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Water Balance, Seasonal Hydroperiod Variation and Time of Residence of a Small Natural Freshwater Wetlands in the Humid Tropics in Costa Rica

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Summary

Hydrological studies of tropical wetlands have traditionally focused on large areas and scant information is available on the role of smaller wetlands. Central American wetlands are generally smaller than other tropical wetlands and are therefore more vulnerable to increasing pressure from agriculture, industrial and urban development. The hypothesis is that their abundance and ubiquitous distribution in the landscape reinforce the importance of their environmental functions (water storage, flood control and water quality improvement). This study was conducted in a small natural, freshwater tropical wetland (< 10ha) in eastern Costa Rica with a single outlet and no specific inlet. This distinctive hydrological characteristic offers an opportunity to evaluate the complex and dynamic system in terms of water balance and hydroperiod during one year of water stages monitoring. Objectives were to quantify the key components in the water balance; to identify the storage and water surface variation and frequency to assess the stability of the hydrologic response and the natural water quality function potential.

A hydrological monitoring network was installed during 2008 and detailed experimental time series was used to quantify hydrologic inputs and outputs of the wetland over a one-year period (with precipitation collected of 4283 mm), allowing for the determination of the water balance and storage capacity of the system. Combining the time series data with a topographical survey allowed quantifying flooding frequency throughout the wetland's catchment by converting surface and storage time series into surface-extent and volume frequency histograms. Stability of the hydrologic response of the wetland was shown during the monitoring year with the exception of some extreme events (rain of high intensity and prolonged duration or short dry periods). The difference of storage between the inputs and the outputs was negative until November 2008 and positive until May 2009 when the cumulated time series of the inputs converged, with the time series of the outputs, bringing the difference of storage close to zero. These results show that the wetland self-regulated naturally during the yearly budget and that there was no net loss of water during the period. Variation of water extent and volume were small during the year with a maximum in the 95% confidence interval of 16.5% and 24.2%, respectively. The stability and low flow characterizing the wetland improves therefore its water quality treatment potential. Based on calculated residence time distributions, the wetland is potentially capable of naturally reducing 70-92% incoming water pollution of common surface water pollutants for 95% of the calculated residence times.

In chapter 2, an investigation to explore the hydraulic characteristics of the wetland and to assess the feasibility of using sulfur hexafluoride (SF_6) as a tracer compared to bromide (Br^-) under humid tropical and slow flow conditions is presented. More than 400 samples collected on 18 sampling sites were analyzed after releasing the tracers in the wetland. Chemical analysis and interpretation of the results between the two tracers is given as a partial conclusion and as starting point for future work. SF_6 analysis showed that it is not an appropriate tracer for this location because of its non-conservative behaviour caused by strong volatilization during transport. Br- showed very good results with different time to peak concentrations that were coupled with the distances between sampling sites to give different flow paths and velocities of the tracer plumes, depending on the injection sites. The average velocities from residence time calculations were found to be in the same range as the velocities found in the tracer study.

Résumé

La plupart des études hydrologiques sur les zones humides tropicales se sont concentrées sur de grands sites, par conséquent, les informations sur le rôle des plus petites zones sont limitées. Cependant, les zones humides tropicales d'Amérique Centrale sont généralement de petite taille et sont donc plus vulnérables à la pression croissante de l'agriculture et du développement industriel et urbain. L'hypothèse de cette étude est que leur abondance et leur large distribution dans le paysage renforcent l'importance de leurs fonctions environnementales (stockage d'eau, prévention des inondations et amélioration de qualité de l'eau). Cette étude a été conduite sur une petite zone humide naturelle d'eau douce (<10ha) à l’est du Costa Rica. Le marais possède un unique exutoire sans spécifique affluent. Ces caractéristiques distinctives offrent une occasion d'évaluer ce système complexe et dynamique en termes de balance hydrique et d’hydro-période. Les objectifs étaient de quantifier les composants clefs de la balance hydrologique; d’identifier la variation et la fréquence du stock et de la surface d'eau afin d’évaluer la stabilité de la réponse hydrologique ainsi que la qualité naturelle de l’eau.

Le réseau d’appareils de mesure mis en place en mai 2008 a permis de quantifier les apports et les pertes régissant la balance hydrique durant l’année étudiée (pour une précipitation de 4283mm). Les hauteurs d’eau mesurées en différents points du marais ont été couplées à un dense relevé topographique pour évaluer les variations de surface et de volume d’eau durant l’année ainsi que leur distribution de fréquence. La différence de stockage entre les apports et les pertes d’eau était négative jusqu'en novembre 2008 puis positive jusqu'à mai 2009 où la série des apports cumulée a convergé avec la série des pertes apportant la différence de stockage près de zéro. Ces résultats montrent que le marais est autorégulé naturellement pendant le budget annuel et qu'il n'y avait aucune perte nette d'eau pendant la période. La surface et le volume d’eau ont très peu variés durant la période d’étude avec une augmentation maximale comprise dans l'intervalle de confiance (95%) de 16.5% et de 24.2%, respectivement. Ces faibles variations démontrent une réponse hydrologique rapide permettant une stabilité hydrologique durant toute l'année à l'exception de quelques événements extrêmes (pluie intense et de durée prolongée ou période sèche). La stabilité hydrologique et le lent débit caractérisant ce marais permettent d’améliorer sa qualité de l'eau en le rendant naturellement efficace à réduire la pollution de l'eau entrante pour les temps de séjour de l’eau dans le système compris dans l'intervalle de confiance de 95 % de sa distribution de fréquence.

Au chapitre 2, une étude complémentaire pour évaluer les caractéristiques hydrauliques du marais et la faisabilité d'utiliser l’hexafluorure de soufre (SF6) comme traceur en comparaison avec le bromure (Br-) dans les conditions d’eau tropicales lentes en surface libre a été menée. L’analyse du SF_6 a montré qu’il n'est pas un traceur adéquat sous les tropiques à cause de son comportement non-conservatif causé par forte volatilisation durant le transport. Br- a en revanche montré de très bons résultats avec des temps de concentration depuis les sites d’injection jusqu’au site d'échantillonnage présentant des chemins préférentiels et des vitesses de plumes différentes. Les vitesses trouvées dans cette étude ont été trouvées dans la même gamme que la vitesse moyenne du temps de séjour.

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1. Water Balance, Seasonal Hydroperiod Variation and Time of Residence of a Small Natural Freshwater Wetlands

1.1. Introduction

Wetlands are recognized to be the cradle of many past civilizations. Maya or Mesopotamian civilizations, for instance, have lived in with harmony aware of the importance of this productive ecosystem which offer unique site for specific cultures and fisheries like rice paddies or harvesting crayfish. Besides values and benefits for humans, natural freshwater wetlands have a great ecological importance for biodiversity and sustainability of natural systems. They provide habitat for fish and crustaceans, habitat for numerous species and endemic species of flora and fauna especially the water birds and are hosting a whole food web. As specific hydraulic functions, they improve water quality, aquifer recharge and discharge, sediment retention, flood control and flow regulation, biomass export, and control of erosion and maintain water levels during dry seasons.

While some present civilizations continue to adapt their life and activity to wetland environments, most human societies drain floodplains and develop water flow control to extend land settlement and agriculture (Dugan, 1993). For the last few decades only, revised understanding of the high socioeconomic and ecological potential of wetlands has led to the identification of important ecosystem values to these areas like wastewater treatment, wildlife preservation, and ecotourism development (Appendix 1.B). Government attitudes are then changing to reorient technical knowledge and scientific researches on wetland restoration and conservation (Roggeri, 1995; Mitsch, 2005). However, this trend has occurred mostly in developing countries located in the temperate region where the political and economical frameworks have allowed plans to make inventories and sustainable management of wetlands (Junk, 2002). A variety of analyses on water quality and water treatment taking place in natural wetlands have been transferred to the concept and development of treatment wetlands. Consequently, temperate wetlands are relatively well-known and studied compared to tropical wetlands which have received much less attention from the scientific and management communities (Barbier, 1992; Bullock, 1993; Roggeri, 1995; Junk, 2002; Ellison 2003; Nahlik and Mitsch, 2006). However, the increase in population and food demand in the tropical regions leads to a rapid deterioration of wetlands to access more land and water supply at the expense of wetlands preservation (Junk, 2002; Daniels, 2008). Inventory and hydrological studies of natural tropical wetlands have been focused mainly on large wetland systems. In Central America, La Selva Biological in Costa Rica (Genereux and Pringle, 1997; Genereux et al 2002; Genereux and Jordan, 2006) and Barro Colorado Island in Panama have been subject to many studies (Genereux et al 2002; Ellison, 2003). Mangrove swamps are also more studied than riparian freshwater wetlands (Ellison, 2003). However, many Central American wetlands are generally of smaller size and their ubiquitous distribution away from the major conservation sites makes them more vulnerable. As a result, small Central American wetlands commonly suffer from increasing pressure from agriculture, industrial and urban development, pollution and over-exploitation (Roggeri, 1995; Junk, 2002; Ellison 2003). Water balance and especially quantification of wetland inputs system constitute the basics to understand how individual wetlands function and how wetland systems differ (Bullock, 1993; Giraldo et al, 2007). Water dynamics and distribution in wetlands are typically highly variable in space and time (Winter, 1999; Mitsch and Gosselink, 2000). For instance, Ringrose shows that the quantification and characterization of the water flow depend on factors like topography, climatic conditions and the vegetation (Ringrose, 2003). Daniels explains that annual and interannual variation of rainfall affects the nature and size of the wetlands at any given time (Daniels, 2008). Finally, Genereux and Jordan found that groundwater flow can interact with surface water and should be accounted for as a water input in some cases (Genereux and Jordan, 2006). The composition and the structure of plant communities around the wetland also depend on the hydrologic characteristics of the water balance (Riis and Hawes, 2002) because vegetation zonation is driven by variation in hydro-period and the frequency and duration of saturation (Mitsch and Gosselink, 2000). Understanding the key components of water balance is therefore essential to the sustainable management of water resources in the Tropical region.

Tropical wetlands are similar to temperate wetlands for their fundamentals components and functions as influences on floods and low flows in river. However case studies and recommendations of management made on temperate wetlands cannot be directly applied in tropical areas because processes and interactions among ecosystem components are different (Appendix 1.A offers a detailed typology and definition of the different types of natural wetland found in the tropics). For instance, tropical wetlands are among the most productive ecosystems in the planet (Roggeri, 1995). Tropical wetlands can potentially improve water quality throughout the year due to their fairly stable warm water (around 25℃). Indeed, temperature has a strong influence on chemical and biological process like nitrogen reduction (Kadlec and Knight, 1996). For wetlands, the fraction of pollutants removal as total nitrogen (TN), total phosphate (TP), TSS and BOD_5 can be approximated with the area-based, first-order k-C* model proposed in Kadlec and Knight (1996). For each pollutant, an average value of the rate constant and the irreducible background wetland concentration is found in the literature. For a given temperature and hydraulic loading rate corresponding to the wetland flow divided by the wetland area, the fraction of hydraulic pollutant removal between the inlet to the outlet of the wetland can be calculated.

Our hypothesis is that due to their abundance and ubiquitous distribution, small wetlands in the tropical landscape of Central America have a critical and multifaceted role in the environmental quality of the area (water storage, flood control and water quality improvement). The present case study of a small wetland with no inlet and a regulated outlet aims to quantify the function of these wetlands and generate hydrological information in support of public decision-making to maintain its sustainability.

The objective of this study is to evaluate the spatially and temporally complex and dynamic hydrology of a natural wetland in the humid Tropics of the Atlantic region of Costa Rica (“La Reserva” EARTH, Guácimo). Specific objectives are (1) to quantify and analyze the key components in the water balance; (2) to identify hydroperiod frequency and inter-annual water surface and storage variation during one year of water stages monitoring; (3) to assess the stability of the hydrologic response and natural water quality function potential of the wetland as affected by seasonality (wet and dry periods).

1.2. Materials and Methods

1.2.1. Description of study area

The study was carried out in the humid tropics in the natural wetland "La Reserva" on the campus of EARTH the University, 60 km from the Caribbean coast in the Limon province, Costa Rica. The campus is located between latitude 10°11' and 10°15' north and longitude 83°40' and 83°55' we st, that correspond geographically to the flat coordinates 239 to 248 and 577 to 586 of the cartographic map of Guácimo 3446-1 with an elevation between 20 and 30 meters above sea level (National Geographical Institute of Central America, 1990) (fig. 1).

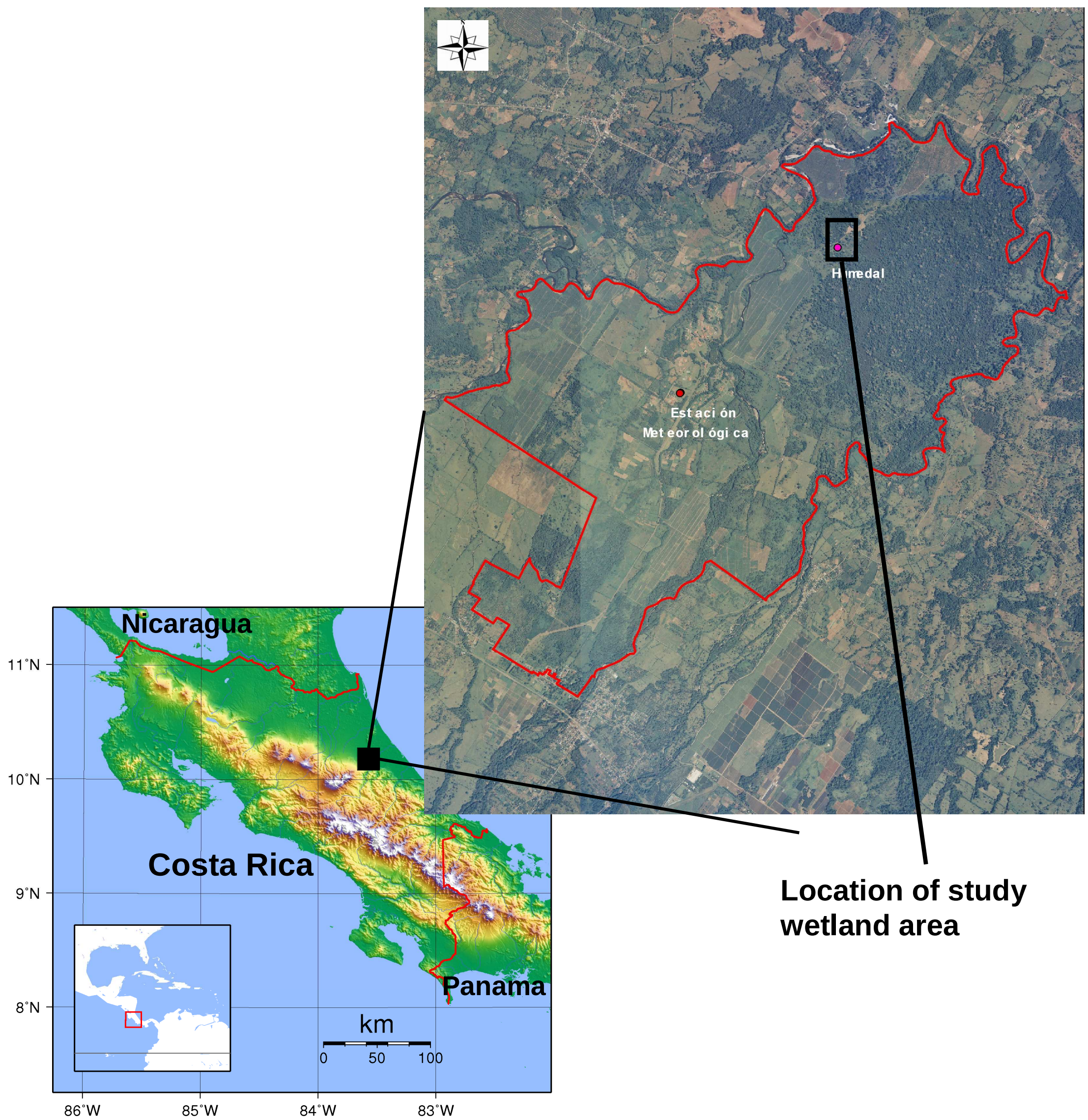


Figure 1: Location of the wetland and the weather station in EARTH University Campus (red), Limon province, Costa Rica.

The formation of the Central American isthmus results from the confluence of five tectonic plates. The plate tectonics have generated a complex network of fractures, mountains, plateaus and depressions that allowed an extensive development of wetlands of different sizes. In Costa Rica, the volcanic Central Cordillera is a geographic limit where the Caribbean and the Pacific coast show slightly different climates corresponding to the humid and dry tropics, respectively. The dry season duration is longer on the Pacific coast, and the windward Caribbean coast receives more rainfall with a dry season of only 1-2 months (Powell et al, 2000).

EARTH university campus contains more than 10 small, natural wetlands on clayey, hydromorphic soils (Aquepts) (Mitsch et al, 2008). These riparian wetlands have not received human intervention for more than 16 years and have reverted quickly into a natural state (Rodriguez, 2006). The natural wetland "La Reserva" (about 10 hectares) is part of the 2950 km^2 Parismina watershed, which extends between the Central Cordillera and the Caribbean coast (fig. 1). The average annual rainfall at the EARTH Campus for the years 1996-2008 is 3227 mm, with an annual temperature of 24,5℃, in line with the long-term a verage for the Limon Province with mean annual temperature of 25.9℃ and rainfall of 3 335 mm (Ellison, 2003), which classify the region as pre-montane wet forest to tropical moist forest. The watershed has little urbanization but intensive agricultural activities, especially in the lower parts. The volcanic heritage characterizes the underlying geology as quaternary sedimentary with volcanic rocks (Mitsch et al, 2008), and the specific chemistry of the geothermal groundwater and their affiliated ecosystems (Pringle and Triska, 1991). In addition to an important amount of rainfall and surface runoff, low evaporation due to dominant saturated air conditions and lowland topography has resulted in poorly drained soils and wetland formation (Ellison, 2003). Forested palustrine is the most commonly known wetland classification in Central America. It is characterized by low plant species diversity and a few dominant tree species. In Costa Rica the *Raphia Taedigera* swamp forest that typically develops on waterlogged soils (Roggeri, 1995) is usually called "forested swamp". The general classification of swamp characterizes isolated, depressional wetlands with muddy, waterlogged soils and relatively low flow. These wetlands are permanent or periodically flooded and can be forested, herbaceous, or made of peat. They depend on nutrient-rich ground water derived from mineral soils (Mitsch and Gosselink, 2000).

The wetland "La Reserva" is classified as a freshwater riparian wetland formed on organic soils. Surface soil composition changes from poorly decomposed plant material with high water content at the surface to upland soils with low organic matter and sediments or high organic matter also with high water to less moist clayey soil. Dominant plant species are grasses (i.e., the endemic herb *Calathea longiflora)*, bushes (i.e., *Spathiphyllum friedrichsthalii*) and the swamp palm (*Raphia taedigera)* (Mitsch et al, 2008). Hardwoods (i.e., *Pentaclethra macroloba)* are also common as the dominant canopy in the wetland, often forming isolated patches.

The wetland investigated in this study is located in a sub-watershed of the main "La Reserva" system, where the irregular topography forms several water-logged basins with three main branches which join together in a central herbaceous marsh (fig. 2). A small fourth branch is also joining the central herbaceous marsh from the west side. Surface flow from precipitation and runoff in the catchment area is the main source of water. The wetland has a single outlet downstream and no specific inlet. The lower part of the wetland is isolated from the larger wetland system by an unpaved access road with a culvert at the outlet connecting it with the rest of the system. Internal water flow is determined by micro topographical differences which direct the surface water flow to smaller elevations, establishing in this manner four preferential channels along the branches delimiting flow and water retention (fig. 2).

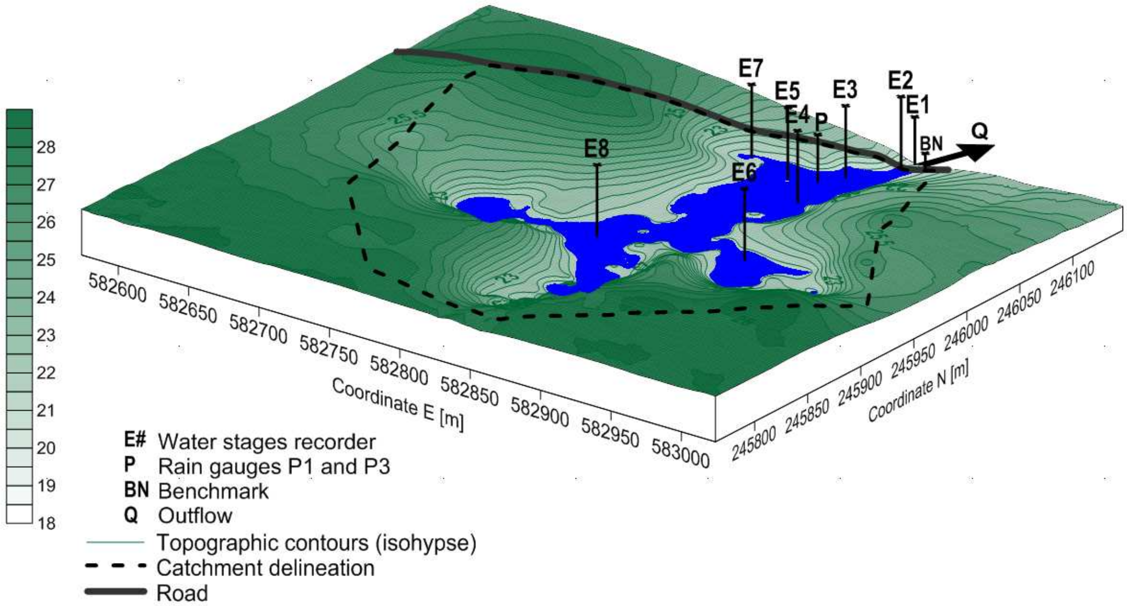


Figure 2: Instrument location in the natural wetland La Reserva.

Water in the wetland is slightly acidic (pH of 5.5-6, David Kaplan, unpublished data, 2008) and of low salinity (conductivity of 25-30 microS/cm) (Mitsch et al, 2008). In 2005 and 2006, two EARTH students' graduation projects (Cocha Barros and Muñoz Bogantes, 2005, Gallardo and César, 2006) analyzed water quality parameters such as the chemical oxygen demand (COD), the biochemical oxygen demand (BOD_5), the total suspended solids (TSS), nitrates (NO_3), ammonium (NH_4) and phosphates (PO_4). Water quality indicators changed spatially along the direction of water flow. In all natural wetlands of the systems, water quality improved at exit compared to the entry points of the natural wetland. NH_4 and NO_3 concentration increased at the entrance of the adjacent river Dos Novillos and can be attributed to inputs from fertilizer applications in the banana plantations that are located between the natural wetland and the river. Their results demonstrated that the natural wetland is efficient in reducing incoming water pollution to lower levels established for drinking water laws of the Costa Rica Health Minister. The efficiency and buffering function of the natural wetland is therefore potentially high, considering that there is no human intervention and an optimal water temperature (25℃) for water treatment (Kadlec and Knight, 1996, Mitsch et al, 2008).

In a parallel study in the wetland "La Reserva", Nahlik and Mistch (2008) reported a relatively low dissolved oxygen level, highly variable and low potential redox, and low inorganic nutrient concentration. They also reported a significant potential of carbon accumulation with sediment carbon rate sequestration greater than that of methane emissions (Nahlik and Mitsch, 2007, 2008, Mitsch et al, 2008). Following work is a modeling analysis of the ratio of carbon sequestration versus methane emissions to improve if the carbon sequestration outweighs methane emissions and therefore if the potential of wetland greenhouse gas accumulation in the atmosphere is achieved.

1.2.2. Field instrumentation

A distributed network of automatic field devices to measure and record rainfall precipitation, water levels, and outflow (fig. 2) was installed in May 2008. Field instruments were selected with special attention to the local conditions to ensure simplicity, easy maintenance, high accuracy, and low cost. Stage recorders proposed by Schumann and Muñoz–Carpena (2002) were built and used to record water levels every 15 minutes (E1 to E8 in fig. 2). E8 was built and installed in May 2009 to observe the upper part of the wetland. The rain gauge (P in fig. 2) is an automatic tipping bucket style (Onset® Data Logging Rain Gauge RG2M). Both instruments are used compact data loggers (HOBO H8, Onset Computer Corp., Bourne, MA) that were downloaded at 2-week intervals. The HOBO data logger used with the rain gauge gives the total amount of precipitation every five minutes using the records corresponding to 0.2 mm per tip. The stage recorders are very simple to install and manage in the field because there is no need for additional external wiring and all components are housed inside the top of a covered PVC pipe. The water elevation is calculated by knowing the sensor range of the device (R) depending on the effective diameter of the pulley (D). A 10–turn potentiometer (10K Bourns Inc., Riverside, CA) was chosen according to the expected change in water elevation (the device can then register water levels varying between D and D+R). For the upper and lower boundary, the analog signal (AN) registered in the logger was AN_0 = 2.485 V and An_n = 0.005 V respectively (Schumann and Muñoz–Carpena, 2002). Details of the construction, calibration and data processing are given in Appendix 2.

The unique outlet of the wetland is regulated with a culvert where two stations measure water levels at same time. One station is located before the entrance of the culvert and the second is located at the tailwater. The geometry and the characteristics of the culvert with those water elevations give the basic information to compute the outflow. The computation method was based on the principle presented in Bodhaine (1968) and used a discharge coefficient based on field measurements (Appendix 3) to calculate culvert flow (Appendix 4). Wu and Imru (2005) presented good results using this method to compute slow flow in road culverts in connecting wetlands. Flow was computed with type 3 (tranquil flow throughout) or type 4 (submerged outlet) equations depending on backwater elevation.

A topographical survey of the internal wetland area was made using an optical level Topcon model AT-G6 following a 15m X 15m grid (Tais Kolln, 2008) and rotary self-levelling laser CST/Berger LaserMark LM500 during the 2009 field campaign (Appendix 5). All the stations where topographically referenced to one local benchmark point (BN in fig. 2). Stations E2 and E1 are located at the single outlet of the wetland, upstream and downstream of a road culvert respectively. Stations E3 to E5 are located in the main body of the wetland while stations E6, E7 and E8 are located on three different branches.

All field data were processed and uploaded in the UF database Hydrobase every 15 to 30 days. HydroBase is a web-based information system for hydrological data storage, maintenance, and mining developed by Muñoz-Carpena and González at the Agricultural and Biological Engineering Department of the University of Florida. Based on industry standard Microsoft SQL server, .NET asp web services, and Java, the application contains powerful on-line web-based graphing, statistical analysis, and reporting capabilities as well as project maintenance and administration. Hydrobase is capable of quick graphical analysis and calculation of daily, weekly, monthly, quarterly, yearly, and entire period statistics including minima, maxima, mean, sum, variance, and standard deviation. In addition a simple Windows client allows remote data upload through web based protocols from any internet location.

1.2.3. Catchment area and wetland water volume and surface area

Data from the topographical survey were processed with the software Surfer (version 9.1, Golden Software, Golden, CO). A 3-D model of the catchment area was generated using the kriging geostatistical gridding method with a linear variogram to produce the grid. This method estimates the values of the points at the grid nodes and produces maps from irregularly spaced data. From the topography grid, a topographic map with contour lines is made and the catchment delineation area is calculated (fig. 2). Water surface and storage volume were computed using the same kriging gridding method with the daily average water elevation from each station and after intersecting this surface with the topographical soil surface. Gridding density was 0.46 m with a grid of 1000 column by 800 rows.

Daily and weekly volume and area of water in the wetland were determined for daily and weekly water stages values using the scripting language provided by Surfer to calculate volume and surface on solids defined by an upper and lower surface. The upper and lower surfaces are defined by the grid files with same number of rows and columns and the same X and Y limits. Results from the computation are displayed in a grid volume report where the results are provided in cubic and square units based on the units of the input grids. Volume calculations are generated for each grid cell. In areas where the surface is tilted at the top or bottom of a grid cell, Surfer approximates the volume of the prism at the top or bottom of the grid cell column. For very coarse grids, the prisms can contain a significant volume. Volume calculations become more accurate as the density of the grid is increased because the relative size of the prisms is reduced compared to the size of the associated column.

The topographical grid was used as lower grid whereas daily water elevation grids were successively used as the upper grid. Consequently, volumes of water correspond to the positive volume (volume between the upper and lower surface when the upper surface is above the lower surface) and water surfaces correspond to the positive planar area (projection of the cut map areas where the upper surface is above the lower surface onto a horizontal plane and calculating the area of the projection). The positive planar area was retained instead of the positive surface area (area of the surface where the upper surface is above the lower surface) to avoid unrealistic irregularities from the water grid due to a time lag of water elevation difference between stations measurements. However, values from the Positive Planar Area calculation matched values from the Positive Surface Area with only a small difference ($<0.7\%$). Similarly, water depth grids were generated subtracting the topographical grid from the water surface grid. Finally, water depth grids were used to create contour maps.

1.2.4. Wetland water budget

For a wetland not connected to an upstream water body and with a single downstream outlet, the change in water volume over an interval of time is the difference between the inflow and the outflow components.

$$dS = P + RO - ET - Q \qquad (1)$$

dS = Change in water volume or storage
P = Precipitation
RO = Runoff from the catchment in the wetland
ET = Evapotranspiration
Q = Outflow through the culvert

All terms in equation 1 are expressed in daily volume [m^3]. Precipitation and evapotranspiration were referred to the most frequent wetland surface area, and runoff to the full catchment area (fig. 2).
Field rainfall and outflow measurements allowed computing the P and Q terms in equation (1). Input from the runoff catchment (RO) was computed with the NRCS Method and using the rainfall time series and a curve number for the area of 68 (Muñoz-Carpena and Ritter Rodriguez, 2005). Details of the NRCS Method used are given in Appendix 6. Climatic data from weather stations with a data logger CR-10 (Campbell Scientific) allowed computing the daily ET based on Penman-Monteith equation (Allen et al., 1998). The two weather stations are located at 10°12'45" N, 83° 35' 39" W, which corresponds to a distance of 3 km south-west of the wetland (fig. 1). The approximate elevation is 30-35 meters above sea level and the weather stations are 10 meters high. See Appendix 7 for detailed ET equation and equipment used in this study.

