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HYDROLOGIE FREIBURG

Assessment of water quality and hydrological functioning in the Pantanal wetland, Brazil

Julia Schwerdtfeger

Diplomarbeit unter Leitung von Prof. Dr. Markus Weiler
Freiburg im Breisgau
März 2009

A rapadura é doce
mas não é mole não.

\- Brazilian proverb -

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Co-supervisor: Dr. Mark Johnson

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A	energy available for evaporation	[mm/d]
A_h	sensible heat transferred into a lake	[mm/d]
a_s	fraction of extraterrestrial radiation	-
α	fractionation factor	-
α_r	short-wave radiation reflection coefficient	-
$\alpha_{v/l}$	fractionation factor of liquid water with respect to water vapour	-
$\alpha_{/v}$	fractionation factor of water vapour with respect to liquid water	-
b_s	fraction of extraterrestrial radiation	-
c_E	Cl^- concentration/isotopic composition of evaporative flux	[mg/l]/[‰]
c_f	final Cl^- concentration	[mg/l]
c_i	initial Cl^- concentration	[mg/l]
c_I	Cl^- concentration/isotopic composition of inflow	[mg/l]/[‰]
c_p	predicted Cl^- concentration/isotopic composition	[mg/l]/[‰]
D	vapour pressure deficit	[kPa]
d	Deuterium excess	-
δ	delta notation of isotopes	[‰]
δ_A	isotopic composition of ambient moisture	[‰]
δ_E	isotopic composition of evaporative flux	[‰]
δ_{IG}	isotopic composition of groundwater inflow	[‰]
δ_I	isotopic composition of inflow	[‰]
δ_{IS}	isotopic composition of surface water inflow	[‰]
δ_L	isotopic composition of lake	[‰]
δ_{OG}	isotopic composition of groundwater outflow	[‰]
δ_{OS}	isotopic composition of surface water outflow	[‰]
δ_P	isotopic composition of precipitation	[‰]
Δ	gradient of function de_s/dT	[kPa/°C]
e	vapour pressure	[kPa]
e_S	saturated vapour pressure	[kPa]
ε	total isotopic separation factor	[‰]
ε^*	separation factor for equilibrium fractionation	[‰]
ε_K	separation factor for kinetic fractionation	[‰]
ε'	net emissivity between the atmosphere and the ground	[kPa]
E	evaporation	[mm]
E_P	potential evaporation rate	[mm]
F	ratio of inflow and evaporation	-

F_p^1	function of temperature and elevation of a site	-
F_P^2	function of temperature, wind speed, elevation of a site and vapour pressure deficit	-
f	adjustment for cloud cover	-
γ	psychrometric constant	[kPa/°C]
^2H	Deuterium	-
h	relative humidity	-
I	inflow	[mm]
I_G	inflow of surface water	[mm]
I_S	inflow of groundwater	[mm]
L_n	long-wave radiation	$[MJ/m^2 \cdot d]$
λ	latent heat of vaporization of water	[MJ/kg]
n	bright sunshine hours per day	[h]
N	total day length	[h]
O	outflow	[mm]
^{18}O	Oxygen-18	-
O_G	outflow of surface water	[mm]
O_S	outflow of groundwater	[mm]
P	precipitation	[mm]
P_a	atmospheric pressure	[kPa]
R	isotope ratio ($^{18}O/^{16}O$ or $^2H/^1H$)	-
R_n	net radiation	$[MJ/m^2 \cdot d]$
S_n	net short-wave radiation	$[MJ/m^2 \cdot d]$
S_0	extraterrestrial solar radiation	$[MJ/m^2 \cdot d]$
S_t	total incoming short-wave radiation	$[MJ/m^2 \cdot d]$
s_e	slope of evaporation line	-
σ	coefficient of surface cover	-
σ_B	Stefan-Boltzmann constant	$[MJ/m^2 \cdot K^4 \cdot d]$
t	time	[h]
T	mean air temperature	[°C]
T_{min}	minimum air temperature	[°C]
T_{max}	maximum air temperature	[°C]
T_W	water temperature	[K]
U	wind speed	[m/s]
V_f	final lake volume	[mm]
V_i	initial lake volume	[mm]
V_L	lake volume	[mm]
V_p	predicted lake volume	[mm]
Z	elevation of a site	[m]

Abbreviations

AMST	Amazon Summer Time
a.s.l.	above sea level
GIS	Geographical Information System
GMWL	Global Meteoric Water Line
GNIP	Global Network of Isotopes in Precipitation Program
GO	Goiás
IAEA	International Atomic Energy Agency
IBAMA	*Instituto Brasileiro do Meio Ambiente e Dos Recursos Naturais Renováveis* (Brazilian Institute for Environment and Natural Renewable Resources)
IC	Ion chromatograph
IHF	Institute of Hydrology
INMET	*Instituto National de Meteorologia* (National Institute of Meteorology)
INTECOL	International Association for Ecology
IRMS	Isotope Mass Spectrometer Type Delta S
ITC	Inner Tropic Convergence
LEL	Local Evaporation Line
LMWL	Local Meteoric Water Line
MINA TrêS	Model for INflow Assessment with three types of input data (*três* = Portuguese for three) for Simulation
MS	Mato Grosso do Sul
MT	Mato Grosso
RPPN	*Reserva Particular do Patrimonio Natural* (Private reserve of national heritage)
SESC	*Serviçio Social do Comércio* (Commerce Social Service)
TDLAS	Tunable Diode Laser Absorption Spectrometry
UBC	University of British Columbia
UFMT	Universidade Federal de Mato Grosso
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTC	Universal Time Coordinated
VSMOW	Vienna Standard Mean Ocean Water
WMO	World Meteorological Organization

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Abstract

Hydrology and climatology with their specific conditions and changes in cycles play a major role in tropical wetland systems. For conservation of such unique environments it is essential to understand the complex connectivity between different processes that take place within the ecosystems.

This study aims at the assessment of the hydrological behaviour between different water bodies in the dry season of the northern Pantanal wetland, Brazil. For the investigation of their water balance and the differences in their hydrological functioning, water was measured in-situ for water quality parameters and sampled for a stable water isotope analysis.

Potential evaporation was calculated on a physical basis by the Penman-Monteith Equation, modified for open water. Furthermore, an established and simplified water balance tracer approach was performed in order to identify the hydrological dynamics of lakes whether they are evaporation controlled or throughflow systems. Thereby, an uncertainty analysis was carried out for all parameters, which indicates large error ranges for the results. A chloride mass balance approach served as an independent method for comparison. The results of those methods show that on one side, strong isotope enrichment is due to high evaporation rates, which are determinant for the hydrochemistry in the wetland. On the other side, not only evaporation but also inflow is a fundamental component of the water balance. It could be proved that even at the end of the dry season all water bodies in the Pantanal have significant inflow rates to counterbalance their water budget. Furthermore, the sampled water bodies show significant differences among each other in their hydrological dynamics.

In a next step, inflow rates were determined for the different lakes by applying the simplified tracer approach on the basis of evaporation rates, calculated by Penman-Monteith. However, this tracer approach did not yield in satisfying results due to the large parameter uncertainty. In addition, it was demonstrated that not all assumptions of this method are appropriate in the case of the Pantanal water bodies.

Inflow rates were also assessed by simulating a model output on observed data with MINA TrêS, a model, which combines isotope and hydrochemistry data. With the model results it was finally possible to quantify the water budget for the different water bodies.

This work shows that the simplified tracer approach is not an adequate method to establish the components of the water balance for the studied water bodies. In fact, the calculation of evaporation by the modified Penman-Monteith approach in connection with modelling of inflow rates by MINA TrêS constitutes a better way for quantifying the water budget of lakes in the Pantanal dry season. The results of water quality parameters as well as the assessment of water balance components point out that even within a very small area with little previous knowledge, large differences can be found in the hydrological functioning of water bodies in the northern Pantanal.

Keywords: Pantanal – tropical wetland – dry season – stable isotopes – deuterium – oxygen-18 – hydrochemistry – water body – hydrological functioning – water balance – evaporation loss – subsurface inflow

Zusammenfassung

Im geographischen Schwerpunkt von Südamerika befindet sich das größte innerkontinentale Feuchtgebiet der Erde: Das Pantanal. Mit seiner enormen Vielfalt an unterschiedlichen Lebensräumen zeichnet sich dieses einzigartige Naturparadies durch einen unglaublichen Reichtum an Flora und Fauna aus. Klima und Hydrologie spielen dort eine wichtige Rolle, da besonders deren Veränderungen sich direkt auf das Ökosystem auswirken. Für die Erhaltung eines solchen Artenraumes ist die Kenntnis seiner verschiedenen Prozesse und deren Zusammenhänge von äußerster Wichtigkeit.

Um dazu einen Beitrag zu leisten, wurden im Rahmen dieser Diplomarbeit unterschiedliche Methoden angewandt, um das hydrologische Verhalten von verschiedenen Gewässern in der Trockenzeit im nördlichen Pantanal zu analysieren. Ziel war es dabei, etwaige Gemeinsamkeiten, Unterschiede oder sonstige Auffälligkeiten zu erkennen und aufzuzeigen. Des Weiteren stand die Quantifizierung der Wasserbilanzkomponenten verschiedener Gewässer im Mittelpunkt. Dazu wurden in situ mit zwei Multisonden hydrochemische Parameter gemessen und Wasserproben für die spätere Analyse auf stabile Umweltisotope des Wassermoleküls entnommen.

Die Bestimmung der Verdunstungsverluste von verschiedenen Seen im nördlichen Pantanal erfolgte mit der gängigen Gleichung nach Penman-Monteith, modifiziert für offene Wasserflächen. Mit einem schon vielfach angewandten Wasserbilanzmodell auf der Grundlage stabiler Umweltisotope wurde die generelle hydrologische Dynamik erfasst. Dabei war es wichtig, die Rolle von Verdunstung und möglichen unterirdischen Zuflüssen einzuschätzen. Für die einzelnen Parameter des Modells wurde eine Unsicherheitsanalyse durchgeführt. Diese ergab jedoch, dass der Wasserbilanzansatz für dieses Gebiet unplausible Ergebniswerte lieferte, die mit unzutreffenden Annahmen für die Gewässer im nördlichen Pantanal erklärt werden können. Mit der Chloridmassenbilanz als unabhängiger Methode wurde festgestellt, ob sich, wie in trockenem Klima zu erwarten, Chlorid in den unterschiedlichen Seen nur aufgrund von Verdunstung anreichert. Einerseits ist die Verdunstung entscheidend für die Isotopenanreicherung und ein bestimmender Faktor für die Wasserchemie in diesem Gebiet. Andererseits spielen in der Trockenzeit eben nicht nur die Verdunstung, sondern auch unterirdische Zuflüsse eine fundamentale Rolle in der Wasserbilanz dieser Gewässer. Mit dem Wasserbilanzansatz und den berechneten Verdunstungsverlusten nach Penman-Monteith konnten die unterirdischen Zuflussraten für die einzelnen Gewässer bestimmt werden.

Allerdings waren die Ergebnisse nicht zufriedenstellend aufgrund der großen Parameterunsicherheit des Wasserbilanzmodells.

Deshalb wurden in einem weiteren Schritt erneut die unterirdischen Zuflussraten berechnet. Dazu wurde das Modell MINA TrêS verwendet, welches Isotopen- und hydrochemische Daten als Eingangsparameter erfordert. Zuletzt konnte mit dessen Ergebnissen die Wasserbilanz der einzelnen Gewässer aufgestellt werden.

Mit dieser Arbeit wurde bewiesen, dass es signifikante Unterschiede im hydrologischen Verhalten zwischen den Gewässern gibt. Diese beruhen einerseits auf unterschiedlichen Prozessen im Wasserkörper, die bestimmend sind für deren Hydrochemie. Andererseits resultieren sie aus den Interaktionen von Grund- und Oberflächengewässer. Weiterhin wurde aufgezeigt, dass sich das Wasserbilanzmodell aufgrund unpassender Annahmen für die Gewässer des nördlichen Pantanal nicht eignet, um deren Komponenten zu bestimmen. Die modifizierte Verdunstungsberechnung nach Penman-Monteith in Verbindung mit der Modellierung von Zuflüssen bietet erwiesenermaßen eine viel bessere Methode, die Wasserbilanz in Seen des Feuchtgebietes zur Trockenzeit zu quantifizieren.

Schlüsselwörter: Pantanal – tropisches Feuchtgebiet – Trockenzeit – Umweltisotope – Deuterium – Sauerstoff 18 – Hydrochemie – Gewässer – Wasserbilanz – Verdunstungsverlust – Grundwasserzustrom

1 Introduction

There are not many wetlands that are comparable in size as well as nearly naturally state conditions with the Pantanal (HECKMAN, 1998). Considering its magnitude it is the largest freshwater wetland in the world with an area of approximately 140,000 km² (HAMILTON et al., 1996). Nevertheless, the Pantanal is one of the least known regions in the world (POR, 1995). Declared by UNESCO (United Nations Educational, Scientific and Cultural Organization) as a Biosphere Reserve and parts of it as a World Heritage Site (HAMILTON, 2002b), the Pantanal is one of the world's most biodiverse ecosystems with hundreds species of mammals, birds, reptiles and plants (CARTER et al., 2004). Until today it has not been extensively modified by man (HECKMAN, 1998).

The Pantanal is markedly heterogeneous in its structure consisting of large-sized rivers and their deltas and thousands of lakes which are interspersed with grassland, forest and savannah (POR, 1995). Therefore, studies and results from one location may not be representative for other locations. Similarly the conditions of one season in the wetland do not equal the conditions of another season. Nearly all of the habitats are in a state of constant change. The wetland must be seen as a dynamic system, regulated by conditions and changes in complex cycles of climatology and hydrology (HECKMAN, 1998).

The complexity of this ecosystem requires further research in order to sustain this unique environment.

1.1 Objectives and approach

The relevance of this study in the Pantanal is based on the assumption that a nature conservation area can only be preserved for the future if the complex mechanisms in all scientific areas are fully understood. Therefore, the aim of this study is

- to identify the behaviour of different water bodies in the dry season
- to understand the hydrological functioning and interactions within and between those water bodies in the wetland by highlighting differences and correlations
- to define the components of the water balance of different water bodies in order to assess the whole water budget

For the investigation of natural hydrological systems it is necessary to obtain a better knowledge about the various processes that take place in this environment. Especially in the Pantanal, it is essential that field methods are adequate to a mostly inaccessible area where hydrological studies still are scarce. Therefore, two different approaches are applied: Firstly, water quality data was collected in a nature reserve with two multi-probes, which continuously measure in-situ water quality parameters. This way, diurnal variations can be highlighted and compared and hydrological cycles of those parameters provide an insight into the behaviour of lakes and rivers. Secondly, water samples were taken in order to analyse them for stable isotopes of water. Their analysis is fairly easy and they contribute to the knowledge about hydrological processes, not only about evaporation, which is one of the most important parts of the water cycle in the tropics.

1.2 State of the art

1.2.1 Wetlands

Wetlands are ecosystems with shallow water, saturated and anaerobic soils (VAN DER WALK, 2006) and generally a high productivity and metabolic activity (MITSCH & GOSSELINK, 1993). They are covering about 6 % of the earth's land surface and can be found on every continent and in every climatic zone (VAN DER WALK, 2006). Common names for wetlands differ throughout the world and are listed by MITSCH & GOSSELINK (1993).

Wetlands have a significant influence on the hydrological cycle by reducing floods, recharging groundwater or augmenting low flow (BULLOCK & ACREMAN, 2003). They play a fundamental role in nutrient cycling and storage, species conservation, global biogeochemical cycles and the greenhouse effect. Furthermore, they are important and determinant for the shape of landscape due to a unique flora and fauna that has adapted to environmental wetland conditions. During the last decades, studies on wetlands have become increasingly important and have been widely discussed in international forums around the world, such as in the series of “INTECOL (International Association for Ecology) wetlands conferences” (MITSCH et al., 1994).

BULLOCK & ACREMAN (2003) give a detailed summary with the main conclusions about the role of wetlands. The variety of wetland types results from differences in their hydrology and geomorphology but they all have an aquatic and a terrestrial system. The “Committee on Characterization of Wetlands” stated: “The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical, and biological features reflective of recurrent, sustained inundation or saturation...” (VAN DER WALK, 2006).

Wetland classifications are based on the following criteria:

- their hydrology (marine, estuarine, riverine, lacustrine or palustrine),
- their landform (slopes with groundwater discharge, plains with saturated soils, depressions, with or without in- and outlet, river channels, floodplains, deltas,...),
- their vegetation (forested, non forested, macrophytes, mangroves,...),
- their major source of water (precipitation, flooding rivers, groundwater, surface flow, tides) or on
- their hydroperiod (permanent inundation, seasonal inundation, intermittent inundation or seasonal waterlogging)

MITSCH et al. (1994) present wetlands in categories of coastal river deltas, inland river deltas, great riverine forests, salt marshes, northern peatlands, inland freshwater marshes, swamps and constructed wetlands. Other wetland categories can be found in the studies carried out by MATTHEWS & FUNG (1987), ASELMANN & CRUTZEN (1989), BRINSON (1993), MITSCH & GOSSELINK (1993) or VAN DER WALK (2006), just to mention a few. Even though there are many common definitions of wetlands, they are often difficult to understand and not always clear or even confusing (MITSCH & GOSSELINK, 1993). MITSCH & GOSSELINK (1993) review studies of wetland hydrology dealing with the exploration of relationships between hydrologic variables and wetland productivity, species composition or hydrological characteristics within specific wetland types, such as hydroperiod, residence time and overall wetland water budget with respect to assign inflow, outflow and evaporation losses.

1.2.2 Water quality of the Pantanal

Within their “Flood Pulse Concept” JUNK et al. (1989) examine the importance of floodplains and their impact on the hydrochemistry and hydrology in the wetlands. Floodwater can increase or dilute the concentration of dissolved substances as well as inorganic and organic material can be mobilised. Furthermore, the hydrochemistry of water bodies follows a seasonal hydrological cycle due to rising and falling water levels in the floodplain. During the period of rising water, the floodplain receives solutes from rivers and intense leaching and deposition processes take place. At low water, evaporation leads to an increase in ion concentration and pH. Especially in shallow wetland lakes the water chemistry depends strongly on the regional water level. Dilution by rain water, evaporation and biological activities are determinative factors as well. Additionally, groundwater interactions and their exchange with surface water play an important role in wetland hydrochemistry (HECKMAN, 1998).

Studies about the physicochemical features of rivers and lakes in the Pantanal wetland are given by SAIJO et al. (1997) and HAMILTON et al. (1999). They provide detailed information on the variation of hydrochemistry and agree that this variation can largely be explained by weathering of carbonate rocks of surrounding highlands as well as by strong evaporation effects that concentrate solutes in water bodies. Studies about the hydrochemistry of lakes, rivers and groundwater in the Pantanal have been recently reviewed by NOGUEIRA et al. (in press). They state that water bodies in the Pantanal show hydrochemical conditions according to the water quality of their tributaries. Mainly calcareous rocks and sandstone compose the mountains bordering the wetland. A number of large streams, so-called *Cerrado* streams, can be found in the highlands, surrounding the Pantanal. Their water contributes to the discharge of the floodplain and thus determines its water chemistry. Cerrado streams can be classified as streams with very low conductivities and their hydrochemical characteristics are well studied by WANTZEN (2003). Within the Pantanal a large part of ion input comes from the atmosphere through precipitation. However, measurements on rainfall show low conductivities (NOGUEIRA et al., in press). Characteristics of groundwater and a comparison with surface water are given by GIRARD & PINTO (2000). Differences between the water quality parameters such as conductivity, pH, dissolved oxygen and nitrate are large and characteristically for the dry season (PINTO et al., 1999). Then, their variations can be more intense in the diel cycles than in the seasonal cycle (NOGUEIRA et al., 2002). Therefore, dry season is the time when most interesting changes in hydrochemistry can be observed.

1.2.3 Water balance studies

Stable isotopes are one of the most important tools to investigate hydrological questions concerning the water budget of water bodies (MATSUYAMA et al., 2005). In 1961, the International Atomic Energy Agency (IAEA) funded the “Global Network of Isotopes in Precipitation” (GNIP). During this programme, they started measuring the isotopic composition of precipitation on meteorological stations throughout the world (URL 1). The content of oxygen-18 (^{18}O) and deuterium (^{2}H) in precipitation, known as stable isotopes or environmental tracers, are determined by isotope exchange processes and distillation of atmospheric moisture. During the evaporation, an enrichment of heavy isotopes in the residual liquid occurs as evaporation moisture flux is depleted in ^{18}O and ^{2}H. Fractionation processes, such as evaporation enrichment, can be in equilibrium or kinetic. The enrichment is controlled by atmospheric processes where humidity, temperature and the isotopic fraction of ambient moisture in the atmosphere play an important role (GAT, 1995). A water body reacts on such processes which is reflected by its isotopic composition (GAT, 1996). Heavy isotope enrichment due to evaporation can be widely observed in surface water (GAT, 1995) and isotopes can be used to determine inflow of groundwater to a lake (FROEHLICH et al., 2005). Evaporation processes of surface water from an isotopic perspective have been published by GAT (1996), GONFIANTINI (1986) or MERLIVAT & JOUZEL (1979). This isotopic labelling of water was applied throughout limnological studies and reviewed in 1968 by IAEA (1968) and DINÇER (1968).

Lakes are dynamic systems, which are connected to the hydrological cycle through the inflow and outflow of surface water, groundwater, precipitation and evaporation. For the quantification of these water fluxes water balance studies are very important and have often been investigated with stable isotopes (ROZANSKI et al., 2000). The isotopic composition of a lake is sensitive to environmental and hydrological changes and thus can be used for their monitoring (GAT, 1996). Compared to other hydrological systems, lakes in general are accessible for water sampling and in-situ measurements. Therefore, they are well suited to carry out studies with environmental isotopes (GONFIANTINI, 1986). Usually, it is easy to estimate surface inflow and outflow of a lake, but it is very difficult to determine groundwater inflow or evaporation losses (PEARSON & COPLEN, 1978). These difficulties make modelling of a lake's water balance rather complex (GAT, 1996). However, studies on water balances of lakes are frequently discussed in the literature. FRIEDMAN et al. (1956) and BONNER et al. (1961) applied water balance approaches assuming that the fractionation accompanying evaporation is in equilibrium. But the evaporation process is more complicated than the results these simple equilibrium models are able to represent. Therefore, CRAIG & GORDON (1965) developed a model considering additionally kinetic fractionation and GAT (1970) used evaporation pan data to determine the total isotopic separation factor. Due to the seasonal variations in the data, LEWIS (1979) and ZIMMERMANN & EHHALT (1970) criticise water balance studies on environmental isotopes. PEARSON & COPLEN (1978) combine that the determination of the amount of evaporative fractionation is a function of many factors and often cannot be calculated precisely. FONTES & GONFIANTINI (1967) give a first application of transient systems in North Africa for the estimation of water balance components and WELHAN & FRITZ (1977) assess the isotopic composition of evaporating flux to study the water balance of a lake without the necessity to measure humidity and atmospheric moisture. The water balance of floodplain lakes in the Amazon basin is studied by MARTINELLI et al. (1989). Thereby, isotopic composition was used to differentiate between waters originating from inundations, from overflowing rivers or residual waters from previous cycles of lakes. Those simple models previously described assume that the isotopic composition of the lake will reach a steady state (PEARSON & COPLEN, 1978). Long-term or annual evaporation has been successfully estimated with steady state models. GONFIANTINI (1986) discusses the most important results of lake studies with stable isotopes. Moreover mass balance approaches have been demonstrated by DINÇER (1968), GAT (1981), ZUBER (1983) or KRABBENHOFT et al. (1990) and have been reviewed by GAT (1995). FROEHLICH et al. (2005) highlight isotopes in lake studies from a historical perspective. GIBSON et al. (1993; 1996; 2002) and GIBSON & EDWARDS (2002) investigate the isotopic behaviour of lakes in North America to determine their water balance in the seasonal, continental climate over the past decades. GIBSON (2002) generally gives an overview of the theory of isotope mass balance of lakes for different non steady state scenarios. A categorisation of the relevant formulations postulated in previous studies can be found as well.

2 Study area

2.1 Geography of the Pantanal wetland

The Pantanal is approximately situated between 16-20° south and 50-58° west in the centre of South America (figure 1). Most of the Pantanal lies within the Brazilian states of Mato Grosso (MT) and Mato Grosso do Sul (MS). The larger part of the area (65 %) is located in Mato Grosso do Sul (URL 2). Smaller parts can be found in Bolivia and another even smaller part in Paraguay (HECKMAN, 1998).

Figure 1: Location of the Pantanal wetland within Brazil (Data source: HASENACK et al., 2003a)

The wetland is a depressed area within the Upper Paraguay River basin. The borders are very irregular and difficult to define because the area is covered by water and changes greatly from season to season. Therefore, different sizes of the whole wetland area can be found in the literature. According to HAMILTON (2002b), the Pantanal occupies an area of approximately 450 km by 250 km. Based on satellite observations, HAMILTON et al. (1996) state that the area comprises between 130,000 and 140,000 km². The elevation of the terrain region ranges between 75 m and about 200 m above sea level (a.s.l.) and forms a narrow panhandle (POR, 1995). In the north, east and south, elevated plateaus and low mountains elevate from 200 m to 1,200 m (HECKMAN, 1998). They form the borders of the Brazilian highlands, the so-called *Planalto*. In the south, the Pantanal's border is the Apa River, a tributary of the Paraguay River (POR, 1995). The western region of the Pantanal is covered by plains (HAMILTON, 2002b). Through an opening in the north, the Upper Paraguay River flows southward through the Pantanal and marks its western border (HECKMAN, 1998). The basin can be seen as a large river delta where the Paraguay River and a great number of its tributaries gather and come down from the plateau. This means that the Pantanal consists basically of alluvial fans of its main rivers, standing water bodies on these fans and a network of deltas of streams, which cross the whole wetland. As a result, the largest part is covered by alluvia (POR, 1995). The Pantanal attenuates from the basin and reduces the runoff until it concentrates at the basins outlet (PONCE, 1995b).

The Pantanal cannot be studied as a unit because many different kinds of habitats can be found. A reason for the differences are the interactions between climate and hydrology as well as their changes in cycles (HECKMAN, 1998). On the other hand however, a very rich and diverse flora and fauna, which are unique on the American continent, compose a part of the whole ecosystem (PONCE, 1995b).

2.2 RPPN SESC Pantanal

Within this huge wetland the study site of this work is the "*Reserva Particular do Patrimonio Natural SESC Pantanal*" (Private reserve of national heritage SESC Pantanal) further on called RPPN SESC Pantanal, located in the northern part of the Pantanal. The reserve was established in 1998 and is fully owned by the private organisation SESC (*Serviçio Social do Comércio, Commerce Social Service*) (RAMSAR, 2002).

The RPPN SESC Pantanal is situated between 16º 28' and 16º 50' south and 56º 00' and 56º 30' west in the municipality of *Barão de Melgaço*, in the state of Mato Grosso, which is located in the central-western region of Brazil (figure 2).

Figure 3 shows the reserve RPPN SESC Pantanal, bordered by the Cuiabá River (*Rio Cuiabá*) in the west and the São Lourenço River (*Rio São Lourenço*) in the east. Within the Pantanal the reserve covers an area of about 106,307 ha (URL 2). The elevation varies from 101 to 117 m a.s.l. (RAMSAR, 2002).

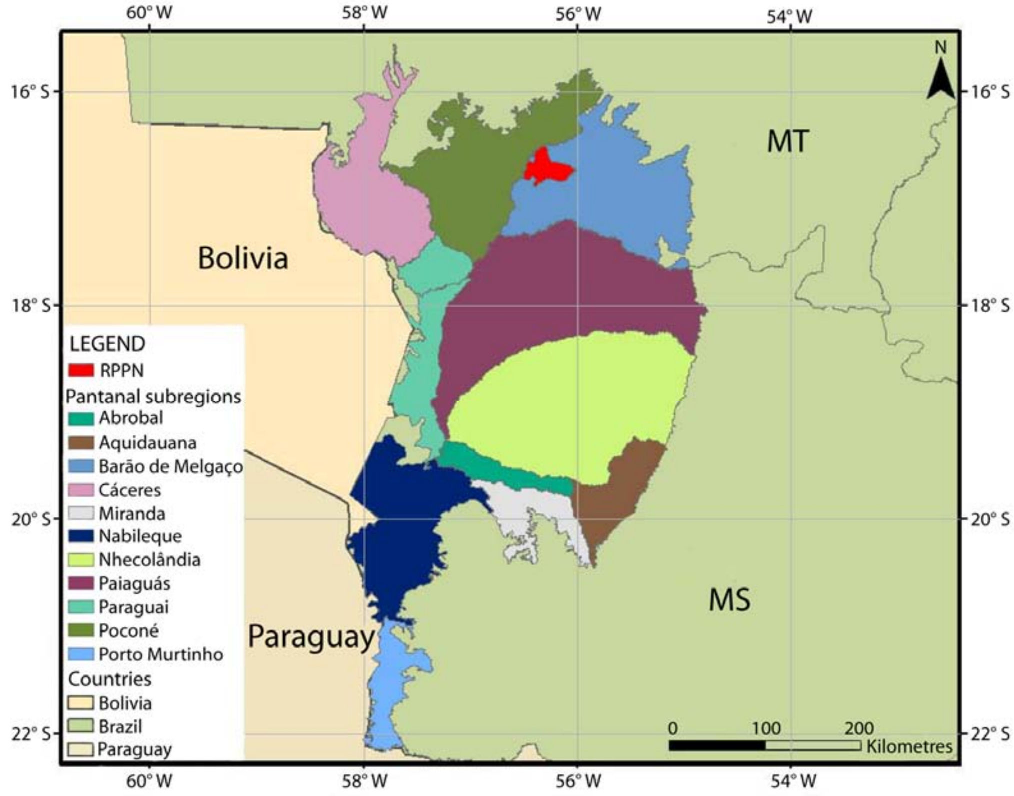

Figure 2: Pantanal subregions and location of the RPPN SESC Pantanal (MT = Mato Grosso, MS = Mato Grosso do Sul, GO = Goiás, Data source: HASENACK et al., 2003a)

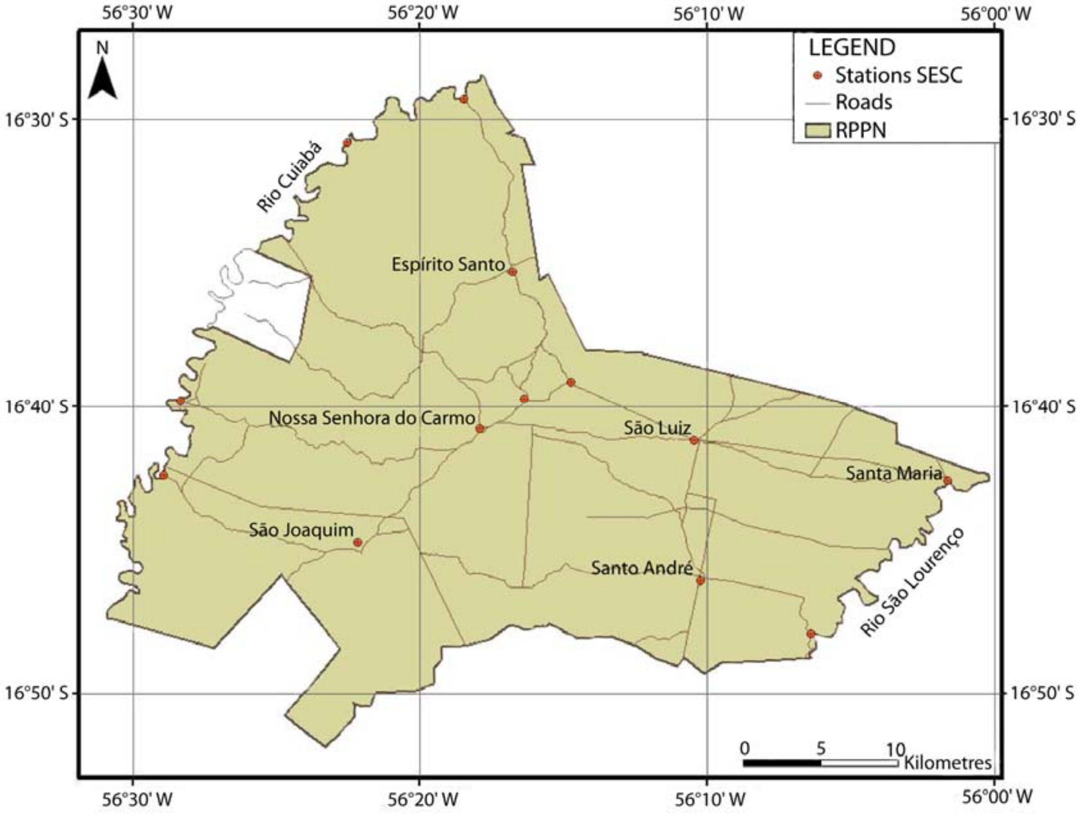

Figure 3: RPPN SESC Pantanal (Data source: HASENACK et al., 2003a)

In 1988, the RPPN SESC Pantanal was declared as a National Heritage Site by the Brazilian Institute for Environment and Natural Renewable Resources (*IBAMA - Instituto Brasileiro do Meio Ambiente e Dos Recursos Naturais Renováveis*). In 2000, it was also declared as a Biosphere Reserve by UNESCO and in 2001, it was accepted as a Ramsar site by “The Ramsar Convention on Wetlands” (RAMSAR, 2002).

2.3 Climate

2.3.1 General characteristics

The Pantanal is approximately situated 2,000 km south from the equatorial belt. Therefore, seasonal changes occur with a dry and a rainy season every year. Their beginning and end is very hard to define as they vary from year to year by several weeks (HECKMAN, 1998). The climate is characterised by dry autumns/winters and springs/summers with heavy rainfall. The dry climate in winter results from the influence of the subtropical anticyclone. The rainy season in summer results from the Inner Tropic Convergence (ITC) that moves southward to the Tropical Capricorn (HASENACK et al., 2003b). According to Köppen-Geiger’s climate classification the study area belongs to the type Aw which is defined as equatorial savannah with dry winter and a minimum winter precipitation below 60 mm (KOTTEK et al., 2006). The letter “A” represents a tropical, humid climate zone that is characterised by tropical vegetation and high temperature. The letter “w” indicates a region with mean annual precipitation between 1,000 and 1,500 mm (HASENACK et al., 2003b).

2.3.2 Precipitation and temperature

From about mid-April until October the dry season is characterised by very little precipitation and July is the driest month (HECKMAN, 1998). Due to the location of the ITC its amount of precipitation is around 40 mm (HASENACK et al., 2003b). The average of precipitation in the rainy season from November to April amounts to 1,500 mm per year and January is the month with the highest rainfall (RAMSAR, 2002). The origin of rainfall are the tropical Atlantic air masses and its regional variability is very high (HECKMAN, 1994).

The yearly average temperature is 25.7 ºC and the hottest month is October with a mean monthly temperature of 27.7 ºC (RAMSAR, 2002). The afternoon temperatures during the dry season often reach the mid-40s (HECKMAN, 1998). The coldest month is July with a mean monthly temperature of 22.2 ºC (RAMSAR, 2002). There can be local differences but the general patterns of monthly temperatures are fundamentally similar (HECKMAN, 1998).

Only a few days in southern winter periodic incursions of air result in reduced temperatures, reaching as far as 0 °C within a few hours (GIRARD et al., 2003). These phenomena are called *friagems* and are accompanied by very fine rainfall. They happen during the dry season if large polar-Antarctic air masses from the south move across South America. Then, the lowest temperatures of a year can be recorded. Between late June and mid-August they occur more or less frequently for about five to eight days (HECKMAN, 1998).

In the RPPN SESC Pantanal the meteorological data is registered in a climate tower close to *Espírito Santo* (figure 3), which was installed in August 2006. The data is given in the annex (A.1). Figure 4 displays the distribution of temperature and precipitation of the RPPN SESC Pantanal.

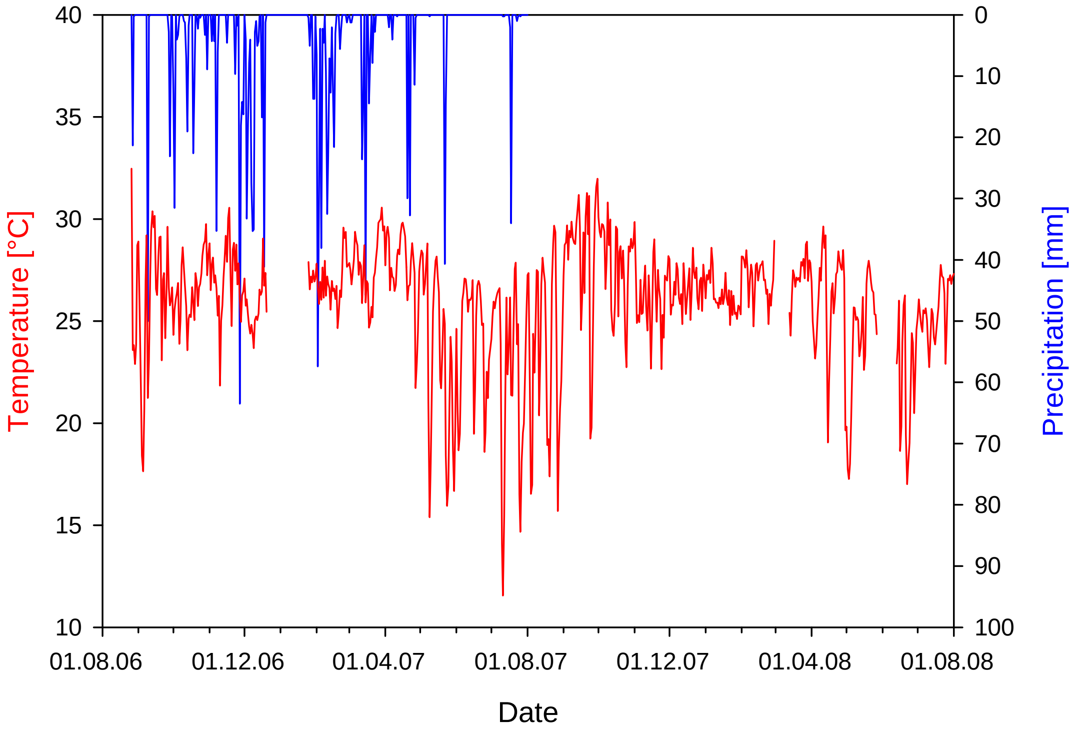

Figure 4: Mean daily temperature and precipitation of the RPPN SESC Pantanal (Data source: *Instituto de Agroclimatologia Tropical, Universidade Federal de Mato Grosso,* UFMT; Institute of Tropical Agroclimatology, Federal University of Mato Grosso)

Temperature data is available from 1st August 2006 until 1st August 2008. Precipitation data is only available for one year from 1st August 2006. Data loss for temperature from 21st December 2006 to 24th January 2007 and for precipitation the whole year 2007 until 1st August 2008 is due to technical problems of the instruments. Mean daily temperature varies between 11.5 and 32.5 °C. Friagems are clearly observable in the dry season. Mean annual precipitation of 2006 amounts to 1,250 mm.

In the Pantanal a regular collection of meteorological data is not always guaranteed. The normal climatic period of 30 years, recommended by the World Meteorological Organization (WMO) to determine a general climate, can rarely be found for the meteorological stations in the Pantanal (HECKMAN, 1998).

2.3.3 Humidity and evaporation

Figure 5 shows the mean daily relative humidity of the RPPN SESC Pantanal. Data loss is due to technical problems as well. Mean daily humidity shows a range between 28.9 and 94.3 % with a mean value of 72.2 % for the observation period from 1st August 2006 until 1st August 2008. According to GIRARD (in press), the mean monthly relative humidity in the northern Pantanal ranges from 85 % during the rainy season to below 60 % when the floodplain is dry at the end of the dry season. At nighttimes falling temperatures can increase the humidity up to 100 %. In the dry season relative humidity during daytime can drop quite low, sometimes below 30 % (HECKMAN, 1998).

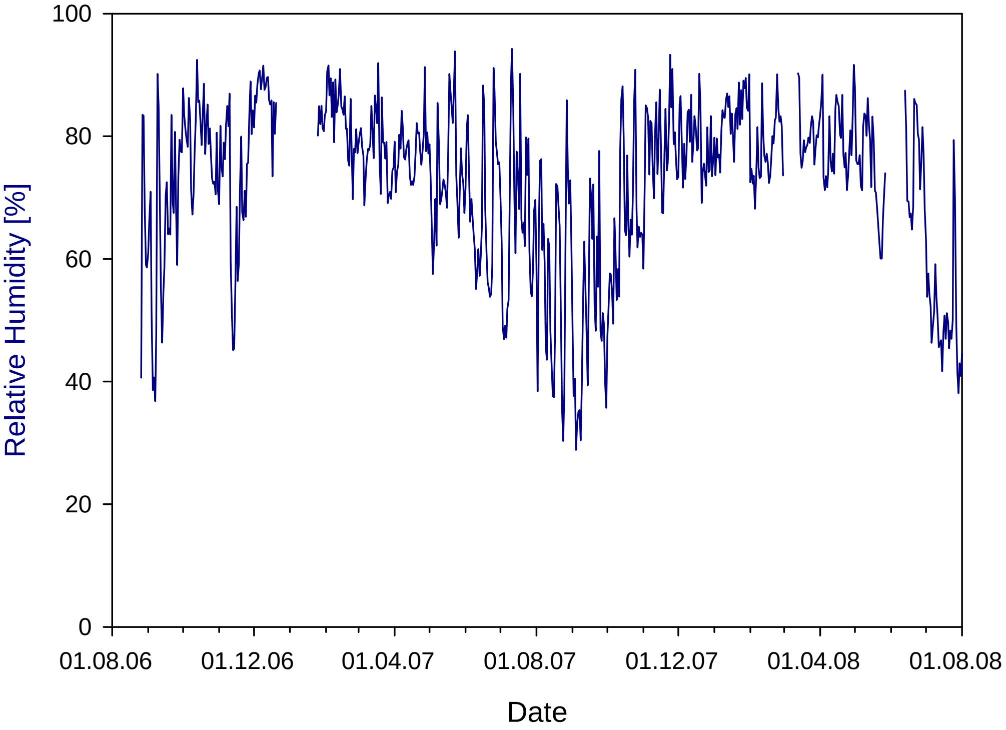

Figure 5: Mean relative humidity of the RPPN SESC Pantanal (Data source: *Instituto de Agroclimatologia Tropical*, UFMT)

In the dry season the evaporation is much higher than precipitation. Sometimes this can also happen in the rainy season (PONCE, 1995b). During at least six months of the year, evapotranspiration surpasses precipitation. Generally it amounts to between 1,100 and 1,400 mm a year (GIRARD, in press). Most of the Pantanal is characterised by a hydrological deficit of about 300 mm, which probably makes it one of the most important areas for evaporative freshwater loss worldwide (POR, 1995). Due to its location in a large basin surrounded by highlands, the Pantanal is little influenced by strong winds. Therefore, a really hot climate results in this region (HECKMAN, 1998). Nevertheless, for an increase in evaporation losses the wind conditions can be very important.

