

# **The role of water level fluctuations in the promotion of phytoplankton and macrophyte pioneer species in a tropical reservoir in the Brazilian semiarid**

vorgelegt  
von  
M. Sc.  
Débora Maciel Barros Lima  
geb. in Barcelos, Portugal

von der Fakultät III – Prozesswissenschaften  
der Technischen Universität Berlin  
zur Erlangung des akademischen Grades

Doktor der Naturwissenschaften  
- Dr. rer. nat. -

genehmigte Dissertation

Promotionsausschuss:

Vorsitzender: Prof. Dr. rer. nat. Ulrich Szewzyk  
Gutachter: Dr. rer. nat. Günter Gunkel  
Gutachter: Prof. Dr.-Ing. Martin Jekel  
Gutachterin: Prof. Dr. rer. nat. habil. Brigitte Nixdorf

Tag der wissenschaftlichen Aussprache: 15. December 2017

Berlin 2018



# **The role of water level fluctuations in the promotion of phytoplankton and macrophyte pioneer species in a tropical reservoir in the Brazilian semiarid**

Débora Maciel Barros Lima

Berlin University of Technology  
Faculty of Process Sciences  
Institute of Environmental Technology  
Department of Water Quality Control

Thesis submitted in fulfillment of the requirements for the Degree of  
“Doktor der Naturwissenschaften”

(Dr. rer. nat.)

Chairman: Prof. Dr. rer. nat. Ulrich Szewzyk  
Examiners: Dr. rer. nat. Günter Gunkel  
Prof. Dr.-Ing. Martin Jekel  
Prof. Dr. rer. nat. habil. Brigitte Nixdorf

Date of Defense: 15. December 2017

Berlin 2018



---

## Acknowledgements

First of all, I wish to thank my supervisor Dr. Günter Gunkel. Since the time of my master studies, his knowledge and experience deeply inspired me to follow the limnology field. I want to thank him for all the support during the last years, the guidance, help and wise advises, particularly in the most stressing moments of field campaigns.

I thankfully acknowledge the Federal Ministry of Education and Research (BMBF) for funding the INNOVATE project and allowing me to develop my expertise and Ph.D. work on this beautiful topic in Brazil.

I want to express my gratitude to the committee members Prof. Dr. Martin Jekel, Prof. Dr. Brigitte Nixdorf and Prof. Dr. Ulrich Szewzyk for their presence and advices.

I wish to thank the “INNOVATE family”, from both sides of the Atlantic. It was a pleasure to get to know so many new and heterogeneous people with the same interests. On the Brazilian side, I would like to thank Prof. Maria do Carmo Sobral, Prof. Silvana Calado and Dr. Maristela Casé for diligent logistic and scientific support. Dr. Maristela Casé and Prof. Silvana Calado students, thanks for your laboratory support. Thank you Prof. José Carlos Barros and your team for helping in invertebrates counting. André Ferreira and Gustavo Melo, my first and stable “anchors” in Recife, thank you so much for your invaluable company. Nailza Arruda, Karina Rossiter and Cacilda Rocha, thanks for your sincere friendship and for the amusing moments we spent together. You made me feel at home in Brazil. Cacilda, I am still inspired by you and our talks. Prof. Silvana Calado, thank you so much for being our beloved mommy and for taking us to the nicest places in Recife. Maristela Casé thank you for the time spent with your beautiful family, with evenings by the microscope. You will all be always in my heart. In addition, I want to express my deepest gratitude to the fisherman José dos Santos and his family in Vila dos Pescadores, without them field work would had been an even greater adventure.

On the German side, I wish to thank the whole INNOVATE project team and in particular the water group (Maricela Rodriguez, Florian Selge and Jonas Keitel). Work in the field is only possible with team spirit and under the Caatinga heat even more. We were all in the same boat (literally) and we did it! I will also miss our productive work meetings by the lakes Müggelsee and Stechlinsee.

I would like to express my sincere gratitude for the work done in the laboratory by the students Katharina Lutscher, Isabell Köppling, Katrin Klobe, Annika Hülsmann and Eric Sannowitz. Thank you to the master student Qinmeg Liang, who started optimizing the sediments experiment setting. I would like to thank lab technicians Gisela Sosna, Katrin Noack and Ulrike Förster for water and sediment analyses. To all the colleagues in the Department of Water Quality Control, thank you so much for the great working atmosphere and friendship.

A very special thank you goes to my parents and sisters for the permanent unconditional support at all levels. Endless Skype talks and regular visits to Portugal keep me moving in Berlin! Finally, I would like to thank Daniel for the constant encouragement and for being there for me.



## Abstract

In the semiarid northeast Brazil, water paucity instigates multiple uses of reservoirs, such as hydropower production, drinking water supply, water supply for livestock and for irrigation, fisheries, aquaculture and leisure activities. As consequence of high anthropogenic pressure, most reservoirs in this region are fragile and eutrophicated systems. Blooms of algae and macrophytes are commonly registered, impacting water quality, water supply, biodiversity, among others. Knowledge on limnic processes underlying phytoplankton and macrophyte blooms in semiarid reservoirs is still scarce but necessary for restoration of such deteriorated waterbodies. In Itaparica reservoir, São Francisco River, Northeast Brazil, intense land and water uses (e.g. nutrient load from watershed and surrounding irrigation agriculture, water level fluctuations due to hydropower production) exert high pressure on aquatic functions and blooms of toxic cyanobacteria (such as *Cylindrospermopsis raciborskii*, *Microcystis* sp.) and macrophytes (*Egeria densa*) have been reported. Under this context, the present work aimed firstly at determining the ecological processes driving cyanobacteria and *E. densa* blooms considering climate, hydrology and morphometric characteristics of the reservoir. Such understanding was essential for the second aim of this study, which consisted in defining appropriate management measures to avoid massive development of such species.

In the main stream of Itaparica reservoir, phytoplankton abundance is controlled mainly by high water discharge rates ( $\sim 2000 \text{ m}^3 \text{ s}^{-1}$ ) applied for hydropower production. This is particularly important during warm rain season, when high loads of organic matter enter the reservoir and together with stratification of the water column, maintain algae density at moderate levels (max.  $4.4 \times 10^4 \text{ Org. mL}^{-1}$ ). Internal fertilization plays also a crucial role in this reservoir, as in the end of rain season isothermal conditions (in combination with water level rise and residence time increase), promoted high diatoms development (max.  $6.6 \times 10^5 \text{ Org. mL}^{-1}$ ). During dry season, nutrients availability gradually subsided and concurrently phytoplankton density (max.  $8.2 \times 10^3 \text{ Org. mL}^{-1}$  in the end of dry season). High water flow rates also seem to prevent cyanobacteria development, as their density was not prevalent in the main stream of Itaparica reservoir. In a drought scenario, higher water retention times increases the risk of cyanobacteria blooms, considering that *C. raciborskii* presence was steady throughout the study period (2007-2010).

In the hydrodynamically isolated Icó-Mandantes bay, the cyanobacteria *C. raciborskii* developed more frequently, with extended effects. Here, the risk of cyanobacteria blooms seems to be regulated by additional drivers. In this shallow bay, the macrophyte *Egeria densa* is widely distributed along the bay down to 6-8 m water depth in dense mats. *E. densa* biomass is a significant nutrients storage in the system. P availability for phytoplankton is affected by the macrophyte growth regime related to water level fluctuations (WLF). *Egeria densa* massive stands result from traits like fast growth rate, light limitation tolerance and high affinity for water N, P and DIC, which allow a fast and outcompeting growth when water level rises. On the contrary, water level drawdown leads to *E. densa* stands decay, and nutrients availability for algae and cyanobacteria. *C. raciborskii*, diazotrophic and well adapted to P pulses, successfully develops in such conditions. Hence, WLF alternately provide opportunity windows for the pioneer species *E. densa* and *C. raciborskii* to develop. Enhanced nutrient load by desiccated sediments rewetting comprise a surplus of at least 50 % and 170 % of P and N, respectively, in comparison to reservoir water. Moreover, the seasonal decay of littoral communities decreases biodiversity, which further foment outbreaks of pioneer species.

Considering the value of water in semiarid northeast Brazil, oligotrophication of this reservoir is very important for maintaining water quality. For that, constant water level, buffer biotopes construction and *Egeria densa* harvesting were the main three measures proposed in this work to improve ecosystem services of Itaparica reservoir.





## Zusammenfassung

Im semi-ariden Nordosten Brasiliens führt die begrenzte Wasserverfügbarkeit zur mehrfachen Nutzung von Stauseen (u.a. für Wasserkraft, Trinkwasserversorgung, Bereitstellung von Wasser für Viehzucht und Bewässerung, Fischerei, Aquakultur und Freizeit-Aktivitäten). Als Folge der starken anthropogenen Belastungen sind die meisten Stauseen dieser Region durch Eutrophierung gefährdet. Algenblüten und Makrophyten-Massenentwicklungen beeinflussen u.a. die Wasserqualität, die Wasserversorgung sowie die Biodiversität. Das Wissen über die limnischen Prozesse, die die Phytoplankton- und Makrophyten-Massenentwicklungen in semi-ariden Stauseen auslösen, ist noch gering. Im Itaparica Stausee, São Francisco Fluss, Nordost Brasilien, führt die intensive Land- und Gewässernutzung (d. h. Nährstoffeintrag aus dem Wassereinzugsgebiet und der Landwirtschaft, Wasserspiegelschwankungen aufgrund von Wasserkraftnutzung) starken Druck auf die aquatischen Ökosystemfunktionen aus. Massenentfaltungen von toxischen Cyanobakterien (*Cylindrospermopsis raciborskii*, *Microcystis* sp.) und Makrophyten (*E. densa*) werden berichtet, und Focus dieser Arbeit ist die für das Auftreten von Cyanobakterien und *Egeria densa* maßgeblichen ökologischen Prozesse unter Einbeziehung von Klima, Hydrologie und Morphometrie des Stausees zu identifizieren. Das Verständnis dieser Prozesse ist essentiell für das Ziel dieser Studie, die Konzeption geeigneter Management Maßnahmen zur Verhinderung der unerwünschten Spezies.

Im Hauptstrom des Itaparica Stausees wird die Phytoplankton-Konzentration im Wesentlichen durch hohe Abflüsse ( $\sim 2000 \text{ m}^3 \text{ s}^{-1}$ ) bestimmt. Dies ist insbesondere in der warmen Regenzeit von Bedeutung, während der hohe Frachten organischen Materials in den Stausee eingetragen werden; das Niveau der Phytoplankton-Konzentration ist jedoch aufgrund der Schichtung des Wassers moderat ( $\text{max. } 4.4 \times 10^4 \text{ Org. mL}^{-1}$ ). Die interne Düngung spielt eine signifikante Rolle, da am Ende der Regenzeit isotherme Bedingungen (Durchmischung) gemeinsam mit hohen Wasserspiegeln und entsprechend hohen Aufenthaltszeiten ein starkes Diatomeen-Wachstum hervorrufen ( $\text{max. } 6.6 \times 10^5 \text{ Org. mL}^{-1}$ ). Während der Trockenzeit nimmt die Nährstoffverfügbarkeit kontinuierlich ab. Im Hauptstrom des Itaparica-Stausees wurden keine massenhaften Entwicklungen von Cyanobakterien gefunden, was darauf hinweist, dass hohe Abflussraten ihre Entwicklung verhindern. Während des gesamten Untersuchungszeitraums (2007-2010) wurde jedoch *C. raciborskii* nachgewiesen, und somit besteht während der Trockenzeit aufgrund der längeren Aufenthaltszeit im Stausee ein erhöhtes Risiko für Blaualgenblüten.

In der hydrodynamisch weitgehend isolierten Bucht Icó-Mandantes entwickelte sich *C. raciborskii* aufgrund der langen Aufenthaltszeit häufiger und über ausgedehnte Zeiträume. Die über den Jahresverlauf schwankenden Blaualgenblüten scheinen jedoch weiteren Einflussfaktoren unterworfen zu sein. Die Wasserpflanze *E. densa* ist in der flachen Bucht weit verbreitet und wächst bis zu einer Wassertiefe von 6-8 m in dichten Matten; sie stellt einen signifikanten Nährstoffspeicher im System dar. Die P-Verfügbarkeit für Phytoplankton ist stark abhängig vom Makrophyten-Wachstum und den damit verbundenen Wasserspiegelschwankungen. Das massenhafte Vorkommen von *E. densa* wird gefördert durch eine schnelle Vermehrungsrate, Toleranz gegen Lichtlimitierung und eine hohe Affinität für N, P und DIC. Bei einem Anstieg des Wasserspiegels führt dies zu einem Konkurrenzvorteil und einem entsprechend schnellem Wachstum. Ein Absinken des Wasserspiegels bewirkt ein Absterben von *E. densa* und damit zu einer Zunahme der Nährstoffverfügbarkeit für Algen. Das diazotrophe und gut an P-Stöße angepasste *C. raciborskii* kann sich unter diesen Bedingungen erfolgreich entwickeln. Nach Regenereignissen bzw. Aufstau des Gewässers finden verstärkt Nährstoffeinträge durch Mineralisierung der trockenen litoralen Sedimente und der abgestorbenen *E. densa* Bestände statt.

Die Einhaltung eines möglichst konstanten Wasserspiegels, die Errichtung von Ausgleichs-Biotopen und die gezielte Entfernung von *E. densa* werden als Gewässermanagement empfohlen, um die ökosystemaren Dienstleistungen des Itaparica Stausees zu verbessern.



## Table of Contents

<b>1</b>	<b>Introduction .....</b>	<b>1</b>
1.1	Water scarcity in Northeast Brazil .....	3
1.2	The research project INNOVATE .....	4
1.2.1	Itaparica reservoir .....	4
1.2.2	Aims .....	4
1.2.3	Structure and working groups .....	5
1.3	Scope of the thesis .....	5
1.3.1	Objectives .....	7
1.4	Structure of the thesis .....	8
<b>2</b>	<b>Theoretical background.....</b>	<b>9</b>
2.1	Role and ecological drivers of primary production .....	10
2.1.1	Phytoplankton .....	10
2.1.2	Macrophytes .....	10
2.1.3	Periphyton.....	11
2.2	Eutrophication in tropical reservoirs.....	11
2.2.1	Water level fluctuations.....	11
2.3	Common blooms in Brazilian reservoirs .....	12
2.3.1	Cyanobacteria .....	12
2.3.1.1	<i>Microcystis aeruginosa</i> .....	13
2.3.1.2	<i>Cylindrospermopsis raciborskii</i> .....	14
2.3.2	Macrophytes .....	14
2.4	Primary production control in the tropical region.....	15
<b>3</b>	<b>Study site and methodology .....</b>	<b>19</b>
3.1	Study area .....	21
3.2	Analyses of monitoring data .....	22
3.2.1	Climate and hydrological data .....	22
3.2.2	Sampling stations.....	22
3.2.3	Water quality .....	23
3.2.4	Weather and hydrological conditions .....	24
3.2.5	Phytoplankton.....	25

3.2.5.1	Sampling and counting.....	25
3.2.5.2	Diversity index.....	25
3.2.5.3	Data treatment.....	25
3.2.6	Macrophyte richness.....	25
3.3	Field campaigns.....	25
3.3.1	Rainfall and water level.....	26
3.3.2	Phytoplankton sampling and counting.....	27
3.3.3	Macrophytes.....	28
3.3.3.1	Macrophyte biodiversity and maximum colonization depth.....	28
3.3.3.2	Taxonomic classification.....	29
3.3.3.3	Biomass.....	29
3.3.3.4	Growth rate.....	29
3.3.3.5	Nutrients assessment.....	29
3.3.3.6	Chlorophyll <i>a</i> assessment.....	30
3.3.4	Sediments.....	30
3.3.4.1	Sampling method.....	30
3.3.4.2	Grain size characterization.....	30
3.3.4.3	Water and organic matter content.....	30
3.3.4.4	Nutrients and elements.....	30
3.3.4.5	Elution experiments.....	31
3.3.4.6	Mean depth calculation in a 4 m water rise scenario.....	32
<b>4</b>	<b>Results .....</b>	<b>33</b>
4.1	Sampling seasons in Itaparica reservoir.....	35
4.2	Phytoplankton in Itaparica reservoir.....	41
4.2.1	Phytoplankton diversity.....	41
4.2.2	Biodiversity index.....	42
4.2.3	Seasonal dynamics.....	43
4.2.3.1	Density of phytoplankton.....	43
4.2.3.2	Diversity patterns.....	45
4.2.3.3	Drivers of seasonal patterns.....	47
4.2.4	Main stream vs. Icó-Mandantes bay.....	51
4.3	Field campaigns in Icó-Mandantes bay.....	53

4.4	Phytoplankton community in the Ic�-Mandantes bay .....	54
4.4.1.1	Presence of <i>C. raciborskii</i> .....	57
4.5	Macrophyte community .....	59
4.5.1	Macrophyte diversity .....	59
4.5.2	<i>Egeria densa</i> distribution and coverage .....	61
4.5.2.1	<i>Egeria densa</i> as habitat for <i>Biomphalaria</i> sp. ....	62
4.5.2.2	<i>Egeria densa</i> composition and growth rate .....	63
4.5.3	Spatial and temporal dynamics of <i>E. densa</i> stands .....	64
4.5.3.1	High water level .....	64
4.5.3.2	Low water level .....	65
4.5.3.3	Long lasting drought period .....	66
4.5.4	Primary production in the bay .....	67
4.5.4.1	Determination of <i>Egeria densa</i> biomass .....	67
4.5.4.2	<i>E. densa</i> vs. phytoplankton competition .....	69
4.6	Desiccated margins .....	71
4.6.1	Sediments characterization .....	72
4.6.2	Elution experiments .....	74
4.7	Effects of water level changes and management tools .....	75
<b>5</b>	<b>Discussion .....</b>	<b>79</b>
5.1	Phytoplankton community in the main stream of Itaparica reservoir .....	81
5.1.1	Spatial and seasonal development .....	82
5.2	<i>Cylindrospermopsis raciborskii</i> in Ic�-Mandantes bay .....	84
5.3	Effects of water level fluctuations in Ic�-Mandantes bay .....	86
5.3.1	Development of pioneer species .....	86
5.3.2	Desiccated sediments .....	88
5.4	Effects of constant water level .....	88
5.5	Implications for reservoir management .....	89
5.5.1	Constant water level .....	90
5.5.2	<i>Egeria densa</i> harvesting .....	91
5.5.3	Buffer biotopes with <i>Egeria densa</i> at drainage channels .....	92
<b>6</b>	<b>Conclusions .....</b>	<b>93</b>

6.1	Main stream .....	95
6.2	Icó - Mandantes bay .....	95
6.3	Management tools .....	97
<b>7</b>	<b>Outlook.....</b>	<b>99</b>
<b>8</b>	<b>Bibliography .....</b>	<b>103</b>
<b>9</b>	<b>Annex.....</b>	<b>113</b>

## List of Figures

Fig. 1-1 Main working groups of the Innovate project working in Itaparica reservoir at micro and meso-scales (SP1, SP2, SP3 and SP4) and at macro- scale in the São Francisco River watershed (SP5, SP6 and SP7). .....	6
Fig. 3-1 Location of São Francisco river basin and of Itaparica reservoir in Northeast Brazil. ....	21
Fig. 3-2 Location of sampling stations in Itaparica reservoir of monitoring data from CHESF (2007-2010) considered in this study. ....	23
Fig. 3-3 Monthly mean values of water level, flow rate, rainfall and air temperature in Itaparica reservoir between September 2007 and December 2010. ....	24
Fig. 3-4 Monthly mean values of water level, flow rate, rainfall and air temperature in Itaparica reservoir region between January 2012 and September 2014. Field campaigns in September 2012, March 2013, October 2013 and June 2014 are indicated with black points along water level line. ....	26
Fig. 3-5 Location of sampling stations of phytoplankton in Icó-Mandantes bay in the period 2012-2014. ....	27
Fig. 3-6 Submerged <i>Egeria densa</i> stands in Icó-Mandantes bay: (A) Example of the spectrum obtained in the acoustic surveys, depicting a stand of <i>E. densa</i> with approximately 2 m height. Green and black/blue colours correspond to plants and sediment signals, respectively. Scale on the right side of the picture: water depth in meters; (B) Photo of stands of <i>Egeria densa</i> underwater which provide such acoustic spectrum. ....	28
Fig. 3-7 Experimental set-up for elution analyses. 1) Eluent (water) ; 2) Peristaltic pump; 3) Sediment core; 4) Eluate; 5) Support plate; 6) Inflow tube; 7) tube connector; 8) Outflow tube; 9) ventilation tube. ....	31
Fig. 4-1 Annual climate and hydrological parameters in Itaparica reservoir (monthly averages of the period 2000-2012. In c) and d) monthly average of the period 2002-2012. Dotted line represents annual average. ....	36
Fig. 4-2 Air temperature and rain as main factors affecting mean surface water temperature in the Itaparica reservoir. ....	37
Fig. 4-3 Correlation between temperature of the surface water and temperature difference between surface and bottom of the reservoir (data of ITA 06, ITA 08 and ITA 09). ....	37
Fig. 4-4 Physical parameters of water quality in the lower middle stretch of Itaparica reservoir per sampling season (2007-2010). Box plot horizontal lines: Q25 (lower), Q50 (middle) and Q75 (upper); little square: mean; whiskers: standard deviation of the mean; cross: max. and min. values. ....	38
Fig. 4-5 Chemical parameters and conductivity of water quality in the lower-middle stretch of Itaparica reservoir per sampling season (2007-2010). Box plot horizontal lines: Q25 (lower), Q50 (middle) and Q75 (upper); little square: mean; whiskers: standard deviation of the mean; cross: max. and min. values. ....	40
Fig. 4-6 Examples of phytoplankton biodiversity in Itaparica reservoir: A) <i>Aulacoseira</i> sp.; B) <i>Pediastrum</i> sp.; C) <i>Fragilaria crotonensis</i> ; D) <i>Dolichospermum</i> sp.; E) <i>Cylindrospermopsis raciborskii</i> ; F) <i>Aphanocapsa</i> sp.. Magnification 400X. ....	42
Fig. 4-7 Mean diversity in the four main sections of the reservoir (Shannon's index) during low and high water level (error bars represent standard deviation). ....	43

Fig. 4-8 Spatial dynamics of phytoplankton concentration along Itaparica reservoir in each sampling season. Data include total density at the inflow (ITA 01), upper-middle section (ITA 04), lower-middle section (ITA 08) and at the dam (ITA12).....	44
Fig. 4-9 Main taxonomic groups occurring along Itaparica reservoir in each sampling period. Vertical dash lines delimit inflow, upper-middle, lower-middle and dam sections. ....	46
Fig. 4-10 Relationship of phytoplankton density and water residence time in the lower-middle stretch of Itaparica reservoir. ....	48
Fig. 4-11 Chlorophyll <i>a</i> concentration in the reservoir in 19 October and 04 November 2009 (A and B, respectively), measured by remote sensing analyses (Lopes et al., 2013). ....	48
Fig. 4-12 Environmental drivers for cyanobacteria concentration in Itaparica reservoir during rainy season in low and high water level periods: a) linear correlation of mean cyanobacteria concentration with dissolved phosphorus (DP); b) exponential correlation of mean cyanobacteria concentration with water residence time. Error bars represent standard deviation of the sampling stations ITA 06, ITA 08 and ITA 09. ....	49
Fig. 4-13 Influence of water column stratification and water residence time on phytoplankton concentration in the lower middle stretch of Itaparica reservoir. ....	49
Fig. 4-14 Exponential regression relating water conductivity with phytoplankton density in the lower-middle stretch of Itaparica reservoir, between 2007 and 2010.....	50
Fig. 4-15 Surface flow simulation in Itaparica reservoir with a mean discharge rate of 2060 m <sup>3</sup> s <sup>-1</sup> (Matta et al., 2014). ....	52
Fig. 4-16 Comparison of main algae species concentration in the main stream of the reservoir (M. Stream) and in the Icó-Mandantes bay (Bay) in March, June, September and December 2008. Colours represent main taxonomic groups: blue – Cyanobacteria; red – Bacillariophyta; green – Chlorophyta. Main species: <i>Aulacoseira ambigua</i> , <i>Aulacoseira granulata</i> , <i>Fragilaria crotonensis</i> , <i>Urosolenia longiseta</i> , <i>Cylindrospermopsis raciborskii</i> , <i>Geitlerinema amphibium</i> , <i>Planktosphaeria gelatinosa</i> .....	52
Fig. 4-17 Bathymetric map of the Icó-Mandantes bay based on echo-sounder depth measurements, satellite images and data interpolation (Selge, 2017). ....	53
Fig. 4-18 Shannon diversity index in the inner, central and outer parts of Icó-Mandantes bay and in the main stream (represented sampling stations: 1, 3, 5 and 6) in each of the sampling campaigns. Bars depict mean Shannon index measured in the water column at different depths and error bars represent standard deviation. Station 1 (inner bay) is the shallowest part with only two sampling depths, and thus lacks a standard deviation value. ....	55
Fig. 4-19 Phytoplankton concentration gradient in Icó-Mandantes bay in the six sampling stations (five along the bay and one in the main stream). Points represent mean concentration present in the water column. Sampling design in September 2012 did not include main stream sampling station. ....	56
Fig. 4-20 Relative abundance (% of total phytoplankton concentration) of <i>Cylindrospermopsis raciborskii</i> along Icó-Mandantes bay at different water depths in the six sampling stations (five along the bay and one in the main stream). Dashed line represents the tendency of abundance gradient from inner bay (0 km) towards outer bay (9 km). ....	58



Fig. 4-21 Phytoplankton composition of water samples from Icó-Mandantes bay, showing a high development of <i>C. raciborskii</i> after P addition. A) control B) 6 days after P addition. Magnification 25X. ....	59
Fig. 4-22 <i>Cylindrospermopsis raciborskii</i> filaments in (A) control sample and in (B) the sample enriched with P, with terminal heterocysts in both edges of the trichome. Magnification 400X..	59
Fig. 4-23 Macrophyte species identified in Icó-Mandantes bay within the study period: <i>Egeria densa</i> on the left; <i>Chara guairensis</i> in the middle; <i>Nymphoides indica</i> on the right. ....	60
Fig. 4-24 Frequency of occurrence of macrophytes in Icó-Mandantes bay in September 2012, March 2013, October 2013 and June 2014 ( <i>Egeria densa</i> , <i>Chara guairensis</i> and <i>Nymphoides indica</i> ). .	61
Fig. 4-25 Spatial distribution of <i>E. densa</i> in Icó-Mandantes bay and vertical thickness of the stands of <i>E. densa</i> in meters in March 2013, based on 428 sampling points with echo-sounder. A profuse growth of <i>E. densa</i> is patent in the inner part of the bay (further away from the main stream of the reservoir). ....	62
Fig. 4-26 <i>Biomphalaria</i> sp. attached in shoots of <i>E. densa</i> in Icó-Mandantes bay. ....	62
Fig. 4-27 Growth rate of <i>Egeria densa</i> at different water depths (1, 2, 3, 4 and 6 m). Growth rate is represented as daily growth of shoots in cm. Experiments were carried out in June 2014. Box plots represent mean (square), Q25, Q50, Q75 (lower, middle and higher horizontal lines of the box, respectively) and minimum and maximum values (error bars). ....	64
Fig. 4-28 Frequency of occurrence of <i>Egeria densa</i> on the surveyed locations by acoustic methods, in high water level (September 2012), in low water level (March 2013), and in drought periods (October 2013 and June 2014) ( $n > 12$ ). Red points at 1 m depth indicate small sampling pool ( $n = 6$ in March 2013, $n = 1$ in October 2013 and $n = 4$ in June 2014). ....	65
Fig. 4-29 Median volume of the water column inhabited by <i>E. densa</i> (PVI) in Icó-Mandantes bay in September 12, March 2013, October 2013 and June 2014. Error bars represent 75% and 25% quartiles. Des. = desiccated margins. Light and dark gray indicate dry and rainy season, respectively. ....	66
Fig. 4-30 Linear regressions used for the calculation of <i>E. densa</i> biomass and Chl <i>a</i> concentration in stands with different heights. ....	68
Fig. 4-31 Biomass (dry weight) of <i>Egeria densa</i> stands at different water depths, in (a) September 2012 (high water level) and March 2013 (low water level) and in (b) October 2013 and June 2014 (low water level). Desic.= desiccated margins. Open and full symbols indicate dry and rainy season, respectively. ....	69
Fig. 4-32 Primary production contribution of phytoplankton and macrophytes based on their correspondent chlorophyll <i>a</i> concentrations in high and low water level in Icó-Mandantes bay. ....	70
Fig. 4-33 Annual water level fluctuations in Itaparica reservoir (2007 to 2014) and monthly rainfall in the region (weather station at Floresta). Water level rise takes place by the end of rain season. After 2013 water level rise did not take place, and water level remained low in the following years. ....	71
Fig. 4-34 Margins of Icó-Mandantes bay in a) high water level (303 m a.s.l.) and b) low water level (300 m a.s.l.). ....	71
Fig. 4-35 Area in Icó-Mandantes bay which desiccated between September 2012 (303.3 m a.s.l.) and March 2013 (300.6 m a.s.l.), due to regular water level drawdown. ....	72

Fig. 4-36 Effects of water level drawdown in Itaparica reservoir: sediments and organic matter mineralization by exposition to air (on the left); breakdown of flora ( <i>Egeria densa</i> ) in desiccated margins and of littoral fauna (ex. <i>Aylacostoma</i> sp.) (left and right side, respectively). ....	72
Fig. 4-37 Grain size distribution of permanently flooded (wet) and desiccated sediments (dry) (more than 2.5 months desiccation) of Icó-Mandantes bay. ....	73
Fig. 4-38 Elution rates of total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) of fresh sediments (0 months) and of sediments desiccated in situ for 2.5, 4.2 and 12.0 months. ....	75
Fig. 4-39 Release of nutrients from rewetted sediments into the water column. DN = total dissolved nitrogen released per m <sup>2</sup> ; DP = total dissolved phosphorus released per m <sup>2</sup> ; TN <sub>water</sub> = amount of total nitrogen in a water column of 3m <sup>3</sup> ; TP <sub>water</sub> = amount of total phosphorus in a water column of 3m <sup>3</sup> . ....	76
Fig. 4-40 Comparison of littoral region of Itaparica reservoir in September 2012 (left side) with high water level and in June 2014 (right side) after almost 2 years drought. The figure shows the growth of terrestrial vegetation in the desiccated margins. ....	77
Fig. 4-41 Vegetated margins of Icó-Mandantes bay in June 2014, after 18 months of low water level. ....	77
Fig. 5-1 Annual dynamics of phytoplankton and macrophytes biomass in Icó-Mandantes bay promoted by water level fluctuations. ....	87
Fig. A - 1 Hypsographic curve of Icó-Mandantes bay for the bay bottom area and bay volume regarding water level elevation (Selge, 2017). ....	115
Fig. A - 2. Sampling points in acoustic survey of macrophytes distribution and biomass in the four field campaigns: A) September 2012; B) March 2013; C) October 2013; D) June 2014. ....	117
Fig. A - 3 Relationship between surface water temperature and water level in Itaparica reservoir. ...	117
Fig. A - 4 Correlations of nutrients concentrations and phytoplankton concentration in Itaparica reservoir in the different sampling seasons. A) dissolved inorganic nitrogen (DIN); B) dissolved P (DP); C) soluble reactive phosphorus (SRP). Symbols and error bars represent mean and standard deviation, respectively, of phytoplankton concentration and nutrient concentration in sampling stations in the lower middle stretch of the reservoir (ITA 06, ITA 08 and ITA 09). ....	118
Fig. A - 5 Preliminary results of remote sensing analyses to determine <i>Egeria densa</i> distribution in Icó-Mandantes bay. ....	119
Fig. A - 6 Examples (A-I) of the biodiversity of terrestrial vegetation in the margins of Icó-Mandantes bay after almost 2 years of constant water level. ....	120

## List of Tables

Table 3-1. Morphometric characteristics of Itaparica reservoir at high water level (304.5 m a.s.l.).....	22
Table 3-2. Short description of the location of the studied sampling stations in Itaparica reservoir in the period 2007-2010.....	23
Table 3-3. Annual median and quantiles Q25 and Q75 of water quality parameters in the main stream of Itaparica reservoir between December 2007 and September 2010. ....	24
Table 3-4. Morphometric characteristic of Icó Mandantes bay at 304 m a.s.l. ....	26
Table 3-5. Short description of phytoplankton sampling stations in Icó-Mandantes bay. ....	27
Table 4-1. Steadiest species in Itaparica reservoir. All year round: species which occurred in the reservoir in all sampling dates within the studied period in at least one sampling station. Season specific: species which always occurred in dry season or in rainy season.....	42
Table 4-2. Main species (regarding steadiness and abundance) present in Itaparica reservoir in each sampling season.....	47
Table 4-3. Characterization of water quality during field campaigns in Icó - Mandantes bay. Median (quartiles Q1 - Q3). Legend: HWL_D - High Water Level, Dry season; LWL_R - Low Water Level, Rain season; Drought_D – Drought period, dry season; Drought_R - Drought period, rain season) (Selge, 2017). ....	54
Table 4-4. Steadiest species in Icó-Mandantes bay between 2012 and 2014. The species in grey background was present in all the four sampling campaigns; species in white background were present in three sampling campaigns.....	56
Table 4-5. Macrophyte species occurring in the main course of São Francisco River, upstream from Itaparica reservoir.....	60
Table 4-6. Nutrient composition of <i>E.densa</i> (dry weight) in Icó-Mandantes bay, in $\mu\text{g mg}^{-1}$ (n = 45). 63	
Table 4-7. Water level, euphotic zone (Zeu), and <i>E. densa</i> maximum colonization depth ( $Z_{\text{maxEd}}$ ) in the four field campaigns. ....	65
Table 4-8. Characterization of permanently flooded sediments and desiccated sediments of Icó-Mandantes bay (mean $\pm$ standard deviation).....	73
Table A - 1 Water depth categories information including area covered (in km <sup>2</sup> ) by <i>Egeria densa</i> in each sampling season in Icó-Mandantes bay.....	115

**Abbreviations**

BMBF	Federal Ministry of Education and Research
CHESF	Companhia Hidrelétrica do São Francisco
Chl <i>a</i>	Chlorophyll <i>a</i>
Chl <i>a</i> -Ed	Chlorophyll <i>a</i> in <i>Egeria densa</i> biomass
Chl <i>a</i> -P	Chlorophyll <i>a</i> in phytoplankton biomass
Chl <i>a</i> -total	Chlorophyll <i>a</i> in <i>E. densa</i> and phytoplankton biomasses
DIC	Dissolved Inorganic Carbon
DIN	Dissolved Inorganic Nitrogen
DOC	Dissolved Organic Carbon
DP	Dissolved phosphorus
dw	Dry weight
Ed	<i>Egeria densa</i>
GLUES	Global Assessment of Land Use Dynamics, Greenhouse Gas Emissions and Ecosystem Services)
INNOVATE	<b>I</b> Nterplay among multiple uses of water reservoirs via <b>i</b> n <b>NO</b> vative coupling of substance cycles in <b>A</b> quatic and <b>T</b> errestrial <b>E</b> cosystems
IPA	Instituto Agronômico de Pernambuco
LOI	Loss on ignition
m a.s.l.	Meters above sea level
MCTI	Ministério da Ciência, Tecnologia, Inovação e Comunicação
N	Nitrogen
n	number of data
NH <sub>4</sub>	Ammonium
NO <sub>3</sub>	Nitrate
Org.	Organisms
P	Phosphorus
PE	Pernambuco state
PIK	Potsdam Institute for Climate Impact Research
PVI	Plant volume inhabited
Q25, Q75	25% and 75% quantiles
RM	Research Module
SP	Sub-Project
SRP	Soluble Reactive Phosphorus
TDN	Total dissolved nitrogen
TDP	Total dissolved phosphorus
TN	Total nitrogen
TP	Total phosphorus
UFPE	Universidade Federal de Pernambuco
UFRPE	Universidade Federal Rural de Pernambuco
UNIVASF	Universidade Federal do Vale do São Francisco
WLF	Water level fluctuations
ww	Wet weight
Z <sub>maxEd</sub>	Maximum colonization depth of <i>Egeria densa</i>

---

## List of publications

- Gunkel, G., Lima, D., Selge, F., Matta, E., Sobral, M., Calado, S., 2015a. Serviços de ecossistemas em reservatórios: produtos finais, capacidade e processos limitantes - exemplo de Itaparica, rio São Francisco, in: Proceedings of XII Simpósio de Hidráulica E Recursos Hídricos Dos Países de Expressão Portuguesa. Brasília, pp. 1–13.
- Gunkel, G., Lima, D., Selge, F., Sobral, M., Calado, S., 2015b. Aquatic ecosystem services of reservoirs in semi-arid areas: sustainability and reservoir management. WIT Trans. Ecol. Environ. 197, 1743–3541. doi:10.2495/RM150171
- Gunkel, G., Selge, F., Lima, D., Severi, W., Sobral, M., 2014. Eutrophication control in tropical reservoirs - internal versus external steering mechanisms, in: 13th IWA Specialist Conference Watershed and River Basin Management. San Francisco, USA, Sept. 2014, p. (extended abstract as e-publication).
- Gunkel, G., Severi, W., Lima, D., Moura, A., Catunda, S., Selge, F., 2017. Tropical reservoir eutrophication control: Top-down or bottom-up regulation? J. Limnol. (*submitted*).
- Gunkel, G., Selge, F., Keitel, J., Lima, D., Calado, S., Sobral, M., Rodriguez, M., Matta, E., Hinkelmann, R., Casper, P. & Hupfer, M., 2017. Management of a tropical reservoir (Itaparica, São Francisco, Brazil): Multiple water uses, impacts, vulnerability, and ecological sustainability. Reg. Environm. Change. Spec. Issue: Follow-up ahead: Large dams lessons in managing the water and land nexus (*submitted*).
- Lima, D., Gunkel, G., 2015. Controlling the growth of *Egeria densa* in Itaparica Reservoir, Brazil, in: Proceedings of 17th IWA International Conference on Diffuse Pollution and Eutrophication (DIPCON). Berlin, p. 7.
- Lima, D., Gunkel, G., 2017. The noxious waterweed *Egeria densa* as challenge for hydropower reservoir management. Lakes & Reservoirs: Research and Management (*submitted*).
- Rocha, C., Lima, D., Cunha, M.C., Almeida-Cortez, J., 2017. Scientometric analyses and research perspectives on macrophytes mediated trophic interactions (*submitted*).
- Tavares Junior, J.R., Lima, D., Candeias, A.L., Gunkel, G., 2017. Submerged macrophyte volume estimation in Itaparica Reservoir, Icó-Mandantes Bay, northeastern Brazil. Reg. Environm. Chang. Spec. Issue Follow. ahead Large dams lessons in managing the water and land nexus (*submitted*).



---

# **1 Introduction**





## 1.1 Water scarcity in Northeast Brazil

The construction of large reservoirs in Brazil began in the early 1900s, as result of the fast growing energy demand of industrial development (Soares et al., 2008). At this point, cascades of reservoirs were constructed in the most important Brazilian rivers for hydropower production, flood control and/or water supply, among others (Nogueira et al., 2010).

This measure was of particular importance in regions like the northeast Brazil, where water availability has always been a crucial topic. This semiarid region is characterized by a mean temperature of 25-30 °C which, unlike other semiarid regions of the world, is also accompanied by low temperature amplitude. The low humidity and rainfall are responsible for severe water scarcity in this region. Here, big and small reservoirs are very common to assure water during dry season for different purposes (human and animal water supply, irrigation, power generation), as due to the geological nature of the soil, groundwater is difficultly available (Maltchick and Florín, 2002). Water paucity instigates thus multiple uses of reservoirs, such as hydropower production, drinking water supply, water supply for livestock and for irrigation, fisheries, aquaculture and leisure activities (Gunkel, 2007). Because of its economic weight, energy production is often privileged in contrast to social and environmental interests, and frequently conflicts arise among the different stakeholders (ex. hydropower company, farmers, riverine population, fishermen, aquatic recreation companies, environment protection associations, etc), which dispute for water availability, water quality, good fish yields, biodiversity, etc. Biodiversity in particular, indirectly fundamental for ecosystems maintenance and for aquatic functions support, is generally disregarded in detriment to other interests.

In tropical lakes high external load of nutrients by runoff during severe rainy seasons take place and algae blooms are very common. The warmer climate, with permanently high temperatures along the year, is known to enhance eutrophication symptoms (e.g. cyanobacteria blooms, lower oxygen concentration in water). Additionally, the intense anthropogenic pressure on water for hydropower production, flood control and diverse water uses has been disrupting natural hydrological cycles, essential for native biotic communities. Many reservoirs in the Brazilian semiarid experience water level fluctuations, resulting in artificial drought/flood cycles, regulated water flow rates, erosion of margins and higher retention times with consequent higher nutrient availability. As a consequence, and with continuing nutrient loading from watersheds, most reservoirs in the semiarid are fragile and non-resilient eutrophicated systems with deteriorated aquatic functions.

The resulting loss of water quality has serious effects on the ecosystem services such reservoirs can deliver and thus worsens conflicts between the different users.

Against this background, there is an increasing need of preserving the natural integrity of reservoirs in the semiarid, by combating eutrophication causes and effects. The restoration of reservoirs is possible if the biogeochemical processes behind anthropogenic pressure are discerned and apprehended. Expertise in aquatic ecology is very advanced for temperate lakes, and mechanisms and drivers underlying growth responses are reasonably understood. However, although much of this understanding can be adopted in low-latitude systems, knowledge on biogeochemical processes and drivers for diversity and ecosystems conservation in semiarid aquatic systems is still scarce.