1.3. Results

1.3.1. Water stages and rainfall time series analysis

Wetland water stages were recorded from May 2008 to May 2009. 15-minute time series include over 36,000 surface water elevation data points per station. Data gaps represent less than three consecutive days in all stations except E1 and E2, where a data logger malfunctioned from 3/4/2009 until its replacement on 3/18/2009. The tipping-bucket gage consistently over-estimated rainfall (by 40% compared to EARTH campus weather station) and was corrected using a field calibration kit (FC-525, Texas Electronics, Inc) (Appendix 9). Because of the high similarity between rainfall records (differences are statistically not significant, see Table 1), gaps in the 5-minute rainfall data from the wetland were filled in with the rainfall data from the tipping-bucket gage of the weather station located 3 km south-west on campus (fig. 1). The water stages for each monitoring station, rainfall totals and descriptive statistics are summarized in Table 1.

	CRTM 90 [m]		Relative	Data collection	Total	Statistics by station for the whole period					
Station	**Coord N**	**Coord E**	**Elevation**	**period**	**data**	**Units**	**Min**	**Max**	**Mean**	**Std**	**CV %**
E 1	1131113	546548	0.142	5/9/08-5/27/09	36535	m	0.25	1.13	0.34	0.06	0.167
E 2	1131108	546554	0	5/9/08-5/27/09	36742	m	0.26	0.96	0.36	0.08	0.216
E 3	1131078	546533	0.649	5/12/08-5/27/09	36450	m	0.81	1.35	0.96	0.07	0.069
E 4	1131032	546534	0.862	5/10/08-5/16/09	35541	m	1.02	1.47	1.17	0.06	0.049
E 5	1131054	546519	0.81	5/10/08-5/27/09	36661	m	0.97	1.41	1.12	0.06	0.051
E 6	1130945	546568	1.388	5/9/08-5/27/09	36404	m	1.65	1.91	1.75	0.03	0.019
E 7	1131066	546478	1.467	5/12/08-5/27/09	36449	m	1.47	1.58	1.52	0.03	0.017
E 8	1130925	546479	1.630								
Q	1131113	546548	0.142	5/9/08-5/27/09	36396	m^3/s	0	0.02	0	0	0.667
WS	1128959	544425		5/1/08-5/26/09	391	mm/day	0.44	10.4	3.14	1.69	0.537
							Sum				
P 1	1131064	546524	2.987	5/12/08-5/27/09	107423	mm/5min	4283	172	11.3	23.1	2.039
Pws	1128959	544425	0	1/1/08-4/22/09	131540	mm/5min	4222	172	13	25.4	1.964
P 3	1131064	546524	2.987	3/6/09-5/27/09	20749	mm/5min	506	112	6.84	16.9	2.478

Table 1: Data summary of all stations (fig. 2) and descriptive statistics from the 5/12/08-5/27/09. Legend: Q= culvert flow, WS = Campus Weather Station, P_{ws} = Rain gauge at the campus weather station, P1 and P3 = Rain gauge in the wetland.

The spatial and temporal patterns of the water stages recorded in the wetland reflect a potential of stability through the year, with an extremely fast response to the important number of rain episodes (fig. 3). In general, water stages for each station consistently maintained regular differences with the other stations through the year, resulting from the location in the wetland, and confirm a spatial gradient from uphill stations away from the outlet (E6, E7 and E8) to downhill at the outlet (E1 and E2).

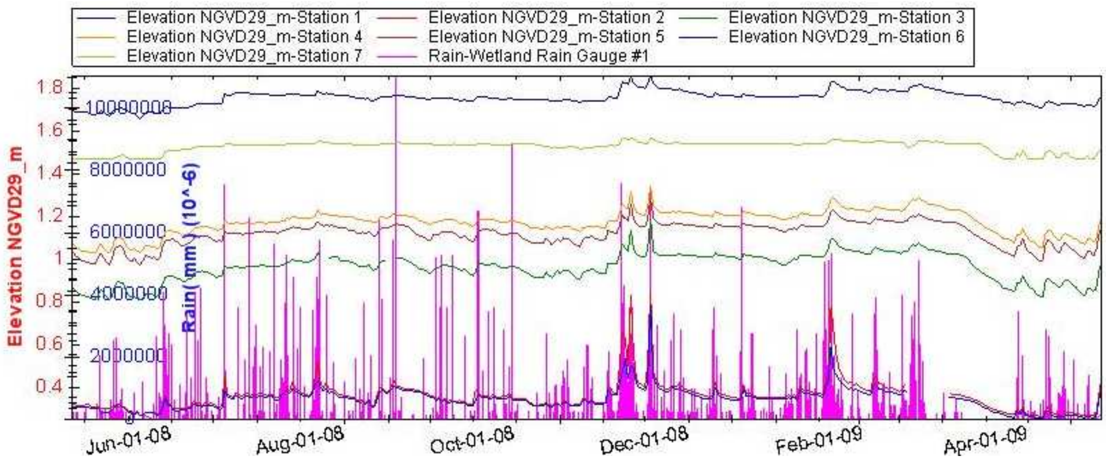


Figure 3: Overview of the water elevation and precipitation at the seven stations in the wetland La Reserva from 5/12/2008 to 5/12/2009.

Stations E3, E4 and E5, located in the main body of the wetland, had close relative water elevations with a minimum of 0.81 m at station E3 to a maximum of 1.47 m at station E4, while values at stations E6 and E7 located in the two opposed wetland branches are much higher (E6 varied from 1.647 to 1.914 m, E7 varied from 1.467 to 1.580 m). The smaller range observed at station E7 arises from its location, which is poorly connected to the main water body. Water at this location is very shallow and found partially dry during the dry season. Although stations E1 and E2 located at the outlet of the wetland presented the smallest relative elevation, the largest ranges through the year were found for these stations because of their location upstream and downstream of the single outlet, which is regulated by a culvert. The ranges were 0.7 m at the inlet and 0.88 m at the outlet. The higher range found at the outlet results from an accumulation (back water effect) due to more time needed to evacuate through the culvert than the extreme events peak water input rate from rainfall over the catchment area.

Water stages exhibited fairly stable dynamics through the year, but a strong and quick response was recorded during rain episodes of high intensity and prolonged duration. In general, the closer the station is to the regulated outlet, the more dynamic its time series were. The biggest amplitude of water stages recorded was found at the end of November 2008 and early February 2009. During those typically rainy months, rainfall was received continuously during seven and eight days, respectively, and water stages did not remain parallel to each other. Water levels increased extremely fast and reached a closer value to each other indicating a decrease of the gradient between water stations' elevation. Although the limitation of the culvert capacity during large events resulted in the accumulation of water in the downstream part of the wetland, the outlet flow matched in general rainfall intensity, closely maintaining its stability. Appendix 8 gives the weekly and monthly tables with data statistics including minima, maxima, mean, sum, variance, and standard deviation.

1.3.2. Water budget and storage

The wetland water budget was calculated based on average daily values of hydrologic and climatic data. Precipitation (P) and evapotranspiration (ET) time series are cumulated on the water surface area, while Runoff (RO), is calculated over the catchment area (fig 2). The grid generated with the topographical survey allowed delineating a catchment area of 91371 m^2, including the surface of the wetland. The mean of the most frequent class of water surface occurring during the year (15556 m^2 representing 20.73% of the period) was chosen to compute the water budget. Precipitation was directly measured at the study area while the flow (Q) and evapotranspiration were calculated based on measurements at the study area (water elevation at the culvert) and the campus 3 km south-west of the site (weather station), respectively. Runoff was calculated based on the precipitation and with an estimated NRCS curve number of 68. The water budget analysis quantifies all of the water exchanges in terms of volumes. The water exchange or the daily difference between input and output can be compared to the measured change in wetland water volume using daily water stages data. This comparative analysis is presented in the final section (Section 1.3.5).

Figure 4 shows that the key components in the water budget are firstly flow and precipitation, followed by runoff and evapotranspiration. Precipitation was the driving, most dynamic factor with a range varying from 0 to 172 mm/day (or 0 to 2682.5 m^3/day). On the other hand, flow presented more constant values with a range from 113 to 1302.3 m^3/day. During days with small or no precipitation, water budget was negative, principally because the flow rate did not decrease as fast as precipitation and was not null. Conversely, during high intensity precipitation events and/or of prolonged duration, the storage was positive. The comparison of time series for discharge outflow and precipitation shows that the discharge was in general less dynamic than rainfall and also that in general there was a time lag of two days between the peak of precipitation and the peak of flow. The regulated outlet allowed a fast outflow until a maximum limiting flow rate, depending on culvert capacity and water elevation upstream and downstream. During long periods of high intensity rain, water accumulated in the upstream water body. As a result, an important accumulation of water occurs in the wetland. The cumulative data in Figure 4 represent this trend with an irregular function for the inputs (precipitation and runoff) and a fairly linear line for the outputs (flow and evapotranspiration).

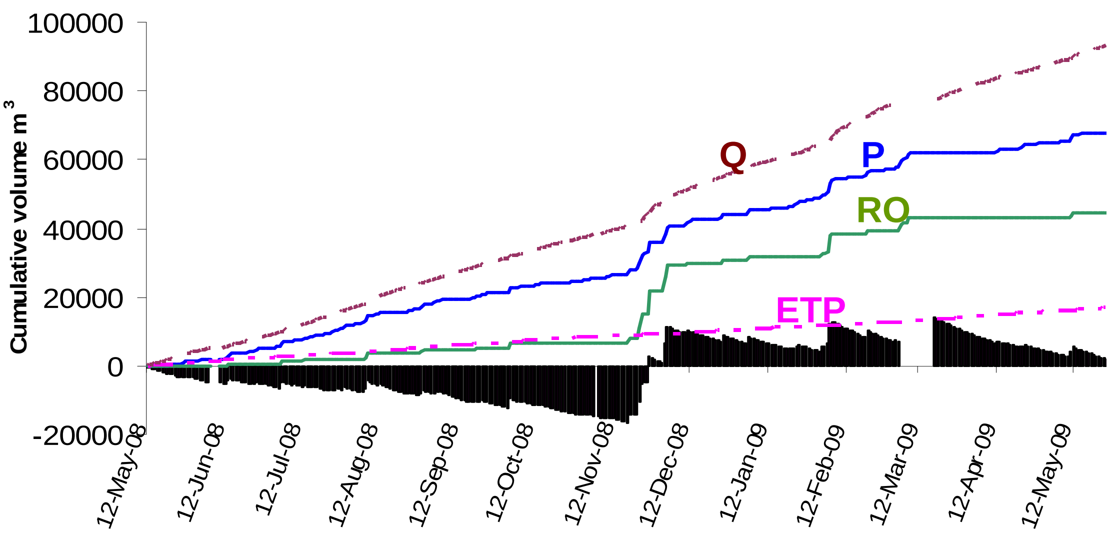


Figure 4: Cumulative water budget [m^3] over one year with the four key components.

The permeability of the oxisols in the upland watershed area coupled with its dense vegetation implied that the contribution of the runoff begins with a lag to precipitation and that relatively large precipitation rates are needed to produce surface runoff. With a curve number of 68, the runoff begins to contribute to the water budget for a precipitation bigger than 23.9 mm/day. Runoff is therefore an additional and important input in the balance during heavy rain periods but does not contribute significantly to the water balance during in other periods. For instance, input series jumped during the huge amounts of rain at the end of November 2008 (7 days of rain) and in early February 2009 (eight days of rain) giving important positive water storage in the wetland (fig. 3). Daily water storage results provided insight into the importance of runoff on the hydrology of this isolated wetland. The knowledge of the hydrologic behavior of the wetland can be improved by the direct measurement of this component. Three runoff plots were installed in May 2009 at this effect and data will be measured continuously during the 2009-2010 period (Appendix 10).

Evapotranspiration is low and fairly constant at the daily scale with a mean value of 3.14 mm/day, although with a wide range from 0.44 to 10.4 mm/day. This indicates that under the conditions of the study, evapotranspiration is a less significant output compared to flow. It represents 24.4% of the total precipitation from May 2008 to May 2009 and was found to be lower than values found in case study in La Selva Biological located in the north part of the Limon province in Costa Rica (Bigelow, 2001; Loescher et al, 2005). The values can not be directly compared because of the location and micro-climate varies widely from one site to another, but the range was found to be consistent between the two sites. The estimates obtained by the standard Penman-Monteith equation would likely be improved if coupled with a plant interception model that accounts for the specific characteristics of the rainforest present in the area.

The difference of storage between the inputs and the outputs was negative from May to November 2008 and positive from December 2008 to May 2009. In May 2009, the cumulated time series of the inputs converged, with the time series of the outputs bringing the difference of storage close to zero (Appendix 11). These results show that the wetland self-regulated naturally during the yearly budget and that there was no net loss of water during the period. Moreover, precipitation was found to be the key hydrodynamic factor under the typical characteristic of the humid tropics studied here.

1.3.3. Catchment area and wetland water volume and surface area

Topography of the wetland can be linked with water stage time series to evaluate the spatial and temporal dimension of the dataset, the evolution of the flooded area and the water storage along the studied year. Most of the isolated wetlands are shallow and the sizes of their flooded areas can change rapidly when water stages change. Extent of flooding in terms of frequency and duration are therefore a decisive factor for the type of vegetation in those transitional areas (Haag and Lee, 2009). However, the water stages and outflow variation presented in the previous sections attested the stable hydrologic behavior of the studied wetland. The time-scale used to analyze the evolution of the flooded area and water storage is important to appreciate the dynamics of the system. Monthly stage data, for example, are sufficient to describe the average annual stage and water-covered area, but may under-represent or miss extreme and brief events. Monthly measurements are therefore more adequate over long-period study. In this case study, more frequent data collection is needed to accurately describe extremes and catch the difference in storage and areal extent of such a stable system. Daily water surfaces, based on 15-

minute water stages measurement, were used to describe the frequency and duration of the water area and volume (fig. 6).

The daily water volume and area evolution during the study was found to be extremely stable. Volume and area evolved similarly with a quick response to precipitation events (fig. 5). During periods with low precipitation, the volume and area decreased principally because outflow was the driving parameter.

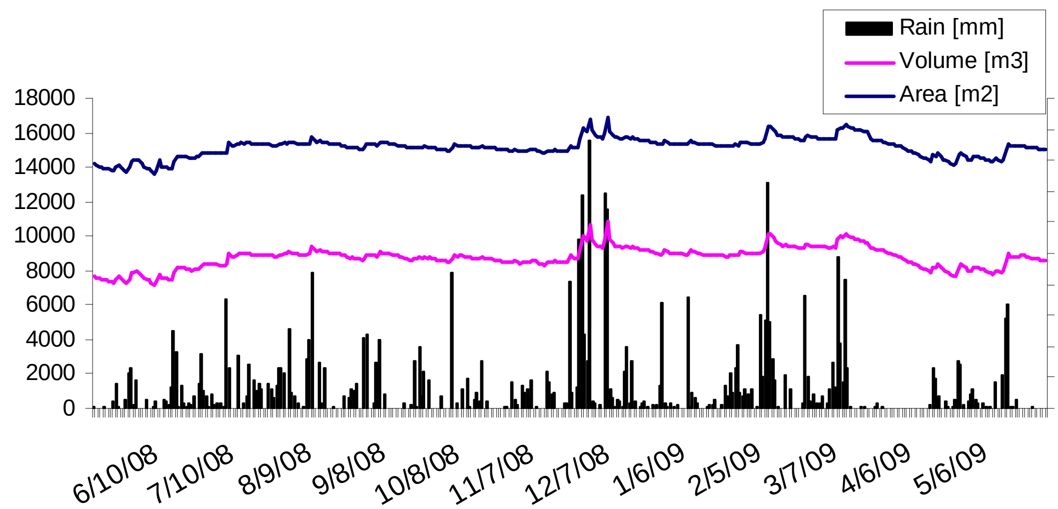
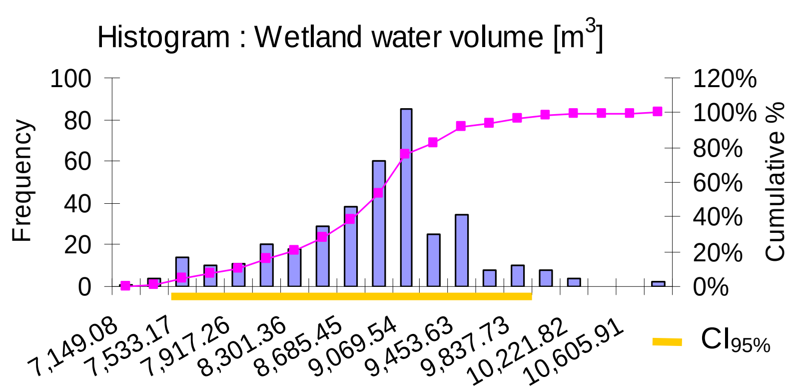


Figure 5: Evolution of the daily volume and area of the wetland with the precipitation.

The frequency analysis of the volume and area described a stable behavior with a shape approaching a central distribution (fig. 6). The mode of the distribution was higher than the mean, representing more occurrences of smaller volume and area to the most frequent value (Table 2). Effectively, 78 and 76% of the data were smaller or equal to the most frequent area or volume respectively. The 22 and 24% water area and volume remaining corresponded to the days with high intensity and duration of precipitation. It is those days that correspond to the peaks value showed in the Figure 5. Data that are out of the 95% confidence interval (comprising only 19 surfaces and 18 volumes out of a total of 381 daily data) can be considered as extreme events of flooding or drought and correspond to the biggest rainfall event in the year (November to December 2008 and February 2009) and the driest period (May-June 2008 and March-April 2009).



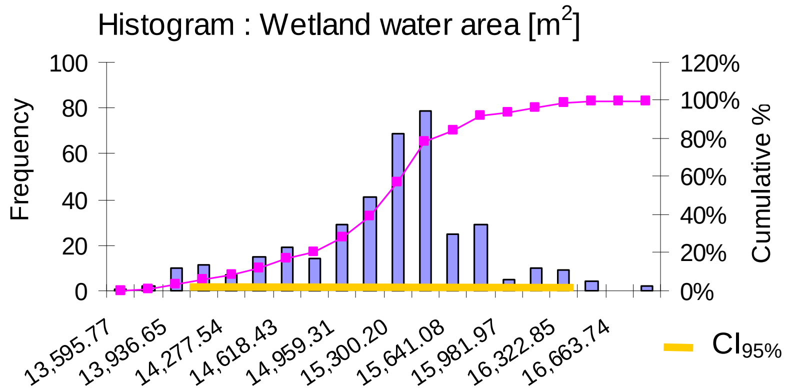


Figure 6: Histogram of the frequencies and cumulative probability of the daily wetland volume (up) and area (down).

Descriptive statistics	Area [m^2]	Volume [m^3]	Tr [day]
Mean	15,152.94	8,749.83	36.99
Standard Error	28.38	31.16	0.44
Median	15,245.97	8,837.64	38.85
Mode	15,307.63	8,945.46	45.95
Standard Deviation	553.94	608.20	8.32
Sample Variance	306,849.64	369,906.84	69.15
Kurtosis	0.51	0.41	1.46
Skewness	-0.37	-0.21	-0.67
Range	3,238.41	3,648.88	62.94
Minimum	13,595.77	7,149.08	8.15
Maximum	16,834.18	10,797.96	71.08
Sum	5,773,270.45	3,333,686.39	13,353.99
Count	381	381	361
CV %	3.66	6.95	22.48
$CI_{95\%}$	13895-16255	7438-9955	18-47

Table 2: Descriptive statistics of the daily wetland area, volume and residence time (Tr). Legend: CV% = Coefficient of variation, $CI_{95\%}$ = Interval of confidence corresponding to the 95% most frequent values.

The range of different data values in the 95% interval of confidence was slightly smaller for areas and therefore for flooding variation than for volumes with 16.5% and 24.2% respectively. This trend may support the fact that the wetland edges are steep enough to allow a small water extent fluctuation and a slightly more important variation in volume and in terms of depth of water. The small difference of water extent was studied with a graphical model of the daily water area where depths were represented with contour lines (example is given in Appendix 12). The water contours representing the depths in the wetland were varying although the general contour and shape of the wetland remained fairly stable. Nevertheless, the most shallow and distant part showed more fluctuations during the driest period. Figure 7 represents this small difference of water extent with an overlay of the most frequent water area with the lower and the upper boundary of the 95% confidence interval of the frequency distribution.

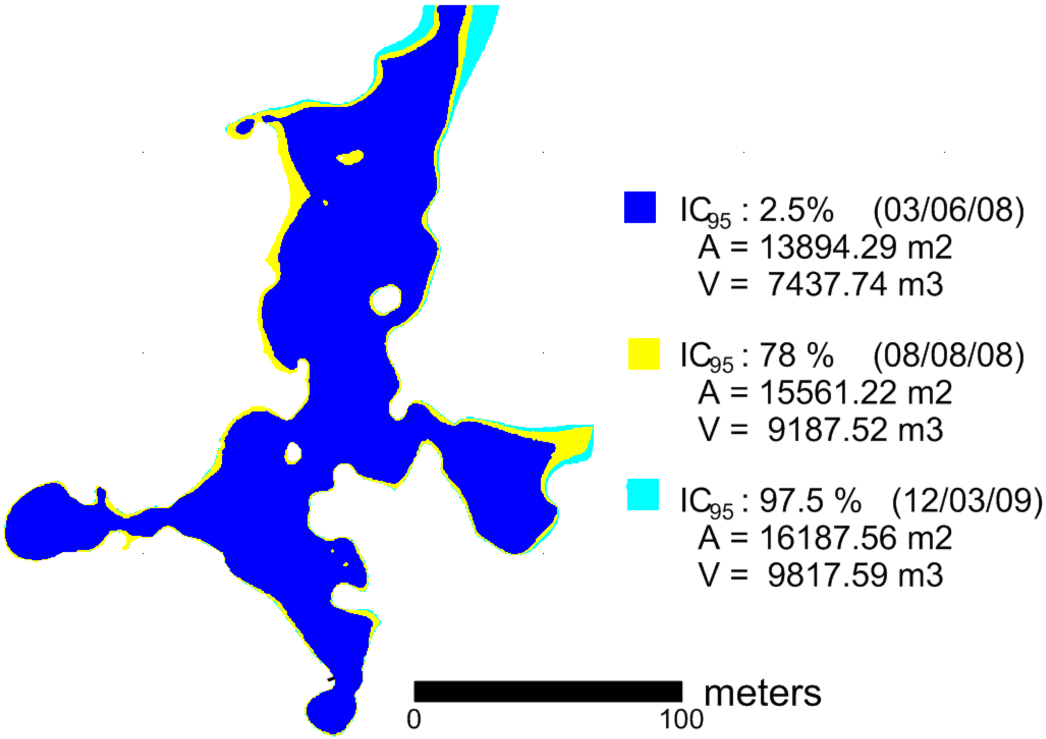


Figure 7: Overlay of three daily water surface representing the most frequent water area (yellow) with the lower (dark blue) and the upper (light blue) boundary of the 95% confidence interval of the frequency distribution.

1.3.4. Residence time analysis and potential water quality function

The residence time of the water in the wetland was computed with the daily volume of water divided by the daily average of the flow. The histogram of frequencies and cumulative probability of residence times are presented in Figure 8.

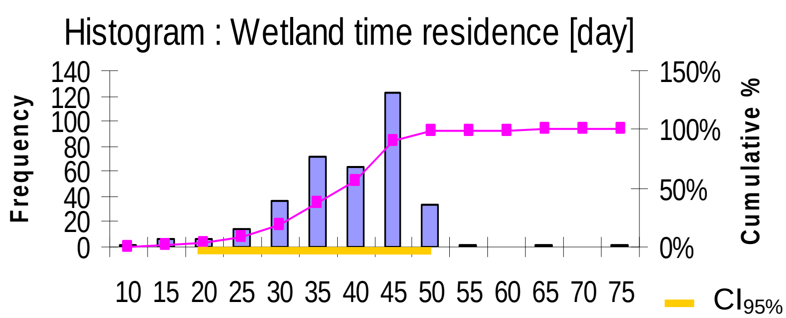


Figure 8: Histogram of the frequencies of residence times.

The residence time varied between 8 to 68 days with a 95% confidence interval of 18 to 47 days. By coupling the studied wetland characteristics with specific pollutant characteristics, a percentage of the pollutant removal expressed for a 10 days class of hydraulic residence time is calculated with equation (2) (Kadlec and Knight, 1996):

$$C_2 = C^*+(C_1-C^*)exp(-kA/0.0365Q) \quad (2)$$

C_1 = Inlet concentration of the pollutant [mg/L]
C_2 = Outlet concentration of the pollutant [mg/L]
C^* = Irreducible background wetland concentrations of the pollutant [mg/L]
k = Reduction rate constant of the pollutant [m/yr]
A = Wetland area [m^2]
Q = Flow [m^3/s]

For each 10-days class of hydraulic residence time corresponds a range of flow and surface water area. Average values of each class were used to calculate the percentage of pollutant removal summarized in the table below (table 1).

Estimated Treatment Wetland Performance Using the k-C* Model for "La Reserva" wetland characteristics					
Hydraulic residence time [day]	**% removal of the initial concentration BOD_5**	**TSS**	**TN**	**TP**	**Cumulative Frequency %**
5-10	68.4	98.0	61.8	34.4	0.28%
10-15	81.5	98.0	75.9	46.7	1.66%
15-20	91.9	98.0	88.6	62.5	4.16%
20-25	**95.3**	**98.0**	**93.5**	**72.0**	**5.82%**
25-30	**96.8**	**98.0**	**95.9**	**79.0**	**13.57%**
30-35	**97.5**	**98.0**	**97.2**	**84.2**	**28.81%**
35-40	**97.8**	**98.0**	**97.9**	**88.4**	**47.37%**
40-45	**97.9**	**98.0**	**98.2**	**91.6**	**66.48%**
45-50	**97.9**	**98.0**	**98.3**	**93.0**	**97.23%**
50-60	98.0	98.0	98.4	96.0	99.45%
60-70	98.0	98.0	98.5	97.7	99.72%
70-75	98.0	98.0	98.5	98.5	100.00%

Table 3: Estimated Treatment Wetland Performance Using the k-C Model for "La Reserva" wetland characteristics. BOD_5= the biochemical oxygen demand, TSS = total suspended solids, TN = total nitrogen, TP = total phosphorous.*

The wetland improves its water quality with a sufficiently long residence time most of the year, with the exception of the short-duration extreme events. The wetland is therefore efficient to naturally reduce incoming water pollution knowing that most of the residence times are between 18 and 47 days (94.7% of the year).

1.3.5. Daily wetland water volume difference: comparison of the methods

The difference of volume of water computed with the model of the daily water stages was compared with the volume resulting from the daily water storage calculating with the hydrologic time series (P, RO, ETP and Q). Both volumes evolved similarly during the studied period showing increases, peaks and decreases at the same time (Figure 9 presents an example of the two time series while Appendix 13 shows the comparison for the entire period).

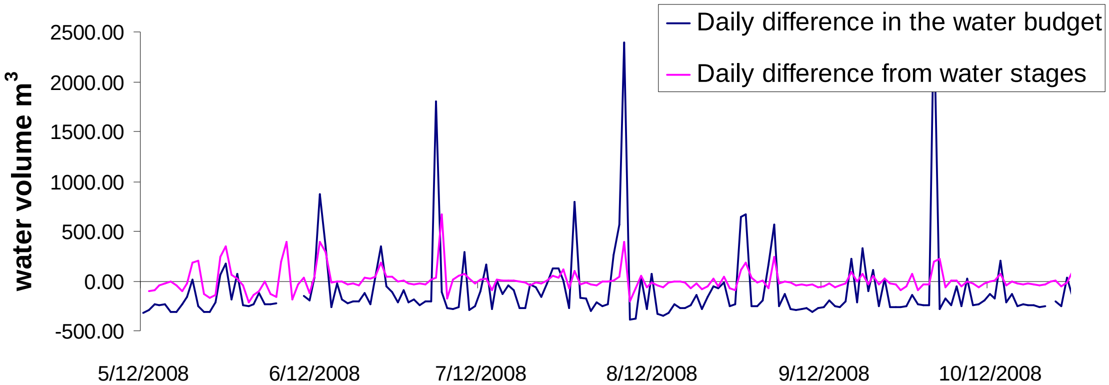


Figure 9: Comparison of the daily difference of volume from the water balance and the water stages model.

The progression between the two time series is similar and attests of the consistency of the two methods to evaluate the inter-annual water storage variation and the stability of the hydrologic response. The difference between volumes computed with the daily water stages was parallel to the difference of storage calculated from the water budget with a shift of approximately 200 m^3. The amplitude was bigger for volumes from the water storage when an important increase occurred. The relation one to one between the two time series presents a similar trend with a correlation of 46.26% (Appendix 13). The difference between the results from the water budget and the model with the water stages might be because of the estimation of some of the hydrologic time series. Firstly, the flow could be over-estimated. The estimation of the flow is based on a discharge coefficient which was calculated with field measurements. However, the range and number of field measurements could be insufficient (Appendix 3). Secondly, the runoff component was estimated with a curve number selected for the soil class and cover type of the studied wetland, but not especially for the studied area (Appendix 6). Finally possible gains or losses due to leakage and recharge-discharge by subsurface flow with the surrounding wetlands could also occur.