2.4 Geology

The Pantanal is located in a geological region that can be classified as a basin at the western border of the Central Brazilian Shield. This shield comprises the upland region mostly in the north and the Paraná basin in the east. The Pantanal is almost a semicircular system that is separated by a high plateau (HECKMAN, 1998). Those mountain ranges surrounding the basin are of Precambrian or Early Palaeozoic origin (POR, 1995). Locally they are rich in iron and manganese and contain large areas of calcareous rocks (KLAMMER, 1982). The immense depression of the Pantanal basin was formed during tectonic uplift associated with the Andes orogenic cycle (BEURLEN, 1970). This caused basement-rock reactivation and formed a basin with unlithified sediments (HAMILTON, 2002b). Today the foredeep of the Andes forms the western boundary. The Pantanal is characterised by so-called Horst and Graben extensional regional tectonics. In the Late Tertiary and Early Quaternary these extensional movements produced blocks separated by thrust or normal faults (BEURLEN, 1970) that have been eroded and leached for a very long period of time (HECKMAN, 1998). In the Cuiabá area crystalline basement of the ancient Precambrian Brazilian shield is outcropping within the so-called Cuiabá formation consisting of mica and sericite schists (EVANS, 1894). Quartzite and greywackes are interstratified within the Late Precambrian to Early Cambrian of the Cuiabá group. The hanging wall of this Cuiabá formation is built of three Palaeozoic to Mesozoic strata (Pantanal formation) consisting of conglomerates, quartzites, schists with tillites, limestones and dolomites and fine to coarse grained sandstones (ALMEIDA, 1965) as well as crystalline rocks (KLAMMER, 1982). In the east of Cuiabá the Sao Vincente granite has intruded into the Cuiabá formation. The youngest stratum in the Pantanal lowland is the Quarternary alluvium. Today most of the area is covered with this alluvium. Palaeozoic to Mesozoic strata is hardly outcropping and the crystalline basement blocks are still subsided (BEURLEN, 1970).

The RPPN SESC Pantanal lies within the fans of the Cuiabá River and São Lourenço River (POR, 1995). Most of the reserve is covered by the Pantanal formation. Only the Cuiabá River in the west and the São Lourenço River in the east are bordered by alluvium (figure 6).

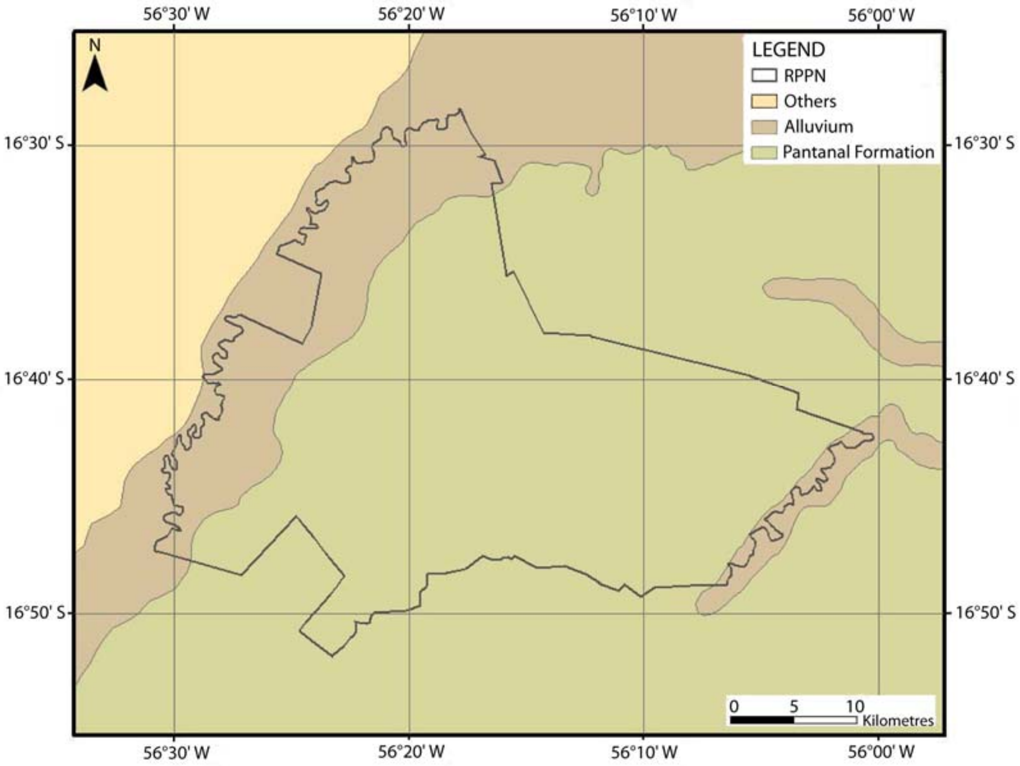

Figure 6: Geology of the RPPN SESC Pantanal
(Data source: HASENACK et al., 2003a)

2.5 Soils

Planosols, hydromorphic podsols, plinthosols, gleysols, vertisols and arenosols are the most common soil types of the Pantanal. They are closely related to the type of sediments that are deposited. In turn, those sediments are a consequence of the type of the source materials and of the processes such as deposition and sedimentation. Several alluvial deltas led to the deposition of sandy sediments (COUTO & DE OLIVEIRA, 2008). Therefore, the wetland consists of alluvial sediments and it is covered by a thin humus layer of fallen leaves from the vegetation that stabilises the soils. These layers of recent sandy deposits are up to 500 m thick. The subsurface layers are classified as loess (HECKMAN, 1994). The sediments can vary in their concentrations of sand, minerals or nutrient content (COUTO & DE OLIVEIRA, 2008). In areas subject to riverine overflow the soils contain more silt and clay. In the higher parts of the alluvial fans they tend to be sandy. Alluvial deposits with a greater distance from the main rivers are older and highly weathered (HAMILTON, 2002b).

DE OLIVEIRA et al. (2004) divide the Pantanal in four pedological zones: The study site lies within the plinthosol-planosol area which is defined as the area to the north of the São Lourenço River and includes as well Barão de Melgaço (figure 2).

Soils in the RPPN SESC Pantanal normally contain above 15 % sand and less than 35 % clay. Eutrophic and dystrophic red-yellow podsols as well as laterites and vertissols cover most of the reserve. Alic and distrofic red-yellow latosols, reddish brunisols and humid eutrofic gleys can be found as well (figure 7) (RAMSAR, 2002).

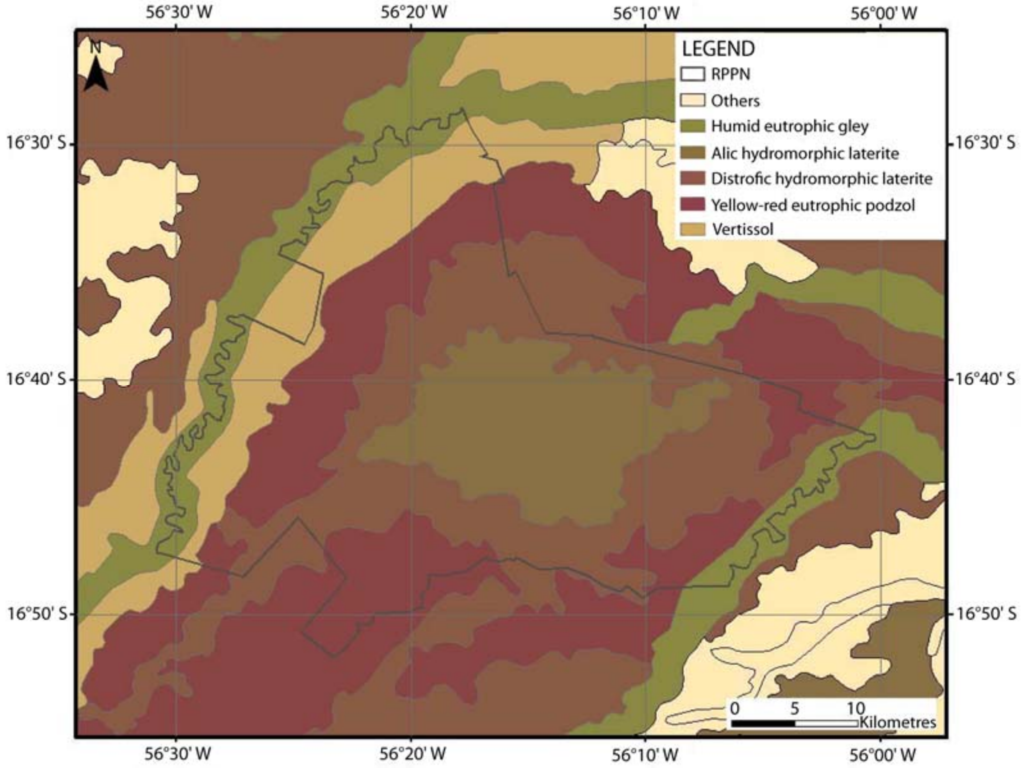

Figure 7: Soils of the RPPN SESC Pantanal
(Data source: HASENACK et al. 2003a)

2.6 Hydrology

As a consequence of its relatively small size, the hydrological value of the RPPN SESC Pantanal is, of course, limited (RAMSAR, 2002). But as part of the Pantanal wetland it shows the same hydrological functioning that will be explained in detail in the following.

The Pantanal belongs to the inland river deltas where the headwaters of the Paraguay River discharge (MITSCH et al., 1994). In the Pantanal annual flooding is the most important hydrological and ecological event (GIRARD, in press) as the wetland is a key factor of water regulation of the Paraguay River (RAMSAR, 2002). It is a riverine floodplain system, a so-called riparian wetland, and not connected to the ocean. This freshwater system is without any influence from the sea (HECKMAN, 1998). In the rainy season it acts like a huge reservoir for surface and subsurface water, which can be stored up to several years. In the dry season it releases the water back to the main channels (PONCE, 1995a). Due to the very mild relief a large amount of possible runoff is evaporating (PONCE, 1995b).

In this complex environment the *pantaneiros* came up with local terms for their water bodies. This local terminology shall be briefly explained in the following since it is used frequently in this context (POR, 1995).

Ríos are defined as rivers with defined headwaters. In the Pantanal all rivers are tributaries to the Paraguay River. Some major contributing rivers to the Pantanal are the Paraguay River, the Cuiabá River and the São Lourenço River (GIRARD, in press).

In the Pantanal wetland *baías* are shallow lakes formed by river activity. These lakes are a combination of erosional and depositional processes and many of them are formed along large rivers. Due to deposition of sediments levees are often formed. When flooded, the lakes become filled with water. This often happens in depressions. Sometimes those lakes dry out, sometimes they persist until it starts raining again after the dry season. Then, the lakes are perched above the river or remain connected to the river (HECKMAN, 1998). Classifications of floodplain lakes on the basis of their geomorphological formations are given by WETZEL (2001) and POR (1995). In the Barão de Melgaço subregion a great number of these *baías* occur, which are connected with the Cuiabá River (HECKMAN, 1998). But during the dry season they may be cut off from the river (URL 2).

2.6.1 Floodpulse

In the Pantanal one flooding takes place per year, so the floodpulse is called monomodal (JUNK et al., 1989). From year to year, floods show large differences in their amplitudes. They happen annually, but with a great variation in space and time (GIRARD, in press).

The Pantanal receives water from the highlands comprising an area twice its size as well as from rainfall directly on the floodplain (PONCE, 1995a). Therefore, seasonal flooding may be pluvial and/or fluvial in origin (POTT & POTT, 2004). There are areas that are mostly flooded by rivers and others normally flooded due to local rainfall, although their geomorphological origin may be alluvial as well (HAMILTON, 2002a).

The general direction of the water flow within the floodplain is from east to west until it reaches the Paraguay River as discharge of various tributaries (HAMILTON, 2002b). When the streams enter the Pantanal the gradient abrupt decreases and flow is drastically reduced. Consequently, deposition of sediment as well as a reduction in erosive energy occurs (TUCCI et al., 1999). During the rainy season, the floodplain is usually covered continuously with water. While the water level recedes, the water drains from the floodplain into the rivers (POR, 1995). Rocks or soil outcrops as well as very low elevation gradients can cause a backwater effect in the floodplain (GIRARD, in press). The elevation gradients in the floodplain average 25 cm/km from east to west and 2 cm/km from north to south along the Paraguay River (HAMILTON, 2002b). In the northern Pantanal inundation coincides with the wet season (HAMILTON, 2002a). In the subregion of Barão de Melgaço the inundation lasts from three to four months (URL 2).

Due to the different origins of water and the rainfall pattern in this region the wetland is characterised by four different seasons. They all show a different hydrological behaviour and are distinct from the climatological seasons. Therefore, they have to be explained individually (HECKMAN, 1998).

2.6.2 Seasons

Enchente

Between September and November, the rainy season, called *Enchente* (flood tide), starts in the Pantanal. It accompanies the period of flooding (HECKMAN, 1998). Between the onset of heavy rainfalls and flooding a time lag occurs since the water needs to discharge from the upper parts of the rivers into the Pantanal (HECKMAN, 1994). There are still numerous depressions in the floodplain that are not directly linked to the main channels at all (TUCCI et al., 1999). At the beginning of the rainy season low-lying areas and drying pools become flooded with rainwater but they may dry up after a short time without rainfall (HECKMAN, 1998). Proceeding rainfall provokes a rise of the water table and those depressions are filled with water and linked together (TUCCI et al., 1999). In the region of Barão de Melgaço isolated low hills are situated at the border of the wetland and deep depressions contain water at a depth of at least a few metres (URL 2). Concomitantly with the rising water the rivers in the upper catchment are swelling. The discharge increases but the rivers cannot convey the increased water volume. As soon as the rivers become bankful, they overflow and the long-term flooding begins (HECKMAN, 1998). The floodplain becomes covered with water depending on the connectivity between the floodplain and the main rivers. During rising water table the water usually runs from the rivers to the floodplain. Duration, extent and depths of flooding depend a lot on this connectivity between the floodplain and the river system (GIRARD, in press). More or less during January, the highest water levels are reached. At this date the season of Enchente ends, changing within weeks from year to year. Then, the rainfall occurs more frequently but less heavily and there are strong water flows in all water courses (HECKMAN, 1998).

Cheia

Usually in January the high water period, called *Cheia* (high tide, full), begins. Nearly the entire Pantanal is flooded during this time, except the levees, which are the highest elevations in the floodplain (GIRARD, in press). The water in the rivers and streams flows rapidly. In the floodplain it is lentic (HECKMAN, 1998). During the flood, the water flow direction can change several times between rivers and floodplain (GIRARD, in press). The water level normally varies between 0.5 and 2 m. It is largely determined by the rivers in the floodplain or those that are fed by rainwater on more elevated sections. During this season, daily rainfall maintains a high water level, but compared to Enchente, rainfall is moderately heavy. The differences in water temperature between day and night are small. The end of Cheia is usually between March and early April. Irregularities occur because of the highly variable rainfall pattern (HECKMAN, 1998).

Vazante

In *Vazante* (ebb tide) the water level in the Pantanal falls rapidly. There is little rainfall and it diminishes greatly (HECKMAN, 1998). The rainy season ends and an increase in direct sunlight is due to a decrease in cloud cover and relative humidity (HECKMAN, 1994). The water level in the river system is no longer high enough to flood the whole wetland. It decreases rapidly and the uppermost parts of the floodplains are completely drying up (HECKMAN, 1998). While the water level decreases, the water runs from the floodplain into the rivers via small connecting channels. In the rivers the water level is dropping more rapid than on the floodplain. The connecting channels dry up during low water or the water remains stagnant (GIRARD, in press). Water bodies are fed by the large drainage area and runoff continues while the water level steadily falls. The floodplain always shows a very thin layer of water cover in this season (HECKMAN, 1998). Fine sediments and organic matter are deposited. In periods without rainfall the water bodies lose water through evaporation and infiltration to the groundwater. Since the terrain gradient is low the infiltration to the groundwater is limited. Due to high temperatures throughout the whole year evaporation losses are very high (TUCCI et al., 1999). Until the end of April or beginning of May most of the Pantanal is dried up and the transition to the Seca begins (HECKMAN, 1998).

Seca

Seca (dry) starts in late July or early August. It is the season when the Pantanal nearly dries up (HECKMAN, 1998). Only little water is left in the main channels. Low lying sites, smaller rivers and smaller lakes dry up completely or are transformed to lentic water bodies (GIRARD, in press). However, a small part of the wetland always remains under water. With great local and annual variation the transition time from Seca to Enchente is in late October or early November (HECKMAN, 1998).

Focus of this work will be on dry season because the time period of field study was between August and October in 2008.

2.6.3 Groundwater

A wetland can have groundwater inflow and outflow, as it often happens in riparian wetlands (MITSCH & GOSSELINK, 1993). In the Pantanal generally less than 10 % of the infiltrating rainfall reaches shallow groundwater bodies at all, but the amount of infiltration can be larger in riparian forests. The groundwater flow has a very large delay reaching its natural outflow like rivers or lakes. This can happen months or years later after the event that initiated infiltration. Therefore, perennial flow in streams or rivers can be sustained or the persistence of seasonal water bodies can be maintained. Especially during the dry season, shallow groundwater plays an important role in maintaining discharge in the rivers. Furthermore, it is crucial in maintaining flood channel flow during the low water phase when the tie channels do not receive direct flow from the main channels (GIRARD, in press). GIRARD et al. (2003) describe at least two distinct floodplain aquifers in the area around the Cuiabá River, indicating confined and semi-confined conditions. They also analysed recharge conditions where flooding was the main recharge event and interactions between river and alluvium took place (GIRARD et al., 2003). Despite the importance of groundwater flows in the water budget of a wetland, there is not much information available in the literature about groundwater and aquifers in the Pantanal region.

2.6.4 Hydrochemistry

Hydrochemical conditions in water bodies of the Pantanal depend on the water quality of tributaries, dilution of rain water, evaporation and biological activity (NOGUEIRA et al., in press). The dry season is the only time of the year when some interesting changes in the water chemistry occur. Before the lentic water bodies dry up, water temperature rises and the content of organic and inorganic components increases tremendously. Especially in the dry season, evaporation happens very quickly (HECKMAN, 1998) and can cause an increase in the electrolyte content and pH (NOGUEIRA et al., in press). However, most of the values for specific conductivity in water bodies in the northern Pantanal are considerably low. There is lack of soluble salts due to the age of the substrate. Soluble substances have been leached out for a long time and rain is the major source of minerals (HECKMAN, 1998). Nevertheless, measurements of Pantanal rain show very low conductivities between 10 and 20 µS/cm (NOGUEIRA et al., in press). The streams flowing into the Pantanal, so-called *Cerrado* streams, are not rich in ions any more due to the local geology (HECKMAN, 1998). WANTZEN (2003) characterises Cerrado streams with extremely low conductivity < 7.5 µS/cm and neutral or acidic pH values. Ranges of temperatures, specific conductivity and pH values for springs in the northern Pantanal are given by HECKMAN (1998). The range of temperature lies between 28 and 30.3 °C, for specific conductivity between 12 and 76 µS/cm and for pH between 5.7 and 5.9. MITAMURA et al. (1985) measured river conductivities around 40 µS/cm of the Paraguay River and others. Concerning the water quality, great extremes in oxygen concentrations can occur during the dry season (HECKMAN, 1998). NOGUEIRA et al. (in press) state that excretes of animal source can play a major role in nutrient dynamics. Especially in shallow lakes the influence of animals can be high. Nevertheless, HECKMAN (1994), SAIJO et al. (1997) and ABDO & DA SILVA (2004) find NO_3^- values, which are lower than 3.3 mg/l. Samples from various water bodies show that there is no natural contamination of metals. Only gold, iron and manganese are metals known to be present (HECKMAN, 1998).

2.7 Landscape and vegetation

It is difficult to group the Pantanal to any vegetation classification scheme. The landscape shows a spatial heterogeneity that is related to the diversity of the geomorphic features (COUTO & DE OLIVEIRA, 2008). Nevertheless, many authors define the Pantanal as “Hyperseasonal savannah” or “Seasonal savannah” (ZEILHOFER & SCHESSL, 1999).

A variegating flora can be found, which consists of more than 200 species of flowering plants and hundreds of endemic grass species as well as lots of different types of forest. A detailed study about vegetation with the most common species, a few of which are considered nationally endangered, has been carried out in various studies by NUNES DA CUNHA & JUNK (2001), DA SILVA (2001), RAMSAR (2002) and POTT & POTT (2004). Where water is permanent, a plentiful variation of aquatic vegetation, including floating vegetation, occurs. The appearance of different vegetation is very dynamic and the alterations depend on seasonal and annual hydrological cycles (POTT & POTT, 2004).

Figure 8 shows the different types of vegetation in the RPPN SESC Pantanal. The centre portion of the RPPN SESC Pantanal is covered by a variety of *Cerrado* forms, a seasonal type of savannah. 45 % of the study area is covered by open *Cerrado* (savannah) and by very dense *Cerradão* (dense wooded savannah), 24 % by *Matas* (forests), 10 % by *Campos* (flat savannah areas that are seasonally flooded) and *Capões* (prairies). Another 6 % of the area is covered by *Campo limpos* (without shrubs and trees) and *Campo sujos* (with shrubs and trees), 4 % consists of aquatic vegetation and 10 % of degraded land (RAMSAR, 2002).

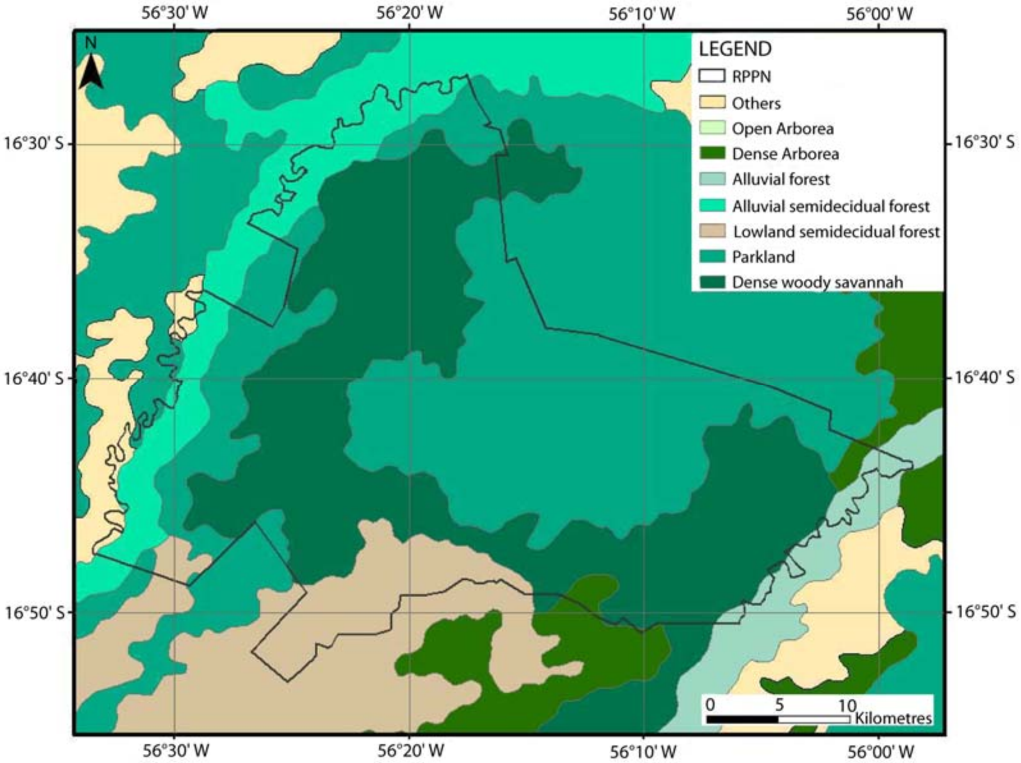

Figure 8: Vegetation of the RPPN SESC Pantanal
(Data source: HASENACK et al. 2003a)

Besides the *Cerrado* there is a great variability of other habitats (COUTO & DE OLIVEIRA, 2008):

- *Cordilheiras* and *capões* (macro elevations and remnants of paleo-levees covered with forest, reaching 1 m above the mean flood level),
- *Campo murundus* (termite mounds, micro elevations),
- *Lundis* (seasonally inundated channels with a close connection to the groundwater table covered with forest),
- *Baías*,
- *Brejos* (permanent swamps),
- *Corixos* (permanent small drainage channels inside the floodplain) and
- *Ríos*

2.8 Land use and threats

Since the RPPN SESC Pantanal has become a protected area there is no land use in the reserve at all. Due to very high temperatures in the dry season and lots of dry material, natural fires frequently occur. During the study period, fires occurred from 2nd to 5th September 2008 in the RPPN SESC Pantanal. While turning off the fires the fence of the reserve needed to be opened. This is why some cattle could enter the reserve and was there until the end of the experimental study in the field.

Furthermore, there are threats that do not only concern the reserve but the area as part of the whole Pantanal. LAABS et al. (2002) for example discuss the increase in pesticide use due to intensive agriculture in the highland region which lead to an increased amount of nutrients in the rivers and consequently this affects the Pantanal. Other serious dangers for the Pantanal ecosystem are proposals or projects of regional economic development that have already been implemented. Examples are dams for electricity production or flood control in the area and further constructions on the rivers in the Pantanal (GIRARD, 2002). Such plans can reduce the area of the Pantanal and therefore result in a reduction of the water volume (HECKMAN, 1998). If the drainage system increased its transport capacity this would be harmful for the area because of channel dredging, removal of flow constructions or dams. Wetland would transform into savannah if the floodplain area was reduced (TUCCI et al., 1999).

Details about anthropogenic effects can be found in the research carried out by GOTTGENS et al. (2001), GIRARD (2002), DA SILVA (2001), GIRARD (in press) or HAMILTON (2002a). The hydrological impact of the *Hidrovia* (waterway in Spanish and Portuguese) Project on the Pantanal is studied and analysed in detail by PONCE (1995a) or HAMILTON (1999).

All these anthropogenic effects are a severe danger for all habitats of the ecosystem in this region.

3 Methodology

3.1 Field methods

3.1.1 Water quality measurement

For in-situ measurements of water quality parameters two multiprobes (DS5 and MS5) of Hydrolab® were applied. Both multiprobes are equipped with five sensors for use in the field. With the multiprobes water quality parameters of five water bodies were measured in-situ. The DS5 was installed in only one water body for long term measurements (approximately 2 months) of water quality parameters. The MS5 was used for short term measurements (24 hours respectively) in four different water bodies. Table 1 displays the sensor options, which are the same for MS5 and DS5, indicating their range, accuracy and resolution (HYDROLAB, 2006).

Table 1: Sensor options for DS5 and MS5

Sensor	Range	Accuracy	Resolution
Temperature	-5 to 50 °C	± 0.1 °C	0.01 °C
pH	0 to 14 units	± 0.2 units	0.01 units
Spec. Conductance	0 to 100 mS/cm	1 % of reading or ± 0.001 mS/cm	0.0001 units
Clark Cell Dissolved Oxygen	0 to 50 mg/l	± 0.2 mg/l at ≤ 20 mg/l ± 0.6 mg/l at >20 mg/l	0.01 mg/l
Nitrate	0 to 100 mg/l-N	greater of ± 5 % of reading or± 2 mg/l-N	0.01 mg/l-N

Unfortunately there are no boreholes in the RPPN SESC Pantanal, so it was not possible to measure the water quality of groundwater with the multiprobes.

3.1.2 Water sampling

A total of 70 samples of groundwater (four samples), rainfall (one sample) and water of nine different water bodies (65 samples) were collected in order to analyse them for stable isotopes of water (^{18}O and ^{2}H). Samples were taken within four measuring periods between August and October 2008. All samples of the water bodies were collected at about 1 m from the shoreline and at a depth of about 10 cm. Water was collected in plastic sampling bottles in the magnitude of 20 ml and stored in the refrigerator as soon as possible. Due to problems with the power generator of *Espírito Santo* the refrigerator was not always working properly. Therefore, not all samples could be stored in a cool place at all times. All samples collected from the RPPN SESC Pantanal were transported to Germany on 14th October 2008. Sampling times in this work are always given in Amazon Summer Time (AMST), which corresponds to UTC-3.

3.2 Field work

3.2.1 Multiprobes

DS5

The multiprobe DS5 was calibrated for the first time on 6th August 2008 following the User's manual of HYDROLAB (2006) in the soils laboratory of the UFMT. Calibration standards of pH and specific conductivity were taken from the soils laboratory. Unfortunately, the standards of the soils laboratory had expired in 2004 but they were the only standards available. The NO_3^- calibration standard was recently prepared by laboratory staff. However, calibration for all parameters was successful. The calibrated DS5 was carried into the reserve on 7th August 2008 and installed on the same day in *Imbauval* (figure 9). In order to install the DS5 water tons were fixed on a pole in the lake. The tons were equipped with a box in which the external car battery was put. This car battery was charged by a solar cell on the top of the box (annex C). The parameter setup of the multiprobe was configured by the Ott software HYDRAS 3 LT. To store data in the multiprobe, log files were created. On the same day the DS5 was started for the first time to log water quality parameters every 15 minutes with a sensor warm up of two minutes. The circulator was always started one minute before logging. This circulator was used for additional flow in order to achieve reliable readings. Afterwards, the following water quality parameters were logged:

- Temperature [°C]
- pH [Units]
- Specific conductivity [µS/cm]
- Dissolved oxygen [DO in % Sat, mg/l]
- Nitrate [NO_3^- in mg/l, mV]

Furthermore the log files contained logging time and date, the status of the external battery and the circulator status.

MS5

The multiprobe MS5 was brought to Brazil from the Institute of Hydrology (IHF) of the University of Freiburg, Germany. It was calibrated for the first time as the DS5 in the soils laboratory of the UFMT and re-calibrated again every time before the next measuring period. Log files were created in the same manner as described above. The water quality parameters were the same as indicated above and were logged every 15 minutes with a sensor warm up of one minute. The circulator was always started one minute before logging too. Unlike the DS5, the MS5 has an optional internal battery pack for 8 size AA alkaline batteries that was used in the field.

3.2.2 Problems

Maintenance of the multiprobes was difficult due to logistical problems because the RPPN SESC Pantanal is located 200 km away from the UFMT at Cuiabá. It was not possible to stay the whole three months in the reserve. Therefore, the maintenance of the probes had to be done during the stay in the RPPN SESC Pantanal, which sometimes did not happen at regular intervals. As a result their uses in surface water, the probes were exposed to mud, dirt and siltation which led to data loss during the time period of field study (annex C).

DS5

The DS5 had to be cleaned every two or three weeks as described in the User's manual (HYDROLAB, 2006). It was cleaned whenever possible in intervals of three to four weeks. After cleaning, the multiprobe was calibrated again in the reserve. The DS5 functioned properly in the first three weeks. Afterwards, there were two days with overcast sky. During this time the solar cell did not provide enough energy to the battery and the logging process stopped. The battery was very old and after this first interruption of logging, it was replaced. The DS5 used a lot of energy so additionally the sensor warm up was changed to one minute before logging. In spite of this precaution a lot of data loss still occurred due to energy problems.

Furthermore, DO and NO_3^- sensors were strongly clogged. Therefore, they did not work properly. Since data loss of those two parameters happened frequently, the DO and NO_3^- sensor had to be replaced. The electrolyte for the oxygen sensor had to be replaced twice, which always took one day as the membrane needed more than four hours to relax prior to calibration (HYDROLAB, 2005).

NO_3^- values in mg/l were never indicated in the log file. Consequently, there were only values in mV given for *Imbauval* from 7th August until 25th August 2008. Therefore, establishing a correlation between mV and mg/l was not possible and this is why the data serious could not be completed. However, such a correlation could be established for NO_3^- data registered by MS5, which will be explained below. Unfortunately, this correlation could not be applied to the DS5 because correlated values were not plausible. Therefore, NO_3^- concentrations of *Imbauval* in mg/l had to be discarded.

MS5

The status of the internal batteries was hardly ever displayed in the log file. There was no indication about the battery status. This error could not have been rectified. Fortunately, they had to be replaced only once, so there was only data loss for one night. DO and NO_3^- sensors were also very sensible and did not work properly. There was data loss due to those two sensors and the electrolyte for the oxygen sensor had to be replaced too. Additionally, data loss of NO_3^- in mg/l was indicated in the log file. But as mV was given every time, missing mg/l values could be completed on the basis of a correlation between NO_3^- values that were recorded in both units, mV and mg/l. Correlations were generated for every measuring period and showed coefficients of determination, which were always higher than 0.89. They are given in the annex (B.1).

3.2.3 Sampling locations for in-situ measurement

Figure 9 shows the five different sampling locations for in-situ measurements.

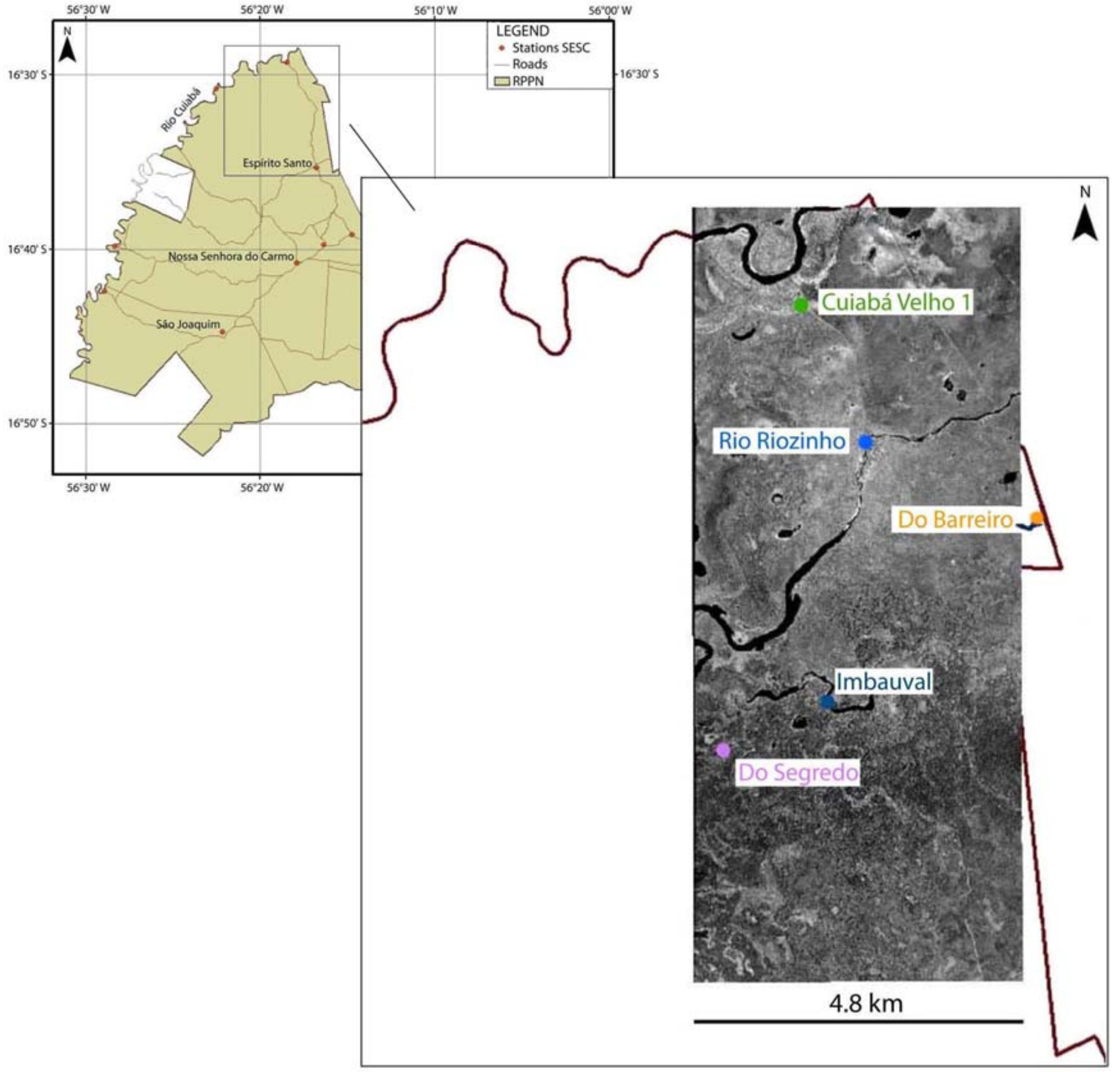

Figure 9: Location of the five sampling points for in-situ measurement (Data source: HASENACK et al., 2003a, and IKONOS Satellite Imaging Corporation, URL 3)

Those five water bodies in the northern RPPN SESC Pantanal were selected mainly due to the fact that they were easy reachable, which is the most important criterion in this inaccessible area.

Imbauval

Imbauval is the largest water body in the study area, covering an area of about 0.18 km². In the rainy season it has an outlet to *Rio Riozinho*, but in the dry season it is cut off from its main channel. Some macrophytes are covering its surface. Water quality parameters of *Imbauval* are measured with the DS5 within a depth of 60 cm.

Do Barreiro

The sampling point is located on the eastern site of *Do Barreiro* at a place, which is always shaded by vegetation. Macrophytes are covering the lake very densely. The MS5 was installed in *Do Barreiro* in a depth of 20 cm. Unfortunately, a satellite image for *Do Barreiro* is not available.

Do Segredo

The sampling location is situated on the western margin of *Do Segredo*, which is the southernmost sampling site of the five water bodies. In the dry season it is cut off from *Rio Riozinho*. Unfortunately, it was not possible to determine the maximum depth of *Do Segredo* since there was no boat available to measure it. But it was estimated by UFMT staff to be about 2 m. Some macrophytes are covering the shore of *Do Segredo*. Water quality parameters are measured with the MS5 in a depth of 30 cm.

Rio Riozinho

Rio Riozinho is a tributary of the Cuiabá River flowing from north-east to south-west. In the dry season, it is cut off from the Cuiabá River due to a decreasing water level. Then, this river also acts nearly like a lentic water body. Its flow is very slow and practically not visible. Water quality parameters are measured with the MS5 at a depth of 40 cm. *Rio Riozinho* is covered by macrophytes and the density and location of coverage depends on the wind conditions.

Cuiabá Velho 1

The sampling point is located in the northern part of the lake, whose water shows always a high turbidity due to suspended sediments. There is no aquatic vegetation in *Cuiabá Velho 1*. In earlier times *Cuiabá Velho 1* was part of the Cuiabá River, lying in an old oxbow lake, which is as well responsible for its name. According to calculations, an area of 300 m² is the smallest lake of those five sampling sites. Water quality parameters are measured with the MS5 at a depth of 20 cm.

Morphometric characteristics and satellite imagery were used to describe the water bodies in detail. It was difficult to distinguish the area of such small water bodies from satellite images and therefore the values given are only estimations. The volume could not be exactly determined as the depth of the lakes could only be estimated. The surface area of each water body was calculated by a GIS (Geographical Information System). It is clearly not possible to determine the maximum width, area and volume of the rivers. A definition of the water body characteristics is given by WETZEL (2001): The maximum length is the distance on the lake surface between the two most distant points on the lake shore. The maximum width is the maximum distance on the lake surface at a right angle to the line of the maximum length between the shores. Table 2 indicates the maximum width, maximum length, area, depth and volume of the five water bodies. All values are only approximations for the dry season.

The RPPN SESC Pantanal has an altitude ranging between 107 and 117 m a.s.l. Unfortunately, it was not possible to determine the exact altitude of the water bodies since the GPS has an error range between 8 and 12 m a.s.l. However, their altitude ranges between 112 and 122 m a.s.l.

Table 2: Sampling sites with its morphometric characteristics (n.m. = not measurable)

Sampling Site	Width [m]	Length [m]	Area [m²]	Depth [m]	Volume [m³]
Imbauval	3200	120	181000	2	362000
Do Barreiro	500	50	26000	0.5	~13000
Rio Riozinho	n.m.	110	n.m.	2.5	n.m.
Do Segredo	390	35	10000	2	20000
Cuiabá Velho 1	50	10	300	< 0.5	~120

In *Imbauval* data was collected continuously using the DS5, whereas for *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1* data was collected with the MS5 over a period of five days each time (table 3). Measuring started with *Do Barreiro* for one day, continuing with *Do Segredo* on the following day, *Rio Riozinho* on the following and *Cuiabá Velho 1* on the last day. This loop was replicated another four times from 1st August until 15th October 2008. The following exceptions occurred:

- 3rd and 4th September were switched due to logistical problems
- On 15th September the DO sensor had to be changed and calibrated again
- 18th and 19th September were switched as well because the multiprobe had to be left one day longer in *Do Segredo*. Due to a dense carpet of macrophytes *Rio Riozinho* was not passable with the boat and thus *Do Segredo* could not be reached (annex C).

Table 3: Sampling times of short term measurement

Sampling site	1. loop	2. loop	3. loop	4. loop	5. loop
Do Barreiro	29.08.08	02.09.08	12.09.08	17.09.08	07.10.08
Do Segredo	30.08.08	04.09.08	13.09.08	19.09.08	08.10.08
Rio Riozinho	31.08.08	03.09.08	14.09.08	18.09.08	09.10.08
Cuiabá Velho 1	01.09.08	06.09.08	16.09.08	20.09.08	10.10.08

3.2.4 Water sampling points

Water body samples

Nine water bodies, two rivers and seven shallow lakes, were chosen within the northern RPPN SESC Pantanal, among other reasons, due to their easy reachability as well (figure 10). The five water bodies from the in-situ measurements were the same as the water bodies for water sampling.

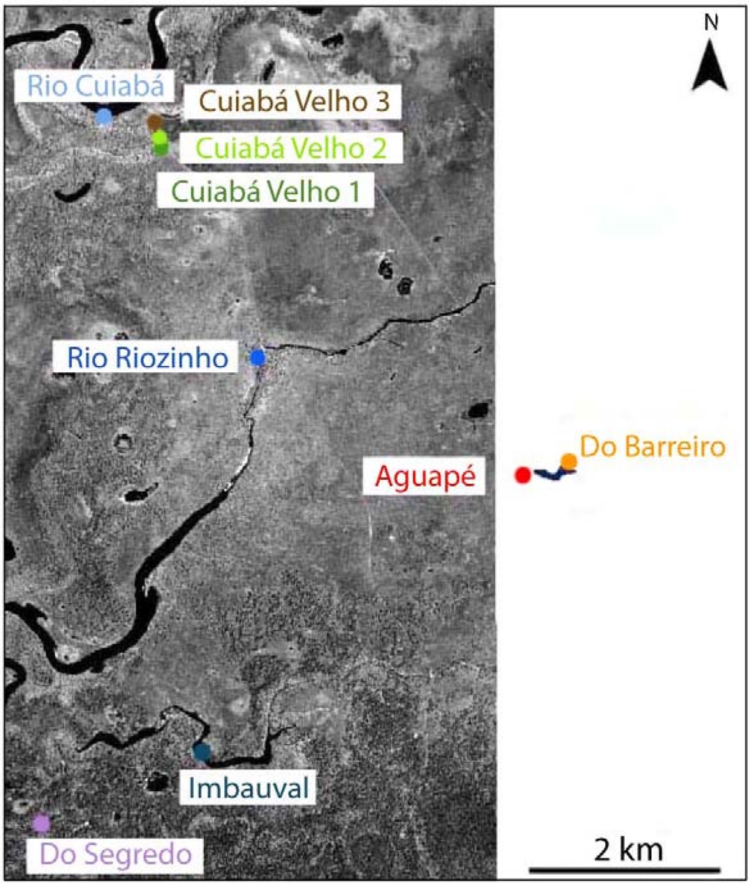

Figure 10: Location of the nine sampled water bodies (Data source: IKONOS Satellite Imaging Corporation, URL 3)

Samples were taken during four measuring periods between 5th August and 11th October 2008. Water samples were collected whenever possible on a basis of intervals ranging from one day to three weeks. Two samples, one sample of groundwater from *Espírito Santo* and one sample of *Imbauval*, were taken outside those measuring periods on 19th August 2008 from UFMT staff (figure 11). The coordinates of all sampling points are given in the annex (A.2). Table 4 displays the morphometric characteristics for the remaining water bodies. Unfortunately, it was not possible to assess *Aguapé* for estimating its size in the field. Therefore no statements can be given about its area and volume.

