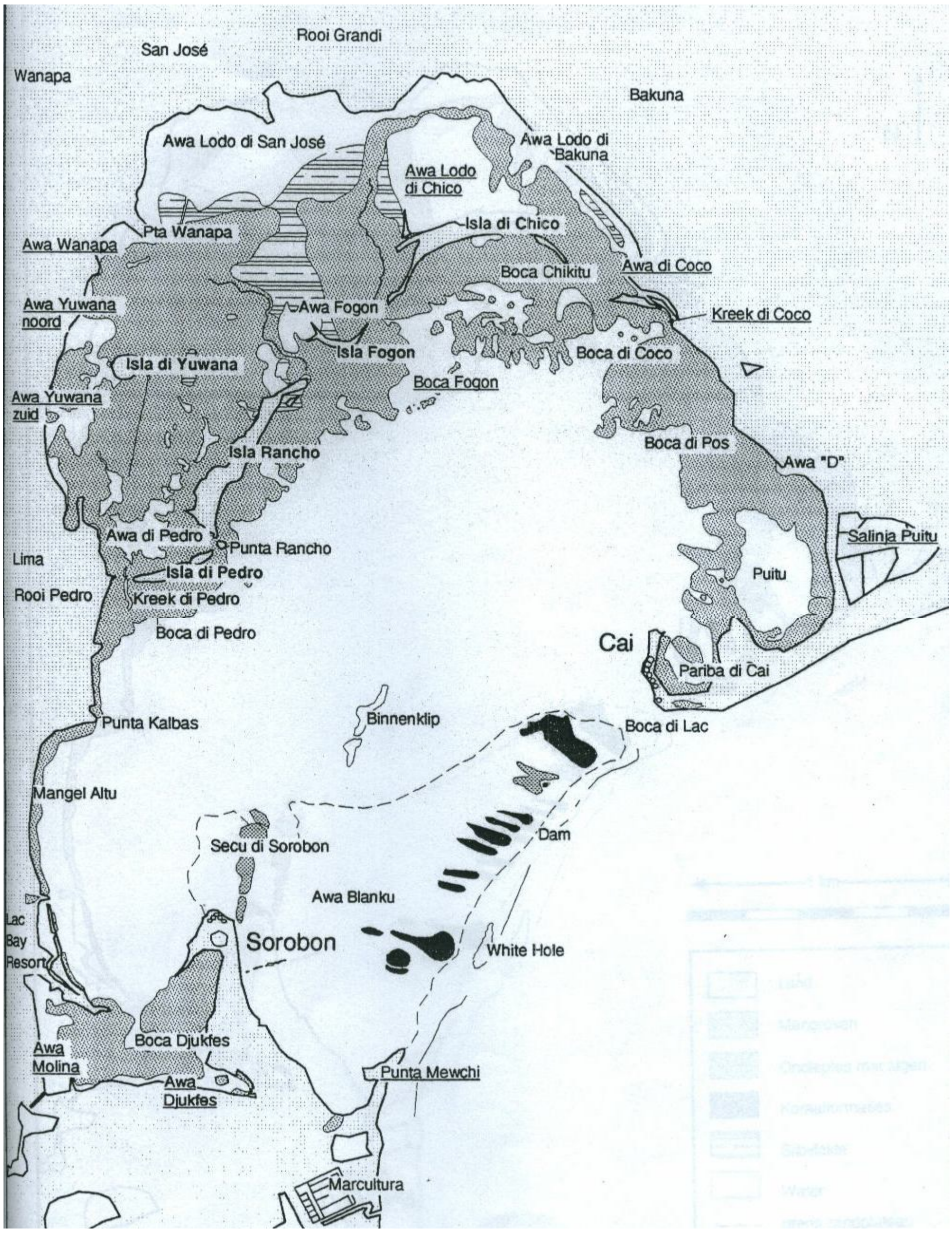

Rooi Grandi
San José
Wanapa
Bakuna
Awa Lodo di San José
Awa Lodo di Bakuna
Awa Lodo di Chico
Isla di Chico
Pta Wanapa
Awa Wanapa
Boca Chikitu
Awa di Coco
Awa Yuwana noord
Awa Fogon
Kreek di Coco
Isla Fogon
Boca di Coco
Isla di Yuwana
Boca Fogon
Awa Yuwana zuid
Isla Rancho
Boca di Pos
Awa "D"
Awa di Pedro
Punta Rancho
Salinja Puitu
Lima
Isla di Pedro
Puitu
Rooi Pedro
Kreek di Pedro
Boca di Pedro
Cai
Pariba di Cai
Punta Kalbas
Binnenklip
Boca di Lac
Mangel Altu
Dam
Secu di Sorobon
Awa Blanku
Lac Bay Resort
Sorobon
White Hole
Boca Djukfes
Awa Molina
Awa Djukfes
Punta Mewchi
Marcultura

APPENDIX II

Simpel tree model (Keesman et al., 2007)