1.4. Conclusion

This case study on a small (<10 ha), tropical, natural, freshwater wetland with no inlet and a regulated outlet allowed us to quantify the wetland's hydrological and water quality function and generate hydrological information to understand its sustainability. The quantification and analysis of the key components in the water balance and the daily variation of the water surface and storage highlighted the stability of the hydrologic response of the wetland over one year of monitoring.

The stability of the hydrologic response of the wetland was shown during all the monitoring year, with the exception of some extreme events during rain episodes of high intensity and prolonged duration or during the two small dry periods. Two very important rainfall events occurred during the most typically rainy months in the year, when precipitation fell continuously during seven and eight days respectively. Water stages, volume and area increased extremely quickly, partly because of the limitation of the outlet culvert capacity, which regulated the outflow rate. After several days, the natural regulation of the system brought the time series back to stable values. In general it was fund that the outlet flow rate matched rainfall intensity with a time lag of two days, closely maintaining its stability.

The fairly stable hydrological dynamics through the year were exhibited through monitoring and calculation of water stages, water volume, water area and the overall water balance. In general, the closer the stage monitoring station is to the regulated outlet, the more dynamic its time series. Precipitation was found to be the key hydrodynamic factor under the typical characteristic of the humid tropics studied here. The difference of storage between the inputs and the outputs was negative from May to November 2008 and positive from December 2008 to May 2009. The contribution of the runoff was observed to be the decisive parameter in this transition. In May 2009, the cumulated time series of the inputs converged, with the time series of the outputs bringing the difference of storage close to zero. These results show that the wetland self-regulated naturally during the yearly budget and that there was no net loss of water during the period. The wetland edges are steep enough to permit only a small water extent fluctuation, causing a slightly more important variation in volume and depth of water. Nevertheless, the most shallow and distant parts of the wetland showed more water surface fluctuations, the frequency and duration of the such event were so short that it could not give an indication of vegetation type that can be found at the edges. However, the stability and low flow characterizing the wetland indicate its potential to improve water quality with a sufficiently long residence time most of the year. The wetland is therefore potentially efficient to naturally reduce 70-92% incoming water pollution of common surface water pollutants for 95% of the calculated residence times.

Finally, the differences between the volumes calculated with the daily water stages model and with the water balance calculation were compared. The progression between the two time series is similar and attests to the consistency of the two methods to evaluate the inter-annual water storage variation and the stability of the hydrologic response. However, the difference found between the time series shows that the computation of the water balance can be improved, especially with additional field measurement of runoff to reinforce the parametric estimation.

2. Multi-tracer field study in a small, natural wetland in the humid tropics of Costa Rica

This study of the chemical analysis of two water surface tracers is part of the larger hydrologic study on the small natural wetland “La Reserva” presented in the previous sections. The motivation of this tracer study is the investigation of the hydraulic characteristics of the wetland as complementary information to the long-term field study using the water level monitoring network. The following sections present the motivation for such a study, the tracers’ selection, experimental field protocol, and the chemical analysis of the water sampled in the wetland. A discussion on the comparison of the results between the two tracers is given as a partial conclusion and as starting point for future work.

2.1. Introduction

Hydraulic characterizations of wetlands, and how these characteristics vary in time and space, are an important part of describing these complex ecosystems. Wetlands, both natural and constructed, are increasingly being studied and used remove nutrients (Bachand and Horne, 2000; Reilly et al., 2000), metals (Debusk et al., 1996; Kadlec and Knight, 1996), pesticides (Schulz and Peall, 2001), and industrial solvents from municipal, agricultural, and stormwater runoff. While contaminant reduction in wetlands has been well studied in temperate climates, less is known about the treatment capabilities of tropical wetlands, and the factors that affect the short- and long-term efficiency and variation of contaminant removal are still poorly understood. However, uptakes by plants, sorption by sediments, microbial degradation and precipitation have been implicated.

A greater reliance on wetlands for water quality improvement and optimization of existing wetland operations require a better understanding of the hydraulic and geochemical factors that govern contaminant behaviour. Field tracer studies are an effective way to study wetland hydraulics, velocities, and pathways through the hydrological systems (Harden et al., 2003) and to assess the residence time distribution and vertical and horizontal water mixing conditions (Martinez and Wise, 2003). A tracer is non-reactive, non-sorbing solute released into a water system to determine its hydraulic characteristics. A precondition for studying wetland hydraulics is the availability of robust tracer methods adapted to the conditions of the study area. The tracer release is generally made in the wetland inlet or an upstream point to study the resulting time of arrival, the concentration, and the dispersion of the tracer through the outlet.

The selection of an appropriate and robust tracer for a natural system requires several key properties (Martinez, 2001). In addition to being chemically inert and non-toxic for the environment, the tracer should also be easily detectable, preferably over several orders of magnitude. For this, it should not be present naturally in the system or appear only in very low concentration to allow relatively small quantities of tracer to be detected along the flow path. Finally, low-cost of the material, handling and chemical analysis are desirable.

The most popular surface and groundwater tracers are chemical salts containing chloride, lithium or bromide (Br^-). Bromide is the most used tracer in natural wetland systems (Martinez, 2001) since it is found at very low background concentrations in the environment compared to chloride. Bromide is also known to be conservative compared with lithium, which can adsorb by ion exchange to sediments. However, in wetland systems with tranquil water flow it is often difficult to track bromide concentration because of high dilution rates.

An interesting alternative to a conventional tracer like bromide is the use of the gas sulphur hexafluoride (SF_6). SF_6 is a non-toxic, colorless, odorless, inert gas with a low solubility in water (Salhani and Stengel, 2001; Harden et al., 2003), which is used primarily as an electrical insulator (Bullister et al., 2002). Natural sources of SF_6 are small, and its atmospheric composition has been well measured since its anthropogenic use began in 1953 (Maiss and Brenninkmeijer, 1998). Background concentrations of SF_6 in the atmosphere are still very low (10^{-15} mol l^{-1}; Harden et al., 2003), and it is detectable at minute concentrations (10^{-16} mol l^{-1}), making it an ideal tracer of hydrologic systems. Although SF_6 is not conservative because of its gaseous nature, it has been successfully used as a tracer in seawater (Wanninkhof et al, 1991; Bullister et al, 2002); groundwater (Dillon et al, 1999; Harden et al, 2003; Corbett et al., 2000); surface water, including in the Hudson River (Ho et al., 2002) and to study horizontal and vertical mixing in lakes (Maiss et al, 1994); and gas transport in wetland plants (Salhani and Stengel, 2001). Although SF_6 is relatively inexpensive ($50 - $100 US per kg gas; various suppliers in NJ, PA, and FL, USA), analysis of water samples through a commercial firm can be very costly ($100 - $200 per sample; various commercial labs in FL, USA), so in most cases its use would be limited to groups or institutions with access to the appropriate chemical analysis equipment (discussed below).

The main purpose of this work was to conduct a multiple-tracer field study to explore the hydraulic characteristics of the small natural wetland “La Reserva” located in the humid tropics in Costa Rica, and to assess the feasibility of using SF_6 as a tracer compared to bromide under humid tropical and slow flow conditions.

2.2. Materials and Methods

2.2.1. Site information and experimental setup

The study was conducted in the humid tropics in the natural wetland "La Reserva" located on the campus of EARTH University, 60 km west of the Caribbean coast in Limon Province, Costa Rica (fig. 1). In May 2008, Br^- and SF_6 tracers were injected into the wetland, followed by frequent sample collection during the three weeks after injection. The tracers were applied to the site as two point sources, each with a single injection. The injection points and the network of eighteen tracer sampling points are presented in Figure 10. Injection points were selected at two accessible, upstream points in opposite branches assumed to have shallow flow channels connecting the wetland (see arrows in fig. 10). Sampling points were distributed downgradient and across the assumed flow paths.

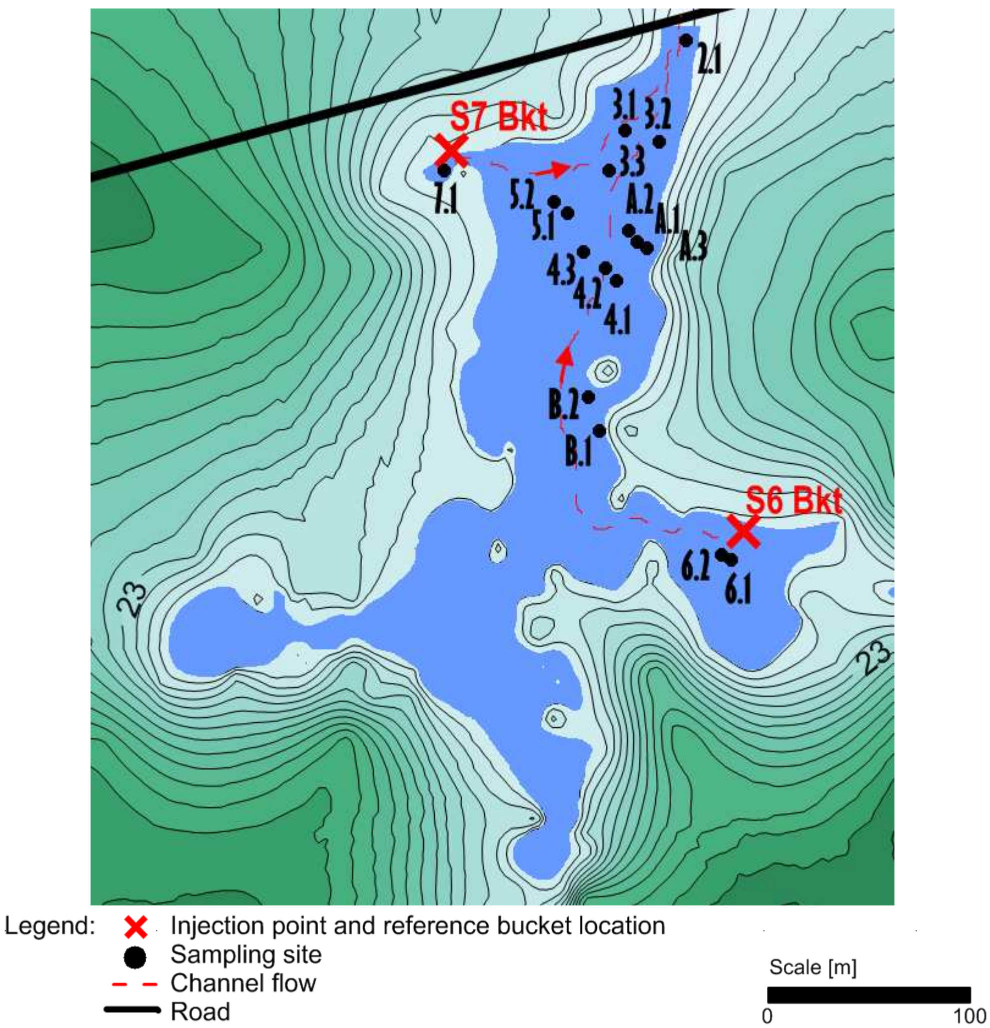


Figure 10: Wetland area with injection and sampling locations.

Approximately one hour prior to injection, two ~100 L plastic barrels were filled with wetland water from each injection site (fig. 10). Next, 13.6 kg (nominally 30 lb) of photograde KBr (99.92% purity; DigitalTruth Photo, Houston, TX, USA) was dissolved into each barrel by carefully pouring and stirring. SF_6 sparging was accomplished using a diffuser made from 1.5-m length of 2-cm diameter landscape “soaker” hose fitted into a ring equal to the diameter of the barrel. The ring was connected with 1-cm diameter Tygon® tubing, plastic couplings and metal hose clamps to the outlet of a 2.27 kg (nominally 5 lb) cylinder of SF_6 (Concorde Gas, Eatontown, NJ, USA). This produced a dense stream of SF6 bubbles emanating from the bottom of the barrel. Sparging was continued for approximately 30 minutes in each barrel, until the cylinder was exhausted. Chemical analysis indicated that about 10% SF_6 saturation was achieved. During sparging and before injection, barrels were covered in plastic sheeting to reduce volatilization of gas (fig. 11).

After securing water samples from each barrel and separating a volume of the injection water in a small bucket, the contents of the two plastic barrels were poured into the wetland, one barrel at point S6 and the other at S7 (fig. 10). The two injections occurred within 9 minutes of each other. The small buckets were tented with plastic sheeting and set in the ground next to stations S6 and S7 and used as a reference for natural tracer dissipation during the study (fig. 11).

Figure 11: SF_6 sparging (left) and barrel with its reference bucket (right; under yellow plastic).

Water samples were collected from the 18 injection and monitoring sites and reference buckets once or twice daily for three weeks after injection. Samples were taken at shorter intervals early in the tracer test to better capture any quick spike of tracer passing through the sampling site. Prior to releasing tracers, background wetland water samples were captured at injection sites. Samples were collected manually in 40 mL septum vials (ThermoFisher, Suwanee, GA) that were completely filled and capped under water, ensuring that no air bubbles were left in the vials. Samples were stored inverted at 4°C after collecti on and kept closed at all times until chemical analysis. Electrical conductivity and pH were measured at each sampling location/date using a hand-held portable meter.

2.2.2. Sample analysis and quality control

The analysis method for the determination of SF_6 and bromide concentrations is different. SF_6 is a non-conservative gas, so to avoid losses it was analyzed first with a gas chromatograph (GC) equipped with electron capture detector (ECD). After

SF_6 analysis, the samples were analyzed for Br^- using high pressure liquid chromatography (HPLC) with electrochemical detection DIONEX ICS-90 ion chromatography equipped with an AS40 autosampler (fig. 12).

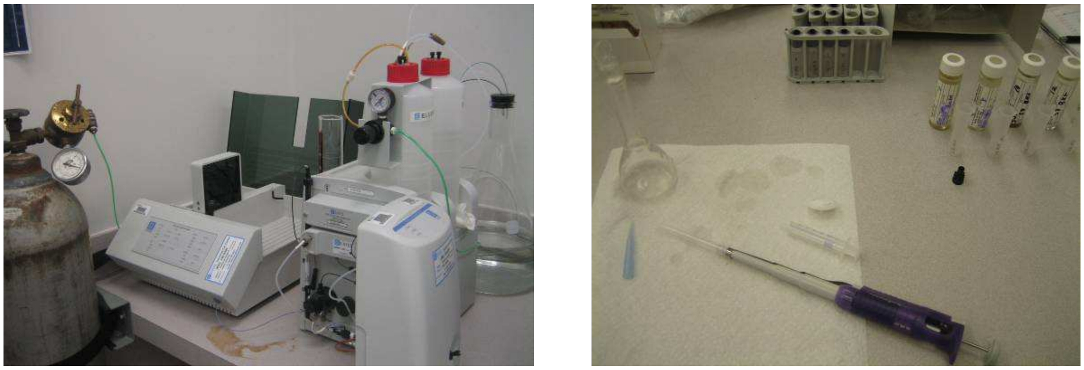


Figure 12: HPLC/EC (left) and preparation of the samples (right).

For the Br^- analysis with HPLC, the reagent used was 5 mL concentrated H_2SO_4 to 2 L of distilled-deionized water and the eluent was 0.9539 g concentrated Na_2CO_3 (0.5M) to 2 L distilled-deionized water. The detection limit of Br^- for this protocol was 0.01 ppm. Each sample set was run after a blank sample of distilled-deionized water to purge the machine and a Br^- dilution standard to compute the calibration curve. The calibration curve is a linear relation between the signals detected at the retention time for Br^- (13.5 min) concentration. The software Peaknet 6 (Dionex, Sunnyvale, CA, USA) allowed a direct calculation of the Br^- concentration for each sample. The samples were ordered chronologically by site (fig. 13).

Figure 13: Ordering samples chronologically and by sites.

The samples with expected high concentration (samples from injection stations and reference buckets) were analyzed at the end to avoid biasing peak detection of samples of lower concentration. Most of the samples had sediments and were filtered prior to injection (Nylon Pores Size 0.2 μm, Fisher Scientific, Pittsburgh, PA, USA). Samples with Br^- concentrations out of the acceptable analytical range were diluted to keep the data in the linear scale of the calibration curve.

For the SF_6 analysis, the procedure described in Muñoz-Carpena et al. (2009, in preparation) was used. After removing 5 mL of water from each vial, vials were recapped, shaken, and placed in a 60º C water bath (fig. 15). Vials were allowed to stand in the water bath for 1 hour and were periodically shaken. Using a 50-μl gas tight syringe, 15-uL of the headspace in each vial was withdrawn and injected on-column into Hewlett-Packard model 5890 series II GC equipped with electron capture detector. The column was a J&W Scientific DB-624 GC Columns, (30m X 0.53 mm i.d; Agilent Technologies, Santa Clara, CA, USA) (fig. 14). The flow of the helium-nitrogen carrier gas was fixed at 75 kPa. Oven, injector, and detector temperatures were held at 100º C, 200º C, and 300º C respectively (fig. 14). The SF_6 peak occurred approximately in 1.5 minutes after manual injections of each vial samples and standards were analyzed in replicate (consecutive injections from the same vial) and the retained peak area agreed within 5%.

Figure 14: GC/ECD connected to Shimadzu (left) and its injection port (right).

SF_6 calibration standards were prepared by sparging empty 40 mL vials with SF_6 for 1 minute, followed by addition of 30 mL of distilled-deionized water, and capping with screw-cap and Teflon faced septum. Vials were shaken and allowed to stand overnight. Next, 1 mL of the water was withdrawn from the saturated solution through the septum using a gas-tight syringe, followed by serial dilution over 10^2 to 10^6 in ten-fold increments (fig. 15). Serial dilutions were stored in septum vials and analyzed concurrently with samples. Standard concentrations were computed using Henry's Law and assuming equilibrium in vials. Linear regression of standard responses yielded R^2 > 0.99. The lowest concentration standard analyzed (10^{-6} dilution) was set as the method detection limit.

Figure 15: Material to prepare the standard dilution (left) and hot bath (right).

2.3. Results

After tracer release (injection), 424 water samples were taken from injections sites, sampling sites, and the reference buckets to measure SF_6 and Br^- concentrations. Most of the samples presented a bromide concentration above the minimum detection limit (0.01ppm) and in the linear scale of the calibration curve requiring therefore only one injection. However concentration at sites 5, 6 and 7 and injection sites 6 and 7 had to be diluted (from 2 – 10 times for sites 5, 6, and 7 and from 500 – 1,000 times for the injection sites).

2.3.1. Tracer concentration and breakthrough curves

Bromide concentration remained relatively constant in the reference buckets, revealing the conservative property of this salt (fig. 16). Changes in water level in the buckets over the 3-week sampling period was not observed, although small changes in volume due to evaporation or dripping of condensed water off of the plastic sheeting may have caused small variation in these concentrations. After injection, Br^- concentrations decreased rapidly at injection sites to a value less than 1 ppm, assumed as the background concentration (fig. 17).

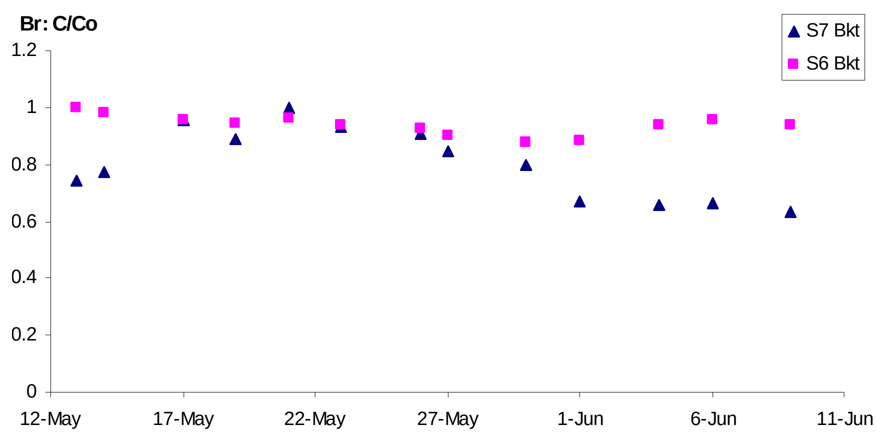


Figure 16: Bromide concentration in reference buckets at sites 6 (S6 Bkt) and 7 (S7 Bkt).

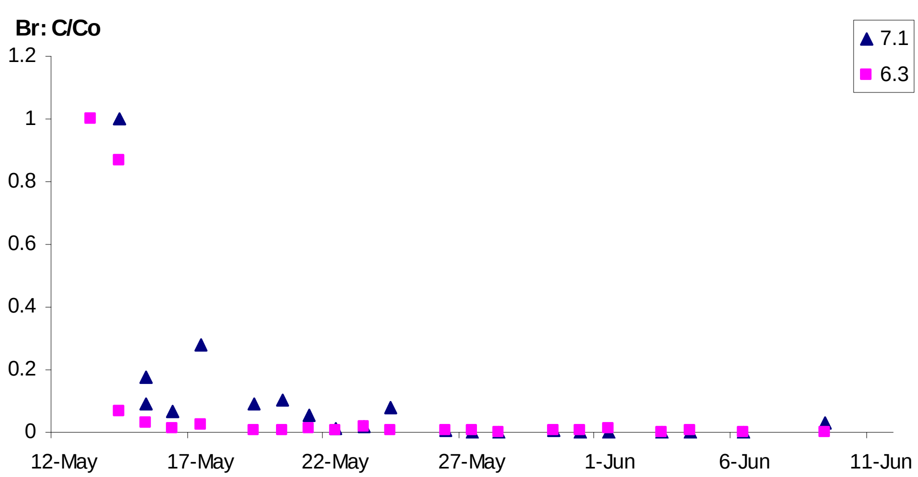


Figure 17: Bromide concentration at the injection site 6.3 and 7.1 respectively.

Breakthrough curves for all other sampling sites showed low bromide concentrations with peaks corresponding to the tracer passing through the site. Sites B and 5, which were located downstream to injection sites 6 and 7 respectively (fig. 10), each showed one clear, isolated peak (fig. 18). This indicates that only the tracer plume from the injection point upstream of these stations was captured at these locations (these two sampling sites are located at the end of the branches chosen to inject the tracers). The ends of those opposite branches arrive in the main body of the wetland and those sampling sites (B and 5) are probably in the same preferential flow channels as 6 and 7, respectively (fig. 10).

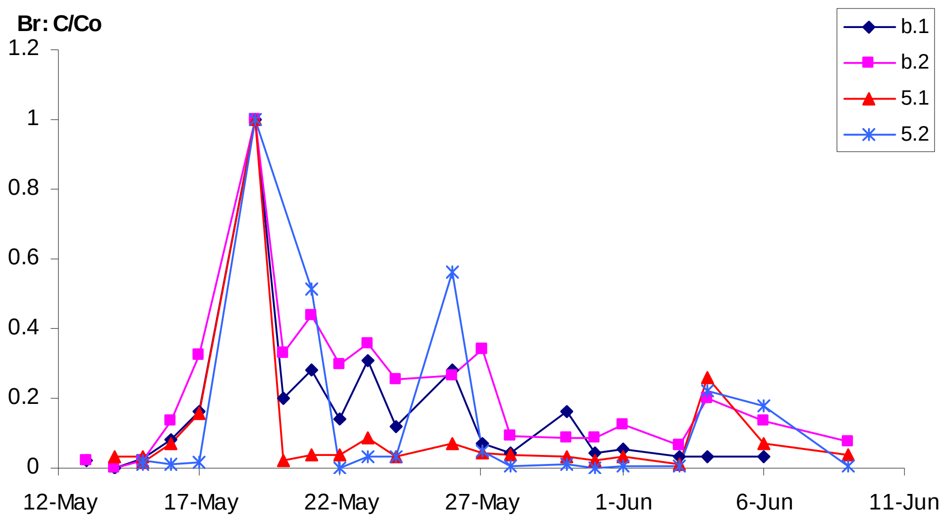


Figure 18: Bromide concentration at site B and 5 showed one peak.

There was evidence of "double peaks" at sites 2 and 3 (fig. 19), which were located close to the outlet and therefore at the confluence of the water from the two injections sites (see arrows in fig. 10). Those double peaks reflect a delayed arrival to the outlet of the tracers released at the two sites.

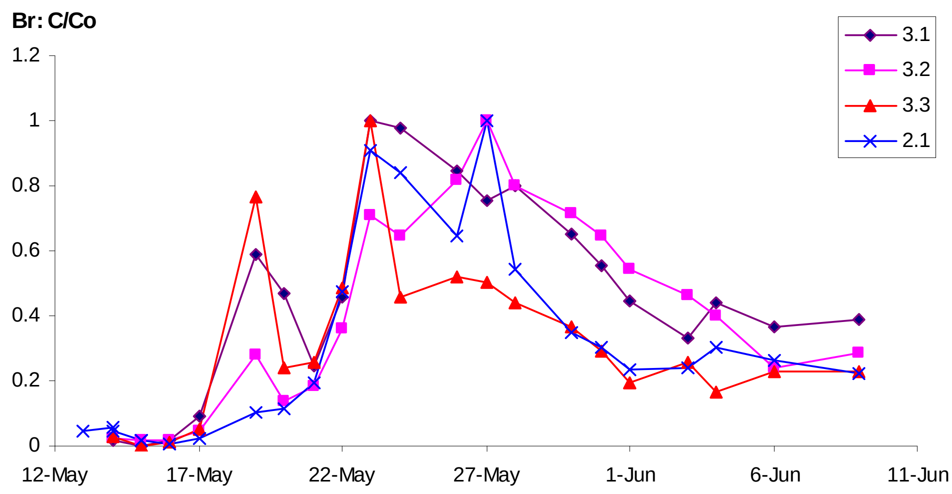


Figure 19: Bromide concentration in the downstream part of the wetland (site 3) and at the outlet (site 2).

Interpretation of tracer concentrations found at site 4 and A is less clear (fig. 10, fig. 20). This might because of the location at the beginning of the junction of the channel flow or the heterogeneity between water body and vegetation (site A) which can cause a mixing of upstream water with stagnant water from the edge.

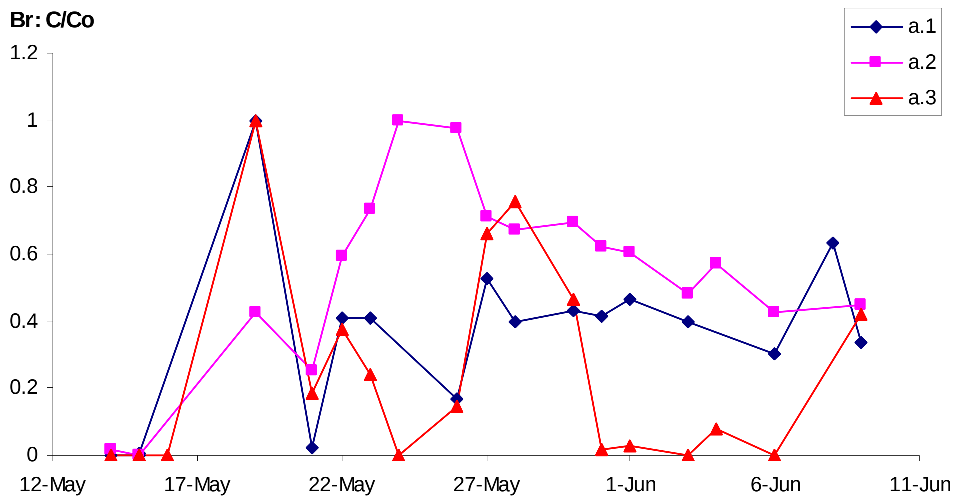


Figure 20: Bromide concentration at the side site A

2.3.2. Flow velocities and principle pathways along the wetland

The different delays observed for both peaks reflect not only the distances from the injection sites to the sampling sites, but also the different flow velocities in each of the wetland branches. For instance, a first peak appeared at sampling sites 3.1, 3.2 and 3.3 five days after injection (Table 4). No peak is detected this day at site 2.1. The first peak arriving at site 2.1 is nine days after injection (fig. 19, Table 4). The second peak is detected with a progressive increase and decrease during the sampling days before and after the peak's day, which could indicate that the tracer plume spread out, passing the sampling site because of low flow and mixing (or the two tracer plumes arriving at site 3 at the same time). A peak was detected at site 3 from nine to thirteen days after injection. A second peak was also recorded at site 2.1 thirteen days after injection. The time to first (and second, if applicable) peak at each location is summarized in table 4 with the corresponding distance from the injection points. These data are then used to estimate flow velocities along the two main flow channels.

Location East channel	Time to Peak 1 [days]	Br- Peak 1 [ppm]	Time to Peak 2 [days]	Br- Peak 2 [ppm]	Distance from Injection at S6 [m]	Distance from Injection at S7 [m]	Eastern flow velocity [m/d]	Western flow velocity [m/d]
6.1	0	6.2	---	---	~0	---	---	---
6.2	0	1.3	---	---	~0	---	---	---
6.3	0	247.3	---	---	~0	---	---	---
B.1	5	20.1	---	---	77.9	---	15.6	---
B.2	5	10.3	---	---	89.2	---	17.8	---
4.1	5	2.3	---	---	127.4	---	25.5	---
4.2	5	1.9	---	---	130.3	---	26.1	---
4.3	5	1.3	---	---	135.1	---	27.0	---
A.1	5	1.3	---	---	143.6	---	28.7	---
A.2	9	0.9	---	---	151.0	---	16.8	---
A.3	5	0.9	---	---	141.7	---	28.3	---
West channel								
7.1	0	2526.8	---	---	---	~0	---	---
5.1	5	139.0	---	---	---	41.6	---	8.3
5.2	5	16.2	---	---	---	36.3	---	7.3
Confluence								
3.1	5	0.4	9	0.7	176.4	58.5	35.3	6.5
3.2	5	0.2	9	0.8	174.0	69.2	34.8	7.7
3.3	5	1.1	13	1.4	164.4	52.4	32.9	4.0
2.1	9	3.2	13	3.6	207.0	93.0	23.0	7.2
					Average Flow Velocity:		26.0	6.8

Table 4: Breakthrough curves characteristics at each sampling site: Time to peaks in days and distance d from the releasing day and site (S6 or S7) with the correspondent bromide concentrations in ppm.