Table 4: Morphometric characteristics of the remaining water bodies (n.a. = not assessable)

Sampling Site	Width [m]	Length [m]	Area [m²]	Depth [m]	Volume [m³]
Aguapé	n.a.	n.a.	n.a.	0.3	n.a.
Cuiabá Velho 2	50	10	500	< 0.5	~250
Cuiabá Velho 3	20	6	120	< 0.5	~60

Precipitation and groundwater samples

There was only one rainfall event during the field study in the RPPN SESC Pantanal in the night from 20th to 21st September 2008. Unfortunately, it was not possible to measure the amount of rainfall since the measuring instruments in the climate tower did not work. However, it can be said that there was very little rainfall. The rain water was collected over night in an open plastic box close to *Espírito Santo* (figure 3) and filled into a sampling bottle at 06.05 AMST when the rain had already stopped.

Four groundwater samples were collected at two different stations in the reserve. Three samples in *Espírito Santo* and one sample in *São Luiz* (figure 3). The stations have groundwater wells, which pump water into a storage tank to supply the households with water for domestic use. In *São Luiz* water is pumped continuously and one groundwater sample could have been collected from the freshly pumped groundwater. Unfortunately, in *Espírito Santo* there is always water in the tank since water is pumped every one to three days in the morning even if the well is not yet empty. Hence, the three groundwater samples could not be collected from the freshly pumped groundwater. Furthermore, the wells are closed with a tab at every time and evaporation losses are minimal. Therefore the isotopic composition should represent the groundwater composition very well.

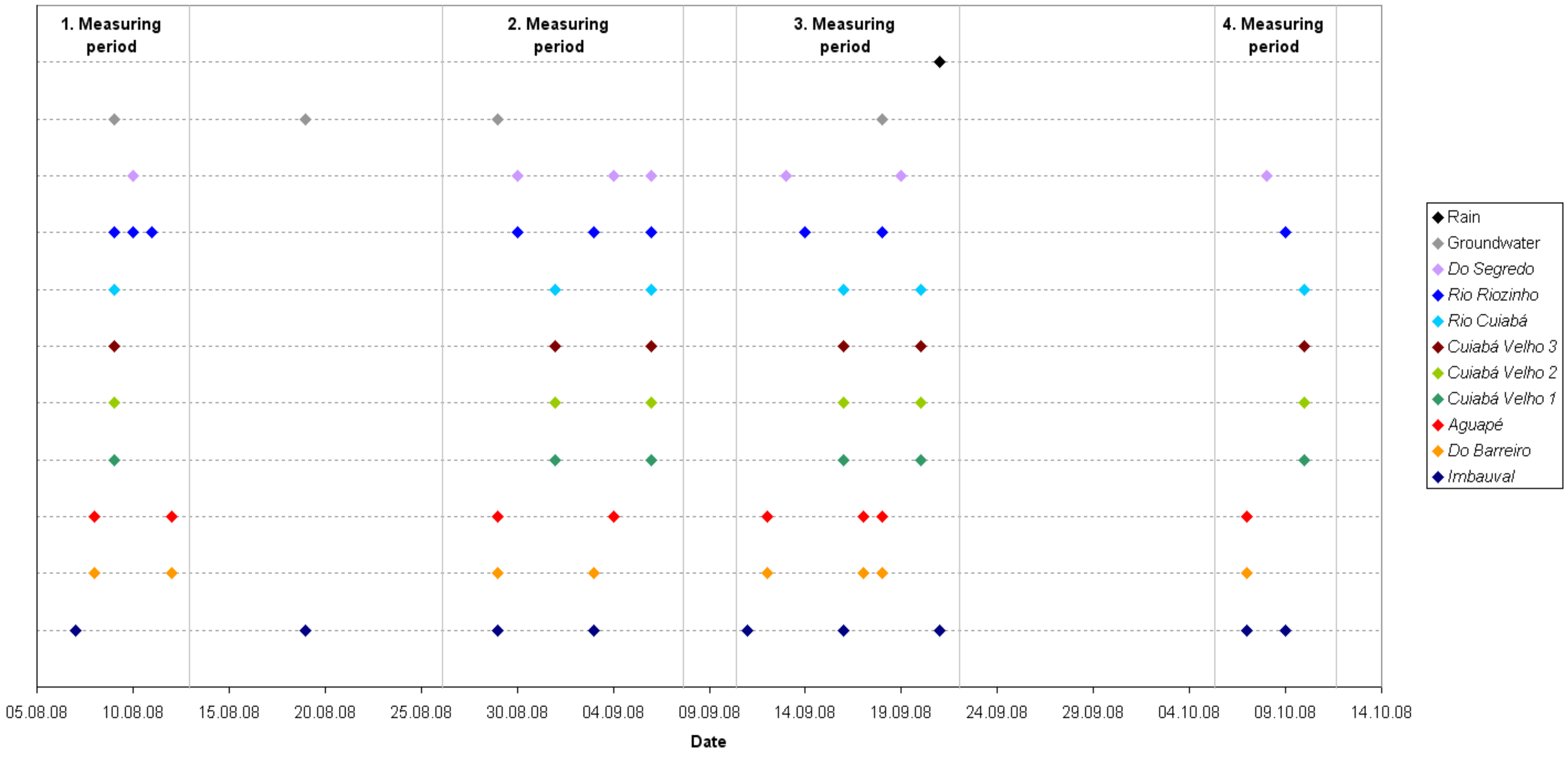

Figure 11: Schedule of water sampling within the four measuring periods in the RPPN SESC Pantanal

3.3 Environmental isotopes

For the investigation of natural hydrological systems it is necessary to obtain a better knowledge of the different processes that take place during the analysis of alternations in stable isotopes. They are defined as materials that occur naturally in the environment and are brought into the system mostly through precipitation or dry deposition. Furthermore, they can be detected easily and in very small amounts (CLARK & FRITZ, 1997). Stable isotopes of the water molecules were used in this work and will be described in the following.

3.3.1 Delta notation

Isotopes of an element have the same chemical characteristics but different nuclear masses. Isotopic concentrations are calculated in ‰ as the difference between the measured ratio and a given standard, divided by the standard. Mostly the given reference is the Vienna Standard Mean Ocean Water (VSMOW) (CLARK & FRITZ, 1997):

$$\delta_{\text{sample}} = \left(\frac{R_{\text{sample}} - R_{\text{reference}}}{R_{\text{reference}}} \right) \cdot 1000 \tag{1}$$

with:

$$R = \frac{^{18}O}{^{16}O} \tag{2}$$

or:

$$R = \frac{^{2}H}{^{1}H} \tag{3}$$

where δ_{sample} is the isotopic composition of a sample and R the measured ratio of less and most abundant isotopes. Due to modern measuring techniques, variations in isotope abundance can be detected with high precision (CLARK & FRITZ, 1997).

3.3.2 Global Meteoric Water Line

CRAIG (1961) discovered that on a global scale, world wide measurements of precipitation plot on the Global Meteoric Water Line (GMWL):

$$\delta^{2}H = 8 \cdot \delta^{18}O + 10 \tag{4}$$

where δ values describe the isotopic composition of $\delta^{18}O$ and $\delta^{2}H$ and 10 is the so-called deuterium excess. Regional isotopic compositions can differ throughout the world. Then, local rainfall plots on a Local Meteoric Water Line (LMWL), which deflects from the GWML in another deuterium excess. Variations in $\delta^{18}O$ and $\delta^{2}H$ values that result in a deviation from the GMWL are mainly influenced by rainout or evaporation.

3.3.3 Isotope fractionation

Stable isotopes show different reaction tendencies of fractionation due to different nuclear masses. Those variations of the stable isotopes of water are caused by meteoric processes. Therefore, water of a particular environment has a characteristic isotope signature. Fractionation processes modify the ratio of isotopes slightly by transition from one state in another, from liquid to vapour for example. Higher binding energies of the heavier isotope explain this phenomenon. More energy is needed to bring them from one energetic level to another, so they change their state less easy than the lighter isotopes. Larger fractionation effects generally occur during lower temperatures. Isotopic fractionation is expressed by the fractionation factor α (DANSGAARD, 1964):

$$\alpha = \frac{R_{reactant}}{R_{product}} \tag{5}$$

According to DANSGAARD (1964), there are five fractionation effects, which result in ratio variations of stable isotopes due to fractionation during changes of state:

- Continental effect: Depletion of $\delta^{18}O$ and $\delta^{2}H$ values of precipitation with increasing distance from the coast
- Altitude effect: Decreasing $\delta^{18}O$ and $\delta^{2}H$ values of precipitation with increasing altitude
- Latitude effect: Decreasing $\delta^{18}O$ and $\delta^{2}H$ values of precipitation with increasing latitude
- Amount effect: Decreasing $\delta^{18}O$ and $\delta^{2}H$ values of precipitation with increasing amount of a precipitation event
- Seasonal effect: Increasing amplitude of seasonal variation in the temperature pattern of a site. The greater the seasonal extremes in temperature the stronger the seasonal variations in $\delta^{18}O$ and $\delta^{2}H$ values of precipitation.

Fractionation can be in equilibrium or kinetic. Under equilibrium conditions the rates of forward and backward reactions are the same. Under kinetic conditions the forward reaction exceeds the backward reaction. Diffusive fractionation is a kinetic process and is based on different diffusive velocities between different isotopes (CLARK & FRITZ, 1997). During the evaporation process of water there is additionally this kinetic effect causing variation in the fractionation of ^{18}O and ^{2}H. This leads to an enrichment of heavy isotopes in the residual liquid as evaporation moisture flux is depleted in $\delta^{18}O$ and $\delta^{2}H$ (GAT, 1995). This evaporatively enriched water plots on a local evaporation line (LEL) (figure 12).

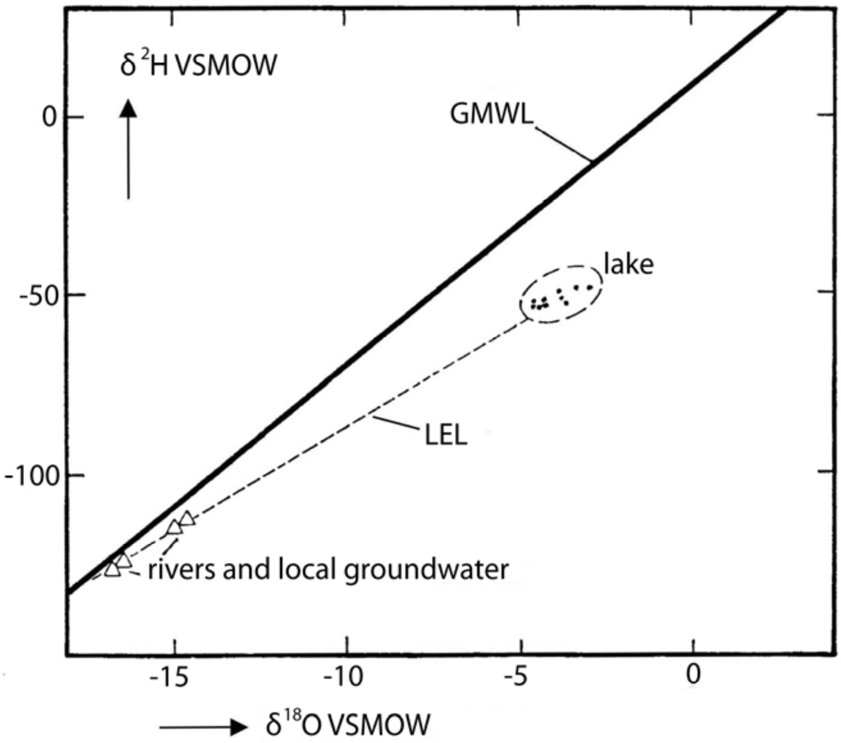

Figure 12: $\delta^{18}O$- $\delta^{2}H$ relationship for enriched water samples of a tropical lake, its feeding rivers and local groundwater (modified from ROZANSKI et al. 2000)

Within one region this LEL shows a characteristic slope between 3.9 and 6.8 (CLARK & FRITZ, 1997).

For the RPPN SESC Pantanal a regression curve was fitted for each water body due to the six to nine water samples in order to construct a LEL. Its slope is the weighted average of slopes of the different regression curves from all water bodies, given in the annex (B.2).

This weighted average finally leads to a slope of 5.1 and then the equation of the LEL is:

$$\delta^{2}H = 5.1 \cdot \delta^{18}O + 10 \tag{6}$$

This slope represents well a typical slope of evaporating water for central South America, as it can be found in the study of MARTINELLI et al. (1996) for the Amazon basin.

3.3.4 Source isotopic composition

For all 70 samples a back extrapolation was calculated to the GMWL to correct the sample values in order to obtain the source isotopic composition (GEYH & PLOETHNER, 1997):

$$\delta^{18}O_{corrected} = \frac{\delta^{2}H_{measured} - s_e \cdot \delta^{18}O_{measured} - d}{8 - s_e} \tag{7}$$

where s_e is the slope of the local evaporation line ($s_e = 5.1$) and d the deuterium excess of global precipitation ($d = 10$). Those corrected values indicate the isotopic composition without enrichment due to evaporation. Then, the source isotopic composition marks the intersection with the GMWL. The $\delta^{18}O$ value is calculated from equation (7) and the corresponding $\delta^{2}H$ value can be obtained by the solution of equation (4). The corresponding values are given in the annex (B.3).

3.4 Laboratory analyses

3.4.1 IRMS

The analysis of $\delta^{18}O$ was conducted by the Isotope Mass Spectrometer Type Delta S (IRMS) in the laboratory of the IHF at the Albert-Ludwigs-University of Freiburg, Germany. Its precision for $\delta^{18}O$ is 0.2 ‰. This value is determined on the basis of long term measurements of different laboratory standards.

3.4.2 TDLAS

The analysis of $\delta^{2}H$ was conducted by a Liquid Water Isotope Analyzer with the Tunable Diode Laser Absorption Spectrometry (TDLAS) in the laboratory of the Institute of Hydrology in Freiburg as well. The precision of this device is 0.6 ‰ (LOS GATOS RESEARCH, 2008).

3.4.3 IC

The analysis of anions was conducted with an ion chromatograph (IC) DX 500. Since the collected water volume was not sufficient to analyse cations and anions, only nitrate (NO_3^-), chloride (Cl^-) and sulphate (SO_4^{2-}) were analysed. These anions were selected in order to check whether the NO_3^- values measured by the multiprobes were correct. Different calibration standards between 0.5 – 100 mg/l are used in one measuring series. All samples were filtered by a 0.45 µm membrane and analysed in the same measuring series. The precision for the anions lies around 5 %. Bicarbonate

(HCO_3^-) cannot be analysed by IC and there was not a sufficient water volume for determining HCO_3^- by titration. During the interpretation of major anions it has to be taken into account that the water samples had not been stored in a cool place at all times.

The isotopic composition of all water samples as well as values of Cl^-, NO_3^- and SO_4^{2-} are given in the annex (A.3 and A.4).

3.5 Identification of hydrological systems

When investigating the hydrological dynamics of a water body, it is essential to apply methods, which give a rough assessment on the type of system. In the case of lakes, the question in this work is whether the lake is mainly controlled by evaporation or by inflow and outflow. Even with only a small number of samples and without any information about the studied system, it is possible to gain a first insight into the hydrological functioning of a lake. Thereby, the dynamic depends on the hydrology and the local climate (ROZANSKI et al., 2000). The two rivers, *Rio Cuiabá* and *Rio Riozinho*, cannot be considered any further because the methods used are not applicable to rivers. Normally, water balance studies with environmental tracers are used for lake identification. But sufficient information for establishing a whole water balance for the Pantanal water bodies is rare. Therefore three different methods are used to assess general lake dynamics. Firstly, the potential evaporation was calculated on a physical basis. Secondly, a chloride mass balance approach was applied as an independent method to understand the impacts of evaporation on the hydrochemistry of a lake. Finally, it was assessed whether the system is evaporation controlled or a throughflow system, using a simplified tracer approach of general water balances.

3.5.1 Open water evaporation

To determine the loss of water due to evaporation from the different water bodies, potential evaporation is determined on a physical basis. Thereby, the approach of SHUTTLEWORTH (1993) for estimating the evaporation rate from open water is used. This approach is an implementation of the Penman-Monteith Equation on the basis of the Reference Crop Evaporation Equation. It was chosen, firstly, because it is one of the most physically based methods for calculating evaporation and the most widely used. Secondly, it provides good evaporation estimates, compared to those determined by other methods (DINGMAN, 2008).

The evaporation rate E_p in mm can be calculated from (SHUTTLEWORTH, 1993):

$$E_p = F_p{}^1 \cdot A + F_p{}^2 \cdot D \qquad (8)$$

where the coefficient F_p^1 is a function of temperature and the elevation of the site, A is the energy available for evaporation in mm/d, the coefficient $F^2{}_p$ is a function of temperature, wind speed and the elevation of the site and D is the vapour pressure deficit in kPa. F_p^1 can be calculated from:

$$F_p^{\,1} = \frac{\Delta}{\Delta + \gamma} \tag{9}$$

where Δ is the gradient of the function de_s/dT and γ is the psychrometric constant. Δ in kPa/°C is derived from:

$$\Delta = \frac{4098 \cdot e}{(237.7 + T)^2} \tag{10}$$

where e_s is the saturated vapour pressure in kPa, which is related to the air temperature T in °C:

$$e_s = 0.6108 \cdot \exp\left(\frac{17.27 \cdot T}{237.3 + T}\right) \tag{11}$$

For T data of the mean value of air temperature in °C is used from the climate tower of the RPPN SESC Pantanal (annex A.1). The psychrometric constant in kPa/°C can be derived from:

$$\gamma = 0.0016286 \cdot \frac{P_a}{\lambda} \tag{12}$$

where λ in MJ/kg is the latent heat of vaporization of water, calculated from:

$$\lambda = 2.501 - 0.002361 \cdot T_W \tag{13}$$

where T_W is the surface temperature of the water in °C. Thereby, mean values of all water bodies are used for T_s. P_a is the atmospheric pressure in kPa, derived from:

$$P_a = 101.3 \cdot \left(\frac{293 - 0.0065 \cdot Z}{293}\right)^{5.256} \tag{14}$$

where Z is the elevation of the site with 118 m a.s.l. as a mean value for the study area. A is defined by:

$$A = R_n + A_h \tag{15}$$

where R_n is the net radiation in MJ/m² · d and A_h in MJ/m² is the sensible heat transferred into the lake. R_n can be calculated from:

$$R_n = S_n + L_n \tag{16}$$

where S_n is the net short-wave radiation and L_n is the long-wave radiation. S_n in MJ/m² · d can be derived from the following equation:

$$S_n = S_t \cdot (1 - \alpha_r) \tag{17}$$

where α_r is the short-wave radiation reflection coefficient. For open water it is defined by $\alpha_r = 0.08$. S_t in MJ/m² · d is the total incoming short-wave radiation, according to:

$$S_t = \left(a_s + b_s \frac{n}{N} \right) \cdot S_0 \tag{18}$$

where a_s and b_s are the fraction of extraterrestrial radiation. For average climates they are defined by $a_s = 0.25$ and $b_s = 0.5$. n/N is the cloudiness fraction with n the bright sunshine hours per day and N the total day length in hours. S_0 is the extraterrestrial solar radiation in MJ/m² · d, calculated on the basis of latitude, day of the year, sunset hour angle and solar declination. L_n in MJ/m² · d is defined by:

$$L_n = -f \varepsilon' \sigma_B (T + 273.2)^4 \tag{19}$$

where f is the adjustment for cloud cover, calculated from:

$$f = 0.9 \cdot \frac{n}{N} + 0.1 \tag{20}$$

ε' is the net emissivity between the atmosphere and the ground, derived from:

$$\varepsilon' = 0.34 - 0.14 \cdot \sqrt{e} \tag{21}$$

where e is the vapour pressure in kPa. e is calculated from:

$$e = e_s \cdot \frac{h}{100} \tag{22}$$

where e_s is calculated from equation (11) and h is the relative humidity in %. Data for h is taken from the climate tower in the RPPN SESC Pantanal as well. σ_B is the Stefan-Boltzmann constant with $\sigma_B = 4.903 * 10^{-9}$ MJ/m² · K^4 · d and T is the mean air temperature in °C. Since the evaporation rate is calculated on a daily basis there is no need to consider A_h. In the RPPN SESC Pantanal during the field study the weather conditions are very constant. Therefore the sensible heat transferred into the lake during the day equals the sensible heat that is used for heating the water body. Then, the coefficient $F_p{}^2$ is:

$$F_p{}^2 = \frac{\gamma}{\Delta + \gamma} \cdot \left(\frac{6.43 \cdot (1 + 0.536 \cdot U)}{\lambda} \right) \tag{23}$$

where U is the wind speed in m/s. The values are taken from the climate tower in the RPPN SESC Pantanal. D in kPa can be calculated from:

$$D = \left(\frac{e_s(T_{max}) + e_s(T_{min})}{2} \right) \cdot \frac{(1-h)}{100} \tag{24}$$

where T_{max} and T_{min} are the maximum and minimum air temperature in °C. The values for maximum and minimum air temperature are taken from the climate tower in the RPPN SESC Pantanal as well. Finally the evaporation rate can be calculated from equation (8) (SHUTTLEWORTH, 1993). The values of potential evaporation calculated for each day of the field study are listed in the annex (B.4).

3.5.2 Chloride mass balance

To link water chemistry and isotope hydrology an independent method is used on the basis of a mass balance approach. Cl^- is a conservative tracer and can be an indication for evaporation (SIMMERS, 2003). With measured Cl^- concentrations it is possible to evaluate whether Cl^- enrichment is taking place due to evaporation only or whether the system has significant inflow and/or outflow rates, which can greatly affect water chemistry as well. Therefore, this method delivers insight into the type of hydrological system on the basis of hydrochemistry data.

The chloride mass balance is based on the fact that the input of Cl^- results from precipitation. It has to be excluded that deposition of Cl^- during the time period of field study takes place. If no additional uptake of Cl^- occurs through overland flow and subsurface inflow as another source of Cl^- can be neglected, the increase of the Cl^- concentration in a water body is an indicator of the degree of evaporation (SIMMERS, 2003).

The chloride mass balance equation is:

$$c_i \cdot V_i = c_f \cdot V_f \tag{25}$$

where c is the Cl^- concentration in mg/l, V is the volume of the water body, which is the average depth in mm if surface area changes can be neglected, and subscribts i and f stand for initial and final Cl^- concentrations. Thereby, final Cl^- concentrations are calculated for each time period between the water samples. Those final Cl^- concentrations are theoretical values calculated assuming that only evaporation leads to an enrichment of Cl^- concentrations.

The Cl^- concentrations from the first water sample of each water body were taken as the initial Cl^- concentration. The initial volumes are given in table 2 and table 4. The final volume is calculated for the time steps between each water sample with the physical approach for estimating evaporation by subtracting evaporation rates from the initial water volume. Thereby, evaporation losses for each water body are cumulated for the time period between each water sample. Then, the remaining water level in mm can be derived. Solving equation (25) led to the calculation of the final Cl^- concentration. Those calculated values are given in the annex (B.5).

3.5.3 Simplified tracer approach

Simplified approaches for identifying the lake system are normally based on water balance tracer approaches, which can be found numerously in the literature (GAT, 1981, GONFIANTINI, 1986, or ROZANSKI et al., 2000). Especially floodplain lakes represent a special case where water bodies follow their hydrological and isotopic evolution from a filled stage into a dry period. Therefore, the water bodies in the northern RPPN SESC Pantanal can be seen as transient water bodies (GAT, 1995).

The higher the role of evaporation in the water balance the larger the enrichment of stable isotopes in the lake (GAT, 1995). On the basis of a law of mass conservation the water balance of a lake is determined as:

$$\frac{dV_L}{dt} = I_S + I_G + P - O_S - O_G - E \qquad (26)$$

where V_L is the lake volume, I_S and I_G are the inflow of surface and groundwater, P is precipitation, O_S and O_G are the outflow of surface and groundwater and E is evaporation. All parameters in mm are functions of time t.

Parameters from equation (26) have to be known to calculate the water budget. On the basis of the mass conservation law for the constituents of the water molecule the tracer approach can be written in the following form (ROZANSKI et al., 2000):

$$\delta_L \frac{dV_L}{dt} + V_L \frac{d\delta_L}{dt} = \delta_{IS} I_S + \delta_{IG} I_G + \delta_P P - \delta_{OS} O_S - \delta_{OG} O_G - \delta_E E \qquad (27)$$

where δ values in ‰ represent the concentration of ^{18}O and ^{2}H for all components of the lake system. For the application of mass balance equations following assumptions have to be made (ROZANSKI et al., 2000):

- The lake has to be well mixed, so the isotopic composition of the groundwater outflow is equal to the isotopic composition of the lake water ($\delta_{OG} = \delta_L$)
- The isotopic composition of the surface outflow is also identical to the isotopic composition of the lake water ($\delta_{OS} = \delta_L$)

In the case of the water bodies in the RPPN SESC Pantanal there is also missing information for establishing a whole water balance. To apply a simplified approach for identifying the lake system and gain insight into the role of the components within a water balance, following assumptions have to be made:

- The lake system has to be hydrologically and isotopically in a steady state
- Mean annual water temperature of the lake is identical to the mean annual surface air temperature in the area
- The weighted mean isotopic composition of annual precipitation is equal to the isotopic composition of the shallow groundwater in this area
- The mean isotopic composition of the atmospheric water vapour above the lake is in isotopic equilibrium with the local precipitation

In order to quantify the ratio F of total inflow I to evaporation E, equation (28) was applied for the lakes in the northern Pantanal to identify whether evaporation or inflow prevails in a studied system. Concerning those two components of the water balance, it is assumed that a lake reaches a steady state in the end of the dry season. Then, the F ratio calculated on the basis of the last water sample of a lake represents the general dynamic concerning inflow and evaporation of the system. Furthermore, this ratio is useful to gain insight into the hydrological characteristics of water bodies. Since outflow did not have an effect on isotopic compositions of the lake, there is no need to consider the outflow within this simplified approach. F is derived from (modified from GAT & BOWSER, 1991):

$$F = I/E = \frac{(\delta_A - \delta_I - \varepsilon/h)}{(\delta_L - \delta_I - 1)} \cdot \frac{h}{1-h} \tag{28}$$

where δ_A, δ_I and δ_L are the isotopic compositions of ambient moisture, total inflow and the lake. All these isotopic signatures are used in ‰. ε is the total isotopic separation factor in ‰ and h is the relative humidity in %.

Figure 13 illustrates the steady state $\delta^{18}O$ isotope enrichment of a lake water as a function of humidity deficit and the ratio F of total inflow to evaporation rate (ROZANSKI et al., 2000).

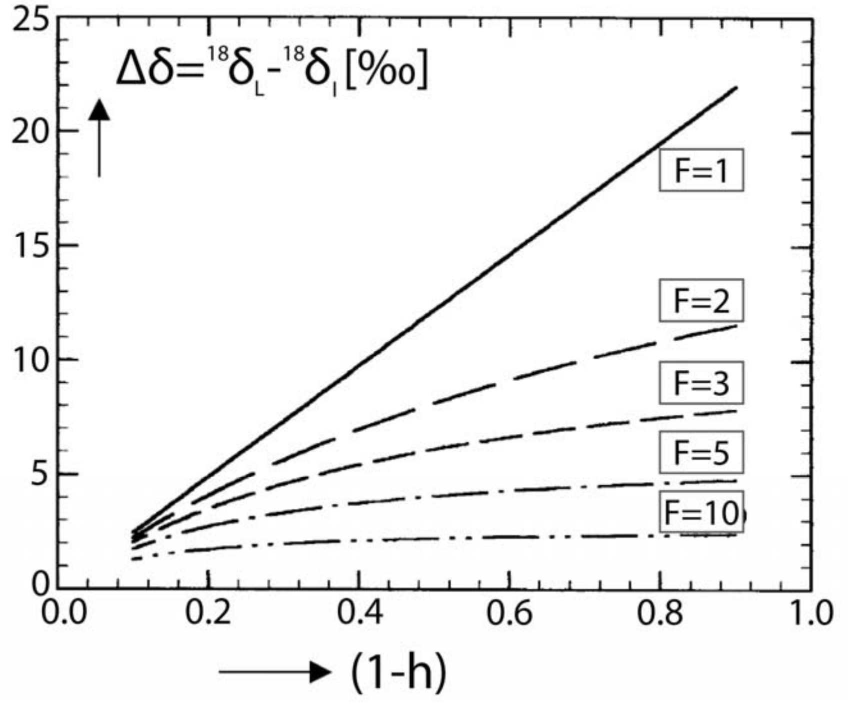

Figure 13: Steady state $\delta^{18}O$ isotope enrichment of a lake water as a function of humidity deficit and ratio of total inflow to evaporation rate (modified from ROZANSKI et al., 2000)

The isotopic composition of the ambient moisture usually is in equilibrium with the isotopic composition of precipitation (ROZANSKI et al., 2000). However, during the field study precipitation did not take place for months. Hence, isotopic equilibrium of ambient moisture with precipitation cannot be assumed.

Throughout this work δ_A values have been calculated with respect to the different types of surface covers within the RPPN SESC Pantanal. In the dry season the isotopic content of ambient moisture is not only in equilibrium with precipitation. It is also influenced by the isotopic composition of the lake water. Therefore, it was calculated as a weighted mean value by looking at the contribution of the lake water to the ambient moisture as well. The calculation is given in the annex (B.6). This was done by calculating the area covered by vegetation and by water, expressed by a surface cover coefficient σ. For the area covered by vegetation it is assumed that the isotopic composition of ambient moisture is in equilibrium with precipitation. For the area covered by water it is assumed that the isotopic signature of ambient moisture is in equilibrium with the lake water.

Thus, δ_A can be calculated as a mean value of isotopic composition in equilibrium with precipitation and the water of the lake:

$$\delta_A = \sigma \cdot \left(\delta_I + \varepsilon^*\right) + (1-\sigma) \cdot \left(\delta_L + \varepsilon^*\right) \tag{29}$$

where σ is 0.933 calculated for the northern RPPN SESC Pantanal and ε* is the separation factor for equilibrium fractionation in ‰. The calculation of ε* is described below in equation (33). δ_I values have been calculated as a weighted mean value of the mean isotopic composition of precipitation from Cuiabá (Data source: National Institute of Meteorology (*INMET – Instituto National de Meteorologia*, precipitation data from 1991 to 2007 and from 1970 to 1977, URL 4) and *Instituto de Agroclimatologia Tropical*, UFMT). This mean value corresponds well with the isotopic composition of groundwater sampled in the RPPN SESC Pantanal. Values of δ_L have been measured by IRMS and TDLAS (section 3.4). The total isotopic separation factor ε in ‰ can be calculated from (GONFIANTINI, 1986):

$$\varepsilon = \varepsilon_K + \varepsilon^* \tag{30}$$

where ε_K and ε* are the separation factors for kinetic and equilibrium fractionation in ‰, respectively. ε_K is calculated

for ^{18}O from:

$$\varepsilon_K = 14.2 \cdot (1-h) \tag{31}$$

and for ^{2}H from:

$$\varepsilon_K = 12.5 \cdot (1-h) \tag{32}$$

Those ε_K values can be seen as representative of typical lake evaporation (GONFIANTINI, 1986). Data of relative humidity is taken from the climate tower within the RPPN SESC Pantanal and is available every 15 minutes. Mean values between 05:00 and 20:00, when evaporation mainly takes place, were derived from the time period between two water samples for every water body, respectively. ε* can be calculated from (CRAIG & GORDON, 1965):

$$\varepsilon^* = \left(\alpha_{v/l} - 1\right) \cdot 1000 \tag{33}$$

where $\alpha_{v/l}$ is the fractionation factor of liquid water (subscript l) with respect to water vapour (subscript v). MAJOUBE (1971) determined the temperature dependence of $\alpha_{v/l}$ experimentally.

Then, it can be calculated
for ^{18}O from:

$$\ln^{18}\alpha_{v/l} = -\ln^{18}\alpha_{l/v} = -2.0667 \cdot 10^{-3} + \frac{0.4156}{T_W} - \frac{1.137 \cdot 10^{3}}{{T_W}^{2}} \tag{34}$$

and for ^{2}H from:

$$\ln^{2}\alpha_{v/l} = -\ln^{2}\alpha_{l/v} = -52.612 \cdot 10^{-3} + \frac{76.248}{T_W} - \frac{24.844 \cdot 10^{3}}{{T_W}^{2}} \tag{35}$$

where T_W in K is the absolute water temperature, which is a mean value for each water body on the basis of the multiprobe data. With all those parameters F can be calculated from equation (28). If evaporation losses are known, inflow rates can be derived from this approach as well.

Uncertainty analysis

While studying the hydrological lake systems with a tracer approach, it is very important to estimate the accuracy of its components. The uncertainties are derived from isotope data and their sensitivity to changes of the measured parameters has to be assessed. Knowledge of the uncertainties is often incomplete, which makes the quantification difficult. However, it can be estimated by a simplified method, which is based on a sensitivity analysis. The simplified tracer approach is calculated for a realistic range of parameters. The impact of higher or lower values on calculated F ratios can be asymmetric and therefore have to be tested as well. Thereby, key variables can be identified and the magnitude of the uncertainty can be assessed (ROZANSKI et al., 2000). Table 5 shows the error range for each parameter of the simplified tracer approach. The uncertainty of h was computed as the standard deviation of mean daily values of measured data during the time period of field study. The uncertainty of T_W for *Imbauval* was calculated as the standard deviation on the basis of values measured every 15 minutes. The uncertainties of T_W for *Do Barreiro*, *Cuiabá Velho 1* and *Do Segredo* were calculated as the standard deviation of the five measured days by the MS5 on the basis of values measured every 15 minutes. T_W for *Aguapé*, *Cuiabá Velho 2* and *3* were derived from fitting a sinus function on values measured by the MS5 for half an hour, once in the morning and once in the afternoon. Thereby the uncertainty of T_W is the standard deviation from such calculated water temperatures. The uncertainties of δ_L and δ_I were computed as the standard deviation from all isotopic compositions of lake water and precipitation from Cuiabá. The uncertainties of δ_A, $\sigma\ \delta_A$, $\alpha_{v/l}$, ε_K, ε^* and ε were derived for each water body from the propagation of uncertainty after Gauss on the basis of the values calculated from the simplified tracer approach.

Table 5: Uncertainties for ^{18}O and ^{2}H parameters of simplified tracer approach

Parameter	**Uncertainty for ^{18}O**	**Uncertainty for ^{2}H**
h	± 15 %	± 15 %
T_W *Imbauval*	± 1.44 °C	± 1.44 °C
T_W *Do Barreiro*	± 1.15 °C	± 1.15 °C
T_W *Aguapé*	± 2.17 °C	± 2.17 °C
T_W Cuiabá *Velho 1*	± 4.06 °C	± 4.06 °C
T_W Cuiabá *Velho 2*	± 2.96 °C	± 2.96 °C
T_W Cuiabá *Velho 3*	± 1.54 °C	± 1.54 °C
T_W *Do Segredo*	± 1.73 °C	± 1.73 °C
δ_L	± 0.2 ‰	± 0.6 ‰
δ_I	± 0.3 ‰	± 1.24 ‰
δ_A	± 0.04 ‰	± 0.36 ‰
$\sigma\ \delta_A$	± 0.04 ‰	± 0.67 ‰
$\alpha_{v/l}$ *Imbauval*	± 0.0001	± 0.0001
$\alpha_{v/l}$ *Do Barreiro*	± 0.0001	± 0.0001
$\alpha_{v/l}$ *Aguapé*	± 0.0002	± 0.0002
$\alpha_{v/l}$ *Cuiabá Velho 1*	± 0.0004	± 0.0004
$\alpha_{v/l}$ *Cuiabá Velho 2*	± 0.0003	± 0.0003
$\alpha_{v/l}$ *Cuiabá Velho 3*	± 0.0002	± 0.0002
$\alpha_{v/l}$ *Do Segredo*	± 0.0002	± 0.0002
ε_K *Imbauval*	± 0.87 ‰	± 0.77 ‰
ε_K *Do Barreiro*	± 0.76 ‰	± 0.67 ‰
ε_K *Aguapé*	± 0.79 ‰	± 0.70 ‰
ε_K *Cuiabá Velho 1*	± 0.77 ‰	± 0.67 ‰
ε_K *Cuiabá Velho 2*	± 0.77 ‰	± 0.67 ‰
ε_K *Cuiabá Velho 3*	± 0.77 ‰	± 0.67 ‰
ε_K *Do Segredo*	± 0.92 ‰	± 0.81 ‰
ε^*	± 0.00 ‰	± 0.00 ‰
ε *Imbauval*	± 0.38 ‰	± 0.29 ‰
ε *Do Barreiro*	± 0.29 ‰	± 0.22 ‰
ε *Aguapé*	± 0.31 ‰	± 0.24 ‰
ε Cuiabá *Velho 1*	± 0.29 ‰	± 0.23 ‰
ε Cuiabá *Velho 2*	± 0.29 ‰	± 0.23 ‰
ε Cuiabá *Velho 3*	± 0.29 ‰	± 0.23 ‰
ε *Do Segredo*	± 0.43 ‰	± 0.33 ‰

3.6 Model application: MINA TrêS

Since the simplified tracer approach shows large uncertainty ranges for its parameters, a simple mass balance model was employed to assess inflow rates as accurately as possible in order to determine all components of the water balance for the lakes. The model is two-dimensional and considers essentially horizontal flow into the water bodies. Concerning the water balance equation (27), evaporation losses E are taken from the Penman-Monteith approach (section 3.5.1). The isotopic composition of evaporative flux has already been calculated from the simplified tracer approachX. Since there was only once very little rainfall during the field study, there is no need to consider precipitation P as part of inflow during the dry season. Furthermore, the water bodies do not have feeding rivers or outlets in the dry season. Therefore, subsurface inflow still needs to be determined because outflow is assumed to be equal to inflow. In order to estimate this component of the water balance, the model MINA TrêS (Model for INflow Assessment, três: Portuguese for three Simulations) was applied, which requires three types of input data for the simulation: Cl^- concentrations and stable water isotope fractions of $\delta^{18}O$ and δ^2H. In this study, the idea was to calibrate the output modelled by MINA TrêS to observed data to investigate inflow rates in an inverse sense with own concentrations of Cl^- and isotopic signatures of $\delta^{18}O$ and δ^2H, respectively.

The concentration c_p (Cl^- concentration and stable isotope fractions of $\delta^{18}O$ and δ^2H) of a lake can be predicted for each day by the following equation:

$$c_p V_p = c_i V_i + c_I I - c_p O - c_E E \tag{36}$$

where V_p is the predicted lake volume, c_i and V_i are initial concentration and volume of the lake, c_I is the concentration of inflow I, O stands for outflow with the predicted concentration c_p, c_E is the concentration of evaporative flux and E stands for evaporation. Concentrations are given in mg/l for Cl^- and in ‰ for $\delta^{18}O$ and δ^2H. As a result, the lake volume, inflow, outflow and evaporation are calculated in mm for each day between first and last water sample of each water body.

Assuming stationary conditions with a constant and spatially uniform inflow and outflow per unit area, the remaining water volume of the lake V_p can be determined after equation (26) where V_p corresponds with V_L. Thereby, it is assumed that inflow and outflow are equalizing. c_i is the measured Cl^- concentration and isotopic composition of $\delta^{18}O$ and δ^2H of the first water sample of each lake, respectively. The concentrations are given in the annex (A.3 and A.4). V_i has been estimated for each water body and values are listed in table 2. c_E is 0 in the case of Cl^- because there is no loss of Cl^- through evaporation. For stable isotopes c_E values can be taken from the tracer approach, calculated from equation (30) where c_E corresponds with ε. For E values of potential evaporation are taken from the Penman-Monteith approach. Since outflow with the predicted lake concentration c_p is assumed to be equal to inflow, only inflow I and its concentration c_I has to be determined.

Subtracting c_p from the measured lake concentration c_L and dividing it by the mean value of c_p, the absolute value of this relative difference should be minimised for Cl^- and the isotopic signatures of $\delta^{18}O$ and δ^2H, respectively, in order to get an adequate fit of predicted and measured lake concentration. Hence, MINA TrêS uses the Add-In “Solver” for Microsoft® Office Excel 2003 for fitting. The precondition for the Solver was to minimise the sum of the calculated differences as absolute values. Thereby, following assumptions have to be made:

- V_i can vary within a range of ± 10 %
- I is equal for all three simulations
- I is constant
- I is >= 0
- I = O
- c_p has at least the lowest Cl^- concentration of sampled groundwater, which is 0.97 mg/l

Only the volume V_i, inflow I, the corresponding Cl^- concentration and the $\delta^{18}O$ value were alterable within the Solver. Assuming that inflow consists only of groundwater, the δ^2H value was derived from equation (4). Further options of the Solver were set to 5000 iterations, an accuracy of 0.01 mg/l and ‰, respectively, and a tolerance of 2 %.

For two water bodies, *Imbauval* and *Do Segredo*, it was not possible to assess inflow rates with the described model, indicated by simulating out of the range isotopic compositions. Therefore, MINA TrêS was improved by not fulfilling any more the assumption of equal inflow and outflow rates in each time step. Then, the volume V_i, inflow I, the corresponding Cl^- concentration, the $\delta^{18}O$ value and in addition the outflow O were alterable within the Solver. For the outflow O no additional constraint was determined. The δ^2H value was derived from equation (4) as well. All other assumptions remained constant as well as the Solver settings described above.

4 Results

4.1 Water chemistry

4.1.1 Short term measurement

Temperature

Figure 14 displays the water temperature of the four water bodies measured by the MS5. All water bodies demonstrate a daily variation, but with different peak times in the afternoon. Their mean values for water temperature differ as well in a few degrees. They are 23.1 °C for *Do Barreiro*, 26.7 °C for *Do Segredo*, 27.8 °C for *Rio Riozinho* and 24.8 °C for *Cuiabá Velho 1*. *Do Barreiro* shows temperature peaks between 15:30 and 17:15 except for the 7th October when its peak is a little bit earlier around 14:45. Water temperature ranges between 20.9 and 25.7 °C. For *Do Segredo* and *Rio Riozinho* water temperature acts in the same manner showing peaks at the same time as *Do Barreiro*. For *Do Segredo* water temperature peaks are found between 14:00 and 15:45, for *Rio Riozinho* between 15:00 and 17:45. They only differ in their ranges of temperature, which are 22.9 to 30.8 °C for *Do Segredo* and 25.7 to 30.3 °C for *Rio Riozinho*.