The urgency of more extensive information on the impacts of eutrophication is stressed by the effects of climate change. According to the report of the Intergovernmental Panel on Climate Change (IPCC, 2013), temperature will rise and stochastic events such as droughts and floods will become more frequent worldwide. Arid and semiarid regions will become warmer and drier by the end of this century. In semiarid northeast Brazil in particular, climate models predict a temperature rise of about 4°C and more intense and longer droughts due to climate change (Brasil et al., 2016). Lower rainfall and higher temperatures are likely to alter hydrology of aquatic systems, a key factor in the functioning of reservoirs of the semiarid (Bakker and Hilt, 2015). High temperatures have been related

to dominance of cyanobacteria over other algae (Romo et al., 2013). Droughts will lead to wide water level fluctuations, as well as increased residence times. Climate change is therefore expected to worsen the situation of the Brazilian semiarid, which is by itself already delicate in what concerns water availability and quality, giving rise to more conflicts of interests.

Land and water use strategies have to be developed and adapted to face the challenges of these expected changes in order to guarantee economic, social and environmental stability. For that, empirical studies which improve our perception of the impacts of current droughts and future climate change on tropical freshwater ecosystems are necessary (Brasil et al., 2016).

## **1.2 The research project INNOVATE**

### **1.2.1 Itaparica reservoir**

The impacts of land and water use on the ecological status of reservoirs in the Brazilian semiarid were the main target of INNOVATE project (INterplay among multiple uses of water reservoirs via inNOVative coupling of substance cycles in Aquatic and Terrestrial Ecosystems), which focused on Itaparica reservoir as study object.

Itaparica reservoir is part of a reservoir cascade in the lower-middle stretch of the São Francisco River, in the Brazilian semiarid. This reservoir was constructed in 1988 mainly for hydropower production, but it was also planned to serve the local communities for crop irrigation and drinking water supply. At that time, the damming of the river flooded around 805 km<sup>2</sup> and this event implied the relocation of 40 000 people. As means of compensation, crop land was distributed by the displaced families, forming agriculture schemes around the reservoir, which benefited from water availability (Gunkel, 2007). Since then, several environmental problems have arisen due to the uncontrolled use of the margins of the reservoir for agriculture activities and urban occupations (Sobral et al., 2006). The expansion of urban settlements and crop land to the margins of the reservoir originated problems on water quality by direct disposal of untreated sewage effluents and by abundant use chemical fertilizers. Because of recurrent water level fluctuations due to hydropower production, the margins of the reservoir are devoid of vegetation, which promotes erosion and worsens the impact of washout and runoff when intense rain events take place, transporting fertilizers from crop fields into the water body.

Itaparica reservoir, as many others reservoirs in the Brazilian semiarid, has multiple uses, namely hydropower production, irrigation, urban water supply, human and animal water supply, leisure activities, fisheries and aquaculture. Here it is also located one of the water abstraction points in the projected water transfer channel (Transposition Project, 2007). The diverse functions of the reservoir cause environmental as well as social challenges that create discussions about the different uses and the quality of water provided. Energy generation, irrigation, water supply, flood control, wastewater dilution and ecological protection are the main topics of such debates (Sobral et al., 2007).

The construction of reservoirs in Brazil in the last few years has promoted a fierce debate about the priority given to the economical over the social and environmental services related to water resources management. Also in Itaparica, water availability for intensive irrigation schemes for product export (loss of virtual water) and especially for hydropower production have been referred as main drivers for river ecosystem services deterioration in the region (Sobral et al., 2006).

### **1.2.2 Aims**

INNOVATE project intends, based in a holistic approach, to analyze Itaparica reservoir as an anthropogenically impacted system, in order to close gaps and create knowledge of the functioning of freshwater systems in the Brazilian semiarid.

The aim of INNOVATE project is the delivery of guidelines for an integrated and sustainable water and land use of Itaparica reservoir, optimizing the ecosystem services of this reservoir by respecting social, environmental and economical needs of the region. An adequate management plan for the sustainable use of Itaparica reservoir is only possible after understanding the processes, impacts, drivers originated from land and water use. For this, INNOVATE project was divided in two main phases. In the first phase, the project aimed at understanding the different biogeochemical processes to close nutrients cycles by coupling land use and water use of Itaparica reservoir, and give a solid economic base for the population. In the second phase, the target was to implement this knowledge and deliver practical guidelines for a sustainable land and water use management.

### 1.2.3 Structure and working groups

The project INNOVATE is a joint research project between German and Brazilian research institutions (INNOVATE, 2017). The institutions involved on the German side are the Berlin University of Technology (TU Berlin), Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Potsdam Institute for Climate Impact Research (PIK), University of Hohenheim and on the Brazilian side are the Federal University of Pernambuco (UFPE) and Rural Federal University of Pernambuco (UFRPE). The steering group was composed by the Brazilian and German SP-leaders and coordination team. A regional stakeholder round table observed the relevance of the project and the feasibility of the presented results. Innovate was included in the GLUES (Global Assessment of Land Use Dynamics, Greenhouse Gas Emissions and Ecosystem Services) interface, which coordinates a network of projects dealing with sustainable land- and water management. The MCTI (Brazilian Ministry of Science and Technology) heads the Brazilian Sponsor Consortium, forming the direct counterpart of BMBF (Federal Ministry of Education and Research), on the German side.

This project was divided in seven sub-projects which were responsible for studies at micro-, meso- or macro-scale of the São Francisco River watershed (see INNOVATE, (2015) for more detailed information). Each one of these working groups included 3 or 4 research modules and was composed by scientists from both nationalities. The seven multidisciplinary sub-projects interaction and focus are depicted in Fig. 1-1.

The present thesis is included in the Sub - Project 4 – Biodiversity and Ecosystem Services - research module 3 (SP4-3), which investigated aquatic biodiversity and the occurrence of undesired species in Itaparica reservoir. Aquatic biodiversity and its dynamics were key factors for assessment, as ecosystem functions only exist in a complex biocoenosis and more or less steady state conditions. A good comprehension on phytoplankton and macrophytes assemblages and dynamics is indispensable for understanding reservoir mechanisms, as adjuvant information on physical and chemical processes of the reservoir. Hence, this study was carried out in close cooperation with the Sub-Project 1 – Aquatic Ecosystem Functions -, which main topics included the role of watershed land use in reservoir nutrient loading, sediment phosphorus dynamics and greenhouse gases emissions. The central target of SP1, together with SP4-3, was the promotion of oligotrophication of the reservoir by assembling technical and management knowledge, to increase biodiversity and maintaining good ecological conditions in the reservoir.

## 1.3 Scope of the thesis

Hydrology has been referred as one of the main drivers for biodiversity of freshwater systems in the Brazilian semiarid (Maltchick and Medeiros, 2006).

Primary producers (namely algae and plants) are organisms which promptly react to hydrology disturbances and eutrophication and thus are good indicators of the cultural transformation level of a waterbody. In systems under anthropogenic pressure, outbreaks of macrophytes and toxic

cyanobacteria are commonly registered, with serious costs at economical, environmental and public health levels (Barbosa et al., 2012; Thomaz et al., 2008).

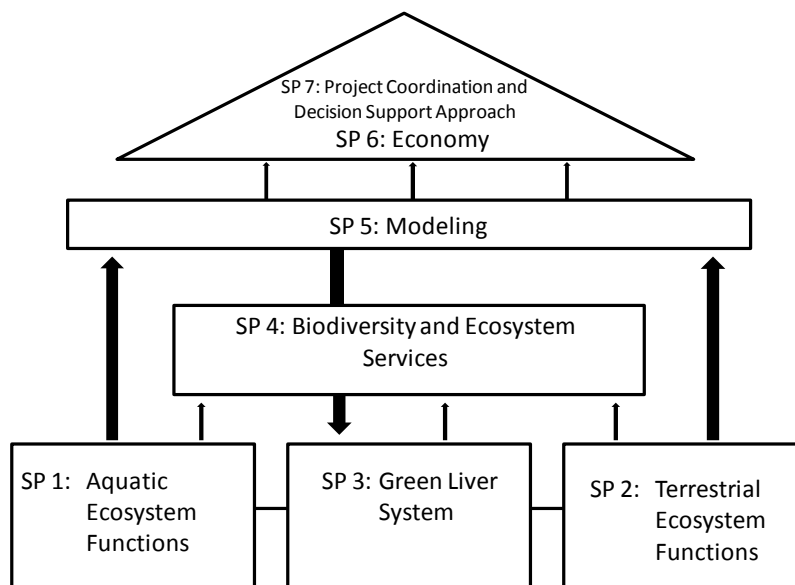


Fig. 1-1 Main working groups of the Innovate project working in Itaparica reservoir at micro and meso-scales (SP1, SP2, SP3 and SP4) and at macro- scale in the São Francisco River watershed (SP5, SP6 and SP7).

In Itaparica reservoir, blooms of toxic cyanobacteria (e.g. *Cylindrospermopsis raciborskii*, *Microcystis* sp.) and macrophytes (*Egeria densa*), and vectors of waterborne diseases (e.g. Schistosomiasis) have been reported (Gunkel, 2007). The degraded ecological status of Itaparica reservoir has damaging effects on aquatic functions, which impact fisheries, navigation, recreation and water supply.

Water level fluctuations of up to 5 m due to hydropower operation take place seasonally in this reservoir, leading to recurrent desiccation of margins and complete breakdown of the littoral biotic community. Such a seasonal dramatic change is expected to impact on the biological populations of this reservoir (namely of primary producers) by promoting the growth of species which, due to their adverse impacts not only at ecological but also economical levels, can be considered undesired in this aquatic ecosystem (cyanobacteria, *Egeria densa*). The high external input of nutrients during rain season and the warm climate support high metabolic rates and productivity.

Itaparica is a long reservoir which comprises sections overexposed to pollution. The bay of Icó-Mandantes is a high risk area, as it serves as dilution pool of diverse types of contamination. Along the shore of Icó-Mandantes bay drainage water of excessively fertilized agricultural fields falls into the bay. Also, untreated sewage from the urbanized shore line areas inflow directly here. In the inner part of this bay, there is an intermittent rivulet (Riacho Mandantes) which, during rainy season, transports high loads of mineral and organic material from the watershed and thus responsible for seasonal nutrient enrichment of the bay. In spite of it, in this bay are located pumps for water abstraction for drinking water supply of the riparian populations and livestock and agriculture irrigation schemes. Also in the inner part of the bay it is located one of the transfer channels of São Francisco River which will divert water to other dry regions in the north of Brazil.

### 1.3.1 Objectives

Itaparica reservoir experiences blooms of cyanobacteria and macrophytes which impact aquatic functions of the reservoir. The causes of those blooms have not been yet fully studied and until now no attempt of combating these blooms has taken place. Therefore, the main aims of this study were to:

- 1) Investigate the main environmental drivers for primary producers' development in Itaparica reservoir, and understand their effects in the promotion of pioneer species.
- 2) Based on the knowledge acquired of the underlying drivers, to provide suitable management tools that could avoid outbreaks of such undesired species, taking into account regional water scarcity and climate change predictions.

The analysis of the main environmental drivers was approached considering the hypotheses that phytoplankton and macrophytes communities in Itaparica reservoir are affected by:

- Climate

Primary production is dependent on nutrients availability. The role of rain/dry seasons and cold/warm seasons in the external and internal loads of nutrients in the reservoir and consequently in species composition and abundance is here assessed.

- Hydrology

Hydrology is a very important factor for aquatic biodiversity in the semiarid (Barbosa et al., 2012). Anthropogenically regulated water flow disrupts natural flow rates and flood/drought cycles of riverine systems. In Itaparica reservoir, water level changes and artificial flow rates related to hydropower production are expected to:

- reduce biodiversity of primary producers
- affect nutrients cycling and availability
- impact littoral biological communities and sediments properties by artificial dry/rewetting cycles
- potentiate outbreaks of pioneer species of macrophytes (*Egeria densa*) and phytoplankton (*C. raciborskii*).

- Morphometry

The morphometric characteristics of Brazilian reservoirs are variable but a large size and dendritic shape are common (Tundisi et al., 1993; Tundisi, 1994). The acknowledgement of spatial dissimilarities is essential to improving predictive capacities and to adequate managing measures for the sustainable preservation of ecosystems services (Huszar et al., 2015). Studies on water body heterogeneity are not abundant and more information is needed about ecological processes in different areas of reservoirs for the development of adequate management tools (Janssen et al., 2014; Pacheco et al., 2015; Soares et al., 2012). Itaparica is a long flow-through reservoir with high shoreline development index, and horizontal spatial heterogeneity of environmental conditions is expected to occur. The development of primary producers is therefore likely to be driven differently in main stream (considered here a deep system) and in a reservoir arm (Icó-Mandantes bay - as example of a shallow system).

This work intends to create important knowledge, necessary primarily for the understanding of semiarid freshwater systems and subsequently for the development of an integrated water resource management, as reservoirs with plants and algae blooms are abundant in the Brazilian semiarid. The information attained is part of the INNOVATE project main aim for the sustainability of ecosystem services and potential management strategies.

## 1.4 Structure of the thesis

This thesis intends to give an insight on the primary production dynamics in the main stream of the reservoir and in the shallow Icó - Mandantes bay. This thesis is subsequently organized as follows:

Chapter 1. This introductory part gives an overview of the motivation of the present work regarding the problematic of multiple uses of reservoirs of the Brazilian semiarid and the importance of primary producers in the natural integrity of ecosystems. The research framework is given in this chapter, with reference to INNOVATE project and description of the transdisciplinary character of this project and overarching objectives. Finally, the scope and main aims of this thesis, included in the subproject SP4-3 of INNOVATE project, are presented.

Chapter 2. The theoretical background introduces the topic of primary production, and the main actors on blooms formation in Brazilian aquatic systems as consequence of eutrophication. Water level fluctuations and their impacts are also here presented, as well as state of the art of management tools in tropical reservoirs.

Chapter 3. This chapter introduces the study site – Itaparica reservoir – and the climate in the region. Moreover, it describes the methodology used to assess the different targets presented in this work.

Chapter 4. Demonstrates the outcomes attained in the framework of the study, comprising three main groups of results:

- a) Main stream. Limnological trimonthly datasets of the Itaparica reservoir surveys between 2007 and 2010 executed by CHESF (CHESF, 2011) were used to characterize environmental seasons and to determine major drivers of phytoplankton diversity and composition in the main stream of the reservoir.
- b) Icó-Mandantes bay. The environmental stability of Icó-Mandantes bay promotes enhanced biomass of *Egeria densa* and cyanobacteria (mainly *C. raciborskii*). In order to understand which drivers lead to the presence and dominance of these species in the bay, a detailed assessment of temporal and spatial processes and gradients inside the bay was done with own measurements of phytoplankton and macrophytes diversity and density, providing evidences of species dominance and ecological shifts between 2012 and 2014.
- c) Eroded margins. A characterization of desiccated sediments in the margins of Icó-Mandantes bay was performed, and leaching experiments were carried out to look over nutrients load potential to locally enrich littoral area upon rewetting during water level rise.

Chapter 5. In this chapter the results of the three major groups were integrated and discussed regarding water level fluctuations, with the perspective of biodiversity promotion in reservoir management. Here, practical recommendations to hinder the massive development of pioneer species are provided, in accordance to project implementation phase requirements.

Chapter 6. The main conclusions of the present thesis are given.

Chapter 7. Outlook of this work with indication of possible future research directions.

Chapter 8. This chapter includes a list of literature references used in this study.

Chapter 9. The annex comprises supplementary material with additional information of study site and of results.

---

## **2 Theoretical background**

## 2.1 Role and ecological drivers of primary production

Primary producers or autotrophs are a class of organisms which are able to transform inorganic compounds into organic material. The great majority of primary production occurs via photosynthesis (e.g. plants), with carbon dioxide (CO<sub>2</sub>) used as carbon source, either in terrestrial or aquatic systems.

In aquatic systems, they are the basic foundation of oceanic and freshwater food webs, as their biomass is food to the first consumers of the trophic chains. Likewise, primary producers have vital effects on the function and structure of whole ecosystems and play an essential role on the turnover of nutrients (phosphorus, nitrogen, carbon and micro nutrients) within a system.

Aquatic primary production is influenced by a combination of various abiotic factors, namely availability of nutrients and light, water temperature, pH, turbulence, water residence time, mixing regimes of water column and biotic factors such as grazing. These can naturally fluctuate within a determined range, in accordance to the climate, basin morphology and hydrology dynamics of the waterbody (Kimmel and Groeger, 1984).

Primary producers are divided in the following major categories: phytoplankton (planktonic algae and cyanobacteria), macrophytes (aquatic plants) and periphyton (attached algae). Other organisms (chemosynthetic bacteria or algae in symbioses with other organisms) are also present but the contribution to total primary production of a system is negligible (Kimmel and Groeger, 1984).

### 2.1.1 Phytoplankton

Phytoplankton includes all photosynthesizing planktonic algae and bacteria. These unicellular or colonial organisms are energy source for zooplankton and planktivorous fishes (Lazzaro, 1987). Planktonic photosynthetic organisms are inevitably dependent on mechanisms that prevent them from sinking in the dark bottom of a water body. Thus, turbulence due to water currents and mixing of water column is essential for their survival. In some specific cases, evolutionary traits provide the capacity to control the vertical movement in the water column (using intracellular gas vesicles) or the use of strategies to slow down the sinking process (colonies formation, production of mucilage) (Reynolds, 2006).

During decades, phytoplankton was considered the main contributor to primary productivity of freshwater systems, as studies were mainly done in deep reservoirs with a minor occurrence of macrophytes and attached algae. Nowadays, even though phytoplankton is the main producer in the limnetic zone of waterbodies, in shallow areas macrophytes and periphyton are recognized as similarly important contributors to primary production (Thomaz et al., 2008).

### 2.1.2 Macrophytes

Macrophytes are vascular plants visible to the naked eye, which grow in permanently or periodically aquatic habitats. They colonize the littoral of water bodies and have different life forms: free floating, when they float on or under the water surface (e.g., *Eichhornia* sp.) or rooted. When rooted, they can grow completely submerged, (ex. *Egeria densa*), or be emergent, with the foliage extending into the air (e.g. *Nymphaeoides indica*) (Thomaz et al., 2008).

Macrophytes are very important for ecosystem structure and functioning in shallow systems. Invertebrates, fishes and birds benefit from the numerous and diverse habitats that the mechanical structure of the different types of macrophytes provide (Boschilia et al., 2012). Biogeochemical cycles in littoral areas are deeply connected to macrophyte communities, as they are organic carbon sinks, phosphorus accumulators and play a role in sediment phosphorus mobilization. By physically reducing water flow, macrophytes promote deposition of suspended matter which results in increased water



transparency. Besides, their metabolism influences the water milieu by affecting thermal regime, gases and ions concentrations (including nitrogen, phosphorus, carbon) and pH, among other factors. For example, under the higher temperatures of tropical waters, oxygen is usually super-saturated, CO<sub>2</sub> is non-detectable and pH values may easily reach 9.5 inside stands of submerged plants (Thomaz et al., 2008). Moreover, their robust structure increases the stability of the margins, protecting against erosion and providing buffer capacity to the shoreline.

### 2.1.3 Periphyton

Periphyton is defined as the benthic community formed by algae, bacteria, fungi, animals, and inorganic and organic detritus that is attached to substrata such as plants, rocks, wood, sediment or animals (Wetzel, 1983). This complex community of microbiota is a source of energy for higher trophic levels, affects the nutrient turnover and the transfer of nutrients between the benthic and the pelagic zone. They can also be vital competitors to macrophytes for light and carbon and to phytoplankton for nutrients (Liboriussen and Jeppesen, 2009). Although they can play a substantial role on primary production in some aquatic systems, primary productivity studies frequently consider macrophytes and phytoplankton contribution.

## 2.2 Eutrophication in tropical reservoirs

Damming rivers results in the transformation of a riverine system into a lacustrine one, with consequent direct and indirect impacts on natural hydrology and ecology. A higher propensity to eutrophication is expected, as the construction of reservoirs leads to, among others: 1) decreased water flow rate; 2) increased water residence time; 3) larger water surface area and thus higher evaporation rates; 4) alterations of water temperature and in mixing regimes of water column; 5) higher sedimentation rates (Kimmel and Groeger, 1984).

All these aspects promote an enhanced trophic state in reservoirs across the globe, independently from the climate. In addition to these drivers, tropical reservoirs have been undergoing intense cultural eutrophication, because of the increasing demographic and economical development in the sub-basins of these systems with associated untreated sewage, fertilized agricultural lands, fish farms, etc. (Soares et al., 2012). Moreover, the warm tropical lakes are naturally more productive and thus eutrophication impacts are more intense than in temperate regions (Jorgensen et al., 2013). In addition, intense rainy seasons are responsible for a high external input of nutrients, by watershed runoff. In these systems, internal fertilization plays a significant role because of the thermal regime of the water column: by stratifying and mixing daily, nutrients previously lost to the hypolimnion, become available again in the epilimnion during mixing. In these reservoirs, there is a higher propensity to hypoxia in the deeper layers mainly during stratification, as the high solar radiation and high water temperature catalyze microbiological activity and decomposing processes.

Water uses of reservoirs, mainly hydropower production and irrigation of intensive agriculture, enhance annual and interannual fluctuations of water levels, occasionally far beyond natural amplitudes (Zohary and Ostrovsky, 2011), with impacts on natural hydrological cycles.

### 2.2.1 Water level fluctuations

The impacts of water level fluctuations (WLF) are more noticeable in shallow than in deep lakes as in the later only the littoral zones change visibly. On the contrary, small water level changes in shallow lakes are translated to significant proportions of the total surface area and total amount of water in those lakes, and naturally the ecological implications are quite distinct. Water level fluctuations result in desiccated margins, littoral erosion and breakdown of biotic communities, with significant changes in lake food web structure and community composition (Zohary and Ostrovsky, 2011).

Water level drawdown, sediment oxidation and subsequent desiccation of margins affect sediment chemistry, mineralogy, and sediment microbial ecology. Upon margins desiccation, sediments and organic material (e. g. previously submerged vegetation) are substrate for heterotrophic bacteria and metabolized until complete mineralization. Hence, when in oxic conditions, much of the organic carbon is converted to CO<sub>2</sub> and released to the atmosphere, denitrification processes decrease with consequent nitrate enrichment, and P is sequestered by oxidized mineral phases such as iron. At the edge of sediment desiccation and mineralization, also microbiological activity and survival are undermined (Baldwin and Mitchell, 2000).

The re-wetting of these sediments (which can occur by water level rise or rainfall) has been shown to culminate in a high pulse of nutrients into the system. The “Birch effect” refers to the flush of N and P occurring immediately after sediments rewetting, connected to the high bacterial mortality and cell lysis (Attygalla et al., 2016).

Hence, water level fluctuations in water bodies have been associated to nutrient enrichment (Kleeberg and Heidenreich, 2004), cyanobacteria dominance and impacts on aquatic biota, including littoral macrophyte or invertebrates communities (Bakker and Hilt, 2015; Boschilia et al., 2012).

However, the responses of lakes to desiccation seem to be quite diverse and site specific. Up to now, studies on effects of water level drawdown on macrophytes assemblages reported diverse results in deep and shallow systems: in deep lakes water level changes promote the breakdown of whole communities, in shallow reservoirs increase biomass due to higher light availability (Hilt, 2015). Yet, the high levels of abiotic turbidity during low water level, caused by sediment re-suspension by wind and fish, may inhibit algae and macrophyte growth, and foster cyanobacteria dominance (Brasil et al., 2016). When water level rises, shifts from a macrophyte dominated system to an algae dominated one were reported to occur in shallow reservoirs (Hilt, 2015). In other lakes, water level rise promoted the shift of a highly turbid system to one dominated by macrophytes (Loverde-Oliveira et al., 2009). In deep waterbodies, the niche of macrophytes is compressed with water level rise, having little effects on cyanobacteria presence (Bakker and Hilt, 2015).

The different feedbacks to water level fluctuations deeply depend on the resilience of the water body and nutrients threshold which trigger shifts from algae to macrophytes dominance and vice-versa. Many of the biogeochemical processes underlying these shifts are still not completely understood (Attygalla et al., 2016). So far, regime shifts from a clear to a turbid state in temperate lakes have been attributed to diverse mechanisms such as increase in nutrient load, heavy storms uprooting plants, increasing salinity releasing phytoplankton from top-down control by cladocerans, water level fluctuations, fish kills, or a combination of several factors. In tropical lakes, the set of mechanisms related to such shifts have not been yet thoroughly studied (Brasil et al., 2016; Loverde-Oliveira et al., 2009).

With climate change, the incidence and intensity of drought events are predicted to increase and accentuate fluctuations in water levels in semiarid regions. Concerted ecological impacts on littoral zones of aquatic systems are expected and thus these are key points of assessment (Jeppesen et al., 2015).

## **2.3 Common blooms in Brazilian reservoirs**

### **2.3.1 Cyanobacteria**

Cyanobacteria outbreaks have been recognized as an health issue in freshwater systems in many countries mainly because some species are capable of producing potent toxins that are harmful to humans and wildlife (Mowe et al., 2015). Additionally, they are associated with changes in the taste of water, produce unpleasant odors, cause ecological damage, such as changes in food chains, with

potential effects on nutrient cycling and biodiversity and lead to increased costs for water treatment (Medeiros et al., 2015). Cyanobacteria show preference for high temperatures in relation to other phytoplankton groups, and therefore blooms of cyanobacteria are very commonly reported in warmer climates (Romo et al., 2013). Although these blooms are often related to the eutrophic conditions of tropical systems, other factors may also contribute to the success of cyanobacteria in relation to eukaryotic algae, such as adaption to low light conditions, environmental constancy, annual rain deficit and lack of nutrient input, low turbulence, water level fluctuations, high temperatures with high column stability, high pH, low N:P ratio, absence of efficient predators (Brasil et al., 2016; Hilt, 2015; Huszar et al., 2000). In South America, an increasingly incidence of outbreaks of such species has been reported, although the real number of cyanobacteria blooms is considered to be underestimated, reaffirming it as an emerging concern to public health authorities (Dörr et al., 2010).

Also in Brazil, an increasing number of environments where cyanobacteria are predominant is remarkable (Dörr et al., 2010). Blooms of cyanobacteria have been documented in almost half of the Brazilian states, from the North to the South region, but mostly in northeast and southeast. Biodiversity of toxic cyanobacteria in the tropical region of Brazil is smaller than in the subtropical region, probably by environmental conditions which boost bloom formation and thus mono-species communities (Dörr et al., 2010; Sant'Anna and Azevedo, 2000). These outbreaks were commonly observed in artificial reservoirs, especially in the semiarid part of the country, which are in general easily eutrophicated, condition that is worsened by their characteristic long water residence time and high water temperatures (Sant'Anna et al., 2008). Brazilian strains have been observed to be more harmful than strains from other countries and tropical regions (Mexico, Asia and Australia) (Antunes et al., 2015; Mowe et al., 2015). Comparisons of the neurotoxic *Cylindrospermopsis* strains from Brazil and Mexico revealed the Brazilian strain to have acute neurotoxicity and the Mexican strains isolated were found to be non-toxic (Mowe et al., 2015). In northeast Brazil, 52 people died in 1996 because of use of cyanotoxin-contaminated water for dialysis in renal patients being this one of the more serious cases in the tropics of cyanobacteria intoxication with human fatalities (Mowe et al., 2015). Several genera of toxic cyanobacteria have been registered in Brazil, in tropical and subtropical regions, such as *Microcystis*, *Radiocystis*, *Planktothrix*, *Dolichospermum* (formerly *Anabaena*), *Aphanizomenon* and *Cylindrospermopsis* (Sant'Anna et al., 2008). Of these, the most frequent and wide spread toxic species in Brazilian reservoirs are *Microcystis aeruginosa* and *Cylindrospermopsis raciborskii* (Sant'Anna and Azevedo, 2000; Soares et al., 2013).

### 2.3.1.1 *Microcystis aeruginosa*

*Microcystis* sp. is common in tropical and subtropical regions, showing a high adaption to different climate and water conditions. In tropical America, *Microcystis* was the bloom-causing genus in 35 % of total blooms (Mowe et al., 2015). They produce microcystins, the most recurrent toxin in Brazilian waterbodies, which are hepatotoxins responsible for livestock poisoning, children skin lesions and mass fish kills (Bittencourt-Oliveira et al., 2014; Mowe et al., 2015).

*Microcystis aeruginosa* is characterized by small coccoid cells with gas vacuoles which benefit from the capacity of forming large colonies with buoyancy control properties, as a strategy to prevent biomass loss by sedimentation and grazing. Therefore, *Microcystis* outbreaks are frequently observed in stratified systems, at water surface (Tundisi et al., 2008a). Blooms of this species have been found in highly enriched waters, with high N concentrations and generally with a total phosphorus content higher than 20  $\mu\text{g L}^{-1}$  (Soares et al., 2013). Hence, *Microcystis* is commonly observed in natural lakes, which have stable water conditions and high trophic state. *Microcystis* has a high affinity for  $\text{CO}_2$ , also when present in very low concentrations, therefore are able to thrive in conditions considered hostile for many other algae species (Wu et al., 2009). Nonetheless, this cyanobacteria is sensitive to flushing, and therefore is frequent in water bodies with high residence times (Reynolds, 2006).

### 2.3.1.2 *Cylindrospermopsis raciborskii*

The *Cylindrospermopsis* genus is the cause of 47 % of the registered cyanobacteria blooms of tropical America (Mowe et al., 2015). Modelling data demonstrated that *C. raciborskii* blooms are likely to occur between the temperatures of 25–32°C, with higher temperatures being favourable to the bloom formation, which explains their regular appearance in tropical regions (Antunes et al., 2015). This species is very common in the semiarid northeast Brazil. The high temperatures, rain regime and high solar radiation typical of this region, together with highly eutrophicated water bodies with long water residence times, give growth advantage on relation to other species.

*C. raciborskii* produces hepatotoxins and neurotoxins, and has been responsible for several cases of animals and human poisoning. Currently, only Brazilian strains were shown to produce saxitoxins (associated to paralytic shellfish poisoning), and their production seems to be related to water hardness (Antunes et al., 2015; Carneiro et al., 2013).

*Cylindrospermopsis raciborskii* is a diazotrophic filamentous cyanobacterium with terminal heterocysts belonging to the order Nostocales. This planktonic organism can dominate phytoplankton biomass for long periods, with a high resilience to environmental variability (Figueredo and Giani, 2009). The success in aquatic systems of the genus *Cylindrospermopsis* has been explained by its highly competitive characteristics. It has high affinity for P and high P-storage capacity; high light limitation tolerance; ability of N<sub>2</sub>-fixation, although also a high affinity for ammonium, a cheaper N source, while other heterocystic species must fix atmospheric N; resistance to grazing due to toxicity; buoyancy control; ability to form akinetes, allowing easy dispersal and environmental resistance; wide thermal tolerance and allelopathic interference (Burford et al., 2016; Figueredo and Giani, 2009).

The physiological attributes of *Cylindrospermopsis raciborskii* allow its spread across climate zones. It has been registered in an increasing number of countries in the Northern and Southern hemisphere, in rivers, lakes and reservoirs (Antunes et al., 2015). This successful geographic spreading is probably being promoted by global warming (Dörr et al., 2010; Soares et al., 2013).

## 2.3.2 Macrophytes

Although macrophytes bring many benefits to ecosystems, these plants can also pose a risk for exploitation of water resources when growing excessively (Thomaz et al., 2015). Abundant growth of aquatic macrophytes is a common feature of large eutrophic reservoir systems in sub-tropical and tropical regions, especially in impoundments which have complex shapes with extensive areas of sheltered and shallow water, ideal for macrophyte growth (Janssen et al., 2014; Thomaz et al., 2008).

If not controlled by appropriate management, aquatic weeds may cause serious restrictions in diverse water uses. Regarding ecosystem services of waterbodies, thick mats of macrophytes can also impact irrigation and drinking water supply systems, mechanically by clogging pipes and irrigation channels and chemically by lowering water quality. Artisanal fishing is also impaired by the dense mats as well as leisure activities, like boat traffic, swimming and recreational fishing. In hydropower production reservoirs, excessive macrophyte growth is also a drawback as loose and floating plants can block turbine grids, hampering energy production (Gunkel et al., 2015b). In some situations, they can also be risk for public health, as they are favourable environment for vectors of diseases such as Schistosomiasis (Thomaz and Bini, 2003). This is an endemic disease in Northeast Brazil, with 700-800 deaths reported annually in the country (Martins-Melo et al., 2015).

Extensive monospecies macrophyte stands hinder the growth of other plants, and decline the heterogeneity of habitats, necessary for the diversity of the littoral fauna. The expansion of floating macrophytes with high growth rates prevent light penetration through the water column, and thus hamper photosynthesis of planktonic and benthic organisms, including submerged macrophytes. The

species *Eichhornia crassipes*, *Eichhornia azurea*, *Salvinia molesta* and *Pistia stratiotes* are spreading in several Brazilian reservoirs with reported deterioration of ecosystem services (Thomaz et al., 2015).

Besides free-floating macrophytes, submerged plants of the Hydrocharitaceae family (namely *Egeria densa* and *Egeria najas*) are also common, and were reported to occur usually in lower parts of reservoirs cascades, in tributaries of Paraná River or São Francisco River (Thomaz et al., 2009, 2008). These can build dense canopies underwater, promoting low gas exchange between water surface and sediment. The lack of oxygen in the interface water-sediment fosters anaerobic decomposition of organic matter, and the release of toxic gases (such as methane), resulting in death of organisms, loss of diversity and eventually the disappearance of complete ecosystems.

*Egeria densa* is a submerged freshwater macrophyte native from South America, recognized worldwide by its opportunistic features in ecologically disturbed systems (Zehnsdorf et al., 2015). Through the thin cellular layer of the leaves, this plant uptakes nutrient from the water by diffusion and from the sediments through roots, providing advantage when nutrients are limiting. The relatively high growth rate and ability to disperse by fragmentation are two physiological features which allow a successful growth in adverse conditions. Additionally, *E. densa* is able to phenotypically adjust to different light conditions, and to grow in low CO<sub>2</sub> concentrations (Yarrow et al., 2009). These features allow a pioneer behavior in hostile conditions for other species, becoming a main target in many management guidelines.

Recently, the massive proliferation of macrophytes in Brazilian hydropower reservoirs has been subject of concern and employment of management measures. Many of the studies arising from macrophytes infestations are being developed in the south of Brazil, especially in the São Paulo state, where most of the large reservoirs are located (Carvalho et al., 2003; Thomaz and Bini, 2003; Velini et al., 2005). The negative effects of eutrophication in the aquatic functions of reservoirs in this urbanized and industrialized region motivate efforts in finding restoration solutions. In contrast, in the northeast Brazil, a poorer region with lower level of development, these problems have also been referred but less studies are available (Oliveira et al., 2005).

## 2.4 Primary production control in the tropical region

Driving factors of primary production have been intensely investigated in temperate lakes in the last decades, as an attempt of understanding the processes on which restoration measures can potentially rely (Lewis, 2000). These drivers are shaped by climate, hydrology, morphology, food webs, water and land use, among others.

In contrast to the temperate natural lakes, in the tropics most of the freshwater impoundments are artificial lakes, with widely heterogeneous compartments. Besides enclosing longitudinal zonation, horizontal heterogeneity occurs by the establishment of lateral sections, which have influence in the structure and biochemical processes within a reservoir, and on the formation of geographically restricted ecosystems (Janssen et al., 2014; Pacheco et al., 2015). Examples of these horizontal differences are the variation in depth, in sediment type, or the sensitivity to external drivers such as wind, rain or anthropogenic pressure. For instance, allochthonous nutrient input mostly enters reservoirs by tributaries, exerting a higher eutrophic stress in the vicinity of inlets than farther away. Generally, the existence of shallow bays protected from wind and water currents favors the growth of macrophytes, which are not able to grow in the turbulent main channel of the reservoir. These spatial differences are intrinsic to large reservoirs and the knowledge of their ecological features is essential for a good understanding of system functioning and sensitivity to eutrophication and other anthropogenic pressures.

In the temperate region, primary production in spring and summer is supported by temperature and solar radiation increase. Later in the year, in autumn and winter, temperature drops and production sinks to very low levels until the next spring (Mowe et al., 2015; Reynolds, 2006). Under this climate,

primary production is relevant only in one part of the year and management efforts are concentrated in those months. Oligotrophication of lakes during productive months is based in efficient techniques such as sewage treatment, control of non point pollution sources, removal of nutrient-rich sediments or biomanipulation, among others.

In contrast, semiarid climate features constant high temperature and solar radiation, promoting primary production all year round. As long as nutrients are available, biomass growth can take place and outbreaks of algae or macrophytes frequently come about, enduring for long periods (Jeppesen et al., 2007).

In tropical systems top-down regulation has been showed to be ineffective, as often large colonies of cyanobacteria are dominant and inedible by zooplankton. Zooplankton communities in tropical systems are dominated by small-bodied rotifers, ciliates and nanoflagellates and lack large filter feeding cladocerans, reducing the importance of zooplankton on phytoplankton regulation (Sarmento, 2012). This means that bottom-up methods must be necessarily applied when aiming at reducing algae biomass (Jeppesen et al., 2007). An essential point in bottom-up strategy is that, in contrast to temperate lakes, often N is limiting factor for biomass growth (Rangel et al., 2012). In eutrophicated systems, high temperatures and the abundance of P foster the growth of algae and cyanobacteria. When N becomes limiting, N-fixing cyanobacteria succeed and dominate the system as long as P is provided, both by external or internal fertilization. Tropical lakes are hence more sensitive to eutrophication, thus making it necessary to exert stricter control on both P and N input (Lewis, 2000; Rangel et al., 2012). Additionally, the control of both external and internal nutrient loads should be the target of any management tool in these systems.

The proliferation of invasive species in lakes and reservoirs worldwide has been reason for numerous ecology studies and financial efforts on restoration programs. The control of massive growth of macrophytes is possible by reducing nutrients availability in these systems. For that, control of pollutions sources, regulation of land use and conservation and reforestation of riparian areas are targets to achieve. However, in a short-term perspective, other measures are usually applied, as the former require inter- institutional actions, planning and economical costs, which can only be expected in a long-term integrated program (Thomaz and Bini, 2003).

For short and mid-term solutions, the control of macrophytes generally relies in chemical, biological and/or mechanical strategies.

### *Chemical treatment*

The treatment of macrophytes blooms with herbicides has been broadly used worldwide. However, the efficiency of these treatments is very dependent on the type of water body and water uses. In Brazil, this method is not been extensively used due to the risk of cumulative toxic effects in aquatic life and also the low availability of allowed herbicides to be used in the combat of submerged species like *Egeria densa* (e.g. fluoridone) (Moura et al., 2007). In addition, herbicides do not always solve the problem, as decomposition take space inside the waterbody with consequent eutrophication processes. Moreover, this is not a definitive measure as macrophytes blooms often recur.

### *Biological methods*

Biological control represents one of the most interesting solutions for macrophytes management, because of the low environmental risk and the possibility of long term solution. Nevertheless, the efficiency of this control depends very much on the characteristics and diversity of the region. The use of exotic species is not recommendable for the risk of invasiveness and food web disturbance, subsequently more complicated to solve. Thus, suitability of native species of each region should be previously tested, which implies preceding studies.

Currently, some efforts are being made by research institutes studying Jupia reservoir in the Paraná River (São Paulo – Brazil). Control agents involving fungi *Fusarium graminearum* and *Cercospora*

spp, insects *Paraponyx* sp. and *Neochetina eichhorniae* or endemic fishes (*Schizodon* sp, *Piaractus mesopotamicus*) are being considered promising possibilities (Thomaz and Bini, 2003). However, regional studies are necessary for each case, as native species vary between the different river systems.

#### *Mechanical removal and use*

In small aquatic ecosystems, mechanical removal of free-floating macrophytes is the main control measure applied, mainly in tropical areas (Bicudo et al., 2007). Besides removing the plant from the water body, a great amount of nutrients enclosed on their biomass is also removed, concomitantly improving the trophic state of the system.

The harvest of macrophytes can be performed with several techniques, from simple removal by hand to large-scale cutting with mechanical weed harvesters.

The characteristics of the site and access points (e.g. size, depth, flow) are determinant on the method of choice, together with the species, life form and density of the macrophyte being harvested. Although disturbance of the system by habitat destruction is unavoidable, other ecological impacts should be taken into account, such as removal of organisms living in the stands, sediments suspension or turbidity increase, potentiating unwanted eutrophication processes. The harvesting of macrophytes is worthwhile if there is a final destination for the plant, turning the process economically viable. Some studies have been focusing on the use of cropped macrophytes as potential substitutes to fertilizers, animals feed, biogas production, among others (Quilliam et al., 2015). The suitability to each final destination depends mostly on the nutrient composition, decomposition rates and water content of the plant.

In any case, invasive macrophytes removal from a system should consider the presence of endemic species with important traits on the ecosystem and which by their ecological importance must be preserved (Thomaz and Bini, 2003). The Brazilian semiarid has a very unique biome, despite the low recognition in terms of biodiversity (only few studies on natural systems ecology) of riparian areas. The resulting low interest and knowledge is one of the main threats for their conservation (Maltchick and Medeiros, 2006). Therefore, the study and understanding of macrophytes role on ecological processes in these systems is essential for management and well-grounded decision making.

Moreover, it is a distinctive feature of South American reservoirs that most of the invasive plants are native species (Thomaz et al., 2008). This implies a change of paradigm in terms of management, as the plants to control are not exotic but natural components of a disturbed system.





---

### **3 Study site and methodology**



### 3.1 Study area

Itaparica Reservoir (also known as Luiz Gonzaga reservoir) is located in the semiarid Brazil, in the São Francisco River (Fig. 3-1). The spring of this long river (2900 km) is located in the southwest state of Minas Gerais. It initially flows towards north and then changes to a west-to-east direction, crossing 6 different states, until it reaches the Atlantic Ocean (in the border between the states of Alagoas and Sergipe) (Tortajada, 2016). Itaparica reservoir is situated in the lower-middle stretch of the river, in Northeast Brazil between the federal states of Pernambuco and Bahia (INNOVATE, 2015). It is located from 8°38'14.99 S to 9°08'34.27" S and from 38°58'44.52 W to 38°11'45.81" W, at 312 Km away from the river mouth.