Flow velocities calculated from time to peak and distance from injection point were different for the eastern and western flow channels. The western branch of the wetland with site 7 is closer to the outlet than the branch with site 6 (and thus reached the outlet sooner), but shows lower flow velocities than those along the eastern branch. Additionally, there is evidence of some lateral dispersion, with tracer peaks arriving more quickly in locations closer to the center of wetland than along the flow paths close to the wetland edge. For example, flow may be distributed between one (or more) flow paths from S6 to a more central flow path (from 6 → B → 4.3 → A.2 → 3.3 → 2) or along the wetland edge (from 6 → B → 4.1 → A. → 3.2 → 2) (fig. 10). Similarly, from S7 flow could be distributed between the pathway from 7 → 3 → 2 and the pathway from 7 → 5 → 3 → 2 (fig. 21).

From S6, velocities were lower upstream with a value of 15.6 to 17.8 m/day between sites 6 and B. Then, the average velocity was 24.8 m/day for the path close to the wetland edge and 22.2 m/day for more central path (fig. 21). In the western channel, velocities from site 7 were higher in the more central pathway than along the wetland edge (average velocities of 7.3 m/day and 6.3 m/day, respectively, fig.21). The residence time of the water between 5/14/08 and 5/28/08 was between 28 to 41 days. The residence time is calculated based on the entire wetland water volume using the distance along the longest path through the wetland. The average velocities calculated from residence time calculations (6 to 11 m/day; see previous section) is in the same range as the velocities found in this tracer study (6.8 to 26 m/day).

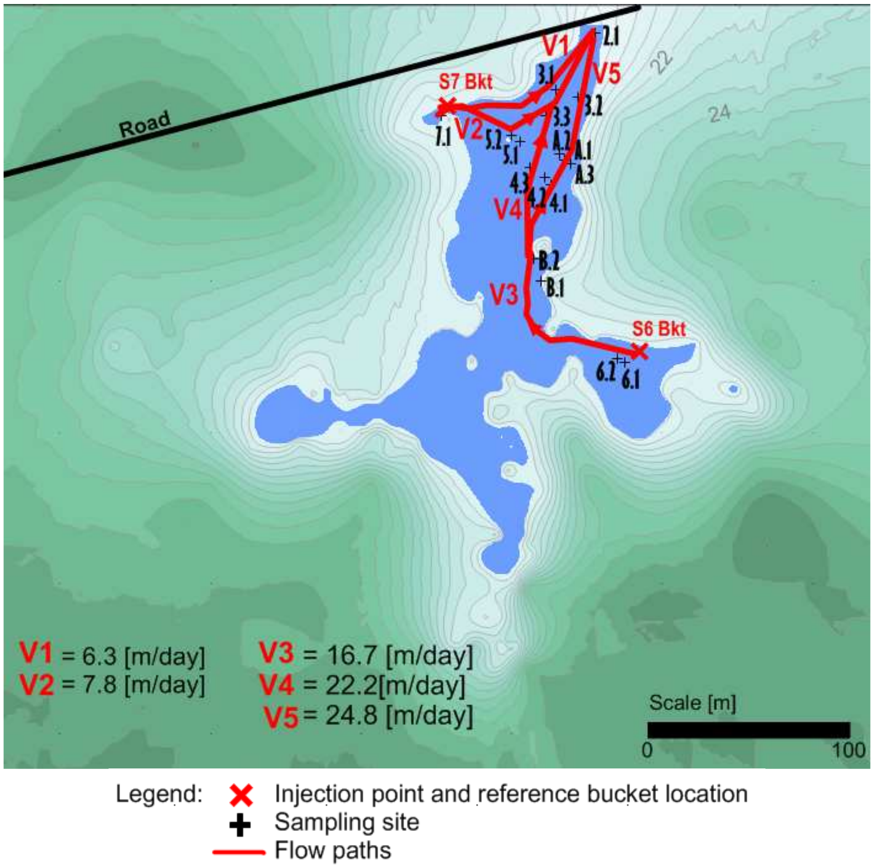


Figure 21: Average velocities distribution for the different flow paths.

2.3.3. Sulfur hexafluoride concentration

Overall, these results showed that bromide can be used successfully as the tracer to study hydraulic characteristics of the tropical wetland. On the other hand, results found with SF_6 confirm that it was not successful as a surface water tracer for the specific conditions of this study, i.e., shallow and slow surface flow under humid tropical conditions. Both tracers were injected into the wetland at the same time at the beginning of the field experiment. Since water samples were then taken at the same sites and times to measure both tracers, it was expected that both tracers would also appear simultaneously. However, no significant SF_6 concentration was detected in any of the sampling sites, except early in the release sites 6 and 7.

The samples collected at the reference buckets explain the situation (fig. 22). The quick dissipation rate observed in these buckets, since the buckets were isolated from flow and dispersion processes this indicates fast volatilization of the gas in these conditions, to concentrations below measurable levels. This deemed the tracer unusable for the purposes of the study. Concentrations found at all other sampling sites (2, 3, 4, 5, A and B) showed the same pattern, with very low and stable background values unaffected by transport from the upstream sites.

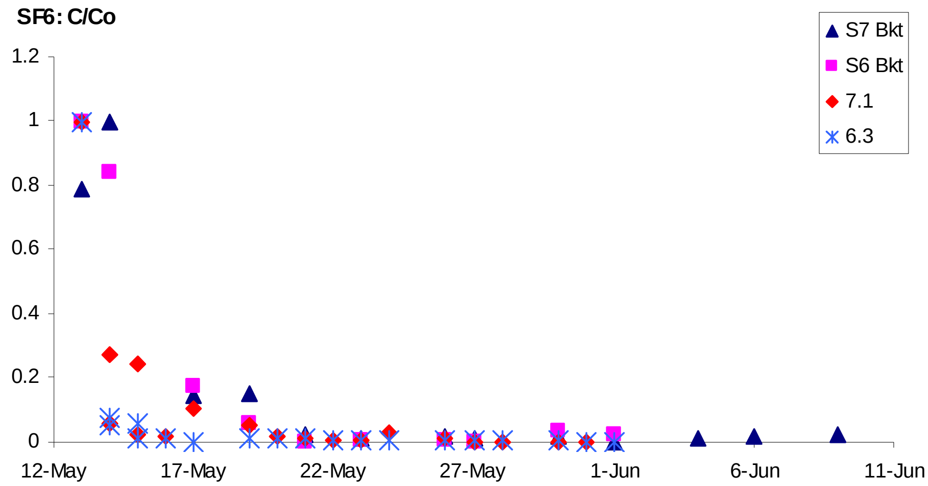


Figure 22: SF6 concentration found at the injection site 6.3 and 71 and in the reference buckets S6 Bkt and S7 Bkt.

Finally, a few remarks on the sample chemical analysis method to detect SF_6 and its analyst should be pointed out. Indeed, the sample analysis method using the gas chromatography technique is very sensitive and therefore variable to the environmental conditions. A calibration curve was made at the beginning of each day of analysis to reference the results to the specific conditions and calculate the concentration correspondent to the peak area detected. The conditions were maintained scrupulously during the experiments. However, a background pollution found during all days of experiment brings the detection limit at the 10^{-5} dilution concentration standard instead of 10^{-6}. Several SF_6 peaks were not isolated from a second close peak. This second peak was considered as a noise and could not be properly detected. Finally the lack of experience of the analyst can also bring a measure of incertitude concerning the exact repetition of the method and the ease and knowledge to adapt the method if needed.

2.4. Conclusion

The results indicate that SF_6 is not a useful surface water tracer for the humid tropical conditions of the area because of its non-conservative behaviour caused by strong volatilization during transport. On the other hand, bromide showed very good results and can be used as a tracer to study hydraulic characteristics of the tropical wetland. This allowed a preliminary analysis of the hydraulics of two wetland branches and a discussion on water quality functioning based on the different residence times in the different parts of the wetland.

Time of the peaks concentration and the distance between each site gave different flow path and velocities of the tracer plumes depending on the injection sites. Velocities were fund to be higher along the eastern branch than the western branch, and were further distributed across central and edge paths through the system. Flow paths along the wetland edge were slower than central paths in the eastern branch, while the opposite was true in the western branch. In the eastern branch, quicker flow closer to the center of the wetland was likely due to the presence of more defined channels away from the wetland edge. In the western branch, the opposite was true with the more central flow path passing through very flat areas of dense vegetation and shallow sheet flow and a slightly more defined channel close to the wetland edge near the outlet. The average velocity from residence time calculations (previous section) was found to be in the same range as the velocities found in the tracer study. These results confirm that bromide can be used successfully as the tracer to study hydraulic characteristics of the tropical wetland.

In addition to the field tracer study and the sample analysis, mathematical models are often used as a tool to help interpret and enhance the value of field observations. To explore the relative importance that the small-scale heterogeneity (centimeter to meter) introduces on the effective average predictions, it is possible to combine the deterministic simulations with a stochastic multivariate sampling approach that explores the natural variability of the surface properties described by probability distribution functions obtained based on field specific values. Bromide results will therefore be analyzed with a multivariate model to find and calculate information about hydraulic characteristics such as the residence time distribution and water mixing. Depending on the accuracy of those results, analysis of the interaction of vegetation and surface water flow could be performed.

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Appendix 1:

A. Natural freshwater wetland in Central America: Definition

Geographic setting:

Central America isthmus was formed three millions years ago. The actual area of about 525'000 km2 allows a biologic corridor between terrestrial species in South and North America, and a barrier stopping the marine exchange between Pacific Ocean and Caribbean Sea. The isthmus was formed at the confluence of five tectonic plates and the tectonic generates a complex network of fractures, mountains, plateaus and depression which allowed and extensive development of wetlands. Lakes and cordillera result from volcano's activity between northwest Costa Rica to Southeast Panama (Ellison, 2003). The central cordillera is a geographic limit where the Caribbean and the Pacific coast show slightly different climates. The Caribbean coast receives more rainfall than the Pacific coast. Surface runoff and lowland topography are also higher on this side which allows more wetland formation (Ellison, 2003).

Typology and definition of tropical and freshwater wetlands:

The wide range of wetland ecosystem is a land ecosystem strongly influenced by water or an aquatic ecosystem with shallow water and influenced by the proximity of land. In any cases, wetland is a type of ecosystem that represent transitional areas or specific ecotone where limits are difficult to define (Roggeri, 1995). Typologies are large and confusing along the world to define such wide range ecosystems. In the last few decades, scientific and management communities become aware of the importance of sustain such ecosystem. Conservation and research studies needed therefore specific terms to regroup these different landscape units. None of those actual definitions are universally approved; however all approved the general term of wetland.

The most famous wetland definition comes from The Ramsar Convention in 1971. The goals of this convention on Wetlands is to promote international cooperation for the conservation and wide use of such ecosystem and their resources by nominating sites of international importance. The proposed definition is:
"Wetlands are area of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does nor exceed six meters."

Alternatively, the United States Fish and Wildlife Service purposes a slightly different definition from Cowardin et al. (1979):
"Wetlands are land transitional between terrestrial and aquatic systems where the water table is usually at or near the surface of the land or the land is covered by shallow water. "

Central American countries have adopted the Ramsar Convention since 1990, but this classification represents some lack of hierarchy to describe correctly all type of wetland found in this region (Roggeri, 1995). In fact, formation of tropical wetlands depends on the geomorphology and on the hydrologic regime and processes of the area. According to Roggeri (1995) inventory for wetland in Central America and following the definition of Cowardin et al. (1979), the proposed hierarchy consists of wetland systems, subsystems, and classes that an be listed in five general levels: Marine, Estuarine, Riverine, Lacustrine and Palustrine. Each level includes several classes that are recognized on the basis of substrate conditions or dominant vegetation cover. This typology is given as a general framework. Indeed, wetlands are complex transitional units and therefore include more than one ecological unit. The characterization of these ecological units and the exchange with neighborhood land depends on variations in water levels, frequency, duration and depths of flooding or the degree of waterlogging (Unesco, 1974). It is important to point out that wetlands present hydrological regime depending on more than local water sources only with some exception for isolated ones (Roggeri, 1995). For the need of this project specifically focused on a natural palustrine wetland in Costa Rica, this section defines briefly the five general levels and is then focused on palustrine wetland definition located in Costa Rica.

1. **Marine wetland:**

Formation of open water from continent or ocean, including beaches, rocky shores, lagoons, and shallow coral reefs. Marine wetland has generally saline water chemistry with a minimal influence from rivers or estuaries. Tidal can occur and mangroves or mudflats may be present.

2. **Estuarine wetland:**

A daily tidal cycle with a range of fresh-brackish-marine water chemistry characterize this wetland. These wetlands are generally classified as salt and brackish marshes, intertidal mudflats, mangrove swamps, bays, and coastal rivers.

3. **Riverine wetland and alluvial lowlands:**

Formation of freshwater wetland in the river floodplain. They appear along river with large variation of flow and flat topography. Depending if the floodplain is temporally or permanently flooded, different types of ecosystems are fund (flooded grassland, flooded forest or lake, lagoon, swamp, marsh, respectively). This trend is accentuated Tropical regions affected by wet and dry season often present high and low water river levels. Wetlands can therefore remain longer depending on the seasonal rainfall amount and duration. Formation in a coastal deltaic floodplain as the Ganges, the Amazon or the Niger are usually also influenced by the tide and the type of ecosystem can be sensibly different. In Costa Rica, Allen (1956) listed vegetation on the riverine area of the Golfo Dulce located on the Pacific coast and define four subtypes of gallery forest. Gomez (1985) also inventoried species assemblages occurring in La Selva Biological on the Caribbean coast (Roggeri, 1995).

4. Lacustrine wetland:

This wetland type includes inland water with less than 30% vegetation cover, and occupies at least 8 ha. Lacustrine wetlands include lakes, lakes shore, large ponds and sloughs. Located in the down shore part or around the shallower shores of a lake, they are recharged by lake's water variation, rainfall and groundwater. Low flow is usually determining in a lake and the wetlands are generally herbaceous (pond, flooded grassland or swamp) or sometimes forested (flooded forest or forest swamp). The floating aquatic vegetation in Central American lacustrine wetlands is dominated by water fern and water hyacinths. Emergent vegetation is often composed with sedges, grasses, cattails and pondweeds (Ellison, 2003). Finally, volcanic lakes with extremely low or high pH provide unique habitats for aquatic plants. These lakes usually host a few type of plant species.

5. Palustrine wetland:

Forested or non-forested palustrine wetlands group all non-tidal wetlands that are substantially covered with emergent vegetation like trees, shrubs or mosses (Ellison, 2003). Most bogs, swamps, floodplains and marshes fall in this system, which also includes small bodies of open water. Water chemistry is normally fresh but may range to brackish and saline in semiarid and arid climates. For the purpose of this project, only freshwater systems are presented. Palustrine wetlands can be located in bottom valley and recharged by rainfall, runoff, subsurface flow and groundwater in addition to a possible river flow. Humid tropics area has usually permanent water with grassy or forest communities instead of dry area where water are usually logged seasonally with small grassy vegetation. Several case studies are found on wetlands located in small arid valley (i.e. Sahel zone in Africa) because of their importance for local communities' subsistence, but also because of most nutrients originate from adjacent slopes. Depressions in lake or river system can lead to formation of different type of wetland as in the alluvial lowlands. Depressions can also occur in a plateau and are the topographic convergence for runoff, subsurface water and groundwater shows on the surface. Those isolated wetland have a natural water quality driven by the nature of the adjacent slopes or by the substratum depending on water input source. They are usually fund during the wet season, but can be also permanent if there is important amount of rainfall or a high groundwater level. Very low flow is usually determining in such isolated depressions and wetlands are generally herbaceous (herbaceous swamp, peat swamp, permanent shallow water bodies) and sometimes forested (swamp forest). Palustrine wetlands can be periodically or permanently flooded ecosystems. Their persistence depends on processes like infiltration and evapotranspiration among others.

Forested swamps occur easily in Central America because important amount of rainfall meets generally low evaporation and poor drained soils. For example, Allen (1956) and Myers (1990) studied and described the floristic of forested wetlands dominated by palms on isolated areas in the Golfo Dulce and the Osa Peninsula (Pacific coast) and around Tortuguero (Caribbean coast) respectively. The study on the palm *Raphia* in Tortuguero demonstrated that the species richness increased with improving drainage and that the structure of the palms was controlled by hydroperiod. Hardwood swamp forests are also common as Hartshorn and Hammel (1994) reported with *Pentaclethra macroloba* as the dominant canopy tree in La Selva Biological. Several swamp forests formed in isolated patches are located in

Osa Peninsula. Dominant tree species have been reported to be *Prioria copaifera* or Mora *oleifera* with the endemic herb *Calathea longiflora*. Holdridge and budowski (1956) studied *Sajal* or *Orey* forest dominated by *Campnosperma panamensis* between Puerto Viejo and the mouth of Rio Sixaola in the Southeastern part of Costa Rica.

Palustrine wetlands which are not forested represent also an important group of wetland in Central Amercia. Depending on the source or on the study, non-forested wetlands can be marshes, herbaceous swamp, peat swamps and savannas. Marshes are characterized by shallow stagnant water and high surface water or groundwater level fluctuations and usually covered by grassy vegetation. These wetlands can be of critical importance for migratory birds. Herbaceous swamps present higher vegetation than in marshes. In Latin America, these swamps are often dominated by *Phragmites* reeds (reed swamps). Peat swamps differentiation is made between bog and fen depending on climate, hydrologic regime, soil acidity and vegetation, but peatland are still poorly studied in Central America. Savanna is a less studied and inventoried wetland type although it occurs naturally on Central American poor soils overlying impermeable clays that are waterlogged during the rainy season.


The wetland is forested in the upper part (left) and non-forested in the lower part (right).

Most of the study and attention about wetland fauna were focused on bird migratory species. Lots of inventories and information are therefore available on birds and other famous threatened species and at the expense of other fauna. Among a wide range of migratory, endemic or resident bird species, there are also lots of mammals, reptiles, amphibians and fish hosted in tropical wetlands. Principal inventoried wetlands in Central America are coastal marine or estuarine. A few marshes have been identified as a Ramsar site because of their small importance for migratory birds.

B. Natural freshwater wetland in Central America: Values

In tropical countries as in temperate climate, wetlands are destructed and altered. For instance, they are altered by drainage for the development of intensive agriculture, mining or urbanization, by dam and embankments to prevent flooding in the floodplain or by uptake for irrigation and water supply (Roggeri, 1995). Natural and tropical freshwater wetlands present a wide range of economic and environmental values. However they usually show a few dominant values because one wetland cannot assume all those by itself. According to Roggeri (1995), this section presents briefly all those economic and environmental values. Only the ones corresponding to the present study are developed.

1. **Resources (Economic values):**

Wetland resources are used directly for human needs and natural resources making a capital.

- **Agriculture**: Permanent wetland offers fresh water source for irrigation and seasonal ones present fertile soils to support culture (floating rice, cassava, yam, sweet potatoes, etc.) because of humidity and sediment and nutrient brought by flooding.
- **Fishery**. Fishery in wetlands is usually an important part of inland source in tropical countries. It usually shows traditional practice to harvest fishes.
- **Forage**: Herbaceous wetland can provide important part of grazing resources for stock farming communities.
- **Forest**: Woods and specific plants species can be used to constructions and art craft.
- **Wildlife**: Haunting animals is a current practice for local communities as an ancestral resource of food but can be in confrontations with wildlife protection managers (endangered and endemic species).
- **Natural** products: Gathering of plants, fruits or minerals for different uses and purposes.
- **Water supply**: Communities use wetlands freshwater as drinking water, households tasks and recreational.
- **Energy**: Plant biomass and peat can be used for energy production.
- **Transport**: During wet season, wide wetlands are used as transport of goods and people.
- **Tourism**: The growing attraction for natural areas increases the notion of ecotourism in wetlands. The input in the economic development for tropical countries is relevant and local communities seem to be also increasingly aware of this potential.
- **Research, education, monitoring**: Wetlands unaltered and not taking part of the subsidence of local communities are very interesting and efficient for the scientific community. Field researches and observations are monitored for education purposes and natural history comprehension. Functions of natural wetlands can be use directly, as we saw above, or indirectly. Some functions performed by wetlands are also essential for the maintenance of other ecosystems. For example, wetlands can protect downstream area from upstream agriculture activities by improving water quality and biodegradation of pollution. They can also limit downstream flooding extension. Finally, information on natural condition, natural quality and function degradation of a wetland bring information on its own performance but also give indication on performance of similar wetlands and information for wetland construction.

2. **Environmental values:**

- **Biological diversity:** The wide diversity of wetlands offer specific habitat for numerous plants and animals. Many wetlands host rare, endemic and endangered species like the Caribbean manatee (*Trichechus Manatus)* in the freshwater lagoons and swamp forests of Quero y Salado in Honduras. Species are living permanently in wetlands or temporarily like migratory birds. The importance of wetlands for migratory birds is one of the most important interests to define a site of international importance in the Ramsar Convention. Migration route of birds define crucial wetlands along their path which can even be of small surface area. Such ecosystem can therefore maintain an ecological balance between ecosystems away from thousands of kilometers.

- **Nutrient retention and export:** Vegetation in wetland is developed during all year or during flood period where nutrients are trapped in. A portion of this vegetal biomass production is consumed and transformed into animal biomass via trophic relationships. The major part is decomposed by invertebrate organisms who consume organic debris and during dry period where aeration of soils occurs. Aerobic condition allows effectively a faster decomposition and also a production of mineral elements and soluble organic compounds which fertilize the wetland. The balance between flora and fauna communities and food resources available in the ecosystem is critical for the ecosystem stability and can vary considerably, depending for example on flood height and duration. Wetlands accumulate therefore an important amount of nutrients during plants growth which can enrich adjacent or downstream ecosystem.
- **Groundwater Recharge and Discharge:** Wetlands can recharge and discharge groundwater by infiltration and reemergence processes respectively. Quantification of those processes and interaction between groundwater and surface water need complex information.
- **Natural flood control and flow regulation:** Riverine wetlands have a major role of delaying downstream flooding by limiting levels of peak flow. However, a large amount of the water stored is not going downstream if evapotranspiration and infiltration processes are significant. Similar processes occur with rainfall and runoff in wetlands with no specific inflow (Dugan, 1990).
- **Sediment retention:** Because of the low flow occurring in wetland, sediments coming from upstream are generally trapped in the wetland. Vegetation at the interface between upland and the wetland trapped also sediments from the runoff. Sediment can represent a source of nutrient.
- **Erosion control:** The rooted vegetation in and around wetlands are stabilizing soils and prevent from erosion.
- **Salinity control:** Accumulation of salt in the soils is predominant in dry tropical region or in marine’s soils where groundwater rises to the surface by capillary action and then evaporates. Salts can be dissolved and removed with periodical and frequent flooding of the area.
- **Water treatment:** Most of chemical substances like pesticides are attached to sediment when they are transported in the water. The function of sediment retention in the wetland cleans the downstream water flow and allows time to degradation of those chemicals in the wetland. In addition, some vegetation species, like the water hyacinth (*Eichhornia*) are capable to retain and store chemicals like copper and iron as nutrients.
- **Climatic stabilization:** Wetlands are known to trap methane and use carbon dioxin for photosynthesis and peat swamps are also known to be a considerable reservoir of carbon dioxide. Those considerations can influence global climate, but the relations are still unclear. It is especially difficult to quantify the influence of tropical wetlands in global climate because of the total wetland areal extend remain unknown.

Appendix 2:

Field instrumentations and processing data

Canal stage recorder:

The material used to record water levels in the field is a canal stage recorder proposed by Schumann and Muñoz–Carpena (2002). All components (potentiometer, pulley, floats and datalogger) are housed inside the top of a PVC pipe “well” and covered with a PVC cap. The water elevation is calculated by knowing the sensor range of the device R depending on the effective diameter of the pulley D. A 10–turn potentiometer was chosen according to the expected change in water elevation (the device can then register water levels varying between D and D+R). For the upper and lower boundary the analog signal (AN) registered in the data logger were AN_0 = 2.485 V and An_n = 0.005 V respectively (L1 and L2 in fig. 23).

The water elevation L, measured from the benchmark is given by equation 3:

$$L = \left(\frac{R}{2.485 - 0.005} \right) \cdot \left(AN_0 - AN \right) \text{, where } R = 10 \cdot d \cdot \pi \qquad (3)$$

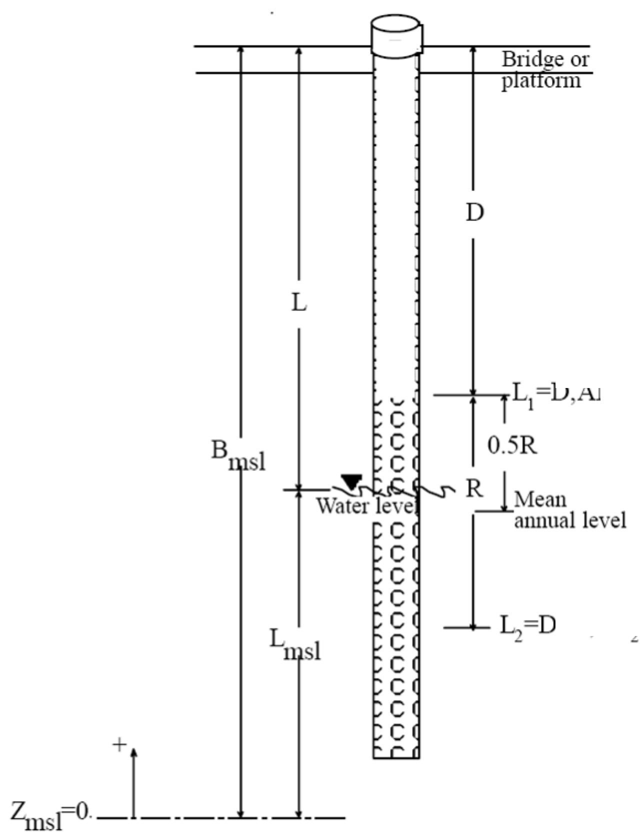


Figure 23: Stage recorder geometry (Source: Schumann and Muñoz–Carpena, 2002).

The data recorder converts the analog signal from the potentiometer to a digital signal. The resolution of the data logger is 8-bit (2^8) and represents in the apparatus 2500 millivolts/2^8 = 9.76mV per step OR 200 cm/2^8 = 0.78 cm per step. All the stations are topographically referenced to the station E2. Water levels corrected with the relative elevation were uploaded in the database Hydrobase from May 2008 for station E1 to E7 and from May 2009 for station E8. At each download, hand readings from staff gages fixed outside of the pipes allowed a supplement checking of the processed data and a comparison with the previous reading.

Potentiometer, pulley and belt

Hobo data logger in the top's pipe

Pulley, belt and float

PVC pipe

Data download and maintenance

Rain gauge:

The rain gauge was installed in the middle of the wetland body, where no canopy can intercept the rainfall records. A second rain gauge was installed in early March 2009 when the first one bugged. The records where also suspected to be too high for the region and to high comparing to the records from the rain gauges located at 3 km south-west in the campus (weather station).

Rain gauges

Data Download and maintenance

Tipping bucket and HOBO data logger

Appendix 3:

Field Measurement of the flow

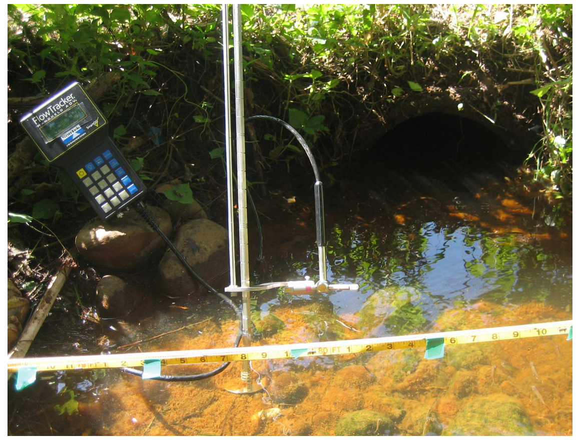
During the field trips in May 2008 and 2009, flow at the outlet of the culvert was measured with a SonTek/YSI FlowTracker. The Flow Tracker is an instrument using the technology of the SonTek/YSI Acoustic Doppler Velocimeter (ADV) from a simple handheld interface. The FlowTracker probe is a bistatic Doppler current meter which uses the Doppler shift by measuring the change in frequency of sound that is reflected by particles in the water. The probe has a central acoustic transmitter to generate a short pulse of sound at a known frequency and two acoustic receivers which receive the signal reflected by the particles present in the water. The measured change in frequency for each receiver gives a velocity with an accuracy of 1% in a one-second sample data from 0.0001 to 4.5 m/s. In addition to velocity, the FlowTracker records a variety of quality control data at each measurement location to quickly evaluate the quality of velocity data.

Flow Tracker

Flow Tracker command and probe

A graduated transect across the outlet was chosen at a distance of about 60 cm of the culvert's outlet to take measurements of velocity at different location. One velocity sample with quality control is recorded each second but mean velocity data are collected at each measurement location over 30 seconds. Mean velocities were taken at 0.6 of the water depth and flow were calculated with the Mid Section Discharge equation using the water depth and the width between locations. Data files (flow and data reports) are downloaded and exported using the given FlowTracker software.

Field measurement at the culvert outlet



Tape measure at the outlet marking the transect

The first flows measured during the field trip in May 2009 were higher than the discharge measured in 2008. This might be because of the important rain event that occurred from the 11th to the 13th of May 2009 comparing to the small rain event in May 2008. There was an amount of 150 mm of rain from the 1st to the 26th of May 2008 and 213 mm in the same period in 2009. Similarly, water elevation upstream and downstream the culvert had more variation in 2009 than in 2008. The field measurements of the flow in May 2009 coincided well with the rainfall recorded (fig. 24). During latest May 2009, there were no significant rain and the discharge recorded agreed with the values recorded in May 2008 (0.003 to 0.002 m^3/s).