Water temperature of *Cuiabá Velho 1* indicates a different behaviour. Peaks are found between 12:45 and 14:30 up to more than two hours earlier relative to the other water bodies. Its water temperature ranges between 18.7 and 37.8 °C, showing the largest variation over all water bodies.

Temperature differences during the five measured days of *Do Barreiro* and *Rio Riozinho* are very small. For *Do Segredo* those differences are a little larger. However, the largest differences between the five measured days can be found in *Cuiabá Velho 1*. There is no consistence between the five measured days within one loop for all water bodies. That means for example, the first measured day for *Do Barreiro*, *Do Segredo* and *Rio Riozinho* show nearly lowest water temperatures of all measured days. For *Cuiabá Velho 1* it was the day with the second warmest water temperatures. The measured day of the fifth loop indicates the warmest water temperatures for *Do Barreiro*, *Rio Riozinho* and *Cuiabá Velho 1*, but for *Do Segredo* a day from another loop shows warmest water temperatures.

The mean water temperature and the range of the five measured days for *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1* are listed below in table 6.

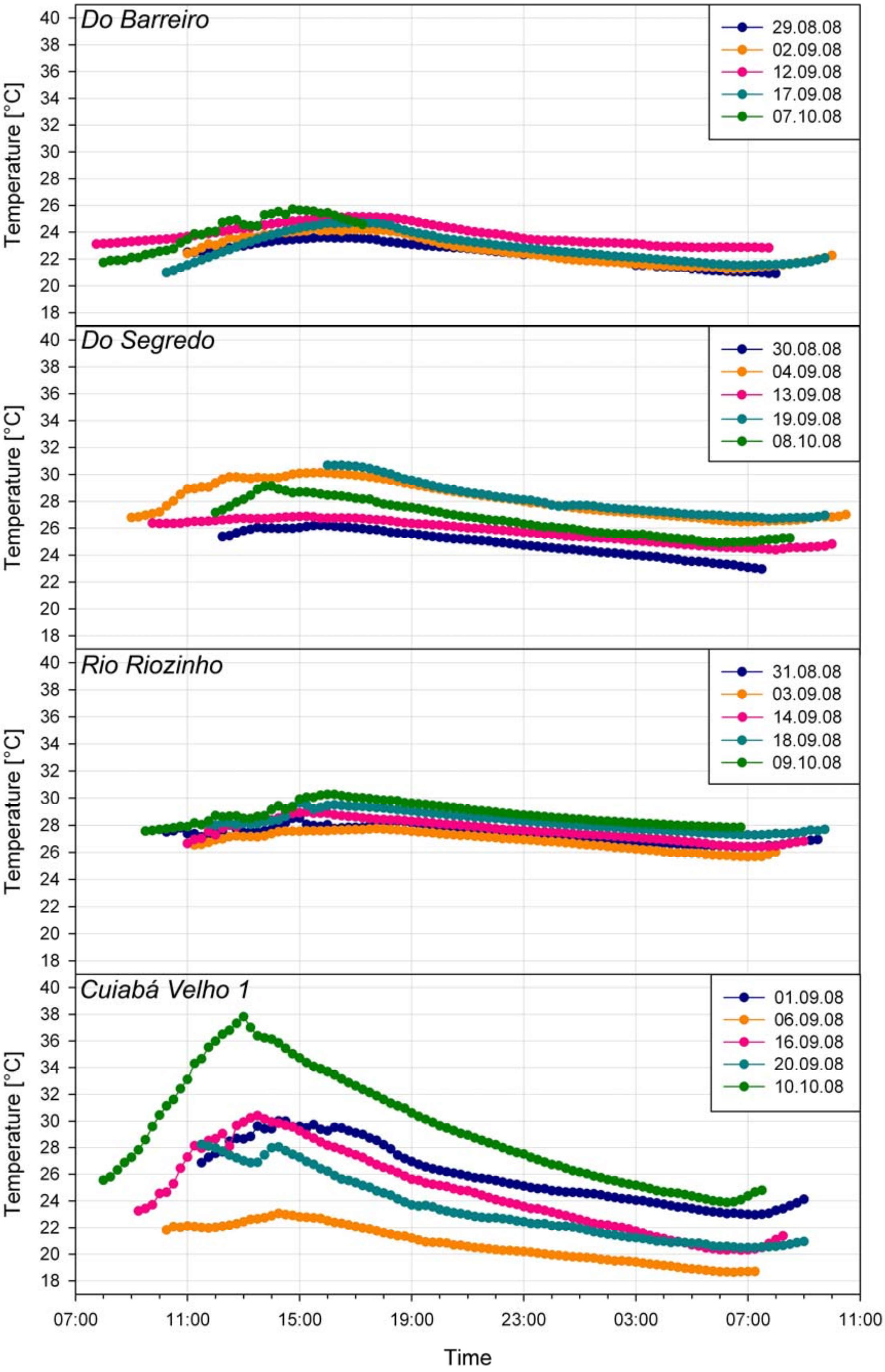

Figure 14: Water temperature of *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1*

Table 6: Mean values and range of water temperature

Water body	Mean water temperature [°C]	Range of water temperature [°C]
Do Barreiro	23.1	20.9 to 25.7
Do Segredo	26.7	22.9 to 30.8
Rio Riozinho	27.8	25.7 to 30.3
Cuiabá Velho 1	24.8	18.7 to 37.8

pH

Figure 15 displays pH values of the four water bodies measured by the MS5. *Do Barreiro*'s mean daily pH values range between 5.8 and 6.1. Due to the measurement accuracy it can be assumed that the pH value of *Do Barreiro* does not change largely. Mean daily pH values of *Do Segredo* and *Rio Riozinho* indicate the same behaviour, ranging between 5.8 and 6.3 for *Do Segred*o and between 6.5 and 7.1 for *Rio Riozinho*. Daily variations are not identifiable because they are within the accuracy range. Mean pH values are 5.9 for *Do Barreiro*, 6.1 for *Do Segredo* and 6.8 for *Rio Riozinho*.

Only *Cuiabá Velho 1* again shows different mean daily pH values relative to the other water bodies. These range between 6.8 and 9.5 with a mean pH value of 7.7. It is the only water body having strongly alkaline pH values in the RPPN SESC Pantanal. Furthermore, there are large daily differences between the five measured days in *Cuiabá Velho 1*. Peaks of pH are between 12:00 and 15:00, falling again at nighttime until 07:00. However, all five data series demonstrate peak values in the earlier afternoon decreasing to the smallest values at nighttime or early morning. pH values indicate a decline during several hours between peak times until around midnight.

Mean pH values and the range of the five measured days for *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1* are listed in table 7.

Table 7: Mean values and range of pH

Water body	Mean pH	Range of pH
Do Barreiro	5.9	5.8 to 6.1
Do Segredo	6.1	5.8 to 6.3
Rio Riozinho	6.8	6.5 to 7.1
Cuiabá Velho 1	7.7	6.8 to 9.3

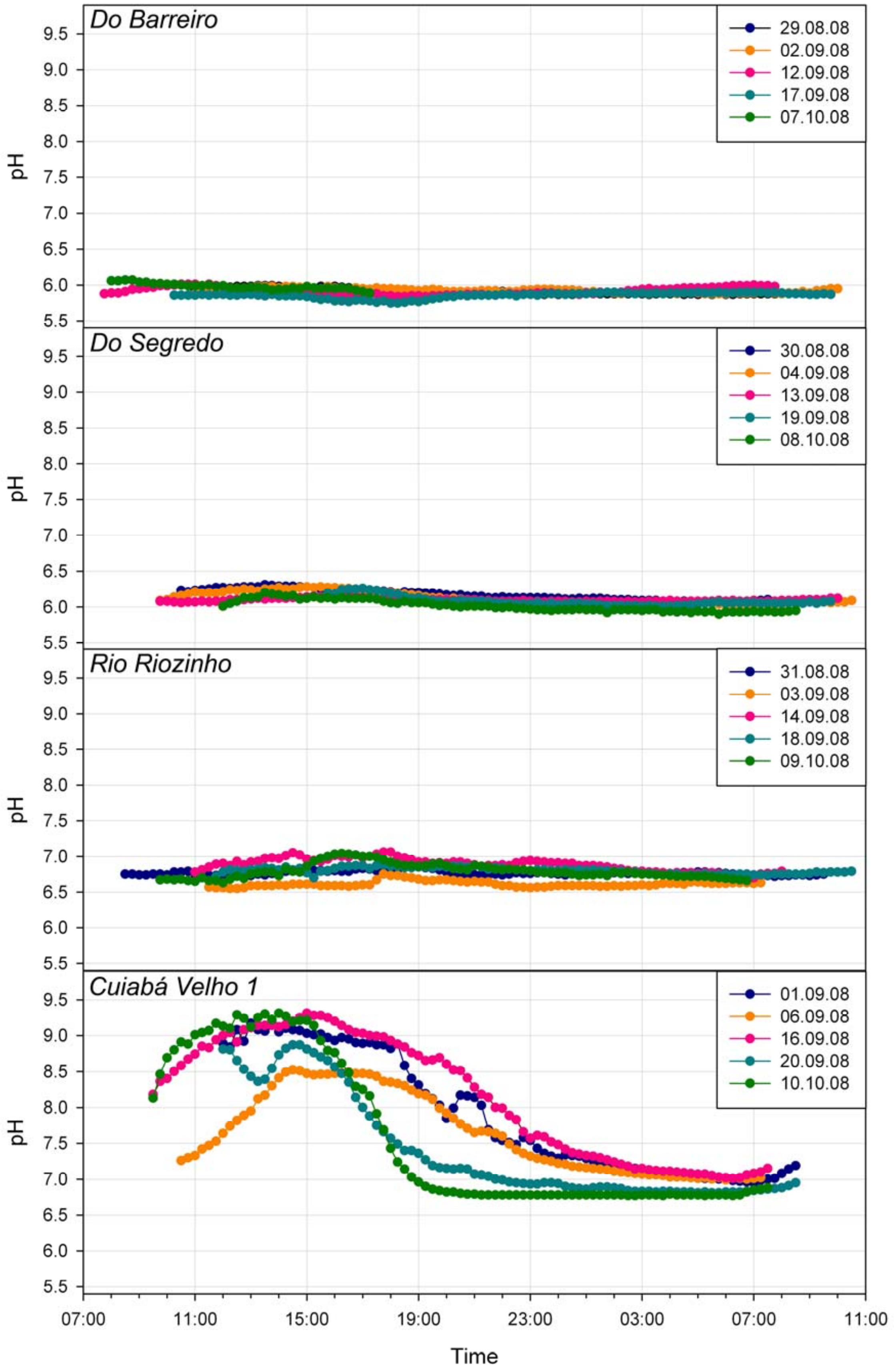

Figure 15: pH of *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1*

Specific conductivity

Figure 16 displays specific conductivity values of the four water bodies measured by the MS5. *Do Barreiro* shows mean daily conductivities between 24 and 32 µS/cm for the first four days and a mean daily conductivity value of 56 µS/cm for the fifth day. The first four days indicate more or less constant values. Daily variations are mostly within the accuracy range. The fifth day shows a slight decrease. Unfortunately, there is data loss due to power loss from 17:15.

Do Segredo and *Rio Riozinho* acts in the same manner showing no daily variations in their conductivity values. Differences between daily measurements are within the accuracy range as well. With a range between 16 and 21 µS/cm *Do Segredo* shows the smallest variation in specific conductivity. Conductivity values of *Rio Riozinho* range between 48 and 55 µS/cm.

Cuiabá Velho 1 conductivities are similar to values of *Do Barreiro* indicating more or less constant values for the first four days and higher values for the fifth day. Mean daily conductivity values are between 75 and 80 µS/cm for the first four measured days and 108 µS/cm for the last measured day. Therefore, conductivity values are highest in *Cuiabá Velho 1* relative to the other water bodies. Mean conductivity values are 33 µS/cm for *Do Barreiro*, 19 µS/cm for *Do Segredo*, 51 µS/cm for *Rio Riozinho* and 84 µS/cm for *Cuiabá Velho 1*.

Mean values of specific conductivity and the range of the five measured days for *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1* are listed in table 8.

Table 8: Mean values and range of specific conductivity

Water body	Mean specific conductivity [µS/cm]	Range of specific conductivity [µS/cm]
Do Barreiro	33	20 to 67
Do Segredo	19	16 to 21
Rio Riozinho	51	48 to 55
Cuiabá Velho 1	84	73 to 118

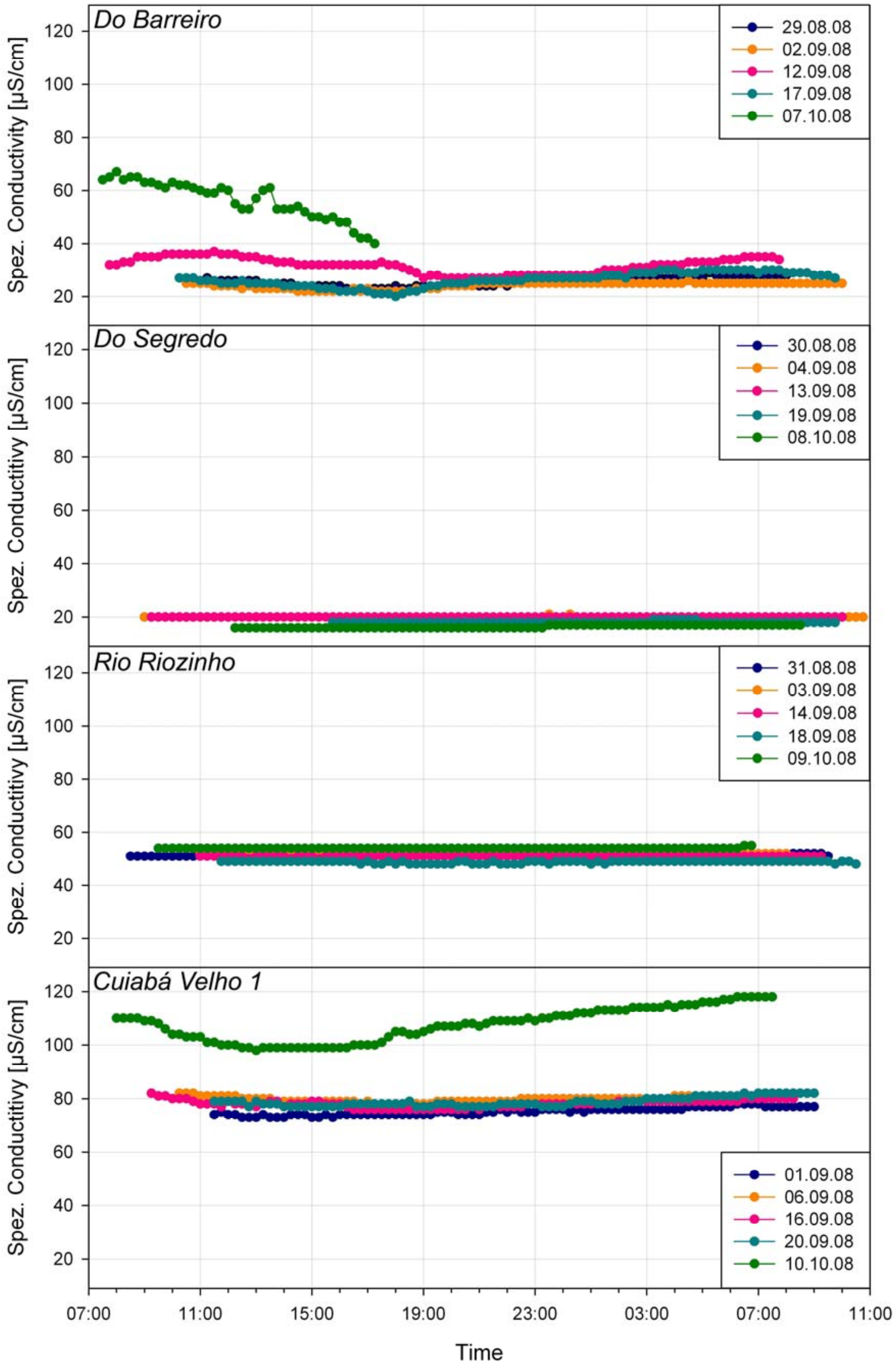

Figure 16: Specific conductivity of *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1*

Dissolved oxygen

Figure 17 displays DO in % saturation of the four water bodies measured by the MS5. According to WETZEL (2001), 0.6 mg/l correspond with around 7 to 8 % saturation for a mean water temperature between 23.1 and 27.8 °C for all water bodies, which is the error range for the DO sensor. Data is only available for four of five measured days for *Do Barreiro*, *Do Segredo* and *Rio Riozinho* and only two days for *Cuiabá Velho 1* due to DO sensor problems.

Do Barreiro indicates the lowest DO values of all four water bodies. Values start increasing at 10:00 from nearly anoxic conditions. Peak values can be found around 16:00 with up to 30 % saturation to decrease afterwards again. After 21:00 nearly anoxic conditions remain over the whole night.

Do Segredo shows peak values around 14:00. Afterwards, values start constantly decreasing over the whole night reaching between 30 and 40 % saturation in the early morning. All sampled days of *Do Barreiro* and *Do Segredo* act in the same manner with only little differences. Only on 19th September *Do Segredo* demonstrates a stronger decrease of DO during nighttime.

By contrast, differences of *Rio Riozinho* between the four measured days are larger. DO values are increasing from early morning reaching peak values between 35 and 90 % saturation during the early afternoon. From late afternoon over the whole night, DO saturation continuously decreases.

Cuiabá Velho 1 acts more or less in the same manner as *Do Barreiro* and *Do Segredo* with an increasing DO saturation starting in the morning. The peak is found around 15:00 on 06th September. Peak values of 1st September are missing due to problems with the DO sensor. Afterwards, values are continuously decreasing over the whole night. 6th September shows peak values over 100 % saturation.

The range of measured values of DO for the five measured days for *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1* are listed in table 9.

Table 9: Range of DO

Water body	Range of DO [% Sat]
Do Barreiro	0.9 to 29.1
Do Segredo	10.2 to 65.7
Rio Riozinho	8.9 to 88.4
Cuiabá Velho 1	32.9 to 105.3

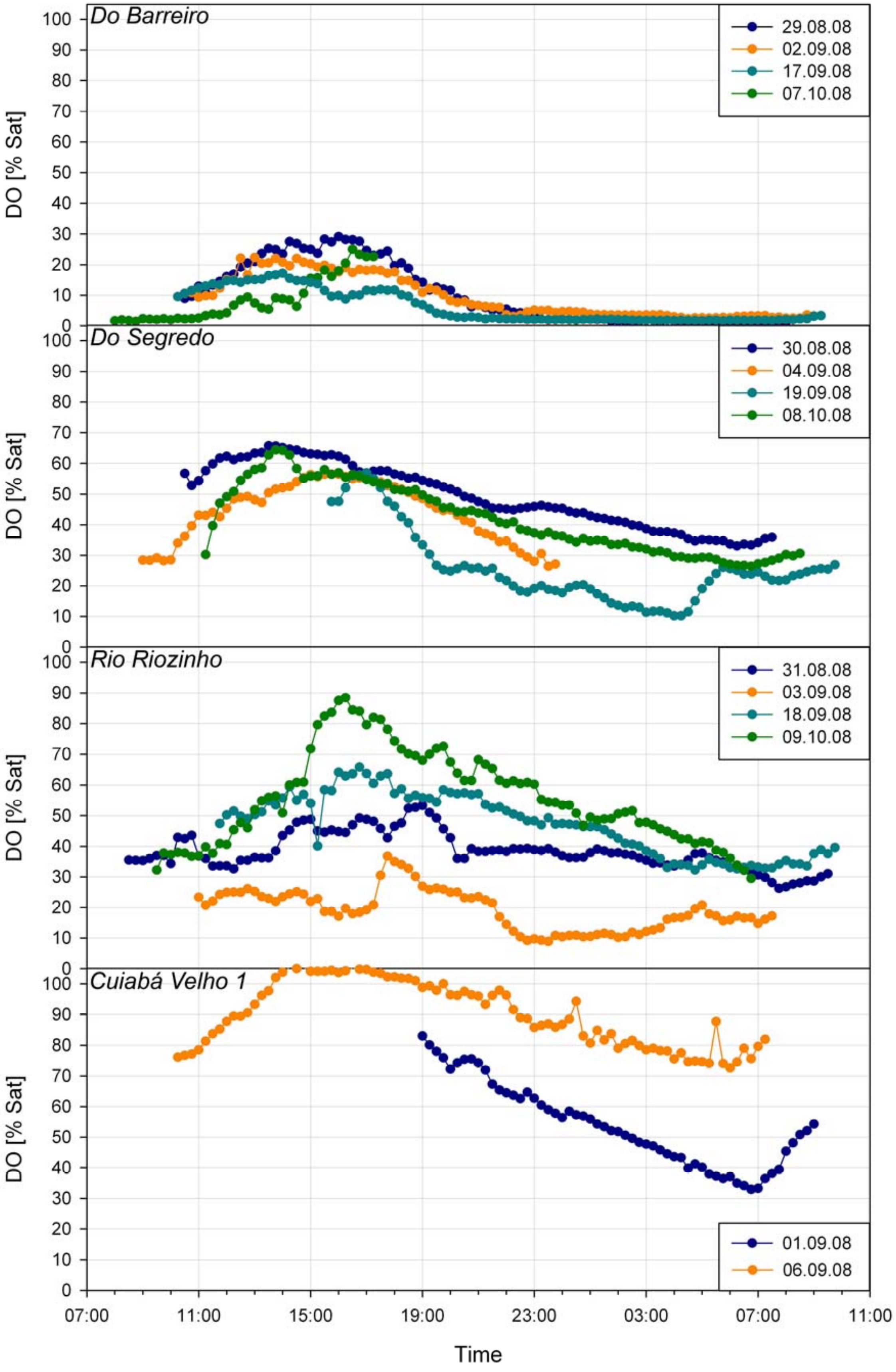

Figure 17: DO of *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1*

Nitrate

Figure 18 displays in-situ measurements of NO_3^- from *Do Barreiro*, *Do Segredo*, *Rio Riozinho* and *Cuiabá Velho 1*. Due to problems with the NO_3^- sensor only NO_3^- data of three measured days is available. The sensor accuracy for NO_3^- is 2 mg/l.

For comparison, NO_3^- values of different water samples are plotted in the same graph. These water samples, analysed by IC, have an error range at around 5 %. But it can be considered a little higher, because cooling of the water samples could not be guaranteed at all time. Error bars in figure 18 are too small to appear behind the samples due to scaling of the axis. Water samples were taken from the same day as in-situ measurements as far as possible. Only from 2nd September no water sample was collected from *Do Barreiro*. Therefore, sample B4 from 3rd September was taken instead.

Twelve water samples can be directly compared with in-situ measurements from the MS5 because the sampling time by MS5 corresponds within 15 minutes with the sampling time of collected water samples. All other samples were taken when in-situ measurements did not take place at the same time and therefore cannot be compared directly. NO_3^- values of all those twelve water samples are displayed in table 10.

Table 10: Comparison of NO_3^- values from water samples and short term measurement

Sampling number	NO_3^- [mg/l] - IC	NO_3^- [mg/l] – MS5
B5	3.20	3.78
B6	4.13	3.19
D4	11.42	7.41
D5	11.50	6.93
I5	3.79	9.89
I8	4.50	4.74
I9	4.90	15.12
J2	< 0,13	6.28
J4	2.19	4.56
J6	0.43	4.97
J7	1.07	3.69
J8	0.99	0.31

All water bodies show large differences between measured NO_3^- values of the samples and in-situ measurements by the MS5. Differences are reaching up to more than 10 mg/l (cf. *Do Segredo*: 30th August, *Cuiabá Velho 1*: 6th or 10th October).

Due to differences of NO_3^- values up to more than 10 mg/l (sample I9), nearly none of the NO_3^- values correspond well with the in-situ measurements by the MS5. Therefore, in-situ measurements of the multiprobe have to be considered with high caution and are not useful for any further interpretation.

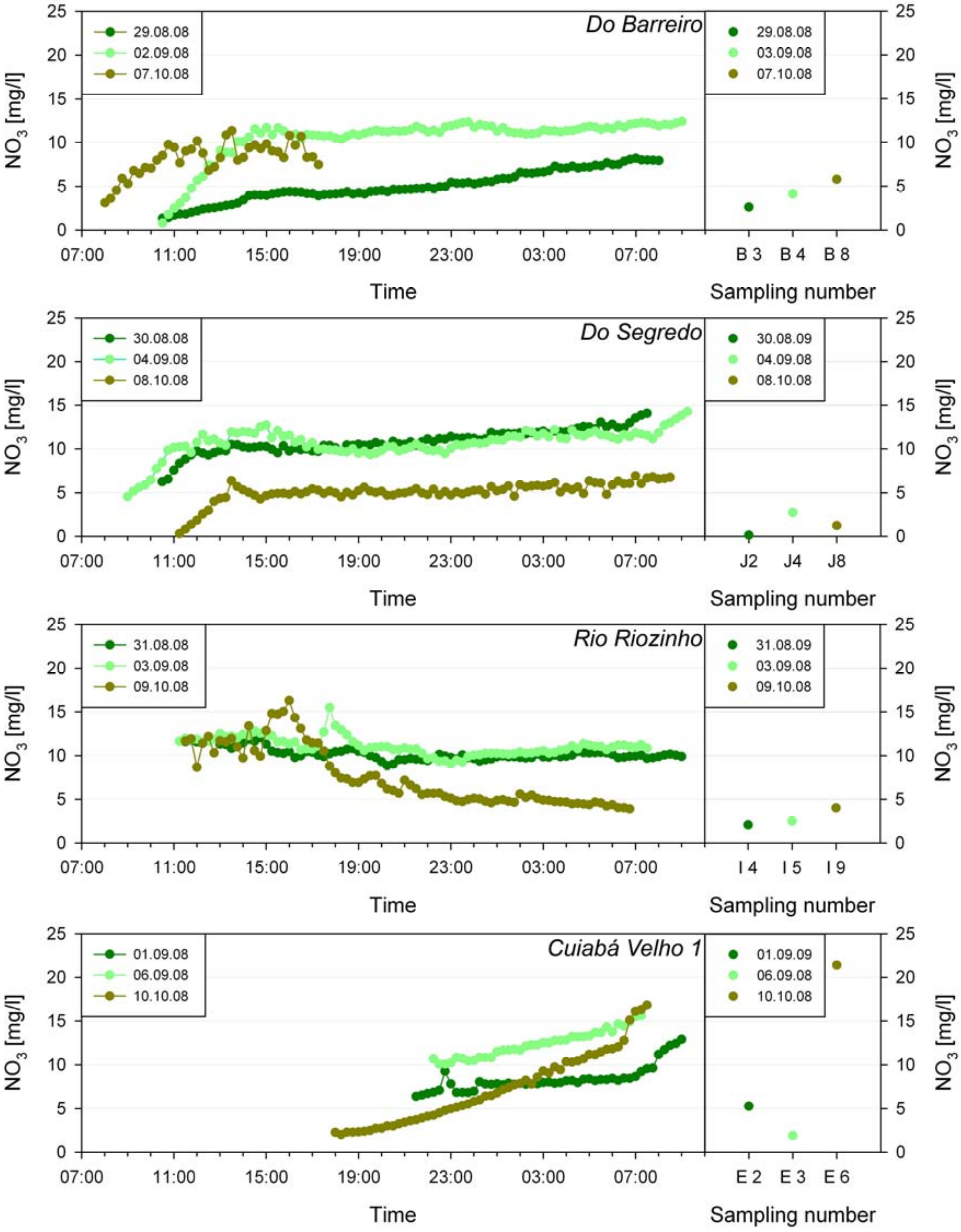

Figure 18: Comparison of NO_3^- values from in-situ measurement by MS5 and collected water samples measured by IC

4.1.2 Long term measurement

Figure 19 displays daily variations of water temperature, pH, specific conductivity and DO with their daily means of *Imbauval*, measured by the DS5. Due to power loss, data loss occurs between 30th August and 14th September 2008. Mean daily water temperature remains more or less constant in the first three weeks (7th August until 29th August) between 27.5 and 28 °C. Water temperature obviously indicates daily variations ranging between 25.9 and 30.3 °C. During the time period of field study from 15th September until 29th September, daily water temperature ranges between 23.1 and 31.5 °C.

pH values of *Imbauval* show a slight decline between 7th August until 29th August. Daily variation of pH ranges between 5.8 and 7.3. From 15th September until 29th September, pH values demonstrate a slight decrease as well ranging only between 6.6 and 7.5.

From 7th August until 25th August specific conductivity primarily remains more or less constant with a slight decrease around 18th August. After 25th August specific conductivity is decreasing until the end of data series on 29th August. After 15th September the decline continues until 19th September. Then, conductivity increases slightly with a peak on 23rd September, afterwards it decreases again. Daily variation of specific conductivity ranges between 44 and 55 µS/cm.

DO only shows plausible values from 7th August until 22nd August, 15th until 16th September and from 18th until 29th September with some short term breaks. Daily variations of DO range between anoxic conditions and 90 % saturation. It is obvious that DO never reaches 100 % saturation. Mean daily DO values decrease until the 23rd August. On 15th and 16th September DO values rise again within their daily variations, this time up to nearly 100 % saturation. Between 21st and 22nd September, DO reaches nearly anoxic conditions showing minimum DO values of 3 % saturation. Afterwards, DO rises again up to mean DO values between 60 and 70 % saturation and decreases continuously until the end of data series on 30th September. Due to problems with the sensors all values have to be considered with high caution.

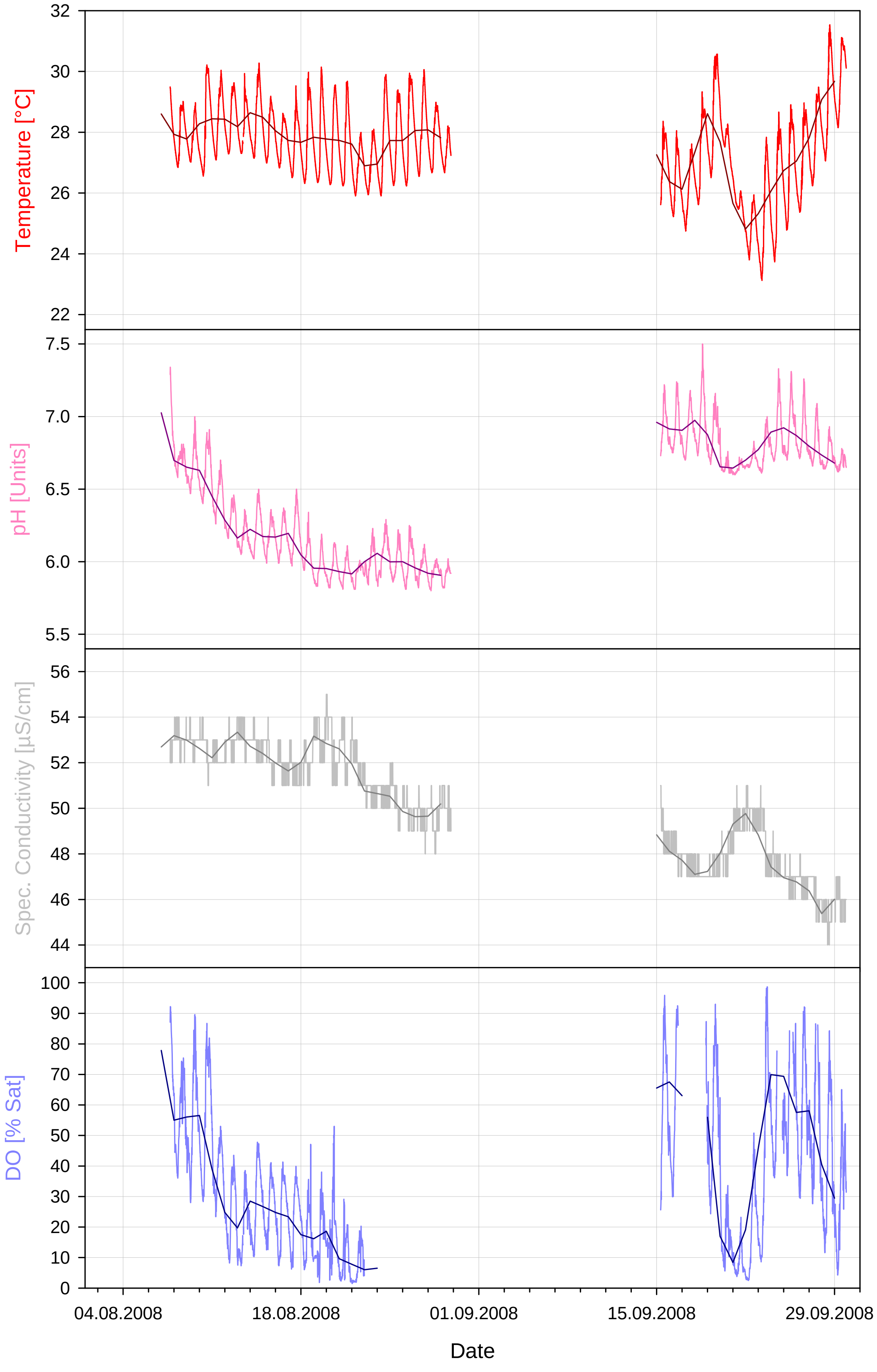

Figure 19: Water temperature, pH, specific conductivity and DO (light colors) with their mean daily values (darker colors) of *Imbauval*

Figure 20 displays the daily variation of water temperature and mean daily air temperature of *Imbauval*, measured by the DS5. It is evident that mean daily values of air temperature cannot be directly compared with daily values of the water temperature, measured every 15 minutes. However, to distinguish the general dynamics they are still suitable. Compared to the air temperature, water temperature is showing more or less the same tendencies. An example is the rapid decline of air temperature at 21st September. Water temperature indicates a decrease as well, but delayed and attenuated. Only small variations of air temperature in August within few degrees for some days are not observable in water temperature.

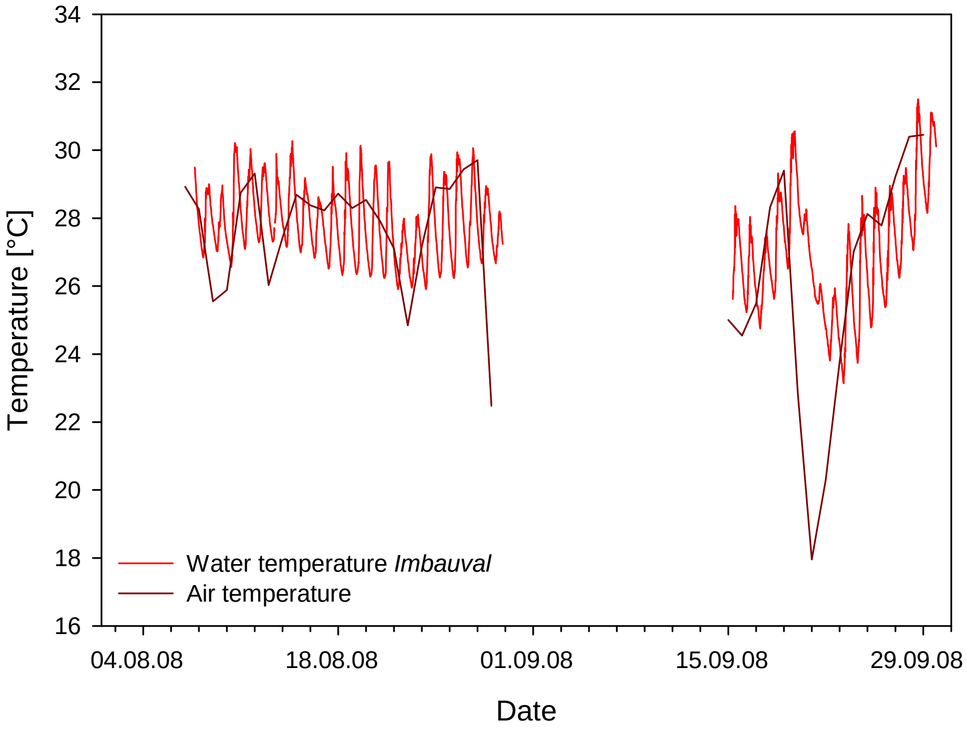

Figure 20: Air temperature and water temperature of *Imbauval*

4.1.3 Major anions

Figure 21 displays the concentrations of measured anions in mg/l for *Imbauval*, *Do Barreiro*, *Rio Cuiabá*, *Rio Riozinho* and *Do Segredo* during the time period of field study. Those water bodies show considerably low Cl^- values. They range between 1.28 and 4.9 mg/l. Water samples of a water body do not demonstrate large variations in Cl^- during the weeks of the field study. Only the sixth sample of *Do Segredo* has a Cl^- concentration of nearly 5 mg/l, which is a little higher relative to the other water samples of *Do Segredo*. NO_3^- values remain more or less constant and range for those five water bodies between 0.43 and 5.89 mg/l. NO_3^- concentrations of *Imbauval* and *Do Barreiro* are increasing very slightly. *Do Segredo* shows lowest NO_3^- values of all water bodies with concentrations < 2.19 mg/l. NO_3^- concentrations of *Rio Riozinho* are higher in the beginning. After the third sample, a small decline is visible to increase slightly again in the end of the field study. SO_4^{2-} concentrations remain more or less constant at every time with values < 1.43 mg/l.

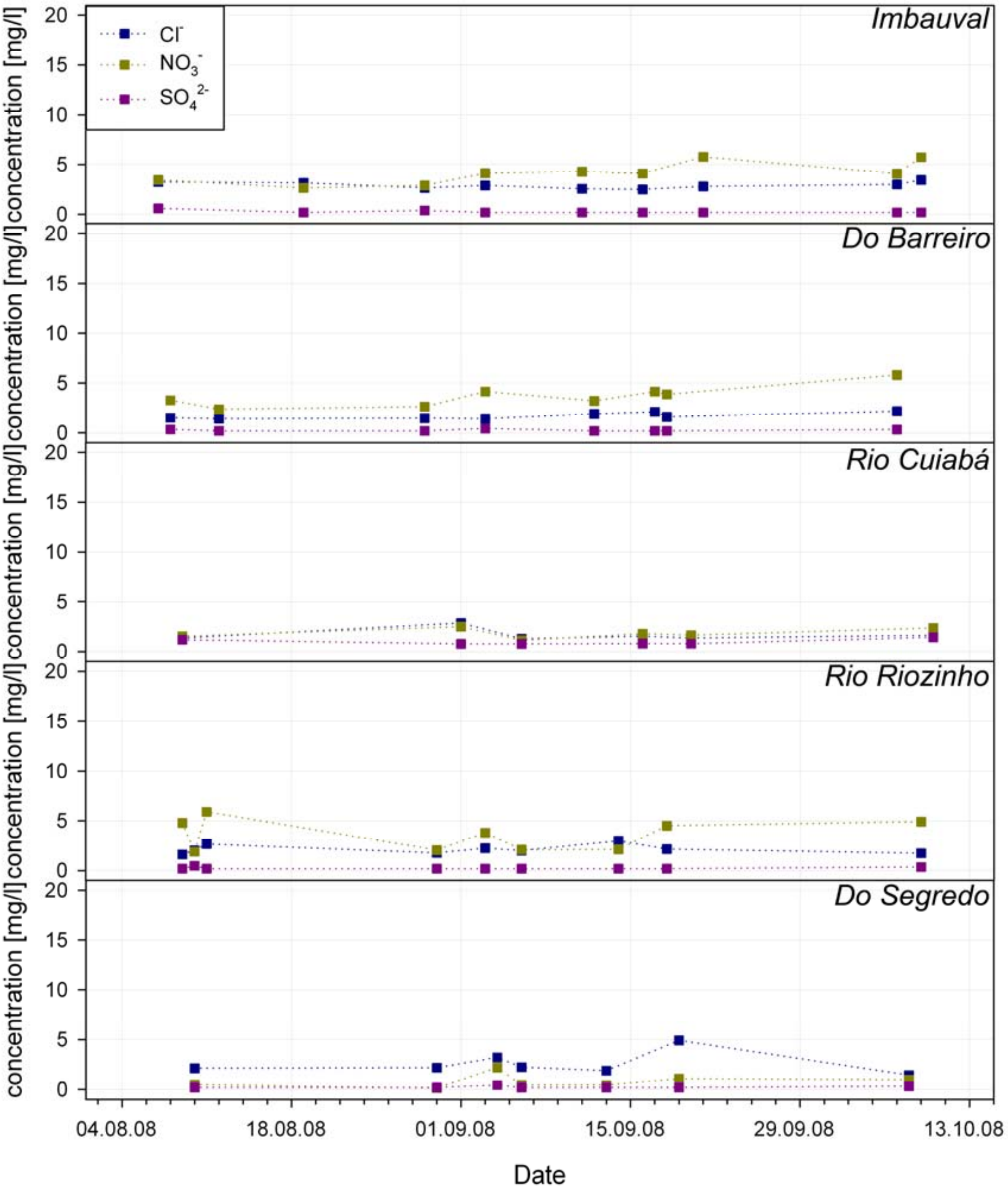

Figure 21: Cl^-, NO_3^- and SO_4^{2-} concentrations of *Imbauval*, *Do Barreiro*, *Rio Cuiabá*, *Rio Riozinho* and *Do Segredo*

Cuiabá Velho water bodies differ more in their concentration of major anions, which is displayed in figure 22. Cl^- concentrations remain more or less constant showing values between 1.58 and 5.5 mg/l. Compared to NO_3^-, Cl^- concentrations are not increasing. NO_3^- values increase in all three Cuiabá Velho water bodies rising from 4.58

to 14.44 mg/l for *Cuiabá Velho 1*, from 5.21 to 21.38 mg/l for *Cuiabá Velho 2* and from 2.22 to 13.57 mg/l for *Cuiabá Velho 3*. Therefore, highest NO_3^- concentrations of all water bodies can be found in *Cuiabá Velho 2*. SO_4^{2-} concentrations again remain more or less constant indicating the same behaviour compared to the water bodies considered above. *Cuiabá Velho 2* shows a slightly increase in the end of the field study and SO_4^{2-} concentrations of *Cuiabá Velho 3* are constantly increasing from 1.73 to 7.48 mg/l.