Itaparica reservoir is a flow through reservoir with the shape of the former river bed. It includes very heterogeneous ecotones due to the many bays formed along its dendritic and sinuous contour. These bays are normally less affected by water currents and therefore present distinct environmental features.

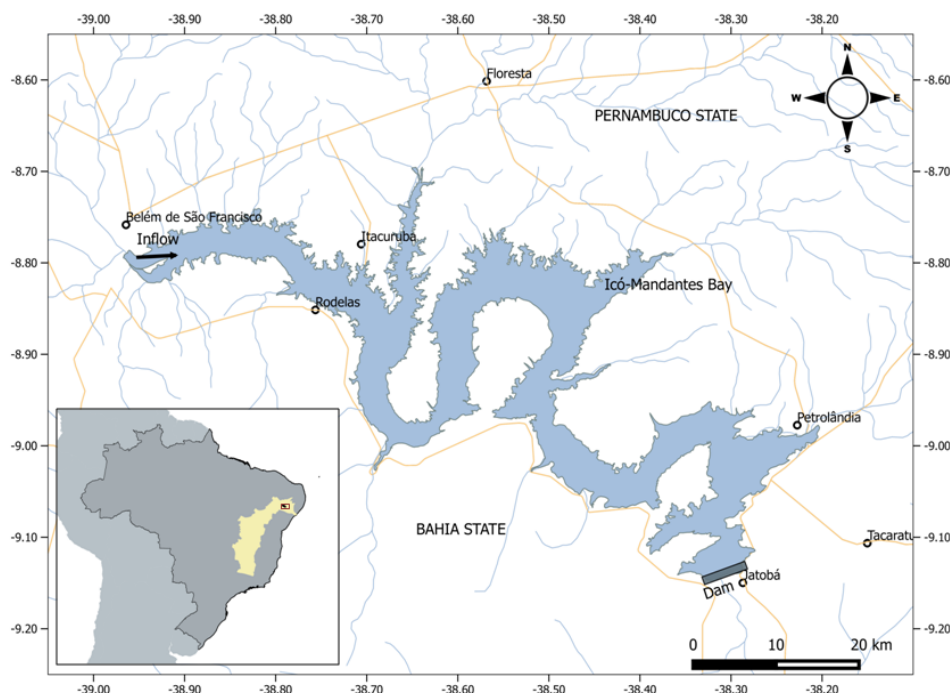


Fig. 3-1 Location of São Francisco river basin and of Itaparica reservoir in Northeast Brazil.

Itaparica reservoir is a hydropower reservoir operated by the HydroElectric Company of the São Francisco (CHESF) and it is the third of a reservoir cascade in this river. The main morphometric characteristics of the reservoir are listed in Table 3-1.

The climate in Itaparica reservoir area is typical of Brazilian semiarid region, which is characterized by an average annual precipitation lower than 800 mm, aridity index below 0.5 (water balance between precipitation and evapotranspiration for the period between 1961 and 1990) and a chance of drought greater than 60% (estimations based on the period between 1970 and 1990) (Barbosa et al., 2012). Additionally, in this region, the thermal amplitude is low, with temperatures above 25 °C throughout the year and there is a high spatial and temporal variation in precipitation, with a marked and intense rain season.

Regardless of the regional water scarcity due to a semiarid climate, Itaparica reservoir has hydropower production purposes, and thus is submitted to high mean water flow rates of 2060 m<sup>3</sup> s<sup>-1</sup>, regulated by operational demands. Consequently, this reservoir is characterized by seasonal water level fluctuations

of up to 5 m (between a minimum operational level of 299 m a.s.l. and a maximum of 304 m a.s.l.). Water level decrease occurs in September/October during dry season and refill of reservoir takes place from March onwards during rain season.

Table 3-1. Morphometric characteristics of Itaparica reservoir at high water level (304.5 m a.s.l.).

<b>Morphometry</b>	<b>Itaparica reservoir</b>
Length	145 km
Surface area	828 km <sup>2</sup>
Total volume	10 782 Hm <sup>3</sup>
Active volume	3 549 Hm <sup>3</sup>
Maximum depth	42 m
Mean depth	13 m
Sub-basin area	93 040 km <sup>2</sup>
Outflow (regulated)	2 060 m <sup>3</sup> s <sup>-1</sup>
Theoretical residence time	61 days
Operational lake level variation	299 – 304.5 m a.s.l.
Hydropower capacity	1 480 MW

## 3.2 Analyses of monitoring data

Limnological analyses in the Itaparica reservoir are periodically performed by the hydropower company CHESF, as means of water quality monitoring (once per trimester from 12/2007 to 09/2010). The monitoring survey comprises a total of 12 sampling stations from inflow until the dam site. The present study analyzed the available data regarding water quality parameters and phytoplankton composition and abundance in the period between December 2007 and September 2010.

### 3.2.1 Climate and hydrological data

Firstly, meteorological and hydrological datasets were analyzed in order to characterize each of the sampling seasons. The closest active weather station is located in the municipality of Floresta-PE, about 30 km distant to Itaparica reservoir. Data of air temperature and wind were collected online from the Instituto Nacional de Pesquisas Espaciais database (INPE, 2015) and of rainfall from Agencia Pernambucana de Águas e Clima (APAC, 2015). Data of the average monthly water level and water flow rate were obtained from Operador Nacional do Sistema Elétrico (ONS, 2015). Theoretical residence time was calculated based on daily data of water flow rate and volume of the reservoir provided by APAC.

### 3.2.2 Sampling stations

A total of nine sampling stations were selected to provide a spatial characterization of the reservoir. Fig. 3-2 shows 8 stations in the main stream along the reservoir and one station in a lateral compartment (Icó-Mandantes Bay - ITA 07), which are listed in Table 3-2.

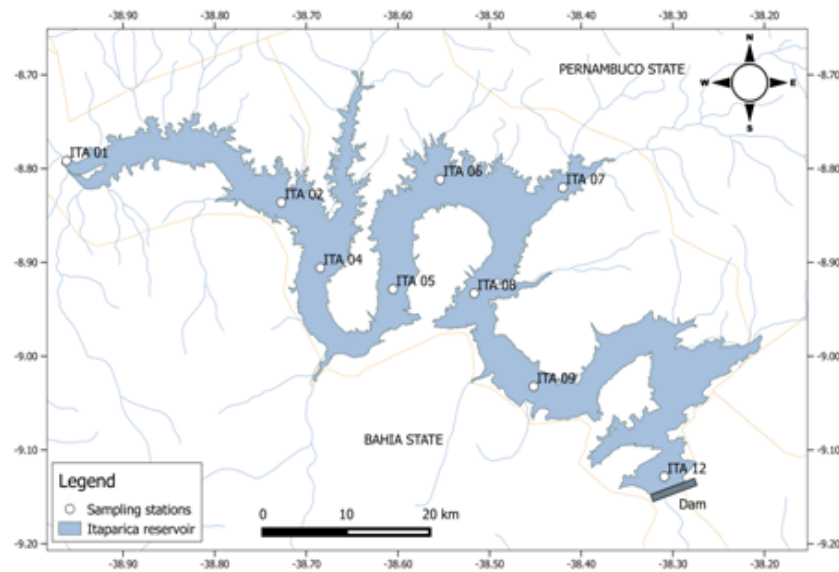


Fig. 3-2 Location of sampling stations in Itaparica reservoir of monitoring data from CHESF (2007-2010) considered in this study.

Table 3-2. Short description of the location of the studied sampling stations in Itaparica reservoir in the period 2007-2010.

Name	Latitude	Longitude	Reservoir section	Distance from inflow (km)
ITA 01	8°47'30.138 S	38°57'41.958 W	Inflow	0
ITA 02	8°50'9.737 S	38°43'38.150 W	Upper -middle	28
ITA 04	8°54'20.963 S	38°41'5.082 W	Upper -middle	38.2
ITA 05	8°55'42.776 S	38°36'19.372 W	Upper -middle	56.9
ITA 06	8°48'41.742 S	38°33'14.015 W	Lower -middle	72.5
ITA 07	8°49'12.407 S	38°25'11.748 W	Icó-Mandantes bay	82.9
ITA 08	8°55'58.321 S	38°31'0.242 W	Lower -middle	92.1
ITA 09	9°1'56.136 S	38°27'6.854 W	Lower -middle	107.6
ITA 12	9°7'42.262 S	38°18'33.494 W	Dam	143.5

### 3.2.3 Water quality

Water quality of Itaparica reservoir was assessed in each of the sampling stations at the surface and bottom of the water column. Overall, the mean values of the different parameters for surface water quality illustrate a reservoir with relatively low trophic state (Table 3-3). Water temperature and pH are high throughout the year, and water is well oxygenated. Transparency range is large but chlorophyll *a* (Chl *a*) is, in average, low. Total phosphorous (TP) and dissolved inorganic nitrogen (DIN) ranged between very low to intermediate values. The low calcium and magnesium concentrations are proper of soft water and in contrast to other semiarid reservoirs (Azevêdo et al., 2015), conductivity is very low.

The methodology used to analyse water quality parameters is described in monitoring reports from CHESF (CHESF, 2011).

Table 3-3. Annual median and quantiles Q25 and Q75 of water quality parameters in the main stream of Itaparica reservoir between December 2007 and September 2010.

Water quality parameter	Median	Q25-Q75
T (°C)	27.1	25.6-28.3
Conductivity ( $\mu\text{S cm}^{-1}$ )	67.0	63.0-70.0
Dissolved Oxygen ( $\text{mg L}^{-1}$ )	7.7	7.3-7.9
pH	7.9	7.7-8.2
TP ( $\mu\text{g L}^{-1}$ )	50.9	33.5-84.4
DIN ( $\mu\text{g L}^{-1}$ )	56.1	33.2-97.7
Chl <i>a</i> ( $\mu\text{g L}^{-1}$ )	2.6	1.5-3.3
Secchi depth (m)	2.5	1.9-3.5
Ca <sup>2+</sup> ( $\text{mg L}^{-1}$ )	6.17	1,44**
Mg <sup>2+</sup> ( $\text{mg L}^{-1}$ )	2.14	0,79**

\*\*standard deviation

### 3.2.4 Weather and hydrological conditions

The flow rate in the reservoir changes seasonally, depending on the water quantity and demand for power production. Fig. 3-3 illustrates hydrology (water level and flow rate) and weather conditions (rain and air temperature) in the reservoir in the monitoring period (between December 2007 and September 2010).

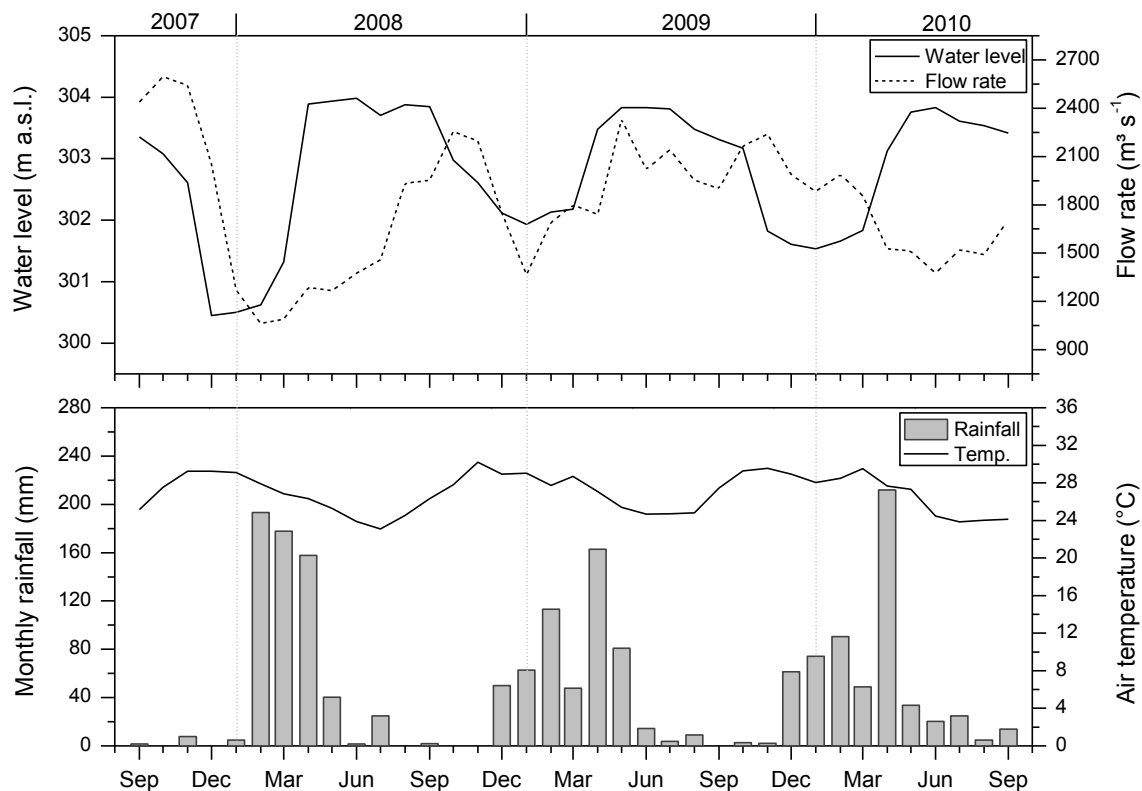


Fig. 3-3 Monthly mean values of water level, flow rate, rainfall and air temperature in Itaparica reservoir between September 2007 and December 2010.

### 3.2.5 Phytoplankton

#### 3.2.5.1 Sampling and counting

Sampling campaigns took place quarterly from December 2007 to September 2010. The field work was carried out during 1-2 days expeditions in 2007 (December), 2008 (March, June, September and December), 2009 (March, June, September and December) and 2010 (March, June, September). Sampling campaigns in December took place before beginning of rain season.

Integrated phytoplankton samples were taken in the euphotic zone, using conical plankton nets of 25 µm mesh size and the filtrated volume calculated after the equation:

$$V = Area \times depth$$

The abundance of phytoplankton was determined with the Utermöhl technique, by organisms counting in sedimentation chambers.

#### 3.2.5.2 Diversity index

Phytoplankton diversity was estimated using Shannon's Index:

$$H = - \sum_{i=1}^n \rho_i \ln \rho_i$$

where  $\rho_i$  is the proportion of individuals in the sample belonging to  $i$ th species.

#### 3.2.5.3 Data treatment

Data was processed and analyzed by descriptive statistics and correlations with linear regression using the software OriginPro 9.0. Significant differences between populations were assessed with paired sample t-test. Level of significance for all tests considered a p-value < 0.05.

### 3.2.6 Macrophyte richness

The biodiversity of macrophytes in the region of the lower-middle São Francisco river basin was assessed by examination of the public scientific reports of a large scale limnological survey (UFPE, 2012) carried out in the influence area of the Itaparica hydroelectric reservoir. Between years 2009 and 2011, different environments in the riverine landscape, such as the main course of the São Francisco River, several small dams, and tributaries were monitored. Macrophytes presence was registered in 19 sampling stations located in the stretches of tributaries of the main river, with only 3 stations located in the main course of the São Francisco River, upstream from Itaparica reservoir (~ 50-100 km).

## 3.3 Field campaigns

Four field campaigns took place in the study site of INNOVATE project, Icó-Mandantes bay, between 2012 and 2014. In comparison to the deep main channel of the reservoir, Icó-Mandantes bay is a shallow section of the reservoir, which by its spatial positioning has low hydrological connectivity with the main stream. The main morphometric characteristics of this bay are described in Table 3-4. The hypsographic curve of the bay can be consulted in Fig. A - 1, in addition to water depth categories information in Table A - 1.

In Icó-Mandantes bay (038°23'W/08°48'S) are located pumps for water abstraction for irrigation agriculture schemes and drinking water supply of the surrounding villages. In the inner part of the bay,

is located an intermittent rivulet (Riacho Mandantes) and drain channels which during rainy season transport nutrients from the watershed and agriculture fields into the bay. Here is also located one of the transfer channels of São Francisco River which will divert water to other dry regions in the north of Brazil.

Table 3-4. Morphometric characteristic of Icó Mandantes bay at 304 m a.s.l.

Morphometry	Icó-Mandantes bay
Length	13.7 km
Surface area	25.1 km <sup>2</sup>
Total volume	166.7 Hm <sup>3</sup>
Active volume	98.7 H m <sup>3</sup>
Max depth	22 m
Mean depth	6.8 m
Sub-basin area	874.7 km <sup>2</sup>
Shoreline length	42.4 km

### 3.3.1 Rainfall and water level

Field campaigns took place in September 2012, March 2013, October 2013 and June 2014. Precipitation and water level during this period are described in Fig. 3-4. Rainy season was very weak throughout 2012 (total of 105 mm) and in 2013 (total of 118 mm) without a truly defined wet period. Rain season in 2014 was more intense: in December 2013, a very strong event occurred with a rainfall of 178 mm. From January to May 2014 rainfall accounted for 276 mm.

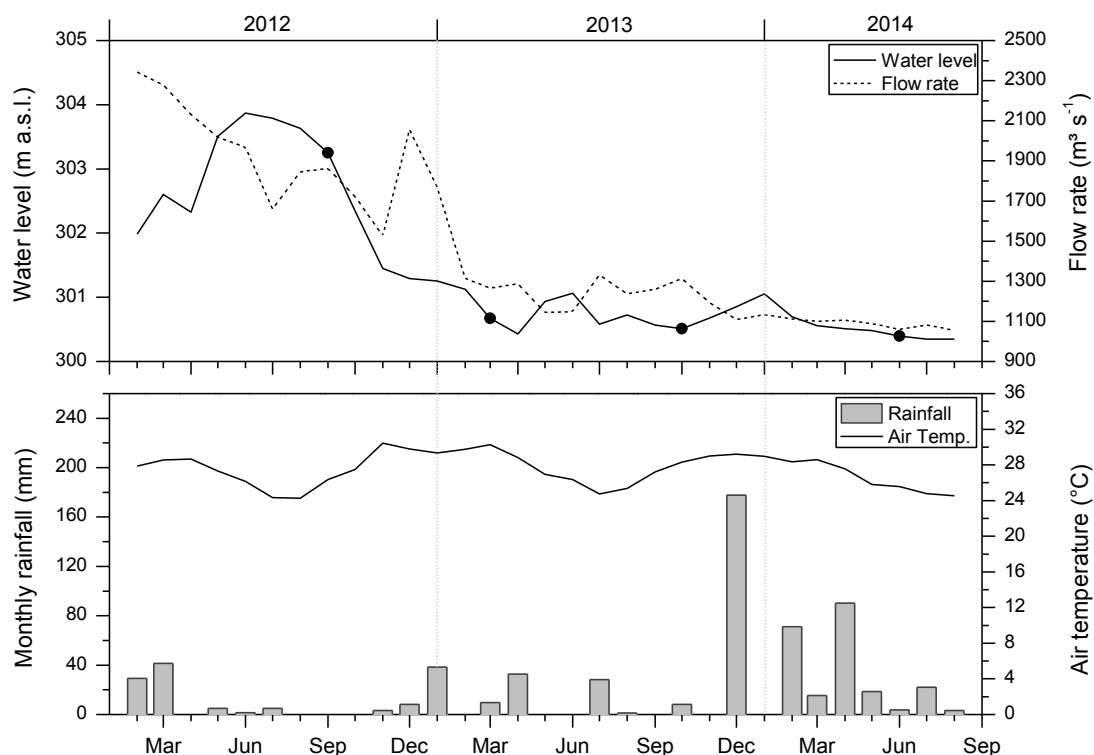


Fig. 3-4 Monthly mean values of water level, flow rate, rainfall and air temperature in Itaparica reservoir region between January 2012 and September 2014. Field campaigns in September 2012, March 2013, October 2013 and June 2014 are indicated with black points along water level line.



In September 2012 the water level was high, and few months after Itaparica reservoir experienced the usual water level drawdown. Due to a severe drought affecting the entire region of São Francisco river basin, water level was maintained low during 2013 and 2014 as a consequence of water scarcity (Fig. 3-4). Therefore, opposing to the regular water level regime, in the months following March 2013 water level did not increase again.

Thus, sampling campaigns took place two times during the regular cycle: high water level in dry season (September 2012) and low water level in wet season (March 2013). The other two sampling campaigns took place during exceptional drought conditions: dry season (October 2013) and end of wet season (June 2014) (Fig. 3-4).

### 3.3.2 Phytoplankton sampling and counting

Phytoplankton was sampled in 6 stations located in a longitudinal axis along the bay (Fig. 3-5 and Table 3-5) from the interior of the bay towards the main stream. Additionally, in each of these points, vertical sampling was executed at 0.5, 1, 2, 3.5, 5, 7.5 and 10 m water depth, and at deeper layers (from 10 m depth on) a 5 m interval down to a maximal depth of 30 m was applied.

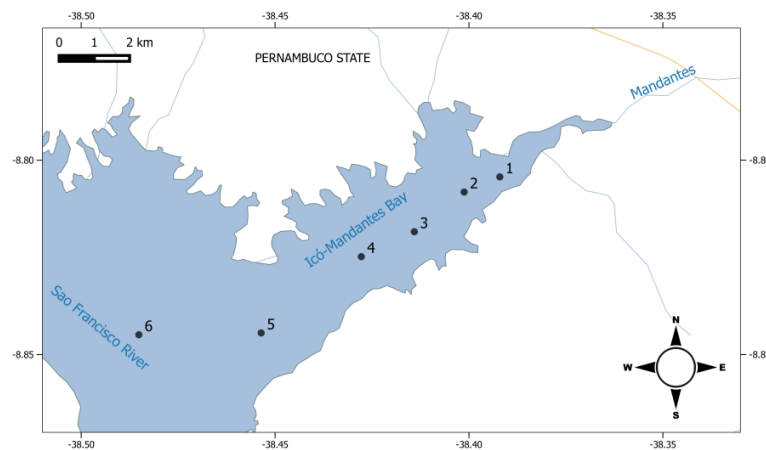


Fig. 3-5 Location of sampling stations of phytoplankton in Icó-Mandantes bay in the period 2012-2014.

Table 3-5. Short description of phytoplankton sampling stations in Icó-Mandantes bay.

Name	Distance from inflow in inner bay (km)	Relative position	Coordinates	
1	0.8	inner	S8°48,258'	W38°23,523'
2	1.9	inner	S8°48,492'	W38°24,075'
3	3.7	central	S8°49,104'	W38°24,846'
4	5.3	central	S8°49,489'	W38°25,666'
5	8.9	outer	S8°50,666'	W38°27,216'
6	11.3	main stream	S8°50,694'	W38°29,108'

Phytoplankton samples were preserved with Lugol's iodine solution and subsequently analyzed in laboratory for species identification using specified algal systematic literature. Phytoplankton abundance was determined using the Utermöhl technique, by cell counting in sedimentation chambers.

Phytoplankton cell density data was processed and analyzed by descriptive statistics and correlations with environmental factors with linear regression. Level of significance considered for all tests considered a p-value < 0.05.

### 3.3.3 Macrophytes

#### 3.3.3.1 Macrophyte biodiversity and maximum colonization depth

Macrophyte community in Icó-Mandantes bay was assessed for diversity richness and abundance by acoustic and dredging methods in the four field campaigns.

For diversity assessment, transects from the left to the right margin of the bay were performed with a rake for shallower areas or with an Ekman-Birge bottom-sampler with grasping area of 225 cm<sup>2</sup> (Hydrobios) in deep areas with very low biomass. Three transverse transects were executed in each of the sampling campaigns: one in the inner bay, one in the central bay and another in the outer bay.

Acoustic observations of submerged macrophytes (Fig. 3-6) were made at 296, 428, 188 and 647 geographic positions (September 2012, March 2013, October 2013 and June 2014, respectively), covering the whole bay area and all depth zones, and with main emphasis on areas with vegetation. For acoustic detection a sonar device from Lowrance (model Elite 4 DSI) was used. Geographic location on the sampling points can be found in Fig. A - 2.

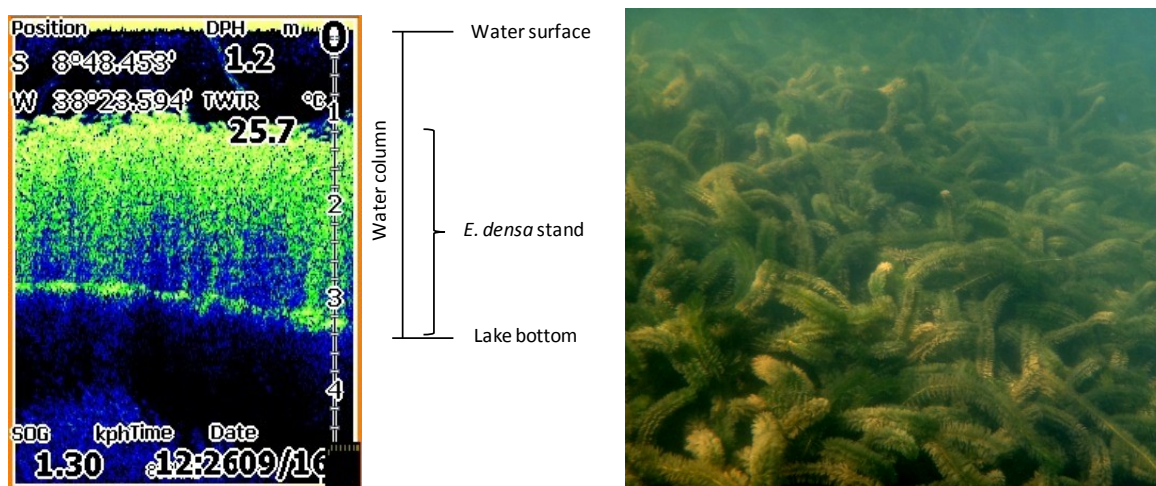


Fig. 3-6 Submerged *Egeria densa* stands in Icó-Mandantes bay: (A) Example of the spectrum obtained in the acoustic surveys, depicting a stand of *E. densa* with approximately 2 m height. Green and black/blue colours correspond to plants and sediment signals, respectively. Scale on the right side of the picture: water depth in meters; (B) Photo of stands of *Egeria densa* underwater which provide such acoustic spectrum.

In regions without visibility from the boat, plants were manually sampled with a rake for species determination. Maximum colonization depth ( $Z_{\max Ed}$ ) and plant volume inhabited (PVI) were determined according to Søndergaard et al. (2010).

Graphic representations were obtained with Origin 9.0 and open source geographical information systems software Quantum GIS 2.8 (2014). *E. densa* distribution was obtained with Inverse Distance Weighted (IDW) interpolation.

### 3.3.3.2 Taxonomic classification

Exsiccatates of the plant species observed in the study area were sent to IPA (Instituto Agronomico de Pernambuco) and Univasf (Universidade do Vale S. Francisco – Petrolina, PE) and classified by semiarid botany experts.

### 3.3.3.3 Biomass

#### i) Determination by quadrat method

Biomass of *E. densa* was assessed using a quadrat (0,5 m x 0,5 m) in randomly chosen sampling sites along the Itaparica bay (interior part, central part and mouth of the bay; n=16). Plants were carefully washed and left drying until constant weight.

#### ii) Determination by data analyses

Biomass of *E. densa* in the bay was calculated with a model developed during the study and presented in the results section, which is based on study site data and establishes a correlation between *E. densa* biomass and stands height:

$$\text{Biomass (g}_{\text{dw}} \text{ m}^{-2}) = 11.220 \times \text{stands height (cm)} \quad (r^2 = 0.9876) \quad (\text{eq. A})$$

To obtain such model, the biomass density (mean 370 g m<sup>-2</sup>, n = 16) measured with quadrat method in October 2013 was plotted against the mean length of plant shoots inside the quadrats. The resulting linear regression, which corresponds to a shoots density of *E. densa* of 780 shoots per m<sup>2</sup>, was used for biomass calculation at different water depths. At each water depth (1, 2, (...), 7 m), the median stands height was calculated and biomass assessed. Biomass of *E. densa* in the bay was calculated based on the bathymetry of the bay and the frequency of occurrence of *Egeria densa* stands per water depth category.

### 3.3.3.4 Growth rate

Methodology for growth rate experiments was adapted from Carrillo et al. (2006). In June 2014, boxes were placed in situ hanging at 1 m, 2 m, 3 m, 4 m and 6 m water depth, containing freshly collected sediments from the bottom of a stand of *E. densa* and 20 similarly aged shoots per box. The shoots were marked with colored bands at 10 cm from the apex after an adaption phase of 6 days, and measured again after 14 days of exposition. Growth rate based on shoot length was determined after Thomaz et al., (2007).

Growth rate per square meter was determined based on equation (eq. A), which considers a shoot density of 780 shoots per m<sup>2</sup>. Doubling time and reproduction rate of *E. densa* at 2 m water depth were calculated with a standing biomass of 673 g m<sup>3</sup> (mean biomass measured in June 2014 in areas with 2 m water column).

Statistical differences between mean growth rates at different water depths were assessed with One-Way ANOVA and Tukey tests.

### 3.3.3.5 Nutrients assessment

*Egeria densa* was dried in a stove at 60 °C until constant weight (n=15). The chemical composition of *Egeria densa* was assessed with a first step of digestion in a pressure bomb (DIN 13805). For that, 3.0 ml nitric acid (70 %, p.a.) were added to 200.0 ± 0.010 mg of grounded dry sample and digested for 1 hour at 100 °C and 3 hours at 180 °C. After cooling, digested suspension was diluted to 50 ml with Millipore water and analyzed. TP was analyzed following EN ISO 15681:2001, using Flow Injection Analyses (FIAstar 5000 Analyzer Foss Tecator). Iron (Fe<sup>2+</sup>) and Manganese (Mn<sup>2+</sup>) were analyzed by

Atomic Absorption Spectrometry (AAAnalyst 400 Varian) following DIN 38406. Heavy metals Cd, Cr, As and Pb were analysed after EN ISO 15586:2003, with Atomic Absorption Spectrometry (PinAAcle 900Z – Graphite tube AAS).

TC and TN content were analyzed by CN analyzer (Elementar Vario EL III). For that,  $2.7 \pm 0.4$  mg dry weight of *E. densa* were weighted and analyzed regarding the instructions DIN ISO 10694 and DIN ISO 13878, respectively.

Canopy, middle stem and lower stem of each sample were examined separately. A weighed mean (20 % canopy, 60 % middle section and 20 % low section of the stem) was used to calculate mean plant nutrient content. Differences in mean nutrients content in the canopy, middle and low sections of the stem were tested statistically with One-Way ANOVA and Tukey tests.

#### 3.3.3.6 Chlorophyll *a* assessment

Chlorophyll *a* quantification in *Egeria densa* stems and leaves was adapted from the German standard methods (DEV L16, 1985), using  $200.0 \pm 1.0$  mg fresh weight of *E. densa* ( $n = 45$ ).

### 3.3.4 Sediments

#### 3.3.4.1 Sampling method

Samples of permanently underwater sediments were taken by a grab-sampler according to Ekman-Birge with grasping area of 225 cm<sup>2</sup> and 20 cm height (Hydrobios) and stored in the dark at 8 °C. These samples ( $n = 5$ ) were collected from different locations inside the Icó-Mandantes bay, at water depths where sediment never desiccates.

Desiccated samples ( $n = 45$ ) were taken along the dried margins of Icó-Mandantes at distinct vertical distances from the shoreline, with the purpose of collecting sediments with different desiccation ages (1, 2, 4, 5, 6 and 12 months desiccation time). The upper 3 cm layer was rejected in order to avoid chemical or biological contaminations.

#### 3.3.4.2 Grain size characterization

The grain size of sediments was analyzed according to DIN 18123, by sedimentation or sieving methods, depending on the type of sediment. Wet fine grain sediments were pre-sieved (0.125 and 0.063 µm mesh) and stirred with anti-coagulant (Na<sub>4</sub>P<sub>2</sub>O<sub>7</sub>). In a glass cylinder, the suspension was measured with a hydrometer and temperature recorded.

Dried sandy sediments were submitted to a sieving cascade between 2 and 0,063 mm.

#### 3.3.4.3 Water and organic matter content

Water content was quantified following DIN 12880. The organic content was measured as instructed by DIN 18128, with oven dried sample (105 °C). After ignition in a muffle furnace at 550 °C for 4 hours, samples were cooled down in a desiccator, weighted, and organic content calculated.

#### 3.3.4.4 Nutrients and elements

The chemical composition of the sediment was analyzed by digestion in a pressure bomb (DIN 13805). For that, 3.0 ml nitric acid (70 %, p.a.) were added to  $0.200 \pm 0.010$  mg of grounded dry sample and digested for 1 hour at 100 °C and 3 hours at 180 °C. After cooling, digested suspension

was diluted to 50 ml with Millipore water and analyzed. TP was analyzed following EN ISO 15681:2001, using Flow Injection Analyses (FIAstar 5000 Analyzer Foss Tecator). Elements  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$  were analysed following DIN 38406 by Atomic Absorption Spectrometry (Spektr. AA- 400 Varian).  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^{+}$  were analysed with Atomic Absorption Spectrometer-Flame (GBC 906 AA), following EN ISO 7980 ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) and DIN 38406 ( $\text{K}^{+}$ ).

TC and TN content were analyzed by CN analyzer (Elementar Vario EL III). Here,  $0.015 \pm 0.001$  g were weighted and analyzed regarding the instructions of DIN ISO 10694 and DIN ISO 13878, respectively.

### 3.3.4.5 Elution experiments

A method for sediments elution was optimized in the laboratory following DIN 19528. The sediments used in this experiment consisted of permanently flooded sediment and sediments desiccated *in situ* at the margins of Icó-Mandantes bay, at distinct topographic elevations in order to obtain samples correspondent to varied drying times (2.5 months, 4.2 months and 12 months desiccation time).

According to the standard method, water was pumped by a peristaltic pump into the base of the sediment cores with 5.5 cm diameter and 24 cm length (Fig. 3-7). For the inflow, tap water was used to mimic lake freshwater, as drinking water supply in Berlin is absent of chemical treatment. In addition, tap water was diluted with deionized water until a conductivity similar to the reservoir water was achieved ( $50 \pm 2 \mu\text{S cm}^{-1}$ ) in order to prevent unwanted side effects of high salts concentration. The inflow water content of TDN and TDP were measured for calibration purposes.

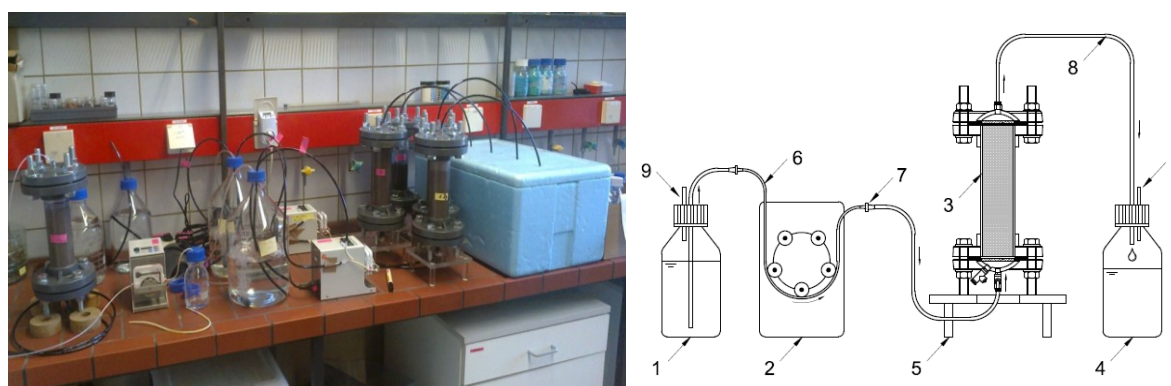


Fig. 3-7 Experimental set-up for elution analyses. 1) Eluent (water) ; 2) Peristaltic pump; 3) Sediment core; 4) Eluate; 5) Support plate; 6) Inflow tube; 7) tube connector; 8) Outflow tube; 9) ventilation tube.

In a first phase, the inflow water was pumped by a peristaltic pump at  $1.5 \text{ mL min}^{-1}$  for sediment saturation, until the emergence of the first drop of eluate in the collecting bottle. Afterwards, flow rate was set at  $0.65 \text{ mL min}^{-1}$ . The eluted water was collected in acid washed bottles placed in the cold inside a Styrofoam box, and analysed daily. The release of nutrients by these four sediments was measured during 6 days.

The collected effluent was filtrated (cellulose acetate membrane pore size  $0.45 \mu\text{m}$  from Millipore) to avoid contamination of suspended particles, and total dissolved nitrogen and total dissolved phosphorus were quantified using standard methods for water parameters (DIN EN ISO 11905-1 and EN ISO 15681:2001, respectively).

To evaluate the statistical difference between permanently flooded and desiccated sediments in terms of nutrients content and release rates, two sample t-tests were performed. The comparison between the

several dried sediments was assessed with One-Way ANOVA and Tukey tests. Level of significance for all tests considered a p-value  $< 0.05$ .

#### 3.3.4.6 Mean depth calculation in a 4 m water rise scenario

A scenario of a 4 m water level rise after March 2013 was considered. The mean water depth of the correspondent submerged area is 3 meters, calculated as the weighted mean of each depth category regarding the hypsographic curve of Icó-Mandantes bay (Fig. A - 1).

---

## 4 Results





## 4.1 Sampling seasons in Itaparica reservoir

Seasonal development of phytoplankton in water bodies is dependent on several drivers, related to climate (e.g. air temperature, solar radiation, precipitation) and hydrology (e.g. flow rate, water currents, water residence time, water level), which shape the physical – chemical parameters of the water. The regular annual variation of these drivers in Itaparica reservoir establishes the different environmental seasons, which eventually affect phytoplankton development.

### *Climate and hydrological parameters*

In the region of Itaparica reservoir there are two main meteorological seasons to be addressed: rain season and dry season. Rain season extends from the end of December until May (total of 350-400 mm accumulated rainfall) and dry season from June until December (total of 70 mm) (Fig. 4-1a).

Water level in the reservoir rises in April in the end of rain season (until 303-304 m a.s.l.), and is maintained high during dry season until October, when water level decreases to approximately 300 m a.s.l.. From November to March the water level is maintained low, and from January on, low water level is coincident with rain season (Fig. 4-1 b).

The annual mean of wind speed in Itaparica region is  $6.3 \text{ m s}^{-1}$ , with a mean maximum in September/October ( $7.6 \pm 3.3 \text{ m s}^{-1}$ ) during dry season and high water level and a minimum of  $5.1 \pm 2.8 \text{ m s}^{-1}$  in March/April, during rainy season and low water level (Fig. 4-1 c).

Typically, mean air temperature (Fig. 4-1 d) is high ( $27^\circ\text{C}$ ): hot season occurs between November and January with highest temperatures in December ( $29.5 \pm 4.3^\circ\text{C}$ ) and the cold season between June and August with lowest temperatures normally happening in July ( $24.1 \pm 3.6^\circ\text{C}$ ).

The flow rate of the water in the main stream of the reservoir fluctuates annually, according to Fig. 4-1 e. Although the discharge rate in the reservoir is determined to be  $2060 \text{ m}^3 \text{ s}^{-1}$  for hydropower purposes, between 2000 and 2012 the mean flow rate in the reservoir was  $1888 \pm 656 \text{ m}^3 \text{ s}^{-1}$ . The highest flow rates take place normally during rain season in the beginning of the year, with a mean maximum in February ( $2228 \pm 1360 \text{ m}^3 \text{ s}^{-1}$ ). Afterwards flow rate start declining and in June the lowest rates are detected with a mean of  $1664 \pm 372 \text{ m}^3 \text{ s}^{-1}$ , before gradually starting increasing again.

Because of the very high discharge rates characterizing this reservoir, the residence time of the water is in average only 65 days (Fig. 4-1 f). The lowest residence times occur during low water level and rain season, between December and March, particularly around December (mean of 58 days). Water residence time starts increasing in April when water level rises, reaching the highest values in June (mean of 77 days). Water residence time is maintained relatively high during high water level and is gradually reduced from September on. The low retention time and low water level are prolonged until March, when the reservoir is gradually refilled again and water residence time restarts increasing.

Sampling seasons were characterized according to the calculated monthly mean values (2000-2012) for climate and hydrological parameters:

### Rain season

1. Low water level (March) - it is the peak of rain season, the wind speed is generally low (mean of  $5.1 \pm 2.7 \text{ m s}^{-1}$ ), air temperature is high (mean of  $28.1 \pm 4.0^\circ\text{C}$ ) and because of the very high water discharge rates ( $2096 \pm 1069 \text{ m}^3 \text{ s}^{-1}$ ), theoretical residence time of the water is short, in the range of  $59 \pm 21$  days.
2. High water level (June) - end of rainy season, the reservoir is full in order to accumulate water for the dry season. The water flow rate is at the lowest ( $1664 \pm 372 \text{ m}^3 \text{ s}^{-1}$ ) and water residence time in this period is the highest measured in the year (mean of  $77 \pm 19$  days). In this time of the year, the air temperature has decreased to a mean of  $24.7 \pm 3.4^\circ\text{C}$ , and wind speed starts progressively increasing (mean of  $6.0 \pm 3.1 \text{ m s}^{-1}$ ).