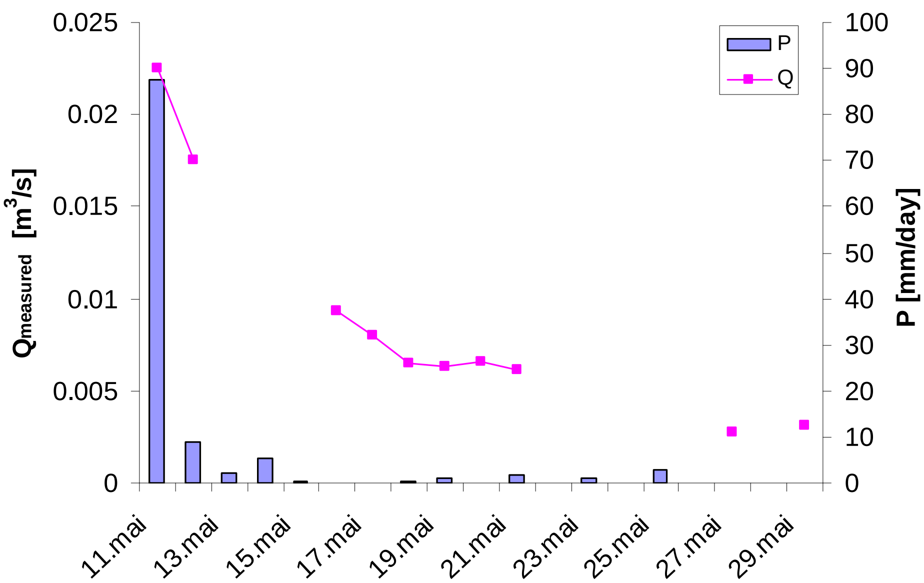


Figure 24: Comparison of the measured flow [m^3/s] with the daily rainfall [mm].

The measured field flows Q were used to estimate the discharge coefficient to compute the outflow time series with the water stages data recorded upstream and downstream to the culvert. Methods and results are presented in the next section (Appendix 4).

At each flow calculation, the FlowTracker gave a summary for each location in the transect with the average of the measurements and the quality control. A second part gives a graphical vision of the transect depth, velocity and flow measured at each section. An example of the 17th of May 2009 is given below (fig. 25):

Discharge Measurement Summary

Date Generated: Wed May 27 2009

File Information	
File Name	090516.03.WAD
Start Date and Time	2009/05/17 18:05:39

Site Details	
Site Name	
Operator(s)	MB

System Information	
Sensor Type	FlowTracker
Serial #	P2280
CPU Firmware Version	3.5
Software Ver	2.20

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty		
Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.5%	2.3%
Velocity	2.3%	14.0%
Width	0.2%	0.2%
Method	2.7%	-
# Stations	4.6%	-
Overall	**5.9%**	**14.2%**

Summary			
Averaging Int.	30	# Stations	11
Start Edge	LEW	Total Width	1.524
Mean SNR	11.1 dB	Total Area	0.221
Mean Temp	24.33 °C	Mean Depth	0.145
Disch. Equation	Mid-Section	Mean Velocity	0.0393
		Total Discharge	**0.0087**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	18:05	0.00	None	0.137	0.0	0.0	0.0000	1.00	0.0472	0.010	0.0005	5.7
1	18:05	0.15	0.6	0.152	0.6	0.061	0.0472	1.00	0.0472	0.023	0.0011	12.6
2	18:06	0.30	0.6	0.152	0.6	0.061	0.0198	1.00	0.0198	0.023	0.0005	5.3
3	18:07	0.46	0.6	0.152	0.6	0.061	0.0743	1.00	0.0743	0.023	0.0017	19.9
4	18:08	0.61	0.6	0.137	0.6	0.055	0.0670	1.00	0.0670	0.021	0.0014	16.1
5	18:11	0.76	0.6	0.122	0.6	0.049	0.0749	1.00	0.0749	0.019	0.0014	16.0
6	18:12	0.91	0.6	0.152	0.6	0.061	0.0368	1.00	0.0368	0.023	0.0009	9.9
7	18:12	1.07	0.6	0.152	0.6	0.061	0.0228	1.00	0.0228	0.023	0.0005	6.1
8	*18:13*	*1.22*	*0.6*	*0.152*	*0.6*	*0.061*	*0.0218*	*1.00*	*0.0218*	*0.023*	*0.0005*	*5.8*
9	*18:15*	*1.37*	*0.6*	*0.137*	*0.6*	*0.055*	*0.0069*	*1.00*	*0.0069*	*0.021*	*0.0001*	*1.7*
10	18:15	1.52	None	0.137	0.0	0.0	0.0000	1.00	0.0069	0.010	0.0001	0.8

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Discharge Measurement Summary

Date Generated: Wed May 27 2009

File Information	
File Name	090516.03.WAD
Start Date and Time	2009/05/17 18:05:39

Site Details	
Site Name	
Operator(s)	MB

Quality Control

St	Loc	%Dep	Message
8	1.22	0.6	Boundary QC is Good; possible boundary interference
9	1.37	0.6	High SNR variation during measurement: 5.2,3.9

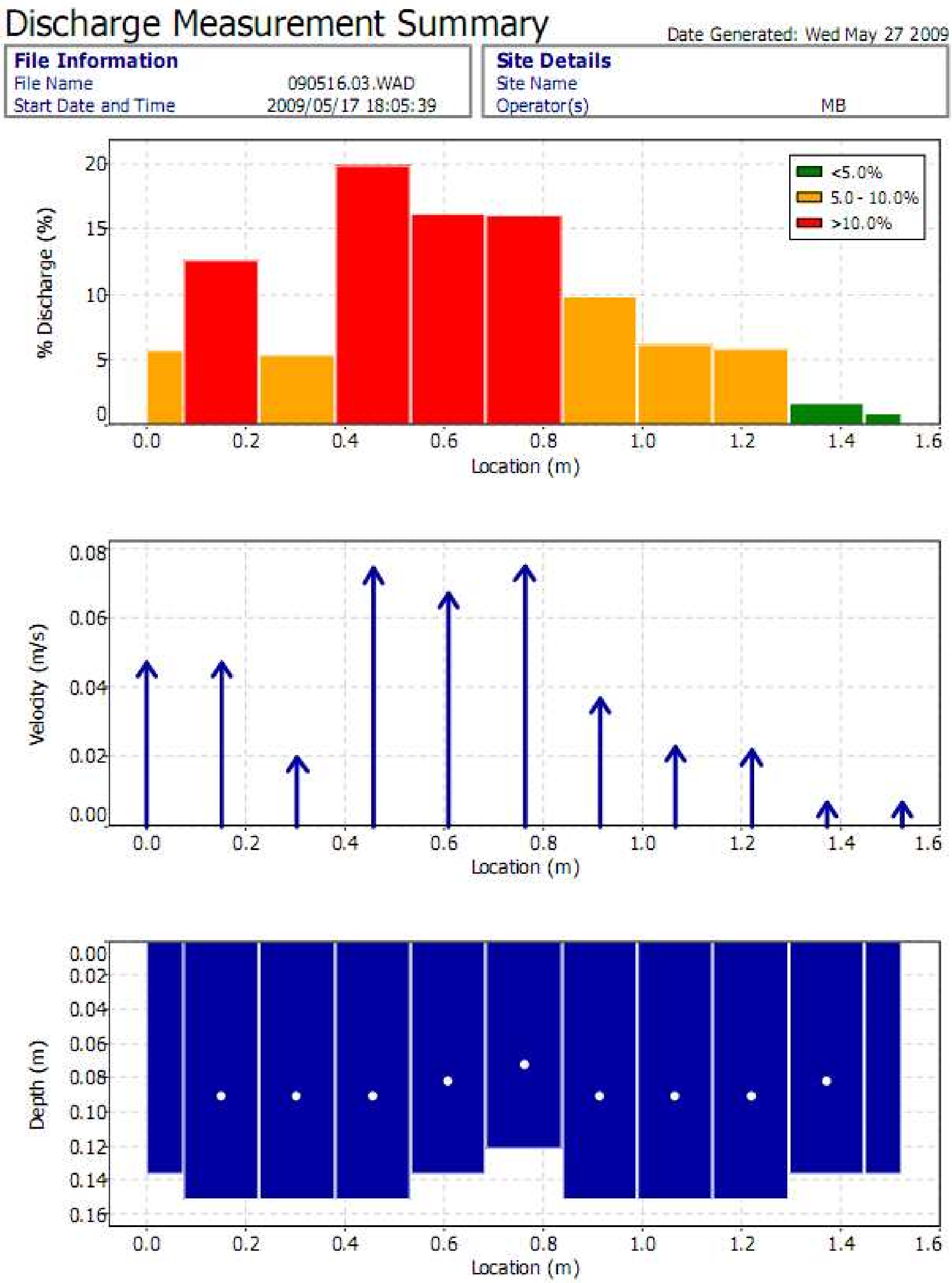


Figure 25: Example of the data given at each flow measurements.

Flow computation through the culvert

The culvert located between station 2 and 1 is the single outlet of the wetland. The simultaneous periodic measurements of water elevation (i.e. every 15 minutes) at both station 1 and 2 allow determining the flow thought the culvert with its known geometric characteristics. An accurate flow computation through the culvert is needed for the wetland water balance and evaluation of the stage-storage capacity.

A first approximation of the flow was based on Manning-Strickler equation and gave results one order of magnitude higher from field measurements. The discrepancy is especially large for the condition of open channel tranquil flow, which is the dominant flow type in this culvert. To overcome the problem, a direct application of a method proposed by the South Florida Water Management district to compute flow in the culverts of the Everglade (Wu and Imru, 2005) is chosen. The method is based on the principle presented in Bodhaine (1968) and uses a discharge coefficient based on field measurements to calculate culvert flow (Appendix 3). This method is used to measure flood flow from small drainage area.

Principles and Method

According to Bodhaine (1968), six types of flow can occur through a culvert based on continuity and energy equations. The function of the culvert is to provide a passage of water under the road and its geometry will causes a change in the character of flow. The hydraulic capacity of pipe spillway is related to the square root of the head; hence they are relatively low-capacity structures. Capacity may be controlled by the inlet section, the conduit or the outlet. The energy loss occurring in culvert is illustrated on Figure 26.

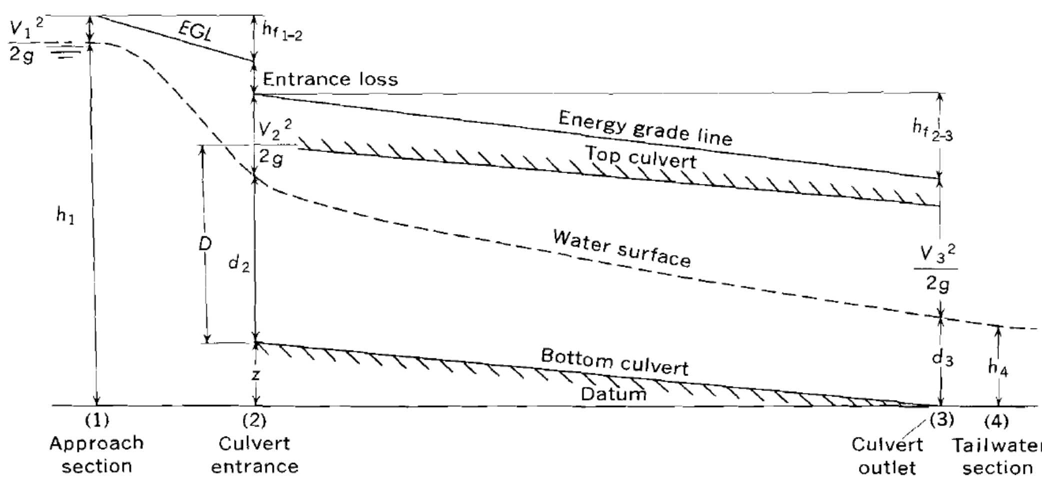


Figure 26: The loss of energy near the entrance is related to the sudden contraction and subsequent expansion of the live stream within the culvert barrel (Bodhaine, 1968).

They are five determinant sections (the approach section; the culvert entrance; the culvert barrel; the culvert outlet and the downstream section) where water elevations are observed to determine the type of flow. Bodhaine (1968) proposes specific discharge equations developed for each type of flow by application of the continuity and energy equation between the approach section and the terminal section. But because the wetland has a relatively flat topography and sufficient accumulation of water which moves at very low velocity, critical flow cannot occur. Thus, only two types of flow are likely to occur. They are type 3 (tranquil flow throughout) and type 4 flow (submerged outlet), as illustrated in Figure 27.

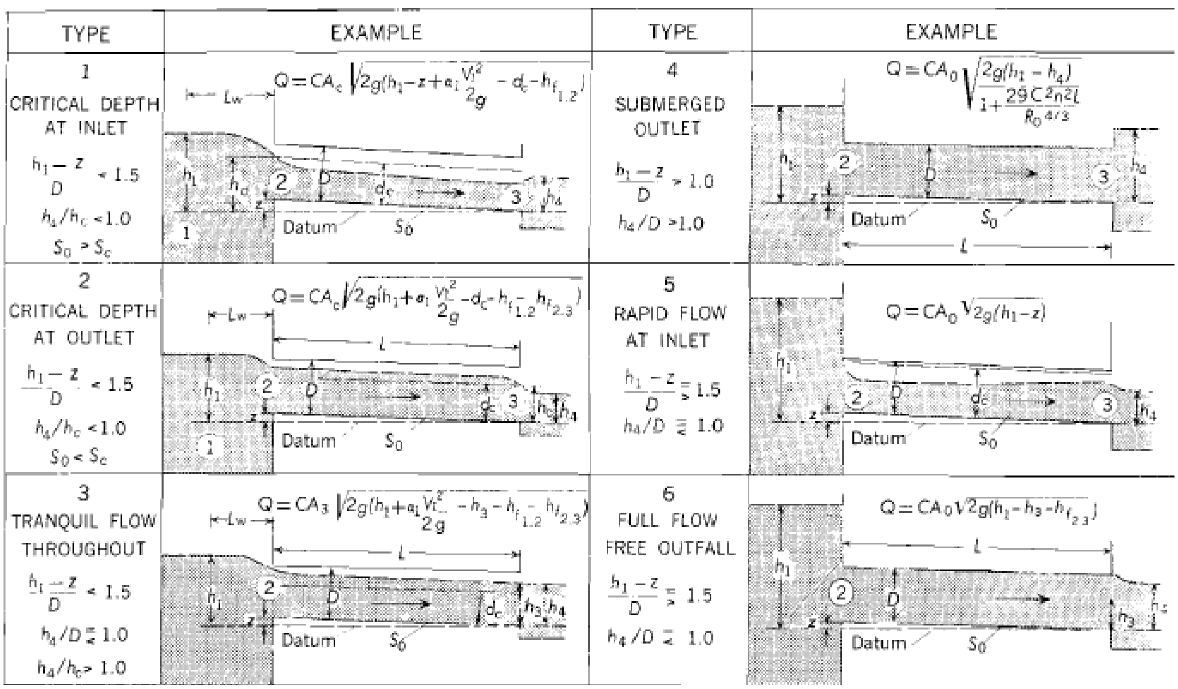


Figure 27: Classification of culvert flow (Bodhaine, 1968).

Backwater is the controlling factor for these two types of flow. If the culvert flows partly full (type 3), the headwater-diameter ratio is less than 1.5; or if it flows full (type 4), both ends of the culvert are completely submerged and the headwater diameter ratio may be any value greater than 1. More recent studies use a boundary condition of 1.2 between the two types of flow (Chanson, 1999, Gupta, 2001) which are not changing the classification in this study because if the headwater-diameter ratio is between 1 and 1.2 or between 1.2 and 1.5, the second condition on section 4 (smaller or bigger than the diameter) is determinant.

Four sections are used to describe the flow in the culvert:

- Section 1 is the approach section. This section is assumed the same as where station E2 records the upstream water elevation h_1;
- Section 2 is the culvert entrance;
- Section 3 is the culvert outlet;
- Section 4 is the location of the tail water level. This section is assumed the same as where station E1 records the downstream water elevation h_4.

According to (Wu and Imru, 2005) and because of mild slope and tranquil flow occurring in the wetland, water level in section 3, h_3, is assumed the same as that in section 4, h_4; and water level at section 2 is assumed as a ratio of water level measuring at Section 1 ($h_2 = 0.9*h_1$).

Geometry of the culvert and flow sections: Geometry and hydraulic properties at the entrance (section 2) and at the outlet (section 3) of the culvert are defined as below**:**

Circular segment height: $h = 2r - d$

Central angle: $\theta = 2\arccos\left(\frac{r-h}{r}\right)$

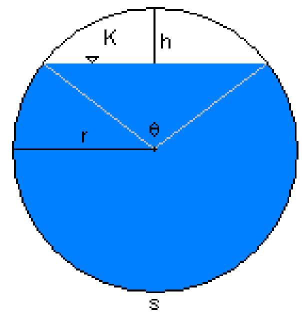
Circular segment area: $K = \frac{r^2(\theta - \sin\theta)}{2}$

Arc length: $s = r \times \theta$

Flow area: $A = \pi r^2 - K$

Wetted perimeter: $P_W = 2\pi r - s$

Hydraulic radius: $R_h = \frac{A}{P_W}$



Source: *http://www.ajdesigner.com/phphydraulicradius/hydraulic_radius_equation_pipe.php*

Description of type of flow

Figure 28 shows the water elevation recorded upstream and downstream of the culvert. The diameter of the culvert is 0.5 m. Thus the discharge flows partly full most of the time with episodic submerged flow.

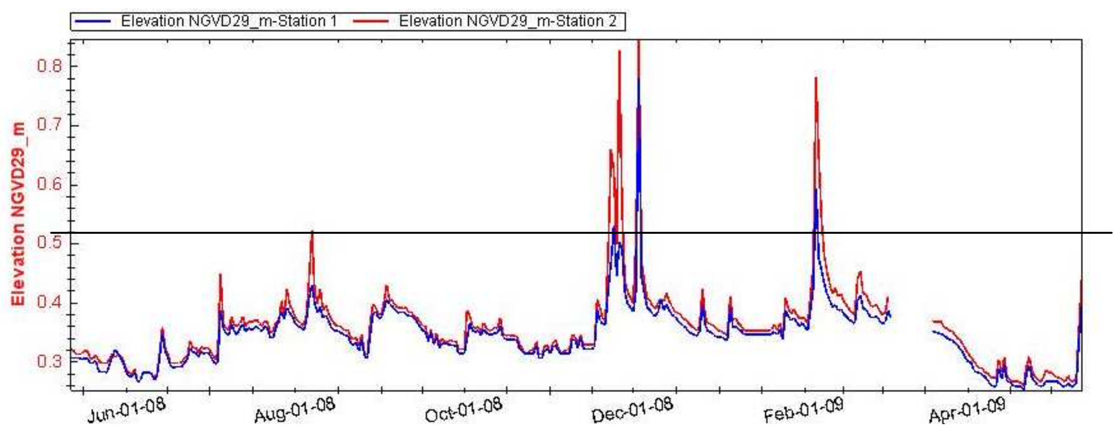


Figure 28: Water elevation upstream (E2) and downstream (E1) of the culvert, May 2008 to May 2009.

Type 3 flow: Figure 29 gives the conditions on the left and general equation on the right.

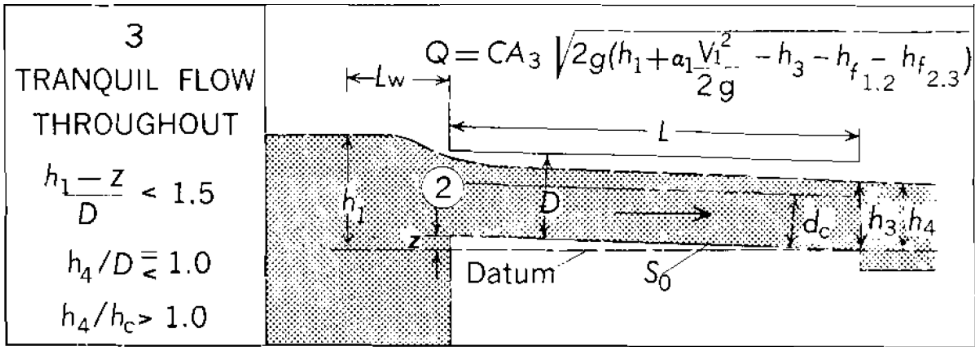


Figure 29: Type 3 flow (Bodhaine, 1968).

The flow equation for type 3 given by Bodhaine (1968) is:

$$Q = C_3 \cdot A_3 \cdot \sqrt{2 \cdot g \cdot \left(h_1 + \frac{\alpha_1 \cdot v_1^2}{2 \cdot g} - h_3 - h_{f1-2} - h_{f2-3} \right)} \quad (4)$$

Assuming that h_{f1-2}, the headloss due to friction between the approach section and the inlet is compensating $\frac{\alpha_1 \cdot v_1^2}{2 \cdot g}$ (fig. 26); equation (4) is simplified as:

$$Q = C_3 \cdot A_3 \cdot \sqrt{2 \cdot g \cdot (h_1 - h_3 - h_{f2-3})} \quad (5)$$

Where the headloss due to friction in the barrel culvert is $h_{f2-3} = L \cdot \left(\frac{Q^2}{K_2 \cdot K_3} \right)$ and the conveyance K is: $K_2 = \frac{R_{h_2}^{2/3} \cdot A_2}{n}$ at section 2 and $K_3 = \frac{R_{h_3}^{2/3} \cdot A_3}{n}$ at section 3.

Thus the flow is expressed with: $Q = C_3 \cdot A_3 \cdot \sqrt{\frac{2 \cdot g \cdot (h_1 - h_3)}{1 + \frac{2 \cdot g \cdot L \cdot C_3^2 \cdot A_3^2}{K_2 \cdot K_3}}}$ (6)

Where
h_1 , h_3 = water level above datum [m]
v_1 = mean velocity at section 1 [m^2 s^{-1}]
C_3 = discharge coefficient for type 3 flow
L = culvert length [m]
g = acceleration of gravity (9.81 [m^2 s^{-1}])
A_2, A_3 = area of section of flow at section 2 and 3 [m^2]
R_h = hydraulic radius [m]
n = manning roughness coefficient [s m$^{-1/3}$]
Q = flow [m^3 s^{-1}]
D = culvert diameter [m]

Type 4 flow (submerged flow): Figure 30 gives the conditions on the left side and general equation on the right.

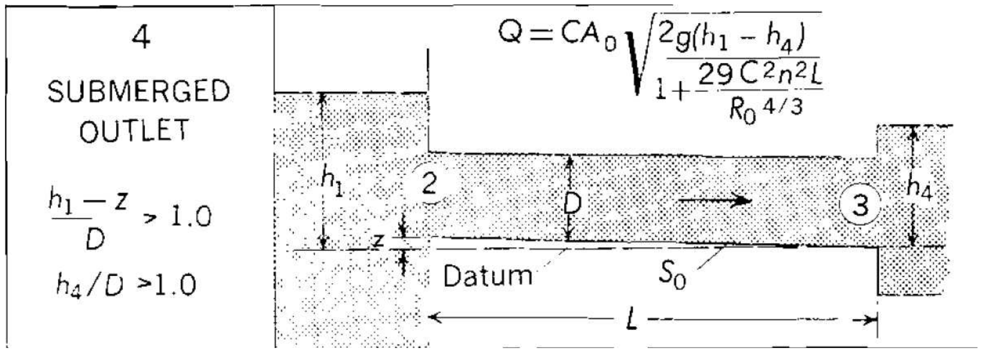


Figure 30: Type 4 flow (Bodhaine, 1968).

The culvert is submerged by both headwater and tailwater in this case. The headwater-diameter ratio can be anything greater than 1.0. If $h_4/D > 1$, only type 4 is possible. No differentiation is made between low-head and high-head flow on this basis for type 4 flow. The culvert flows full and the flow may be computed directly from the energy equation between sections 1 and 4:

$$Q = C_4 \cdot A_0 \cdot \sqrt{2 \cdot g \cdot \left(h_1 - h_4 - \frac{L \cdot Q^2}{K_0^2} \right)} \qquad (7)$$

Rearranging the terms to express the flow: $Q = C_4 \cdot A_0 \sqrt{\frac{2 \cdot g \cdot (h_1 - h_4)}{1 + \frac{2 \cdot g \cdot L \cdot C_4^2 \cdot n^2}{\left(\frac{D}{4}\right)^{\frac{4}{3}}}}}$ (8)

Where

h_1 , h_4 = water level above datum [m]

C_4 = discharge coefficient for type 4 flow

L = culvert length [m]

g = acceleration of gravity (9.81 [m^2 s^{-1}])

A_0 = area of section of flow equivalent to the culvert section [m^2]

R_h = hydraulic radius [m]

n = manning roughness coefficient [s m$^{-1/3}$]

Q = flow [m^3 s^{-1}]

D = culvert diameter [m]

Methodology and results:

1. Determine the discharge coefficient with the measured flows

Equation given for type 3 flow in Bodhaine (1968) is rearranging as below to obtain coefficients of discharge for each given flows and water elevations:

$$C_3 = \sqrt{\frac{Q^2}{2 \cdot g \cdot A_3^2 \cdot \left(h_1 - h_3 - \frac{Q^2 \cdot L}{K_2 \cdot K_3}\right)}} \tag{9}$$

Field measurements (Appendix 3) of flow are summarized in the table 5 below with the closest value of recorded water elevation:

Date	Time	Q_{field} [m^3/s]	Time	E2 [m]	E1 [m]	Q_{estim} [m3/s]
5/21/2008	11:28	0.0019	11:27	0.306	0.299	0.0022
5/27/2008	10:06	0.0022	9:57	0.290	0.291	0.0021
5/27/2008	10:20	0.0032	10:27	0.290	0.283	0.0021
5/27/2008	10:37	0.0025	10:42	0.290	0.283	0.0021
6/1/2008	9:04	0.0015	9:12	0.282	0.283	0.0019
6/1/2008	9:22	0.0015	9:27	0.282	0.283	
6/2/2008	10:01	0.0014	9:57	0.282	0.276	0.0019
6/2/2008	10:36	0.0013	10:27	0.282	0.276	0.0019
6/3/2008	9:43	0.0013	9:42	0.274	0.276	0.0019
6/3/2008	10:01	0.0016	9:57	0.274	0.276	
5/12/2009	17:05	0.0237	17:15	0.424	0.385	0.0049
5/12/2009	17:41	0.0175	17:45	0.416	0.385	0.0049
5/13/2009	7:53	0.0156	7:45	0.369	0.346	0.0041
5/16/2009	9:44	0.0093	9:45	0.330	0.314	0.0032
5/17/2009	15:37	0.0073	15:45	0.322	0.307	0.0031
5/17/2009	15:51	0.0080	16:00	0.322	0.307	0.0031
5/17/2009	16:05	0.0087	16:15	0.322	0.307	0.0031
5/18/2009	6:59	0.0065	7:00	0.314	0.307	0.0021
5/19/2009	11:35	0.0063	11:30	0.314	0.299	0.0030
5/20/2009	11:30	0.0066	11:30	0.314	0.299	0.0030
5/21/2009	11:42	0.0061	11:45	0.314	0.299	0.0030

Table 5: Summary of the measured field flows with the correspondent water elevations and estimated flows.

Field measurements were made in May-June 2008 and in May 2009. In 2008, no important rainfall event occurs and water levels were very low and similar before and after the culvert. Water elevations downstream are slightly greater (0.0012 m) than water elevation upstream for tow days on five. With this methodology, no flow can be calculated for those field measurements. Water stage recorder has an error margin of ±0.007 m, so in case of very low flow and water level difference at E1 and E1 smaller than 0.007m, flow is considered as null. At the opposite, an important rainfall of 175 mm between the 10th to the 13th of May 2009 increased the water elevation to the limit of the flow type 3. The flow data were at the limits between type 3 and type 4 where the outlet of the culvert was almost submerged and h_4/D equaled 1.05, 0.98 and 0.91. This data could not be used to compute coefficient C_4 because the only data satisfying the type 4 flow condition did not have a good summary of quality control and had a too high uncertainty on the measured flow. On the other hand, there were enough data to compute the discharge coefficient C_3 (Table 6). The relationship between the measured flow and the estimated flow presented a good correlation of 93.2%, but a small slope (0.167) meaning that the estimated flow should be under-estimated (Fig. 31).

Date	Q (m^3/s)	h4/D < 1	C_3
21.5.2008	0.0019	0.8857	0.0265
27.5.2008	0.0022	0.8535	0.0319
27.5.2008	0.0025	0.8535	0.0367
1.6.2008	0.0015	0.8535	---
1.6.2008	0.0015	0.8535	---
2.6.2008	0.0014	0.8391	0.0222
2.6.2008	0.0013	0.8391	0.0208
3.6.2008	0.0013	0.8391	---
3.6.2008	0.0016	0.8391	---
5.12.2009	0.0237	1.0580	---
12.5.2009	0.0175	1.0580	---
13.5.2009	0.0156	0.9800	---
16.5.2009	0.0093	0.9160	0.0882
17.5.2009	0.0073	0.9020	0.0723
17.5.2009	0.0080	0.9020	0.0792
19.5.2009	0.0063	0.8860	0.0632
20.5.2009	0.0066	0.8860	0.0662
21.5.2009	0.0061	0.8860	0.0612

Table 6: Calculated discharge coefficient for type 3 flow.