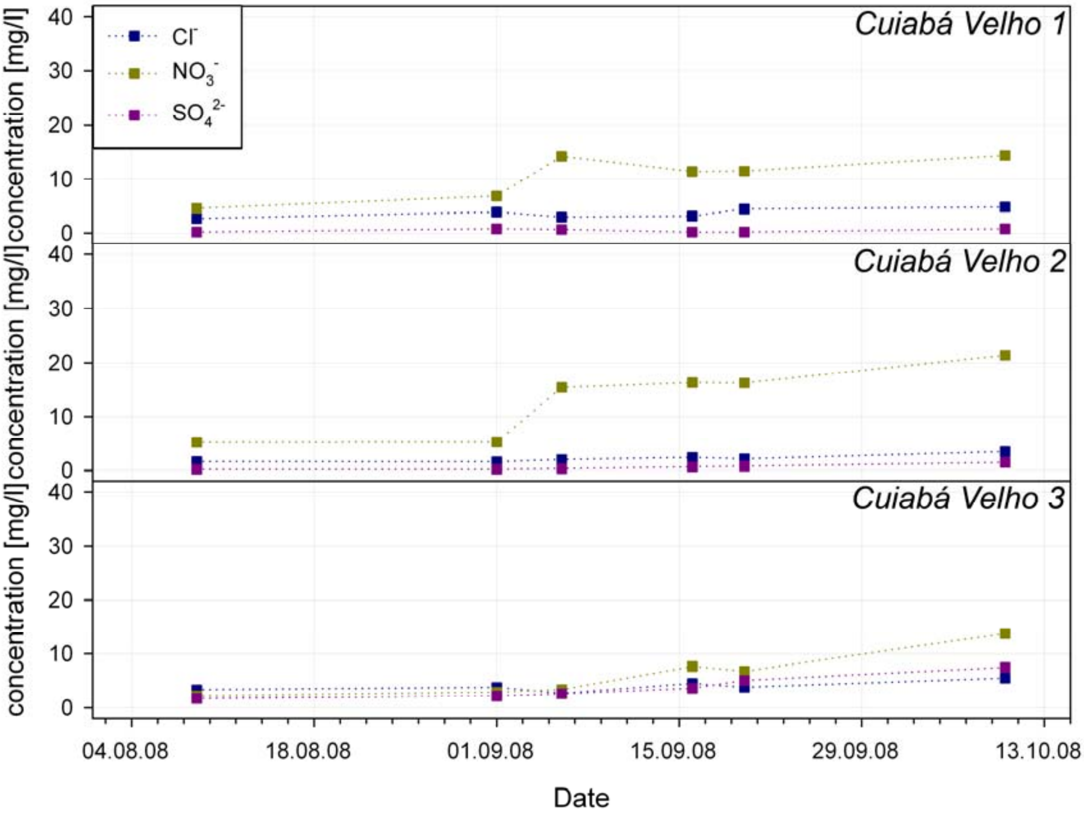

Figure 22: Cl^-, NO_3^- and SO_4^{2-} concentrations of *Cuiabá Velho 1*, *2* and *3*

Aguapé indicates a very different behaviour in its concentrations of major anions relative to the other water bodies. Concentrations of its major anions are displayed in figure 23. In the beginning its Cl^- concentration decreases slightly. Then, from the second until the seventh water sample, Cl^- values are strongly increasing. The range of *Aguapé* Cl^- values is rising between 11.38 and 80.18 mg/l. Therefore, *Aguapé* demonstrates the highest Cl^- concentrations of all water bodies. Only the last sample again has a lower value, measured with 14.44 mg/l. Reacting in the same manner like its Cl^- concentration NO_3^- values decrease slightly from 7.78 to less than 0.13 mg/l. Followed by a strong increase of NO_3^- values between the second and the fifth sample, values are rising up to 31.35 mg/l. Afterwards, the NO_3^- concentration is decreasing to nearly initial condition with 7.67 mg/l. SO_4^{2-} concentrations strongly increase between the first and seventh water sample. Values rise from 0.72 to 14.31 mg/l. With 1.5 mg/l the seventh sample again shows nearly initial conditions. Therefore, *Aguapé* has highest SO_4^{2-} concentrations of all water bodies.

Error bars in figure 21, figure 22 and figure 23 are too small to appear behind the samples due to the scaling of the axis.

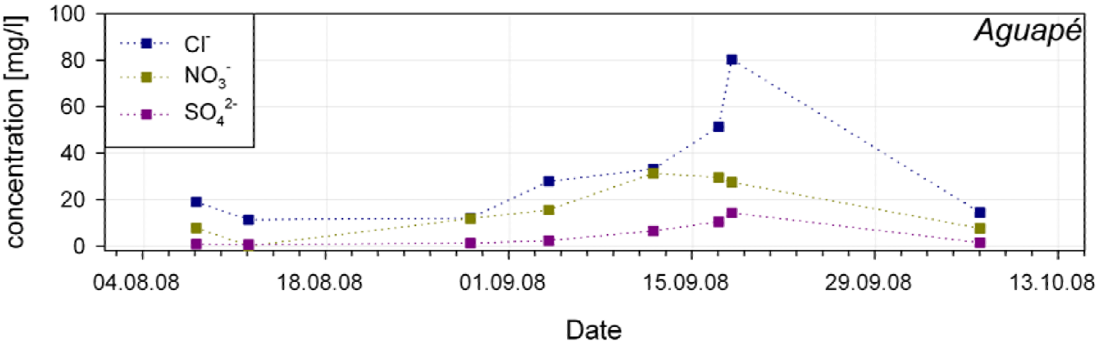

Figure 23: Cl^-, NO_3^- and SO_4^{2-} concentrations of *Aguapé*

4.2 Isotope analysis

4.2.1 Precipitation

Figure 24 shows the isotopic composition of precipitation from Cuiabá (1961-1987).

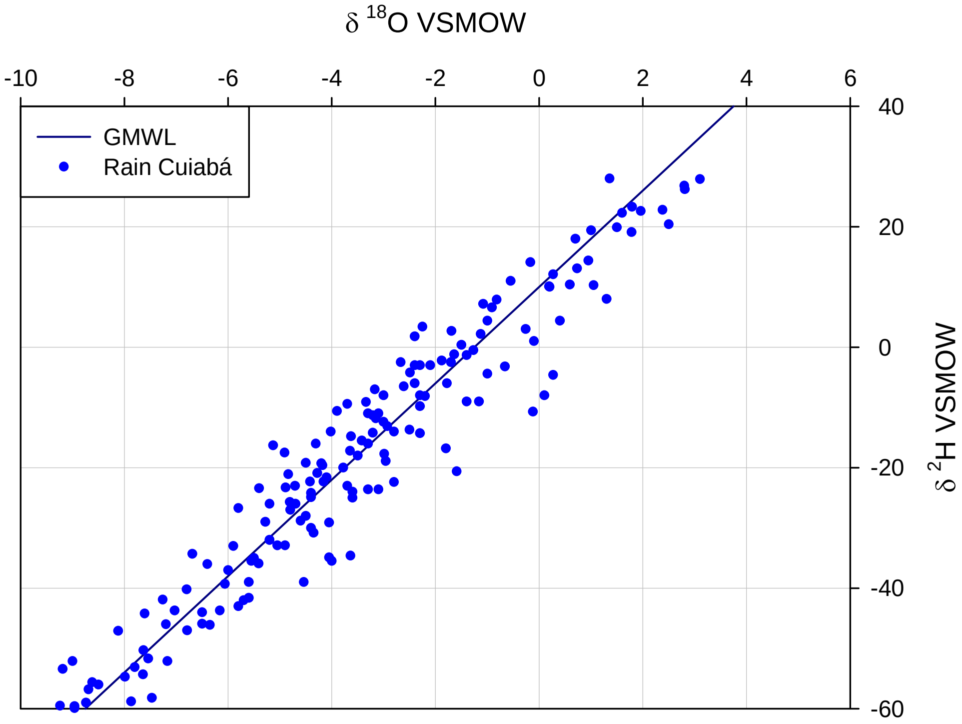

Figure 24: Isotopic composition of precipitation from Cuiabá (1961-1987) (Data source: GNIP database, URL 1)

As displayed, precipitation from Cuiabá generally plots close to the GMWL. Therefore, the GMWL can be used as the LMWL. Precipitation data is taken from the GNIP database (URL 1), which contains the isotopic composition of precipitation from the GNIP Station Cuiabá. It lies approximately 200 km in the north of the RPPN SESC Pantanal. Observations of precipitation data, which already is treated statistically, are available from the year 1961 to 1987. Information about the statistical treatment can be found in GNIP (2006).

Figure 25 displays the seasonal effect for Cuiabá on the basis of the same precipitation data from 1961 to 1987. δ values for ^{18}O range between -7.1 ‰ in February and 1.7 ‰ in August. δ values are given in the annex (B.7).

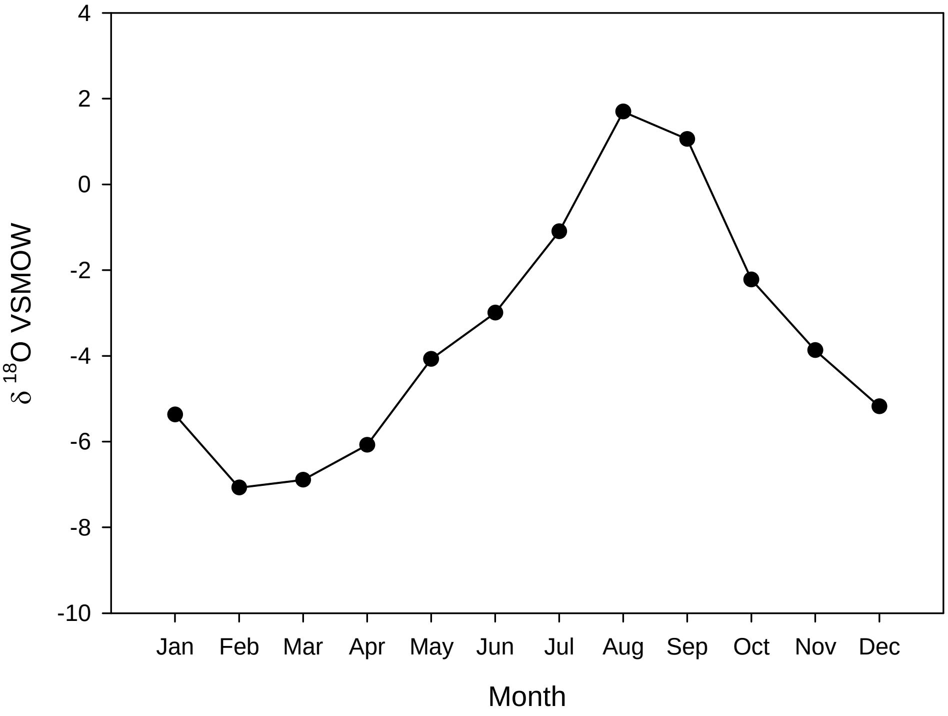

Figure 25: Seasonal effect of precipitation from Cuiabá (1961-1987) (Data source: GNIP database, URL 1)

Figure 26 shows the isotopic signature of the rain sample collected from *Espírito Santo*. The rain water plots close to the GMWL as well. It is within the range of precipitation from Cuiabá between 1961 and 1987. The measured $\delta^{18}O$ value of the rain sample (21st September 2008) is 1.01 ‰. With a measuring error of 0.2 ‰ the $\delta^{18}O$ value of the rain water accords with the isotopic content of precipitation from Cuiabá (1961-1987), even though the rain water of *Espírito Santo* plots within the heaviest range of isotopic compositions.

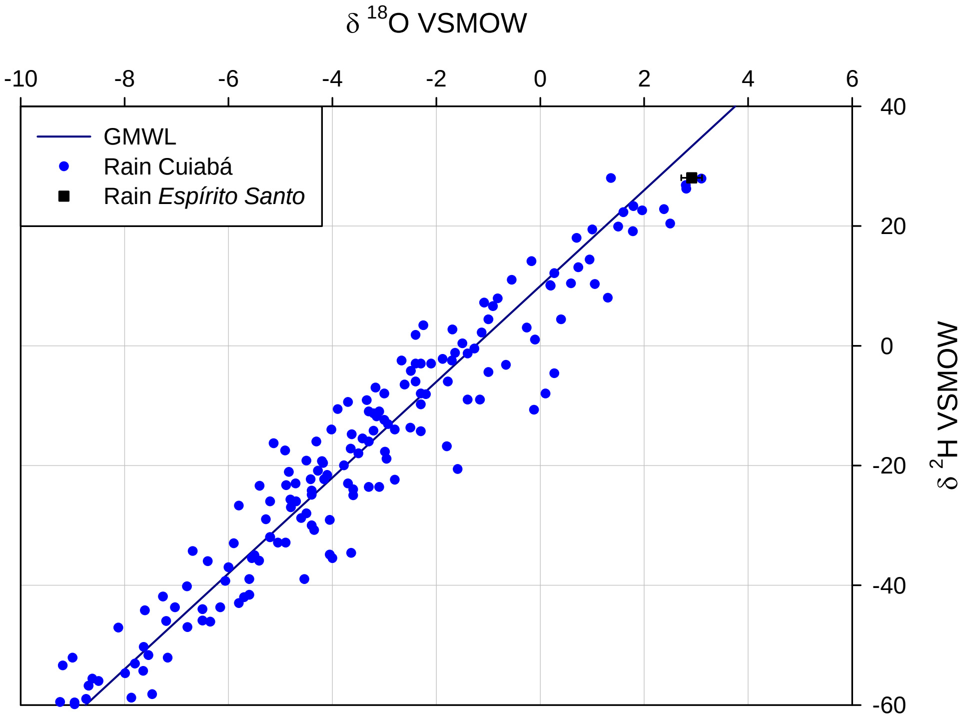

Figure 26: Isotopic composition of rain sample collected from *Espírito Santo* and precipitation from Cuiabá (1961-1987) (Data source: GNIP database, URL 1)

4.2.2 Groundwater

Figure 27 shows the isotopic composition of the four collected groundwater samples.

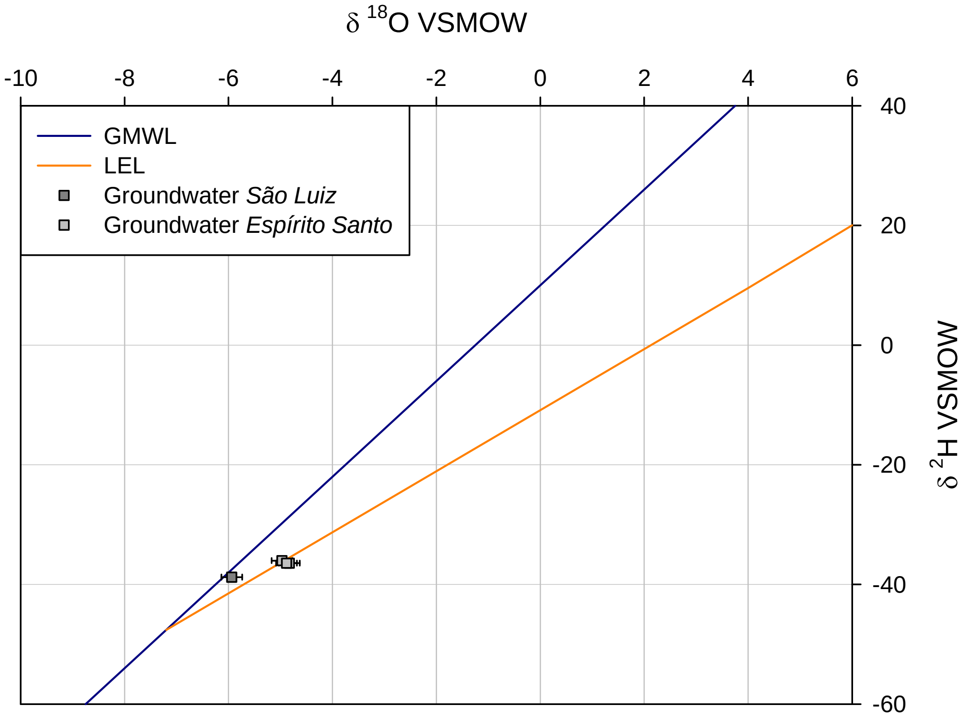

Figure 27: Isotopic composition of groundwater samples collected from the RPPN SESC Pantanal

The groundwater sample of *São Luiz* plots fairly close to the intersection of GMWL and LEL. Its deviation from the GMWL is within the error range. The δ^{18}O value is analysed with -5.94 ‰ and for δ^{2}H it is -38.8 ‰. With respect to the GMWL the three groundwater samples of *Espírito Santo* indicate a slight enrichment towards higher δ values and plot on the LEL. The range of the δ^{18}O values is between -4.97 and -4.83 ‰ and for δ^{2}H between -36.45 and -36.03 ‰.

4.2.3 Local Evaporation Line

Figure 28 shows the LEL with all samples collected from the RPPN SESC Pantanal. They all demonstrate a very good correlation with the LEL. δ values for ^{18}O range between -5.94 and 14.75 ‰ and for ^{2}H between -38.8 and 58.87 ‰. Error bars are too small to appear behind the sampling points due to scaling of the axis.

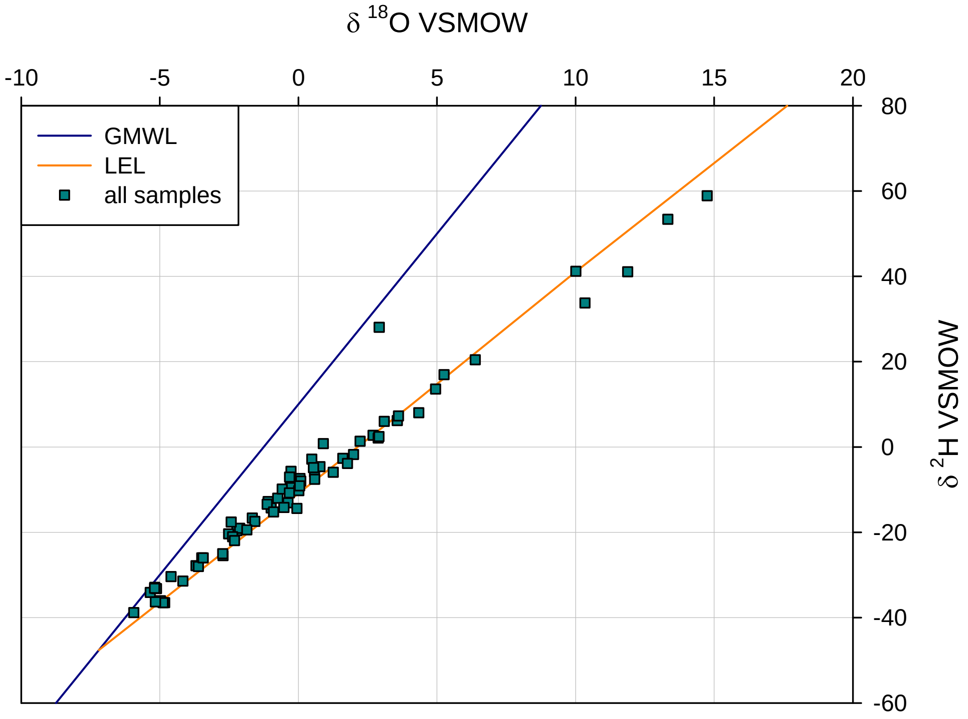

Figure 28: LEL with all samples collected from the RPPN SESC Pantanal

4.2.4 Source water composition

The back extrapolation of all 70 samples was calculated in order to get the source isotopic composition. Figure 29 displays that nearly all corrected samples have δ^{18}O values between -10.18 and -4.75 ‰ and δ^{2}H values between -71.45 and -28.02 ‰. Only one sample shows a noticeable less depleted isotopic fraction compared to all other samples. Its δ^{18}O value is 1.1 ‰ and the δ^{2}H value is 18.83 ‰. This sample is the rain water collected from *Espírito Santo*. Since this precipitation is from 21st September in the dry season, the value of 1.1 ‰ for δ^{18}O corresponds with the mean value of isotopic composition for September which is 1.1 ‰ as well (figure 25).

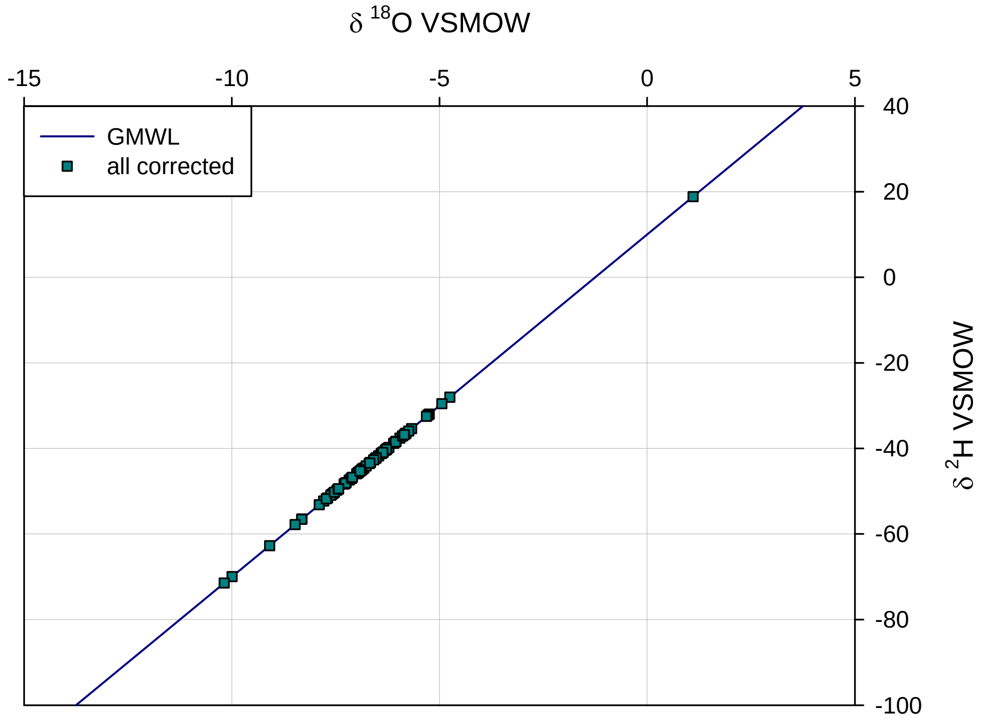

Figure 29: Isotopic composition of source water

4.2.5 Water bodies

The following figures show the isotopic content of the nine sampled water bodies. All values indicate isotopic enrichment towards higher δ values and plot on or close to the LEL. All water samples of the water bodies, respectively, demonstrate a very good correlation with the LEL. Error bars of some water samples are too small to appear behind the sampling points due to scaling of the axis. Furthermore, all samples of the water bodies plot close to the LEL with respect to their sampling date as well. This means that the first sample indicates the slightest enrichment, the second sample a stronger enrichment relative to the first and so on. Therefore, the last sample of each water body shows the strongest enrichment in δ values and the enrichment of water samples accords with the order in which they were taken.

Imbauval

Figure 30 displays the isotopic composition of the nine water samples collected from *Imbauval*. Within their error range the samples show a very good correlation with the LEL. δ values for ^{18}O range between -1.67 and 2.88 ‰. The δ^{2}H values range between -16.64 and 2.73 ‰.

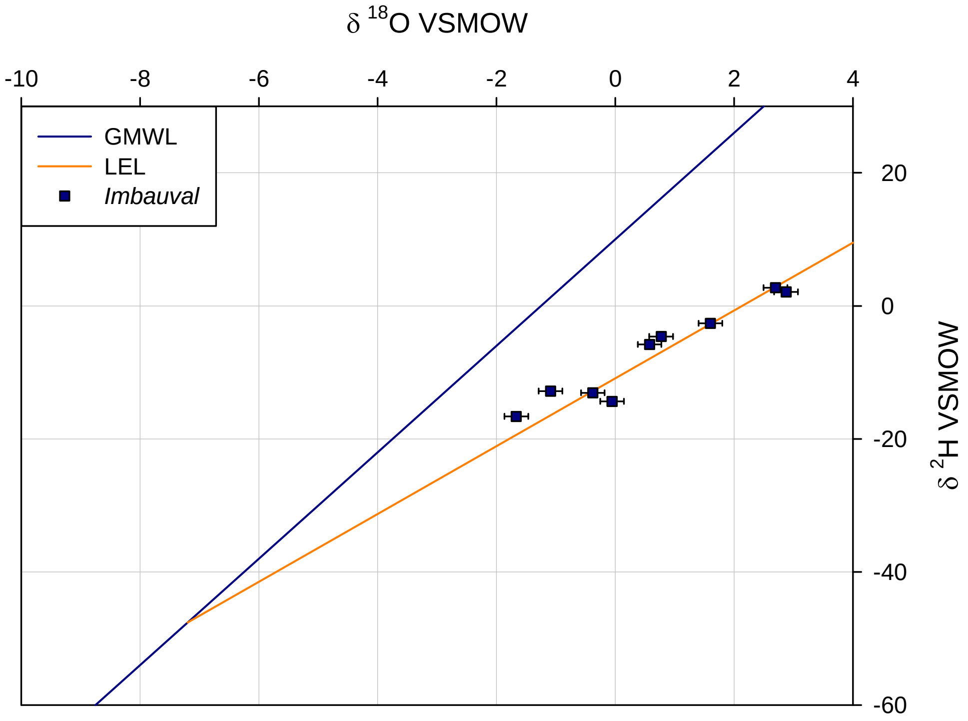

Figure 30: δ^{18}O- δ^{2}H relationship for water samples collected from *Imbauval*

Do Barreiro

Figure 31 displays the δ^{18}O- δ^{2}H relationship for the eight water samples collected from *Do Barreiro*.

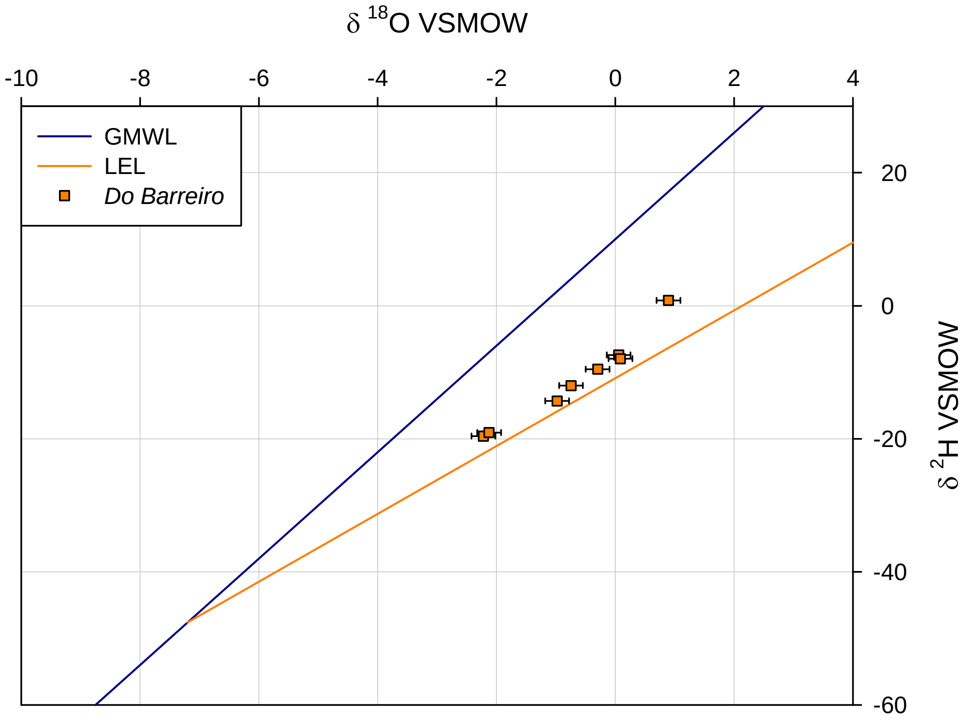

Figure 31: δ^{18}O- δ^{2}H relationship for water samples collected from *Do Barreiro*

All water samples plot slightly above the LEL. The δ^{18}O values range between -2.22 and 0.9 ‰, the δ^{2}H values between -19.6 and 0.79 ‰.

Aguapé

Figure 32 shows the isotopic composition of the eight water samples collected from *Aguapé*.

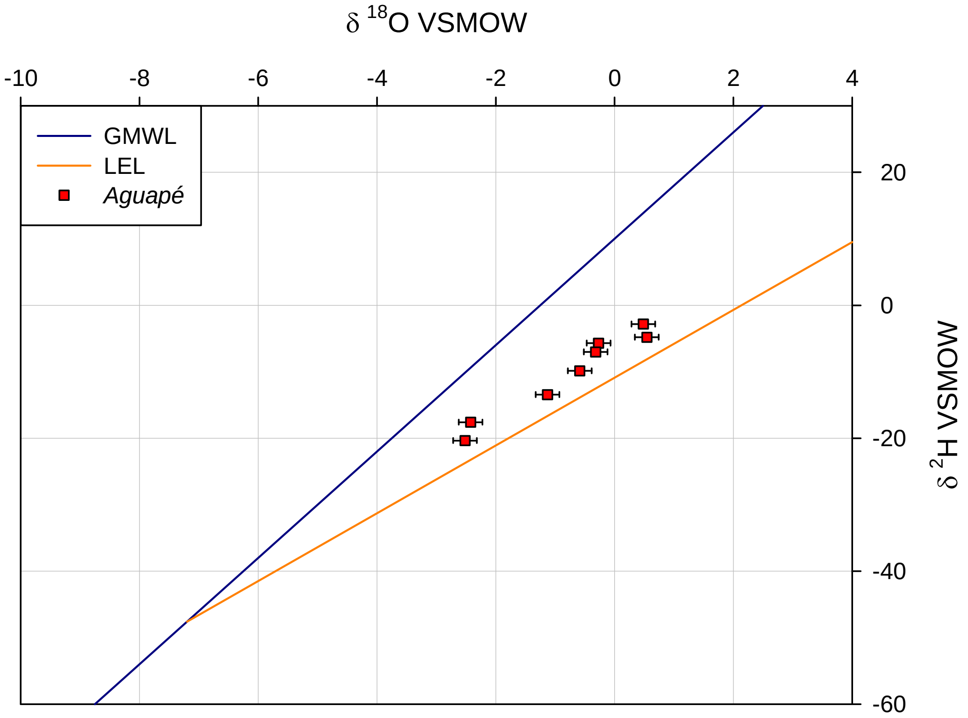

Figure 32: δ^{18}O- δ^{2}H relationship for water samples collected from *Aguapé*

All water samples plot slightly above the LEL indicating the same behaviour as water samples collected from *Do Barreiro*. The δ^{18}O values range between -2.52 and 0.54 ‰ and the δ^{2}H values between -20.36 and -2.83 ‰.

Cuiabá Velho 1

Figure 33 displays the isotopic composition of the six water samples collected from *Cuiabá Velho 1*. The samples correlate very good with the LEL. Except for one water sample, they all plot on the LEL within their error range. δ^{18}O values range between 0.01 and 6.38 ‰ and δ^{2}H values range between -10.21 and 20.43 ‰. Compared to all other water bodies above, *Cuiabá Velho 1* indicates a stronger enrichment of its lake water. The other Cuiabá Velho water bodies, *Cuiabá Velho 2* and *3*, show more or less the same behaviour. Their isotopic fraction is displayed in the following figures.

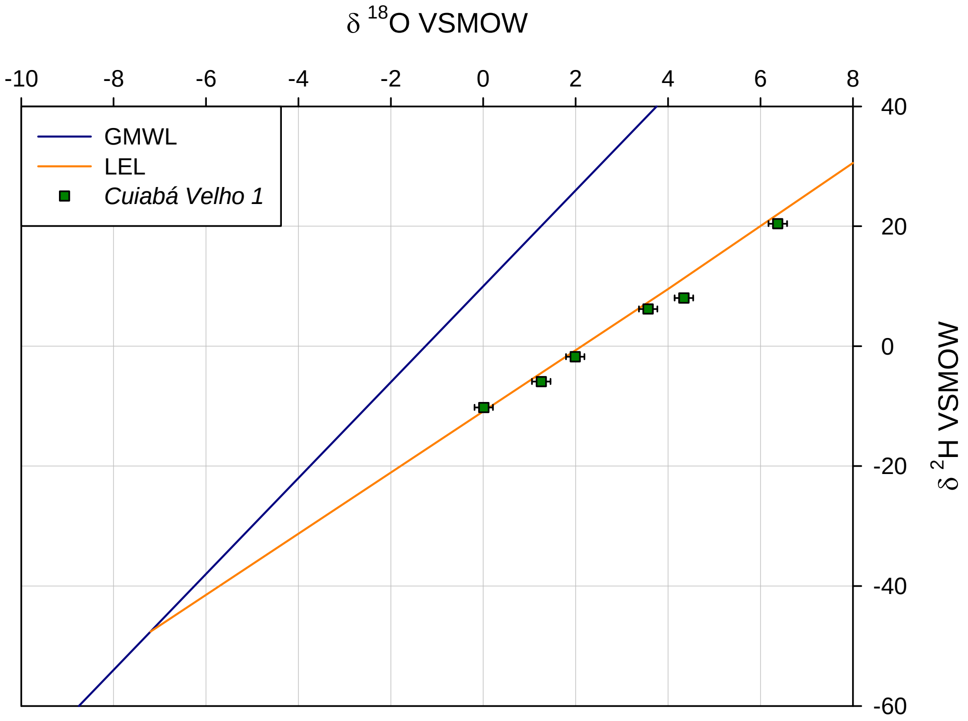

Figure 33: δ^{18}O- δ^{2}H relationship for water samples collected from *Cuiabá Velho 1*

Cuiabá Velho 2

Figure 34 shows the isotopic composition of the six water samples collected from *Cuiabá Velho 2*.

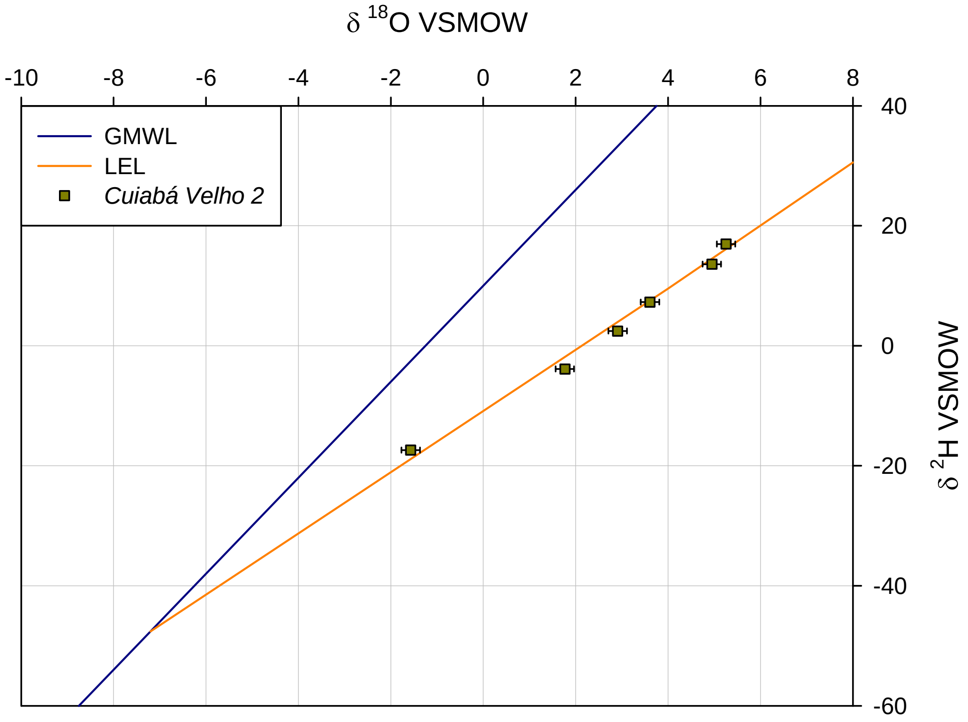

Figure 34: δ^{18}O- δ^{2}H relationship for water samples collected from *Cuiabá Velho 2*

Within their error range the samples plot all on the LEL indicating the same behaviour as water samples collected from *Cuiabá Velho 1*. The δ^{18}O values range between -1.57 and 5.26 ‰ and the δ^{2}H values between -17.4 and 16.94 ‰.

Cuiabá Velho 3

Figure 35 displays the isotopic composition of the six water samples collected from *Cuiabá Velho 3*.

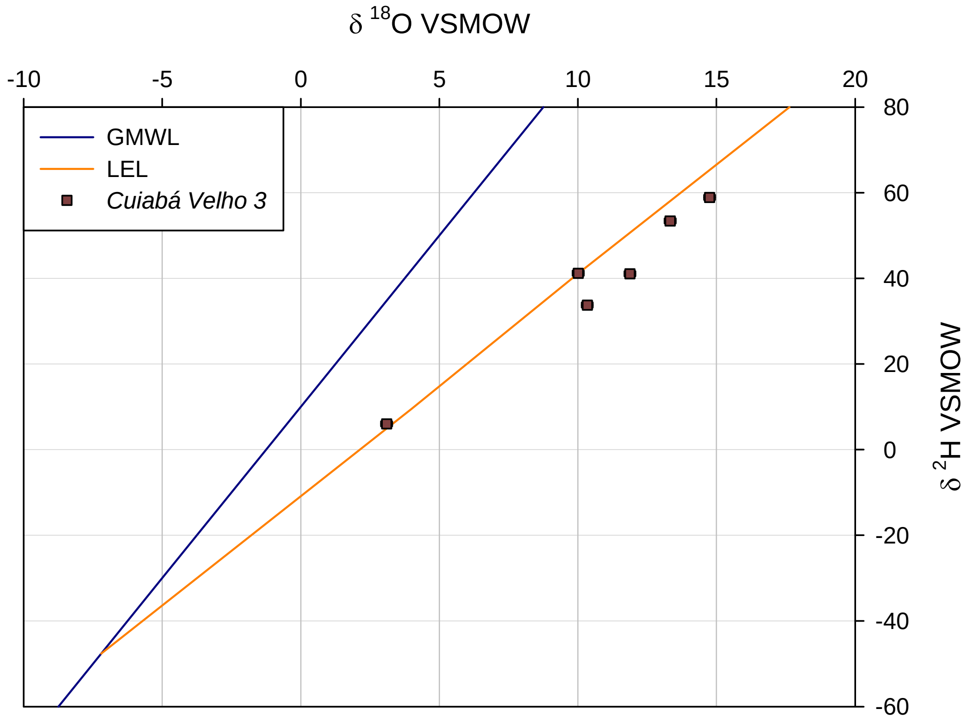

Figure 35: δ^{18}O- δ^{2}H relationship for water samples collected from *Cuiabá Velho 3*

Within their error range the samples show a good correlation with the LEL. All samples are extremely enriched with values higher than VSMOW. The δ^{18}O values range between 3.1 and 14.75 ‰ and the δ^{2}H values between 6.03 and 58.87 ‰. *Cuiabá Velho 3* water samples demonstrate the highest enrichment of all water bodies and the largest difference of δ values between the first and the last water sample.

Rio Cuiabá

Figure 36 displays the isotopic composition of the six water samples collected from *Rio Cuiabá*. All values show only a very slight enrichment. Within their error range they plot very close to the GMWL and fairly close to the intersection of GMWL and LEL. Only one sample plots on the LEL indicating an asymptotic enrichment towards a higher δ value. The range of δ^{18}O is between -5.35 and -4.59 ‰ and δ^{2}H values range between -36.32 and -30.39 ‰. Thereby, the δ values of *Rio Cuiabá* show the slightest enrichment of all water bodies and the smallest difference of δ values between the first and the last water sample.

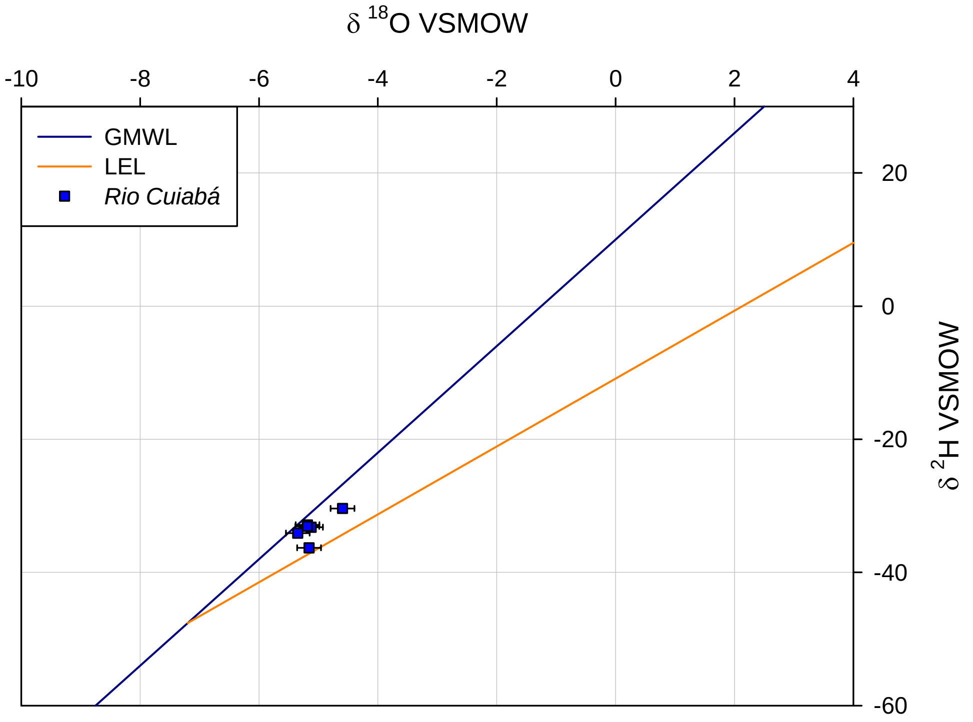

Figure 36: δ^{18}O- δ^{2}H relationship for water samples collected from *Rio Cuiabá*

Rio Riozinho

Figure 37 displays the isotopic composition of the nine water samples collected from *Rio Riozinho*.

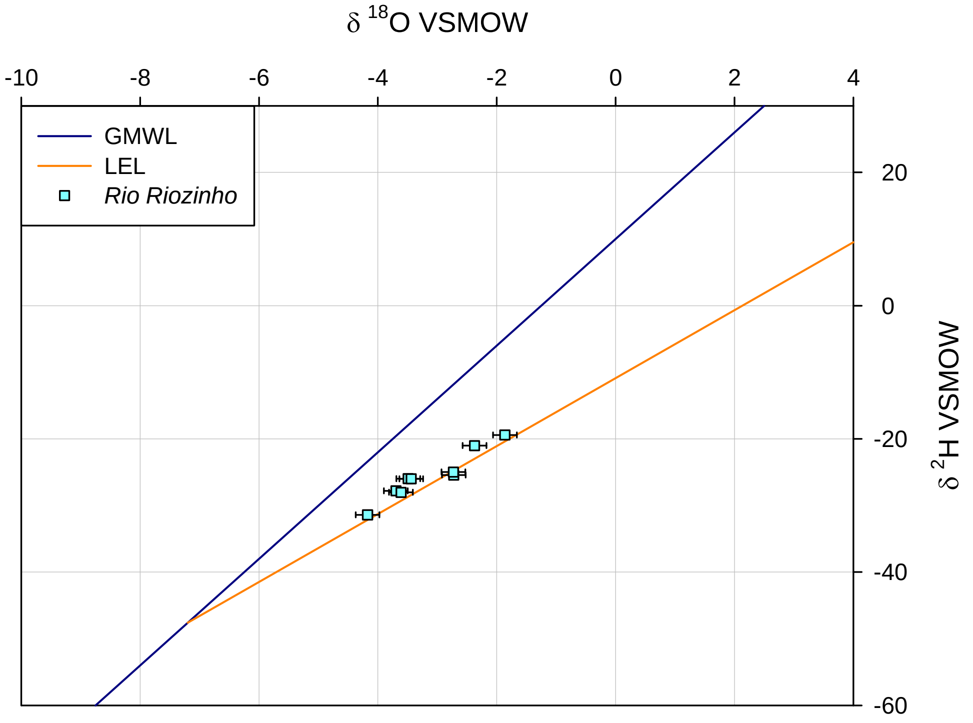

Figure 37: δ^{18}O- δ^{2}H relationship for water samples collected from *Rio Riozinho*

Within their error range the samples nearly plot all on the LEL. The δ^{18}O values range between -4.17 and -1.86 ‰ and the δ^{2}H values between -31.42 and -19.43 ‰. Therefore, water samples of *Rio Riozinho* are with respect to their isotopic content within an intermediate position between the larger *Rio Cuiabá* and the lakes.