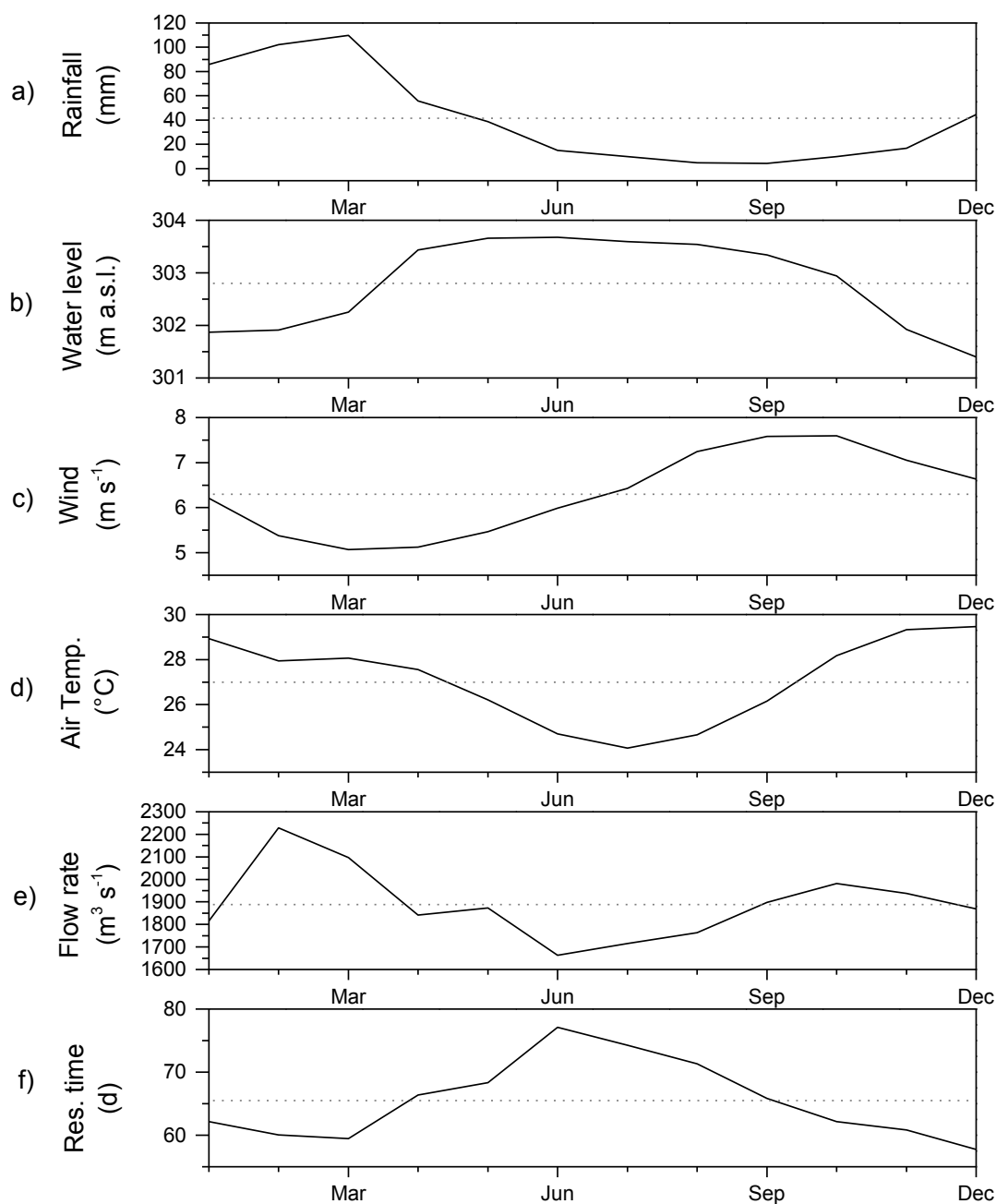


Fig. 4-1 Annual climate and hydrological parameters in Itaparica reservoir (monthly averages of the period 2000-2012. In c) and d) monthly average of the period 2002-2012. Dotted line represents annual average.

#### Dry season

1. High water level (September) - the flow rate is in average  $1898 \pm 398 \text{ m}^3 \text{s}^{-1}$  and water residence time  $66 \pm 14$  days. September is also characterized by lack of rain, low temperature ( $26.2 \pm 4.7 \text{ }^{\circ}\text{C}$ ) and increasingly higher wind speed (mean of  $7.6 \pm 3.3 \text{ m s}^{-1}$ ).
2. Low water level (December) – sampling campaigns took place right before beginning of rain season. In this period, wind speed begins to decline (mean of  $6.6 \pm 2.9 \text{ m s}^{-1}$ ) and mean air temperature is very high ( $29.5 \pm 4.3 \text{ }^{\circ}\text{C}$ ). Retention time in this time of the year is at the lowest with a mean of  $58 \pm 13$  days and high water flow rate ( $1869 \pm 429 \text{ m}^3 \text{s}^{-1}$ ).

### Water physical and chemical parameters

#### Water temperature and water column stratification

During hot period (between November and March), the relationship between water temperature and air temperature (mean of the previous 23 days) was high ( $r^2 = 0.7226$ ,  $p < 0.001$ ), and even higher during dry season ( $r^2 = 0.9839$ ,  $p < 0.001$ ) (Fig. 4-2). During rain season, for the same air temperature, water temperature was 1- 2 °C higher than in dry season, suggesting that rainfall may play a role on water temperature variation.

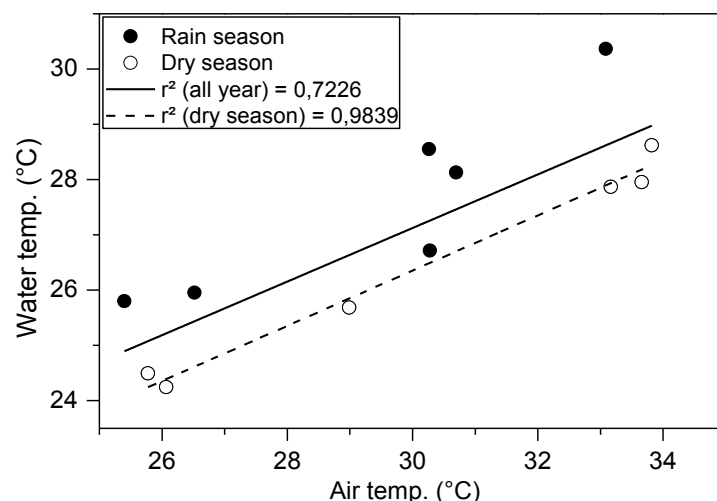


Fig. 4-2 Air temperature and rain as main factors affecting mean surface water temperature in the Itaparica reservoir.

Remarkably, at water temperatures above 27 °C, a proportional temperature difference between surface and bottom occurred, suggesting water column stratification ( $r^2 = 0.9285$ ,  $p < 0.001$ ). At water temperatures lower than 27 °C, this association was not apparent (Fig. 4-3). Accordingly, water column stratification (total or only partial) was considered when temperature difference between surface and bottom of the reservoir surpassed 1 °C. When below 1 °C, then mixing conditions were assumed.

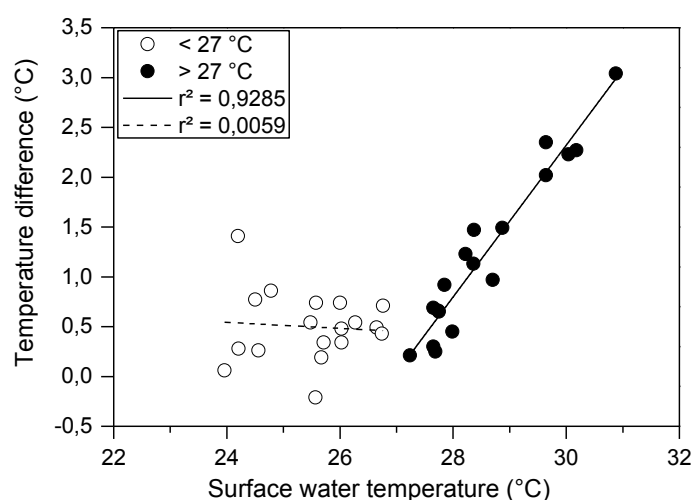


Fig. 4-3 Correlation between temperature of the surface water and temperature difference between surface and bottom of the reservoir (data of ITA 06, ITA 08 and ITA 09).

Water temperature and water level are moderately associated ( $r^2 = 0.6298$ ,  $p < 0.05$ ) (Fig. A - 3), with lower water temperature occurring during high water level. Although water level rise may in some extent promote temperature decrease, this relation is subjective as high water level period takes place during cold season (Fig. 4-1 b and d).

#### Water physical parameters during sampling campaigns

The characteristics of the surface water in the lacustrine zone (lower middle stretch- ITA 06, ITA 08 and ITA 09) of the reservoir in each season of the monitoring period are depicted in Fig. 4-4.

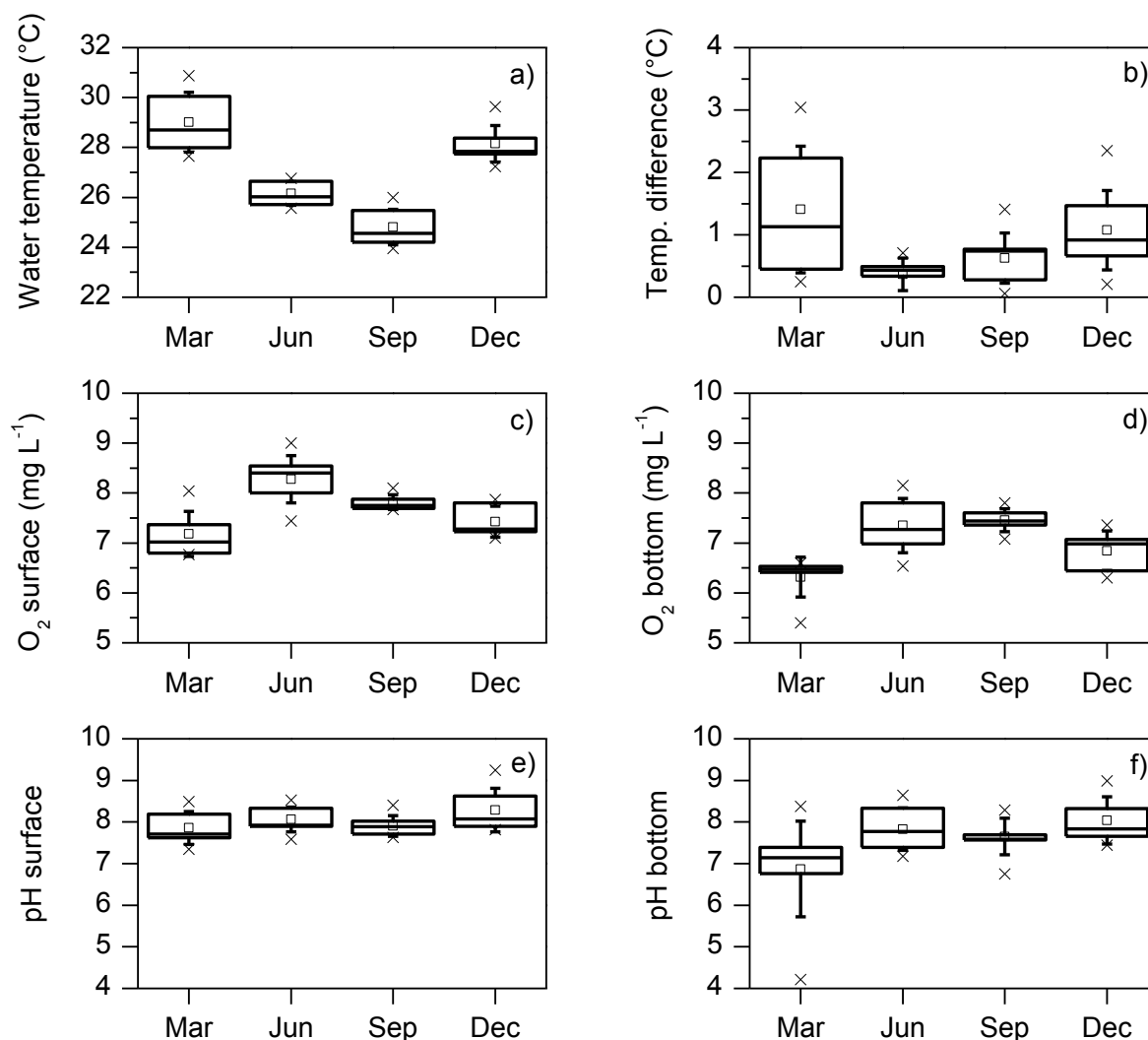


Fig. 4-4 Physical parameters of water quality in the lower middle stretch of Itaparica reservoir per sampling season (2007-2010). Box plot horizontal lines: Q25 (lower), Q50 (middle) and Q75 (upper); little square: mean; whiskers: standard deviation of the mean; cross: max. and min. values.

Water temperature was high in hot season (with a mean of 28.5 °C in December and March), and lower during cool season (mean of 25.5 °C in June and September) (Fig. 4-4 a). Hence, during low water level, high water temperatures potentiated water column stratification and water temperature differences between water column surface and bottom were higher, reaching a maximum of 3.0 °C in March 2010. In contrast, isothermal conditions during colder months (June and September - high water level period) potentiated mixing of the water column: a maximum difference of 1.4 °C was observed in September 2010 (Fig. 4-4 b).

Dissolved oxygen levels in the surface water were mostly above  $7 \text{ mg L}^{-1}$ , with highest values in June (Fig. 4-4 c).  $\text{O}_2$  concentrations at the bottom ranged between  $5.4$  and  $8.2 \text{ mg L}^{-1}$ , with a mean of  $7.0 \pm 0.6 \text{ mg L}^{-1}$  (Fig. 4-4 d). These are mostly conditions close to equilibrium with atmosphere near the surface ( $\text{O}_2$  solubility at  $24\text{-}31^\circ\text{C}$  is  $8.4\text{-}7.4 \text{ mg L}^{-1}$ , respectively) (Benson and Krause, 1984), suggesting an oxic environment across the water column. During mixing, oxygen is vertically well distributed, which is demonstrated by the highest mean values at the bottom in June and September. In March, oxygen levels were lowest, perhaps due to a higher content of decaying organic material inflowing during rain season and tendency to stratification.

The water in Itaparica reservoir is alkaline, as showed by the high pH values across the year (median  $\text{pH} = 7.9$ ) (Fig. 4-4 e). On the other hand, pH at the bottom relatively changed with the seasons, particularly during hot period: it was highest in December, during dry season, and lowest in March, rain season (Fig. 4-4 f). Organic material carried by rain accumulates in the hypolimnion due to a stratified water column. The mineralization of this material results in the production of  $\text{CO}_2$ . The high  $\text{CO}_2$  concentrations in the lower layers of the water column are likely to acidify the water in this period. High  $\text{CO}_2$  levels were also measured in the deeper layers of the reservoir by Rodriguez and Casper, (2017). In June, when vertical mixing takes place,  $\text{CO}_2$  is released to the atmosphere or taken up for algae growth and pH at the bottom increases again. The high pH observed in the end of dry season (December) might thus indicate  $\text{CO}_2$  deficiency in the system.

#### Water chemical parameters during sampling campaigns

##### 1) Nitrogen

During rain season in Itaparica region, N and P in both dissolved and particulate forms enter the reservoir by watershed surface runoff. Indeed, DIN reached highest concentrations in March (mean  $100 \mu\text{g L}^{-1}$  at the water surface) (Fig. 4-5 a). In June, DIN concentration was lower than in March (mean  $57 \mu\text{g L}^{-1}$ ) perhaps due to prior cell uptake, as algae density in June was usually high. DIN decreased gradually along the year, and lowest amounts were observed in the end of dry season, in December (mean of  $17.2 \mu\text{g L}^{-1}$ ). At the bottom of the reservoir the tendency was similar, although concentrations were generally slightly higher than at the surface (Fig. 4-5 b).

##### 2) Phosphorus

Regarding P availability, total phosphorus (TP) was highest during rainy season with similar values at the surface and at the bottom, probably by rain carried organic material from the watershed (Fig. 4-5 c and d). During rain season, mean TP concentrations were higher than during dry season, revealing the role of rain related processes on P load of the reservoir. Additionally, water level rise in April leads to an extra nutrient loading from organic material of submerged margins. Dissolved phosphorus (DP) concentrations in the water column disclose other processes (Fig. 4-5 e and f): in the peak of rain season (March), the higher concentrations at the bottom of the reservoir in comparison to the surface are indicative of deposition of organic matter during periods of thermal stratification, which is easily metabolized with the high water temperature typical of this season. In June, because of vertical mixing, these high values are uniform across the water column. In the dry season, DP concentration was lower, particularly in December. Inorganic phosphate (SRP) concentrations were generally low both at the surface and in the bottom of the reservoir, with mean concentrations slightly higher during rain season (March and June) (Fig. 4-5 g and h).

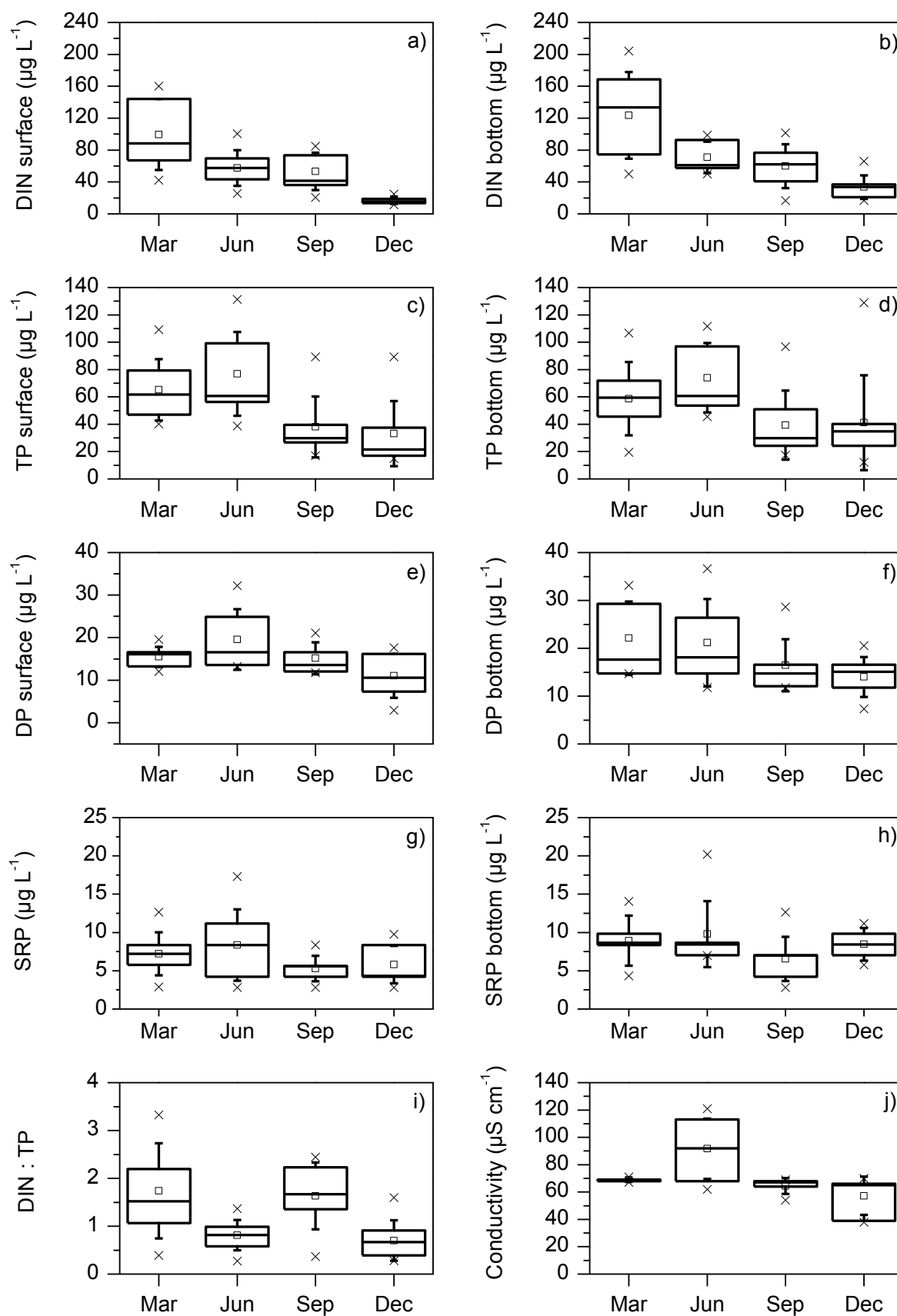


Fig. 4-5 Chemical parameters and conductivity of water quality in the lower-middle stretch of Itaparica reservoir per sampling season (2007-2010). Box plot horizontal lines: Q25 (lower), Q50 (middle) and Q75 (upper); little square: mean; whiskers: standard deviation of the mean; cross: max. and min. values.

### 3) DIN:TP

DIN:TP mass ratio was generally higher than 1.5 in March, which indicates N abundance in relation to P, as also verified by the high DIN concentrations measured (Fig. 4-5 i). In June, DIN:TP was generally lower than 1, confirming the previous consumption of nitrogen (allowed by the higher availability of dissolved P in this period) leading to N limitation in the system. In September, although DIN concentrations were similar to those in June, DIN:TP was commonly higher than 1.5, which indicates P depletion since then, confirmed by the generally low TP concentrations ( $38 \mu\text{g L}^{-1}$ ) in this time of the year. At last in December, despite the similar values of DIN:TP ratio as the ones observed in June (ranging between 0.3 and 1.6), DIN and TP concentrations were very low, suggesting generalized nutrients deficiency. This is probably the result of a combination of processes:

- Period subsequent to algae bloom – after a period of mixing and high biomass production, nutrients exhaustion takes place.
- End of dry season - absence of external nutrient load.
- Increasingly high discharge rates – flush out of residuals.
- Hot season with stratification of the water column – nutrient loss to the hypolimnion.

### 4) Specific conductivity

Water specific conductivity measures ions concentrations in the water (Fig. 4-5 j). Due to the type of soil in the reservoir basin, the water generally presents low minerals concentrations, including low calcium carbonate content, being thus classified as soft water (Table 3-3). Accordingly, conductivity in the reservoir was generally very low (mean  $71 \pm 18 \mu\text{S cm}^{-1}$ ), particularly in December ( $38 - 70 \mu\text{S cm}^{-1}$ ). In contrast, the highest values were observed in June, in the early phase of water column mixing, with maximum values of  $121 \mu\text{S cm}^{-1}$ . The high conductivity in this month reveals the presence of ions in the water column, possibly as by-products of mineralization of organic matter carried in during rain season. Therefore, conductivity variations in Itaparica reservoir may be majorly related to the availability of ionic forms of P, N and C (DP, SRP, nitrate, ammonium, bicarbonate, etc.).

## 4.2 Phytoplankton in Itaparica reservoir

### 4.2.1 Phytoplankton diversity

In the period from December 2007 to September 2010, phytoplankton community in the longitudinal channel of Itaparica reservoir consisted of a total of 133 taxa. The majority of species belong to the Chlorophyta taxonomic group (66), followed by the Bacillariophyta (27), Cyanophyta (25), Euglenophyta (7), Cryptophyta (5), Dinophyta (2) and Chrysophyta (1) groups. Euglenophyta, Cryptophyta, Dinophyta and Chrysophyta species occurred only sporadically. Although Chlorophyta was the richest class, the highest densities and relative abundances occurred within the Bacillariophyta group. A few phytoplankton species occurring in Itaparica reservoir are illustrated in Fig. 4-6. The most representative taxa in terms of steadiness are listed in Table 4-1.

Although usually in low densities (almost always less than  $3.5 \times 10^2 \text{ Org. mL}^{-1}$ ), *Pediastrum simplex*, *Pediastrum duplex* and *Cylindrospermopsis raciborskii* were always present in the reservoir. *Pediastrum* strains occurred particularly in the upstream monitoring stations and *C. raciborskii* was more often present downstream. Other much occurring species are the green algae *Planktosphaeria gelatinosa* which constantly occurred during rainy season, and the species *Fragilaria crotonensis*, *Oscillatoria* sp. and *Ulnaria ulna* which were always present in dry season.

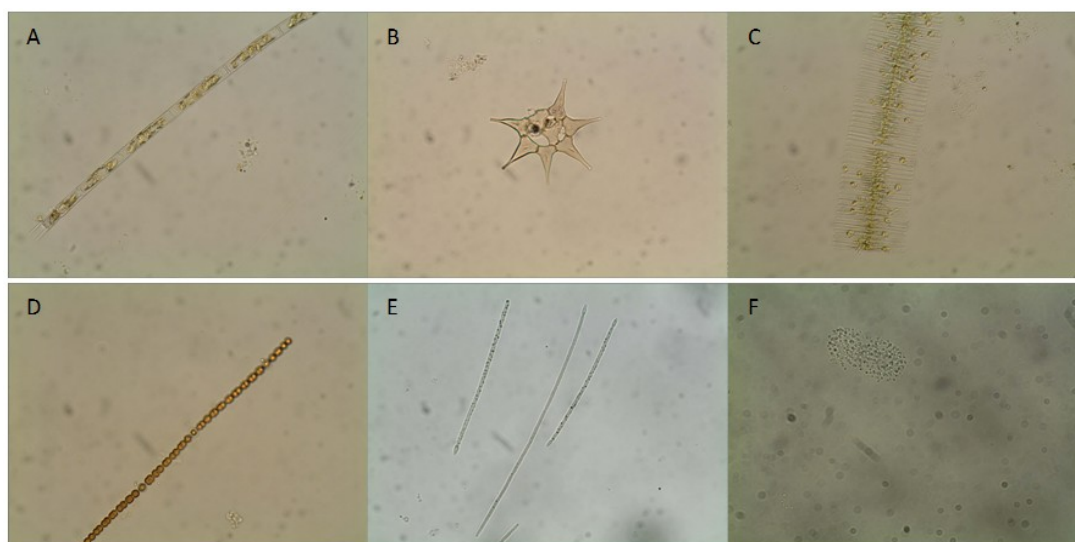


Fig. 4-6 Examples of phytoplankton biodiversity in Itaparica reservoir: A) *Aulacoseira* sp.; B) *Pediatrum* sp.; C) *Fragilaria crotonensis*; D) *Dolichospermum* sp.; E) *Cylandrospermopsis raciborskii*; F) *Aphanocapsa* sp.. Magnification 400X.

Table 4-1. Steadiest species in Itaparica reservoir. All year round: species which occurred in the reservoir in all sampling dates within the studied period in at least one sampling station. Season specific: species which always occurred in dry season or in rainy season.

Season	Dry (September and December)	Rainy (March and June)
All year round	<i>Cylandrospermopsis raciborskii</i> <i>Pediatrum duplex</i> <i>Pediatrum simplex</i>	
Season specific species	<i>Fragilaria crotonensis</i> <i>Oscillatoria</i> sp. <i>Ulnaria ulna</i>	<i>Planktosphaeria gelatinosa</i>

The relative contribution of the steadiest species to total algae density was often low, while other not so frequent species often dominated. Monodominance happened generally during high water level in downstream regions. The diatoms *Aulacoseira ambigua*, *Fragilaria crotonensis* and *Fragilaria capucina* reached more than 90 % of the total density in different occasions. Other sporadic dominances with more than 70 % of total density occurred during low water level: *Aulacoseira granulata* and *Planktosphaeria gelatinosa* in rainy season and the cyanobacteria *Cylandrospermopsis raciborskii* and the green algae *Sphaerocystis Schroeteri* in dry season.

## 4.2.2 Biodiversity index

Shannon's index is an indicator of diversity which considers not only the species richness but also the relative abundance of each species in the algae community. The highest the index, the better is the relation between high number of species and their evenness. In general, in Itaparica reservoir, diversity was high and alike along the reservoir during low water level. On the contrary, during high water level a gradient of decreasing diversity was observed from the inflow towards the dam region ( $p < 0.05$ ) (Fig. 4-7). In view of that, upstream region of Itaparica reservoir was characterized by annual high diversity, especially during low water level period. The highest diversity (2.53) took place in ITA 02



in March 2010: 10 Chlorophyta species with 61% biomass and 3 Cyanobacteria species with 24 % of biomass. Bacillariophyta (2 species) and Euglenophyta (1 species) occurred in lower proportions (9 % and 7 %, respectively).

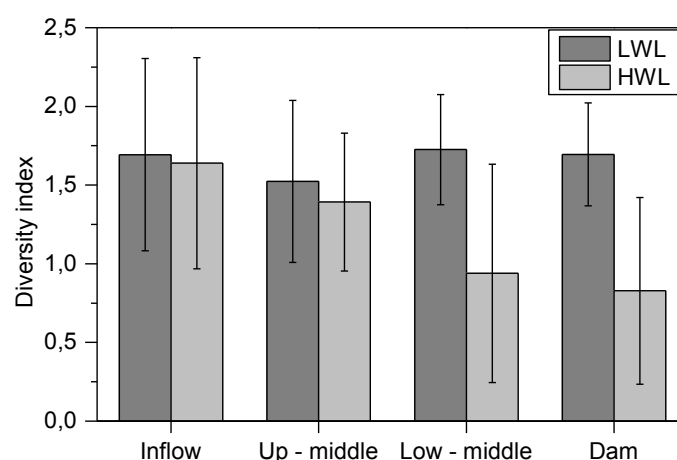


Fig. 4-7 Mean diversity in the four main sections of the reservoir (Shannon's index) during low and high water level (error bars represent standard deviation).

A major difference in floristic diversity during the two water level seasons was observed in the downstream regions of the reservoir (lower-middle and dam regions). Here, diversity was significantly lower during high water level ( $p < 0.05$ ) with Bacillariophyta as dominant group (dominant species were *Fragilaria crotonensis*, *Aulacoseira ambigua* and *Fragilaria capucina*). The lowest biodiversity index (0.22) was detected in June 2009 at the dam site (ITA 12). Only 2 species were present, with a share of 94 % of *Aulacoseira ambigua*.

## 4.2.3 Seasonal dynamics

### 4.2.3.1 Density of phytoplankton

Regarding biomass development, phytoplankton density changed temporally (intra- and inter-annually) and spatially along the Itaparica reservoir. Overall, in the 3 years monitoring period, the median density of phytoplankton inside the reservoir was  $9.3 \times 10^3$  Org. mL<sup>-1</sup>, ranging between a minimum of  $8.8 \times 10^2$  Org. mL<sup>-1</sup> in upper-middle stretch of the reservoir (ITA 04) in December 2009 and a maximum of  $6.6 \times 10^5$  Org. mL<sup>-1</sup> in June 2008 in the lower-middle section (ITA 08) (Fig. 4-8).

#### a) Low water level

The lowest algae concentrations were registered during low water level (mean of  $1.0 \times 10^4$  Org. mL<sup>-1</sup>). In general, in this period algae density decreased when entering the reservoir. In the dry season (December), high densities of phytoplankton inflowing did not subsist and decreased gradually along the reservoir. At the dam, algae concentration remained constant or slightly increased. In the lacustrine area, algae density was the lowest in an annual perspective, ranging between  $1.2 \times 10^3$  and  $8.2 \times 10^3$  Org. mL<sup>-1</sup>.

In rainy season (March) phytoplankton biomass also gradually decreased until the dam. However, the concentration in the last stretch of the reservoir ranged between  $2.0 \times 10^3$  and  $4.4 \times 10^4$  Org. mL<sup>-1</sup>, i.e., in some extent higher than in dry season. The higher biomass in rainy season is supported by a higher availability of nutrients in the water.

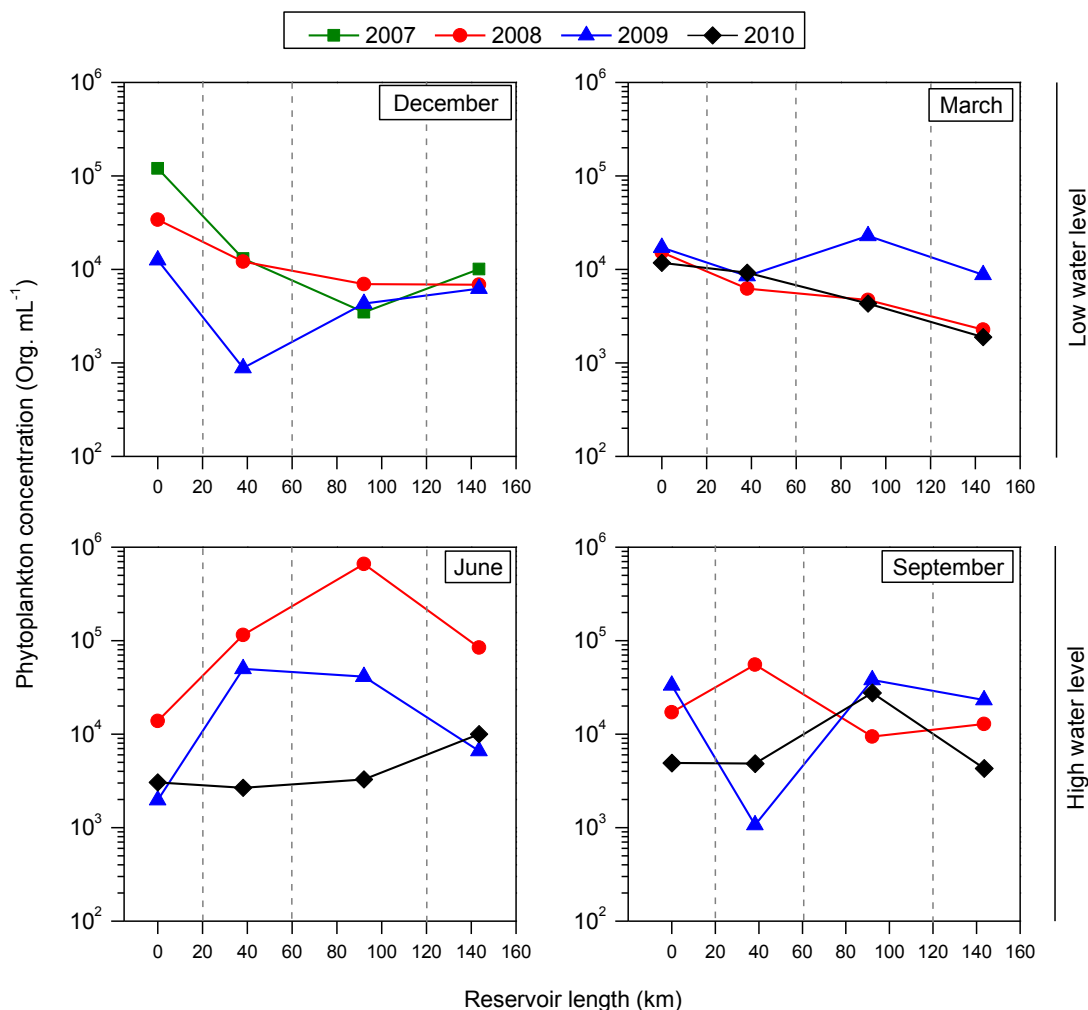


Fig. 4-8 Spatial dynamics of phytoplankton concentration along Itaparica reservoir in each sampling season. Data include total density at the inflow (ITA 01), upper-middle section (ITA 04), lower-middle section (ITA 08) and at the dam (ITA12).

#### b) High water level

The period of high water level was characterized by high algae densities (mean of  $1.0 \times 10^5$  Org. mL<sup>-1</sup>), particularly during rainy season (June). In this time of the year, phytoplankton concentration was usually relatively low at the beginning of the reservoir and successively increased along the transition zone (upper and lower middle section), reaching high densities in 2008 around ITA 08 (92.1 km). Annually, the highest phytoplankton concentration in the reservoir was generally detected in June. Total density increase in the middle of the reservoir was mainly attributed to the growth of diatoms. In the dam region, algae concentration decreased again, probably due to advection currents. In June 2010 exceptionally, this expansion was not detected in the middle stretch of the river and a slight increase in algae density took place only at the dam region. Algae concentration in June in the lower middle stretch of the reservoir varied between  $3.3 \times 10^3$  and  $6.6 \times 10^5$  Org. mL<sup>-1</sup>.

In dry season (September), algae density fluctuated along the reservoir and a spatial pattern in growth or decline of phytoplankton was not detected for the three studied years. However, algae density tended to increase in the lower-middle section of the reservoir, varying between  $3.3 \times 10^3$  and  $3.8 \times 10^4$  Org. mL<sup>-1</sup>. These concentrations are similar to those observed during rain season and low water level (March), despite the greater water volume and lower nutrients concentration.

Overall, higher densities of phytoplankton were observed:

- In the lacustrine region of the reservoir.
- During high water level, especially in June, when the early stages of vertical mixing take place and higher nutrients availability occur.

#### 4.2.3.2 Diversity patterns

The main algae groups present in Itaparica reservoir in each sampling campaign are illustrated in Fig. 4-9 and the main species characteristic of each season are listed in Table 4-2. Patterns were observed along the reservoir and also between seasons:

##### a) Low water level

When water level was low in Itaparica reservoir, phytoplankton concentration was lowest and different classes occurred and dominated along the reservoir (Fig. 4-9 columns March and December). In the dry season (col. December) there was a clear dominance of Chlorophyta (~80% in 2007 and 2008) in the initial stretch of the reservoir with high species richness. Species as *Chlorella vulgaris*, *Sphaerocystis schroeteri*, *Pediastrum duplex*, *P. simplex*, *Coelastrum reticulatum* and *Planktosphaeria gelatinosa* were representative of the phytoplankton community in this time of the year. Downstream, Bacillariophyta was the most abundant class, particularly the diatom *Fragilaria crotonensis*. Green algae were also present often in this section of the reservoir. Cyanobacteria occurred in small proportions along the reservoir with filamentous species as *C. raciborskii* and *Oscillatoria* sp.. In 2009, however, Cyanobacteria showed a higher relative contribution to total phytoplankton density than Bacillariophyta, being *C. raciborskii* the most abundant species.

During rain season (col. March), the initial stretch of the reservoir was mainly populated with Bacillariophyta, namely *Aulacoseira ambigua* and *Aulacoseira granulata*. In the last stretch of the reservoir usually green algae occurred. Chlorophyta species as *Pediastrum duplex*, *Pediastrum simplex* and *Staurostrum* sp. were always present in this season and *Planktosphaeria gelatinosa* and *Coelastrum reticulatum* were also very common. In March 2010, green algae were dominant in the different sections along the reservoir. Potentially toxic cyanobacteria as *Cylindrospermopsis raciborskii* and *Anabaena circinalis* were also recurrent, especially in the middle and last stretch of the reservoir. Overall, the longitudinal stretch in March was fairly inhabited by species from the 3 classes, in the three years. The higher species richness, in comparison to the previous season, is probably related to the higher nutrient concentration in the water, which supports the growth of species with varied traits.

##### b) High water level

A more defined longitudinal compartmentalization of the main channel took place during high water level (Fig. 4-9 columns June and September).

The species occurring were dependent on the season. The initial stretch of the reservoir contained a fraction of Chlorophyta up to a maximum of 60 % with species as *Pediastrum duplex* and *Planktosphaeria gelatinosa* in June (rainy season), and *Pediastrum duplex*, *Pediastrum simplex* and *Coelastrum reticulatum* in September (dry season). The last stretch of the reservoir was dominated by diatoms reaching more than 80 % of total composition in some cases: in rain season *Aulacoseira ambigua* was always present and in dry season this fraction was composed by *Fragilaria crotonensis* and *Aulacoseira granulata*. Cyanobacteria portion was usually not higher than 30 % along the reservoir and was composed by *Microcystis wesenbergii*, *Cylindrospermopsis raciborskii*, *Anabaena circinalis*, among others, during rain season.

In dry season (col. September), the cyanobacteria portion was generally smaller than in June, and composed by mostly filamentous species, frequently occurring in turbulent and mixed layers, like *Cylindrospermopsis raciborskii*, *Oscillatoria* sp., *Gleiterinema* sp. and *Aphanizomenon* sp.. The lower

concentration of DIN in this time of the year and P depletion in comparison to June concentrations is consistent with the occurrence of nitrogen-fixing species.

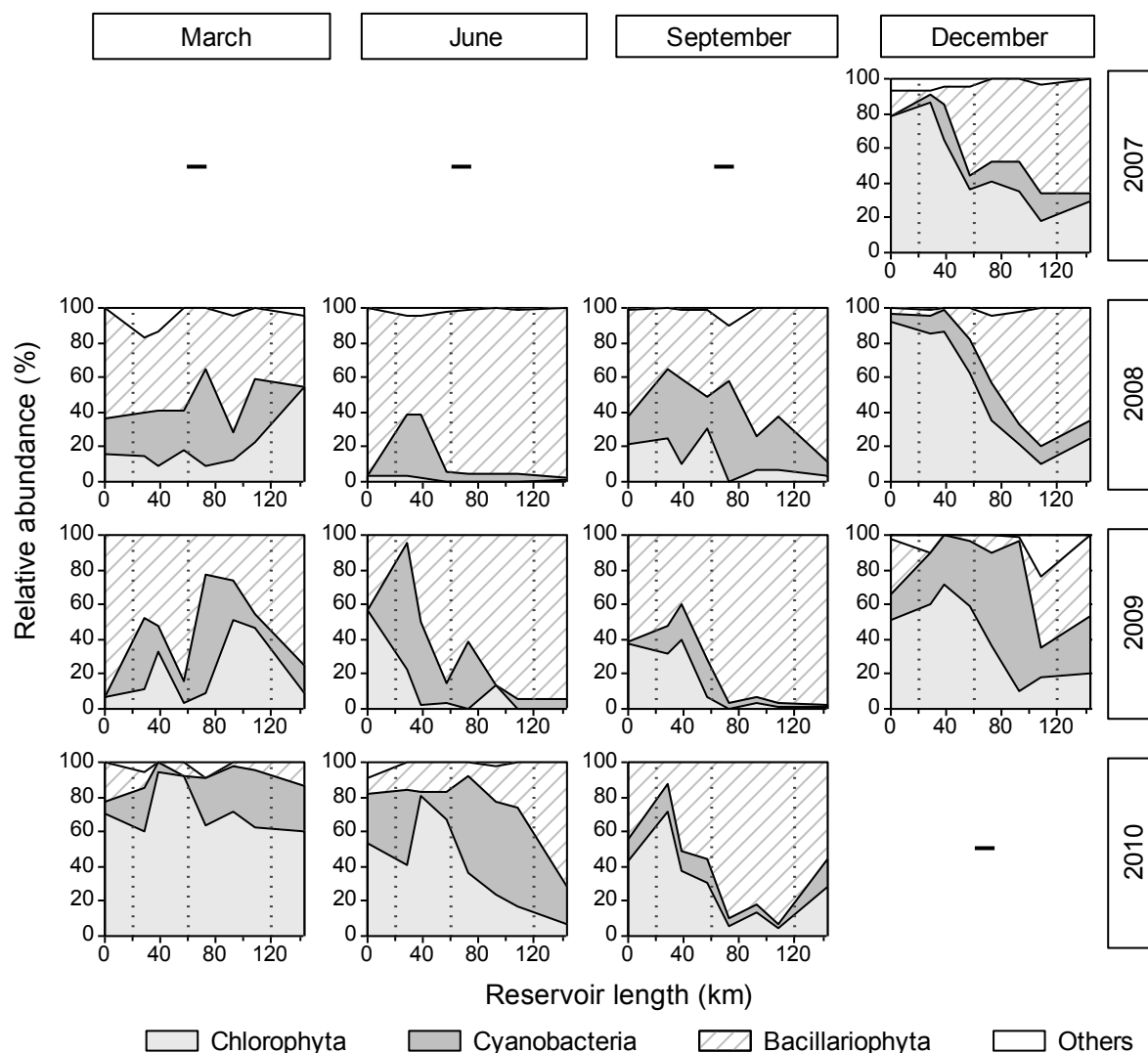


Fig. 4-9 Main taxonomic groups occurring along Itaparica reservoir in each sampling period. Vertical dash lines delimit inflow, upper-middle, lower-middle and dam sections.