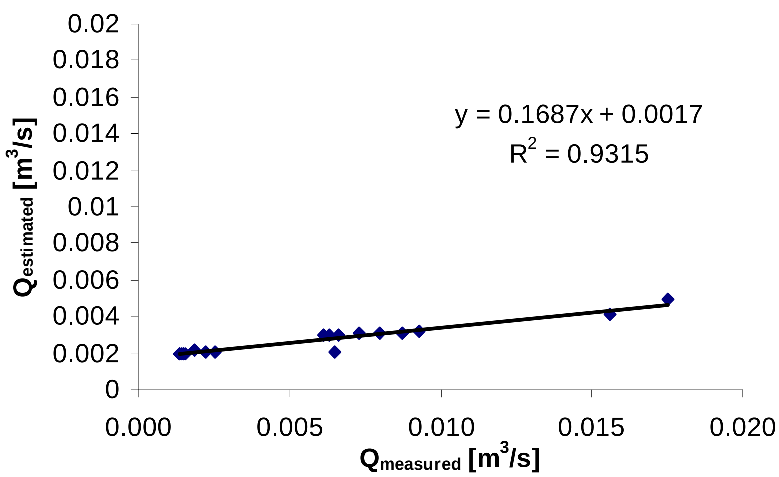


Figure 31: Relationship between measured and estimated flows.

2. **Assume an appropriate discharge and Manning roughness coefficient**

In 2008, the discharge coefficient was taken as the mean value of all calculated ones because of the small number of field measurements and the poor relation between discharge coefficient and headwater. In 2009, the increase of data allowed improving the value of the discharge coefficient C_3. The discharge coefficient was firstly assumed as 0.031 and then as 0.052 for type 3 flow calculation. Because of lack of field measurements when the culvert was submerged, the same discharge coefficient is used for type 3 flow and type 4 flow.

Slope and hydraulic radius are readily calculated from geometry of the culvert however, Manning roughness coefficient is more difficult to evaluate because it varies with the depth of flow. Resistance of flow is also influenced by the gradient of the channel, the vegetation and the sediments which can stay temporarily in the culvert barrel or at the entrance/outlet of the culvert. Roughness coefficient is greater if vegetation, sediments or soils are lying at the bottom of the culvert barrel. Because sediments and lots of vegetation are in the culvert, the used value is taken as the highest value proposed in the literature for the type of material of the culvert: a cast-iron uncoated pipe. Manning roughness coefficient is thus assumed as 0.016 [$s*m^{-1/3}$] (Isco Open Channel Flow Measurement Handbook, 2006).

3. **Graphical results**

An overview of the flow for the whole period (May 2008 to may 2009) is showed in Figure 32. Daily average of the flow is presented with the 5-min rainfall data. The trend shows an increase of flow corresponding to rainfall event.

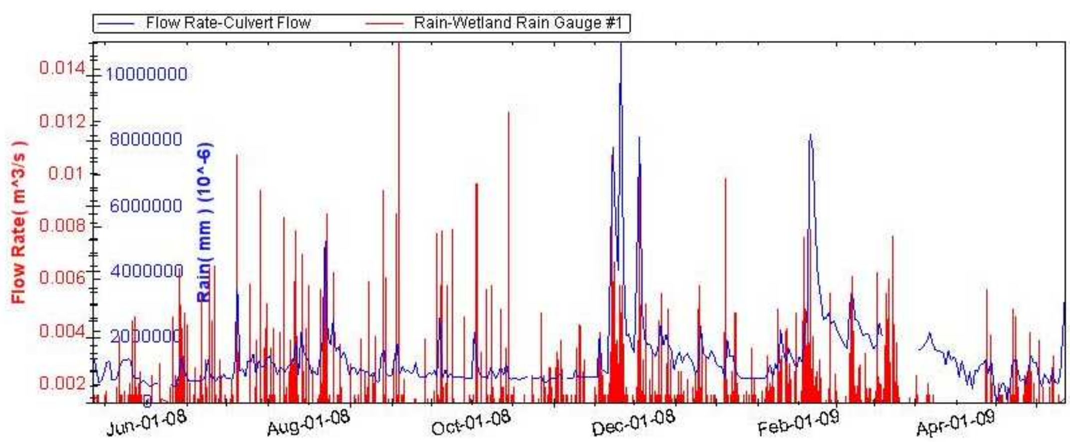


Figure 32: Flow daily average (m^3/s) with 5-min rainfall data from May 2008 to May 2009.

A zoom in Figure 18 (January, 19th to March 4th 2009) of the 15-min flow data with the 5-min rainfall data give a better view of the small delay between peak of precipitation and peak of flow. A time lag of approximately 2 day was between the peak of precipitation and the peak of flow. The hydrologic response is therefore fast implying a quick water concentration from the wetland and its catchment area.

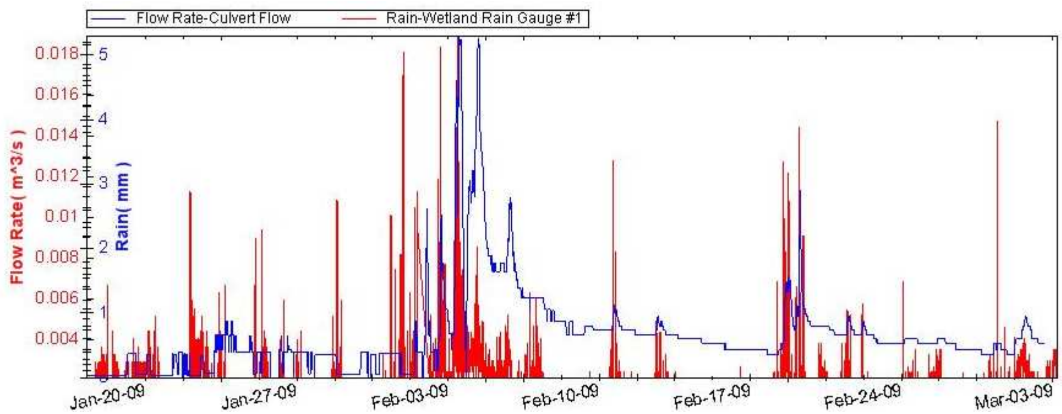


Figure33: 15-min flow data (m^3/s) with 5-min rainfall data from January 19th to March 4th.

Culvert inlet

Culvert outlet

Topographical survey

The topography of the wetland area is important information to understand the surface shape and features which drives the surface water. A topographical survey was made in May 2008 to determine the catchment area and the general relief driving the superficial flow with an optical level Topcon (AT-G6). Coordinates were calculated using angles and distance from the benchmark referenced in the cartographic map de Guácimo 3446-1 (BN, fig. 1). The 15x15 meters grid resulting from this topographical survey of 183 data points gave a very good first approximation of the wetland and the limits of its catchment area. There were however some areas that have not been covered (fig. 34, left) and therefore presented some lack of punctual information in the micro-topography that the kriging method using with Surfer was approximated with the other data points (fig. 35, left).

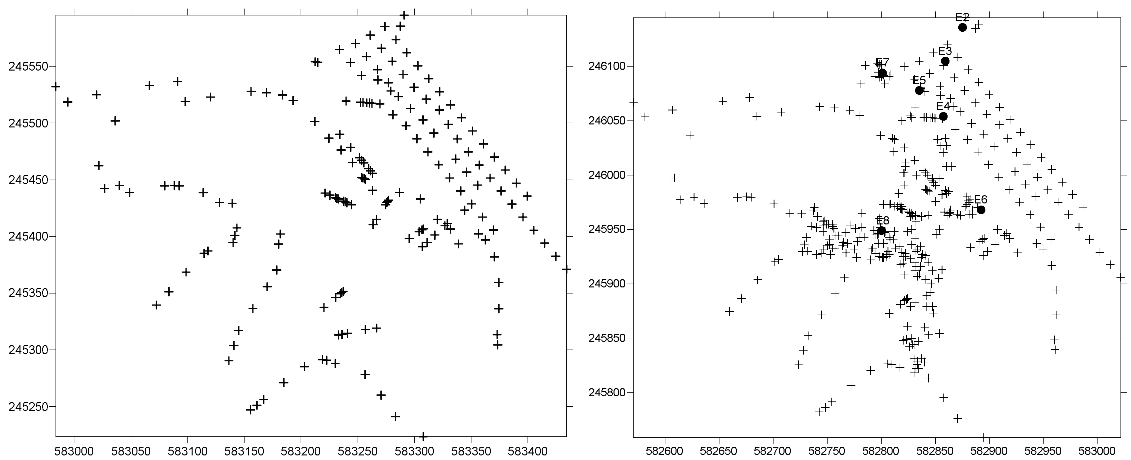


Figure 34: Data points from the survey in 2008 (left) and survey 2008 and 2009 (right).

An additional survey was therefore realized in May 2009 with a laser (CST/ Berger LaserMark LM500) to fill in those gaps and improve the knowledge of the wetland's area. Additional data points were especially located in the upstream part of the wetland and water level stations were re-surveyed (fig.34, right). The coordinates were taken with a GPS (Garmin GPSmap 60CSx) and all data points were converted to the coordinate system of Lambert North. The additional 181 data points from the 2009 survey allowed obtaining a better representation of the relief in the catchment area (9.14 ha) corresponding to the natural shape of the wetland (fig 35, right). The kriging made with Surfer to grid the topography of the wetland was improved in details to give more accurate data in the water surface and volume modeling (fig. 36).

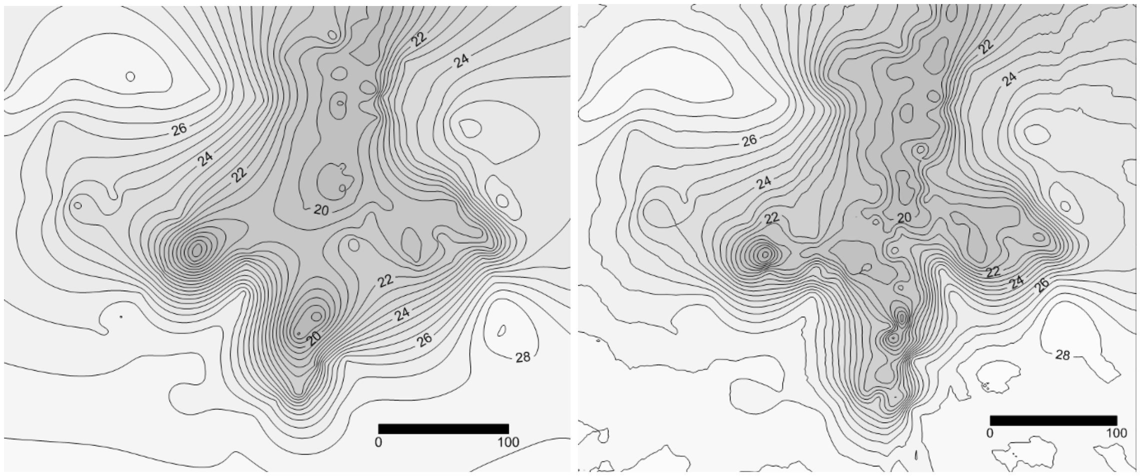


Figure 35: Contour map with the grid generated with 2008 (left) and 2008-9 points (right).

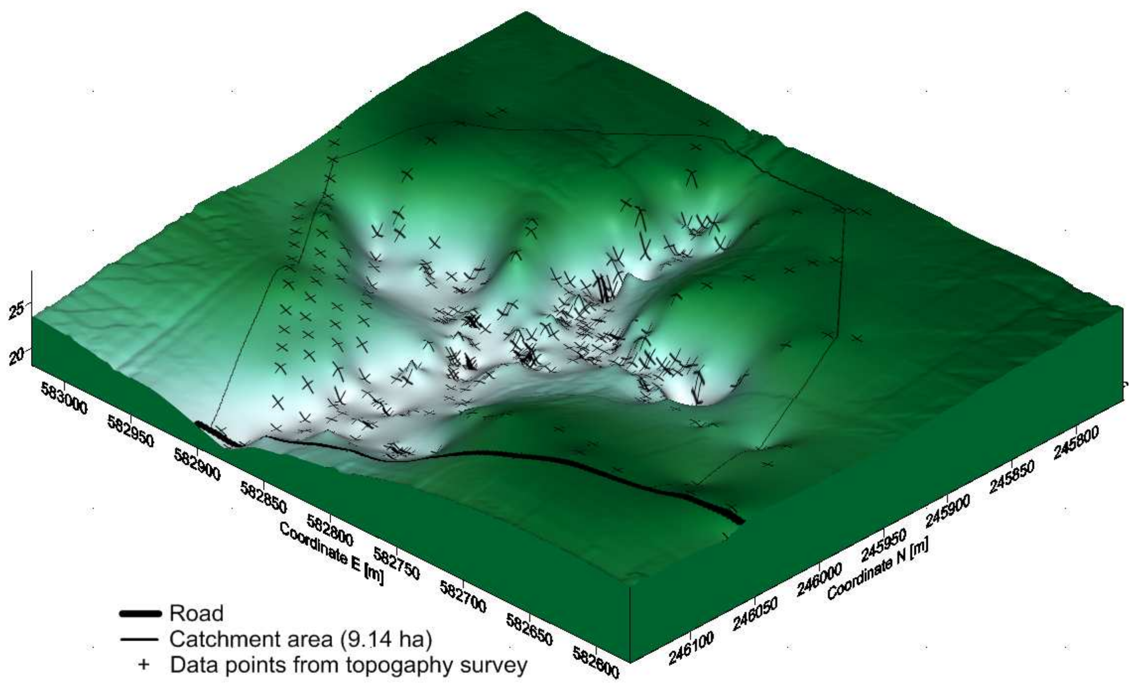


Figure 36: Representation 3D of the topography (grid generated with the kriging method in Surfer) and catchment delineation.

Optical level, survey 2008

Laser and receptor, survey 2009

Appendix 6:

Runoff estimation using the NRCS Method

Runoff is the rainfall that flows off of the surrounding upland and into the wetland. It is the fraction of precipitation coming to the soil surface from all the catchment area after that the soil reaches its full capacity of infiltration. The water volume represents the excess water draining from the catchment area to a common point. The process depends on meteorological factors (rainfall amount, intensity, duration, distribution of rainfall, antecedent precipitation and resulting soil moisture), but also on physical characteristics (land use, vegetation type and cover, soil type, drainage area, slope, etc.) and it is therefore complex to describe. The method to calculate the runoff was chosen according to the data set available in this project. The Natural Resource Conservation Service (NRCS) hydrologic method requires basic data similar to the Rational Method to compute the input of runoff from the recorded precipitation. However, the NRCS Method gives more details because it considers the time distribution of the rainfall, the initial rainfall losses by interception and infiltration (I_a) and the infiltration rate that decreases during the rainfall event (Muñoz-Carpena, R., Ritter Rodriguez, 2005). The NRCS Method implies to determine a curve numbers specific to a soil type and land cover that represents the infiltration potential of the drainage area.

The equation is:

$$Ro = \frac{(P - I_a)^2}{P - I_a + S} \qquad (10)$$

Where:
Ro = volume of accumulated runoff [m]
P = rainfall [m]
S = potential maximum retention of rainfall on the watershed at the beginning of the storm [m]
I_a = initial abstraction, including surface storage, interception, and evaporation
F = infiltration prior to runoff [m]

I_a is the estimated variable. The method gives a good approximation by taking into account soil and land cover parameters: $I_a = 0.2 * S$, where $S = \frac{25400}{CN} - 254$

Finally, the equation is: $$Ro = \frac{(P - I_a)^2}{P + 0.8 * S} \qquad (11)$$

The curve number CN can be estimated if rainfall and runoff volume are known with the corresponding curves figure or be estimated with a table if the type of soil and land cover is known. In this case study, the estimated curve number was 68 according to the forested and dense land cover and a moderate infiltration rate of the soil.

Climatic data and evapotranspiration

The daily evaporation of the wetland was estimated using the data of a weather station located in EATH University campus. The daily recorded data (solar radiation, barometric pressure, relative humidity, temperature, wind speed and orientation) allowed computing the estimated reference evapotranspiration with Penman-Monteith equation according to Allen *et al.* (1998). In 1990 the Food and Agriculture Organization (FAO) held a group of experts to revise and update the procedure of Penman-Monteith equation (1948) .From the original Penman-Monteith equation and the equations of the aerodynamic and canopy resistance, the FAO Penman-Monteith equation has been derived as following:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (12)$$

Where: ET_o : reference evapotranspiration [mm day^{-1}]
R_n : net radiation at the crop surface [MJ m^{-2} day^{-1}]
G : soil heat flux density [MJ m^{-2} day^{-1}]
T : air temperature at 2 m height [℃]
u_2 : wind speed at 2 m height [m s^{-1}]
e_s : saturation vapour pressure [kPa]
e_a : actual vapour pressure [kPa]
$e_s - e_a$: saturation vapour pressure deficit [kPa]
Δ : slope vapour pressure curve [kPa ℃$^{-1}$]
γ : psychometric constant [kPa ℃$^{-1}$]

ET_o as the reference evapotranspiration determines the evapotranspiration from the hypothetical grass reference surface. This standard evapotranspiration is estimation because only the effects of the weather variation conditions are incorporated. A more specific evapotranspiration value is the crop evapotranspiration; ET. ET is calculated by multiplying the reference crop evapotranspiration, ET_o, by a crop coefficient, K_c. The coefficient K_c varies predominately with the specific crop characteristics, which is unknown for the studied wetland. Figure 37 below shows the daily evapotranspiration for the studied period:

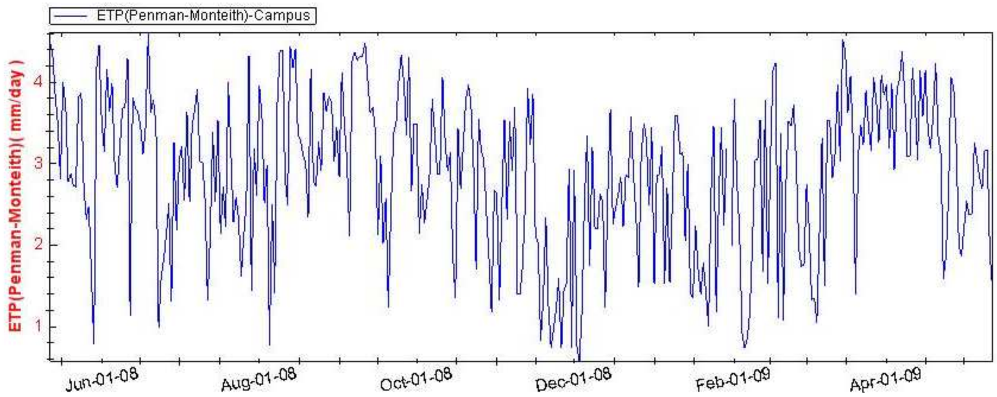


Figure 37: ET calculated for the period May 2008 to May 2009.

The calculated evapotranspiration was fund to be a little bit smaller comparing to the literature. A possible uncertainty fund in EARTH University campus is its specific overall patchy landscape above canopy. In a small scale, hotter and drier ecosystems are fund in a mosaic of forest types and land use change. The unknown crop coefficient was assumed to be 1. Moreover the weather station is located at 3 km south-west from the wetland with an elevation between 30 to 35 msm. The climatic condition can be slightly different. An interesting future step for the project could be the installation of a weather station in the wetland to compare the data or to observe directly evapotranspiration in the field to estimate the crop coefficient.

Weather station located in Earth Campus University.

Appendix 8:

Data statistics

A. Water elevation data statistics

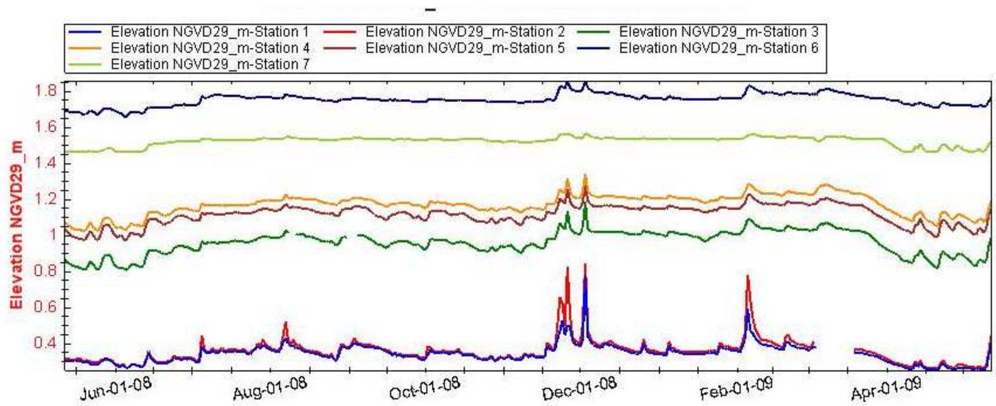


Figure 38: Overview of the water elevations for the period May 2008 to May 2009.

A.1 Water Elevation Weekly statistics

Station	Week	Min	Max	Mean	Variance	Std
Station 1						
	20(5/2008)	0.299	0.307	0.306	0	0.002
	21(5/2008)	0.283	0.314	0.295	0	0.009
	22(5/2008)	0.283	0.37	0.298	0	0.018
	23(6/2008)	0.267	0.291	0.277	0	0.006
	24(6/2008)	0.267	0.416	0.292	0.001	0.03
	25(6/2008)	0.283	0.393	0.298	0	0.019
	26(6/2008)	0.291	0.448	0.312	0.001	0.022
	27(6/2008)	0.314	0.322	0.315	0	0.003
	27(7/2008)	0.291	0.487	0.321	0.002	0.041
	28(7/2008)	0.338	0.432	0.353	0	0.013
	29(7/2008)	0.346	0.44	0.357	0	0.014
	30(7/2008)	0.33	0.401	0.354	0	0.014
	31(7/2008)	0.362	0.472	0.382	0	0.018
	31(8/2008)	0.362	0.37	0.363	0	0.003
	32(8/2008)	0.346	0.48	0.382	0.001	0.03
	33(8/2008)	0.354	0.456	0.369	0	0.017
	34(8/2008)	0.322	0.37	0.34	0	0.011
	35(8/2008)	0.307	0.511	0.341	0.002	0.043
	36(8/2008)	0.37	0.378	0.375	0	0.004
	36(9/2008)	0.37	0.535	0.392	0.001	0.025
	37(9/2008)	0.37	0.385	0.381	0	0.004
	38(9/2008)	0.307	0.456	0.35	0	0.022
	39(9/2008)	0.314	0.424	0.331	0	0.017
	40(9/2008)	0.314	0.362	0.319	0	0.011

	40(10/2008)	0.314	0.503	0.344	0.001	0.036
	41(10/2008)	0.338	0.393	0.349	0	0.009
	42(10/2008)	0.338	0.456	0.345	0	0.013
	43(10/2008)	0.314	0.338	0.323	0	0.01
	44(10/2008)	0.299	0.37	0.316	0	0.014
	44(11/2008)	0.314	0.314	0.314	0	0
	45(11/2008)	0.314	0.385	0.319	0	0.011
	46(11/2008)	0.314	0.354	0.33	0	0.011
	47(11/2008)	0.322	0.527	0.366	0.001	0.037
	48(11/2008)	0.393	0.747	0.465	0.005	0.073
	49(11/2008)	0.393	0.393	0.393	0	0
	49(12/2008)	0.378	1.131	0.473	0.031	0.177
	50(12/2008)	0.378	0.464	0.389	0	0.014
	51(12/2008)	0.354	0.393	0.372	0	0.01
	52(12/2008)	0.338	0.448	0.358	0	0.02
	53(12/2008)	0.338	0.362	0.348	0	0.006
	1(1/2009)	0.338	0.346	0.341	0	0.004
	2(1/2009)	0.338	0.464	0.358	0	0.02
	3(1/2009)	0.346	0.346	0.346	0	0
	4(1/2009)	0.33	0.401	0.347	0	0.009
	5(1/2009)	0.362	0.401	0.372	0	0.009
	6(2/2009)	0.354	0.958	0.434	0.01	0.1
	7(2/2009)	0.385	0.44	0.403	0	0.016
	8(2/2009)	0.362	0.541	0.383	0.001	0.024
	9(2/2009)	0.369	0.406	0.38	0	0.009
	10(3/2009)	0.362	0.406	0.374	0	0.011
	11(3/2009)					
	12(3/2009)	0.346	0.354	0.352	0	0.003
	13(3/2009)	0.322	0.354	0.339	0	0.007
	14(3/2009)	0.307	0.322	0.315	0	0.007
	14(4/2009)	0.283	0.307	0.292	0	0.008
	15(4/2009)	0.259	0.283	0.269	0	0.009
	16(4/2009)	0.259	0.33	0.273	0	0.017
	17(4/2009)	0.251	0.322	0.269	0	0.017
	18(4/2009)	0.259	0.267	0.263	0	0.004
	18(5/2009)	0.267	0.267	0.267	0	0
	19(5/2009)	0.259	0.267	0.262	0	0.004
	20(5/2009)	0.259	0.511	0.335	0.004	0.063

Table 7: Weekly water elevation [m] at station E1.

Station	**Week**	**Min**	**Max**	**Mean**	**Variance**	**Std**
Station 2						
	20(5/2008)	0.314	0.322	0.317	0	0.004
	21(5/2008)	0.298	0.33	0.306	0	0.008
	22(5/2008)	0.29	0.376	0.308	0	0.016
	23(6/2008)	0.267	0.298	0.281	0	0.008
	24(6/2008)	0.274	0.455	0.297	0.001	0.036
	25(6/2008)	0.29	0.424	0.305	0	0.021
	26(6/2008)	0.29	0.541	0.32	0.001	0.028
	27(6/2008)	0.322	0.338	0.324	0	0.004
	27(7/2008)	0.298	0.927	0.341	0.008	0.09

	28(7/2008)	0.353	0.487	0.363	0	0.016
	29(7/2008)	0.353	0.518	0.369	0	0.018
	30(7/2008)	0.338	0.424	0.364	0	0.016
	31(7/2008)	0.376	0.754	0.399	0.002	0.044
	31(8/2008)	0.369	0.385	0.373	0	0.006
	32(8/2008)	0.361	0.872	0.407	0.005	0.072
	33(8/2008)	0.361	0.636	0.384	0.001	0.03
	34(8/2008)	0.33	0.376	0.35	0	0.011
	35(8/2008)	0.314	0.746	0.352	0.003	0.057
	36(8/2008)	0.376	0.385	0.381	0	0.004
	36(9/2008)	0.376	0.841	0.403	0.002	0.047
	37(9/2008)	0.376	0.393	0.388	0	0.006
	38(9/2008)	0.306	0.605	0.356	0.001	0.03
	39(9/2008)	0.322	0.463	0.337	0	0.019
	40(9/2008)	0.322	0.369	0.326	0	0.011
	40(10/2008)	0.322	0.95	0.362	0.008	0.09
	41(10/2008)	0.345	0.424	0.356	0	0.011
	42(10/2008)	0.345	0.589	0.354	0	0.021
	43(10/2008)	0.314	0.345	0.327	0	0.012
	44(10/2008)	0.314	0.385	0.323	0	0.015
	44(11/2008)	0.314	0.322	0.316	0	0.004
	45(11/2008)	0.314	0.401	0.324	0	0.013
	46(11/2008)	0.322	0.361	0.336	0	0.012
	47(11/2008)	0.33	0.95	0.384	0.006	0.075
	48(11/2008)	0.416	0.95	0.575	0.033	0.183
	49(11/2008)	0.408	0.416	0.409	0	0.003
	49(12/2008)	0.393	0.958	0.512	0.034	0.186
	50(12/2008)	0.385	0.565	0.406	0.001	0.023
	51(12/2008)	0.369	0.408	0.385	0	0.011
	52(12/2008)	0.353	0.518	0.371	0.001	0.027
	53(12/2008)	0.353	0.369	0.362	0	0.005
	1(1/2009)	0.345	0.353	0.351	0	0.003
	2(1/2009)	0.345	0.565	0.369	0.001	0.027
	3(1/2009)	0.353	0.353	0.353	0	0
	4(1/2009)	0.338	0.424	0.356	0	0.011
	5(1/2009)	0.369	0.432	0.386	0	0.013
	6(2/2009)	0.361	0.95	0.51	0.027	0.166
	7(2/2009)	0.408	0.495	0.433	0.001	0.025
	8(2/2009)	0.376	0.707	0.407	0.001	0.039
	9(2/2009)	0.385	0.44	0.401	0	0.012
	10(3/2009)	0.376	0.44	0.392	0	0.016
	11(3/2009)					
	12(3/2009)	0.361	0.376	0.369	0	0.002
	13(3/2009)	0.338	0.369	0.355	0	0.009
	14(3/2009)	0.314	0.338	0.33	0	0.007
	14(4/2009)	0.29	0.314	0.305	0	0.008
	15(4/2009)	0.274	0.29	0.281	0	0.007
	16(4/2009)	0.267	0.345	0.282	0	0.02
	17(4/2009)	0.259	0.345	0.279	0	0.02
	18(4/2009)	0.267	0.29	0.276	0	0.008
	18(5/2009)	0.274	0.282	0.28	0	0.004
	19(5/2009)	0.267	0.29	0.271	0	0.005

	20(5/2009)	0.267	0.73	0.363	0.008	0.088

Table 8: Weekly water elevation [m] at station E2.