Do Segredo

Figure 38 shows the isotopic composition of the seven water samples collected from *Do Segredo*. Within their error range the samples nearly plot close to the LEL with a very high correlation. The δ^{18}O values range between -2.3 and 2.23 ‰ and the δ^{2}H values between -21.92 and 1.33 ‰.

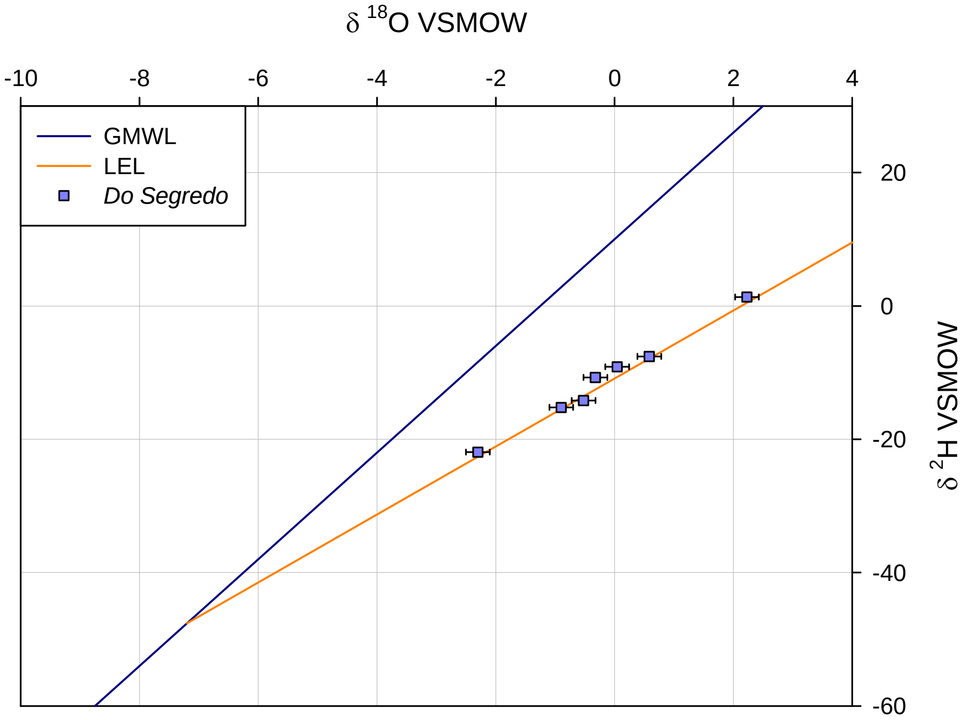

Figure 38: δ^{18}O- δ^{2}H relationship for water samples collected from *Do Segredo*

The absolute enrichment of the isotopic fraction of δ^{18}O between first and last water sample is 0.75 ‰ for *Rio Cuiabá* and 2.31 ‰ for *Rio Riozinho*. For *Imbauval* the absolute difference of the isotopic composition of δ^{18}O between first and last water sample is 4.54 ‰, for *Do Barreiro* 3.12 ‰, for *Aguapé* 3.06 ‰ and for *Do Segredo* 4.53 ‰. The absolute difference of the isotopic content of δ^{18}O between first and last water sample from *Cuiabá Velho 1* is 6.36 ‰, for *Cuiabá Velho 2* 6.83 ‰ and for *Cuiabá Velho 3* 11.65 ‰.

Imbauval, *Cuiabá Velho 1* and *2* and *Do Segredo* indicate an excellent correlation with the LEL. Water samples of *Do Barreiro* and *Aguapé* plot above the LEL. Only *Cuiabá Velho 3* have water samples, which plot below the LEL. Both rivers, *Rio Cuiabá* and *Rio Riozinho*, and the groundwater show water samples with less enriched isotopic signatures than all *baías*. These results correspond well with the general behaviour of water samples from different locations within the tropics (figure 12).

4.3 Evaporation losses

Figure 39 displays daily rates of potential evaporation in mm, calculated as an implementation of the Penman-Monteith Equation for the whole time period of field study (15th July until 15th October 2008). Mean values indicate an upward trend within these three months.

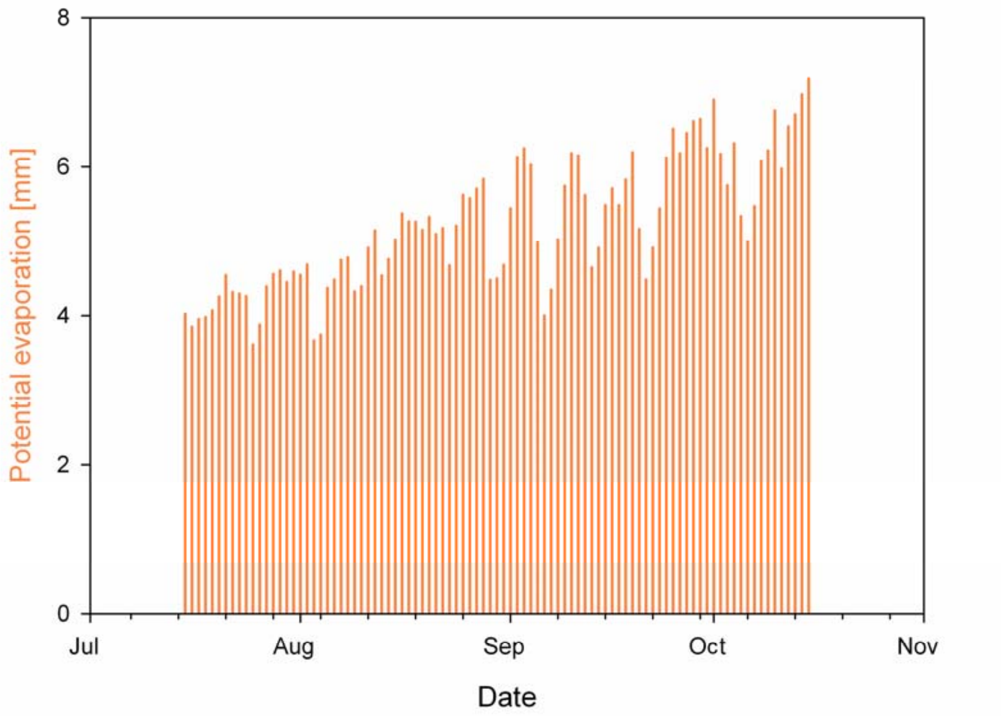

Figure 39: Potential evaporation after Penman-Monteith for the time period of field study in the RPPN SESC Pantanal

Minimum, maximum and mean values as well as the total amount of potential evaporation are listed in table 11.

Table 11: Minimum, maximum, mean values and total amount of potential evaporation

	Minimum	Maximum	Mean	Total amount
Potential evaporation rate [mm]	3.6	7.2	5.2	484.9

The total amount of potential evaporation in mm was calculated for the time period between first and last water sample for each lake. Figure 40 shows the cumulative potential evaporation for each water body, respectively. The corresponding values are given in the annex (B.4). Since water samples were collected from the water bodies within five days of each measuring loop, total amounts of potential evaporation do not differ significantly.

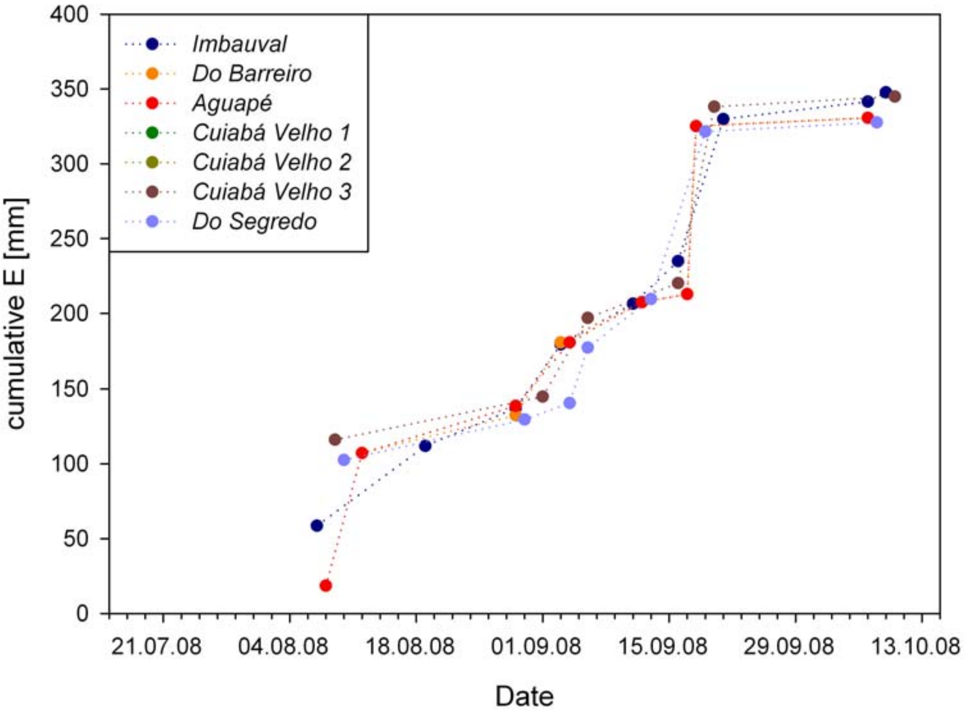

Figure 40: Cumulative potential evaporation

4.4 Chloride enrichment

With the chloride mass balance approach Cl^- concentrations were calculated assuming that only evaporation is responsible for Cl^- enrichment. The corresponding values for each water body are given in the annex (B.5). Evaporation calculated from the Penman-Monteith Equation versus the theoretical Cl^- concentrations (circles with dashed line) is compared with Cl^- concentrations measured by IC (squares).

Figure 41 displays the calculated and measured Cl^- concentrations for *Imbauval*, *Do Barreiro* and *Do Segredo*. Those three water bodies were chosen to plot in the same graph because measured Cl^- values are ranging within the same order between 1 and 5 mg/l. Only *Do Segredo* shows Cl^- concentrations of two samples where measured Cl^- values are higher relative to the calculated Cl^- concentrations.

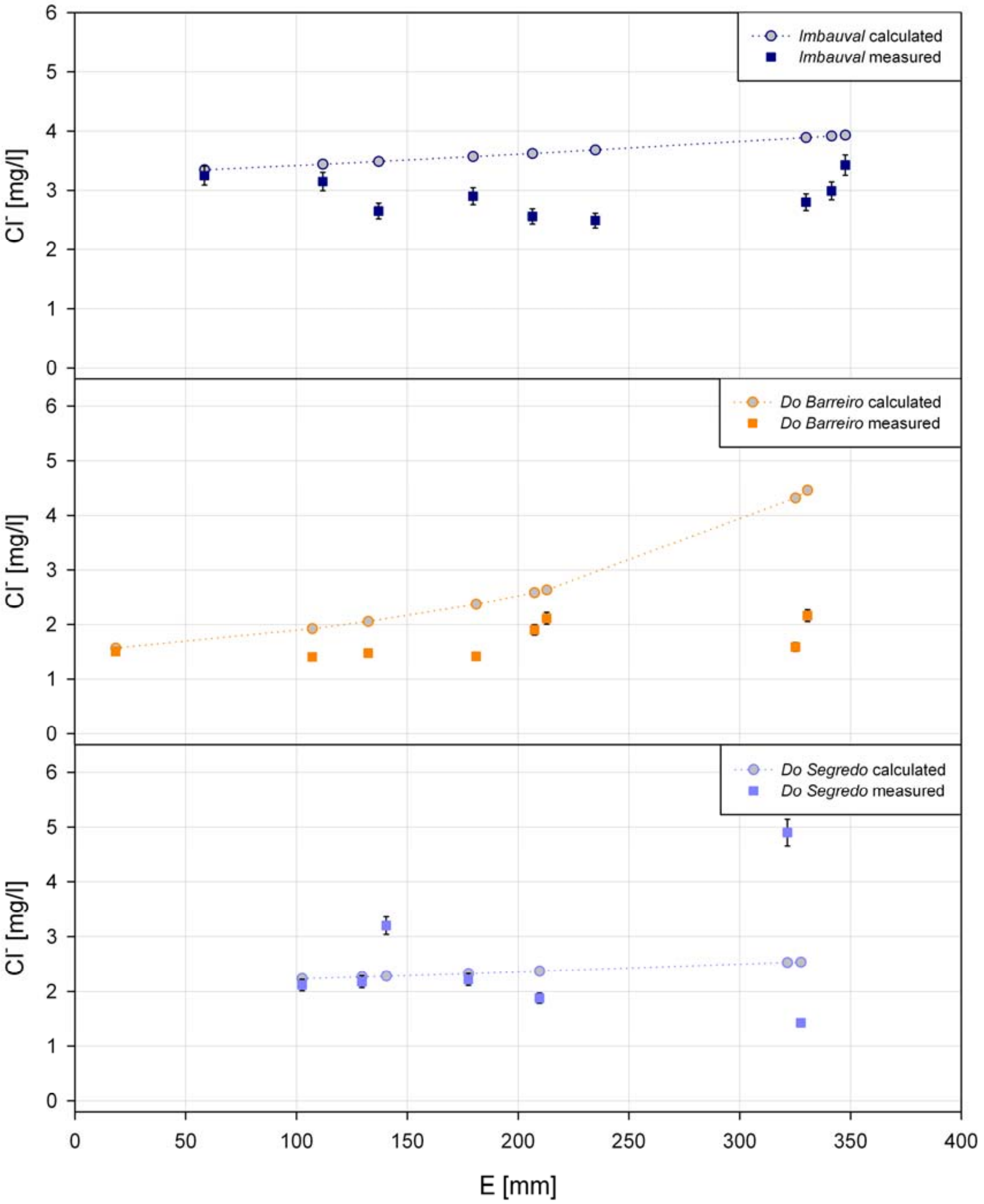

Figure 41: Calculated and measured Cl$^-$ concentrations for *Imbauval*, *Do Barreiro* and *Do Segredo*

Figure 42 displays calculated and measured Cl$^-$ concentrations for *Cuiabá Velho 1*, *2* and *3*. All measured Cl$^-$ values of the Cuiabá Velho water bodies range between 2 and 13 mg/l. Two calculated values for *Cuiabá Velho 3* are missing because the chloride mass balance equation resulted in negative values due to the calculation of a negative water volume. Theoretical Cl$^-$ concentrations for the Cuiabá Velho water bodies are ranging between 2 mg/l up to nearly 14 mg/l for *Cuiabá Velho 3*.

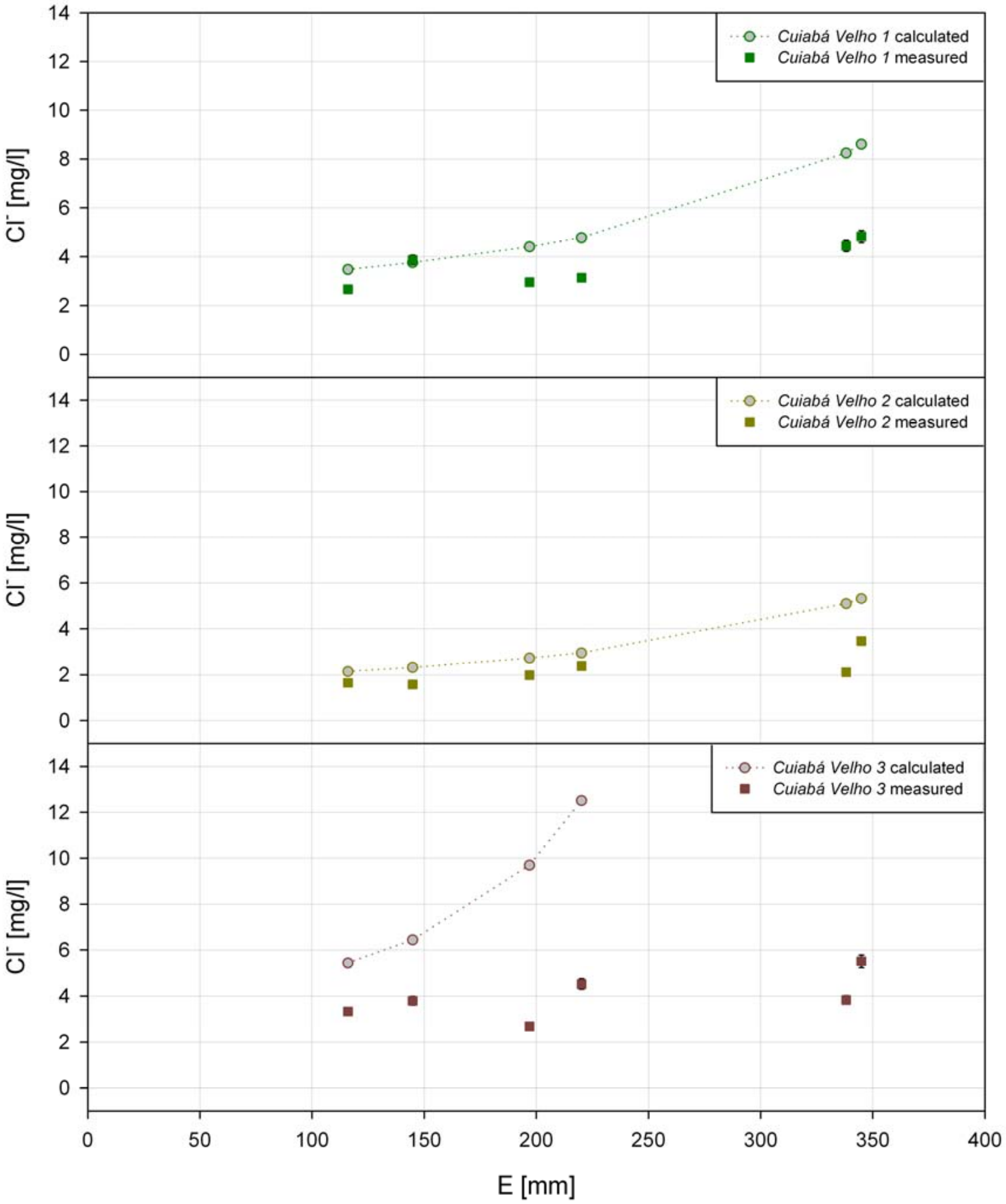

Figure 42: Calculated and measured Cl^- concentrations for *Cuiabá Velho 1*, *2* and *3*

Only *Aguapé* indicates a different behaviour (figure 43). It is the only water body where Cl^- concentrations reach up to 80 mg/l. Two calculated values for *Aguapé* are missing due to the same reasons as mentioned above.

All Cl^- concentrations of the water bodies, except two samples of *Do Segredo*, plot below the calculated values. Thereby, differences between measured and calculated concentrations are considerable and there is often no pattern observable that measured Cl^- concentrations follow a constant enrichment factor.

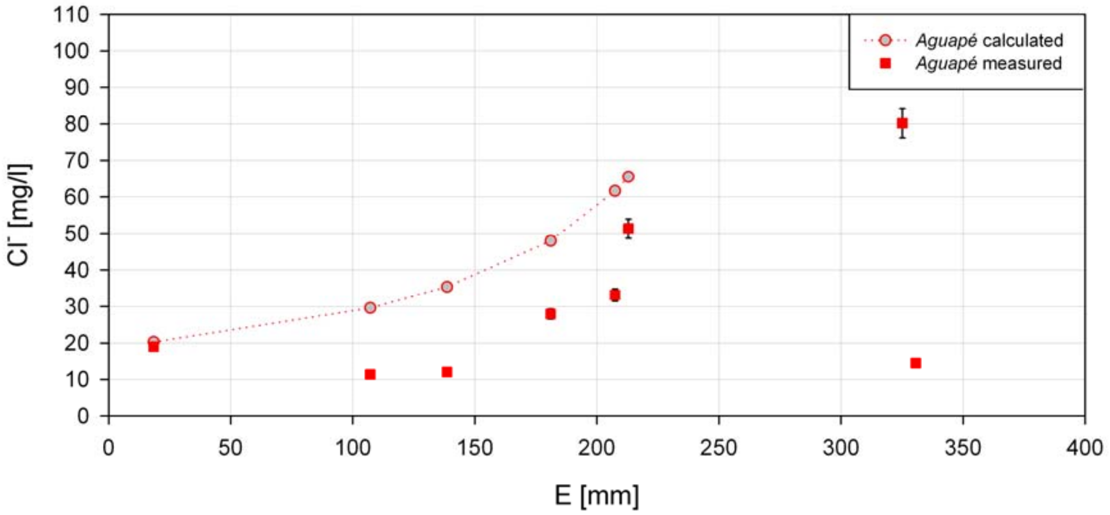

Figure 43: Calculated and measured Cl^- concentrations for *Aguapé*

4.5 Determination of hydrological systems

To identify the lake systems and the role of inflow and evaporation in the water budget of a lake, F values were calculated as the ratio of inflow I and evaporation E assuming that this ratio reaches a steady state in the end of the dry season. The corresponding values with their large uncertainties (F_{min}, F_{max}), as described in section 3.5.3, are given in the annex (B.8). Figure 44 and figure 45 show these calculated ratios for all water samples of the water bodies in the RPPN SESC Pantanal.

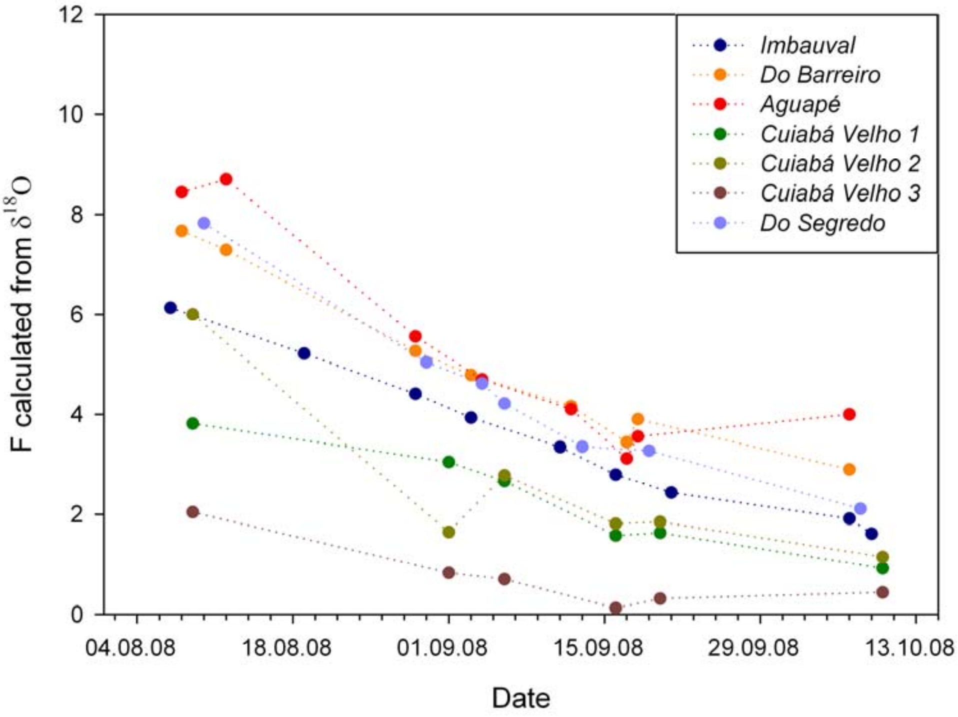

Figure 44: F ratios calculated from the simplified tracer approach with $\delta^{18}O$

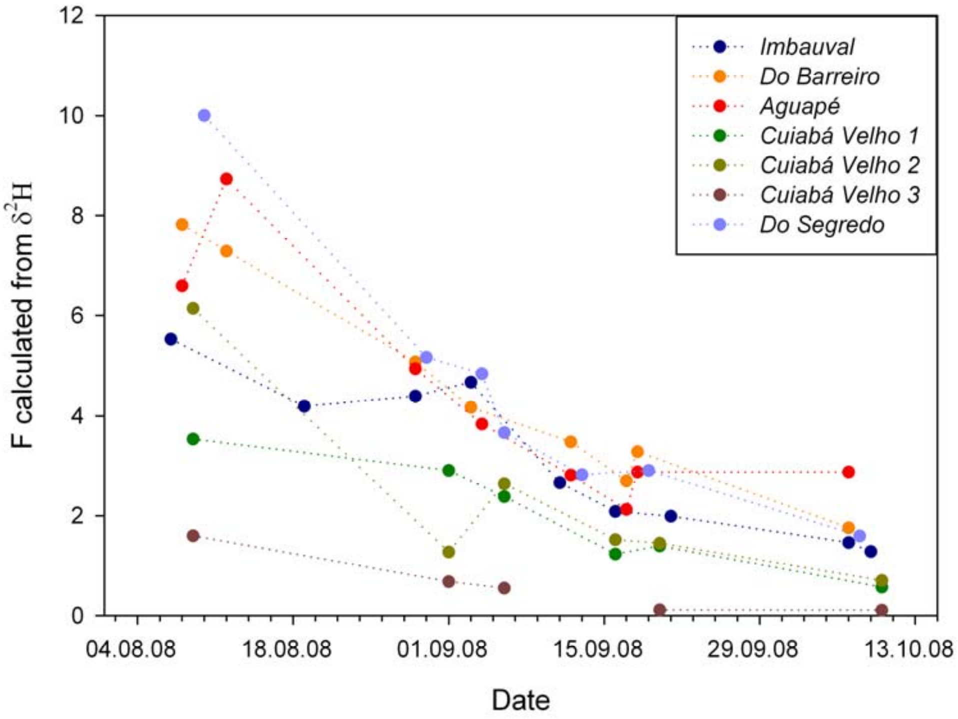

Figure 45: F ratios calculated from the simplified tracer approach with δ^{2}H

For all water bodies it can be seen that the lake systems are stabilising at the end of the field study. Nevertheless, F ratios differ largely and it is obvious for most of the water bodies that the systems have not yet reached a steady state between inflow and evaporation. Especially the larger water bodies still do need more time to stabilise. However, at least for all Cuiabá Velho water bodies it is displayed that the systems are nearly stabilised in mid-October. For *Cuiabá Velho 3* it can be even supposed that it is rather close to steady state. From the calculation from δ^{2}H it can be reasoned that the water bodies are closer to steady state relative to the calculation from δ^{18}O.

Nevertheless, F ratios from the last water samples, respectively, are used to identify the type of water balance for the studied lakes. The calculation from δ^{18}O is displayed in figure 46. It is obvious that *Imbauval* has a different humidity deficit than all other water bodies. This results from the fact that the humidity deficit is derived from the time period between first and last water sample, explained in section 3.5.3.

Concerning the F ratio calculated from δ^{18}O, only *Cuiabá Velho 1* and *3* show F ratios < 1. In all other water bodies the reverse is the case where inflow is higher than evaporation in the water balance of those lakes, indicated by F ratios > 1.

Concerning the F ratios calculated from δ^{2}H (figure 47), the water bodies indicate more or less the same behaviour relative to the calculation from δ^{18}O.

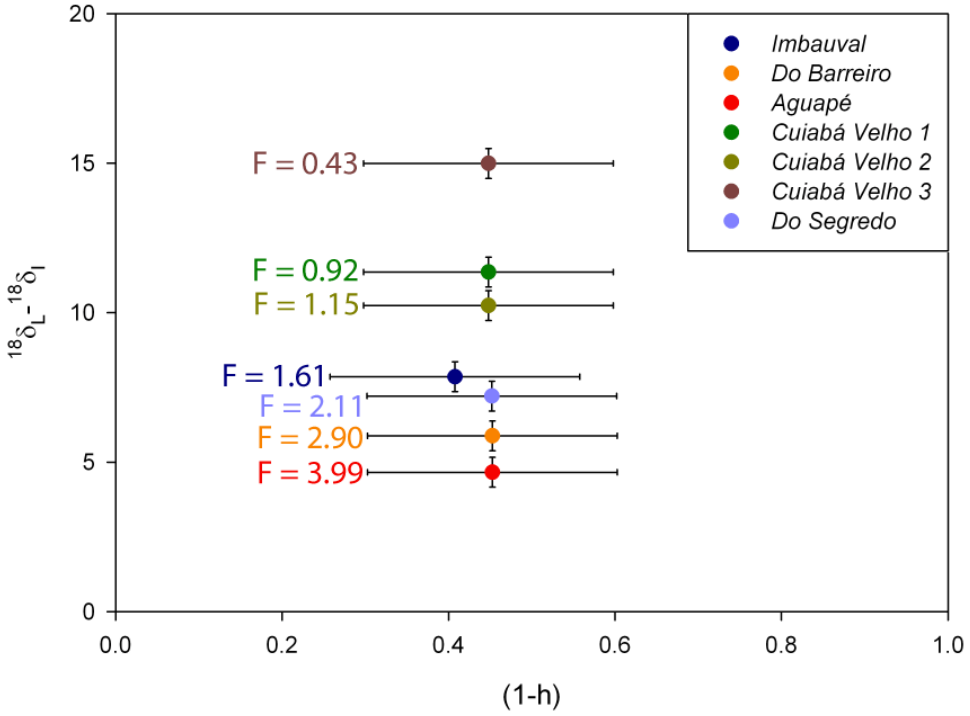

Figure 46: F ratios of the last water samples calculated from $\delta^{18}O$

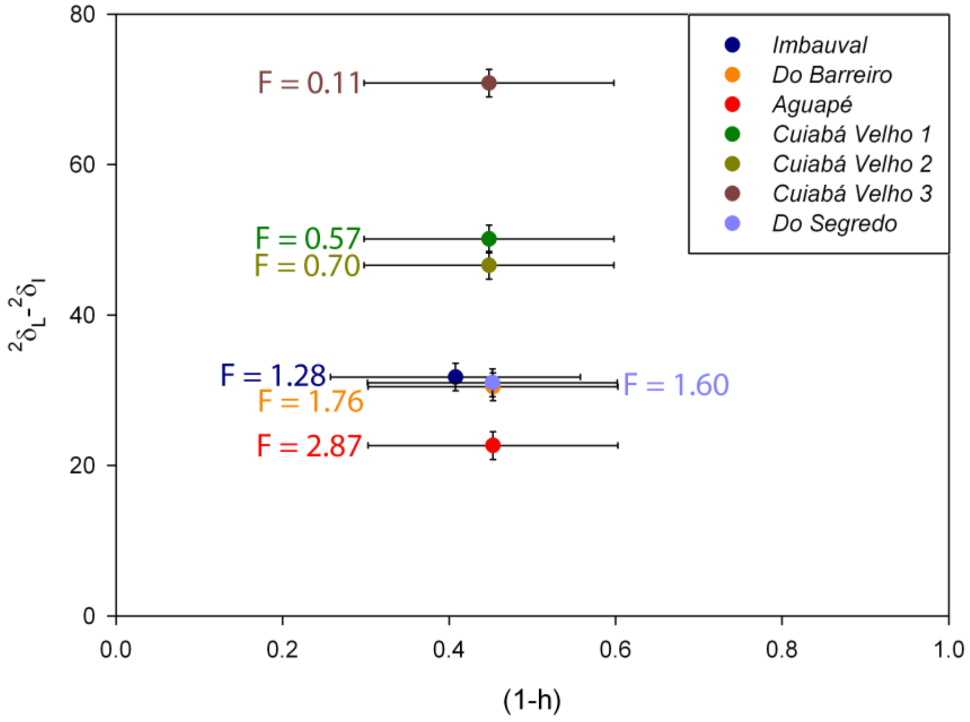

Figure 47: F ratios of the last water samples calculated from $\delta^{2}H$

Cuiabá Velho 3 is a water body where evaporation is more important in the water budget compared to the inflow with the lowest F ratio of 0.11. *Cuiabá Velho 1* and *2* are evaporation controlled systems as well. In *Imbauval*, *Do Barreiro*, *Aguapé* and *Do Segredo*, inflow is higher than evaporation due to F ratios > 1. The calculation from both environmental tracers indicates the same behaviour for all water bodies, except for *Cuiabá Velho 2*. Calculated from $\delta^{18}O$ this water body is a throughflow system compared to the calculation from $\delta^{2}H$ where it is evaporation controlled. *Aguapé* is the lake, which is mostly controlled by inflow. It has a groundwater inflow, which exceeds evaporation nearly about three times derived from $\delta^{2}H$ and nearly about four times derived from $\delta^{18}O$. However, the importance of inflow and evaporation in the water budget is equal in both calculations for the different lakes. This is derived from the fact that the order of F ratios is the same for all water bodies, either from the calculation from $\delta^{18}O$ or from $\delta^{2}H$. The error range for the calculated humidity deficit is enormous, being the most doubtful parameter within this tracer approach, which is discussed below in section 5.4.

Using calculated evaporation rates from the Penman-Monteith approach and the calculated F ratios within their uncertainty range, it is finally possible to estimate ranges of inflow rates for the different water bodies for the time period of field study (I_{min}, I, I_{max}). The calculated values are listed in table 12. They vary greatly in their calculation from $\delta^{18}O$ and $\delta^{2}H$. The calculated inflow rates differ largely due to the high parameter uncertainties, which interfere with the derived F ratios as well. Four inflow rates (I_{min} calculated for *Cuiabá Velho 3* from $\delta^{18}O$ and I_{min} for all Cuiabá Velho water bodies from $\delta^{2}H$) could not be determined due to the calculation of negative F ratios.

Table 12: Inflow I within the uncertainty range derived from the simplified tracer approach

Water body	I_{min} $\delta^{18}O$ [mm]	I $\delta^{18}O$ [mm]	I_{max} $\delta^{18}O$ [mm]	I_{min} $\delta^{2}H$ [mm]	I $\delta^{2}H$ [mm]	I_{max} $\delta^{2}H$ [mm]
Imbauval	339.9	559.58	681.1	9.94	445.50	678.3
Do Barreiro	859.1	957.53	1053.2	256.1	580.76	776.1
Aguapé	1237.3	1320.53	1441.9	600.6	949.71	1187.8
Cuiabá Velho 1	120.6	317.34	427.9	-	197.01	377.7
Cuiabá Velho 2	212.8	395.91	502.5	-	242.57	425.2
Cuiabá Velho 3	-	149.65	271.9	-	36.75	213.1
Do Segredo	548.7	691.08	793.0	198.9	522.56	714.8

4.6 Assessment of inflow rates

From the application of the MINA TrêS model estimates of inflow rates for six water bodies, except for *Do Segredo*, with their Cl^- concentration and isotopic compositions of $\delta^{18}O$ and $\delta^{2}H$ were derived. The calculated lake volume, daily inflow rates, total inflow during the time period of field study as well as their concentration of Cl^-, $\delta^{18}O$ and $\delta^{2}H$ for all water bodies are given in table 13. The lake volumes of *Imbauval*, *Do Barreiro* and *Aguapé* were calculated with another value relative to the estimation at the beginning of the field study. For *Imbauval*, the lake volume varies in in the modelled range of -10 %, for *Do Barreiro* and *Aguapé* in the range of +10 %. The results demonstrate that the inflow rates show a strong spatial variation between the different water bodies.

They range between 9.7 and 18.5 mm/d resulting in a total inflow between 662.2 mm for *Cuiabá Velho 1* and 1278.1 mm for *Aguapé*. Furthermore, Cl^- concentrations vary between 1.4 and 23.9 mg/l. Although the assumptions were more complex for *Imbauval* and *Do Segredo*, MINA TrêS did not assess a different outflow rate for *Imbauval*.

Table 13: Results for *Imbauval*, *Do Barreiro*, *Aguapé* and *Cuiabá Velho 1*, *2* and *3* modelled by MINA TrêS

Water body	Lake volume [mm]	Inflow rate [mm/d]	Total inflow [mm]	c_p Cl^- [mg/l]	c_p $\delta^{18}O$ [‰]	c_p δ^2H [‰]
Imbauval	1800	11.1	776.2	1.0	1.4	21.1
Do Barreiro	550	13.7	950.3	1.4	-5.5	-34.2
Aguapé	400	18.5	1278.1	23.9	-4.8	-28.3
Cuiabá Velho 1	500	9.7	662.2	2.6	-4.9	-29.2
Cuiabá Velho 2	500	11.2	760.9	1.7	-4.2	-23.6
Cuiabá Velho 3	383	16.2	1103.9	2.8	0.8	16.7

Figure 48 shows measured water samples and modelled Cl^- concentrations for the inflow rate of *Imbauval*.

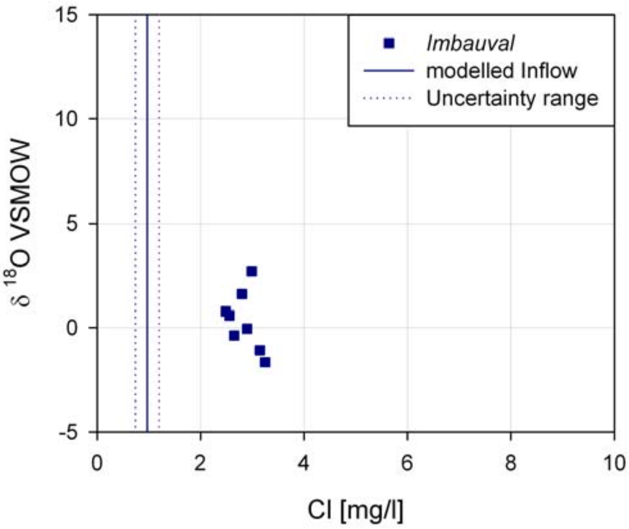

Figure 48: Measured water samples (squares) and modelled inflow concentrations of Cl^- (solid line) with uncertainty range (dotted lines) for *Imbauval*

Unfortunately, MINA TrêS modelled the Cl^- concentration of *Imbauval* inflow with the defined value for groundwater inflow. Therefore, the modelled Cl^- concentration of the input is 0.97 mg/l.

Figure 49 displays the measured water samples and modelled Cl^- concentrations for the inflow rates of *Do Barreiro* and *Cuiabá Velho 1*, *2* and *3*. The calculated uncertainty ranges for the modelled inflow concentration of Cl^- are small ranging between 0.18 and 0.57 mg/l. The measured Cl^- concentrations of all water samples from *Do Barreiro* and five water samples from *Cuiabá Velho 2* match fairly well with the modelled inflow concentrations. Three water samples of *Cuiabá Velho 1* and four of *Cuiabá Velho 3* show Cl^- concentrations that are higher than the inflow concentration modelled by MINA TrêS.

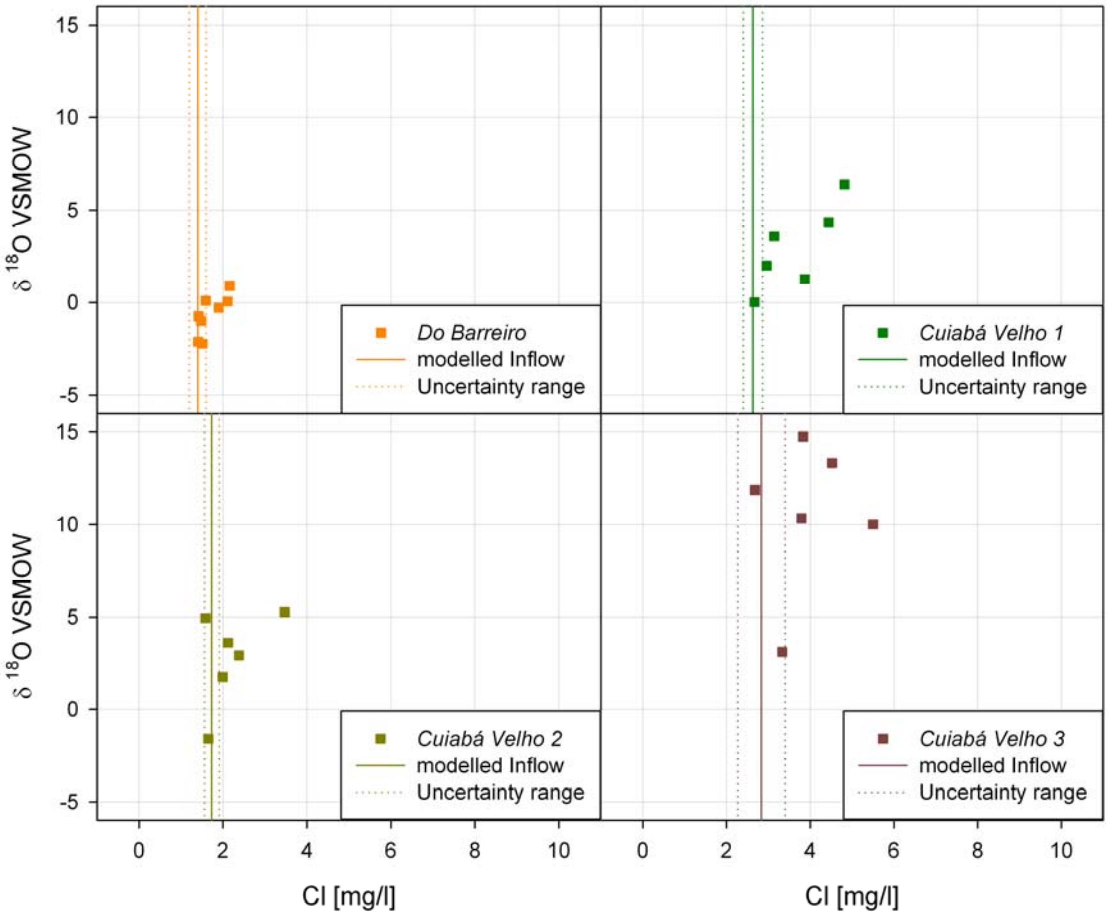

Figure 49: Measured water samples (squares) and modelled inflow concentrations of Cl^- (solid line) with uncertainty range (dotted lines) for *Do Barreiro*, *Aguapé* and *Cuiabá Velho 1*, *2* and *3*

Aguapé is the only water body where modelled and measured Cl^- concentrations are significantly higher relative to all other water bodies. The measured water samples and the inflow concentration of *Aguapé*, modelled by MINA TrêS, are displayed in figure 50. The inflow concentration of Cl^- is modelled with a value of 23.9 mg/l, even though the uncertainty range is very high in comparison with the other water bodies. Six water samples plot within the uncertainty range of modelled inflow. Only two water samples indicate a higher Cl^- concentration relative to the modelled results.