On the whole, and independently from the season, riverine zone was often populated with Chlorophyta species and the lacustrine zone of the reservoir was dominated by Bacillariophyta. Cyanobacteria concentration was generally not substantial on total phytoplankton assemblage. However, in December 2009 and along 2010 phytoplankton composition was different than in the previous years, with a higher incidence of Chlorophyta and Cyanobacteria and lower share of Bacillariophyta.

Cyanobacteria occurred more often in rain season (March and June) than in dry season, in the different locations of the reservoir. Although during low water level (March) cyanobacteria share was in average higher than during high water level (June), algae concentration during high water level was higher, despite the greater water volume. The higher percentage of cyanobacteria during low water level is related to a smaller presence of other taxonomic groups, probably due to nutrient scarcity and high water flow rates. Cyanobacteria prevalence in this time of the year occurred thus during hostile conditions for other algae growth. Higher cyanobacteria concentrations were observed during high water level, when diatoms and green algae were also abundant. The co-occurrence of different algae groups was related to more favorable growth conditions, including higher nutrient availability.

Table 4-2. Main species (regarding steadiness and abundance) present in Itaparica reservoir in each sampling season.

Season	Water level	Main species		
		Chlorophyta	Bacillariophyta	Cyanobacteria
Rain	Low (March)	<i>Pediastrum duplex</i> <i>Pediastrum simplex</i> <i>Staurastrum</i> sp. <i>Planktosphaeria gelatinosa</i> <i>Coelastrum reticulatum</i>	<i>Aulacoseira ambigua</i> <i>Aulacoseira granulata</i> <i>Fragilaria crotonensis</i>	<i>Cylindrospermopsis raciborskii</i> <i>Anabaena circinalis</i> <i>Microcystis</i> sp.
	High (June)	<i>Pediastrum duplex</i> <i>Planktosphaeria gelatinosa</i>	<i>Aulacoseira ambigua</i>	<i>Microcystis wesenbergii</i> <i>Cylindrospermopsis raciborskii</i> <i>Anabaena circinalis</i>
Dry	High (September)	<i>Pediastrum duplex</i> <i>Pediastrum simplex</i> <i>Coelastrum reticulatum</i> <i>Planktosphaeria gelatinosa</i>	<i>Fragilaria crotonensis</i> <i>Aulacoseira granulata</i> <i>Ulnaria ulna</i>	<i>Cylindrospermopsis raciborskii</i> <i>Microcystis</i> sp. <i>Aphanocapsa elachista</i> <i>Oscillatoria</i> sp. <i>Gleiterinema</i> sp. <i>Aphanizomenon</i> sp.
	Low (December)	<i>Chlorella vulgaris</i> <i>Sphaerocystis schroeteri</i> <i>Pediastrum duplex</i> <i>P. simplex</i> <i>Coelastrum reticulatum</i> <i>P. gelatinosa</i> <i>Staurastrum rotula</i> <i>Dictyosphaerium pulchellum</i>	<i>Fragilaria crotonensis</i> <i>Urosolenia longiseta</i>	<i>C. raciborskii</i> <i>Oscillatoria</i> sp.

#### 4.2.3.3 Drivers of seasonal patterns

As previously showed, the highest phytoplankton densities in Itaparica reservoir developed already inside the reservoir and occurred mainly in the transition/lacustrine region (Fig. 4-8).

The main factors for phytoplankton growth in the main stream of Itaparica reservoir are ultimately related to nutrients accessibility. However, nutrients were available in the water column for different reasons, depending on the season. Nevertheless, prior to nutrients availability, hydrology was observed to be a first parameter for phytoplankton growth in the main stream of the reservoir.

##### a) Water residence time

Water residence time seems to be a major parameter for algae control in this reservoir. Phytoplankton abundance was lowest mainly during high discharge rates and, thus, low water residence times. Theoretical residence time further referred was calculated as a mean of the daily theoretical residence time of the 15 days prior to the sampling campaign. During low water level and dry season (December), water residence time in Itaparica reservoir was typically under 60 days (Fig. 4-10). In March 2010, water residence time lied below 60 days and mean flow rate was close to 2 000 m<sup>3</sup> s<sup>-1</sup>. It was observed that, at very low residence times, phytoplankton concentration declined with decrease of residence time. Such relation indicates that biomass development in Itaparica reservoir is limited by high flow rates at residence times below 60 days ( $r^2 = 0.9908$ ,  $p < 0.05$ ).

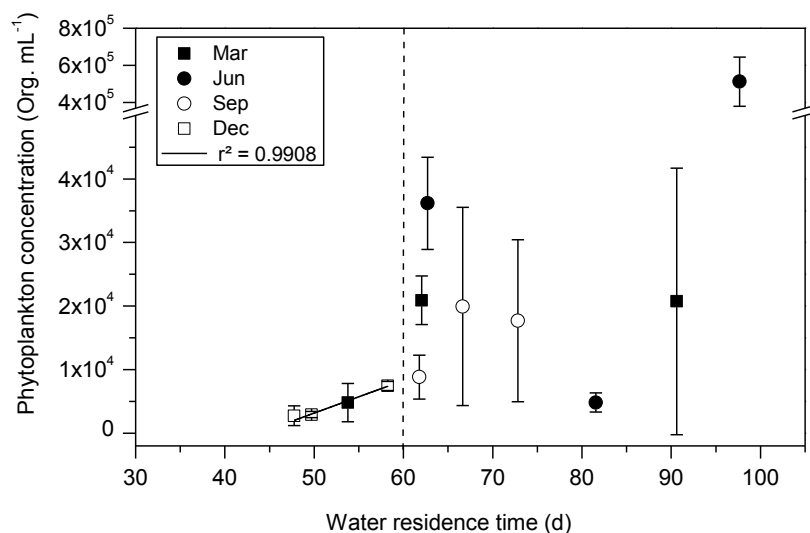


Fig. 4-10 Relationship of phytoplankton density and water residence time in the lower-middle stretch of Itaparica reservoir.

Transport of plankton along the reservoir during high discharge rates is also confirmed by a study developed in the framework of INNOVATE project (Lopes et al., 2015), based on remote sensing analyses. Based on satellite images of 19 October and 04 November 2009 (two weeks interval), phytoplankton biomass in Itaparica reservoir was quantified (as chlorophyll *a* concentration). The study showed the local fading of Chl *a* particularly in the second half of reservoir in a period with high flow rates (November) and consequent low residence time (< 60 days), which is visible when comparing the lower- middle section of the reservoir depicted on the two images (Fig. 4-11).

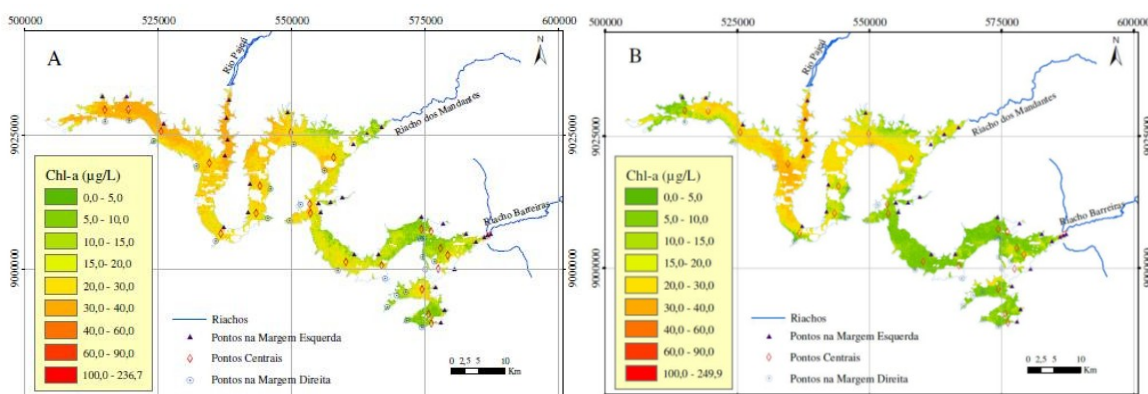


Fig. 4-11 Chlorophyll *a* concentration in the reservoir in 19 October and 04 November 2009 (A and B, respectively), measured by remote sensing analyses (Lopes et al., 2013).

The occurrence of cyanobacteria was also low during low water residence time, with a maximum concentration of only  $3.8 \times 10^3$  Org. mL<sup>-1</sup>, comprising 87 % of total abundance in December 2009 (residence time < 60 d). As mentioned above, the period with higher presence of cyanobacteria was rain season, when residence time was superior to 60 days. With lower water flow rates, nutrients availability became of importance. Accordingly, during rain season cyanobacteria abundance seemed to be reliant on P availability ( $r^2 = 0.9065$ ,  $p < 0.05$ ) and on residence time ( $r^2 = 0.9344$ ,  $p < 0.001$ ) (Fig. 4-12).

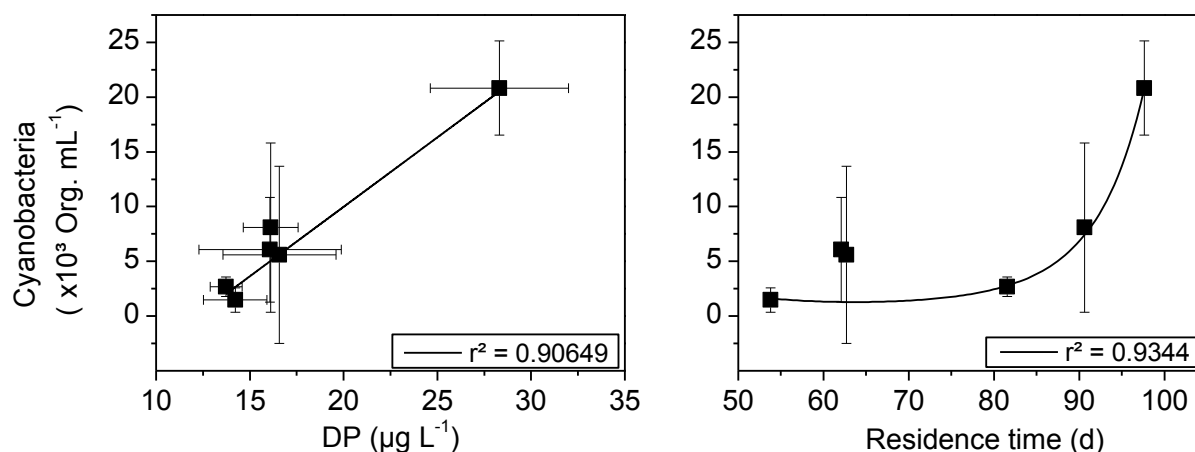


Fig. 4-12 Environmental drivers for cyanobacteria concentration in Itaparica reservoir during rainy season in low and high water level periods: a) linear correlation of mean cyanobacteria concentration with dissolved phosphorus (DP); b) exponential correlation of mean cyanobacteria concentration with water residence time. Error bars represent standard deviation of the sampling stations ITA 06, ITA 08 and ITA 09.

#### b) Water column mixing effects

Periods with residence time lower than 60 days occurred mainly during hot season and resulted in low phytoplankton densities (below  $1.0 \times 10^4$  Org. mL<sup>-1</sup>), independently if stratified or mixed water column (Fig. 4-13). This shows that in fact, high water discharge rates have a crucial effect on phytoplankton abundance.

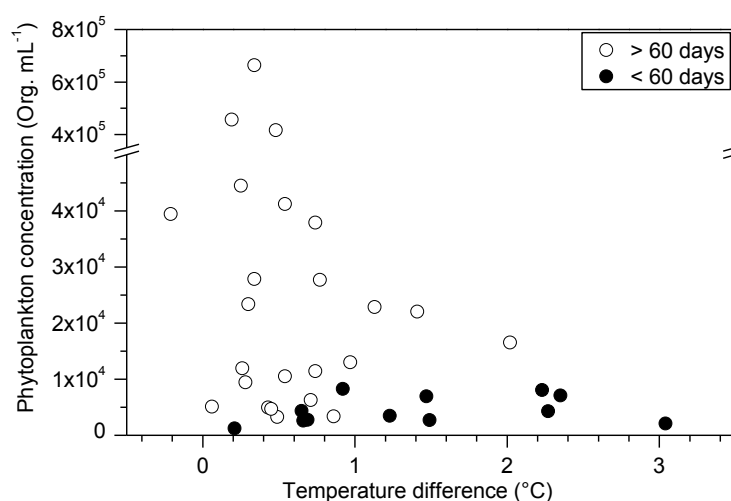


Fig. 4-13 Influence of water column stratification and water residence time on phytoplankton concentration in the lower middle stretch of Itaparica reservoir.

On the contrary, the highest algae densities were detected in periods with higher residence times (above 60 days) and mixed water column, i.e., water temperature difference between surface and bottom lower than 1 °C. Mixing conditions potentiate algae growth by promoting the resuspension of nutrients, making them available again for plankton. The high residence time typical of high water level period and the isothermal conditions in the water column are likely promoters of the high algae abundance observed in this period. Particularly in June, when higher phytoplankton concentrations were detected, the temperature difference between water surface and reservoir bottom was close to zero, indicating a thoroughly mixed water column.

The lack of weekly records in the monitoring program prevents sound correlations of algae concentration with nutrients availability. It is possible that when high densities were measured, N and P concentrations were already low due to previous uptake. Therefore, a good correlation between nutrients availability and algae abundance was not always found. DIN and algae density were not correlated ( $r^2 = 0.1789$ , Fig. A - 4A). Algae density was related to DP ( $r^2 = 0.8788$ ,  $p < 0.001$ ), Fig. A - 4B) and to SRP only to some extent ( $r^2 = 0.4135$ ,  $p < 0.05$ , Fig. A - 4C), suggesting that P availability plays a role on phytoplankton abundance in this reservoir.

### c) Conductivity

June was the period with higher algae concentrations in 2008 and 2009, in the lower middle section of the reservoir. The highest density values were observed when conductivity was also high ( $r^2 = 0.8401$ ,  $p < 0.001$ ) (Fig. 4-14). The increased availability of nutrients at the end of rain season, vertical mixing due to isothermal conditions and high retention time after water level rise created optimal conditions to enhance diatoms development. In June 2010, the very low algae concentrations coincided with low conductivity, although temperature between surface and bottom differed only 0.4 - 0.7 °C. The mean air temperature in 2010 was higher than normal, with air temperature superior to 30 °C until May (Fig. 3-3). The stable water column promoted the deposition of suspended solids, prevented the resuspension of sediments to the epilimnion and nutrient limitation hindered phytoplankton development. Stratification also barred the resuspension of vegetative propagules of diatoms, necessary for the proliferation in the water column. In this period, Cyanobacteria were dominant (more than 50% of total density) and only *Microcystis wesenbergii*, which normally develops in stratified systems, accounted for 38-46 %, depending on the sampling station.

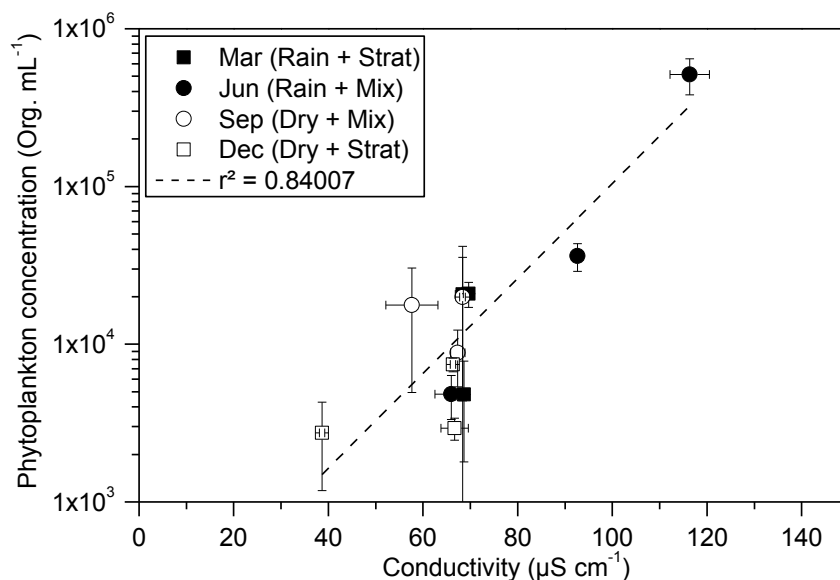


Fig. 4-14 Exponential regression relating water conductivity with phytoplankton density in the lower-middle stretch of Itaparica reservoir, between 2007 and 2010.

The lowest conductivity values were measured during dry season. In each of the seasons, conductivity was highest during mixing conditions, suggesting that internal loading is a major source of ions in the water column. Thus, high conductivity is indicative of mixed water column. Regarding the low alkalinity and hardness of reservoir water (CHESF, 2011), conductivity may also show linkage with DIC availability in the water column.

In dry season (September and December), phytoplankton density was generally lower. The entrance of allochthonous material in the system by run-off events is absent and internal loading is the only



nutrient source. Nevertheless, water column mixing is occurring since a few months, and many nutrients have probably been flushed away and taken up by other organisms. The lower algae concentration measured in September was possibly due to nutrients limitation, indicated by the low conductivity of the water, both at the surface and bottom.

#### d) Multifactorial drivers system

In conclusion, the main stream of Itaparica reservoir is a multifactor driven system in what concerns phytoplankton development. According to the analyses above, algae growth in this system is mainly regulated by the following parameters, by decreasing order of importance:

1. Water residence time - when lower than  $\sim 60$  days (mean of the previous 15 days) phytoplankton and nutrients are rapidly transported along the reservoir. The high flow rates in combination with thermal stratification result in losses of biomass and nutrients from the reservoir or to the hypolimnion, and thus suppression of algae growth. At longer residence times, algae density depends more directly on nutrients availability.
2. Nutrients availability is regulated by:
  - a) Rain – rainfall and consequent runoff across the watershed is the main source of allochthonous nutrient loading of the reservoir. Organic matter entering the reservoir can be in the particulate form, not readily available for microbial uptake (Bormans et al., 2016). A time gap between particulate matter input and dissolved form availability is expected.
  - b) Thermal regime of the water column – water column mixing is the main driver for internal loading. Therefore, algae density was highest in the end of rain season with mixed water column (generally in June). When water column stratifies, the supply of nutrients in the epilimnion is shorter (also during rainy season). Additionally, water characteristics suggest dissolved P and DIC accumulation in the hypolimnion and shortage in epilimnion during stratification period. Mixing events allow the dispersion of P and DIC to upper layers, fostering photosynthesis.
  - c) Water level rise – the area flooded during water level increase is a source of nutrients (in dissolved and particulate forms) which eventually become available to algae growth, due to the high residence time typically registered after water level rise.
3. Predation by zooplankton is not considered to be a significant factor for phytoplankton biomass control in tropical systems, due to their small size (typically  $< 1$  mm) (Frau et al., 2017; Lewis, 1996).

### 4.2.4 Main stream vs. Icó-Mandantes bay

The outcome of complementary studies in the INNOVATE project based on hydrodynamics modeling of Itaparica reservoir showed a hydraulic disconnection between the Icó-Mandantes bay and the main channel (Matta et al., 2014) (Fig. 4-15). The low water exchange between the two regions of the reservoir has implications on the residence time of the water inside the bay, which is notably higher than in the main stream ( $> 1$  year) (Matta et al., 2016). With a partially disconnected flow, the main stream of the reservoir has little contribution on the water residence time and nutrient load in the bay and vice-versa.

This low communication between the two reservoir sections was also visible in what regards phytoplankton community and biomass. Algae concentrations in the bay (ITA 07) during the study period were fairly in the same range as in the main flow (ITA 08 - downstream from the bay), as they fluctuated between  $1.0 \times 10^3$  Org.  $\text{mL}^{-1}$  (December 2009) and  $3.5 \times 10^5$  Org.  $\text{mL}^{-1}$  (June 2008) (Fig. 4-16). Nevertheless, differences were observed and the tendency was of increased steadiness in the bay.

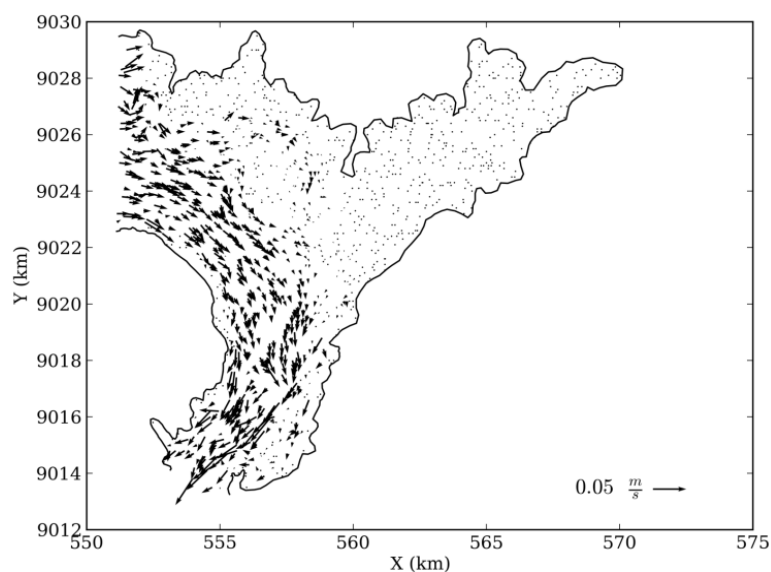


Fig. 4-15 Surface flow simulation in Itaparica reservoir with a mean discharge rate of  $2060 \text{ m}^3 \text{ s}^{-1}$  (Matta et al., 2014).

In 2008, when algae abundance in the bay was higher than in the main flow, it was due to Cyanobacteria presence (September 2008 and December 2008) (Fig. 4-16). Cyanobacteria concentration in the bay was often higher than in the main flow. In June 2008, cyanobacteria concentration in the bay was 31 % ( $1.1 \times 10^5 \text{ Org. mL}^{-1}$ ), in contrast to only 4 % ( $2.5 \times 10^4 \text{ Org. mL}^{-1}$ ) in the main flow. In the bay, *C. raciborskii* and *Geitlerinema amphibium* represented 17 % of total concentration. Phytoplankton density in the bay in September 2008 ( $4.7 \times 10^4 \text{ Org. mL}^{-1}$ ) and December 2008 ( $6.7 \times 10^4 \text{ Org. mL}^{-1}$ ) corresponded to four and ten times the concentration in the main flow, respectively. *C. raciborskii* comprised 55 % and 78 % (respectively) of the total density in the bay whereas in the main flow was practically absent ( $< 1 \%$ ).

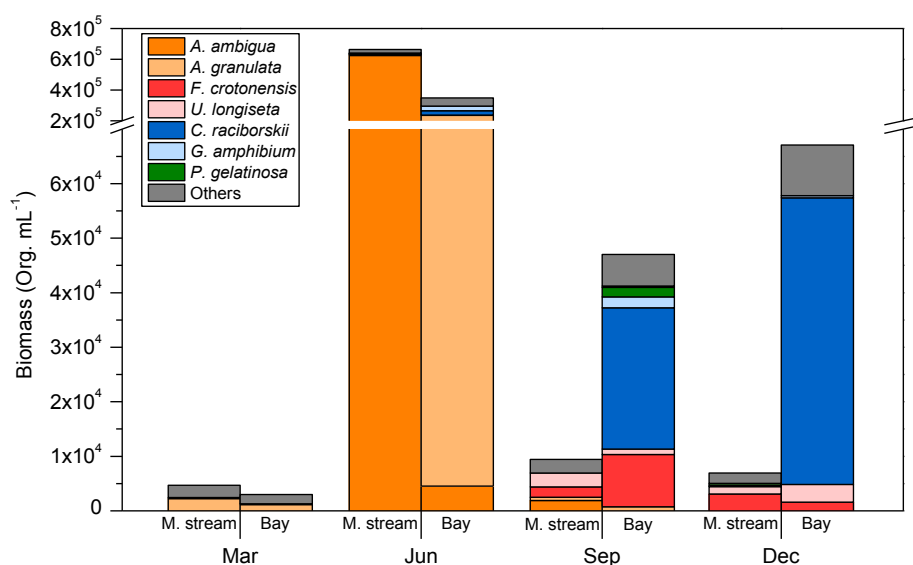


Fig. 4-16 Comparison of main algae species concentration in the main stream of the reservoir (M. Stream) and in the Ic6-Mandantes bay (Bay) in March, June, September and December 2008. Colours represent main taxonomic groups: blue – Cyanobacteria; red – Bacillariophyta; green – Chlorophyta. Main species: *Aulacoseira ambigua*, *Aulacoseira granulata*, *Fragilaria crotonensis*, *Urosolenia longiseta*, *Cylindrospermopsis raciborskii*, *Geitlerinema amphibium*, *Planktosphaeria gelatinosa*.

### 4.3 Field campaigns in Icó-Mandantes bay

The Icó-Mandantes bay has a mean depth of 6.8 m (at high water level) and is characterized by gentle slopes below 2° (92.0 % of the bay area). The water depth at the mouth of the bay is around 20 – 25 m and it becomes shallower towards the inner bay with 1-5 m water depth (Selge, 2017). With echo-sounder depth measurements, satellite images and data interpolation, a bathymetric map of the bay was developed (Fig. 4-17). This bay has a surface area of 25.1 km<sup>2</sup> and a volume of 0.18 km<sup>3</sup> (Fig. A - 1) developed in the framework of INNOVATE project (Selge, 2017), which was also used as basis on the macrophyte biomass analyses.

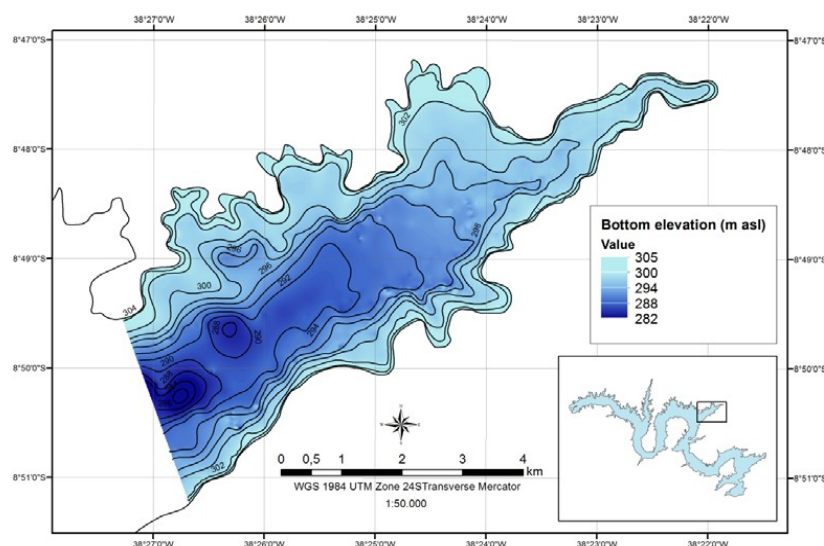


Fig. 4-17 Bathymetric map of the Icó-Mandantes bay based on echo-sounder depth measurements, satellite images and data interpolation (Selge, 2017).

Geoprocessing studies (Tavares Junior et al., 2017) are still ongoing in order to achieve a more detailed bathymetry of the bay based on cartographic databases and remote sensing, which can be used in the future as base for other limnological and ecological studies (see section 4.5.2).

Icó-Mandantes bay is considered a shallow system, with different environmental settings than the main stream of the reservoir. The high water residence time, extensive shallow area and constant mixing of the water column due to wind waves promote the development of species which in the main stream do not thrive, like cyanobacteria and submerged macrophytes.

Sampling campaigns in Icó-Mandantes bay were carried out in 2 regular seasons - dry season with high water level (September 2012) and rainy season with low water level (March 2013) -, as well as in a long lasting drought period which resulted in an exceptionally prolonged low water level: sampling was done in the dry period (October 2013) and in the rainy period (June 2014), two typically high water level seasons. This drought event during study timeframe allowed an insight of the effects of long lasting low water level on the development of phytoplankton and macrophytes in the bay.

Water chemistry characterization in each of these sampling campaigns is described in Table 4-3. Changes in water quality were observed in the course of the study, particularly before and after water level drawdown.

- During dry season with high water level (September 2012), water transparency was high and nutrients and chlorophyll *a* (Chl *a*) concentrations were very low.

- In March 2013, low water level in rain season, a very high increase of Chl *a* (20 times the concentration during high water level) and of nutrients concentrations was observed. Water transparency was accordingly very low. Very low oxygen concentrations took place in the inner part of the bay.
- During drought, in October 2013 and in June 2014, nutrients and Chl *a* concentrations decreased again, but Secchi depth was still relatively low, due to non - algal turbidity. In rain season (June 2014) pH was lowest, revealing low photosynthetic rates and prevalence of respiration processes.

Table 4-3. Characterization of water quality during field campaigns in Icó - Mandantes bay. Median (quartiles Q1 - Q3). Legend: HWL\_D - High Water Level, Dry season; LWL\_R - Low Water Level, Rain season; Drought\_D - Drought period, dry season; Drought\_R - Drought period, rain season) (Selge, 2017).

Parameter	HWL_D	LWL_R	Drought_D	Drought_R
	Sep 2012	Mar 2013	Oct 2013	Jun 2014
Secchi depth (m)	4,7 (4,7 - 4,8)	0,9 (0,8 - 0,9)	1,9 (1,8 - 2,4)	2,0 (1,8-2,4)
pH	8,4 (8,2 - 8,6)	8,8 (8,7 - 9,0)	7,9 (7,7 - 8,3)	6,2 (6,2-6,4)
T (°C)	24,7 (24,5 - 25,0)	27,6 (27,2 - 28,1)	26,9 (26,1 - 27,3)	24,2 (24,1-24,5)
O <sub>2</sub> (mg L <sup>-1</sup> )	6,9 (5,5 - 9,9)*	5,4 (2,9 - 7,8)*	6,7 (5,4 - 8,8)*	8,2 (7,7 - 9,9)*
Spec. Cond. (µS cm <sup>-1</sup> )	77,0 (74,0 - 82,0)	70 (67,7 - 73,0)	66,0 (64,3 - 67,0)	73,0 (68,0 - 75,0)
TN (mg L <sup>-1</sup> )	0,2 (0,17 - 0,23)	0,5 (0,44 - 0,71)	0,18 (0,15 - 0,21)	0,29 (0,24 - 0,33)
DIN (µg L <sup>-1</sup> )	93,6 (55,8-124,8)	77 (51,1-155,8)	32,9 (25,3-50,7)	131,2(113,4-139,5)
TP (µg L <sup>-1</sup> )	19,2 (15,1 - 27,0)	34,1 (45,5 - 31,3)	16,7 (14,0 - 20,0)	17,2 (14,5 -20,5)
Chl <i>a</i> ( µg L <sup>-1</sup> )	1,9 (0,5 - 2,7)	37,8 (26,4 - 42,9)	0,7 (0,4 - 1,8)	1,2 (0,5 - 1,9)

\* Median (min-max)

## 4.4 Phytoplankton community in the Icó-Mandantes bay

During the sampling campaigns between 2012 and 2014 a thorough assessment of the bay was carried out with detailed longitudinal sampling from the inner part of the bay towards the main stream of the reservoir, in order to understand the dynamics and gradients of phytoplankton abundance and composition inside the bay.

### a) Biodiversity

The gradient of biodiversity along the bay towards the main stream in each of the sampling periods is presented in Fig. 4-18. Shannon diversity index during dry season (September 2012 and October 2013) was generally higher than in the rain period and increased in the direction to the main stream. During high water level, algae were practically absent and the highest biodiversity occurred in the outer bay, where N concentration was also higher. Shannon index gradient was not correlated with any of the parameters analyzed (DIN, NH<sub>4</sub>, NO<sub>3</sub>, TP, SRP, DIN:TP, DOC, Secchi depth, water temperature, pH, conductivity and location), but species richness was correlated with nitrate concentration ( $r^2 = 0.9995$ ,  $p < 0.05$ ). During drought period (October 2013), diversity significantly increased in direction to the main stream ( $r^2 = 0.9965$ ,  $p < 0.05$ ) and was associated to transparency of the water column ( $r^2 = 0.9607$ ,  $p < 0.05$ ), which was highest in the outer bay and main stream. In the inner part of the bay, turbidity most likely promoted species with buoyancy control (namely *C. raciborskii*), which partially

dominated. N and P were more concentrated inside the bay and diversity was negatively correlated with TP ( $r^2 = 0.9467$ ,  $p < 0.05$ ) and conductivity ( $r^2 = 0.9223$ ,  $p < 0.05$ ).

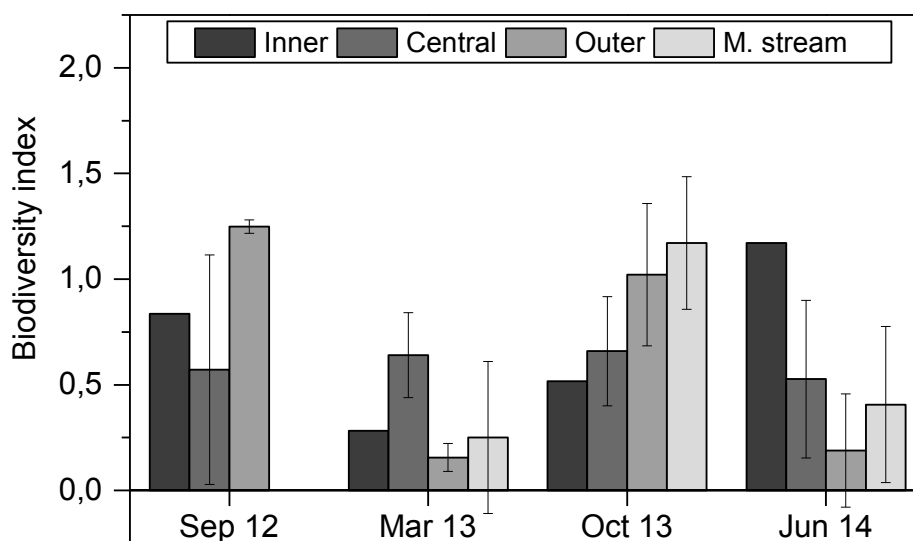


Fig. 4-18 Shannon diversity index in the inner, central and outer parts of Icó-Mandantes bay and in the main stream (represented sampling stations: 1, 3, 5 and 6) in each of the sampling campaigns. Bars depict mean Shannon index measured in the water column at different depths and error bars represent standard deviation. Station 1 (inner bay) is the shallowest part with only two sampling depths, and thus lacks a standard deviation value.

During rain season diversity index was slightly lower than in dry season. The low Shannon index in March 2013 is related to the bloom of the cyanobacteria *C. raciborskii* observed in this period, concomitant with high trophic state of the bay and high temperatures. In point of fact, the high trophic state promoted the growth of many species and the highest species richness was measured in this period ( $n=36$ ). However, because of the high dominance of *C. raciborskii*, evenness of algae assemblages was very low and consequently Shannon index too. In this period, Shannon index and species richness was not significantly correlated to any of the analyzed parameters. During drought (June 2014), the diversity index gradient along the bay was similar to that in March 2013, except in the inner bay, where diversity was higher. Shannon index gradient in June 2014 was correlated to TP concentration ( $r^2 = 0.9386$ ) and DOC concentration ( $r^2 = 0.9234$ ), and inversely related to DIN:TP ( $r^2 = 0.9466$ ), suggesting P limitation in the central and outer bay. The high P concentration in the inner bay probably resulted from the intense rainfall occurring during the rainy season.

The steadiest species was *Cylindrospermopsis raciborskii*, which was the only species present in each of the sampling campaigns in the bay. Moreover, this cyanobacterium was usually present in high proportions in the phytoplankton community. Other species, belonging to Cyanobacteria, Bacillariophyta and Chlorophyta groups, were also recurrent during the study, occurring in three of the four sampling campaigns, but generally in lower magnitudes (Table 4-4).

#### b) Phytoplankton density

On the whole, phytoplankton density in Icó-Mandantes bay was significantly correlated to SRP concentration ( $r^2 = 0.5830$ ,  $p < 0.05$ ) throughout the several sampling campaigns. Moreover, seasonal tendencies and longitudinal gradients were observed, suggesting changes in nutrients requirements with the seasons and spatially along the bay (Fig. 4-19).

Table 4-4. Steadiest species in Icó-Mandantes bay between 2012 and 2014. The species in grey background was present in all the four sampling campaigns; species in white background were present in three sampling campaigns.

Taxonomic group	Species	Mean biomass (%)
Cyanobacteria	<i>Cylindrospermopsis raciborskii</i>	73 ± 14
Bacillariophyta	<i>Aulacoseira granulata</i>	32 ± 28
Cyanobacteria	<i>Chroococcus dispersus</i>	20 ± 19
Bacillariophyta	<i>Fragilaria crotonensis</i>	14 ± 9
Chlorophyta	<i>Monoraphidium arcuatum</i>	12 ± 18
Chlorophyta	<i>Oocystis</i> sp.	8 ± 13
Bacillariophyta	<i>Synedra</i> sp.	8 ± 7
Bacillariophyta	<i>Nitzschia</i> sp.	7 ± 8
Chlorophyta	<i>Scenedesmus</i> sp.	3 ± 5
Cyanobacteria	<i>Oscillatoria</i> sp.	3 ± 1
Chlorophyta	<i>Monoraphidium contortum</i>	2 ± 3

During high water level in September 2012, algae density was very low, particularly in the interior of the bay (max. 245 cell mL<sup>-1</sup>), slightly increasing towards the main flow. The lowest algae densities in the study were registered in this period. The low concentration observed was nevertheless significantly related to NH<sub>4</sub> ( $r^2 = 0.9964$ ,  $p < 0.05$ ), DIN:TP ( $r^2 = 0.9983$ ,  $p < 0.05$ ) and water transparency ( $r^2 = 0.9970$ ,  $p < 0.05$ ).

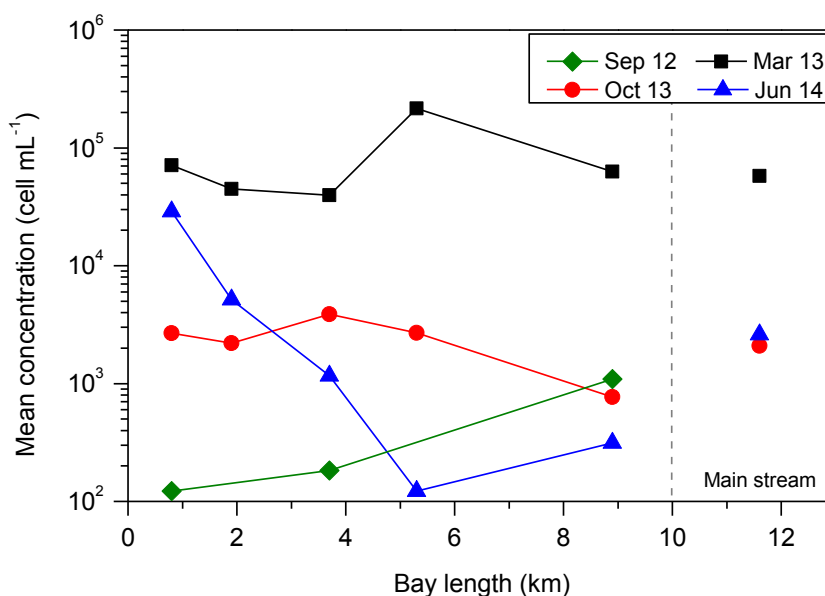


Fig. 4-19 Phytoplankton concentration gradient in Icó-Mandantes bay in the six sampling stations (five along the bay and one in the main stream). Points represent mean concentration present in the water column. Sampling design in September 2012 did not include main stream sampling station.

In typical rain season with low water level (March 2013), a massive phytoplankton bloom occurred, reaching impressive concentrations both in the bay and in the main flow (mean  $1.1 \times 10^5$  cell mL<sup>-1</sup>). In this period, the trophic state of the bay was very high in comparison to the dry season, and significant

correlations between biomass and nutrients were not found, perhaps due to the unrestrained availability of nutrients.