Station	**Week**	**Min**	**Max**	**Mean**	**Variance**	**Std**
Station 3						
	20(5/2008)	0.821	0.869	0.839	0	0.013
	21(5/2008)	0.806	0.861	0.829	0	0.017
	22(5/2008)	0.806	0.916	0.862	0.001	0.035
	23(6/2008)	0.806	0.837	0.822	0	0.01
	24(6/2008)	0.821	0.939	0.851	0.001	0.033
	25(6/2008)	0.892	0.931	0.909	0	0.01
	26(6/2008)	0.892	0.979	0.93	0	0.017
	27(6/2008)	0.931	0.939	0.934	0	0.004
	27(7/2008)	0.908	1.073	0.93	0.001	0.027
	28(7/2008)	0.955	0.994	0.961	0	0.005
	29(7/2008)	0.955	1.002	0.967	0	0.006
	30(7/2008)	0.963	0.987	0.968	0	0.007
	31(7/2008)	0.979	1.057	0.992	0	0.01
	31(8/2008)	0.987	0.994	0.989	0	0.003
	32(8/2008)	0.987	1.081	1.002	0	0.018
	33(8/2008)	0.994	1.042	1.003	0	0.009
	34(8/2008)	0.963	0.994	0.979	0	0.011
	35(8/2008)	0.931	1.05	0.969	0	0.022
	36(8/2008)	0.987	0.994	0.99	0	0.004
	36(9/2008)	0.987	1.01	1.003	0	0.004
	37(9/2008)	0.947	1.002	0.974	0	0.018
	38(9/2008)	0.931	1.034	0.949	0	0.019
	39(9/2008)	0.939	1.01	0.962	0	0.012
	40(9/2008)	0.923	0.971	0.942	0	0.013
	40(10/2008)	0.916	1.152	0.956	0.002	0.04
	41(10/2008)	0.955	0.994	0.972	0	0.008
	42(10/2008)	0.939	1.025	0.96	0	0.01
	43(10/2008)	0.908	0.947	0.925	0	0.011
	44(10/2008)	0.908	0.963	0.927	0	0.015
	44(11/2008)	0.923	0.931	0.93	0	0.003
	45(11/2008)	0.9	0.979	0.928	0	0.018
	46(11/2008)	0.9	0.963	0.943	0	0.012
	47(11/2008)	0.923	1.214	0.971	0.001	0.034
	48(11/2008)	1.01	1.277	1.054	0.003	0.051
	49(11/2008)	1.01	1.01	1.01	0	0
	49(12/2008)	1.002	1.348	1.054	0.006	0.079
	50(12/2008)	1.018	1.057	1.02	0	0.006
	51(12/2008)	1.01	1.025	1.017	0	0.004
	52(12/2008)	1.002	1.057	1.014	0	0.008
	53(12/2008)	1.01	1.018	1.014	0	0.004
	1(1/2009)	0.994	1.01	1.006	0	0.005
	2(1/2009)	0.994	1.065	1.013	0	0.011
	3(1/2009)	0.979	1.01	0.998	0	0.008
	4(1/2009)	0.963	1.018	0.985	0	0.012
	5(1/2009)	1.01	1.018	1.015	0	0.004
	6(2/2009)	1.01	1.19	1.049	0.001	0.038

	7(2/2009)	1.034	1.065	1.045	0	0.008
	8(2/2009)	1.025	1.104	1.034	0	0.013
	9(2/2009)	1.034	1.05	1.037	0	0.005
	10(3/2009)	1.025	1.096	1.045	0	0.018
	11(3/2009)	1.034	1.089	1.052	0	0.013
	12(3/2009)	1.025	1.034	1.029	0	0.004
	13(3/2009)	0.955	1.025	0.999	0	0.022
	14(3/2009)	0.923	0.955	0.942	0	0.009
	14(4/2009)	0.9	0.923	0.912	0	0.008
	15(4/2009)	0.837	0.9	0.866	0	0.016
	16(4/2009)	0.837	0.939	0.884	0.001	0.024
	17(4/2009)	0.821	0.939	0.867	0.001	0.038
	18(4/2009)	0.861	0.9	0.885	0	0.014
	18(5/2009)	0.877	0.9	0.884	0	0.008
	19(5/2009)	0.829	0.885	0.852	0	0.017
	20(5/2009)	0.837	1.042	0.93	0.003	0.057

Table 9: Weekly water elevation [m] at station E3.

Station	**Week**	**Min**	**Max**	**Mean**	**Variance**	**Std**
Station 4						
	20(5/2008)	1.034	1.082	1.049	0	0.016
	21(5/2008)	1.027	1.082	1.042	0	0.018
	22(5/2008)	1.019	1.129	1.075	0.001	0.03
	23(6/2008)	1.027	1.066	1.045	0	0.012
	24(6/2008)	1.042	1.152	1.073	0.001	0.028
	25(6/2008)	1.105	1.152	1.122	0	0.009
	26(6/2008)	1.113	1.192	1.14	0	0.015
	27(6/2008)	1.144	1.152	1.147	0	0.004
	27(7/2008)	1.129	1.27	1.146	0	0.021
	28(7/2008)	1.16	1.2	1.167	0	0.005
	29(7/2008)	1.16	1.207	1.169	0	0.005
	30(7/2008)	1.168	1.192	1.173	0	0.005
	31(7/2008)	1.184	1.255	1.194	0	0.01
	31(8/2008)	1.192	1.192	1.192	0	0
	32(8/2008)	1.192	1.278	1.204	0	0.015
	33(8/2008)	1.2	1.247	1.205	0	0.006
	34(8/2008)	1.176	1.2	1.192	0	0.007
	35(8/2008)	1.16	1.255	1.181	0	0.015
	36(8/2008)	1.192	1.192	1.192	0	0
	36(9/2008)	1.192	1.286	1.205	0	0.011
	37(9/2008)	1.176	1.207	1.192	0	0.01
	38(9/2008)	1.16	1.238	1.171	0	0.012
	39(9/2008)	1.16	1.215	1.179	0	0.009
	40(9/2008)	1.152	1.176	1.164	0	0.007
	40(10/2008)	1.144	1.317	1.173	0.001	0.029
	41(10/2008)	1.168	1.192	1.181	0	0.006
	42(10/2008)	1.16	1.231	1.173	0	0.007
	43(10/2008)	1.136	1.168	1.15	0	0.008
	44(10/2008)	1.136	1.168	1.145	0	0.008
	44(11/2008)	1.144	1.144	1.144	0	0
	45(11/2008)	1.121	1.176	1.144	0	0.011

	46(11/2008)	1.121	1.16	1.151	0	0.006
	47(11/2008)	1.144	1.38	1.172	0.001	0.026
	48(11/2008)	1.207	1.427	1.248	0.002	0.042
	49(11/2008)	1.207	1.207	1.207	0	0
	49(12/2008)	1.207	1.474	1.249	0.003	0.055
	50(12/2008)	1.215	1.255	1.219	0	0.007
	51(12/2008)	1.207	1.223	1.214	0	0.004
	52(12/2008)	1.2	1.255	1.209	0	0.008
	53(12/2008)	1.207	1.215	1.208	0	0.003
	1(1/2009)	1.207	1.207	1.207	0	0
	2(1/2009)	1.2	1.263	1.212	0	0.008
	3(1/2009)	1.192	1.207	1.203	0	0.005
	4(1/2009)	1.176	1.207	1.19	0	0.006
	5(1/2009)	1.207	1.215	1.209	0	0.004
	6(2/2009)	1.207	1.372	1.244	0.001	0.035
	7(2/2009)	1.231	1.263	1.239	0	0.009
	8(2/2009)	1.223	1.294	1.232	0	0.01
	9(2/2009)	1.231	1.238	1.234	0	0.004
	10(3/2009)	1.223	1.309	1.249	0.001	0.024
	11(3/2009)	1.247	1.302	1.265	0	0.013
	12(3/2009)	1.231	1.247	1.238	0	0.007
	13(3/2009)	1.176	1.231	1.21	0	0.017
	14(3/2009)	1.144	1.176	1.164	0	0.009
	14(4/2009)	1.121	1.144	1.136	0	0.008
	15(4/2009)	1.074	1.121	1.097	0	0.013
	16(4/2009)	1.074	1.144	1.106	0.001	0.023
	17(4/2009)	1.05	1.144	1.095	0.001	0.035
	18(4/2009)	1.082	1.121	1.105	0	0.013
	18(5/2009)	1.098	1.113	1.102	0	0.006
	19(5/2009)	1.066	1.105	1.084	0	0.012
	20(5/2009)	1.066	1.238	1.147	0.002	0.046

Table 10: Weekly water elevation [m] at station E4.

Station	**Week**	**Min**	**Max**	**Mean**	**Variance**	**Std**
Station 5						
	20(5/2008)	0.982	1.046	1.005	0	0.018
	21(5/2008)	0.975	1.03	0.994	0	0.019
	22(5/2008)	0.967	1.084	1.029	0.001	0.034
	23(6/2008)	0.967	1.022	0.994	0	0.016
	24(6/2008)	0.982	1.108	1.023	0.001	0.034
	25(6/2008)	1.053	1.108	1.079	0	0.013
	26(6/2008)	1.061	1.14	1.097	0	0.017
	27(6/2008)	1.092	1.108	1.102	0	0.005
	27(7/2008)	1.069	1.203	1.094	0.001	0.023
	28(7/2008)	1.108	1.148	1.12	0	0.005
	29(7/2008)	1.108	1.155	1.125	0	0.007
	30(7/2008)	1.116	1.14	1.126	0	0.006
	31(7/2008)	1.14	1.195	1.146	0	0.008
	31(8/2008)	1.14	1.148	1.142	0	0.003
	32(8/2008)	1.14	1.218	1.152	0	0.014
	33(8/2008)	1.148	1.195	1.153	0	0.006

	34(8/2008)	1.116	1.148	1.13	0	0.009
	35(8/2008)	1.092	1.195	1.125	0	0.019
	36(8/2008)	1.148	1.148	1.148	0	0
	36(9/2008)	1.148	1.226	1.157	0	0.009
	37(9/2008)	1.1	1.155	1.129	0	0.02
	38(9/2008)	1.084	1.186	1.105	0	0.019
	39(9/2008)	1.092	1.163	1.118	0	0.014
	40(9/2008)	1.084	1.124	1.098	0	0.011
	40(10/2008)	1.077	1.257	1.112	0.001	0.034
	41(10/2008)	1.108	1.155	1.131	0	0.01
	42(10/2008)	1.1	1.179	1.117	0	0.01
	43(10/2008)	1.069	1.1	1.082	0	0.008
	44(10/2008)	1.061	1.124	1.084	0	0.015
	44(11/2008)	1.077	1.092	1.079	0	0.004
	45(11/2008)	1.053	1.132	1.08	0	0.018
	46(11/2008)	1.053	1.116	1.097	0	0.011
	47(11/2008)	1.069	1.319	1.121	0.001	0.027
	48(11/2008)	1.152	1.364	1.191	0.002	0.041
	49(11/2008)	1.152	1.152	1.152	0	0
	49(12/2008)	1.152	1.409	1.192	0.003	0.053
	50(12/2008)	1.16	1.198	1.164	0	0.006
	51(12/2008)	1.152	1.167	1.159	0	0.004
	52(12/2008)	1.145	1.198	1.153	0	0.008
	53(12/2008)	1.152	1.16	1.153	0	0.003
	1(1/2009)	1.152	1.152	1.152	0	0
	2(1/2009)	1.145	1.206	1.157	0	0.008
	3(1/2009)	1.138	1.152	1.148	0	0.005
	4(1/2009)	1.122	1.152	1.136	0	0.006
	5(1/2009)	1.152	1.16	1.154	0	0.003
	6(2/2009)	1.152	1.311	1.188	0.001	0.034
	7(2/2009)	1.175	1.206	1.183	0	0.009
	8(2/2009)	1.167	1.236	1.176	0	0.01
	9(2/2009)	1.171	1.182	1.179	0	0.003
	10(3/2009)	1.171	1.226	1.185	0	0.015
	11(3/2009)	1.179	1.218	1.193	0	0.011
	12(3/2009)	1.171	1.179	1.173	0	0.003
	13(3/2009)	1.108	1.171	1.142	0	0.019
	14(3/2009)	1.084	1.108	1.098	0	0.008
	14(4/2009)	1.053	1.084	1.071	0	0.009
	15(4/2009)	1.006	1.053	1.031	0	0.013
	16(4/2009)	1.006	1.108	1.05	0.001	0.027
	17(4/2009)	0.99	1.108	1.04	0.002	0.041
	18(4/2009)	1.022	1.084	1.053	0	0.019
	18(5/2009)	1.038	1.061	1.045	0	0.006
	19(5/2009)	0.998	1.061	1.022	0	0.016
	20(5/2009)	1.006	1.195	1.102	0.002	0.049

Table 11: Weekly water elevation [m] at station E5.

Station	Week	Min	Max	Mean	Variance	Std
Station 6						
	20(5/2008)	1.686	1.694	1.688	0	0.003
	21(5/2008)	1.67	1.694	1.682	0	0.008
	22(5/2008)	1.662	1.726	1.695	0	0.014
	23(6/2008)	1.647	1.694	1.676	0	0.013
	24(6/2008)	1.67	1.741	1.69	0	0.013
	25(6/2008)	1.702	1.741	1.71	0	0.004
	26(6/2008)	1.71	1.773	1.722	0	0.009
	27(6/2008)	1.726	1.726	1.726	0	0
	27(7/2008)	1.726	1.859	1.737	0.001	0.023
	28(7/2008)	1.764	1.804	1.774	0	0.007
	29(7/2008)	1.773	1.812	1.774	0	0.004
	30(7/2008)	1.764	1.789	1.767	0	0.004
	31(7/2008)	1.764	1.812	1.771	0	0.007
	31(8/2008)	1.764	1.773	1.766	0	0.003
	32(8/2008)	1.757	1.812	1.77	0	0.011
	33(8/2008)	1.764	1.812	1.769	0	0.005
	34(8/2008)	1.749	1.764	1.757	0	0.006
	35(8/2008)	1.741	1.812	1.75	0	0.01
	36(8/2008)	1.757	1.757	1.757	0	0
	36(9/2008)	1.749	1.859	1.762	0	0.009
	37(9/2008)	1.749	1.764	1.757	0	0.004
	38(9/2008)	1.749	1.812	1.75	0	0.006
	39(9/2008)	1.741	1.789	1.748	0	0.005
	40(9/2008)	1.741	1.757	1.743	0	0.004
	40(10/2008)	1.741	1.875	1.753	0	0.017
	41(10/2008)	1.749	1.773	1.753	0	0.004
	42(10/2008)	1.749	1.804	1.75	0	0.005
	43(10/2008)	1.741	1.749	1.748	0	0.003
	44(10/2008)	1.741	1.764	1.743	0	0.004
	44(11/2008)	1.741	1.741	1.741	0	0
	45(11/2008)	1.733	1.764	1.741	0	0.005
	46(11/2008)	1.733	1.749	1.741	0	0.002
	47(11/2008)	1.741	1.898	1.754	0	0.018
	48(11/2008)	1.796	1.898	1.823	0	0.021
	49(11/2008)	1.804	1.804	1.804	0	0
	49(12/2008)	1.796	1.914	1.817	0.001	0.025
	50(12/2008)	1.789	1.835	1.795	0	0.005
	51(12/2008)	1.773	1.796	1.782	0	0.007
	52(12/2008)	1.757	1.828	1.767	0	0.009
	53(12/2008)	1.764	1.764	1.764	0	0
	1(1/2009)	1.757	1.764	1.761	0	0.004
	2(1/2009)	1.757	1.828	1.764	0	0.008
	3(1/2009)	1.749	1.757	1.757	0	0.001
	4(1/2009)	1.749	1.773	1.757	0	0.003
	5(1/2009)	1.757	1.773	1.765	0	0.002
	6(2/2009)	1.757	1.883	1.793	0.001	0.032
	7(2/2009)	1.789	1.82	1.798	0	0.008
	8(2/2009)	1.781	1.859	1.788	0	0.009
	9(2/2009)	1.781	1.804	1.789	0	0.003
	10(3/2009)	1.781	1.835	1.794	0	0.013

	11(3/2009)	1.789	1.828	1.805	0	0.009
	12(3/2009)	1.773	1.796	1.783	0	0.007
	13(3/2009)	1.764	1.773	1.767	0	0.004
	14(3/2009)	1.757	1.764	1.763	0	0.003
	14(4/2009)	1.749	1.757	1.751	0	0.004
	15(4/2009)	1.718	1.749	1.735	0	0.009
	16(4/2009)	1.718	1.749	1.728	0	0.008
	17(4/2009)	1.71	1.749	1.723	0	0.012
	18(4/2009)	1.718	1.733	1.724	0	0.003
	18(5/2009)	1.726	1.726	1.726	0	0
	19(5/2009)	1.71	1.726	1.72	0	0.006
	20(5/2009)	1.71	1.812	1.744	0	0.022

Table 12: Weekly water elevation [m] at station E6.

Station	Week	Min	Max	Mean	Variance	Std
Station 7						
	20(5/2008)	1.467	1.467	1.467	0	0
	21(5/2008)	1.467	1.474	1.468	0	0.002
	22(5/2008)	1.467	1.488	1.477	0	0.009
	23(6/2008)	1.467	1.467	1.467	0	0
	24(6/2008)	1.467	1.509	1.474	0	0.012
	25(6/2008)	1.502	1.516	1.51	0	0.004
	26(6/2008)	1.516	1.524	1.521	0	0.003
	27(6/2008)	1.524	1.524	1.524	0	0
	27(7/2008)	1.524	1.545	1.527	0	0.006
	28(7/2008)	1.531	1.538	1.534	0	0.003
	29(7/2008)	1.531	1.538	1.532	0	0.002
	30(7/2008)	1.531	1.538	1.531	0	0.001
	31(7/2008)	1.538	1.545	1.539	0	0.003
	31(8/2008)	1.538	1.538	1.538	0	0
	32(8/2008)	1.538	1.552	1.543	0	0.007
	33(8/2008)	1.538	1.552	1.54	0	0.003
	34(8/2008)	1.531	1.538	1.534	0	0.003
	35(8/2008)	1.531	1.545	1.533	0	0.004
	36(8/2008)	1.538	1.538	1.538	0	0
	36(9/2008)	1.538	1.559	1.541	0	0.004
	37(9/2008)	1.538	1.538	1.538	0	0
	38(9/2008)	1.531	1.545	1.536	0	0.003
	39(9/2008)	1.531	1.538	1.534	0	0.003
	40(9/2008)	1.531	1.531	1.531	0	0
	40(10/2008)	1.531	1.552	1.535	0	0.005
	41(10/2008)	1.531	1.538	1.534	0	0.003
	42(10/2008)	1.531	1.538	1.535	0	0.003
	43(10/2008)	1.531	1.538	1.536	0	0.003
	44(10/2008)	1.509	1.531	1.523	0	0.003
	44(11/2008)	1.509	1.524	1.518	0	0.003
	45(11/2008)	1.509	1.524	1.522	0	0.003
	46(11/2008)	1.502	1.524	1.521	0	0.004
	47(11/2008)	1.524	1.566	1.529	0	0.006
	48(11/2008)	1.531	1.573	1.558	0	0.008
	49(11/2008)	1.545	1.545	1.545	0	0

	49(12/2008)	1.531	1.58	1.552	0	0.011
	50(12/2008)	1.538	1.545	1.542	0	0.004
	51(12/2008)	1.538	1.545	1.538	0	0.002
	52(12/2008)	1.538	1.545	1.538	0	0.002
	53(12/2008)	1.538	1.538	1.538	0	0
	1(1/2009)	1.538	1.538	1.538	0	0
	2(1/2009)	1.538	1.545	1.538	0	0.002
	3(1/2009)	1.538	1.538	1.538	0	0
	4(1/2009)	1.531	1.538	1.536	0	0.003
	5(1/2009)	1.531	1.538	1.537	0	0.002
	6(2/2009)	1.538	1.566	1.548	0	0.01
	7(2/2009)	1.545	1.559	1.553	0	0.004
	8(2/2009)	1.545	1.559	1.547	0	0.003
	9(2/2009)	1.545	1.552	1.548	0	0.004
	10(3/2009)	1.516	1.552	1.537	0	0.01
	11(3/2009)	1.516	1.552	1.551	0	0.004
	12(3/2009)	1.516	1.552	1.541	0	0.005
	13(3/2009)	1.538	1.538	1.538	0	0
	14(3/2009)	1.524	1.538	1.535	0	0.005
	14(4/2009)	1.481	1.524	1.508	0	0.014
	15(4/2009)	1.467	1.495	1.472	0	0.009
	16(4/2009)	1.467	1.509	1.482	0	0.018
	17(4/2009)	1.467	1.509	1.485	0	0.018
	18(4/2009)	1.467	1.495	1.486	0	0.012
	18(5/2009)	1.467	1.488	1.473	0	0.007
	19(5/2009)	1.467	1.495	1.469	0	0.007
	20(5/2009)	1.467	1.531	1.502	0	0.017

Table 13: Weekly water elevation [m] at station E7.

A.2 Water Elevation Monthly statistics

Station	Week	Min	Max	Mean	Variance	Std
Station 1						
	mai.08	0.283	0.37	0.299	0	0.012
	juin.08	0.267	0.448	0.296	0.001	0.024
	juil.08	0.291	0.487	0.354	0.001	0.028
	août.08	0.307	0.511	0.359	0.001	0.032
	sept.08	0.307	0.535	0.358	0.001	0.032
	oct.08	0.299	0.503	0.335	0	0.022
	nov.08	0.314	0.747	0.369	0.005	0.07
	déc.08	0.338	1.131	0.389	0.008	0.09
	janv.09	0.33	0.464	0.354	0	0.016
	févr.09	0.354	0.958	0.4	0.003	0.056
	mars.09	0.307	0.406	0.344	0	0.02
	avr.09	0.251	0.33	0.272	0	0.015
	mai.09	0.259	0.511	0.281	0.002	0.044
Station 2						
	mai.08	0.29	0.376	0.31	0	0.012
	juin.08	0.267	0.541	0.304	0.001	0.029
	juil.08	0.298	0.927	0.367	0.002	0.046
	août.08	0.314	0.872	0.373	0.003	0.051
	sept.08	0.306	0.841	0.365	0.002	0.039
	oct.08	0.314	0.95	0.343	0.001	0.039
	nov.08	0.314	0.95	0.402	0.019	0.138
	déc.08	0.353	0.958	0.408	0.01	0.099
	janv.09	0.338	0.565	0.365	0	0.02
	févr.09	0.361	0.95	0.438	0.009	0.096
	mars.09	0.314	0.44	0.361	0	0.022
	avr.09	0.259	0.345	0.283	0	0.017
	mai.09	0.267	0.73	0.296	0.003	0.059
Station 3						
	mai.08	0.806	0.916	0.844	0.001	0.028
	juin.08	0.806	0.979	0.882	0.002	0.048
	juil.08	0.908	1.073	0.964	0	0.022
	août.08	0.931	1.081	0.988	0	0.021
	sept.08	0.923	1.034	0.964	0.001	0.023
	oct.08	0.908	1.152	0.948	0.001	0.026
	nov.08	0.9	1.277	0.974	0.003	0.057
	déc.08	1.002	1.348	1.024	0.001	0.038
	janv.09	0.963	1.065	1.003	0	0.015
	févr.09	1.01	1.19	1.041	0	0.021
	mars.09	0.923	1.096	1.023	0.001	0.036
	avr.09	0.821	0.939	0.88	0.001	0.028
	mai.09	0.829	1.042	0.876	0.002	0.046

Table 14: Monthly water elevation [m] at station E1, E2 and E3.

Station	Week	Min	Max	Mean	Variance	Std
Station 4						
	mai.08	1.019	1.129	1.056	0.001	0.026
	juin.08	1.027	1.192	1.1	0.002	0.042
	juil.08	1.129	1.27	1.17	0	0.017
	août.08	1.16	1.278	1.195	0	0.014
	sept.08	1.152	1.286	1.184	0	0.017
	oct.08	1.136	1.317	1.164	0	0.019
	nov.08	1.121	1.427	1.178	0.002	0.048
	déc.08	1.2	1.474	1.22	0.001	0.029
	janv.09	1.176	1.263	1.204	0	0.01
	févr.09	1.207	1.372	1.237	0	0.02
	mars.09	1.144	1.309	1.233	0.001	0.034
	avr.09	1.05	1.144	1.105	0.001	0.025
	mai.09	1.066	1.238	1.103	0.001	0.036
Station 5						
	mai.08	0.967	1.084	1.01	0.001	0.029
	juin.08	0.967	1.14	1.052	0.002	0.047
	juil.08	1.069	1.203	1.122	0	0.018
	août.08	1.092	1.218	1.14	0	0.017
	sept.08	1.084	1.226	1.124	0.001	0.025
	oct.08	1.061	1.257	1.105	0.001	0.026
	nov.08	1.053	1.364	1.122	0.002	0.049
	déc.08	1.145	1.409	1.164	0.001	0.028
	janv.09	1.122	1.206	1.149	0	0.009
	févr.09	1.152	1.311	1.181	0	0.019
	mars.09	1.084	1.226	1.166	0.001	0.032
	avr.09	0.99	1.108	1.047	0.001	0.029
	mai.09	0.998	1.195	1.046	0.002	0.044
Station 6						
	mai.08	1.662	1.726	1.688	0	0.012
	juin.08	1.647	1.773	1.702	0	0.02
	juil.08	1.726	1.859	1.766	0	0.017
	août.08	1.741	1.812	1.761	0	0.011
	sept.08	1.741	1.859	1.753	0	0.009
	oct.08	1.741	1.875	1.749	0	0.008
	nov.08	1.733	1.898	1.765	0.001	0.037
	déc.08	1.757	1.914	1.786	0.001	0.023
	janv.09	1.749	1.828	1.761	0	0.005
	févr.09	1.757	1.883	1.792	0	0.018
	mars.09	1.757	1.835	1.785	0	0.017
	avr.09	1.71	1.757	1.731	0	0.012
	mai.09	1.71	1.812	1.727	0	0.016
Station 7						
	mai.08	1.467	1.488	1.471	0	0.007
	juin.08	1.467	1.524	1.495	0.001	0.024
	juil.08	1.524	1.545	1.532	0	0.005
	août.08	1.531	1.552	1.537	0	0.006
	sept.08	1.531	1.559	1.536	0	0.004
	oct.08	1.509	1.552	1.533	0	0.006
	nov.08	1.502	1.573	1.532	0	0.016
	déc.08	1.531	1.58	1.542	0	0.007
	janv.09	1.531	1.545	1.537	0	0.002

	févr.09	1.538	1.566	1.549	0	0.006
	mars.09	1.516	1.552	1.541	0	0.008
	avr.09	1.467	1.524	1.485	0	0.018
	mai.09	1.467	1.531	1.478	0	0.017

Table 15: Monthly water elevation [m] at station E4, E5, E6 and E7.

B. Precipitation Data Statistics

B.1 Precipitation Weekly statistics

Station	Month	Sum	Max	Mean	Variance	Std
Wetland Rain Gauge #1						
	20(5/2008)	2.524	1.082	0.421	0.23	0.479
	21(5/2008)	23.073	16.343	3.296	35.996	6
	22(5/2008)	74.386	26.077	10.627	126.502	11.247
	23(6/2008)	11.296	6.129	1.883	6.941	2.635
	24(6/2008)	113.802	49.871	18.967	385.9	19.644
	25(6/2008)	32.326	14.3	4.618	23.447	4.842
	26(6/2008)	80.154	35.571	11.451	143.821	11.993
	27(6/2008)	5.648	3.725	2.824	1.625	1.275
	27(7/2008)	101.424	70.54	20.285	905.575	30.093
	28(7/2008)	45.425	33.888	6.489	155.101	12.454
	29(7/2008)	86.523	28	12.36	98.6	9.93
	30(7/2008)	102.265	26.197	14.609	89.533	9.462
	31(7/2008)	91.931	50.832	18.386	396.932	19.923
	31(8/2008)	3.245	3.245	1.622	5.264	2.294
	32(8/2008)	165.475	87.965	23.639	1132.114	33.647
	33(8/2008)	60.806	29.802	8.687	174.518	13.211
	34(8/2008)	28.48	12.858	4.069	26.386	5.137
	35(8/2008)	120.291	47.227	17.184	438.245	20.934
	36(8/2008)	0	0	0		
	36(9/2008)	86.643	44.583	14.441	342.444	18.505
	37(9/2008)	4.326	3.966	0.618	2.197	1.482
	38(9/2008)	80.514	39.776	11.502	271.306	16.471
	39(9/2008)	41.819	23.433	5.974	105.49	10.271
	40(9/2008)	8.532	8.172	2.844	21.32	4.617
	40(10/2008)	91.81	87.604	22.953	1861.01	43.139
	41(10/2008)	38.094	19.588	5.442	58.119	7.624
	42(10/2008)	50.472	30.163	7.21	115.494	10.747
	43(10/2008)	2.884	1.562	0.412	0.413	0.643
	44(10/2008)	50.832	17.545	8.472	45.765	6.765
	44(11/2008)	12.498	12.498	12.498		
	45(11/2008)	26.918	18.626	3.845	48.011	6.929
	46(11/2008)	59.845	24.274	8.549	89.132	9.441
	47(11/2008)	221.595	109.355	31.656	1997.005	44.688
	48(11/2008)	397.525	172.445	56.789	4910.468	70.075
	49(11/2008)	2.764	2.764	2.764		
	49(12/2008)	288.049	138.076	48.008	4413.462	66.434
	50(12/2008)	110.076	40.137	15.725	237.86	15.423
	51(12/2008)	14.541	4.687	2.077	3.869	1.967
	52(12/2008)	94.815	68.617	13.545	613.322	24.765
	53(12/2008)	7.33	3.725	1.833	2.93	1.712
	1(1/2009)	0	0	0	0	0
	2(1/2009)	94.094	72.102	13.442	683.489	26.144

	3(1/2009)	11.897	5.288	1.7	3.651	1.911
	4(1/2009)	124.136	40.618	17.734	170.985	13.076
	5(1/2009)	50.952	12.738	7.279	27.967	5.288
	6(2/2009)	371.036	145.531	53.005	2145.188	46.316
	7(2/2009)	53.105	21.207	7.586	87.138	9.335
	8(2/2009)	96.579	72.456	13.797	726.892	26.961
	9(2/2009)	28.452	8.748	4.065	12.201	3.493
	10(3/2009)	213.835	97.728	30.548	1038.992	32.233
	11(3/2009)	110.098	82.971	15.728	969.866	31.143
	12(3/2009)	5.768	3.245	0.824	1.36	1.166
	13(3/2009)	0.601	0.601	0.086	0.052	0.227
	14(3/2009)	0	0	0	0	0
	14(4/2009)	0	0	0	0	0
	15(4/2009)	2.163	2.163	0.309	0.668	0.818
	16(4/2009)	59.845	25.596	8.549	103.395	10.168
	17(4/2009)	68.257	31.124	9.751	191.523	13.839
	18(4/2009)	35.21	12.738	7.042	14.474	3.804
	18(5/2009)	4.206	3.845	2.103	6.072	2.464
	19(5/2009)	20.309	17.545	2.901	41.996	6.48
	20(5/2009)	87.484	67.416	43.742	1120.88	33.48

Table 16: Weekly statistics for the rain gauge P1 [mm] located in the wetland.