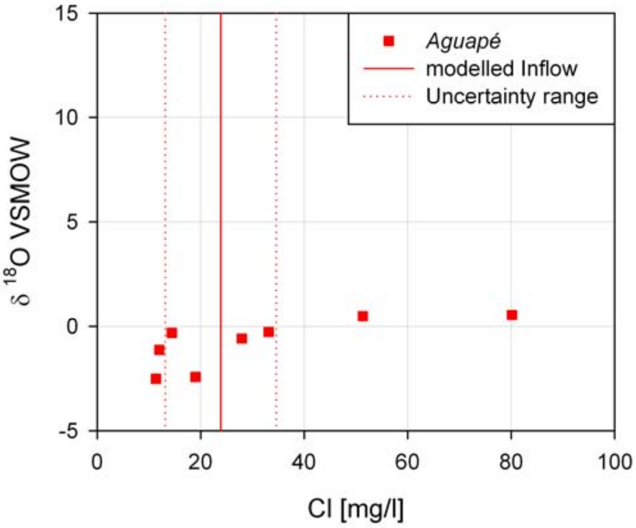

Figure 50: Measured water samples (squares) and modelled inflow concentrations of Cl$^-$ (solid line) with uncertainty range (dotted lines) for *Aguapé*

The δ^{18}O isotopic signatures of modelled inflow are displayed in figure 51. It is obvious that the modelled inflow rates can be divided in two groups, derived from the range of modelled δ^{18}O values. *Do Barreiro*, *Aguapé*, *Cuiabá Velho 1* and *2* compose one group. Their δ^{18}O values match with the measured isotopic compositions of the groundwater samples (section 4.2.2). The δ^{18}O values range for those water bodies between -5.5 and -4.2 ‰.

Imbauval and *Cuiabá Velho 3* compose another group. Both water bodies have an inflow component with a more enriched isotopic signature of δ^{18}O. For *Imbauval* the δ^{18}O value is modelled with 0.8 ‰ and for *Cuiabá Velho 3* the δ^{18}O value is 1.4 ‰.

The isotopic composition of inflow for *Do Segredo* is modelled with a δ^{18}O value of 20.3 ‰. Therefore, the isotopic content of its inflow rate is not displayed in figure 51 due to implausible high isotopic signatures.

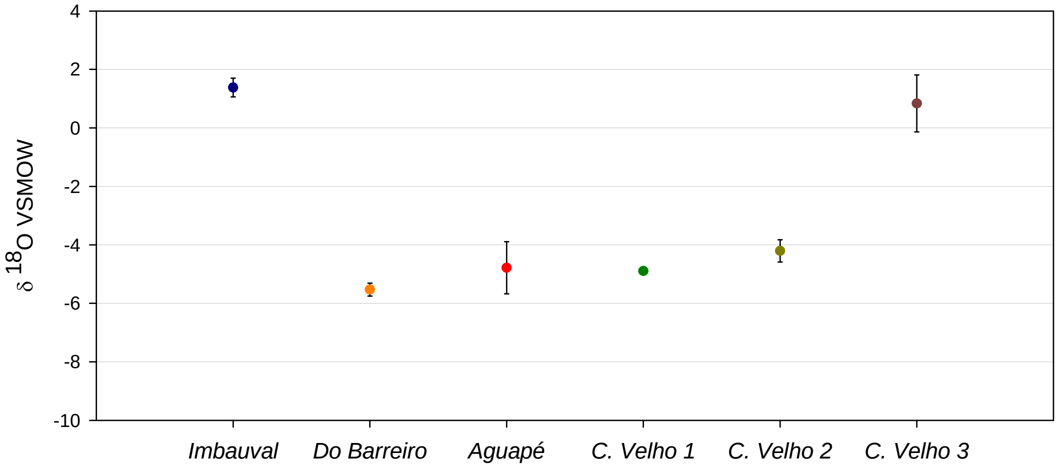

Figure 51: δ^{18}O isotopic composition of modelled inflow rates

For *Do Segredo* the calculated lake volume, daily inflow rate, total inflow during the time period of field study as well as its concentration of Cl^-, $\delta^{18}O$ and δ^2H are displayed in table 14. Assuming that outflow has not to be equal to inflow, the daily outflow rate as well as total outflow are modelled as listed below. The lake volume modelled by MINA TrêS is within the range of -10 %.

Table 14: Results for *Do Segredo* modelled by MINA TrêS

Water body	Lake volume [mm]	Inflow rate [mm/d]	Total inflow [mm]	Outflow rate [mm/d]	Total outflow [mm]	c_p Cl^- [mg/l]	c_p $\delta^{18}O$ [‰]	c_p δ^2H [‰]
Do Segredo	1994	2.3	152.1	1.1	222.7	1.0	20.3	172.5

4.7 Final water budget

With the modelled inflow rates of MINA TrêS it is finally possible to establish the water balance for the different water bodies. The modelled values for the initial lake volume, the predicted volume of a lake at the end of field study in October, total inflow, evaporation loss and total outflow in mm are displayed in table 15. Evaporation losses were taken from the Penman-Monteith approach for the time period between first and last water sample for each water body, respectively.

Table 15: Final water balance

Water body	V_i [mm]	V_p [mm]	I [mm]	E [mm]	O [mm]
Imbauval	1800	1412	776	388	776
Do Barreiro	550	167	950	383	950
Aguapé	400	17	1278	383	1278
Cuiabá Velho 1	500	122	662	378	662
Cuiabá Velho 2	500	122	761	378	761
Cuiabá Velho 3	383	5	1104	378	1104
Do Segredo	1994	1550	152	374	223

4.8 Summary

Following tables (tables 16 - 20) show all water bodies with their specific characteristics and the different results from the methods applied in this work.

Table 16: Morphometric parameters

Water body	Width [m]	Length [m]	Depth [m]	Area [m²]	Volume [m³]
Imbauval	3200	120	2	181000	362000
Do Barreiro	500	50	0.5	26000	~13000
Aguapé	n.a.	n.a.	0.3	n.a.	n.a.
Cuiabá Velho 1	50	10	< 0.5	300	~120
Cuiabá Velho 2	50	10	< 0.5	500	~250
Cuiabá Velho 3	20	6	< 0.5	120	~60
Do Segredo	390	35	2	10000	20000

Table 17: Major anions

Water body	Range of Cl^- [mg/l]	Range of NO_3^- [mg/l]	Range of SO_4^{2-} [mg/l]
Imbauval	2.49 - 3.43	2.64 - 5.75	0.39 - 0.60
Do Barreiro	1.41 - 2.16	2.36 - 5.79	0.32 - 0.43
Aguapé	11.38 - 80.18	7.67 - 31.35	0.72 - 14.31
Cuiabá Velho 1	2.67 - 4.82	4.58 -14.44	0.68 - 0.81
Cuiabá Velho 2	1.58 - 3.47	5.21 - 21.38	0.32 - 1.47
Cuiabá Velho 3	2.68 - 5.50	2.22 - 13.75	1.73 - 7.48
Do Segredo	1.43 - 4.9	0.43 - 2.19	0.33 - 0.43

Table 18: Water quality parameters

Water body	Mean water temperature [°C]	Range of water temperature [°C]	Mean pH	Range of pH	Mean specific conductivity [µS/cm]	Range of specific conductivity [µS/cm]	Range of DO [% Sat]
Imbauval	27.9	25.9 to 30.3	6.2	5.7 to 7.3	52	46 to 55	1.5 to 92.1
Do Barreiro	23.1	20.9 to 25.7	5.9	5.8 to 6.1	33	20 to 67	0.9 to 29.1
Do Segredo	26.7	22.9 to 30.8	6.1	5.8 to 6.3	19	16 to 21	10.2 to 65.7
Rio Riozinho	27.8	25.7 to 30.3	6.8	6.5 to 7.1	51	48 to 55	8.9 to 88.4
Cuiabá Velho 1	24.8	18.7 to 37.8	7.7	6.8 to 9.3	84	73 to 118	32.9 to 105.3

Table 19: Inflow calculated from simplified tracer approach

Water body	I_{min} $\delta^{18}O$ [mm]	I $\delta^{18}O$ [mm]	I_{max} $\delta^{18}O$ [mm]	I_{min} δ^2H [mm]	I δ^2H [mm]	I_{max} δ^2H [mm]
Imbauval	339.9	559.58	681.1	9.94	445.50	678.3
Do Barreiro	859.1	957.53	1053.2	256.1	580.76	776.1
Aguapé	1237.3	1320.53	1441.9	600.6	949.71	1187.8
Cuiabá Velho 1	120.6	317.34	427.9	-	197.01	377.7
Cuiabá Velho 2	212.8	395.91	502.5	-	242.57	425.2
Cuiabá Velho 3	-	149.65	271.9	-	36.75	213.1
Do Segredo	548.7	691.08	793.0	198.9	522.56	714.8

Table 20: Water balance components and concentrations of inflow rates

Water body	V_i [mm]	V_p [mm]	Inflow rate [mm/d]	I [mm]	E [mm]	Outflow rate [mm/d]	O [mm]	c_p Cl^- [mg/l]	c_p $\delta^{18}O$ [‰]	c_p δ^2H [‰]
Imbauval	1800	1412	11.1	776	388	11.1	776	1.0	1.4	21.1
Do Barreiro	550	167	13.7	950	383	13.7	950	1.4	-5.5	-34.2
Aguapé	400	17	18.5	1278	383	18.5	1278	23.9	-4.8	-28.3
Cuiabá Velho 1	500	122	9.7	662	378	9.7	662	2.6	-4.9	-29.2
Cuiabá Velho 2	500	122	11.2	761	378	11.2	761	1.7	-4.2	-23.6
Cuiabá Velho 3	383	5	16.2	1104	378	16.2	1104	2.8	0.8	16.7
Do Segredo	1994	1550	2.3	152	374	1.1	223	1.0	20.3	172.5

5 Discussion

5.1 Water chemistry

Temperature, pH, specific conductivity, DO and NO_3^- were measured in five different water bodies in the RPPN SESC Pantanal. Within the scope of this work only daily variations as well as comparisons between individually measured days and between the different water bodies can be considered, since only some weeks of field study were carried out during the dry season. The sampling period was too short for interpretation of the interannual variability of chemical variables (HAMILTON et al., 1999).

All water bodies in the northern RPPN SESC Pantanal show daily variations in water temperature varying in relation to air temperature, which largely determines their water temperature. Water temperature is a result of absorption of solar energy (WETZEL, 2001). Therefore, large daily variations can be expected for the water bodies in the RPPN SESC Pantanal. DREWS (1986) defines that shallow lakes with a depth < 1 m allow the light to pass to the bottom and the most part of light energy is absorbed in the first centimetres of depth. Depths stratifications were not performed in the lakes of the reserve because some test measurements indicated no remarkable differences. This finding is in accordance with a study carried out by NOGUEIRA et al. (in press), throughout which a test in the Cuiabá River showed that the water level was too low to show any difference of the variables with depth in the dry season. Although it is assumed that air temperature is very consistent during the dry season, friagems (section 2.3.2) happened during the time period of field study and dropping air temperature was observed. Cooling of surface water results from brief shifts of local meteorological conditions like clouds or from increased evaporation rates, cold rain or from a decrease of air temperature. Shallow lakes normally show large changes in temperature but especially floodplain lakes can be covered by vegetation which leads to a reduction of heating. Furthermore, dissolved organic matter may significantly increase absorption and loss of temperature also results through evaporation (WETZEL, 2001).

The only difference in temperature between the water bodies is observable in their ranges, as all show a daily variation with a peak in the afternoon hours. The daily variation is smallest for *Rio Riozinho*, which can be explained by the largest water volume of measured water bodies and the slow but existing flow in this river, which avoids high thermal gradients (HAMILTON et al., 1995). Standing water bodies show higher temperature increases in the afternoon than rivers (WETZEL, 2001). Although *Do Barreiro* has a smaller depth than *Do Segredo*, the smaller daily variation can be explained by the sampling location, which was always located in a shaded place in contrast to the sampling point at *Do Segredo*. It is not surprising to find a large daily variation for *Cuiabá Velho 1*, which amounts sometimes up to 10 °C, since this water body has only a depth of around 30 cm.

The long-term measurement of *Imbauval* shows small daily water temperature variations of around 3 to 4 °C, which can be explained by its very large water volume. Water temperature is more or less related to air temperature, whereas water temperature shows a time lag. But the tendency is observable. Especially friagems in the middle of September result in a rapid decrease of *Imbauval* water temperature.

pH of natural waters is useful to assess reactions of the water because it is a particularly dynamic factor. pH values are highly influenced by the daily weather and the rate of evaporation (HECKMAN, 1998). In-situ measured pH values should be seen as more representative than analysed pH in the laboratory (HEM, 1992).

pH can reach a steady value, which is obvious for *Do Barreiro*, *Do Segredo* and *Rio Riozinho* resulting in slightly acidic pH values without a remarkable daily variation. Small variations are within the error range and therefore they are not interpreted further on. pH < 7 can be a hint for oxidation processes in the water or for organic soils (REDDY & D'ANGELO, 1994). Rainwater determines pH as well, mostly ranging around 5.6. Therefore the slightly acidic pH in the Pantanal water bodies can be explained by precipitation. Most natural waters can be seen as buffered. Therefore, pH does not show great alterations. Furthermore, sediments can contain reduced minerals, which can result in lower pH values (HEM, 1992).

Cuiabá Velho 1 and *Imbauval* show daily variations in pH. A rise of pH during the afternoon can be due to biological assimilation (SCHÖNBORN, 2003). During nighttime, pH values of *Cuiabá Velho 1* decrease due to a higher respiratory activity. For *Imbauval* it can be assumed that there is more biological activity relative to the other water bodies and therefore daily variations in pH are clearly observable (REDDY & D'ANGELO, 1994). The decline of the pH values from *Imbauval* over the first weeks of the measuring time is peculiar and cannot be explained without further information about biological processes within the water body.

More alkaline pH values of *Cuiabá Velho 1* can theoretically result from the presence of limestones. However, HAMILTON et al. (1995) reply that in the Pantanal even the most alkaline waters do not carry detectable concentrations of carbonate solids. But surrounding highlands of the Pantanal are partly consisting of weathered carbonate rocks and KLAMMER (1982) state that calcareous rocks can locally occur. Furthermore, daily pH variation in *Cuiabá Velho 1* may just reflect changes in water temperature due to a small water volume and missing aquatic vegetation (REDDY & D'ANGELO, 1994). Nevertheless, the carbonate system is mainly controlling pH in natural fresh waters (HEM, 1992) and carbon dioxide (CO_2) utilisation during photosynthesis may increase pH values (REDDY & D'ANGELO, 1994). Additionally, lower water temperature at night results in higher amounts of dissolved CO_2 and therefore lowers pH and the reverse the case for the daytime. Unfortunately, data about CO_2 is not available for all water bodies and HCO_3^- could not be analysed due to missing water volume of the collected water samples. Thus, further interpretation about processes concerning pH due to the carbonate presence is not possible.

Specific conductivity in all water bodies of the Pantanal is extremely low. All measured values are < 80 µS/cm. This corresponds well with specific conductivities given in the literature (HECKMAN, 1998). To last in dry season wetland lakes have to have a bottom of silt or clay or contact with rock or groundwater (DREWS, 1986). Low conductivity values can be allocated to the fact that this region consists of substrate with a great age. Furthermore, groundwater of this area, which can alter specific conductivity, is not rich in ions any more. Most waters in the Pantanal are ionically diluted. The relatively low ion content can be explained by generally sandy soils and the importance of rainfall as a source of flooding (HAMILTON et al., 1999).

Differences in specific conductivity between the five measured days of the water bodies are not observable or are within the error range. Only the last measured day of *Do Barreiro* and *Cuiabá Velho 1* shows higher values. It is possible that the small rainfall event at the end of September is responsible for those increased values. For *Cuiabá Velho 1* this can be assumed because the water volume is very small and even a small amount of rainfall can considerably change the value of specific conductivity (HAMILTON et al., 1999). CALHEIROS & HAMILTON (1998) explain that those higher values can result from leaching of solutes from dry soils and dead plant material. An increase in the specific conductivity values in shallow lakes, which is enhanced by a decrease in water volume due to evaporation, is not observable (NOGUEIRA et al., in press). Daily variations of *Imbauval* are due to temperature variation or they are also within the error range.

O_2 distribution is directly linked to the productivity of aquatic ecosystems (WETZEL, 2001) and especially in the dry season fluctuations in DO are extreme (HECKMAN, 1998). For establishing equilibrium between DO and the atmosphere water circulation is required. Furthermore, the diffusion of gases into air is very slow. In open water, O_2 is consumed by plants and animals, by chemical oxidation of organic matter and by bacterial respiration (HEM, 1992). Two important processes that alter the O_2 concentration are photosynthesis and respiration (NOGUEIRA et al., in press). For most aquatic organisms DO is essential to respiratory mechanisms (WETZEL, 2001). In slow moving rivers or standing water bodies with abundant macrophytes O_2 elevates during the daytime due to photosynthesis. At night, respiration processes occur and only physical oxygen inputs aerate the water body (NOGUEIRA et al., in press). The changes of O_2 concentration can provide a mean of estimating photosynthesis and respiration (ALLAN, 1995). Strong biological control causes such changes because if this biological activity is absent, temperature would cause just the opposite pattern. If additionally the compound of humic organic matter is high, lakes are often undersaturated. Typically, wetland lakes have a large input of organic matter where decomposition leads to O_2 depletion (HEM, 1992). To large part O_2 is consumed at the sediment-water interface where organic matter accumulates and bacterial metabolism takes place. This interface can become anaerobic very quickly (NOGUEIRA et al., in press).

Undersaturation is mostly observed in the water bodies in the reserve as well as an increase in DO values in the afternoon hours. According to NOGUEIRA et al. (in press), water columns during the low water period can be completely oxidised during the day, but during nighttime concentrations can be very low. All water bodies show more or less this tendency. Shifts in temperature also result in daily changes of O_2 concentrations. Pressure alterations due to changes in height can be neglected because all water bodies are located more or less in the same altitude.

High DO saturation values in *Rio Riozinho* can be explained by its flow. Even if it is very slow equilibrium between DO and the atmosphere can be easier established. But 100 % saturation in *Rio Riozinho* is never reached, possibly due to missing circulation and slow diffusion. Obvious is that *Do Barreiro* nearly shows anoxic conditions at night and early morning. If O_2 consumption exceeds the input due to missing circulation, biochemical oxidation and eutrophication processes can result in undersaturation, as it happens often in standing waters of wetlands (NOGUEIRA et al., in press). Further on, depletion on O_2 can also be due to the dense carpet of macrophytes (HAMILTON et al., 1999). Decomposition of macrophytes and attached microflora can also be responsible for nearly anoxic conditions or can lead to severe O_2 deficits. DO values of *Do Segredo* are in between those of *Do Barreiro* and *Rio Riozinho*. Therefore, one can suppose that due to a larger water volume and only few macrophytes, O_2 depletion is less than in *Do Barreiro* but larger than in *Rio Riozinho* due to missing flow. *Cuiabá Velho 1* shows DO values reaching 100 % saturation in the afternoon hours. It is possible that due to evaporation the concentration of dissolved and suspended sediments is rising in a small water body. When the water table falls, the sediments, which are normally aerobe, can get in contact with O_2. This process contributes to raise mineralisation and concentration of nutrients in the water (DREWS, 1986).

Nevertheless, for the lakes in the RPPN SESC Pantanal, it should not emphasised too much trust in the O_2 measurements because many problems with the DO sensor due to its sensitivity and the difficulty of maintenance occurred.

In the IHF laboratory at Freiburg, an additional analysis of some major anions has been carried out and their results can possibly give indications for the processes in the different water bodies.

Salinity in natural waters results from leaching of rocks, soil runoff, atmospheric precipitation, deposition and the balance between evaporation and precipitation. The presentation of Cl^- in various rocks is lower than any other major constituent of natural waters. Cl^- is conservative, which means that only minor changes in concentration are due to changes in environment. Only sedimentary rocks can be more important sources for Cl^-. Sources and sinks within the wetland ecosystem are assumed negligible compared to inputs and outputs (WETZEL, 2001).

It can be assumed for the study area that deposition and rainfall should mostly be responsible for Cl^- input to the water bodies. Cl^- is present in rainfall due to physical processes that take place at the surface of the ocean. Then, it reaches the land by dry fallout (HEM, 1992). The Pantanal is situated more than 1,500 km from the Atlantic Ocean, but no large mountain ranges are located within this distance. It would still be possible that deposition of Cl^- takes place, but the measured Cl^- concentration in the rain sample is 11.4 mg/l. For such a high Cl^- concentration the origin solely from the ocean cannot be assumed. In the dry season it is furthermore possible, that Cl^- can be dispersed by wind from salt marshes, which are present in the southern Pantanal (BARBIERO et al., 2002) and deposited again. It can be supposed that Cl^- concentrations of all water bodies, except *Aguapé*, mainly result from dry fallout and evaporation enrichment.

For *Aguapé* other sources must be responsible for its high Cl^- concentrations. About those sources only assumptions can be made. Natural waters normally show low Cl^- concentrations, but exceptions are areas where inflow of high-chloride groundwater occurs (HEM, 1992). Hence, inflow with a high Cl^- concentration might be the reason for *Aguapé* to reach Cl^- concentrations up to 80 mg/l. For the southern Pantanal it is already known that saline waters exist (BARBIERO et al., 2002), but corresponding studies about saline aquifers for the northern Pantanal cannot be found in the literature. However, their presence cannot be excluded. Furthermore, it is likely that dried out periods of previous years led to accumulation of Cl^- in the lake. Then, the high Cl^- concentrations could be explained by accumulation of salts in the lake during many years. If groundwater recharge is very small or insignificant, loss of Cl^- does not take place. This corresponds with field observations, since *Aguapé* nearly dried out at the end of field study. High Cl^- concentrations can also occur after land-use changes such as clear-cutting. Since the Pantanal still counts to one of the least modified areas by men, land-use changes are not very probable.

NO_3^- can be an indicator for pollution as well as SO_4^{2-} concentrations. NO_3^- values measured by the MS5, as already mentioned above, are not considered any more for further interpretation (section 4.1.1).

Imbauval, *Do Barreiro*, *Rio Cuiabá*, *Rio Riozinho* and *Do Segredo* show NO_3^- concentration, which do not differ greatly throughout the time period of field study. NO_3^- in unpolluted freshwater ranges between undetectable levels to 10 mg/l and is highly variable in time and space (HEM, 1992). Therefore, only high NO_3^- concentrations of *Aguapé* and Cuiabá Velho water bodies are noticeable. Their increase in NO_3^- concentrations can be explained by local concentration of birds or caimans or it is further possible that cattle feaces could enter the shallow lakes (section 2.8). Especially terrestrial animals and their excreta can be responsible for transient eutrophication or for extreme fluctuations of physical and chemical variables in shallow eutrophicated lakes. They can play an important role in their nutrient dynamics (NOGUEIRA et al., in press). Locally very fast mineralisation processes can take place, which can be a biogene reason for the measured NO_3^- concentrations. Normally NO_3^- is a parameter that does not change within large ranges up to more than 10 mg/l within short times, when anthropogenic effects can be excluded (HEM, 1992). Therefore, the reasons for elevated NO_3^- concentrations in those water bodies are most probable due to animals or anthropogenic pollution, which even has to be considered in a nature reserve. To give further evidence about other processes in the nitrogen cycle such as denitrification or ammonification, concentrations of other nitrogen states are required, which unfortunately could not be measured within the scope of this work.

SO_4^{2-} concentrations of nearly all water bodies are considerably low. Only *Aguapé* and *Cuiabá Velho 3* show a steep increase in SO_4^{2-} during the time period of field study. Without additional information about the several different states of sulphur oxidation in wetlands, it is difficult to draw conlusions from this single information. Higher SO_4^{2-} concentrations can be due to the occurrence of evaporate sediments or biochemical sources. Drainage from calcareous rocks shows SO_4^{2-} in high concentrations and mineral soils can be another source (WETZEL, 2001). The same reasons, as for NO_3^- concentrations, animal or anthropogenic pollution, can be assumed for elevated SO_4^{2-} concentrations.

However, without information about groundwater systems and a detailed geological study for the RPPN SESC Pantanal, there is no more interpretation about major anions possible.

In general, variability in hydrochemistry can also result from different residence times of water in the water bodies, which depend on their morphology and interactions with groundwater. Due to lack of information about groundwater chemistry, aquifer systems and atmospheric deposition in this region (HAMILTON et al., 1999), it is still difficult to draw final conclusions about the reasons for the variability in hydrochemistry.

5.2 Isotope analysis

From the isotopic point of view within the Pantanal lots of unanswered questions about the hydrological cycle still remain (MATSUYAMA et al., 2005). However, from the isotopic signature of the water samples collected from the RPPN SESC Pantanal some conclusions can be drawn with respect to their different sampling locations. First of all, precipitation and groundwater samples are considered in the following.

Although the seasonal effect is based on precipitation data from 1961 to 1987, it has to be considered that rainfall during the dry season is very scarce. Therefore, the seasonal effect mainly is an amount effect. The lighter $\delta^{18}O$ values of the winter months between November and April can be explained by strong rainfall events in the rainy season. Hence, it is obvious that δ values in the dry season are heavier even though rainfall is sparse and the seasonal effect is based on fewer and lighter events in the dry season (annex B.9). However, for the area of Cuiabá the amplitude of the seasonal effect ranges for $\delta^{18}O$ between -7.1 and 1.7 ‰. This range is typical for the subequatorial region (CLARK & FRITZ, 1997). The rain sample collected from *Espírito Santo* matches with heavier isotopic compositions of precipitation from Cuiabá corresponding with the mean δ value for September. As mentioned above, this results from the smaller amount of precipitation, which can be expected at the end of dry season. The rainwater sample was collected some hours after the rainfall event. With a small deviation from the GMWL it can be supposed that evaporation and therefore stable isotope enrichment already took place.

The groundwater sample of *São Luiz* plots on the GMWL within its error range. As described in section 3.2.3, it is the only groundwater sample, which could be collected from freshly pumped groundwater. Therefore, it can be concluded that the collected groundwater only encountered very small evaporation effects. This is possibly due to a very short residence time at the surface and fast infiltration processes, which can occur with respect to the alluvial sediments in this region. The three groundwater samples taken from *Espírito Santo* indicate a slight enrichment. This is not remarkable because the samples were collected from the tank where pumped groundwater remains for some days after pumping. Although the tank is tapped, evaporation cannot be excluded, which leads to the slight enrichment of $\delta^{18}O$ and $\delta^{2}H$ of the groundwater sample. Nevertheless, deviation from the GMWL is very small and the source composition of all groundwater samples indicate that it was recharged from precipitation of the winter months (December to March), which correspond with the rainy season. It has to be mentioned additionally that only four samples of groundwater were collected within three months of a year. Therefore, more assumptions about groundwater recharge conditions or its isotopic composition in the northern Pantanal require more extensive groundwater studies.

Water samples were collected from seven lakes and two rivers in order to identify the hydrological functioning of the different water bodies. From all sampled water bodies the two rivers, *Rio Cuiabá* and *Rio Riozinho*, show the least enriched $\delta^{18}O$ values. Both rivers, of course, have a current, even if flow is drastically reduced in the dry season. Therefore, the enrichment of stable isotopes is less because of mixing processes and additionally as a consequence of the larger water volume and a shorter residence time compared to the lakes. Particular is that *Imbauval* shows a higher enrichment than *Do Barreiro* and *Aguapé*, despite having a larger water volume, which is the main difference between the water bodies. The enrichment of *Do Segredo* is similar to *Imbauval* even though the water volume of *Imbauval* is a lot larger than that of *Do Segredo*. All Cuiabá Velho water bodies show largest enrichment relative to all other water bodies. It can be concluded that Cuiabá Velho water bodies have the smallest water volume and therefore show the highest enrichment. Conspicuous are the very high δ values of *Cuiabá Velho 3*. Due to the fact that they were measured three times, it can be assumed that they are correct. FONTES & GONFIANTINI (1967) observed $\delta^{18}O$ values of +31.3 ‰ and $\delta^{2}H$ values of +129 ‰. But this very strong enrichment in heavy isotopes is probably due to the very arid environment in their studied area. For the isotopic signature of *Cuiabá Velho 3* a very dry environment in the Pantanal dry season also seems to be responsible for such a strong enrichment. The meteorological conditions can be seen as equal for all water bodies. Potential enrichment due to evaporation depends not only on the meteorological conditions but also on the reservoirs. This explains why water bodies differ in their isotopic enrichment. The only conclusion, which can be drawn from this, is that the water bodies must have subsurface inflow, which differ in its isotopic composition, but it cannot be revealed anything about its amount. This is in correspondence with FROEHLICH et al. (2005). They state that groundwater can be significant for the isotopic composition of a lake and therefore for its lake balance, which is discussed in section 5.5. Furthermore, it has to be considered that inflow to the water bodies can already have enriched δ values as well.

Concerning the backwater extrapolation all corrected water samples of surface and groundwater plot on the GMWL within the lighter range of isotopic compositions from Cuiabá precipitation data (1961-1987). The most depleted mean values of precipitation can be found between December and April (figure 28). The corrected samples correspond well with the mean values of those months. This is as well likely since precipitation mostly occurs in the rainy season between November and April. Nearly all water samples of *Do Barreiro* and *Aguapé* plot above, nearly all water samples of *Cuiabá Velho 3* plot below the LEL. It can be supposed that there are differences in the isotopic content of their groundwater reservoirs, which feed the different lakes. But all these groundwater reservoirs were recharged from precipitation of the rainy season, as already mentioned above. For example, this can result from different groundwater ages, but further conclusions cannot be drawn because information about aquifer systems or the groundwater age in the RPPN SESC Pantanal is not available. Deviations from the LEL can also be explained by different mixing processes. However, since those deviations are very small, further interpretation is dispensed.

5.3 Evaporation losses and effects

Evaporation losses from open water bodies were calculated on the basis of meteorological data measured in the RPPN SESC Pantanal. Meteorological data is given with a high resolution of measurements every 15 minutes. Calculated values of the evaporation rate show a slightly increasing trend. This trend results from the calculation of solar radiation and the energy available for evaporation during the time period of field study. The Penman-Monteith approach is the most used method to determine potential evaporation on a physical basis. Therefore, its potentiality is clear and it can be seen as very useful to get a good approximation of real processes in nature (DINGMAN, 2008). Confirming and opposing statements are given in the literature. KOHLER & PARMELE (1967) applied successfully a generalised version of the Penman Equation and state that the method delivers good results if evaporation is calculated on a daily basis. Nevertheless, MITSCH & GOSSELINK (1993) explain that for estimating evaporation losses this method is most cost-effective to get a first approximation, but it is not entirely satisfactory for estimating wetland evaporation due to many meteorological and biological factors that affect it. However, it is obvious from the results that evaporation losses are significant in the water budget of lakes in the northern Pantanal.

All water bodies are situated within a very small area where meteorological conditions can be assumed constant. On one hand, it can therefore be supposed that calculated evaporation rates do not significantly change for the water bodies in the reserve. On the other hand, one can consider the oasis effect because water bodies differ largely in their surface areas. The oasis effect cannot be neglected for those water bodies because it can be the reason for differences in results at about more than 1.5 times higher than calculated evaporation (SHUTTLEWORTH, 1993). Nevertheless, for the reserve the implementation of the Penman-Monteith approach constitutes the most reliable method in line with available data. Furthermore, as approximation calculated evaporation losses are close enough for the purpose of this work.

DINÇER et al. (1979) point out that in wetlands water cannot only be removed by intense evaporation or outflow, but as well by aquatic vegetation. It can remove unneglible water volume if the surface is largely covered by macrophytes, which is the case for *Do Barreiro*, *Do Segredo* and *Cuiabá Velho 2*. Since predications about the density of macrophytes in the RPPN SESC Pantanal cannot be made, moreover interpretation is disclaimed.

With the chloride mass balance approach the idea was to verify whether Cl^- enrichment of the water bodies is only due to evaporation because of lacking knowledge about groundwater contribution to their water volume at the beginning of field study. The simplification that the average depth is used instead of the water volume is valid, when the surface area is independent of the water level (TURNER & TOWNLEY, 2006). This can be assumed for the studied water bodies because the calculation is based on time steps of only few days between different water samples.

Measured Cl^- values did not show significant enrichment for most water bodies, except for *Aguapé*, which already was discussed in section 5.1. Theoretical Cl^- concentrations of all water bodies indicate that significant enrichment only due to evaporation does not take place and groundwater inflow also determines to large part hydrochemistry. Additionally, nearly no precipitation occurred during the time period of field study, why input of Cl^- due to precipitation can be neglected. Furthermore, it has to be considered that exchange processes with groundwater can take place, which could also influence the Cl^- concentration (TURNER & TOWNLEY, 2006). However, due to missing information about groundwater-surface water interactions moreover predications are not possible.

Measured Cl^- concentrations do not follow a constant enrichment factor. This could be an indicator that inflow plays a major role in the water chemistry of wetland lakes, which is in correspondence with TURNER & TOWNLEY (2006) and does possibly not take place continuously. On the other side, however, it can be the case that inflow is taking place continuously but mixing of the lake cannot be assumed. This fact cannot be refused because all water bodies are lentic and mixing processes can be very slow in the dry season (GONFIANTINI, 1986).

Negative Cl^- concentrations were calculated from the chloride mass balance equation in the case of *Aguapé* and *Cuiabá Velho 3*. They result from the calculation of negative water volumes, which of course are not possible in nature. This calculation is another indicator that the lakes are not only non-terminated systems but also groundwater significantly contributes to the lake volume. However, it corresponds with field observations that both lakes experience the largest water loss of all water bodies since they were nearly dried out at the end of field study.

Two water samples of *Do Segredo* show Cl^- concentrations, which are higher than calculated concentrations assuming that Cl^- enrichment is taking place due to evaporation only. Reasons for this can be that the lake is not well mixed, which can be assumed in the dry season, as already mentioned above. Furthermore, local contamination, for example from animals, can cause higher Cl^- concentrations as well.

With the assumption that the Penman-Monteith approach lead to correct evaporation losses and the chloride enrichment would be only due to evaporation, it would be possible to determine subsurface inflow rates with a two end member mixing analysis. Unfortunately, the Cl^- concentration of the groundwater inflow is not known. Therefore, an end member mixing analysis could not be carried out within this work. It only can be assumed that the groundwater inflow has a lower Cl^- concentration as measured Cl^- concentrations of the lakes. This is in accordance with statements of TURNER & TOWNLEY (2006).

The role of evaporation and inflow in the water budget of the Pantanal water bodies was also assessed with a simplified tracer approach. The results are discussed in the following section.

5.4 Simplified tracer approach

The simplified water balance tracer approach was applied in order to assess general lake dynamics of the different water bodies in the RPPN SESC Pantanal. First of all, the discussion concerning the tracer approach starts with evaluating its parameters, since they are, of course, fundamental components. They are sorted according to their influence on the ratio of inflow and evaporation, starting with the most important.

Many authors state that the influence of relative humidity h is largest on the tracer approach (GONFIANTINI, 1986, GAT, 1981 and GIBSON et al., 1993). Although it can be assumed for the dry season that the meteorological conditions remain more or less constant, a fluctuation of ± 15 % has been measured in the climate tower of the RPPN SESC Pantanal. It has to be considered that the daily mean values were calculated on the basis of values measured every 15 minutes. For the water bodies in the northern Pantanal the most sensitive parameter is h as well being responsible for the large uncertainty range of F. Applying the tracer approach within this large uncertainty range for h, results for F differ greatly.

Among all parameters δ_A is described in the literature as another most sensitive parameter. The parameters h and δ_A in particular are very difficult to determine with reasonable accuracy because they can change largely across a lake (GONFIANTINI, 1986). Within a study of GONFIANTINI (1986) h and δ_A were responsible for about 90 % of the estimated error. δ_A was most responsible for a high uncertainty of the results by evaluating the water balance in a study of ZIMMERMANN & EHHALT (1970) as well. In contrast, GAT (1995) reports, that δ_A and h can be measured or estimated close enough. But this statement cannot be confirmed for the calculation in this work, at least for h. *Imbauval*, *Do Barreiro*, *Aguapé* and *Do Segredo* show large surface areas where it can be assumed that humidity and the isotopic composition of ambient moisture are changing across the lake. For the simplified tracer approach within the scope of this study δ_A has been estimated on the basis of another background. The dry season causes that an isotopic equilibrium with precipitation cannot be assumed due to missing precipitation in the past months. Therefore, δ_A above the lake is not in isotopic equilibrium with the local precipitation during the dry season. According to ROZANSKI et al. (2000), the calculation reported in the literature does not work satisfactorily in extensive dry periods in the tropics. Therefore, the method described in section 3.5.3 is used instead. The total area covered by water and vegetation is difficult to estimate exactly. However, varying areas within the uncertainty of estimation the coefficient of surface cover σ did not change largely. Hence, it can be assumed that during the dry season the calculated value for δ_A represents well the conditions in the reserve.

GAT (1970) and LEWIS (1979) consider δ_A and the kinetic fractionation factor ε_K to be the most doubtful parameters of the water balance approach. Due to the fact that h is involved in the calculation of ε_K, the uncertainty of h interferes with the uncertainty of ε_K (GONFIANTINI, 1986). ε_K depends on the moisture deficit of the atmosphere and the relative difference of transport resistance in air. Many authors determined this transport resistance in air, which is the ratio $(D/Di)^n$ where D and D_i are the molecular diffusion coefficients in air of $^1H_2{}^{16}O$ and $^1H_2{}^{18}O$, respectively, and n is the turbulence parameter. This ratio depends on evaporation conditions and can in principle range between 0 and 1. A value of 0.5 was found for oxygen isotopes, which represents well the conditions that most frequently occurred in nature (CRAIG & GORDON, 1965). CRAIG & GORDON (1965) obtained the ratio D/D_i from the kinetic theory of gas but experiments were carried out as well to evaluate ε_K. The results for $\delta^{18}O$ are ranging between 13 and 21 ‰

and for δ^2H between 12.5 and 16.6 ‰ (GONFIANTINI, 1986). Those differences result from variable evaporation and aerodynamical conditions during day and night and from variable transport conditions of moisture on the lake's surface (MOSER & RAUERT, 1980). Therefore, the kinetic effect by diffusion is stronger for oxygen isotopes than for deuterium isotopes. In general, kinetic fractionation in natural systems is smaller than diffusion only. However, GONFIANTINI (1986) concludes that for evaporation conditions most frequently encountered in nature, ε_K can be adequately estimated by the applied method. Therefore, those ε_K values can be seen as representative of typical lake evaporation. However, values calculated for the water bodies in the RPPN SESC Pantanal show error ranges between 0.6 and nearly 1 ‰. Therefore, they contribute as well to the high uncertainty of the tracer approach.

δ_I is calculated on the basis of many years of precipitation data. However, for the time period of field study there was no precipitation, which has to be considered. Only one rainfall event took place with a very small amount, which unfortunately could not be measured due to instrument problems. δ_I corresponds well with measured groundwater in the reserve and should represent the isotopic composition of total inflow very well. Nevertheless, changing δ_I within its uncertainty range, the results for F differ highly. It has to be considered that inflow can largely vary in its isotopic composition of the water bodies and inflow with already enriched isotopic content is possible as well.

δ_L, besides h, is another parameter, which was directly measured in the field. Today it is possible due to modern measuring techniques that variations in isotope abundance can be detected with high precision. Hence, the isotopic composition of the different lakes only has a small uncertainty range. It can be suggested that the limiting isotopic composition has not yet been reached because the rainy season with constant precipitation is not starting until November. GAT (1981) explains that in natural situations limiting isotopic composition may not be reached at all.

ε^* can be determined very well because the equilibrium factor only depends on the fractionation factor α. The uncertainty range of α remains small and, therefore, lead to very small uncertainties for ε^* after Gauss' propagation of uncertainty.

The determination of the fractionation factor α was often done experimentally in the past. But values reported by MAJOUBE (1971) are most frequently used in recent years. In general, α is considered satisfactory consistent by a number of authors and differences are not really important, but differences can also be larger than the experimental error. However, the quality of determination of all those studies cannot be assessed critically (GONFIANTINI, 1986). The calculation of α depends only on the water temperature T_W. T_W of the different water bodies were calculated on the basis of the five measured days by the multiprobes where possible. For *Aguapé*, *Cuiabá Velho 2* and *3* it was necessary to fit a sinus function on rarely measured values. It can be supposed that this function represents a good approximation of the daily variation of water temperature. A sinus function for comparison on the daily variation of *Do Barreiro* where measured data is available verified a good fitting as well (annex B.9). Therefore, α calculated for the water bodies in the reserve following the propagation of uncertainty after Gauss corresponds well with values stated in the literature (GONFIANTINI, 1986) and shows only a very small uncertainty range.

For the simplified tracer approach a few assumptions had to be considered. Concerning complete mixing of the lake, GONFIANTINI (1986) states that shallow lakes in general show vertically a good mixing, but horizontally they are often poorly mixed. MOSER & RAUERT (1980) reply that in lakes with a depth < 1 m a very good mixing can be expected. DINÇER et al. (1979) assumes for an African wetland hydrological balance, which means that each water sample is representing a different stage of evaporation of the same initial water requiring complete mixing. Regarding the results of the tracer approach with a huge uncertainty it has to be supposed that mixing cannot be accepted without any qualification for the water bodies in the reserve.

Concerning steady state conditions GAT (1995) refers that steady state can rarely be encountered in nature because surface water systems depend on random processes and are highly changeable. Furthermore, seasonal changes have an effect on inflow, atmospheric moisture and evaporation rates influencing the mixing regime of lakes. For a temporary set of parameter it can be supposed that shallow lakes are close to the steady isotope composition at any time, which was assumed at the beginning of this work. Nevertheless, if these parameters vary the isotopic composition will change extremely (GAT, 1995). Additionally, GAT (1995) point out that desiccating lakes are not well represented by steady state, which makes modelling of their water balance components rather complicated. For the case of the Pantanal water bodies without any previous knowledge about the hydrological dynamics of the lakes, it could be shown that steady state conditions are not yet reached as expected for the end of the dry season. All lakes indicate a stabilisation of the F ratio, but due to the fact that the lakes did not yet reach steady state it could be demonstrated that an essential assumption of this tracer approach is not appropriate for the water bodies in the RPPN SESC Pantanal. If a lake volume and its isotopic composition are changing over time, a numerical solution would perhaps be a better way. Thereby, the adopted time steps and changes of all other parameters have to be known (ROZANSKI et al., 2000). A numerical solution could not be applied in this work, but perhaps would lead to better results, especially in the case of *Aguapé* and the Cuiabá Velho water bodies where volume changes cannot be neglected.

Due to the fact that the water samples were all taken in the dry season where the meteorological conditions do not change significantly, the mean annual water temperature of the lake should be identical to the mean annual surface air temperature in this area. Anyway, air temperature is having an effect on the water balance in a hidden way. Its changes are linked with humidity through the dependence on the saturated vapour pressure of the water surface and the equilibrium fractionation factor (GAT, 1995). Furthermore, GAT (1981) discusses the averaging over the lake's surface. The modification of humidity and aerodynamic properties in the atmosphere may cause major errors in the determination of a lake's water balance components. But their influence during the air/water interaction is not yet well known.

Concerning the isotopic composition of groundwater, it was already discussed in section 5.2 that the groundwater samples represent well the weighted mean isotopic composition of annual precipitation.