Nutrients load in the bay due to runoff from rainfall and agriculture irrigation takes place mainly in the inner bay, as here are located drainage channels and an intermittent river which flows only in rain season (Riacho Mandantes). Phytoplankton concentration in the inner bay always increased from dry to rainy season, revealing the role of rain and runoff processes in the development of algae in this season.

In dry season of drought period (October 2013), phytoplankton abundance was low in the whole bay. Still, algae concentration in the inner part of the bay was about 20 fold the concentration one year before at high water level (September 2012), decreasing towards the main flow. In this period, no significant association between biomass and environmental drivers was detected.

In June 2014 (rain season of drought period), phytoplankton concentration was notably higher in the interior of the bay (mean  $2.9 \times 10^4$  cell mL<sup>-1</sup>) than in the central part of the bay ( $\sim 1.2 \times 10^3$  cell mL<sup>-1</sup>), where it was analogous to the one recorded in the previous sampling campaign (October 2013). Phytoplankton density was associated to SRP ( $r^2 = 0.9670$ ,  $p < 0.05$ ), TP ( $r^2 = 0.9267$ ,  $p < 0.05$ ) and pH ( $r^2 = 0.9474$ ,  $p < 0.05$ ) and inversely correlated to NO<sub>3</sub> ( $r^2 = 0.9325$ ,  $p < 0.05$ ). The dominant species in the inner bay in this season was *C. raciborskii*, due to the high affinity for P.

The decrease of phytoplankton concentration during low water level at the mouth of the bay (8.9 km) was possibly because of advection processes due to contact with higher flow rates occurring in the main stream.

#### 4.4.1.1 Presence of *C. raciborskii*

As previously pointed out in this chapter, *Cylindrospermopsis raciborskii* was the only species observed to be always present in the bay within the study period. In September 2012, although total phytoplankton abundance was very low, *C. raciborskii* was nevertheless present (max.: 660 cell mL<sup>-1</sup> at 5 m water depth in the outer bay - 20 % of total density) (Fig. 4-20). In fact, in the inner bay phytoplankton density was very low, and concentration and share of *Cylindrospermopsis raciborskii* increased towards the mouth of the bay, where nutrients were also higher, particularly NH<sub>4</sub> ( $r^2 = 0.9957$ ,  $p < 0.05$ ).

In March 2013, during rain season with low water level, phytoplankton in the bay reached occasionally very high concentrations not only in a horizontal but also in a vertical profile ranging between  $4.5 \times 10^2$  cell mL<sup>-1</sup> and  $4.3 \times 10^5$  cell mL<sup>-1</sup>. The high values measured were due to the significant development of *C. raciborskii* which contributed to generally more than 90 % of total density (Fig. 4-20). The highest concentration was located in the middle of the bay at the surface, where *C. raciborskii* accounted for 99 % of total density. In the main stream, *C. raciborskii* presence was registered in very high proportions as well, being absent only at 25m water depth. The bloom of *C. raciborskii* happened in a season with very high nutrient concentrations. The high P and N concentrations in this season supported *C. raciborskii* major development.

The exceptional development of *C. raciborskii* was probably maintained along the following months throughout drought period, considering that in October 2013, even though algae density was significantly lower ( $p < 0.05$ ), the proportion of this species to total density was still high (more than 70 %) particularly in the interior of the bay (Fig. 4-20). Although the highest nutrients concentrations were also observed in the inner part of the bay (Selge, 2017), no statistically significant correlation was obtained between phytoplankton density and N and P concentrations, although a not significant positive tendency between phytoplankton concentration and SRP was patent ( $r^2 = 0.8938$ ,  $p\text{-value} = 0.0546$ ).

In June of the following year, phytoplankton abundance was highest in the inner part of the bay and *C. raciborskii* accounted for more than 70 % of total density in some of the samples. Analogous to the previous season, the highest P concentrations were present in the inner bay. In fact, *C. raciborskii* concentration was correlated with SRP ( $r^2 = 0.9452$ ,  $p < 0.05$ ) and TP ( $r^2 = 0.9487$ ,  $p < 0.05$ ) and inversely correlated with DIN:TP mass ratio ( $r^2 = 0.9105$ ,  $p < 0.05$ ) and  $\text{NO}_3$  ( $r^2 = 0.9155$ ,  $p < 0.05$ ), confirming the importance of P on biomass growth in this period.

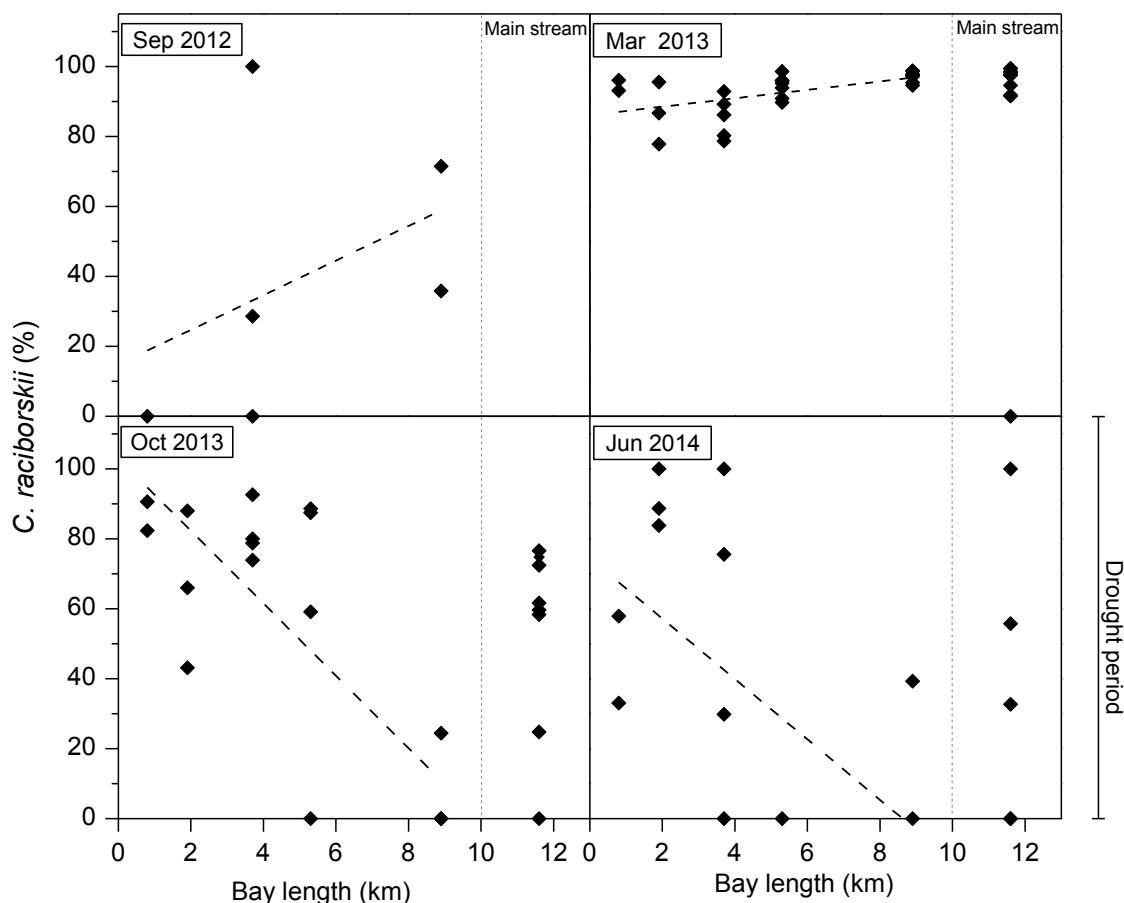


Fig. 4-20 Relative abundance (% of total phytoplankton concentration) of *Cylindrospermopsis raciborskii* along Icó-Mandantes bay at different water depths in the six sampling stations (five along the bay and one in the main stream). Dashed line represents the tendency of abundance gradient from inner bay (0 km) towards outer bay (9 km).

Bioassays for nutrient limitation assessment were carried out in the framework of INNOVATE project in October 2013 (Selge, 2017): water of the bay was enriched with phosphorus and nitrogen and analyzed after 6 days incubation *in situ*. Chlorophyll *a* was observed to increase in the sample with P enrichment ( $17.6 \pm 2.7 \mu\text{g L}^{-1}$ , against  $1.7 \pm 0.6 \mu\text{g L}^{-1}$  in the control sample), revealing a P limited system. Microscopy analyses of this sample showed a high development of *C. raciborskii* (Fig. 4-21).

Phenotypically, *C. raciborskii* presented heterocysts (Fig. 4-22), which indicates N limitation in system as well, and that N limitation was overcome by atmospheric N fixation. This shows that in that period, a sudden P pulse in the bay could result in a bloom of *C. raciborskii*, even in nitrogen absence. These results complement data of the present study, which showed that *C. raciborskii* abundance was highest when P concentration was high, also in low concentration of N. Indeed, a significant weak correlation was found between *C. raciborskii* concentration and SRP ( $r^2 = 0.4456$ ) for all seasons. On the whole, *Cylindrospermopsis raciborskii* was regularly present species in this bay, showing growth advantage over all the other algae species and opportunistic when P concentration increased.



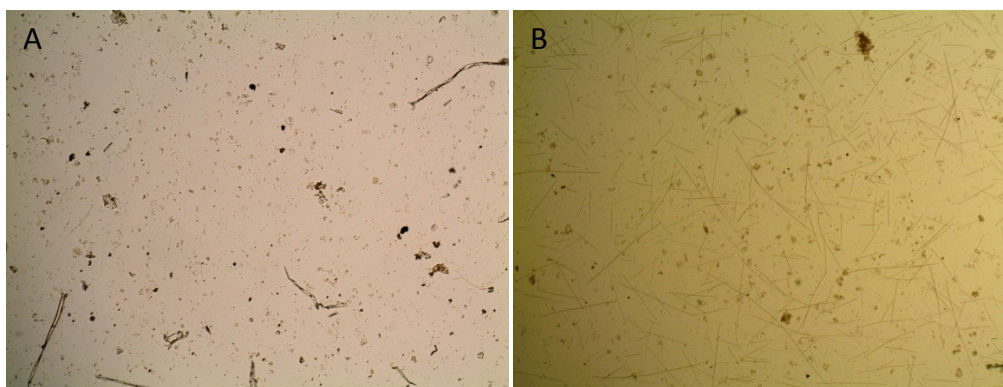


Fig. 4-21 Phytoplankton composition of water samples from Icó-Mandantes bay, showing a high development of *C. raciborskii* after P addition. A) control B) 6 days after P addition. Magnification 25X.

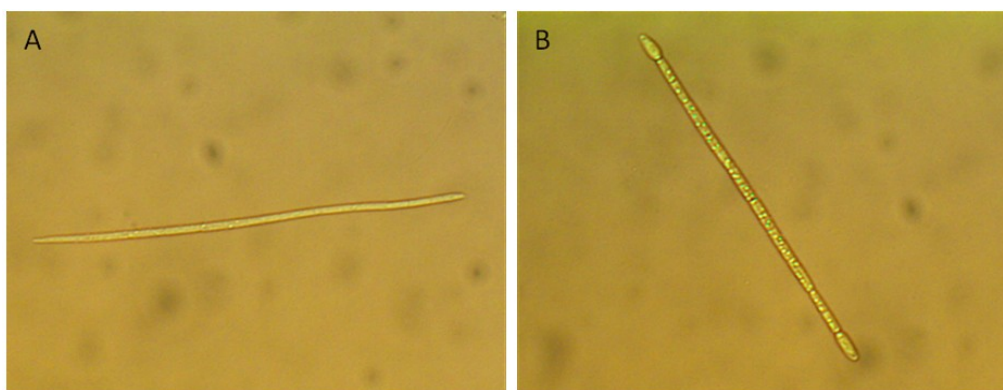


Fig. 4-22 *Cylindrospermopsis raciborskii* filaments in (A) control sample and in (B) the sample enriched with P, with terminal heterocysts in both edges of the trichome. Magnification 400X.

During drought period (October 2013 and June 2014), *C. raciborskii* was also present in the main stream. Although in relatively high proportions along the water column (particularly in October), the actual abundance of this species was low (max. 1450 and 650 cell mL<sup>-1</sup>, respectively). The residence time of the water in the main stream of the reservoir during drought period was atypically high (mean of  $83 \pm 7$  d), which can have supported the permanence of this species since the bloom observed in March 2013.

## 4.5 Macrophyte community

### 4.5.1 Macrophyte diversity

#### a) Macrophyte diversity in Itaparica Reservoir sub-basin

Biodiversity of macrophytes in the watershed of Itaparica reservoir was assessed based on the examination of ecological monitoring reports between 2009 and 2011. A high diversity was found with a total amount of 49 species identified in all biological forms (submerged, emergent, or free-floating). In the stations located in main course of the São Francisco River immediately before Itaparica reservoir, 17 of those species occurred, belonging to 12 different families (Table 4-5).

## Results

Macrophyte community is represented by species with diverse life cycles, with perennial plants like *Eichhornia* sp. and *Paspalum repens* or small free-floating plants with a very fast doubling time such as *Pistia* sp. and *Lemna* sp. – around 7 days (Junk, 1997).

Table 4-5. Macrophyte species occurring in the main course of São Francisco River, upstream from Itaparica reservoir.

Family	Species	Type
Amaranthaceae	<i>Alternanthera aquatica</i>	Emergent
Araceae	<i>Lemna</i> sp.	Free - floating
Araceae	<i>Pistia stratiotes</i>	Free - floating
Ceratophyllaceae	<i>Cerathophyllum demersum</i>	Submerged
Characeae	<i>Chara fragilis</i>	Submerged
Cladophoraceae	<i>Cladophora</i> sp.	Submerged
Convolvulaceae	<i>Ipomoea</i> sp.	Emergent
Cyperaceae	<i>Oxycaryum cubense</i>	Free - floating
Hydrocharitaceae	<i>Najas guadalupensis</i>	Submerged
Hydrocharitaceae	<i>Vallisneria</i> sp.	Submerged
Poaceae	<i>Paspalum repens</i>	Emergent
Poaceae	<i>Poaceae</i> sp.	Emergent
Poligonaceae	<i>Poligonaceae</i> sp.	Emergent
Pontederiaceae	<i>Eichhornia azurea</i>	Free - floating
Pontederiaceae	<i>Eichhornia crassipes</i>	Free - floating
Salviniaceae	<i>Salvinia auriculata</i>	Free - floating
Salviniaceae	<i>Salvinia minima</i>	Free - floating

### a) Macrophyte biodiversity in Icó-Mandantes bay

In contrast to the river basin, in the Icó-Mandantes bay macrophyte diversity was very low, as only three taxa were detected in the water: the submerged species *Egeria densa* and *Chara guairensis* and the emergent *Nymphoides indica* (Fig. 4-23). Those species were also present in the tributaries of the sub-basin of the reservoir, but not specifically in the main course of the river.



Fig. 4-23 Macrophyte species identified in Icó-Mandantes bay within the study period: *Egeria densa* on the left; *Chara guairensis* in the middle; *Nymphoides indica* on the right.

*Egeria densa* was the most frequent species in the four field campaigns, with a relative frequency of more than 80 % (Fig. 4-24). The maximum colonization depth during high water level was 8.0 m and 6.2 m at low water level. *Chara guairensis*, the second most frequent species, occurred less frequently during low water level (33 – 37 %) than at high water level (52 %). This species co-occurred with *Egeria densa*, but merely in exposed areas with sandy sediments, such as the region where the bay

connects to the main channel of the reservoir. Here water currents of the main stream are stronger and *Egeria densa* cannot fix to the ground. *C. guairensis* can grow as deep as 8.5 m water depth, in sparse stands. The presence of *Nymphoides indica*, as rooted emergent plant generally growing at the shoreline, was sporadic (less than 5 % of occurrence from September 2012 to October 2013). However, in June 2014, the occurrence of *N. indica* slightly increased (11 %) while the frequency of the two submerged species remained similar.

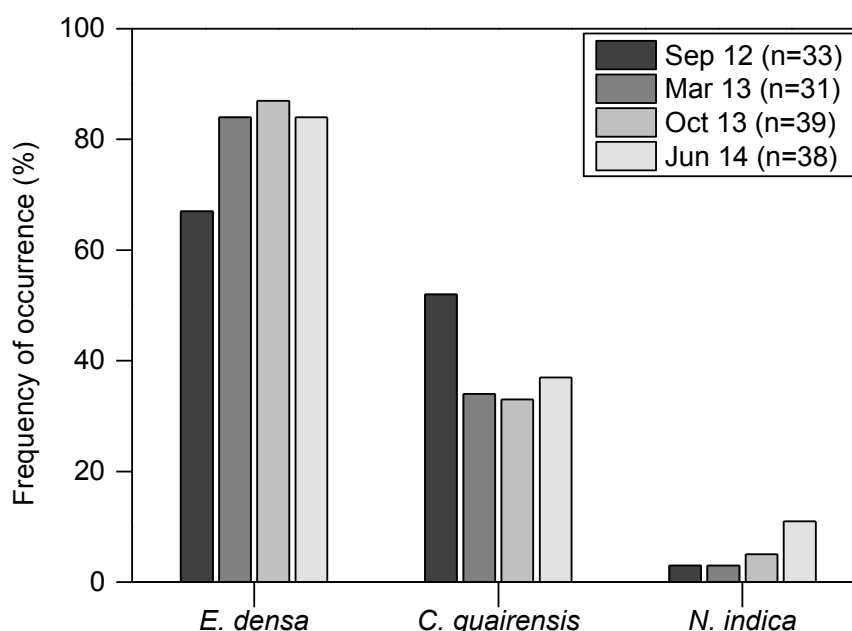


Fig. 4-24 Frequency of occurrence of macrophytes in Icó-Mandantes bay in September 2012, March 2013, October 2013 and June 2014 (*Egeria densa*, *Chara guairensis* and *Nymphoides indica*).

### 4.5.2 *Egeria densa* distribution and coverage

*Egeria densa* was dominant in the bay in relation to the other two species. The submerged macrophyte was broadly distributed, occurring in practically the entire littoral area down to 6 - 8 m water depth, at low and high water level, respectively. The total coverage corresponded to 35 - 45 % of the bay. *E. densa* was particularly profuse in the inner bay (Fig. 4-25), which was characterized by shallow areas (see bathymetry in Fig. 4-17) protected from wind and water currents. Here large monospecific stands were registered with up to 2.5 m thickness during high water level (see Fig. 3-6).

Currently, the development of a digital terrain model in the region is in process, performed in the framework of INNOVATE project (Tavares Junior et al., 2017), using the database obtained in this study. These analyses aim at calculating the biovolume of stands of submerged macrophyte based on cartographic databases and remote sensing (Fig. A - 5). The development of such a method can have outstanding applications in monitoring programs of reservoirs. Macrophytes monitoring, particularly submerged ones, is laborious work which imply manual effort and significant costs. This technique would be an innovative way of circumventing the obstacles, and able to supply results with higher accuracy in extensive regions and within shorter periods.

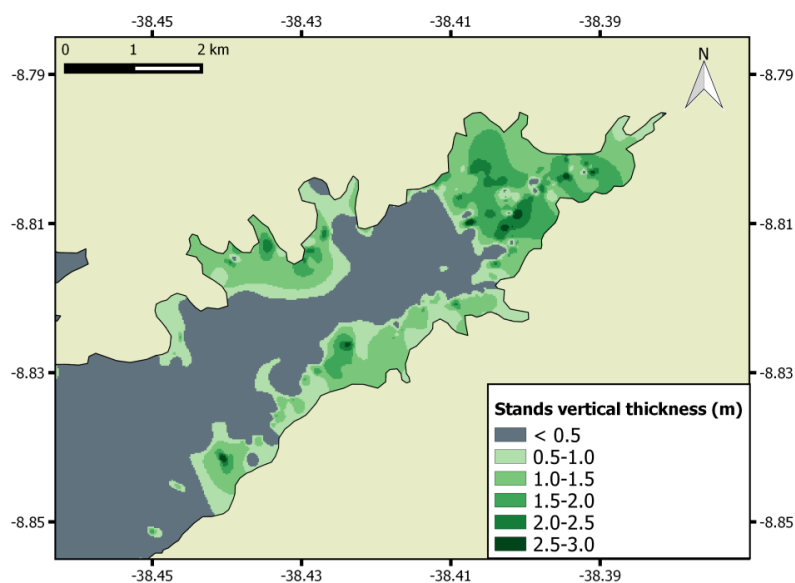


Fig. 4-25 Spatial distribution of *E. densa* in Icó-Mandantes bay and vertical thickness of the stands of *E. densa* in meters in March 2013, based on 428 sampling points with echo-sounder. A profuse growth of *E. densa* is patent in the inner part of the bay (further away from the main stream of the reservoir).

#### 4.5.2.1 *Egeria densa* as habitat for *Biomphalaria* sp.

Dense stands of submerged macrophytes in reservoirs are often a favoured habitat for the spread of waterborne diseases, such as Schistosomiasis, which uses snails as dissemination vectors. In this study, the presence of the snails *Biomphalaria* sp. in *Egeria densa* stands was recorded (Fig. 4-26).



Fig. 4-26 *Biomphalaria* sp. attached in shoots of *E. densa* in Icó-Mandantes bay.

*Biomphalaria* sp. was registered mainly in the interior part of the bay in a patchy pattern, where *E. densa* mats are more exuberant, reaching 7 Org. per g<sub>dwEd</sub> in June 2014. This is a very high concentration taking into account that this mollusk is a host of the human parasite *Schistosoma mansoni*, which is responsible for the waterborne disease Schistosomiasis, endemic in Northeast Brazil (Martins-Melo et al. 2015).

#### 4.5.2.2 *Egeria densa* composition and growth rate

*Egeria densa*, as a submerged plant, has a high content of water: 87 %. The dry matter of this aquatic plant in Icó-Mandantes bay is composed by 34 % total carbon, 2.3 % total nitrogen and 0.2 % total phosphorus (Table 4-6).

Chlorophyll *a* concentration amounted to 0.06 % of fresh weight. The presence of heavy metals in *E. densa* in this region was negligible (Cd, Cr, As, Pb < 0.01 µg mg<sup>-1</sup>). N and P content in the canopy of the plant was significantly higher than in the middle and low sections of the stem, but not chlorophyll *a* or carbon contents.

Growth rate experiments showed different mean growth rates dependent on the water depth (Fig. 4-27): at 2 meters and 3 meters water depth, mean growth rates were significantly higher than at 1, 4 and 6 meters water depth ( $p < 0.05$ ). At 1 m water depth, plant growth was disturbed by wind waves and high solar radiation. At 4 and 6 m water depth, growth was probably hindered by low light conditions. Plants located at 2-3 m water depth had advantageous growth conditions with low disturbance by wind waves and yet a high exposition to light. These results give an insight on the distribution of *Egeria densa* in the bay, with thicker stands between 2 m and 3 m water depth. Considering light a major limiting factor for *Egeria* growth in deep regions of the bay, in high transparency conditions enhanced growth rates can be expected also at 4 to 6 m (*Egeria densa* was registered at 8 m water depth during high water level).

Table 4-6. Nutrient composition of *E. densa* (dry weight) in Icó-Mandantes bay, in µg mg<sup>-1</sup> (n = 45).

Component	Concentration (µg mg <sup>-1</sup> )
Total Phosphorus (TP)	1.9 ± 0.7
Total Nitrogen (TN)	23.0 ± 4.4
Total Carbon (TC)	342 ± 25
Iron (Fe)	5.1 ± 1.6
Manganese (Mn)	2.2 ± 0.8
Chlorophyll <i>a</i>	0.59 ± 0.35*
*Wet weight	

Mean daily growth rate at 2 m water depth was  $1.26 \pm 0.47$  cm per shoot, resulting in an estimated growth per day of  $14.1 \pm 5.3$  g<sub>dw</sub> m<sup>-2</sup> (with a density of 780 shoots per m<sup>2</sup>). At this depth, the mean standing biomass of *E. densa* in the bay in June 2014 amounted 673 g m<sup>-2</sup>, which means a reproduction rate of 2.1 % d<sup>-1</sup> and a doubling time of 48 days, besides vegetative propagation.

Such a growth rate implies a daily uptake from the water column and sediments of 27 mg P m<sup>-2</sup>, 325 mg N m<sup>-2</sup> and 5 g C m<sup>-2</sup>. These amounts are very significant in the system, as these correspond to 78 % of the TP available in the water column, and 56 % of TN, in June 2014. These results show the superior capacity of *Egeria densa* on nutrient abstraction from the water in this bay, with probable competition with algae or other plants.

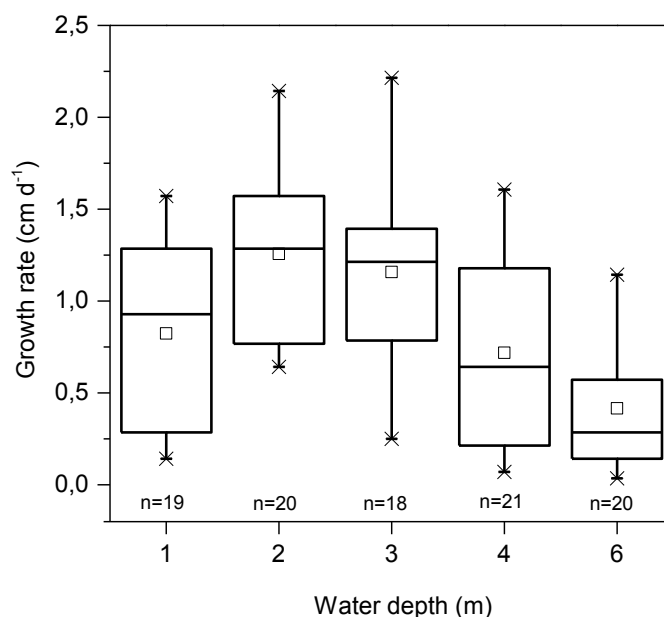


Fig. 4-27 Growth rate of *Egeria densa* at different water depths (1, 2, 3, 4 and 6 m). Growth rate is represented as daily growth of shoots in cm. Experiments were carried out in June 2014. Box plots represent mean (square), Q25, Q50, Q75 (lower, middle and higher horizontal lines of the box, respectively) and minimum and maximum values (error bars).

### 4.5.3 Spatial and temporal dynamics of *E. densa* stands

Itaparica reservoir experiences water level fluctuations seasonally with several associated impacts (see section 4.6). With water level drawdown also *Egeria densa* stands are affected and become, in part, desiccated in the dried banks of the bay. The effects of water level drawdown and of extended low water level on the submerged *E. densa* standing crop in Ic -Mandantes bay were assessed by analyzing the biomass of this plant before and after water level decrease and during drought period.

#### 4.5.3.1 High water level

In September 2012 water level was high and the stands of *E. densa* were profuse. Until 2 m water depth, *E. densa* was present in almost 60 % of the sonar surveyed locations, and in regions between 3 m and 7 m water depth it occurred almost everywhere (more than 70 % of survey sites) (Fig. 4-28). Although less frequently, *E. densa* was detected at 8 m water depth (295.3 m a.s.l.), supported by the deep euphotic zone down to 11 m (Table 4-7).

With regard to plant volume inhabited (PVI) (Fig. 4-29), in this period of high water level the water column was only partially filled with *E. densa*: no more than 30 % in regions deeper than 3 m water depth. The highest median plant volume occurred at 2 m water depth (61 % of the water column).

In this period, nutrients concentration (TP and TN) in the water column were very low, and pH was very high, particularly in the inner bay (pH = 9.2), revealing CO<sub>2</sub> limitation in the middle of the stands. With these water conditions, only rooted species can thrive, and/or species with nutrient concentration mechanisms in their organelles, to overcome nutrient depletion. *Egeria densa* has both features: it is a submerged rooted plant able to uptake P and N from sediments and also a C<sub>4</sub>-like plant, with high bicarbonate affinity and thus can grow in milieus with very low CO<sub>2</sub> concentrations. The ability of taking up nutrients from the roots or by passive diffusion from the water column is a competitive advantage during high water level, which endorses dominance in the system, not allowing the growth of other plants.



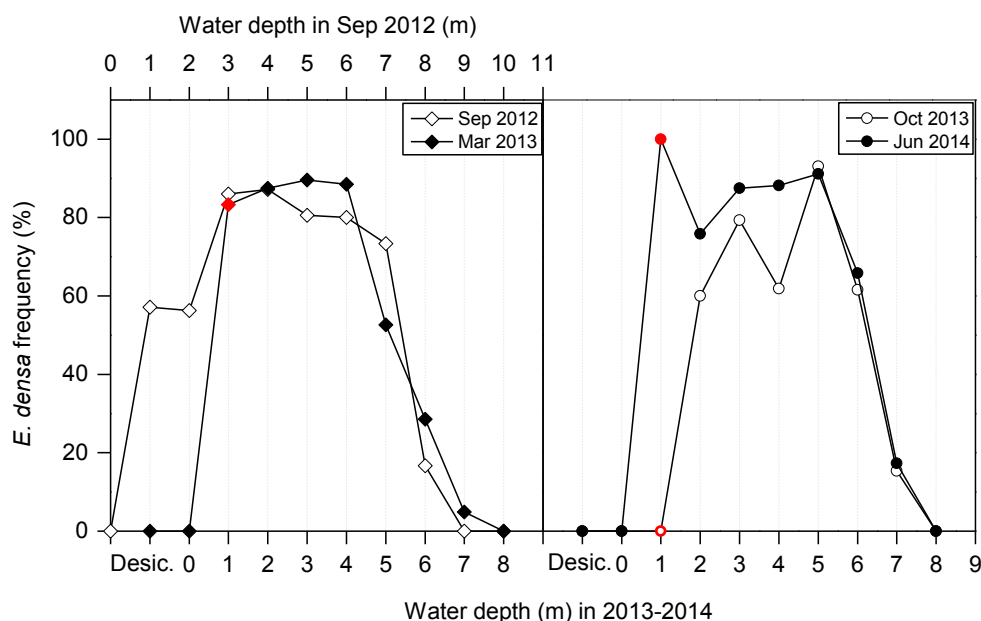


Fig. 4-28 Frequency of occurrence of *Egeria densa* on the surveyed locations by acoustic methods, in high water level (September 2012), in low water level (March 2013), and in drought periods (October 2013 and June 2014) ( $n > 12$ ). Red points at 1 m depth indicate small sampling pool ( $n = 6$  in March 2013,  $n = 1$  in October 2013 and  $n = 4$  in June 2014).

Table 4-7. Water level, euphotic zone ( $Z_{eu}$ ), and *E. densa* maximum colonization depth ( $Z_{maxEd}$ ) in the four field campaigns.

Water level season	Field campaign	Water level (m a. s. l.)	$Z_{eu}$ (m)	$Z_{maxEd}$ (m)	Water depth with highest stands (m)
High	Sep 12	303.3	11,0	8.0 (295.3 m a.s.l.)	6
Low	Mar 2013	300.6	4,5	6.2 (294.4 m a.s.l.)	6
Drought	Oct 2013	300.5	6,9	5.6 (294.9 m a.s.l.)	4
Drought	Jun 14	300.4	7,1	6.2 (294.2 m a.s.l.)	5

#### 4.5.3.2 Low water level

After September 2012, water level decreased and lead to a change in *E. densa* distribution. In the field campaign during low water level in rainy season (March 2013), *E. densa* was very frequent along the littoral area, as it was registered in more than 80 % of the survey positions until 4 m water depth (Fig. 4-28). In deeper regions, it was present less regularly, until a maximum of 6.2 m water depth (294.4 m a.s.l.). Despite the 3 m water level decrease, *E. densa* spread down only 1 m (from 295.3 to 294.4 m a.s.l.) (see Table 4-7). This was due to the poor water quality conditions (high nutrient and chlorophyll *a* concentrations – see Table 4-3), which turned out to impact the water transparency ( $Z_{eu} = 4.5$  m) and consequently light availability in deep regions of the bay.

Water level drawdown also impacted the water column, which became in a great extent filled by the dense stands of the macrophyte. That was particularly patent in the littoral area until 4 m water depth, where the plant biovolume accounted for more than 60 % of the water column (Fig. 4-29). In many regions until 2 m water depth, which occurred mostly in the inner part of the bay, *E. densa* occupied the water column entirely, by growing until water surface (PVI = 100 %).

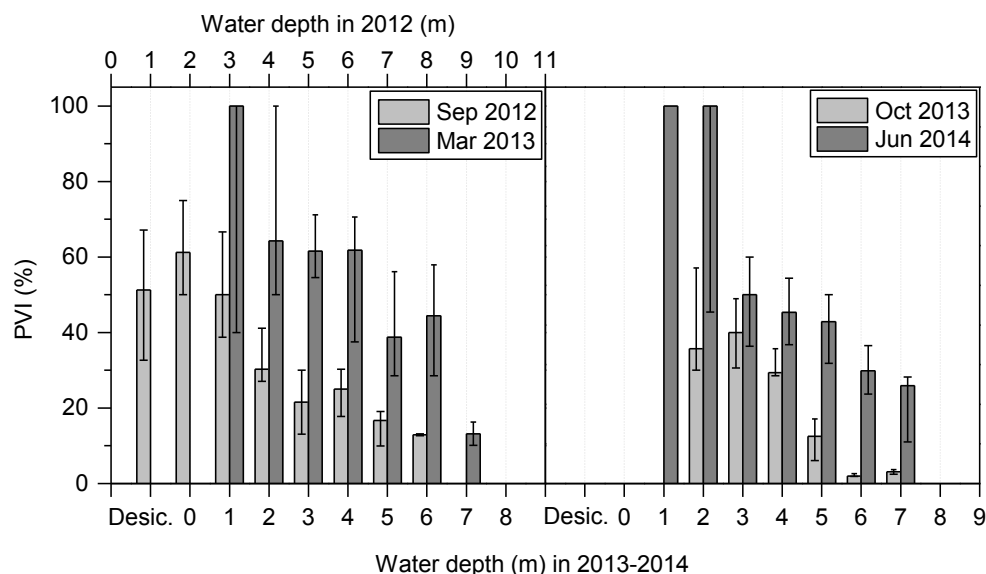


Fig. 4-29 Median volume of the water column inhabited by *E. densa* (PVI) in Icó-Mandantes bay in September 12, March 2013, October 2013 and June 2014. Error bars represent 75% and 25% quartiles. Des. = desiccated margins. Light and dark gray indicate dry and rainy season, respectively.

At the shore and in shallow regions, *Egeria densa* was exposed to high water temperatures and direct sunlight – in regions where PVI was approximately 100 % - as well as to low transparency. The decay of the plant because of these hostile conditions was certainly an extra source of nutrients to the surrounding medium, which may have worsened transparency conditions and trophic state. Plus, at the bottom of the stands in the inner bay, very low concentrations of  $O_2$  were measured, indicating anoxic conditions. In fact, high methane emissions were detected also in this region by Rodriguez and Casper, (2017).

On the contrary, in deep regions of the bay this plant developed and even colonized new areas, despite the high turbidity. The high stands of *Egeria* in deeper areas in this season evidenced the capacity of *E. densa* of phenotypically adapt to light intensity by elongating its shoots towards water surface when light is too low (Yarrow et al., 2009).

#### 4.5.3.3 Long lasting drought period

In the months succeeding March 2013, water level remained low due to the drought and the low light conditions of the water persisted during several months, which seem to have had a detrimental effect on the standing biomass of *E. densa*. In October 2013, the coverage of *E. densa* and PVI in shallow areas decreased since the previous sampling campaign (Fig. 4-29). Contrarily, in regions deeper than 5 m, the frequency of occurrence increased (Fig. 4-28), even though PVI was very low with very short mats between 5 and 7 m water depth (3 % of water column). Regions deeper than 5 m occurred only in the central and outer bay where transparency was also higher. Although euphotic zone had increased to 6.9 m, the maximum colonization depth ( $Z_{maxEd}$ ) did not show noteworthy variation since March 2013 (Table 4-7).

In the following rain season (June 2014), *E. densa* had recovered its presence in more locations of the bay, especially until 5 m water depth (Fig. 4-28). Furthermore, a considerable growth of *E. densa* was observed, as the water column in regions until 2 m water depth was again fully occupied by *E. densa* (PVI = 100 %) and also in deeper regions the mats of the plant were thicker than in October 2013, occupying approximately 25 % of the water column (Fig. 4-29). The recovery of *E. densa* stands from October 2013 to June 2014 is probably related to enhanced nutrients availability due to rainfall.



### 4.5.4 Primary production in the bay

The assessment of ecological shifts in lakes presumes the quantification of the contribution of phytoplankton and macrophytes on total primary production of a system. This comparison has been done mainly based on phytoplankton biomass (Chl *a* concentration) vs. macrophytes coverage area, or phytoplankton vs. macrophytes biovolume (Hilt, 2015; Loverde-Oliveira et al., 2009). However, this evaluation is subjective in terms of actual quantification of the total potential primary productivity of a system and correspondent nutrient cycling involved, because of the absence of a standardized comparison parameter. Chlorophyll *a*, the pigment necessary for photosynthesis, is present in all photoautotrophic organisms (phytoplankton and macrophytes included). The use of chlorophyll *a* as a uniformization parameter between macrophytes and phytoplankton has been already used elsewhere (Hu et al., 2014), for the determination of the trophic state of lakes considering the presence of macrophytes. Also in the present study, chlorophyll *a* concentrations derived from phytoplankton and from *E. densa* were used as a criterion to compare the contribution of each to total primary production in Icó-Mandantes bay, and based on that, infer their importance on the total primary production in this reservoir. Even though photosynthesis efficiency can change between species, the main factors generally affecting synthesis yields are water temperature and light availability (Reynolds, 2006), which in this case should influence both groups similarly. Also, most photoautotrophic organisms can adjust light sensitivity by regulation of cellular chlorophyll *a* content.

Phytoplankton Chl *a* was measured together with water quality parameters survey (Table 4-3). For the assessment of the chlorophyll *a* present in *Egeria densa* in each sampling campaign, the biomass of *E. densa* at different water depths was first determined.

#### 4.5.4.1 Determination of *Egeria densa* biomass

The calculation of biomass of submerged macrophytes such as *Egeria densa* offer difficulties, as the impenetrable stands hinder the sampling by divers, or require the use of equipments constructed specifically for that purpose and location, which only work if stands are not too dense (Carrillo et al., 2006). The associated error to biomass estimation is nevertheless relatively high (Dromgoole and Brown, 1976). Therefore, the biomass density of *E. densa* in literature is normally referring to the density measured at the margins until one meter water depth, where the use of quadrat or similar systems is still possible. In this study, the mean density of *E. densa* stands was assessed by quadrat as well, and a succession of correlations was carried out to calculate biomass values in deeper regions (Fig. 4-30).

At the margins, biomass amounted to  $370 \pm 189 \text{ g}_{\text{dw}} \text{ m}^{-2}$  ( $n = 16$ ), which corresponds to a wet biomass of  $2.9 \pm 1.5 \text{ kg}_{\text{ww}} \text{ m}^{-2}$ , as *E. densa* major component is water (Fig. 4-30 a). The mean shoot length of *E. densa* measured at the margins was  $33.1 \pm 10.3 \text{ cm}$  ( $n = 658$ ). According to the correlation of Fig. 4-30 b, each of these shoots weighs  $3.9 \text{ g}_{\text{ww}}$ . Then, shoot density at the margins of the bay is  $780 \text{ shoots m}^{-2}$ . Assuming this shoot number per  $\text{m}^2$  for the whole bay, a correspondence between stands height and biomass density was established. This allows, together with acoustic survey data which provides the mean height of *E. densa* stands, an estimation of the biomass per depth category (Fig. 4-30 c). As an example, after this model, the biomass of a stand with 1 m height corresponds to approximately  $1.1 \text{ kg}_{\text{dw}} \text{ m}^{-2}$ .

Chlorophyll *a* (Chl *a*) of *E. densa* in Icó-Mandantes bay is present at a concentration of  $0.6 \text{ mg g}_{\text{ww}}^{-1}$  which is equivalent to  $1.7 \text{ g m}^{-2}$  at the margins. Assuming the same premises as before, *E. densa* Chl *a* in the bay can be estimated after the linear regression in (Fig. 4-30 d).