Basic equations are:

$$\frac{dB_t}{dt} = \omega_t \frac{\varepsilon_t f_t}{\rho} I - aB_t$$

$$f_t = 1 - e^{-k_t L_t}$$

$$\frac{dA}{dt} = \rho N \frac{A_m - A}{\tau}$$

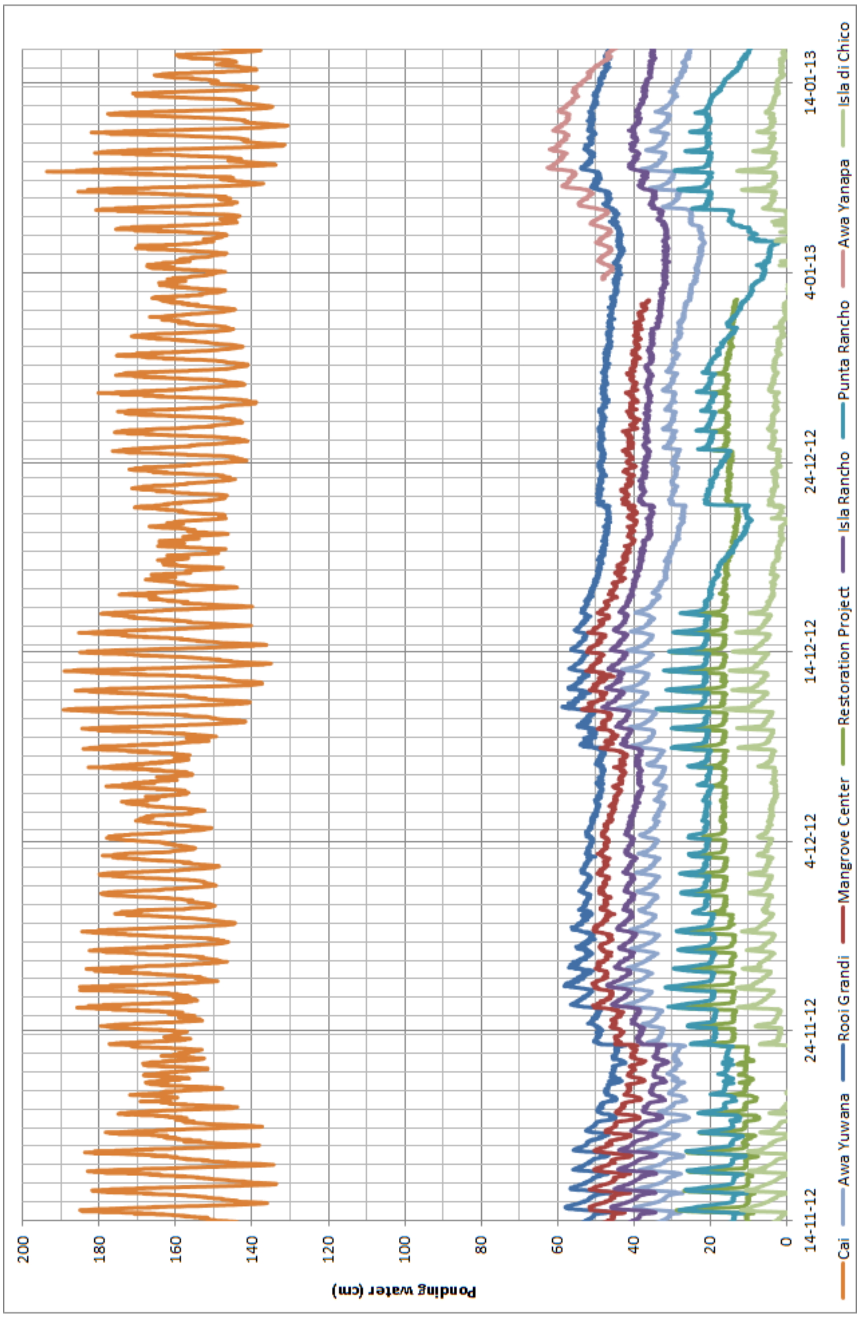
$$L = NA$$

$$\frac{dN}{dt} = \frac{dB_t}{dt} \frac{N}{B_t}\left(1 - \frac{N}{N_m}\right)$$

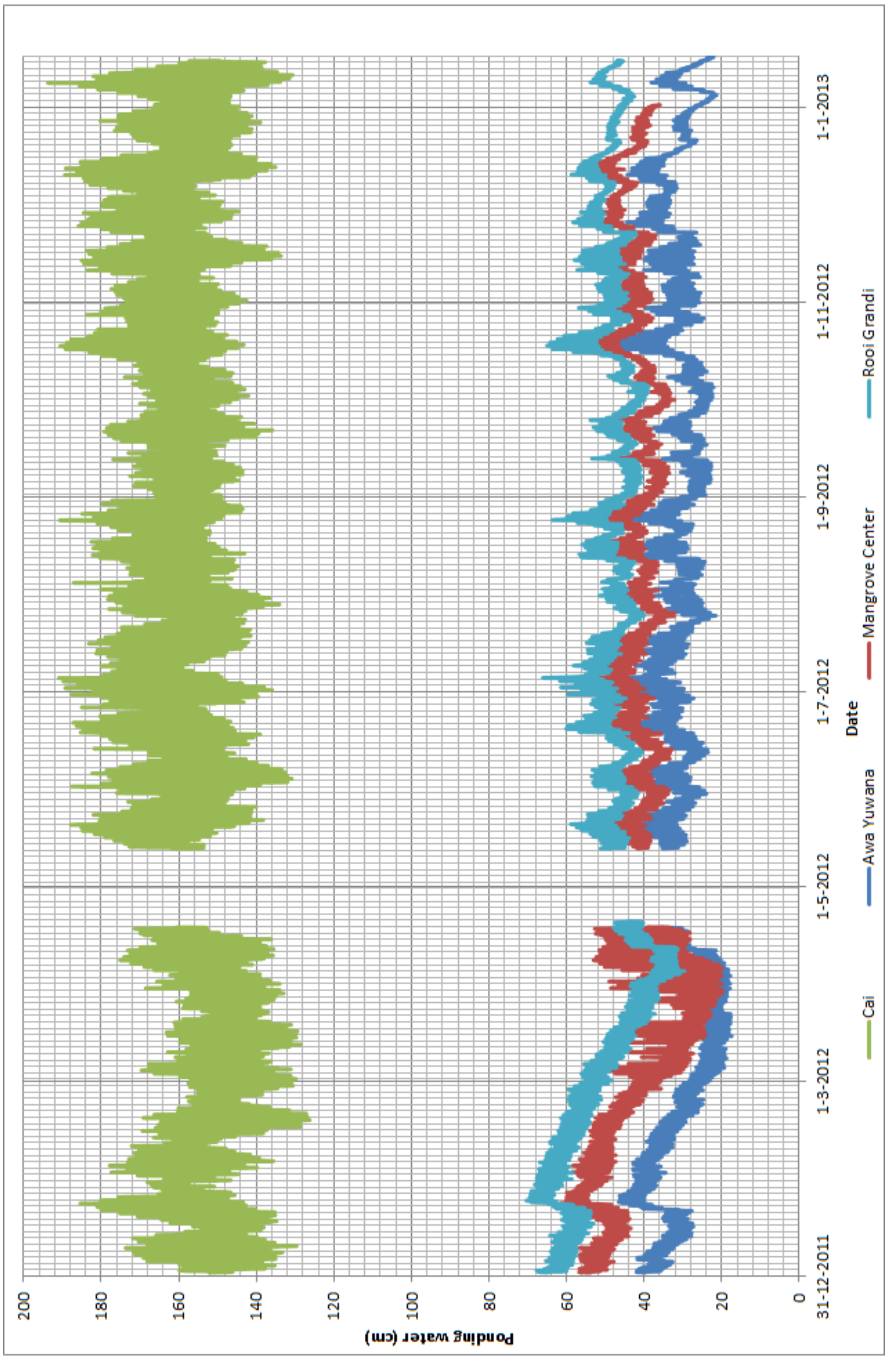
Spring – i.e. leaf area starts to grow at day 100. Leaf area growth ends (i.e. all leaf area is set to 0) at day 265. Number of shoots is not reset. Leaf biomass is negligible compared to tree biomass (assumption).

Symbols	Description	unit
B_t	tree biomass	g dry matter per tree
t	time	day
ω_t	water stress	[]
ε_t	radiation use efficiency	[g perMJ]
f_t	fraction radiation intercepted	[]
ρ	tree density	[number per m2]
I	radiation	MJ per m2 per day
a	relative biomass loss	[]
L_t	tree leaf area index	[m2 leaf per m2 total area]
k_t	extinction coefficient	[]
N	number of shoots on a tree	[]
A_m	maximum leaf area per shoot	m2 per shoot
A	current leaf area per shoot	m2 per shoot
τ	time constant for leaf area growth per shoot	days
N_m	maximum number of shoots on a tree	[]
N_0	initial number of shoots	[]

Before implementing the equations in Excel the above differential equations have to be written as difference equations (i.e. replacing d by Δ, and then Δ by a difference in state variables at different times (e.g. i and i-1).


Ponding water (cm)
200
180
160
140
120
100
80
60
40
20
0
14-11-12
24-11-12
4-12-12
14-12-12
24-12-12
4-01-13
14-01-13
Cai
Awa Yuwana
Rooi Grandi
Mangrove Center
Restoration Project
Isla Rancho
Punta Rancho
Awa Yanapa
Isla di Chico

APPENDIX IV


Ponding water (cm)
200
180
160
140
120
100
80
60
40
20
0
31-12-2011
1-3-2012
1-5-2012
1-7-2012
1-9-2012
1-11-2012
1-1-2013
Date
Cai
Awa Yuwana
Mangrove Center
Rooi Grandi