ROZANSKI et al. (2000) state that persisting difficulties originate from the reconciliation of the water balance components. They are mainly derived from data of the stable isotopes of water. The simplified tracer approach shows strongly discrepancies in its results derived from either ^{18}O or ^{2}H. ZUBER (1983) points out that the discrepancy is especially visible in evaporation-dominated systems. Many authors confine themselves to apply the tracer approach only with one of the stable isotopes. ZIMMERMANN & EHHALT (1970) preferred hydrogen isotopes due to the smaller fractionation factor, which results in a smaller contribution to kinetic fractionation. On the other hand, GAT (1970) reports the better understanding of the kinetic term in the case of ^{18}O. Therefore, he explains that the application with ^{18}O normally provides more reliable results even though the reasons for it are not well studied. However, the results of the tracer approach within this work do not agree with the last statement possibly due to the high uncertainty of the kinetic fractionation factor.

ROZANSKI et al. (2000) recommend carrying out both analyses for all collected samples. In this work, the simplified tracer approach was applied with ^{18}O and ^{2}H, respectively, for comparison of their results. Since the results for ^{18}O and ^{2}H differ largely, it is furthermore absolutely essential conducting an uncertainty analysis. Hence, the simplified tracer approach should always be applied with both stable isotopes of water in order to set more precise limits to the uncertainty of calculated F ratios. High uncertainties lead to a huge range of calculated inflow. Since F ratios differ extremely for the lakes in the northern Pantanal they cannot be used to determine the inflow rates of the water bodies. However, inflow rates could successfully be modelled with MINA TrêS, which is discussed in the following section.

Some examples of already applied water balance tracer approach studies, summarised by GONFIANTINI (1986), give fairly good ideas of their potential and limitations, but the capability of this method is also quite obvious (GIBSON & EDWARDS, 2002). Additionally, ZIMMERMANN & EHHALT (1970) point out that too much trust is put in the power of water balance studies. However, MOSER & RAUERT (1980) state that the tracer approach gives first valuations and deliver hydrological insight into the common water balance of a lake.

5.5 Modelling inflow rates

With MINA TrêS it was possible to assess inflow rates for the different water bodies and finally to quantify all components of the water balance equation for each lake based on hydrochemistry and stable water isotope data. There is no consensus reached, which concentration of each inflow is determined with most accuracy, as it differs highly between the water bodies. The sum of the calculated differences as absolute values was minimised in order to achieve a good fitting between measured and predicted concentrations. The optimum would be the minimisation to 0, but it is not surprisingly that 0 is never reached. Reasons for it can be the underlain constraints of the model, which are discussed below as well as possible measurement errors of Cl^- concentrations or isotopic signatures.

For *Do Barreiro*, *Aguapé* and *Cuiabá Velho 3* the model MINA TrêS determined a higher initial lake volume than estimated at the beginning of field study. The assumption that the lake volume can vary at about ± 10 % led to a larger lake volume for those water bodies. This tolerance for the lake volume can be justified with the fact that the values for the average depth of the water bodies were only estimations and could not be determined exactly. Without this assumption it would have resulted in a dried out stage for those lakes, which does not correspond with field observations. The average depth of all water bodies is used instead of the lake volume. This simplification can be assumed for the case of the Pantanal water bodies since modelling took place in time steps of days, as already discussed above (section 5.3).

Additionally, it was assumed that modelled Cl^- concentrations should at least correspond with Cl^- concentrations measured in the groundwater samples. This corresponds with a study of CROSS et al. (2001) where the input value represents a mean of measured inflow concentrations. Not taking into account this mentioned constraint, the Cl^- concentration of *Imbauval* would have resulted in an inflow without Cl^-, which can be assumed to be impossible for a water contribution originating from groundwater. Nevertheless, the model MINA TrêS modelled an inflow with the same Cl^- concentration as it was determined. It can be reasoned that for *Imbauval* this parameter is the parameter with the lowest sensitivity. Therefore, the results are unlikely for the Cl^- concentration of *Imbauval* because measured water samples of this water body show a considerably higher Cl^- concentration than the modelled inflow. For all other water bodies, except for *Do Segredo*, Cl^- concentrations correspond well with measured concentrations in the groundwater samples collected from the RPPN SESC Pantanal.

Uncertainty ranges of modelled inflow concentrations are small. Therefore, it can be concluded that inflow rates are modelled by MINA TrêS with high accuracy. The constraint for MINA TrêS that inflow is equal to outflow should be in correspondence with the natural conditions in the wetland. Since the wetland shows only a very small terrain gradient, one can imagine that if a water body is supplied by groundwater inflow, its outflow is more or less equal depending on the water table level. Furthermore, in a closed system the assumption should fairly be fulfilled if water is only lost by evaporation.

As a simplification it was assumed that the inflow rate is constant over the whole time period of field study to quantify the generell fluxes of the wetland system. Considering poor data availability and little knowledge about the hydrological systems the assumption can be justified with the intention to generally assess subsurface inflow. However, measurements are required to verify this assumption, which was not possible within the scope of this work.

Modelled isotopic compositions of inflow correspond for nearly all water bodies well with the isotopic content of the groundwater samples. Therefore, it can be concluded for *Do Barreiro*, *Aguapé*, *Cuiabá Velho 1* and *2* that they are fed by local groundwater reservoirs. It is not possible to determine whether subsurface inflow derives from the same aquifer system or from different systems. *Imbauval* and *Cuiabá Velho 3* show more enriched isotopic compositions of subsurface inflow. This could be an indicator for the connection between water bodies in the Pantanal wetland. Then, a water body is fed by local groundwater, isotopic enrichment takes place in a water body and the same water again reaches another water body as groundwater inflow (FROEHLICH et al., 2005). If this would be the case it would explain the stronger enrichment of the isotopic signature of *Imbauval* and *Cuiabá Velho 3*. To furnish proof of their enriched subsurface inflow it would be necessary to have the corresponding δ^2H values. However, since they were derived from equation (4), further interpretation can not be undertaken.

Do Segredo is the only water body where modelling with MINA TrêS did not lead to satisfying results. The Cl^- concentration is not a sensitive parameter as well and inflow concentrations of $\delta^{18}O$ and δ^2H are implausible high. Furthermore, MINA TrêS modelled very small inflow and outflow rates leading to the result that the water volume of *Do Segredo* is diminishing not only due to evaporation but also due to a higher outflow rate relative to inflow. The reasons for the model results for *Do Segredo* can depend on quantities, which are unknown (CROSS et al., 2001) and could not be investigated within this work. Furthermore, a sensitivity and uncertainty analysis should be undertaken, which was also not possible in this study. They could give further evidence on the limitation of this model. They could also be an indicator for the reasons of the nonsatisfying results for *Do Segredo*. However, this model serves to assess groundwater interactions where prior information is scarce or not available (TURNER & TOWNLEY, 2006).

6 Conclusion

The aim of this study was to understand the hydrological functioning within and between some water bodies in the northern Pantanal wetland. The two methods that were used in the field are basically suitable to study the hydrological behaviour of different water bodies in an area, which is difficult to access. Fewer problems resulted from the water sampling in the field than from measurements with the two multiprobes. The results about the water quality parameters measured by the multiprobes are not always reliable without restrictions. Especially DO and NO_3^- sensors are not recommended for surface water of wetlands due to a high sensitivity. Therefore, only short term measurements led to reasonable readings in surface water as opposed to the long term application where sensor problems result more frequently in data loss.

It was shown that even within a small area of a nature reserve large differences between water quality parameters are due to various processes, which encounter in the water bodies and their specific characteristics. Generally, water temperature of the water bodies in the northern Pantanal is a result of air temperature and the volume of the water body. Furthermore, smaller temperature ranges in rivers follow from their flow even if it is very slow in the dry season. pH values and specific conductivity are mainly controlled by the local geology of the Pantanal. However, water temperature, evaporation processes and ion input by precipitation are responsible for pH and specific conductivity values as well. In the dry season extreme DO variation is due to photosynthesis and respiration by bacteria and local aquatic vegetation. Beyond, decomposition and eutrophication processes, bacterial metabolism as well as circulation within the water body are determinative factors. The concentrations of major anions are mainly due to evaporation processes and groundwater inflow. Exchange processes between groundwater and the Pantanal water bodies most probably take place, but enough knowledge about aquifer systems and groundwater discharge or recharge conditions in this study area is still lacking. In turn, the water volume of the water bodies is also determinative for the enrichment of major anions due to evaporation. Local gathering of animals can result in higher concentration of anions due to their faeces, particularly in a region, which is famous for its biodiversity. Additionally, even in a nature reserve anthropogenic pollution can not be excluded. Unfortunately, it could not be proved in this work, which effects different coverage of macrophytes has on biological processes in a water body.

Evaporation losses were derived from an implementation of the Penman-Monteith approach, modified for open water. It constitutes the most reliable method for the determination of evaporation rates in line with available data. The Penman-Monteith approach considers the meteorological conditions influencing the water loss through evaporation as well as the surface area, which can be a determinative factor due to the oasis effect. The results show that evaporation is an important component of the water balance of the studied water bodies, which is not surprisingly in this arid time period of field study.

From the chloride mass balance it can be concluded that not only evaporation but also groundwater inflow is a fundamental component of the water budget and, therefore, an important factor for the hydrochemistry of the Pantanal wetland lakes. Even in the dry season all water bodies have significant inflow rates, which determine to large part Cl^- concentrations and isotopic compositions of the water bodies. Nevertheless, other methods have to be applied to give detailed information on subsurface inflow rates and groundwater interactions with the water bodies.

The analysis of stable isotopes of water was applied to gain insight into the evaporation process of surface water and the source of water. Not only evaporation largely determines the isotopic content but also the water volume of the Pantanal water bodies and mixing processes have an influence on isotopic signatures. Furthermore, $\delta^{18}O$ and $\delta^{2}H$ were used to study hydrological questions concerning the water budget of different water bodies. It was demonstrated that environmental tracers are quite adequate tools to investigate the evaporation effects and the general dynamics of the lakes by applying a simplified tracer approach. However, the tracer approach indicates a very high parameter uncertainty, whereas inflow rates calculated on the basis of this method do not yield in satisfying results. In addition, assumptions of the tracer approach do not match exactly with the hydrological situation in the Pantanal dry season due to missing steady state conditions. Hence, it is not recommended to assess inflow rates in this way. However, since there was no information available about the connectivity between water bodies, their inflow, evaporation losses and groundwater in the RPPN SESC Pantanal before starting field work, it was not clearly obvious which assumptions can be accepted or not. Hence, the simplified tracer approach can rather be used to get a rough assessment on the type of lake systems and the role of evaporation and inflow on their water balance than to yield quantitative results.

The model MINA TrêS was successfully employed to determine subsurface inflow rates for the different water bodies with their specific concentration of Cl^-, $\delta^{18}O$ and $\delta^{2}H$. For the water bodies in the RPPN SESC Pantanal it could be proved that they are closely connected to the groundwater in this region. The contribution of groundwater to the water volume is significant, which can not necessarily be assumed for the dry season. It can be concluded that the water bodies in the floodplain are fed by local groundwater reservoirs. It is also possible that they are connected among each other through subsurface flow. Except for one, the model MINA TrêS leads to satisfying results for all water bodies and is suitable to assess inflow rates with its specific concentration of Cl^-, $\delta^{18}O$ and δ^2H. Moreover, considering the simplicity of the model and its assumptions, it is capable to deliver promising results for an area with poor data availability and little previous knowledge. Limitations of this model are also evident mainly due to missing parameter sensitivity. Nevertheless, the application of hydrochemistry and stable water isotope data provides a way to reflect the inflow component of the water balance. Futhermore, it is a useful tool to investigate groundwater-surface water interactions in wetland systems.

For further research it is recommended to quantify the water balance of wetland lakes by applying different and independent methods or more complex water balance tracer approaches with adequate assumptions.

Finally, the sustainment of such a unique environment is an incitement in its own for further investigations. Following studies should as well contribute to the preservation of the Pantanal, one of the oldest areas in the world, as Claude Lévi-Strauss described this area with hydrological words:

“A paisagem é fantástica demais para ser monótona...como se esse terreno, um dos mais antigos do mundo, fragmento intacto do continente de Gondwana, que na era mesozóica unia o Brasil e a África houvesse se mantido jovem demais para que os rios tivessem tempo de cavar um leito.”

(Claude Lévi Strauss – Tristes Trópicos - 1954)

“The landscape is way too fantastic to be monotonous...as though these areas - some of the oldest in the world – intact fragment of the Gondwana Continent that once united Brazil to Africa – had been kept way too young for the rivers to have enough time to dig up a channel.”

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Annex

A Data

A.1 Meteorological data

Date	T [°C]	T_{max} [°C]	T_{min} [°C]	h [%]	U [m/s]
15.07.2008	24.19	30.33	18.13	41.64	2.26
16.07.2008	23.86	30.57	16.07	48.24	1.82
17.07.2008	24.50	31.04	17.28	50.76	2.08
18.07.2008	25.13	32.47	16.88	46.97	1.38
19.07.2008	25.71	33.07	18.13	51.17	1.64
20.07.2008	27.00	34.45	19.54	49.70	1.60
21.07.2008	27.75	34.93	19.50	45.41	2.34
22.07.2008	27.20	33.69	20.95	48.33	1.47
23.07.2008	27.11	33.90	19.84	46.98	1.27
24.07.2008	26.36	34.50	18.85	49.96	1.63
25.07.2008	22.91	28.46	19.73	79.39	1.58
26.07.2008	24.66	33.42	17.23	69.75	1.37
27.07.2008	27.06	34.67	18.41	49.38	1.58
28.07.2008	26.99	34.00	18.94	41.48	1.93
29.07.2008	27.25	33.50	20.10	38.09	1.68
30.07.2008	26.82	33.82	18.01	42.97	1.37
31.07.2008	27.17	34.00	19.22	40.90	1.60
01.08.2008	27.31	34.81	20.26	44.67	1.27
02.08.2008	27.97	34.52	20.85	46.14	1.58
03.08.2008	22.20	26.41	20.04	83.91	1.06
04.08.2008	23.01	28.25	19.29	85.43	0.79
05.08.2008	27.17	33.91	20.90	69.91	1.37
06.08.2008	27.52	33.65	21.96	67.09	1.51
07.08.2008	28.92	36.72	21.45	55.79	1.12
08.08.2008	28.27	35.53	21.98	54.11	1.50
09.08.2008	25.55	31.92	21.45	73.81	2.12
10.08.2008	25.88	34.09	18.34	65.25	1.28
11.08.2008	28.74	36.25	21.02	49.64	1.20
12.08.2008	29.31	36.22	22.83	42.90	1.41
13.08.2008	26.03	33.10	20.38	68.60	2.06
14.08.2008	27.43	35.21	19.58	55.10	1.13
15.08.2008	28.69	35.90	20.09	36.93	0.64
16.08.2008	28.38	35.52	22.13	35.11	2.02
17.08.2008	28.22	35.51	19.82	35.27	1.67
18.08.2008	28.72	35.40	19.95	36.93	1.35
19.08.2008	28.30	36.80	19.03	40.75	1.10
20.08.2008	28.54	34.96	19.23	33.88	1.40
21.08.2008	27.91	34.99	17.46	34.06	0.63
22.08.2008	27.10	35.06	19.19	43.97	1.73
23.08.2008	24.84	31.54	18.18	66.37	1.89
24.08.2008	27.17	35.42	17.10	49.45	2.04
25.08.2008	28.91	37.48	21.23	35.15	1.64
26.08.2008	28.85	38.33	20.65	37.55	1.46
27.08.2008	29.44	36.85	21.59	32.72	1.37
28.08.2008	29.70	37.47	22.41	36.02	1.74
29.08.2008	22.47	26.45	19.81	77.76	2.24
30.08.2008	20.50	27.83	15.30	52.91	2.10
31.08.2008	23.44	33.27	14.13	57.42	0.64

01.09.2008	28.22	36.59	18.75	49.10	1.13
02.09.2008	30.80	37.69	21.93	33.35	1.64
03.09.2008	31.13	37.58	24.48	32.83	1.64
04.09.2008	30.19	38.19	22.82	39.79	1.56
05.09.2008	23.35	27.36	19.14	58.77	2.36
06.09.2008	15.78	19.04	13.42	69.21	2.38
07.09.2008	18.96	26.22	12.87	69.25	1.54
08.09.2008	23.74	32.74	14.89	58.83	1.46
09.09.2008	28.70	37.02	20.21	54.59	1.44
10.09.2008	31.39	39.45	22.21	45.82	1.11
11.09.2008	30.76	37.95	23.60	48.86	1.37
12.09.2008	26.91	32.57	21.96	64.00	2.51
13.09.2008	20.97	23.66	18.48	82.69	2.05
14.09.2008	22.60	30.15	16.52	74.66	1.47
15.09.2008	25.01	31.81	18.32	57.03	2.17
16.09.2008	24.54	31.86	18.83	37.75	2.29
17.09.2008	25.49	34.95	15.97	45.97	0.62
18.09.2008	28.32	36.30	20.27	49.77	0.45
19.09.2008	29.40	37.48	21.61	49.39	1.44
20.09.2008	22.82	28.30	16.64	75.45	2.87
21.09.2008	17.95	22.01	15.45	83.12	1.46
22.09.2008	20.30	25.36	14.38	59.83	1.31
23.09.2008	23.77	32.00	13.57	39.39	0.62
24.09.2008	27.02	36.61	15.70	28.04	1.13
25.09.2008	28.12	38.12	17.92	33.48	2.12
26.09.2008	27.78	36.67	18.13	43.07	1.29
27.09.2008	29.23	37.53	20.02	42.72	1.44
28.09.2008	30.40	38.46	22.61	45.42	1.37
29.09.2008	30.45	37.37	24.68	51.63	1.69
30.09.2008	28.48	36.44	24.40	60.91	1.51
01.10.2008	31.30	38.84	23.50	50.47	2.10
02.10.2008	27.41	34.06	22.43	68.60	2.71
03.10.2008	25.70	30.06	22.04	77.79	1.84
04.10.2008	28.77	34.98	22.37	58.90	1.12
05.10.2008	22.39	26.83	18.53	84.20	2.40
06.10.2008	20.11	22.04	17.97	90.96	1.50
07.10.2008	22.73	27.65	18.70	78.81	2.29
08.10.2008	26.48	34.18	20.15	62.42	1.27
09.10.2008	27.41	35.14	21.08	60.05	1.02
10.10.2008	29.51	36.82	22.21	52.84	1.91
11.10.2008	24.79	27.97	21.99	72.39	3.32
12.10.2008	28.48	36.26	19.90	56.56	1.65
13.10.2008	30.23	37.17	23.56	52.24	0.67
14.10.2008	31.16	38.38	24.64	49.66	1.09
15.10.2008	31.53	40.17	24.46	49.35	1.68

A.2 Coordinates of sampling points

Sampling point	Latitude South	Longitude West
Imbauval	16° 32' 47.3	56° 18' 07.6
Do Barreiro	16° 31' 17.2	56° 16' 09.8
Aguapé	16° 31' 18.0	56° 16' 23.5
Cuiaba Velho 1	16° 29' 31.7	56° 18' 20.7
Cuiaba Velho 2	16° 29' 29.2	56° 18' 20.8
Cuiaba Velho 3	16° 29' 24.1	56° 18' 22.5
Rio Cuiabá	16° 29' 21.8	56° 18' 39.3
Rio Riozinho	16° 30' 24.6	56° 16' 44.9
Do Segredo	16° 33' 11.7	56° 19' 00.0

A.3 Isotopic composition of water samples

Imbauval

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
A1	-1.67	-16.64
A2	-1.09	-12.81
A4	-0.38	-13.07
A5	-0.05	-14.36
A6	0.58	-5.79
A7	0.77	-4.61
A8	1.60	-2.63
A9	2.70	2.73
A10	2.88	2.09

Do Barreiro

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
B1	-2.22	-19.60
B2	-2.12	-19.06
B3	-0.98	-14.30
B4	-0.74	-11.99
B5	-0.30	-9.54
B6	0.06	-7.40
B7	0.09	-7.97
B8	0.90	0.79

Aguapé

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
C1	-2.42	-17.58
C2	-2.52	-20.36
C3	-1.13	-13.44
C4	-0.59	-9.86
C5	-0.27	-5.70
C6	0.49	-2.83
C7	0.54	-4.80
C8	-0.32	-7.03

Cuiabá Velho 1

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
D1	0.01	-10.21
D2	1.26	-5.91
D3	1.99	-1.76
D4	3.57	6.20
D5	4.34	8.04
D6	6.38	20.43

Cuiabá Velho 2

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
E1	-1.57	-17.40
E2	4.95	13.59
E3	1.77	-3.88
E4	2.91	2.45
E5	3.61	7.27
E6	5.26	16.94

Cuiabá Velho 3

Water sample	**$\delta^{18}O$ [‰]**	**$\delta^{2}H$ [‰]**
F1	3.10	6.03
F2	10.34	33.74
F3	11.88	41.04
F4	13.33	53.40
F5	14.75	58.87
F6	10.01	41.16

Rio Cuiabá

Water sample	**$\delta^{18}O$ [‰]**	**$\delta^{2}H$ [‰]**
H1	-5.35	-34.11
H2	-5.16	-36.32
H3	-5.18	-32.87
H4	-5.12	-33.20
H5	-5.19	-33.10
H6	-4.59	-30.39

Rio Riozinho

Water sample	**$\delta^{18}O$ [‰]**	**$\delta^{2}H$ [‰]**
I1	-3.49	-25.99
I2	-4.17	-31.42
I3	-2.72	-25.43
I4	-3.69	-27.81
I5	-2.73	-24.99
I6	-3.61	-28.02
I7	-3.44	-26.00
I8	-2.37	-21.02
I9	-1.86	-19.43

Do Segredo

Water sample	**$\delta^{18}O$ [‰]**	**$\delta^{2}H$ [‰]**
J1	-2.30	-21.92
J2	-0.90	-15.22
J4	-0.52	-14.19
J5	-0.32	-10.74
J6	0.05	-9.13
J7	0.59	-7.59
J8	2.23	1.33

Groundwater RPPN SESC Pantanal

Water sample	**$\delta^{18}O$ [‰]**	**$\delta^{2}H$ [‰]**
G1	-4.83	-36.45
G2	-4.97	-36.03
G3	-4.88	-36.45
G5	-5.94	-38.80

Rain *Espírito Santo*

Water sample	**$\delta^{18}O$ [‰]**	**$\delta^{2}H$ [‰]**
R1	2.91	28.06

A.4 Major anions

Imbauval

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
A 1	3.25	3.44	0.60
A 2	3.15	2.64	< 0,19
A 4	2.65	2.90	0.39
A 5	2.90	4.11	< 0,19
A 6	2.56	4.26	< 0,19
A 7	2.49	4.08	< 0,19
A 8	2.80	5.75	< 0,19
A 9	2.99	4.06	< 0,19
A 10	3.43	5.72	< 0,19

Do Barreiro

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
B 1	1.51	3.26	0.34
B 2	1.41	2.36	< 0,19
B 3	1.48	2.61	< 0,19
B 4	1.42	4.12	0.43
B 5	1.90	3.20	< 0,19
B 6	2.11	4.13	< 0,19
B 7	1.59	3.86	< 0,19
B 8	2.16	5.79	0.32

Aguapé

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
C 1	19.0	7.78	0.92
C 2	11.4	< 0,13	0.72
C 3	12.0	11.9	1.28
C 4	28.0	15.6	2.40
C 5	33.1	31.4	6.57
C 6	51.3	29.6	10.5
C 7	80.2	27.5	14.3
C 8	14.4	7.67	1.50

Cuiabá Velho 1

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
D 1	2.67	4.58	< 0,19
D 2	3.87	6.85	0.79
D 3	2.96	14.3	0.68
D 4	3.14	11.4	< 0,19
D 5	4.44	11.5	< 0,19
D 6	4.82	14.4	0.81

Cuiabá Velho 2

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
E 1	1.65	5.21	< 0,19
E 2	1.58	5.26	< 0,19
E 3	1.99	15.4	0.32
E 4	2.38	16.3	0.66
E 5	2.12	16.2	0.78
E 6	3.47	21.4	1.47

Cuiabá Velho 3

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
F 1	3.33	2.22	1.73
F 2	3.79	2.89	2.19
F 3	2.68	3.38	2.60
F 4	4.52	7.64	3.60
F 5	3.83	6.77	5.08
F 6	5.50	13.8	7.48

Rio Cuiabá

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
H 1	1.35	1.54	1.20
H 2	2.86	2.49	0.77
H 3	1.28	1.13	0.78
H 4	1.54	1.79	0.80
H 5	1.36	1.64	0.79
H 6	1.62	2.36	1.43

Rio Riozinho

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
I 1	1.62	4.78	< 0,19
I 2	2.03	1.89	0.48
I 3	2.68	5.89	< 0,19
I 4	1.78	2.06	< 0,19
I 5	2.26	3.79	< 0,19
I 6	2.01	2.10	< 0,19
I 7	2.99	2.14	< 0,19
I 8	2.17	4.50	< 0,19
I 9	1.74	4.90	0.35

Do Segredo

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
J 1	2.12	0.48	< 0,19
J 2	2.18	< 0,13	< 0,19
J 4	3.20	2.19	0.43
J 5	2.22	0.44	< 0,19
J 6	1.88	0.43	< 0,19
J 7	4.90	1.07	< 0,19
J 8	1.43	0.99	0.33

Groundwater RPPN SESC Pantanal

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
G 1	1.42	2.09	1.54
G 2	5.94	1.41	1.29
G 3	0.97	0.93	0.91
G 5	1.39	0.39	0.78

Rain *Espírito Santo*

Water sample	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]
R 1	11.4	1.68	2.82

B Calculation

B.1 Regression NO_3^-

Measuring periods	R² between NO_3^- values in mg/l and mV
27.08.08 – 06.09.08	0.9983
11.09.08 – 22.09.08	0.8906
06.10.08 - 11.10.08	0.9991

B.2 Slope of LEL

Sampling site	Slope
Imbauval	4.4
Do Barreiro	7.3
Aguapé	5.3
Cuiabá Velho 1	4.8
Cuiabá Velho 2	5.0
Cuiabá Velho 3	4.5
Rio Cuiabá	4.0
Rio Riozinho	4.7
Do Segredo	5.2
Weighted mean	**5.1**

B.3 Source isotopic composition

Imbauval

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
A1	-6.49	-41.92
A2	-6.20	-39.58
A4	-7.64	-51.15
A5	-8.73	-59.81
A6	-6.82	-44.57
A7	-6.77	-44.12
A8	-7.62	-50.95
A9	-7.75	-52.03
A10	-8.33	-56.63

Do Barreiro

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
B1	-6.51	-42.08
B2	-6.50	-41.99
B3	-6.95	-45.59
B4	-6.56	-42.44
B5	-6.52	-42.15
B6	-6.42	-41.32
B7	-6.68	-43.43
B8	-5.04	-30.31

Aguapé

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
C1	-5.39	-33.14
C2	-6.22	-39.78
C3	-6.35	-40.80
C4	-6.08	-38.66
C5	-5.18	-31.44
C6	-5.57	-34.55
C7	-6.40	-41.16
C8	-5.57	-34.53

Cuiabá Velho 1

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
D1	-7.35	-48.78
D2	-8.15	-55.20
D3	-8.04	-54.33
D4	-8.15	-55.23
D5	-8.96	-61.68
D6	-8.33	-56.60

Cuiabá Velho 2

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
E1	-6.95	-45.60
E2	-8.10	-54.78
E3	-8.39	-57.08
E4	-8.26	-56.09
E5	-7.84	-52.73
E6	-7.46	-49.71

Cuiabá Velho 3

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
F1	-7.32	-48.59
F2	-11.03	-78.20
F3	-11.30	-80.40
F4	-9.58	-66.64
F5	-10.30	-72.37
F6	-7.71	-51.70

Rio Cuiabá

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
H1	-5.83	-36.64
H2	-6.99	-45.96
H3	-5.69	-35.56
H4	-5.93	-37.43
H5	-5.77	-36.15
H6	-4.59	-30.39

Rio Riozinho

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
I1	-6.42	-41.33
I2	-7.09	-46.69
I3	-7.67	-51.38
I4	-6.68	-43.47
I5	-7.50	-49.99
I6	-6.92	-45.39
I7	-6.51	-42.12
I8	-6.73	-43.87
I9	-7.13	-47.05

Do Segredo

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
J1	-7.20	-47.59
J2	-7.43	-49.48
J4	-7.78	-52.21
J5	-6.90	-45.22
J6	-7.02	-46.15
J7	-7.49	-49.88
J8	-7.37	-48.99

Groundwater RPPN SESC Pantanal

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
G1	-7.66	-51.32
G2	-7.24	-47.90
G3	-7.56	-50.50
G5	-6.41	-41.29

Rain *Espírito Santo*

Water sample	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]
R1	1.01	18.10

B.4 Penman-Monteith

Total amount of potential evaporation calculated for each water body between first and last water sample

Water body	Total amount of evaporation [mm]
Imbauval	347.7
Do Barreiro	330.6
Aguapé	330.6
Cuiabá Velho 1	344.9
Cuiabá Velho 2	344.9
Cuiabá Velho 3	344.9
Do Segredo	327.6

Date	Potential evaporation [mm]	Date	Potential evaporation [mm]
15.07.2008	4.03	01.09.2008	5.44
16.07.2008	3.85	02.09.2008	6.13
17.07.2008	3.96	03.09.2008	6.24
18.07.2008	3.98	04.09.2008	6.03
19.07.2008	4.07	05.09.2008	4.98
20.07.2008	4.26	06.09.2008	4.00
21.07.2008	4.54	07.09.2008	4.35
22.07.2008	4.32	08.09.2008	5.02
23.07.2008	4.30	09.09.2008	5.74
24.07.2008	4.26	10.09.2008	6.18
25.07.2008	3.61	11.09.2008	6.15
26.07.2008	3.88	12.09.2008	5.62
27.07.2008	4.39	13.09.2008	4.65
28.07.2008	4.56	14.09.2008	4.91
29.07.2008	4.61	15.09.2008	5.48
30.07.2008	4.45	16.09.2008	5.71
31.07.2008	4.59	17.09.2008	5.48
01.08.2008	4.55	18.09.2008	5.83
02.08.2008	4.69	19.09.2008	6.19
03.08.2008	3.67	20.09.2008	5.16
04.08.2008	3.74	21.09.2008	4.49
05.08.2008	4.37	22.09.2008	4.91
06.08.2008	4.49	23.09.2008	5.44
07.08.2008	4.75	24.09.2008	6.12
08.08.2008	4.78	25.09.2008	6.51
09.08.2008	4.32	26.09.2008	6.18
10.08.2008	4.39	27.09.2008	6.45
11.08.2008	4.91	28.09.2008	6.61
12.08.2008	5.14	29.09.2008	6.64
13.08.2008	4.54	30.09.2008	6.25
14.08.2008	4.76	01.10.2008	6.90
15.08.2008	5.02	02.10.2008	6.17
16.08.2008	5.37	03.10.2008	5.75

17.08.2008	5.26	04.10.2008	6.31
18.08.2008	5.26	05.10.2008	5.33
19.08.2008	5.15	06.10.2008	5.00
20.08.2008	5.33	07.10.2008	5.47
21.08.2008	5.09	08.10.2008	6.08
22.08.2008	5.17	09.10.2008	6.22
23.08.2008	4.68	10.10.2008	6.76
24.08.2008	5.20	11.10.2008	5.97
25.08.2008	5.62	12.10.2008	6.54
26.08.2008	5.58	13.10.2008	6.70
27.08.2008	5.70	14.10.2008	6.97
28.08.2008	5.84	15.10.2008	7.19
29.08.2008	4.48	**Maximum**	**3.6**
30.08.2008	4.50	**Minimum**	**7.2**
31.08.2008	4.68	**Mean**	**5.2**

B.5 Chloride enrichment

Imbauval

Water sample	**Cl^- measured [mg/l]**	**Cl^- calculated [mg/l]**
A1	3.25	3.35
A2	3.15	3.44
A4	2.65	3.49
A5	2.90	3.57
A6	2.56	3.62
A7	2.49	3.68
A8	2.80	3.89
A9	2.99	3.92
A10	3.43	3.93

Do Barreiro

Water sample	**Cl^- measured [mg/l]**	**Cl^- calculated [mg/l]**
B1	1.51	1.57
B2	1.41	1.92
B3	1.48	2.05
B4	1.42	2.37
B5	1.90	2.58
B6	2.11	2.63
B7	1.59	4.32
B8	2.16	4.46

Aguapé

Water sample	**Cl^- measured [mg/l]**	**Cl^- calculated [mg/l]**
C1	19.02	20.26
C2	11.38	29.59
C3	12.03	35.35
C4	27.95	47.97
C5	33.14	61.64
C6	51.33	65.52
C7	80.18	-226.98
C8	14.44	-186.41

Cuiabá Velho 1

Water sample	**Cl^- measured [mg/l]**	**Cl^- calculated [mg/l]**
D1	2.67	3.48
D2	3.87	3.76
D3	2.96	4.41
D4	3.14	4.77
D5	4.44	8.25

D6	4.82	8.61

Cuiabá Velho 2

Water sample	Cl^- measured [mg/l]	Cl^- calculated [mg/l]
E1	1.65	2.15
E2	1.58	2.32
E3	1.99	2.72
E4	2.38	2.95
E5	2.12	5.10
E6	3.47	5.32

Cuiabá Velho 3

Water sample	Cl^- measured [mg/l]	Cl^- calculated [mg/l]
F1	3.33	5.43
F2	3.79	6.44
F3	2.68	9.69
F4	4.52	12.51
F5	3.83	-26.21
F6	5.50	-22.26

Do Segredo

Water sample	Cl^- measured [mg/l]	Cl^- calculated [mg/l]
J1	2.12	2.23
J2	2.18	2.27
J4	3.2	2.28
J5	2.22	2.33
J6	1.88	2.37
J7	4.90	2.53
J8	1.43	2.54

B.6 Coefficient of surface cover σ

σ is introduced in the water balance calculation as a coefficient of surface cover. Within the northern Pantanal all shallow lakes are within an area of approximately 45 km². With GIS the areas covered by vegetation and by water have been calculated.

Area of surface cover, fraction of total area and σ

Surface cover	Area [km²]	Fraction of total area [%]	σ
Vegetation	42	6.667	0.066
Water	3	93.333	0.933

B.7 Seasonal effect

Mean isotopic composition of precipitation from GNIP Station Cuiabá (1961-1987) on the basis of n events

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dez
n	21	20	21	21	20	10	10	9	17	13	21	20
δ [‰]	-5.4	-7.1	-6.9	-6.1	-4.1	-3.0	-1.1	1.7	1.1	-2.2	-3.9	-5.2

B.8 Simplified tracer approach

Imbauval

Water sample	**F (^{18}O)**	**F (^{2}H)**	**F_{max} (^{18}O)**	**F_{max} (^{2}H)**	**F_{min} (^{18}O)**	**F_{min} (^{2}H)**
A1	6.13	5.52	6.77	6.76	5.80	4.32
A2	5.21	4.19	5.66	5.00	4.94	3.31
A4	4.41	4.39	4.72	5.18	4.19	3.58
A5	3.93	4.67	4.22	5.61	3.70	3.70
A6	3.34	2.66	3.60	3.23	3.10	1.89
A7	2.79	2.09	3.11	2.79	2.37	0.93
A8	2.43	1.99	2.71	2.60	2.05	1.02
A9	1.91	1.46	2.19	2.03	1.46	0.49
A10	1.61	1.28	1.96	1.95	0.98	0.03

Do Barreiro

Water sample	**F (^{18}O)**	**F (^{2}H)**	**F_{max} (^{18}O)**	**F_{max} (^{2}H)**	**F_{min} (^{18}O)**	**F_{min} (^{2}H)**
B1	7.67	7.82	8.69	9.84	7.29	6.17
B2	7.29	7.29	8.21	9.14	6.97	5.67
B3	5.27	5.07	5.69	5.99	5.07	4.18
B4	4.79	4.17	5.17	4.96	4.61	3.29
B5	4.16	3.48	4.48	4.18	3.98	2.60
B6	3.44	2.70	3.79	3.46	3.15	1.51
B7	3.90	3.28	4.18	3.89	3.73	2.53
B8	2.90	1.76	3.19	2.35	2.60	0.77

Aguapé

Water sample	**F (^{18}O)**	**F (^{2}H)**	**F_{max} (^{18}O)**	**F_{max} (^{2}H)**	**F_{min} (^{18}O)**	**F_{min} (^{2}H)**
C1	8.44	6.59	9.73	8.08	7.94	5.23
C2	8.70	8.73	10.10	11.19	8.19	6.79
C3	5.56	4.93	6.04	5.80	5.32	4.07
C4	4.70	3.84	5.07	4.52	4.51	3.05
C5	4.10	2.81	4.44	3.44	3.89	1.93
C6	3.12	2.12	3.46	2.81	2.77	0.98
C7	3.56	2.87	3.81	3.42	3.37	2.17
C8	3.99	2.87	4.36	3.59	3.74	1.82

Cuiabá Velho 1

Water sample	**F (^{18}O)**	**F (^{2}H)**	**F_{max} (^{18}O)**	**F_{max} (^{2}H)**	**F_{min} (^{18}O)**	**F_{min} (^{2}H)**
D1	3.81	3.53	4.11	4.26	3.63	2.64
D2	3.05	2.91	3.26	3.44	2.87	2.23
D3	2.66	2.38	2.86	2.85	2.48	1.76
D4	1.58	1.23	1.88	1.80	1.10	0.22
D5	1.63	1.39	1.86	1.85	1.30	0.67
D6	0.92	0.57	1.24	1.10	0.35	-0.41

Cuiabá Velho 2

Water sample	**F (^{18}O)**	**F (^{2}H)**	**F_{max} (^{18}O)**	**F_{max} (^{2}H)**	**F_{min} (^{18}O)**	**F_{min} (^{2}H)**
E1	6.00	6.14	6.60	7.53	5.77	4.85
E2	1.65	1.27	1.84	1.65	1.39	0.69
E3	2.78	2.64	2.98	3.14	2.60	2.00
E4	1.81	1.52	2.10	2.11	1.37	0.50
E5	1.85	1.45	2.07	1.90	1.54	0.72
E6	1.15	0.70	1.46	1.23	0.62	-0.28

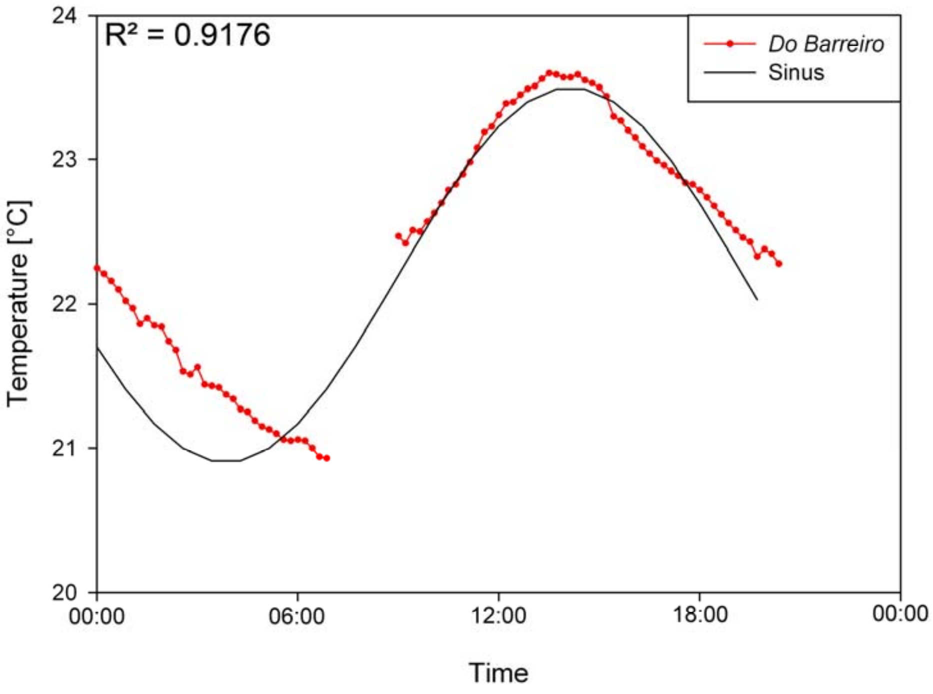
Cuiabá Velho 3

Water sample	F (^{18}O)	F (^{2}H)	F_{max} (^{18}O)	F_{max} (^{2}H)	F_{min} (^{18}O)	F_{min} (^{2}H)
F1	2.04	1.60	2.31	2.07	1.75	0.86
F2	0.83	0.68	1.05	1.03	0.48	0.11
F3	0.70	0.55	0.92	0.89	0.34	-0.01
F4	0.12	-0.10	0.51	0.42	-0.62	-1.12
F5	0.31	0.11	0.61	0.52	-0.20	-0.61
F6	0.43	0.11	0.79	0.62	-0.23	-0.88

Do Segredo

Water sample	F (^{18}O)	F (^{2}H)	F_{max} (^{18}O)	F_{max} (^{2}H)	F_{min} (^{18}O)	F_{min} (^{2}H)
J1	7.82	10.00	9.00	13.37	7.31	7.69
J2	5.04	5.16	5.50	6.17	4.79	4.20
J4	4.62	4.84	5.00	5.72	4.39	3.97
J5	4.22	3.66	4.58	4.37	3.98	2.83
J6	3.35	2.82	3.75	3.65	2.95	1.55
J7	3.27	2.90	3.58	3.55	3.01	2.04
J8	2.11	1.60	2.42	2.18	1.67	0.61

B.9 Sinus function



It has to be considered that R^2 is derived from temperature values of every hour, since the sinus function is only based on hourly values. The example of *Do Barreiro* is given from 29th August 2008.

C Impressions of field work

DS5 installed at *Imbauval*

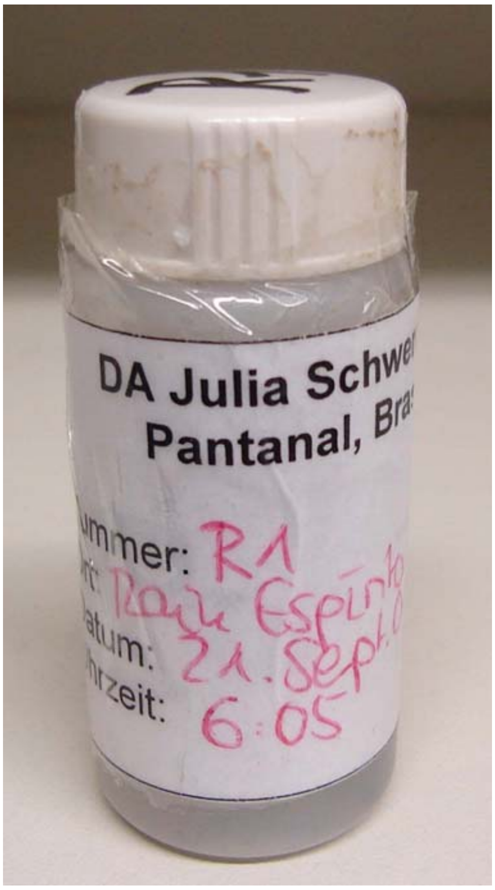
MS5

Downloading log files from DS5

Clogged DS5

***Rio Riozinho* closed by macrophytes**

Groundwater well close to *Espírito Santo*



Rain sample collected from *Espírito Santo*

Espírito Santo

Dry season

Eidesstattliche Erklärung

Hiermit erkläre ich, dass die Arbeit selbständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Ort, Datum

Unterschrift