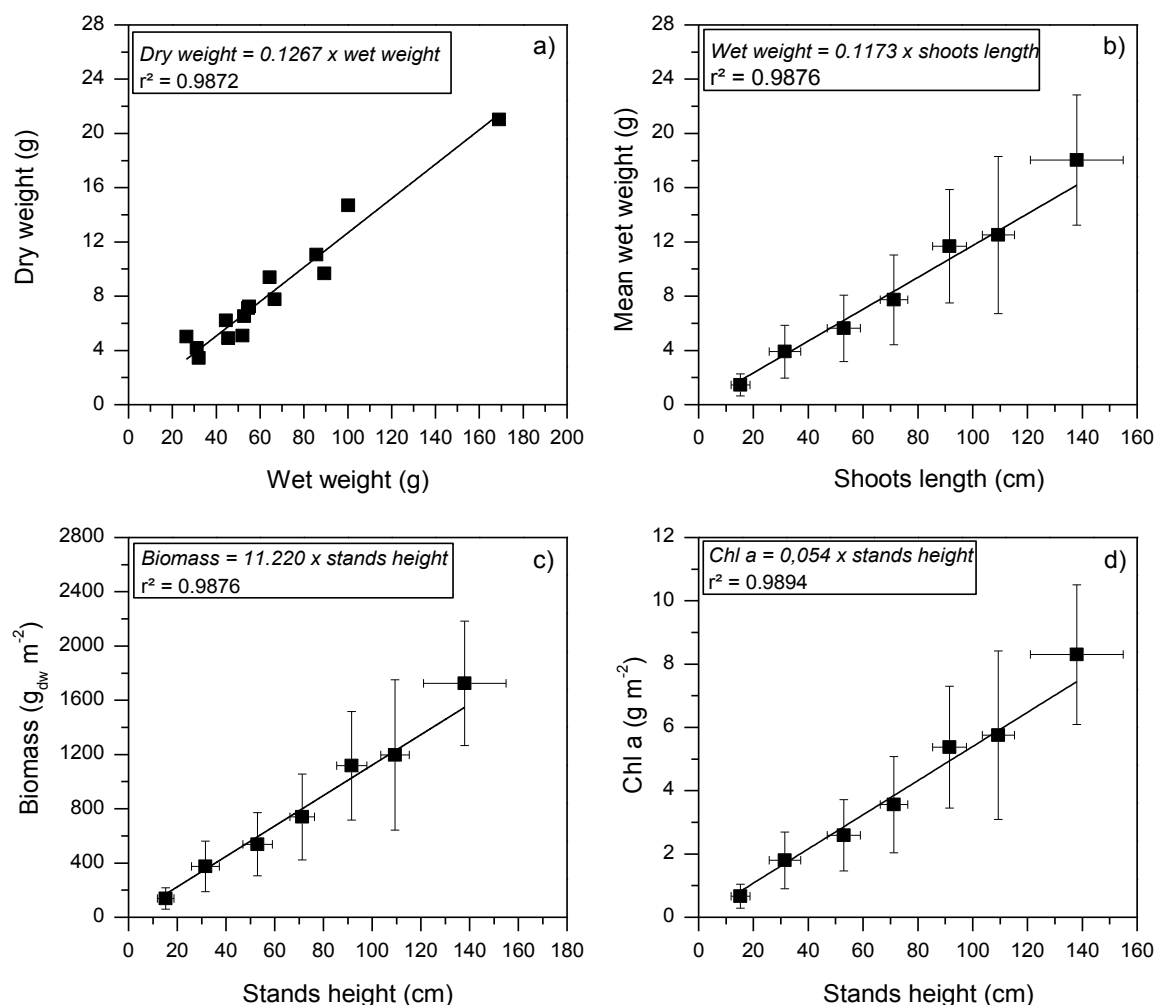


Fig. 4-30 Linear regressions used for the calculation of *E. densa* biomass and Chl *a* concentration in stands with different heights.

Based on these correlations, the mean biomass density of *E. densa* before and after water level drawdown at different water depths was first calculated (Fig. 4-31). During high water level (September 2012), the highest density with  $1.6 \text{ kg m}^{-2}$  was detected at 6 m water depth (297 m a.s.l.). Additionally, other locations showed high densities, at 3 m and 4 m water depth ( $1.6 \text{ kg m}^{-2}$  and  $1.4 \text{ kg m}^{-2}$ , respectively). These results agree with growth rate experiments which showed higher growth rates at intermediate depth regions. At low water level (March 2013), the biomass had increased in deep regions and a peak at 6 m water depth (295 m a.s.l.) reached a density of  $2.4 \text{ kg m}^{-2}$ .

In a regular year, water level would rise after March and kept high until October but, due to the severe drought in 2013, water level remained low. The impacts of a long lasting low water level were observed in the stands of *E. densa*, as the biomass density decreased from March to October in the whole bay, showing low biomass concentrations (max.  $1.1 \text{ kg m}^{-2}$ ). Some months later however, in June 2014, the plants had recovered their biomass particularly in deep regions: at 5 m water depth (296 m a.s.l.) *E. densa* biomass reached  $1.8 \text{ kg m}^{-2}$ .

Overall, biomass was observed to increase in the rain periods of March 2013 and June 2014, when compared to the previous dry periods (September 2012 and October 2013, respectively), particularly at water depths between 4-7 m. This is related to the higher availability of nutrients in the water column carried from the sub basin to the bay by surface runoff, which potentiates macrophyte growth.

The determination of biomass of *E. densa* standing crop across the different sampling campaigns reveals the large quantities of nutrients potentially involved in the dynamics of growth and decay of this plant in Icó-Mandantes bay. This knowledge is essential for the understanding of Itaparica reservoir and for the development of adequate management tools.

#### 4.5.4.2 *E. densa* vs. phytoplankton competition

The comparison of concentration of chlorophyll *a* from macrophytes and phytoplankton inside Icó - Mandantes bay in each sampling campaign intended to assess the role of the two groups of organisms in total primary production potential of the bay. The exchange of importance from one group to the other reveals the occurrence of ecological shifts in the system, which might have very serious outcomes on whole food webs and main processes regulating nutrients cycling inside the system.

Chlorophyll *a* present in *E. densa* was calculated based on the correlation described in Fig. 4-30 d, and on the area of Icó-Mandantes covered by *E. densa* in each sampling season (Table A - 1), and compared with chlorophyll *a* from phytoplankton.

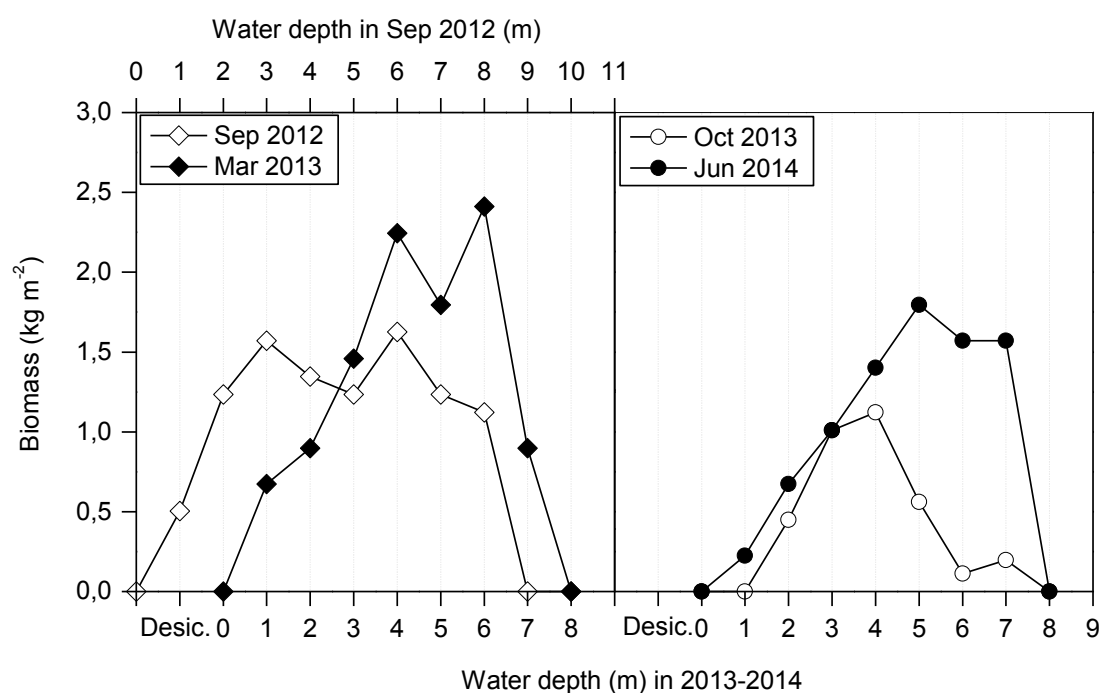


Fig. 4-31 Biomass (dry weight) of *Egeria densa* stands at different water depths, in (a) September 2012 (high water level) and March 2013 (low water level) and in (b) October 2013 and June 2014 (low water level). Desic.= desiccated margins. Open and full symbols indicate dry and rainy season, respectively.

During high water level, the standing crop of primary producers was correspondent to a concentration of  $481 \mu\text{g L}^{-1}$  of total chlorophyll *a* (Chl *a*-total - Chl *a* derived from phytoplankton and from *Egeria densa*). Phytoplankton biomass was very low with little opportunity to grow, due to the low trophic state of the water. *Egeria densa* accounted for 99.6% of this value, being therefore the most competitive photoautotroph in the system during this period (Fig. 4-32).

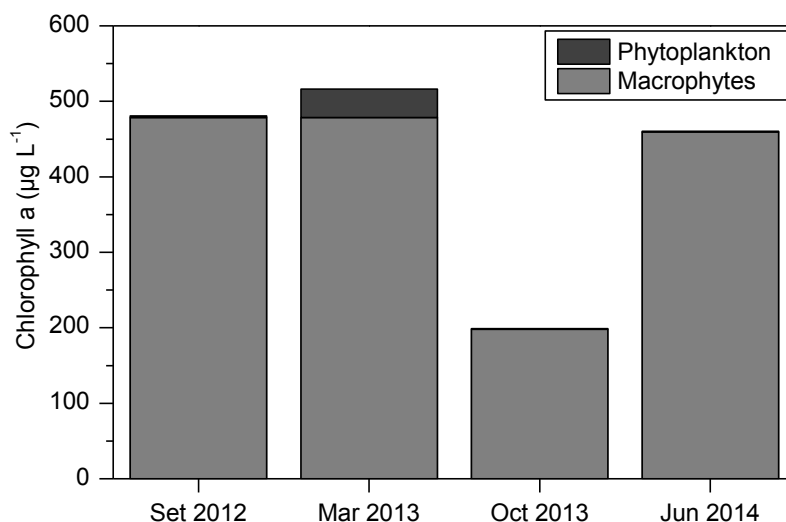


Fig. 4-32 Primary production contribution of phytoplankton and macrophytes based on their correspondent chlorophyll *a* concentrations in high and low water level in Icó-Mandantes bay.

The submerged area where *E. densa* was present decreased from September 2012 to March 2013, and a large amount of *Egeria densa* desiccated at the margins. Although *E. densa* biomass decreased in absolute terms, the concentration of the plant chlorophyll *a* (Chl *a*-Ed) in the smaller water volume remained similar ( $478 \mu\text{g L}^{-1}$  Chl *a*-Ed). The effect of water nutrients loading with water level drawdown during rain season is evidenced by total Chl *a* increase ( $516 \mu\text{g L}^{-1}$  Chl *a*-total). In fact, phytoplankton was present in a higher proportion (mainly *C. raciborskii*) with 7 % of total chlorophyll *a*, showing a change in the system from a macrophyte dominated state to a increasingly co-dominance of both species.

The prolongation of low water level during drought period hindered the typical recuperation to a macrophyte dominated system, expected with water level rise. On the contrary, in the months following March 2013 until October 2013 the cyanobacteria bloom persisted and has most likely hindered *Egeria densa* growth by shading, and nutrients exhaustion (mainly P). In October 2013, nutrient concentrations in the water column were very low, similar to those of the previous dry season September 2012 (see Table 4-3). *E. densa* standing crop decreased since March 2013. Nevertheless, the share of the plant in the bay was 99.6 % of total production potential ( $198 \mu\text{g L}^{-1}$  Chl *a*-Ed), as phytoplankton in this period had significantly decreased, too (only  $0.7 \mu\text{g L}^{-1}$  Chl *a*-P). Thus deficit in light and nutrients may have been limiting factors for macrophyte and phytoplankton growth in this period, respectively. In June 2014, rain season during long lasting low water level, *E. densa* role as main primary producer in the bay recovered, showing a biomass similar to that observed in the previous rain season (total of  $459 \mu\text{g L}^{-1}$  Chl *a*-Ed), accounting for 99.7% of potential primary production.

These results show that *E. densa* is the main primary producer in this bay but also that is quite vulnerable to sudden nutrient loading. Rain season after water level drawdown seems to trigger phytoplankton development and propensity for phytoplankton domination. As a consequence, an ecological shift takes place and cyanobacteria blooms (e.g. *C. raciborskii*) are expectable with deterioration of aquatic functions of the bay. In contrast, during drought period the share of phytoplankton concentration was very low after rain season. The constant water level during study timeframe was essential to assess the role of water level drawdown on phytoplankton development.

Moreover, the observed dominance and capacity of recovery of *E. densa* revealed the importance of this macrophyte in nutrient cycling in the bay and therefore on the regulation of phytoplankton growth.

Therefore, the evaluation of the trophic state of the system must consider not only Chl *a* concentration from phytoplankton but also from the standing crop of macrophytes.

## 4.6 Desiccated margins

Every year Itaparica reservoir experiences seasonal water level fluctuations, resultant from a combination of rainfall in the São Francisco River watershed and hydropower operational needs. After rain season in the river basin, the water is stored in Itaparica reservoir for energy production in the following dry season and therefore, water level rises (Fig. 4-33).

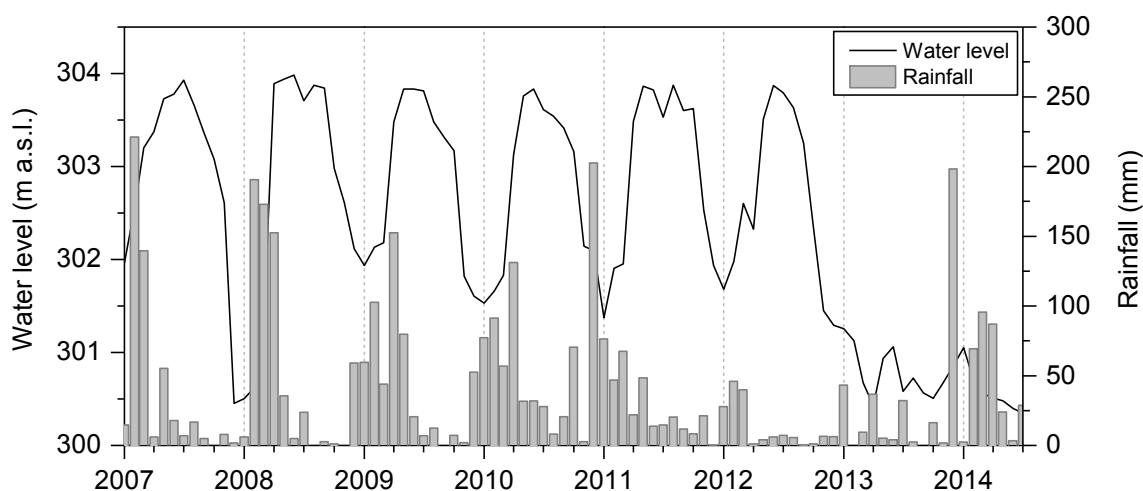


Fig. 4-33 Annual water level fluctuations in Itaparica reservoir (2007 to 2014) and monthly rainfall in the region (weather station at Floresta). Water level rise takes place by the end of rain season. After 2013 water level rise did not take place, and water level remained low in the following years.

The periodic water drawdown of about 3 m impacts not only the submerged stands of *E. densa* but also the littoral area by regular desiccation with consequent banks erosion (Fig. 4-34).

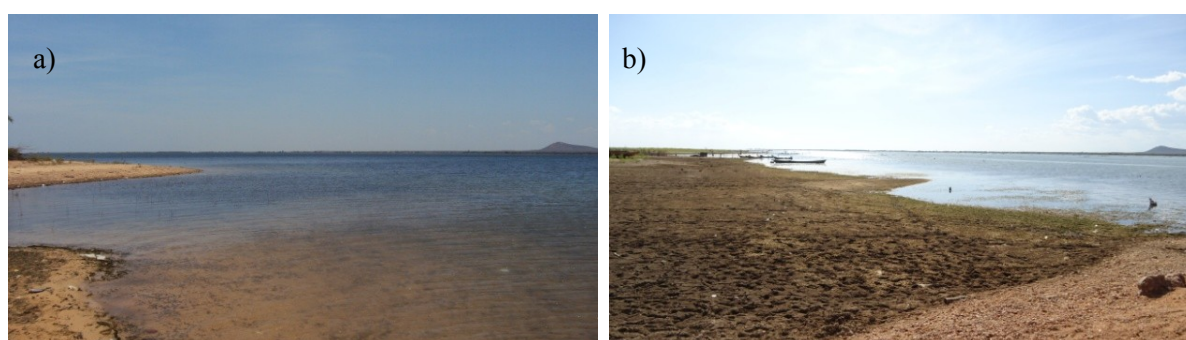


Fig. 4-34 Margins of Icó-Mandantes bay in a) high water level (303 m a.s.l.) and b) low water level (300 m a.s.l.).

Between September 2012 and March 2013, a wide littoral shallow area dried out with water level drawdown (from 303.3 m a.s.l. to 300.6 m a.s.l.) (Fig. 4-35). This area was calculated to be correspondent to 8.0 km<sup>2</sup>, 32 % of Icó-Mandantes bay (Selge, 2017).

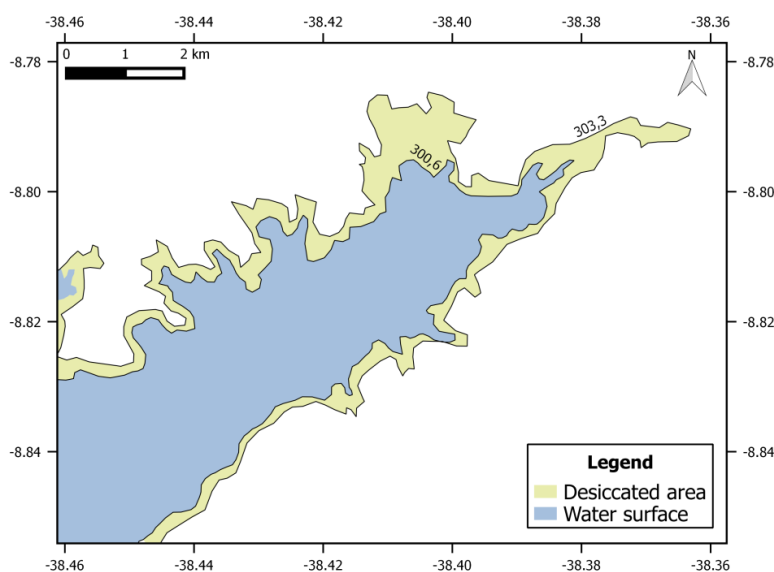


Fig. 4-35 Area in Icó-Mandantes bay which desiccated between September 2012 (303.3 m a.s.l.) and March 2013 (300.6 m a.s.l.), due to regular water level drawdown.

In this period, the banks previously flooded became aerated and littoral vegetation and fauna died out by drought (Fig. 4-36, on the centre and right side). A large amount of *Egeria densa* stands desiccates in the margins of this bay every year after water level decline. Within these mats, various species of invertebrates subside by breakdown and dehydration of the habitat.

The action of intense climate conditions in the dried margins, namely high air temperature (mean 30 °C) with direct sunlight, low humidity and high wind speeds, result in the rapid mineralization of organic material of the desiccating vegetation and sediments (Fig. 4-36, left).



Fig. 4-36 Effects of water level drawdown in Itaparica reservoir: sediments and organic matter mineralization by exposition to air (on the left); breakdown of flora (*Egeria densa*) in desiccated margins and of littoral fauna (ex. *Aylacostoma* sp.) (left and right side, respectively).

#### 4.6.1 Sediments characterization

Desiccated sediments along the margins of the bay were characterized for grain size composition and main nutrients composition. These sediments, with distinct desiccation times (between 2.5 months and 1.5 years), sampled at different levels above water level, presented a very homogeneous composition,

with sand as major component (mean 97 % sand and 3 % silt) (Table 4-8). In contrast, sediments permanently underwater were composed mostly by silt and clay (> 70 %), evidenced in Fig. 4-37.

Table 4-8. Characterization of permanently flooded sediments and desiccated sediments of Icó-Mandantes bay (mean  $\pm$  standard deviation).

Parameter	Underwater sediments	Desiccated sediments
Water content (%)	69.9 $\pm$ 1.8	4.7 $\pm$ 5.3
LOI (%)*	9.1 $\pm$ 1.5	0.9 $\pm$ 0.5
TN (%)*	0.245 $\pm$ 0.033	0.03 $\pm$ 0.02
TC (%)*	2.26 $\pm$ 0.33	0.29 $\pm$ 0.28
TP (mg g <sup>-1</sup> )*	0.57 $\pm$ 0.21	0.03 $\pm$ 0.01
Ca (mg g <sup>-1</sup> )*	4.12 $\pm$ 2.23	0.96 $\pm$ 0.48
Fe (mg g <sup>-1</sup> )*	50.2 $\pm$ 11.7	2.6 $\pm$ 1.3
Mn (mg g <sup>-1</sup> )*	0.48 $\pm$ 0.18	0.03 $\pm$ 0.02
Mg (mg g <sup>-1</sup> )*	4.0 $\pm$ 2.8	0.7 $\pm$ 0.4
K (mg g <sup>-1</sup> )*	8.5 $\pm$ 1.3	0.7 $\pm$ 0.4
Particles size (%)	Sand	22.4 $\pm$ 8.4
	Silt	97.1 $\pm$ 3.3
	Clay	n.d.

\*of dry weight

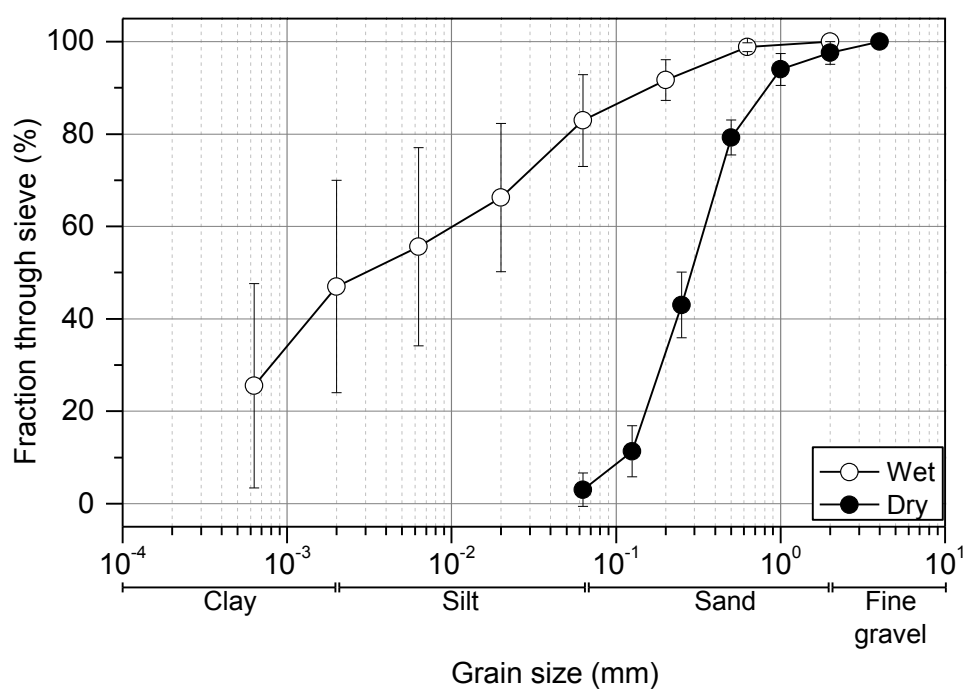


Fig. 4-37 Grain size distribution of permanently flooded (wet) and desiccated sediments (dry) (more than 2.5 months desiccation) of Icó-Mandantes bay.

Accordingly, desiccated sediments also differed to permanently flooded sediments in what concerns nutrient composition. In fact, desiccated sediments were, overall, significantly poorer in organic matter and nutrients than underwater sediments ( $p < 0.05$ ).

Underwater sediments were composed by a high content of organic matter because of the effect of the submerged macrophyte stands, which stabilize the water column and promote deposition of suspended particles. Additionally, a typical sorting effect occurs with the resuspension of fine particles due to wind induced waves in shallow zones at the shoreline, which are transported by water currents and re-settles in deeper lake areas. Thus, nutrients accumulate in regions with dense stands of macrophytes but mostly in the deep regions of the bay.

After reservoir drawdown (September/October), mineralization of sediments rich in clay and organic material takes place, by exposition to air, high temperatures and wind. Inorganic P and N are produced and organic C is transformed and lost to the atmosphere in the form of  $\text{CO}_2$ . The desiccated margins are subjected to more than one process of erosion in different seasons, as characteristic of the semiarid (Song et al., 2006). Wind action prevails during dry season and runoff during rain season. Thus, fine particles in the banks are blown by wind (until December/January) and leached by rain, ending up in sandy and nutrients poor soils, as the ones encountered at Icó-Mandantes margins.

## 4.6.2 Elution experiments

In order to understand some of the effects of the recurrent water level changes and the resulting desiccated margins in the promotion of outbreaks of macrophytes and phytoplankton, sediment elution experiments were conducted in the laboratory. These experiments aimed at studying nutrient release from desiccated sediments when re-wetted. Sediments with diverse desiccation times were used (2.5, 4.2 and 12 months) and the release rates compared (Fig. 4-38).

It has been observed that in the first day of elution, a pulse of nutrients from the sediments into the water occurred in all types of sediments. Desiccated sediments are therefore a nutrient source on the first 24 h of rewetting, releasing approximately 2 g of dissolved N per square meter and a mean of 25 mg of dissolved P per square meter (Fig. 4-38). The second phase of elution takes place from the second day on, releasing progressively lower amounts of N and P.

The amount of dissolved N released by fresh sediments was substantially lower than by naturally dried sediments (Fig. 4-38). The mean concentration of N released by the rewetted sediments in the 6 days elution period ( $2.6 \pm 0.4 \text{ g m}^{-2}$ ) was approximately 4 times that of permanently flooded sediment.

Rewetted sediments were also a source of P (mean  $54 \pm 17 \text{ mg m}^{-2}$  after 6 days of elution) whilst permanently underwater sediments seemed to behave as a P sink, revealed by the negative release rates. This means that the desiccation and following rewetting of margins promotes the release of P to the water body, which otherwise would not ensue. The capacity of submerged sediments of P retention were also observed in other experiments in the INNOVATE project (Keitel et al., 2015). Underwater sediments contain more silt and clay as well as Fe, which are responsible for the P binding capacity of this sediment (Keitel et al., 2015).

Desiccation times between 2.5 and 12.0 months do not seem to significantly influence the amount of leached nutrients, as the released concentrations were similar among the sediments with distinct drying times ( $p < 0.05$ ). These sediments are also very similar in terms of nutrients content and grain type, which result in an analogous release capacity. The uniform features of sediments with varied drying times indicate that the transformation process from typical submerged sediments (rich in organic matter) into nutrient poor sandy sediments due to desiccation occurs quickly ( $< 2.5$  months).



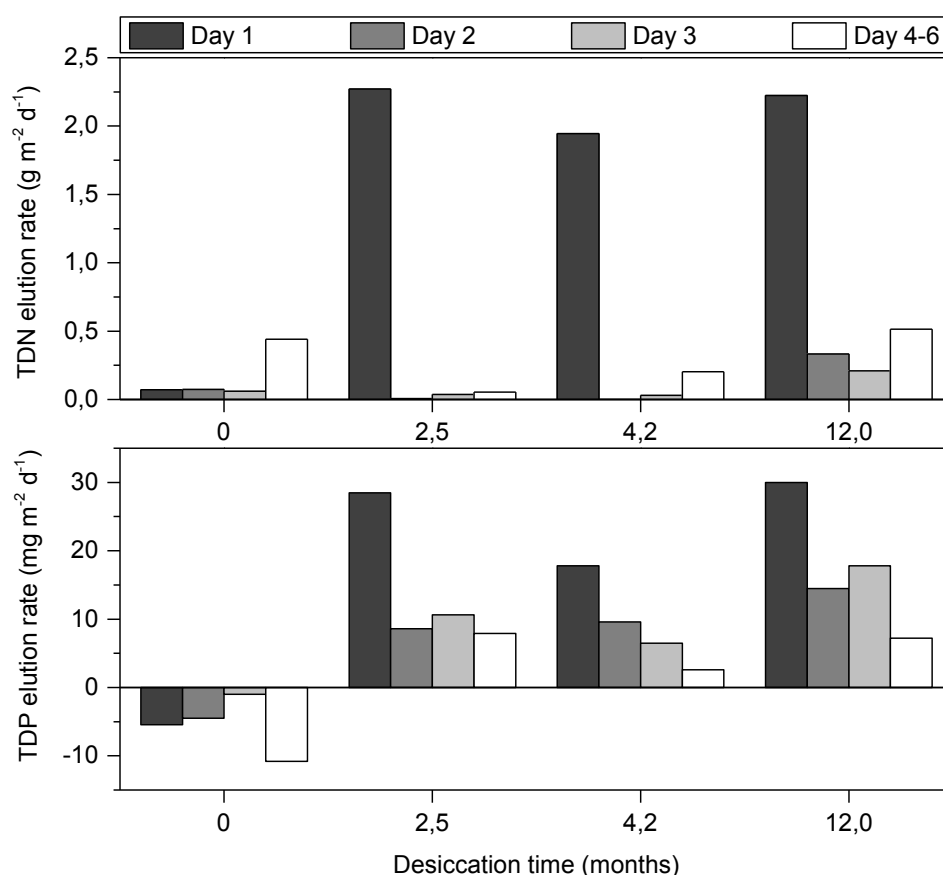


Fig. 4-38 Elution rates of total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) of fresh sediments (0 months) and of sediments desiccated in situ for 2.5, 4.2 and 12.0 months.

## 4.7 Effects of water level changes and management tools

Taking into account *E. densa* density (during high water level) and the nutrients composition of the plant tissue, the bulky mats of this plant stock a large quantity of nutrients in the biomass (31 g N m<sup>-2</sup>, 2.5 g P m<sup>-2</sup> and 458 g C m<sup>-2</sup>). The amount of desiccated *E. densa* in the bay when water level decreased in the end of 2012 was 7.5 x 10<sup>3</sup> t in whole Ic -Mandantes bay, correspondent to 0.9 x 10<sup>3</sup> t km<sup>-2</sup> biomass, 1.8 t km<sup>-2</sup> TP, 21.7 t km<sup>-2</sup> TN and 323 t km<sup>-2</sup> TC. In March 2013, P and N concentrations in the water of the bay were the highest measured in all field campaigns (see Table 4-3). *Egeria densa* breakdown due to water level decrease is one of the major anthropogenic P sources in the bay (78 %), in comparison to wastewater inflow (13 %), drainage water from agricultural areas (1.3 %) and P mobilization in desiccated areas (6.4 %) (Selge, 2017). The dieback of macrophytes when water level decreases plays therefore a crucial role on nutrients turnover in this bay that cannot be ignored due to its implication on the system management.

When water level rises, mineralized biomass enters the water body again, readily available for immediate cellular incorporation by primary producers, as evidenced in the sediment elution experiments.

Water level rise takes place in the end of rain season (from April on), in a period when the nutrients concentrations in the water are at the highest. The scenario of a water level increase of 4 m in Ic -Mandantes is illustrated in Fig. 4-39, based on the water nutrient concentrations in March 2013. The mean P release from rewetted sediments is 54 mg - almost 50 % of that present in the water column (TP = 102 mg). The mean release of N from rewetted sediments is 2.6 g, 1.7 fold the concentration in

the overlying water ( $TN = 1.5 \text{ g}$ ). These P and N loads are an extra source of nutrients to the water body, locally enriching the littoral of the bay.

The high affinity of *E. densa* for P and N showed by the high growth rate measured *in situ* is an advantage for the rapid development of this plant in the newly submerged areas. On a daily basis, *Egeria densa* can uptake half of the amount of P released for 6 days upon rewetting ( $27 \text{ mg P m}^{-2}$ ) and approximately one eighth of the released nitrogen ( $325 \text{ mg N m}^{-2}$ ). Nutrients uptake efficiency of algae and *Egeria* thus becomes a key factor concerning dominance of phytoplankton or macrophytes. The uptake of a great part of the available P results on the higher competitiveness in relation to phytoplankton, as the system becomes gradually P limited, if no external load of P takes place. The highly competitive features of nutrients absorption between *E. densa* and phytoplankton were also confirmed in littoral mesocosms experiments developed within the INNOVATE project. In these systems, *E. densa* was observed to be the major sink of the P and N added to the water column with impairment of phytoplankton growth (Selge, 2017).

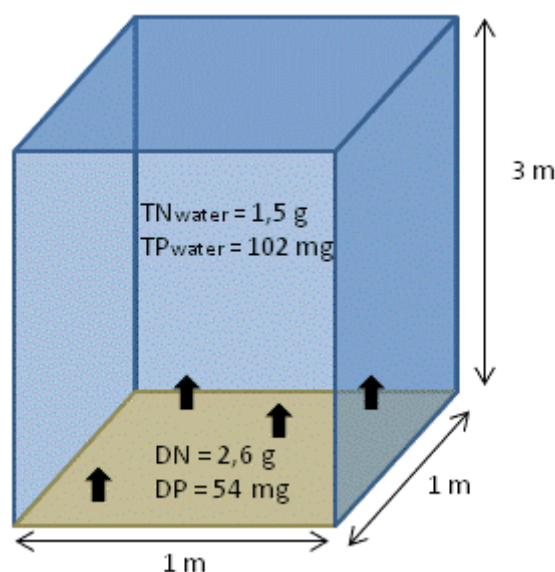


Fig. 4-39 Release of nutrients from rewetted sediments into the water column. DN = total dissolved nitrogen released per  $\text{m}^2$ ; DP = total dissolved phosphorus released per  $\text{m}^2$ ;  $TN_{\text{water}}$  = amount of total nitrogen in a water column of  $3\text{m}^3$ ;  $TP_{\text{water}}$  = amount of total phosphorus in a water column of  $3\text{m}^3$ .

In addition to N and P depletion, in the period of vigorous growth, *E. densa* consumes the available  $\text{CO}_2$ , which was verified by the high pH measured within *Egeria* stands ( $\text{pH} > 9$ ). Only species with high affinity for low  $\text{CO}_2$  concentrations, such as *Egeria*, can prosper in this period.

#### Long lasting low water level

During drought, water level was maintained low, at approximately 20 % of operative volume, in order to assure energy production yields. The relatively constant low water level for at least 2 consecutive years culminated in the development of a new littoral zone (Fig. 4-40).

The margins that once were submerged were then filled with terrestrial vegetation, particularly in the inner part of the bay, which enclosed a higher diversity than before Fig. 4-41. Some of the flora species registered in June 2014 in Icó-Mandantes bay margins are illustrated in Fig. A - 6. These observations reveal the intrinsic potential of re-vegetation of the banks and of forming ecosystems with higher complexity. Besides, nutrient input by run-off during rain season would be more easily prevented with a vegetation stripe with buffering capacity.



Fig. 4-40 Comparison of littoral region of Itaparica reservoir in September 2012 (left side) with high water level and in June 2014 (right side) after almost 2 years drought. The figure shows the growth of terrestrial vegetation in the desiccated margins.



Fig. 4-41 Vegetated margins of Icó-Mandantes bay in June 2014, after 18 months of low water level.

This extreme climate event is an additional matter of concern in Itaparica water management. When refill of the reservoir takes place, the currently growing vegetation will be flooded, with underwater degradation and decomposition of organic matter promoting eutrophication, mainly in undisturbed areas such as the interior part of this bay.

Overall, seasonal water level changes in Icó-Mandantes bay were seen to promote low diversity of littoral fauna and flora, spread of *Egeria densa* as pioneer plant and the massive decrease of *Egeria densa* in the littoral zone.

The loss of littoral biodiversity is fomented by the breakdown of vegetation and animals (mainly invertebrates), and by the incapacity of plants with annual cycles to succeed due to periodic margins desiccation. Additionally, submerged plants have to compete for light in a shallower water column

with high turbidity during rain season, meaning that only species with highly competitive features prosper, such as *Egeria densa*.

*Egeria densa* holds traits which support a prolific growth: it is a submerged plant with vegetative growth; it can easily adapt to low light conditions, by elongation of shoots; despite of algae bloom shading effects, the plant resisted and showed recovery capacity; high growth rate with high affinity for nutrients - grows faster than other species, competing for P and DIC – allowing a pioneer behavior during water level rise.

Massive decay of *Egeria densa* in desiccated margins results in nutrient input to the bay and GHG emissions. Carbon is then lost to the atmosphere, leading possibly to DIC limitation in the system. Inside the bay, very dense stands at the water surface decompose by sunlight exposition, decreasing oxygen concentration in water column and favoring anoxia at the bottom of the stands. Anoxia can potentiate nitrification reactions, and this process is as a possible N loss path (Lewis, 2002). Nutrients (mainly P) become then available for blooming of perennial algae species like the N-fixing *C. raciborskii*, which has a high affinity and capacity of accumulation of P and hence can prosper in hostile conditions for other species.

---

## **5 Discussion**



## 5.1 Phytoplankton community in the main stream of Itaparica reservoir

Itaparica reservoir is an artificial lake with multiple uses in the semiarid Brazil, a region where water scarcity is in the background of the low economical development associated to this region. For the riverine populations, Itaparica reservoir is source of food and economic sustainability as fisheries are a very important part of the local economy, together with aquaculture. The water of the river is used for agriculture schemes where fruit and vegetable crops are produced and exported to other states or countries. Currently, water in the reservoir has been mainly managed in accordance to hydropower production needs. Water level increases in the end of rain season in order to assure a constant flow rate to produce energy during dry season. However, this implies wide water level fluctuations regularly every 6 months, which are certainly not adjusted to the biological and ecological needs of a semiarid aquatic system.

Reservoirs are dynamic systems with a high spatial and temporal variability in physical processes and biological responses. Variations within reservoirs can be studied via phytoplankton associations, as planktonic organisms respond quickly to environmental changes and exhibit more conservative characteristics than physical and chemical variables. In this study dynamics of primary producers in the reservoir were assessed in order to understand the ecological state of Itaparica reservoir and evaluate which drivers influence these dynamics.

Nutrients and light are two factors of foremost importance for photosynthesis, and consequently, bioproduction. These can be regulated by climatological (rainfall patterns, erosion by wind, wind waves, solar radiation, temperature, etc.) and hydrological drivers (flow rate, thermal mixing regime, residence time, sediment resuspension by waves, etc.), which hence indirectly shape the biomass and composition of phytoplankton in freshwater systems (Nogueira et al., 2010; Silva et al., 2014).

A high variation in phytoplankton biomass is typical of regions with marked hydrological seasonality and a significant washout period (Nogueira et al., 2010). This seems to apply to Itaparica reservoir, where the theoretical retention time ranged between a minimum of 46 days during low water level period and a maximum of 110 days in high water level period. Although theoretical residence time with high water level is reasonably high, the estimated values are not common in reservoirs of the Brazilian semiarid. Due to the adverse climatic conditions (high evaporation and low precipitation), water residence time in reservoirs in this region is often higher than one year (Barbosa et al., 2012). Phytoplankton assemblages in those systems are characterized by low abundance but high richness of Chlorophyta, and by high biomass of Cyanophyta and Bacillariophyta (Allan and Castillo, 2007; Barbosa et al., 2012; Nogueira et al., 2010). Itaparica reservoir showed similar characteristics: the highest number of species was observed in the green algae group, while diatoms showed the highest densities. The total number of taxa detected in this reservoir was comparable to other Brazilian reservoirs (Costa et al., 2009; Dellamano-Oliveira et al., 2008; Nogueira, 2000). In general, the algae community in the main channel of Itaparica reservoir is representative of semiarid region reservoirs, even though the relative contribution of cyanobacteria was not as significant as commonly observed in other systems (Barbosa et al., 2012). The high discharge rates associated to Itaparica reservoir are likely to affect cyanobacterial growth, which usually prefer stable water column with high residence times (Elliott, 2010; Nogueira et al., 2010; Romo et al., 2013). In a similar fashion, also in a cascade of eight reservoirs in Paranapanema River in Brazil, cyanobacteria only developed in the reservoir (located in the middle of the cascade) with highest water residence time (135-150 days), concluding that the flow rates were too high in the other impoundments for cyanobacteria development (Nogueira et al., 2010).

### 5.1.1 Spatial and seasonal development

Spatial and seasonal oscillations in phytoplankton assemblages and abundance were found along the main stream of Itaparica reservoir. Green algae adapted to shallow eutrophic systems typically occurred in the initial stretch of the Itaparica reservoir, as commonly observed in other reservoirs with riverine zones characterized by turbulence and shallower areas with lotic features (Nogueira, 2000). The most representative species of this taxonomic group in Itaparica included unicellular non-motile Chlorococcales which are typically prominent in shallow, highly enriched systems. The highest diversity index was observed in this region during low water level. Abundance and richness of Chlorophyta were highest in December, end of dry season, when water level was low and flow rate very high. A few months later, during rain season in March, *Aulacoseira* species dominated in this region. The alternation of *Pediastrum* sp. dominated communities with *Aulacoseira* sp. dominated ones has already been reported elsewhere (Reynolds, 2006). These are species adapted to highly enriched riverine conditions, being able to survive in turbulent systems with high light fluctuations (Reynolds, 2006; Soares et al., 2012).

A few kilometers downstream, the assemblages were replaced, and other species arose. The middle stretch of the reservoir, as a typical river-lake transition zone, was populated by Chlorophyta but also Cyanobacteria and Bacillariophyta, probably indicating the presence of both lotic and lentic communities. The disturbance on the system promotes the growth of diverse species, according to the disturbance theory from Folke et al., (2004). During rain season and low water level, green algae *Pediastrum* sp. and diatoms *Aulacoseira* sp. were the most typical species. Later in the year, when water level was high, Bacillariophyta were gradually more abundant along the reservoir and the presence of cyanobacteria like *Microcystis wesenbergii* and *Anabaena* sp. was usual in this region, when retention time was higher. According to the functional classification system, *Microcystis wesenbergii* (functional group M) is sensitive to flushing, and thus occurred mainly in the season with highest residence times. During dry season, in September, species of the functional group P, which require a continuous or semicontinuous mixed layer, were abundant. At the end of dry season, already with low water level (December), diversity in this transition region was high, and the most abundant species belonged to the Chlorophyta and Bacillariophyta groups. The green algae species present in this time are typical of clear, deep mixed regimes (Padisák et al., 2008), and the promotion of this sort of plankton can be explained by high flow rate and good light conditions.

Lacustrine areas are the deepest region in reservoirs and are expected to be prone to stratification and with better light conditions, as turbidity decreases due to the sedimentation of suspended solids.