Station	Month	Sum	Max	Mean	Variance	Std
EARTH campus Rain Gauge						
	20(5/2008)	6.2	6	1.033	5.923	2.434
	21(5/2008)	33.2	11.2	4.743	21.616	4.649
	22(5/2008)	88.6	28.3	12.657	165.523	12.866
	23(6/2008)	27.7	14.9	3.957	39.17	6.259
	24(6/2008)	146.7	52.1	20.957	427.393	20.673
	25(6/2008)	38.7	14.2	5.529	26.432	5.141
	26(6/2008)	86.6	41.6	12.371	213.692	14.618
	27(6/2008)	4.1	3.2	2.05	2.645	1.626
	27(7/2008)	58.5	31.3	11.7	169.365	13.014
	28(7/2008)	38.5	28.9	5.5	109.683	10.473
	29(7/2008)	74.7	22	10.671	72.646	8.523
	30(7/2008)	112.5	34.1	16.071	122.469	11.067
	31(7/2008)	117.2	49.5	23.44	355.943	18.866
	31(8/2008)	1.2	0.6	0.6	0	0
	32(8/2008)	196.4	92.2	28.057	1579.813	39.747
	33(8/2008)	51.4	23.4	7.343	100.826	10.041
	34(8/2008)	36.4	12.7	5.2	27.09	5.205
	35(8/2008)	117.4	57.1	16.771	406.732	20.168
	36(8/2008)	0	0	0		
	36(9/2008)	108.8	67.4	18.133	641.291	25.324
	37(9/2008)	4.3	3.4	0.614	1.595	1.263
	38(9/2008)	44.4	25.4	6.343	82.326	9.073
	39(9/2008)	90.7	49.8	12.957	367.406	19.168
	40(9/2008)	9.8	9.2	3.267	26.493	5.147

	40(10/2008)	111.3	80.4	27.825	1300.163	36.058
	41(10/2008)	54.5	25	7.786	100.711	10.036
	42(10/2008)	48.5	27	6.929	91.616	9.572
	43(10/2008)	2.8	1.5	0.4	0.29	0.539
	44(10/2008)	42.8	14.9	7.133	31.511	5.613
	44(11/2008)	9.8	9.8	9.8		
	45(11/2008)	36.9	21.7	5.271	63.232	7.952
	46(11/2008)	56.9	25.3	8.129	85.246	9.233
	47(11/2008)	222.2	105.8	31.743	1980.603	44.504
	48(11/2008)	425.7	171.9	60.814	5319.345	72.934
	49(11/2008)	3.8	3.8	3.8		
	49(12/2008)	291.4	142.6	48.567	4711.923	68.643
	50(12/2008)	58	28.6	11.6	133.965	11.574
	1(1/2009)	3.4	3.4	1.133	3.853	1.963
	2(1/2009)	86.4	71.4	12.343	692.206	26.31
	3(1/2009)	16.3	7.4	2.329	9.026	3.004
	4(1/2009)	88.4	24	12.629	77.652	8.812
	5(1/2009)	102.8	51.4	14.686	277.862	16.669
	6(2/2009)	391.2	164.7	55.886	3073.191	55.436
	7(2/2009)	60.1	24	8.586	111.605	10.564
	8(2/2009)	109.3	82	15.614	930.988	30.512
	9(2/2009)	32.2	9.9	4.6	15.627	3.953
	10(3/2009)	242	110.6	34.571	1330.719	36.479
	11(3/2009)	124.6	93.9	17.8	1242.183	35.245
	12(3/2009)	8.2	4.9	1.171	3.349	1.83
	13(3/2009)	11.7	6.6	1.671	8.336	2.887
	14(3/2009)	0	0	0	0	0
	14(4/2009)	0	0	0	0	0
	15(4/2009)	5.1	4.9	0.729	3.389	1.841
	16(4/2009)	52.8	18.2	7.543	47.966	6.926
	17(4/2009)	29.3	27.6	7.325	183.236	13.536

Table 17: Weekly statistics for the rain gauge [mm] located at the weather station in campus.

Station	**Month**	**Sum**	**Max**	**Mean**	**Variance**	**Std**
Wetland Rain Gauge #3						
	10(3/2009)	79	39.8	39.5	0.18	0.424
	11(3/2009)	148.4	111.6	21.2	1724.48	41.527
	12(3/2009)	7.2	4.8	1.029	3.139	1.772
	13(3/2009)	0	0	0	0	0
	14(3/2009)	0	0	0	0	0
	14(4/2009)	0	0	0	0	0
	15(4/2009)	3.6	3.6	0.514	1.851	1.361
	16(4/2009)	85.4	39.2	12.2	244.107	15.624
	17(4/2009)	100.6	46.6	14.371	430.646	20.752
	18(4/2009)	47.4	19	9.48	36.972	6.08
	18(5/2009)	5.6	5.2	2.8	11.52	3.394
	19(5/2009)	27.4	24.4	4.567	94.935	9.743

Table 18: Weekly statistics for the rain gauge P3 [mm] located in the wetland.

B.2 Precipitation Monthly statistics

Station	Month	Sum	Max	Mean	Variance	Std
Wetland Rain Gauge #1						
	mai.08	99.982	26.077	4.999	70.731	8.41
	juin.08	243.225	49.871	8.687	152.57	12.352
	juil.08	427.567	70.54	13.792	265.936	16.308
	août.08	378.297	87.965	12.203	421.487	20.53
	sept.08	221.835	44.583	7.395	166.982	12.922
	oct.08	234.092	87.604	7.551	273.288	16.531
	nov.08	721.144	172.445	24.038	1906.955	43.669
	déc.08	514.811	138.076	16.607	1184.82	34.421
	janv.09	281.079	72.102	9.067	220.843	14.861
	févr.09	549.173	145.531	19.613	1058.344	32.532
	mars.09	330.302	97.728	10.655	560.364	23.672
	avr.09	165.475	31.124	5.516	80.845	8.991
	mai.09	111.999	67.416	10.182	413.31	20.33
EARTH campus Rain Gauge						
	mai.08	128	28.3	6.4	85.186	9.23
	juin.08	303.8	52.1	10.127	194.622	13.951
	juil.08	401.4	49.5	12.948	166.037	12.886
	août.08	402.8	92.2	12.994	516.659	22.73
	sept.08	258	67.4	8.6	248.724	15.771
	oct.08	259.9	80.4	8.384	239.949	15.49
	nov.08	755.3	171.9	25.177	2047.725	45.252
	déc.08	349.4	142.6	31.764	2782.239	52.747
	janv.09	297.3	71.4	9.59	241.042	15.526
	févr.09	592.8	164.7	21.171	1350.789	36.753
	mars.09	386.5	110.6	12.468	710.069	26.647
	avr.09	87.2	27.6	3.964	53.753	7.332
Wetland Rain Gauge #3						
	mars.09	234.6	111.6	9.023	580.923	24.102
	avr.09	237	46.6	7.9	181.864	13.486
	mai.09	33	24.4	4.125	70.125	8.374

Table 19: Monthly statistics for the rain gauges P1 and P3 [mm] located in the wetland and the rain gauge located at the weather station in campus.

C. Evapotranspiration Data Statistics

C.1 Evapotranspiration Weekly statistics

Station	Week	Min	Max	Mean	Variance	Std
ET						
	20(5/2008)	2.821	4.489	3.827	0.369	0.608
	21(5/2008)	2.714	3.867	3.212	0.304	0.551
	22(5/2008)	0.786	4.457	2.653	1.716	1.31
	23(6/2008)	2.708	4.165	3.447	0.284	0.533
	24(6/2008)	1.135	4.296	3.353	1.063	1.031
	25(6/2008)	3.117	4.613	3.672	0.217	0.466
	26(6/2008)	0.993	3.474	1.979	0.689	0.83
	27(6/2008)	2.191	3.262	2.726	0.574	0.758
	27(7/2008)	2.53	3.637	2.997	0.22	0.469
	28(7/2008)	1.328	3.912	2.993	0.745	0.863
	29(7/2008)	2.145	3.532	2.67	0.337	0.58
	30(7/2008)	1.618	3.995	2.577	0.6	0.775
	31(7/2008)	1.439	4.32	2.815	1.108	1.052
	31(8/2008)	3.589	3.959	3.774	0.068	0.261
	32(8/2008)	0.776	4.396	2.616	1.563	1.25
	33(8/2008)	2.493	4.441	3.728	0.681	0.825
	34(8/2008)	2.347	4.164	3.062	0.33	0.574
	35(8/2008)	2.92	3.878	3.473	0.156	0.395
	36(8/2008)	3.446	3.446	3.446		
	36(9/2008)	2.111	4.265	3.304	0.666	0.816
	37(9/2008)	3.62	4.487	4.204	0.085	0.292
	38(9/2008)	1.244	3.69	2.592	0.739	0.86
	39(9/2008)	2.398	4.331	3.569	0.406	0.638
	40(9/2008)	2.668	4.312	3.489	0.676	0.822
	40(10/2008)	2.14	3.485	2.662	0.368	0.607
	41(10/2008)	2.557	4.06	3.199	0.309	0.556
	42(10/2008)	1.358	3.44	2.668	0.601	0.775
	43(10/2008)	1.698	3.964	3.274	0.601	0.775
	44(10/2008)	1.185	3.144	2.38	0.572	0.756
	44(11/2008)	2.634	2.634	2.634		
	45(11/2008)	1.323	3.692	2.828	0.725	0.851
	46(11/2008)	1.398	3.926	2.582	1.228	1.108
	47(11/2008)	0.745	2.347	1.523	0.414	0.644
	48(11/2008)	0.739	2.936	1.49	0.504	0.71
	49(11/2008)	0.742	0.742	0.742		
	49(12/2008)	0.577	3.348	1.887	1.402	1.184
	50(12/2008)	1.242	3.201	2.25	0.399	0.632
	51(12/2008)	2.234	3.664	2.671	0.239	0.488
	52(12/2008)	1.489	3.568	2.725	0.429	0.655
	53(12/2008)	2.486	3.494	3.178	0.22	0.469
	1(1/2009)	1.534	2.867	2.417	0.585	0.765
	2(1/2009)	1.525	3.595	2.666	0.771	0.878
	3(1/2009)	1.35	3.146	2.329	0.606	0.778
	4(1/2009)	1.011	3.46	1.915	0.708	0.841

	5(1/2009)	1.183	3.449	2.431	0.681	0.825
	6(2/2009)	0.738	3.796	1.779	1.387	1.178
	7(2/2009)	1.535	3.779	2.661	0.83	0.911
	8(2/2009)	1.075	4.234	2.819	1.691	1.3
	9(2/2009)	1.74	3.724	2.737	0.795	0.892
	10(3/2009)	1.046	3.318	2.019	0.688	0.829
	11(3/2009)	1.505	3.97	3.071	0.624	0.79
	12(3/2009)	1.398	4.529	3.487	1.128	1.062
	13(3/2009)	3.166	4.061	3.583	0.115	0.339
	14(3/2009)	3.265	4.086	3.732	0.178	0.422
	14(4/2009)	2.92	3.991	3.519	0.294	0.542
	15(4/2009)	3.093	4.372	3.792	0.256	0.506
	16(4/2009)	3.054	4.142	3.614	0.186	0.431
	17(4/2009)	1.592	4.23	2.908	0.888	0.942
	18(4/2009)	1.871	4.059	3.01	1.067	1.033
	18(5/2009)	2.216	2.54	2.378	0.052	0.229
	19(5/2009)	2.368	3.263	2.823	0.13	0.361
	20(5/2009)	1.452	3.166	2.168	0.793	0.891

Table 20: Weekly statistics of the evapotranspiration [mm].

C.2 Evapotranspiration Monthly statistics

Station	**Month**	**Min**	**Max**	**Mean**	**Variance**	**Std**
ET						
	mai.08	0.786	4.489	3.201	0.969	0.984
	juin.08	0.993	4.613	3.087	0.922	0.96
	juil.08	1.328	4.32	2.798	0.544	0.738
	août.08	0.776	4.441	3.263	0.735	0.857
	sept.08	1.244	4.487	3.428	0.738	0.859
	oct.08	1.185	4.06	2.868	0.561	0.749
	nov.08	0.739	3.926	2.078	1.021	1.01
	déc.08	0.577	3.664	2.502	0.639	0.799
	janv.09	1.011	3.595	2.34	0.661	0.813
	févr.09	0.738	4.234	2.499	1.227	1.108
	mars.09	1.046	4.529	3.107	0.925	0.962
	avr.09	1.592	4.372	3.377	0.587	0.766
	mai.09	1.452	3.263	2.585	0.311	0.558

Table 21: Monthly statistics of the evapotranspiration [mm].

D. Flow Data Statistics

D.1 Flow Weekly statistics

Station	Week	Min	Max	Mean	Variance	Std
Culvert Flow						
	20(5/2008)	0.002	0.003	0.003	0	0
	21(5/2008)	0.002	0.003	0.003	0	0
	22(5/2008)	0.002	0.003	0.003	0	0
	23(6/2008)	0.002	0.002	0.002	0	0
	24(6/2008)	0.002	0.005	0.002	0	0.001
	25(6/2008)	0.002	0.005	0.002	0	0
	26(6/2008)	0.002	0.008	0.002	0	0.001
	27(6/2008)	0.002	0.003	0.002	0	0
	27(7/2008)	0.002	0.018	0.003	0	0.002
	28(7/2008)	0.002	0.006	0.003	0	0.001
	29(7/2008)	0.002	0.008	0.003	0	0.001
	30(7/2008)	0.002	0.005	0.003	0	0.001
	31(7/2008)	0.002	0.015	0.003	0	0.002
	31(8/2008)	0.002	0.003	0.003	0	0
	32(8/2008)	0.002	0.017	0.004	0	0.002
	33(8/2008)	0.002	0.012	0.003	0	0.001
	34(8/2008)	0.002	0.003	0.003	0	0
	35(8/2008)	0.002	0.013	0.003	0	0.001
	36(8/2008)	0.002	0.002	0.002	0	0
	36(9/2008)	0.002	0.015	0.003	0	0.001
	37(9/2008)	0.002	0.003	0.002	0	0
	38(9/2008)	0.002	0.011	0.002	0	0.001
	39(9/2008)	0.002	0.005	0.002	0	0
	40(9/2008)	0.002	0.003	0.002	0	0
	40(10/2008)	0.002	0.019	0.003	0	0.002
	41(10/2008)	0.002	0.005	0.002	0	0
	42(10/2008)	0.002	0.01	0.002	0	0.001
	43(10/2008)	0.002	0.002	0.002	0	0
	44(10/2008)	0.002	0.003	0.002	0	0
	44(11/2008)	0.002	0.002	0.002	0	0
	45(11/2008)	0.002	0.004	0.002	0	0
	46(11/2008)	0.002	0.003	0.002	0	0
	47(11/2008)	0.002	0.019	0.003	0	0.002
	48(11/2008)	0.003	0.019	0.008	0	0.005
	49(11/2008)	0.003	0.004	0.003	0	0
	49(12/2008)	0.002	0.019	0.005	0	0.004
	50(12/2008)	0.002	0.009	0.004	0	0.001
	51(12/2008)	0.002	0.004	0.003	0	0.001
	52(12/2008)	0.002	0.007	0.003	0	0.001
	53(12/2008)	0.002	0.003	0.003	0	0
	1(1/2009)	0.002	0.003	0.003	0	0.001
	2(1/2009)	0.002	0.009	0.003	0	0.001
	3(1/2009)	0.002	0.002	0.002	0	0
	4(1/2009)	0.002	0.004	0.002	0	0

	5(1/2009)	0.002	0.005	0.003	0	0.001
	6(2/2009)	0.002	0.019	0.006	0	0.004
	7(2/2009)	0.004	0.007	0.005	0	0.001
	8(2/2009)	0.003	0.011	0.004	0	0.001
	9(2/2009)	0.003	0.005	0.004	0	0
	10(3/2009)	0.003	0.005	0.004	0	0
	11(3/2009)					
	12(3/2009)	0.003	0.004	0.004	0	0
	13(3/2009)	0.002	0.004	0.003	0	0
	14(3/2009)	0.002	0.003	0.003	0	0
	14(4/2009)	0.002	0.004	0.003	0	0
	15(4/2009)	0.002	0.003	0.002	0	0
	16(4/2009)	0	0.004	0.002	0	0.001
	17(4/2009)	0	0.004	0.002	0	0.001
	18(4/2009)	0.002	0.003	0.003	0	0
	18(5/2009)	0.002	0.003	0.003	0	0
	19(5/2009)	0.002	0.003	0.002	0	0
	20(5/2009)	0.002	0.013	0.004	0	0.002

Table 22: Weekly statistics of the outflow [m^3/s] estimated at the culvert outlet.

D.2 Flow Monthly statistics

Station	**Month**	**Min**	**Max**	**Mean**	**Variance**	**Std**
Culvert Flow						
	mai.08	0.002	0.003	0.003	0	0
	juin.08	0.002	0.008	0.002	0	0.001
	juil.08	0.002	0.018	0.003	0	0.001
	août.08	0.002	0.017	0.003	0	0.001
	sept.08	0.002	0.015	0.002	0	0.001
	oct.08	0.002	0.019	0.002	0	0.001
	nov.08	0.002	0.019	0.004	0	0.004
	déc.08	0.002	0.019	0.004	0	0.002
	janv.09	0.002	0.009	0.003	0	0.001
	févr.09	0.002	0.019	0.005	0	0.002
	mars.09	0.002	0.005	0.003	0	0
	avr.09	0	0.004	0.002	0	0.001
	mai.09	0.002	0.013	0.003	0	0.001

Table 23: Monthly statistics of the outflow [m^3/s].

Appendix 9:

Calibration kit for the rain gauge

The calibration of the rain gauge was made with a field calibration FC-525 kit (Texas Electronics, Inc, TX). The calibration kit contained two nozzles with a different diameter to test the tipping-bucket rain gage. The different diameters correspond to different rainfall intensities and a slightly different number of tips for the same amount of water. Results of the calibration showed a reading 40% higher that it should be (counted 40% more tips than the instructions). Precipitation time series was adjusted with linear regression using to expect and the measured number of tips for each nozzle. The tipping-bucket rain gage was also adjusted following the procedure given with the calibration kit.

Calibration kit with two types of nozzles.

Appendix 10:

Runoff field instrumentation

During the field trip in May 2009, an automatic field instrumentation device was set to study and record runoff in the wetland. Runoff is an important process in the hydrologic cycle and this quantification will improve the knowledge about the hydrology and the water balance of the studied wetland. Three plots of 4 by 1 meters were installed on a side of the wetland without trees. The water collecting system is using the natural slope to direct the runoff water to a buried barrel where the water level is recorded. The same low technology as used to records water elevations along the wetland is used to record the water elevation in the barrel. An eco probe measuring the soil humidity is added to the field instrumentation as a rain gauge in supplement. There is no data at this point because of insufficient rainfall, but the maintenance and test of the plots are promising for the continuity of the project.

Runoff plot delineation and isolation from local runoff (left) and system of collecting water (middle) and outlet (right).

Runoff plots with water stage recorders in blue barrels.

Cumulative water balance

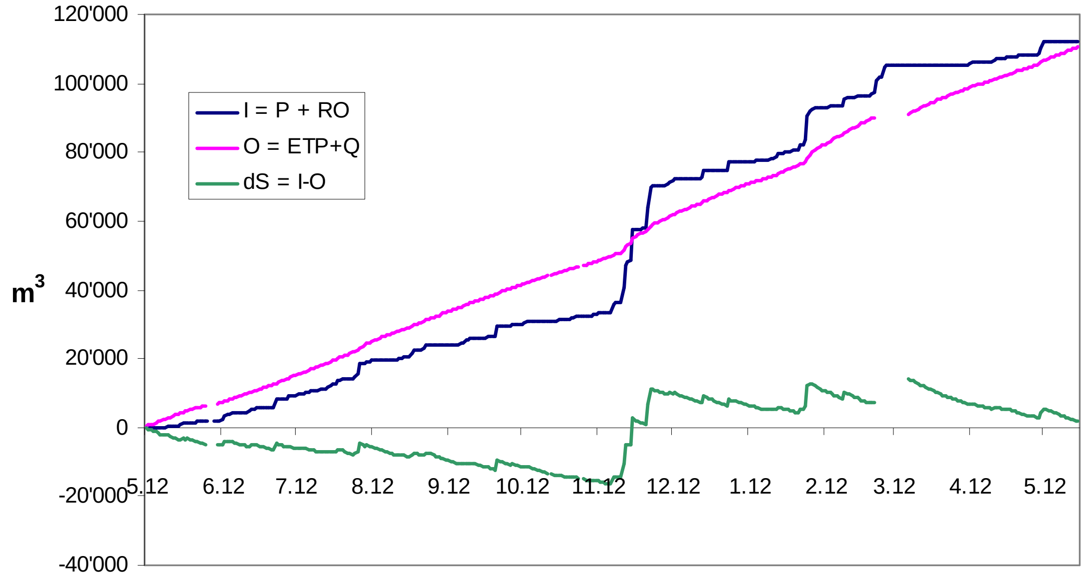


Figure 39: Cumulative water budget [m3] with the evolution of the input (I) and the output (O).

Appendix 12:

Maps of the wetland area with water depth contours

Daily and weekly averages of the water elevation recorded at the six stations (E2 to E7, fig. 2) in the wetland were used to model the variation of the wetland area and volume through the year. One of the outputs from the model was the 3D daily and weekly wetland water surface that could be mapped as water contour maps. The contours represent the water depths in the wetland. An animation made with those successive contour maps gave a better visualization of the small variation of water area and depth. The example of the contour maps given in the figure below represents the lower boundary, the middle class and upper boundary of the 95% confidence interval of the frequency distribution of the daily water area (fig. 40)

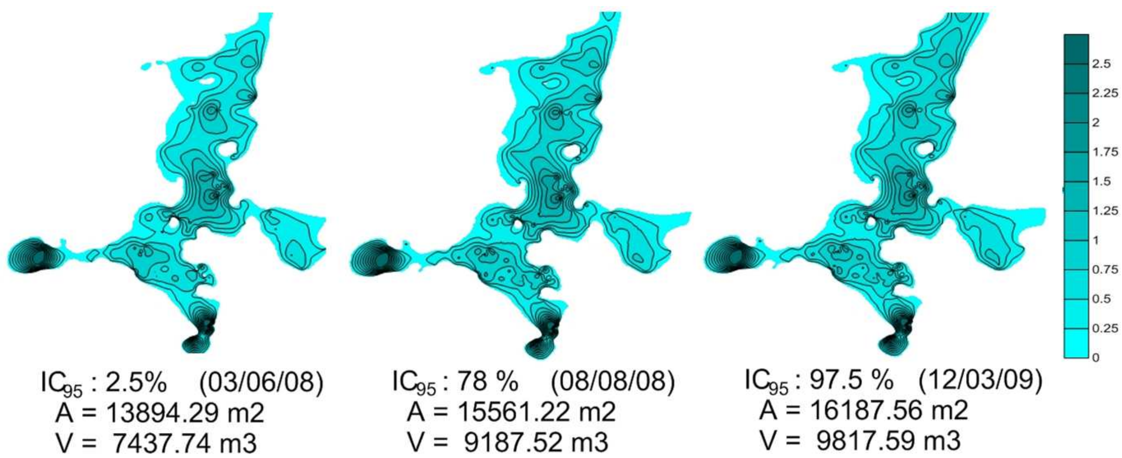


Figure 40: Example of three daily water surface areas and depths representing the most frequent shape (middle) and the lower (left) and upper (right) boundary of the $CI_{95\%}$.

Appendix 13:

Comparison of the water volume from the two methods

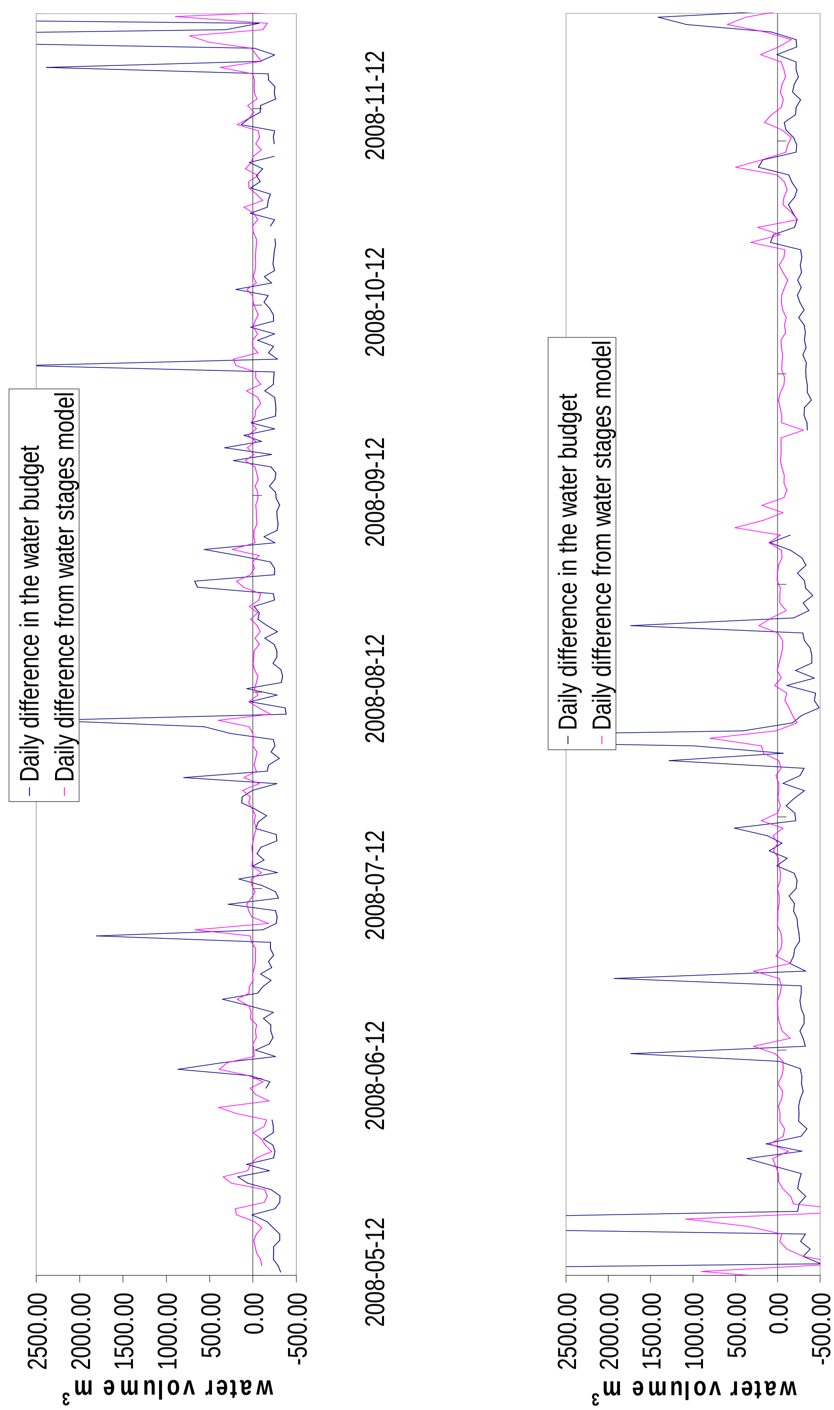


Figure 41: Comparison between the daily water storage from the water balance and the difference of daily volume from the water stages model.

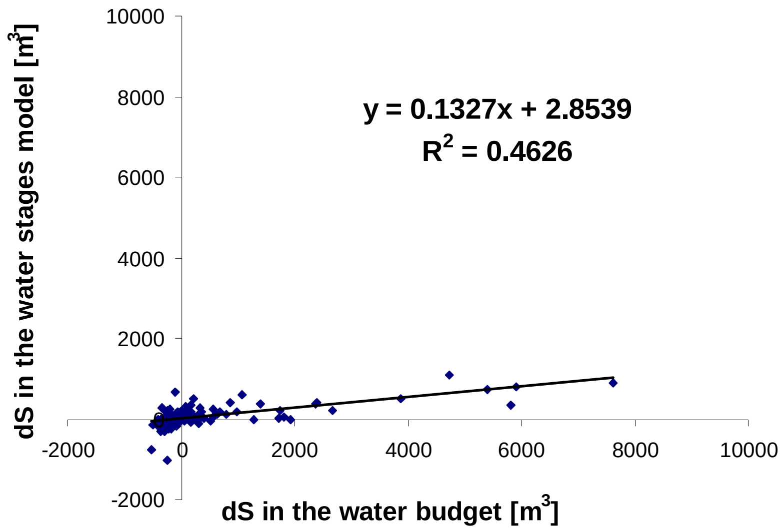


Figure 42: Difference of the daily water storage from the water balance in function of the difference of daily volume from the water stages model.