Indeed, hot season in Itaparica reservoir seemed to impact the water column in the last stretch of the reservoir, which includes lower-middle and dam region, by forming a thermocline at water temperatures higher than 27 °C. The correspondent change in density of water that accompanies the change in temperature of 1 °C is much higher in warm water (> 28 °C) than in colder water (15-20 °C) (Lewis, 2000). Therefore, although unusual in temperate systems, in the tropics water column temperature differences of 1-2 °C between top and bottom are sufficient for stratification. Stratification of the water column fosters nutrients and plankton loss to deeper layers, shortening their supply for phytoplankton growth in the epilimnion.

During low water level, thermal stratification in combination with short residence time generally resulted in very low algae densities. Advective losses of nutrients and organisms result in a renewal rate of the water higher than growth rate of phytoplankton species. As a result, only species with high growth rates are able to endure, and species doubling time, prior to nutrient availability becomes a key factor. Water residence times up to 100 days have been reported to hydrologically impact algal growth in lakes and reservoirs of the United States (Allan and Castillo, 2007; León et al., 2016). In Itaparica, the lowest phytoplankton abundances were measured in seasons with residence times below 60 days. Additionally, after work developed by (Lopes et al., 2015), phytoplankton is rapidly transported out of



the reservoir by the high water discharge rates. This is in accordance with other studies, which refer hydrology as one of the most important factors in phytoplankton development in tropical reservoirs (Calijuri et al., 2002; Pacheco et al., 2015; Rangel et al., 2012) and consider advection processes an efficient strategy to reduce eutrophication effects in a water body, by means of phytoplankton control (Nogueira et al., 2010; Romo et al., 2013). In fact, the regulated mean operational discharge rate of  $2060 \text{ m}^3 \text{ s}^{-1}$ , established by the hydropower company CHESF, corresponds to approximately 60 days water residence time in Itaparica reservoir, which in this study was assessed as the threshold for higher phytoplankton development. The high flow rates applied are particularly efficient in the rain season, as strategy for eliminating highly enriched waters, which either lose nutrients to the hypolimnion by stratification or by washout.

In contrast, during high water level, water residence time in Itaparica was always above 60 days. The highest phytoplankton concentrations were measured in this period and Bacillariophyta was the most important algae group both in rain and dry seasons. In addition to the high residence time, the massive growth of these algae inside the reservoir is explained by the occurrence of different coincident factors which promoted nutrient availability. When water level rises during April and May, desiccated margins rich in mineralized organic matter are rewetted, functioning as a source of nutrients into the water body, as evidenced in the present study. Furthermore, rainfall from December to May transport sediments of the watershed to the river, and the reservoir is thus refilled with nutrient-rich water (particulate and dissolved form). Moreover, the role of internal fertilization was observed to be very important in this period. In this region, air temperature declines gradually from April/May on. The consequent decrease of water temperature at the surface promotes isothermal conditions and vertical circulation of nutrients, formerly lost into the hypolimnion during rainy hot season. This event marks a shift from a season with high nutrients concentrations at the bottom, due to stratified water column, to a season when these nutrients become again available in the euphotic zone. During stratification period, it is probable that microbiological metabolism assimilates the deposited organic matter, and mineralization products become trapped in the deeper regions of the reservoir. The lower oxygen levels at the bottom of the reservoir measured in this season are common in semiarid reservoirs because of decomposing processes (Barbosa et al., 2012). Also, DIN and DP concentrations in the bottom of the reservoir were higher than at the surface in this period (March). Based on the fact that oxygen levels at the bottom indicate an entirely oxic water column, high dissolved inorganic carbon was probably also retained in the bottom of the reservoir as by-product of organic material mineralization, as suggested, too, by the lower pH values at the bottom. During mixing period (June), surface and bottom water characteristics were more homogeneous and the high conductivity values measured confirm nutrient abundance and vertical circulation of dissolved solids.

In rain season (June), the highest phytoplankton densities were due to development of the centric diatom *Aulacoseira ambigua*, which has been reported to be dominant in other tropical lakes during the early stages of mixing (Heo and Kim, 2004; Reynolds, 2006). This species is closely associated to a changeable structure of the water column, being tolerant to frequent disturbance of the mixing layer and low light conditions. The maintenance of centric diatoms in the water column is dependent of turbulence associated to a mixing regime, which hinders the settling of the non-motile cells into lower regions of the water column. Mean water temperature is lower than in the months before, which also encourages the growth this stenothermic diatom (Reynolds, 2006).

In September, abundance was generally lower than in June, and phytoplankton was commonly dominated by the colony forming diatom *Fragilaria crotonensis*. This species has been reported to develop in the enriched epilimnion of semi-stratified aquatic systems (functional group P) (Padisák et al., 2008). During dry season, internal nutrient loading by physical mixing is the main source of nutrients in the water column. After the biomass peak in June in the first mixing phase, in September nutrient supply becomes shorter also at the bottom of the water column, and concordantly algae density in September was generally lower than in June. The long lasting mixing events with nutrients

depletion during dry season is also assumed by the thin layer of fine particles (down to a few centimeters) measured in the lacustrine zone of Itaparica reservoir (Rodriguez and Casper, 2017).

The succession from *Aulacoseira* sp. to *Fragilaria* sp. (as dominant species) during mixing period suggests a priori a generalized DIC limitation in the system, as these are two C deficiency tolerant species (Reynolds, 2006). Nevertheless, *Fragilaria* sp. can also use bicarbonate, being thus less sensitive to CO<sub>2</sub> limitation than *Aulacoseira* sp..

Overall, spatial and temporal patterns were clear in what regards algal assemblages and abundance in Itaparica reservoir. Here, as common in other tropical reservoirs (Rangel et al., 2012), phytoplankton seems to be mainly driven by water residence time and nutrients availability, which in Itaparica reservoir's case are promoted by water level rise, and rain carried nutrients and mixing of the water column, respectively.

Due to the higher availability of nutrients, rain season is also the period with higher probability of cyanobacteria blooms. These seem to be impeded by two main factors: during hot season, when stratification takes place and only cyanobacteria could thrive, high discharge rates are applied in the reservoir. Most cyanobacteria are sensitive to flushing and this is the reason for the low occurrences. In June, when residence time is higher, a natural mixing of the water column takes place, which promotes diatoms development. This natural event is similar to a commonly used method for cyanobacteria combat in drinking water reservoirs, which in those cases must be promoted artificially (artificial destratification using pressurized oxygen in the hypolimnion of reservoirs) (Bormans et al., 2016; Heo and Kim, 2004; Sherman et al., 2000). Thus, the main algae blooms in the lacustrine region of Itaparica reservoir between 2007 and 2010 were due to diatoms growth, during rain season and mixed water column period.

## 5.2 *Cylindrospermopsis raciborskii* in Icó-Mandantes bay

In Icó-Mandantes bay, water residence time is notably higher than in the main body of the reservoir (> 1 year), because of the low water exchange between these two systems. Thus, inside the bay phytoplankton biomass and composition are not affected by the stipulated operational high discharge rates of 2060 m<sup>3</sup> s<sup>-1</sup> that regulates the main stream of the reservoir. Water residence time in the bay is analogous to the residence time of other semiarid reservoirs, which frequently experience cyanobacteria blooms with consequent public health complications (Barbosa et al., 2012). During 2007-2010, the water in Icó-Mandantes was rich in green algae species, and diatoms biomass peaks were observed regularly, like in the main body of the reservoir. However, as anticipated, cyanobacteria played a greater role on the phytoplankton community in the bay than in the main channel, and toxic species were dominant at least once in each annual cycle. For a long period in 2008 (June to December) and in June 2009, cyanobacteria concentrations in the bay exceeded the limit of 20 000 cell mL<sup>-1</sup>, established by the national public health authorities (Brazilian Health Ministry) for drinking water supply (BMH, 2011). It is likely that in other periods this value was exceeded as well, however, our data units refer to Org. mL<sup>-1</sup> and thus it is not possible to confirm it, evidencing inadequacy of monitoring strategy. Abstraction of drinking water takes place inside the bay, which was observed to contain even higher concentrations of algae than the deep central part of the bay.

The cyanobacteria *Cylindrospermopsis raciborskii* was the most important species in the bay in terms of abundance and steadiness. Although more adapted to dry periods (Figueredo and Giani, 2009; Soares et al., 2013), confirmed by the high abundance observed in Icó-Mandantes bay during dry season, *C. raciborskii* was also always present in rain season, showing the high level of adjustment to the environment. This species dominates phytoplankton biomass for long periods, if ecological conditions are stable (Figueredo and Giani, 2009). The low renovation rate of the water in Icó-Mandantes promotes stability of the environmental settings, which persist for several months.

Therefore, long-term blooms of *C. raciborskii* (as the one observed in dry season from June to December 2008) are likely to happen in this bay.

Other studies developed in INNOVATE framework established that the main natural source of nutrients in this bay is the intermittent river during rainy season, which carries nutrients from erosion and from anthropogenic use of the sub-basin (Selge, 2017). High loads of N and P reach the bay via surface runoff after heavy rainfall and are mainly result of animal and human wastewater, fertilizers from agriculture fields and soil erosion. Drainage channels from the agriculture schemes around the bay end up in the interior of the bay transporting water with high TN and TP concentrations ( $194 \pm 246 \mu\text{g L}^{-1}$  and  $182 \pm 219 \mu\text{g L}^{-1}$ , respectively), which results in a correspondent surplus of 302 % and 610 % (respectively) in relation to the reservoir water. These nutrients sources increase the trophic state of the bay during rainy season, especially in the inner bay. On the contrary, during dry season external input is minor and Icó-Mandantes bay gradually undergoes nutrient limiting conditions (Selge, 2017).

*Cylindrospermopsis raciborskii* and *Microcystis* sp. are the most common cyanobacteria in eutrophic Brazilian reservoirs (Sant'Anna et al., 2008). Although these species are not prevalent in the main stream of the reservoir because of the high discharge rates, the high residence time in Icó-Mandantes enhances the probability of their occurrence. The dominance of *Cylindrospermopsis raciborskii* in relation to *Microcystis* sp. in Icó-Mandantes is related to:

a) Seasonal nutrient limitation

- Limitation of P - *Microcystis* sp. occurs preferably in eutrophic aquatic systems and thus the low concentrations of P in the water of Icó-Mandantes hinder the species development. In contrast, the high affinity for P and capacity of intracellular P accumulation make *C. raciborskii* very adapted to nutrient poor systems (Wu et al., 2009), allowing an efficient and quick uptake whenever P becomes available.
- Limitation of N - *C. raciborskii* has the capacity of fixing molecular nitrogen, and thus can thrive in N limited systems. Nevertheless, N fixation requires energy expenditure, so this species has preference for dissolved N, competing with species which are not able to fix N, such as *Microcystis* sp.. The occurrence of *Microcystis* sp. is more associated to high nitrogen concentration conditions (Mowe et al., 2015).
- N+P co-limitation – *C. raciborskii* is therefore very well adapted to a system with P pulses, which allow intracellular accumulation of P, which can be expended in P limiting conditions. At the same time, when N is also limiting, it can fix N from atmosphere. In N+P limited systems, with occasional P pulses from rain runoff, like in Icó-Mandantes, *C. raciborskii* is perfectly adapted, in contrast to other species which need P and N in abundance to thrive.
- Limitation of CO<sub>2</sub> – Both *C. raciborskii* and *Microcystis* sp. are able to use bicarbonate as inorganic carbon source (Holland et al., 2012; Talling, 1976), which is an important advantage in alkaline systems like Icó-Mandantes. However, the rate of CO<sub>2</sub> uptake of *C. raciborskii* is higher than of *Microcystis* sp., although this can uptake CO<sub>2</sub> at lower concentrations than *C. raciborskii* (Wu et al., 2009).

b) Soft water - The soft waters of Itaparica and in particular Icó-Mandantes bay may also play a role on the low competitive features of *Microcystis* sp., as low Ca concentrations have been reported to affect the buoyancy capacity of *Microcystis* sp. and ability of forming colonies (Wang et al., 2011). Small colonies of *Microcystis* sp. are also more exposed to zooplankton predation.

c) Constant high temperature - *C. raciborskii* does not tolerate high variations of temperature and the high temperatures across the water column in the shallow Icó Mandantes of up to 30 °C support its steady presence (Wu et al., 2009).

- d) Mixing regime - In permanently mixed layers light is increasingly the limiting constraint, and filamentous algae show preferential adaption (Reynolds, 2006). The filamentous *C. raciborskii* is detected often in high turbidity and greatly mixed systems (Mowe et al., 2015). In contrast, *Microcystis* sp. prefers stable water conditions, being hence sensitive to the turbid and mixed conditions of the bay (Reynolds, 2006).

*C. raciborskii* was always present, developing particularly in the inner side of the bay, where generally trophic conditions were more favorable. *Cylindrospermopsis* abundance was correlated with P concentration in the water, showing a quick response to a sudden P increase and a massive development in nutrient rich conditions, also confirmed by nutrients enrichment bioassays. On the contrary, N availability was not necessary for *C. raciborskii* development, which is explained by the capacity of fixation of atmospheric N.

The frequent dominance of cyanobacteria and particularly of *C. raciborskii* throughout the study period in Icó-Mandantes bay, even when total algae abundance was very low, shows the high susceptibility of this bay to nutrients pulses during rain season, with risk of *Cylindrospermopsis raciborskii* blooms. Also in other Brazilian reservoirs, the dominance of this species has been reported to be promoted by phosphate pulses (Posselt et al., 2009).

## 5.3 Effects of water level fluctuations in Icó-Mandantes bay

### 5.3.1 Development of pioneer species

In this work, water level fluctuations were observed to be a major driver conducting the growth and decay of *Egeria densa*, and to be responsible for the dominance of this plant in Icó-Mandantes bay. The effects of water level fluctuations on the expansion of macrophytes species is far from being fully understood (Bakker and Hilt, 2015; Jeppesen et al., 2015)(Bakker and Hilt, 2015). In lake Coqueiro in central Brazil, *Egeria najas* showed the same dynamics with water level fluctuations as *E. densa* in this bay (Loverde-Oliveira et al., 2009). In other lakes, it was seen that water level drawdown is an efficient measure for the elimination of invasive species (Zehnsdorf et al., 2015). On the contrary, periodical water level fluctuations, like in Icó-Mandantes bay, promotes the growth of pioneer plants (Cooke, 1980; Vivian et al., 2014).

During high water level, phytoplankton concentration and richness were very low, suggesting adverse conditions for phytoplankton development. The constancy of environmental conditions in terms of low precipitation and high water level in the preceding months of field campaign explains the high transparency values and the low nutrient concentrations in the water, which were certainly limiting for phytoplankton development. In this season, *E. densa* stands were copious, also favored by the high water column with deep euphotic zone. The success of *Egeria densa* is related to the very high affinity for the nutrients available in the water column: very high affinity for P uptake and cellular P accumulation, ability to use  $\text{NH}_4$  directly as source of N, and the capacity of growing in low  $\text{CO}_2$  concentration conditions (as low as  $17 \mu\text{L CO}_2 \text{ L}^{-1}$ ) (Casati et al., 2000). Additionally, as rooted macrophyte, it has the opportunity of uptaking nutrients from sediments, allowing growth without nearly any other competitors (Feijóo et al., 2002). The presence of profuse stands of this plant in the interior of the bay is in accordance with the gradient of phytoplankton density at this time, which was slightly higher at the bay mouth, where the effect of *E. densa* presence was minor. *Egeria densa* is considered an ecological engineer in this terms, because of the ability of clearing water (Yarrow et al., 2009). Loverde-Oliveira et al.,(2009) also reported growth period of *E. najas* (physiologically very similar to *E. densa*) with phytoplankton biomass decay during high water level in a tropical lake.

A few months after water level drawdown, rainy season started. The overload of nutrients from rain runoff and the breakdown of *E. densa* large stands together with the high temperature characteristic of this season are likely to have promoted enhanced water trophic conditions. The decay of *Egeria densa* underwater enhances dissolved CO<sub>2</sub>, N and P concentrations. In March 2013, nutrients and chlorophyll *a* concentrations were consistent to mesotrophic waters (Selge, 2017). *Cylindrospermopsis raciborskii* achieved remarkably high concentration in the bay in this period. This species has a very high affinity and accumulation capacity of P, which provides a very rapid reaction to nutrients increase, being therefore in advantage in relation to other algae species. Although *C. raciborskii* was dominant, algae richness was high, evidencing the role of nutrients abundance in the development of various algae groups. The high biogenic turbidity in the water column was shown, nevertheless, to be detrimental to *Egeria densa* expansion, particularly in deep regions (maximum colonization depth was 6 m, in comparison to 8 m during high water level).

Regularly, the state of high turbidity with high phytoplankton production is interrupted annually around April by water level rise. During this period, dilution of suspended solids and dissolved nutrients takes place, turbidity decreases, the flooded area increases, and *E. densa* which is light limited in deep regions, can easily expand to the shallow and freshly submerged surrounding, supported by a high daily growth rate. *E. densa* growth is encouraged both by nutrients already available in the water column and nutrients leached from the rewetted sediments, as already described elsewhere (Baldwin and Mitchell, 2000). The nutrient uptake efficiency is very high which makes *E. densa* a significant sink of P, N and C, limiting algae growth by nutrient competition, shading and allelopathy (Espinosa-Rodríguez et al., 2016; Yarrow et al., 2009).

The mechanisms behind natural regime shifts are still to be completely unravelled and research has mainly focused on the role of nutrient levels, water fluctuations and fish kills (Scheffer and Jeppesen, 2007). In Icó-Mandantes bay, the change from one state to another seems to be triggered by water level drawdown and rise, as already reported for other tropical reservoirs (Love-de-Oliveira et al., 2009; O'Farrell et al., 2011).

The processes described above are summarized in Fig. 5-1, which shows the annual regime occurring in Icó-Mandantes bay.

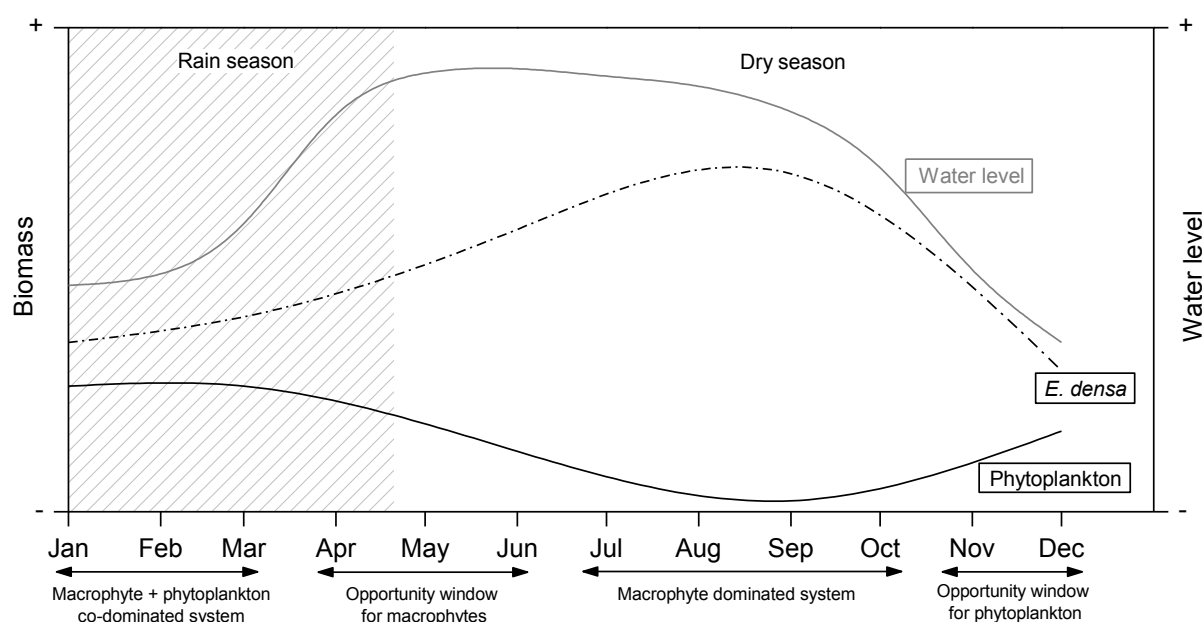


Fig. 5-1 Annual dynamics of phytoplankton and macrophytes biomass in Icó-Mandantes bay promoted by water level fluctuations.

When the year starts, rain season and *Egeria densa* decomposition are a pulse of nutrients in the bay, after a long period of nutrients scarcity. This opens a window for phytoplankton development, particularly high competitive species like *C. raciborskii*. This is a scum forming cyanobacteria with buoyancy regulation, able to uptake atmospheric nitrogen and to uptake P from the water column. The surface bloom is harmful to *Egeria densa*, which although being very competitive in terms of nutrients, is sensitive to shading (Carrillo et al., 2006). The decay process is accompanied by the release of senescence substances which encourages further decay. It is then expected a macrophyte and phytoplankton co-dominated system, with gradual benefit to phytoplankton, as submerged *Egeria* decomposition is a long lasting nutrients source. When water level rises in April, a shift in the system takes place and *Egeria densa* has again opportunity to grow, due to water dilution and wide shallow area of newly submerged areas. *Egeria densa* thrives during dry season, being a strong competitor for the available nutrients in the water, reaching dense canopies in oligotrophic waters. When water level decreases again around November, a new cycle begins: nutrients pulse from decomposing *Egeria densa* and posterior rainfall facilitate phytoplankton development, with risk of *Cylindrospermopsis raciborskii* blooms.

### 5.3.2 Desiccated sediments

*Egeria densa* massive dry out in the margins of Icó-Mandantes bay (and other protected bays with high biomass of *Egeria*) has impacts on the nutrients turnover in the Itaparica reservoir. The high metabolic rates due to high air temperature and unlimited oxygen availability promote a fast mineralization of the whole biomass and after 2.5 months sediments are practically devoid of organic matter.

During this process, N accumulates in the sediments in the form of nitrates as oxic conditions inhibit denitrification processes. Attygalla et al., (2016) showed that sediments capacity to adsorb P is reduced after desiccation, as also observed in the sediments of Icó-Mandantes bay. The recurrent water level fluctuations in Itaparica reservoir are, thus, likely to diminish the capacity of littoral zone sediments of retaining P with time. Likewise, internal P loading can become more significant with effects on enhanced P concentrations on overlying water.

The total mineralization of organic material results in the production of CO<sub>2</sub>, which is released to the atmosphere. These high emissions of GHG concentrated in a short period worsen the reservoir environmental performance. Additionally, water level drawdown results in the loss of carbon from the system, which is likely to potentiate DIC limitation during dry season.

The sediments desiccating in the margins of Icó-Mandantes after water level drawdown were shown to experience the Birch effect, with the highest nutrient flushes in the first day of rewetting. Such nutrients pulse is known to be immediately used by macrophytes with pioneer features and by microbial consortia in the rewetted sediments.

## 5.4 Effects of constant water level

Due to drought in the river watershed, water level was maintained constant in Itaparica reservoir in 2013 and 2014. The opportunity of sampling in this exceptional period provided an insight of the impact of rain in Icó Mandantes bay in the absence water level drawdown.

As water level rise did not occur in April 2013, the existing environmental settings observed in March 2013 (high density of *C. raciborskii*, high trophic state, deterioration of *E. densa* stands at the water surface in high PVI areas) affected the water body for a longer period than in a regular year. In 2008, a bloom of *Cylindrospermopsis raciborskii* lasted for half a year during dry season in this bay, and subsided only after beginning of rainy season. In a similar fashion, it is plausible that the bloom of this N-fixing cyanobacteria observed in March 2013 has endured in the following dry months, until P

depletion. P limitation is evidenced by higher phytoplankton abundance in areas where P concentration was also higher (in the interior of the bay). The algae bloom may have contributed for the slow growth of *Egeria densa* during those months, because of shading and nutrient competition, culminating in the low biomass stands of this macrophyte observed in October 2013. In this period, nutrients and ions concentrations in the water were low, and so was phytoplankton abundance. Still, *C. raciborskii* fraction was still high. The maintenance of low water level enhanced sediments resuspension by wind waves, which may have contributed for the high turbidity measured in October 2013. Light attenuation affected *Egeria densa* growth, and macrophyte lower stands facilitated sediments resuspension, which in turn, worsened light conditions for macrophyte growth. Sediments in the bay are rich in clay, which may have played a role on the removal of P from the water column, by adsorption to suspended clay particles in oxic conditions. At the mouth of the bay, P concentration was limiting for primary production, and even though in small number, *C. raciborskii* was dominant, evidencing the competitive advantage of this cyanobacterium to adverse conditions in relation to other species.

According to the processes illustrated in Fig. 5-1, nutrients depletion in the water column during dry season function as a window of opportunity for macrophyte development. The growth of *Egeria densa*, as a submerged macrophyte, promotes suspended solids deposition, the uptake of nutrients in the water column and in improved light conditions, which further enhance macrophyte growth and hinder phytoplankton development.

Heavy rain occurred in the beginning of 2014 and eroded sediments from the watershed increased nutrients availability in the bay. In June 2014, several cyanobacteria species, some of them diazotrophic, were abundant in the interior of the bay where P concentration was higher. *Egeria densa* stands had recovered, particularly in deeper areas, when compared to biomass of October 2013. These data suggest that rain related surface runoff was a source of nutrients to the bay, and it is possible that heavy rain events deteriorated transparency in the bay. In such conditions, cyanobacteria have a window of opportunity to develop, but if environmental conditions are reasonably favorable for *Egeria densa* growth, P and N sequestration by the plant can be critical for phytoplankton development (Feijoó et al., 2002).

The low water level for a long period impacted not only the water quality, but also had repercussions on the desiccated margins. In June 2014, littoral vegetation had developed and was composed by several terrestrial plant species distributed along the banks. These observations confirm the potential of the shore for a higher richness when conditions are advantageous. Additionally, it is possible that the riparian strip may have worked as a buffer, preventing a bulky load of runoff nutrients to reach the bay during intense rainfall in the beginning of 2014, favoring *E. densa* growth.

At the current practice of water level regulation, the growth of terrestrial vegetation should be taken into account when water level is predicted to increase again, due to the effects of biomass decomposition on the water quality.

## 5.5 Implications for reservoir management

The present study shows that water level fluctuations have impacts on the water quality of Itaparica reservoir and promote the massive growth of undesirable species, namely *Egeria densa* and *Cylindrospermopsis raciborskii* in Icó-Mandantes bay. In this bay, the seasonal decay of vast mats of *E. densa* due to water level drawdown during rain season and low water level comprises a significant source of nutrients in the water. This event supports blooms of the potentially toxic *C. raciborskii*, which undermines drinking water and irrigation water supplies. Also in Itaparica reservoir, *E. densa* should be a major focus of any attempts at ecosystem management because of the central role it can play in regime shifts, as suggested elsewhere for other systems (Yarrow et al., 2009).

Moreover, *Egeria densa* bloom should be prevented as well, regarding the impacts on ecosystem services of this bay. In fact, concerning the importance of reservoir multiple uses, *Egeria densa* can hinder a range of activities in this reservoir, such as recreation, artisanal fishery, aquaculture, bathing, navigation, and hydropower production by blockage of turbine grids, resulting in economic losses (Gunkel et al., 2015b). Additionally, the dense cover of macrophytes creates a favorable habitat for the establishment of vectors of waterborne diseases like schistosomiasis (Mustapha, 2008). The distribution of *Biomphalaria* sp., the host of the human parasite *Schistosoma mansoni*, is a good indicator of the occurrence of this disease and the identification and mapping of this disease vector is referred to be an important tool for spatial targeting of national disease control programs (Scholte et al., 2012). Indeed, the occurrence of *Biomphalaria* sp. in Icó-Mandantes bay increases the risk of disease propagation in the region and the most successful action against Schistosomiasis is attained by the control of aquatic plants, if molluscicides are banned for ecological reasons.

To improve aquatic functions in the reservoir, three main tools based on reservoirs management premises (Tundisi et al., 2008b) are here recommended: avoidance of water level fluctuations, *Egeria densa* removal and implementation of buffer biotopes.

### 5.5.1 Constant water level

A water level without major fluctuations throughout the year would mainly prevent the decomposition of *E. densa* when water level decreases, which in this study revealed to be a major source of nutrients for algae and cyanobacteria development. Concerning water level regulation, a more stable water level with only short flood – like event during rain season (mimicking the typical ecological flow of the semiarid) would be beneficial for various reasons. An analysis of the current water management of Itaparica reservoir concludes that hydropower production is not adjusted to the seasonal water availability and that wide water level fluctuations should be avoided if other services are to be considered (Gunkel et al., 2015a).

In the main stream, low water residence times associated to high discharge rates are a very important factor in maintaining an adequate trophic state of the water and hindering blooms of cyanobacteria. However, this procedure is not adapted to the quantity of water available in the region. An opportune natural mixing of the water column promotes phytoplankton growth, namely diatoms. With climate change, an increase of 2-3 °C as prognosticated (including during colder months), would imply a permanently stratified water column. A stratified water column with expected high residence times due to water scarcity is very favorable for cyanobacteria blooms, so common in other reservoirs in the region. If the water level would be maintained constant, a better operating effort should be done, in order not to increase the retention time. A constant water level would circumvent the seasonal increase of water residence time and the load of nutrients from rewetted areas, which happen when water level increases. If retention time must be increased, concerns on the external loads of nutrients into the reservoir should be taken in account. Additionally, artificial destratification should also be regarded as a possible strategy in avoiding cyanobacteria development during rain season with long residence times.

A stable shoreline would be beneficial for the littoral zone, supporting the growth and subsistence of littoral vegetation, and consequent increase of diversity at different trophic levels. Macrophytes communities enclose higher biodiversity in reservoirs with narrower water level fluctuations (Krolová et al., 2013; Thomaz et al., 2015; Zohary and Ostrovsky, 2011). Also in this study, it was showed that the drought during 2013 and 2014 conferred opportunity to other species to develop in the desiccated area, evidencing the revegetation potential of these margins with a stabilized water table. Such a water level regulation would, likewise, result in the occurrence of more plant species, especially those with an annual or biannual life cycle, which are adapted to the semiarid climate and show good survival rates when extreme events take place. More stable ecological conditions would also hinder the



proliferation of pioneer species such as *Egeria densa*, by nutrients and light competition. In addition to biodiversity increment, a vegetated littoral zone would provide increased stability against erosion without investment in extra remediation actions, and also act as a buffer strip, inhibiting the inflow of nutrients from runoff during intense rain events.

### 5.5.2 *Egeria densa* harvesting

A second important aspect in the management of Itaparica reservoir is the growth control of *Egeria densa*, as this plant is a pioneer dominant species in Icó-Mandantes bay. The massive growth of this macrophyte is promoted by the system of water level fluctuations and is associated to loss of ecosystem services such as water quality, fisheries, recreation and also to the promotion of spread of Schistosomiasis, which altogether result in economical and social costs.

This study showed that the bay is eutrophicated and that the nutrients are in a great part assimilated and stored in *Egeria densa* biomass. Considering *Egeria* as an efficient nutrient sink, the harvest of *E. densa* would not only be an efficient way of controlling macrophyte beds growth, but also of removing nutrients from the bay.

The removal of *Egeria* can be, however, a challenging task. Because *E. densa* is a submerged macrophyte, extra effort must be expended for harvesting underwater. There are several ecological impacts to be considered, such as the re-suspension of sediments and unintended removal of other organisms living within the plant mats. *Egeria densa* reproduces by fragmentation and care must be taken to avoid the dissemination of the plant (Zehnsdorf et al., 2015).

Theory predicts that when a critical, in practice unknown, amount of vegetation is removed, positive feedbacks propel the system to the turbid state with phytoplankton dominance. When less vegetation is removed, on the other hand, the system may show a swift recovery back to the vegetated equilibrium state, undoing the impact of mowing (Kuiper et al., 2017). Also, submerged macrophytes play an important role in the ecological status of aquatic systems, by improving biotic interactions and community structure, so the main focus should not be aiming at its complete removal, as this is a native plant and would constantly re-occur, but to control its spread and make use of its efficiency in storing nutrients. In this context, *E. densa* should not be uprooted but cut at the apical segment close to water surface. This prevents sediments resuspension and high disturbance of the water column. Moreover, this study showed that the canopy of the plant has the highest P and N concentrations, and therefore the cut of this section would be a proficient mean of nutrient removal from the system. The plant should be harvested from a boat connected by a line from shore to shore, in order to keep an overview of the area already harvested, and the release of plant fragments in the water should be avoided (Velini et al., 2005). As drawback, in Icó-Mandantes bay, the high density of submerged trees can complicate the harvesting process, and thus it is necessary to study the harvesting locations previously. The promotion of *Egeria densa* growth by cutting should be done preferably before rainy season starts, as the associated pulse of nutrients is an opportunity for algae, namely *C. raciborskii*, to develop.

#### *Biomass disposal*

The harvested biomass can have different disposals, but acknowledging the low fertility and moisture of the surrounding crop soils, the cut plants should be considered for soil melioration. *E. densa* has been successfully used with this purpose, because it has a suitable nutrient composition and the nutrients are rapidly released (Lara et al., 2009; Sampaio and Oliveira, 2005). The limited presence of potentially harmful heavy metals in the *E. densa* at this site is also advantageous (Sampaio and Oliveira, 2005). The use of this plant for animal feeding has also been studied in the region with experiments involving a diverse range of livestock such as goats, sheep or pigs (Dutra Júnior et al.,

2009; Oliveira et al., 2004). However, the nutritional value of *E. densa* is not sufficient for its use as a sole livestock feed, which implies that *E. densa* should be included as a fraction of the main forage (Batista et al., 2004). A study was conducted focusing on the use of *Elodea nuttallii* in the production of biogas, which results can be transferred to *E. densa*, because the plants have similar properties. This plant has a low fraction of organic dry matter (~10 %) and the study showed that the low yields of biogas generated by *E. nuttallii* fresh biomass makes it economically unviable (Zehnsdorf et al., 2015). For a more cost efficient process, a pre-step of biomass drying would have to be considered in this case, what should not be a setback in a semiarid region (low humidity with high mean temperatures).

Water level stabilization complemented with *E. densa* harvesting would likewise result in less *E. densa* biomass inside the bay and in a higher biodiversity of plants.

### 5.5.3 Buffer biotopes with *Egeria densa* at drainage channels

Rain carried nutrients reach Icó-Mandantes bay by an inlet in the inner bay and by open drains, which transport high concentrations of fertilizers of the agriculture schemes in the surrounding area of the bay. The construction of small impoundments along the inlet and the drainage channels was subject of study of other colleagues in INNOVATE project (Selge, 2017), as measure to avoid direct nutrient input in the bay. The present study complements this suggestion, as the pre-dams would be very useful if used as wetlands next to the agriculture fields. These ponds should have a base population of *Egeria densa* established. During rain season, water level would rise, and *E. densa* would grow and assimilate the nutrients carried into the pond. When plant stands present enough biomass and the water is clear (according to the dynamics in Icó Mandantes, this would happen in the peak of dry season) the water would be released to the bay. The water level decrease in these pounds would be useful to collect the plants and use them in the agriculture fields nearby. *Egeria* biomass is rich in nutrients and can keep the soil moisturized, very important in the semiarid soils. The harvest of *Egeria densa* biomass in these ponds would also be easier than in the Icó Mandantes bay and the farmer directly benefited. This would therefore be a closed cycle of nutrients which are flushed out from the fields during intense rain events and which would eventually be brought back in the form of *Egeria* biomass, prior to reaching the reservoir.

As a result, the quantities of nutrients inflowing in the reservoir would be much lower and the effects of rain in trophic level increase would be less significant. According to the previously referred measures, *Egeria densa* would still be present in the bay and ready to compete with phytoplankton for the upcoming nutrient loads. With these three measures, nutrient load in the bay would drop, and therefore the likeliness of algae blooms, particularly *C. raciborskii*, would be lower.

Icó-Mandantes bay has several functions, as it is base for leisure activities, for artisanal and recreational fishing and water abstraction for drinking and irrigation supply. As a shallow and protected part of the bay, it works as nursery for fishes and zooplankton. It is important to provide and maintain ecosystem services in this area.

The management tools here proposed can be used in implementation phase of INNOVATE and in future restoration programs and as basis of approach and analyses of other reservoirs, as hydropower reservoirs prone to eutrophication are abundant in the Brazilian semiarid. Water scarcity is a regional major problem and climate change scenarios indicate higher temperatures in the future with intensification of the current ecological problems. It is crucial to maintain good ecological status in the existing water bodies but the knowledge on the ecological dynamics of those systems is still limited. Thus the conclusions derived from this work may have importance not only locally but also across the rest of the economically developing and highly populated Brazilian semiarid.

---

## **6 Conclusions**



## 6.1 Main stream

The present study showed that in the main channel of Itaparica reservoir, phytoplankton abundance is affected not only by nutrient loading, but also by high water discharge rates. Advection processes inhibit the development of biomass during the season with favorable conditions for cyanobacteria blooms (rain season and hot period). Therefore, unlike other reservoirs in the semiarid, the main body of Itaparica reservoir is not affected by massive blooms of cyanobacteria. On the contrary, phytoplankton community is characterized by diatoms and green algae in the main stream with only punctual occurrences of Cyanobacteria.

Such management method assumes unlimited availability of water for the maintenance of water quality. However, water quantity and quality for the multiple purposes of the reservoir become seriously undermined in years of drought, when water scarcity does not allow such flow rates.

In mid-term and long-term perspectives, and regarding climate change forecasts for the Brazilian semiarid, this approach is not sustainable and must be changed. Effects of global warming have already been experienced with the drought in the São Francisco River watershed during the last 4 years, which is claimed to be the worst drought of the last 100 years in northeast Brazil. Such extreme event forced the reduction of water flux to  $< 1000 \text{ m}^3 \text{ s}^{-1}$  and a permanent low water level.

In this study it was found out that in seasons without high flushing of nutrients and algae, the availability of nutrients is the main driver for algae blooms. This availability is currently promoted by mixing events in the water column, which enhance nutrients and  $\text{CO}_2$  concentrations and consequent algae growth, mainly diatoms. These nutrients stock are result of decomposing organic material accumulated during rain season in the bottom of the reservoir, when stratification and high flow rates occur. In a situation of high temperature and high water retention time, cyanobacteria blooms are likely to occur in stratified water column, as in many other reservoirs in the region.

This means that in the future, the external load of nutrients, particularly during rain season should be hindered. Water level changes result in the erosion of the margins, with mainly sandy areas with low level of plant colonization. Such a system is very sensitive to intense rain events because of surface runoff, especially in regions with intensive agriculture. As observed, *Cylindrospermopsis raciborskii* is a perennial species in Itaparica reservoir and opportunistic when water retention time is high and pulses of P take place. In this sense, mainly P load in the system should be prevented.

Nevertheless, although high discharge rates were shown to be effective in suppressing algae biomass in the main stream, this method is neglecting hydrodynamically isolated bays, where flow rate of the main stream does not play a role and the risk of cyanobacterial blooms seems to be favored by other drivers than the ones of the main flow.

## 6.2 Icó - Mandantes bay

Bays with low connection with main channel of the reservoir show higher eutrophication risk. This was observed in Icó-Mandantes bay, where cyanobacteria develop more frequently and with extended effects, seasonally impairing the use of the abstracted water.

Overall, water level changes in this bay were seen to be involved in many different processes and to promote:

### *Decrease of littoral biotic community*

The dry out of littoral vegetation and invertebrates during 6 months and consequent extended flooding for another 6 months is not adapted to semiarid ecosystems, where quick and intense floods are mandatory condition for survival of autochthonous species (Maltchick and Florín, 2002). Only few species can adapt to the established artificial regime and normally those who do, have invasive and

pioneer characteristics like *Egeria densa* in Icó Mandantes bay. Low diversity of flora and fauna is a consequence of the water level fluctuations, which prevent the subsistence of a defined shoreline along the year, where highly diverse aquatic and terrestrial vegetation could become established. For these reasons, diversity and abundance of other macrophyte species in the bay were very low. When water level decreases, several species of invertebrates become exposed to direct sunlight and high temperatures, and their breakdown is evident along the desiccated margins.

### *Enhanced nutrient load in the bay*

A naked shoreline is more susceptible to erosion, and the low buffer capacity of these margins foster wash out and runoff events. The release of nutrients from desiccated sediments when re-wetted supports system eutrophication. The erosion severity of the soils surrounding Itaparica reservoir is a matter of concern and reported to have effects on the lifespan of the reservoir (Ramos and Pedroza, 2014).

### *Egeria densa dominance*

*E. densa* is dominant because is adapted to the ever changing conditions, it has high growth rate, fairly high tolerance to light limitation and high affinity for nutrients. The pioneer behaviour of *E. densa* prevents the growth of other plant species resulting in a fragile and low resilient system. Additionally, *Egeria densa* also competes with other species by allelopathy (Espinosa-Rodríguez et al., 2016). The dense stands of this submerged macrophyte are feeding ground for small fishes with consequent effects on zooplankton and algae populations (Pelicice and Agostinho, 2006).

This work also depicts the growth dynamics of *E. densa* during a drought event. The understanding of the ecological inter-relations, dynamics and drivers in such situations is crucial to apply adjusted measures for the control of this waterweed.

### *Schistosomiasis expansion*

The dense mats of *Egeria densa* in Icó –Mandantes bay are habitat for *Biomphalaria* sp., the vector of the parasite *Schistosoma* responsible for 3-6 million infected people in Brazil (Martins-Melo et al., 2015). Maps of the distribution of *Biomphalaria* sp. snails are not numerous and can be a useful tool for spatial targeting of Schistosomiasis control interventions (Scholte et al., 2012).

### *Massive decay of Egeria due to water level drawdown*

The decay of large amounts of biomass in the desiccated margins and at the surface of the water column is a representative source of nutrients in the bay. Besides, the mineralization of the biomass results in the loss of C to the atmosphere in the form of greenhouse gases. Decaying organic matter of *E. densa* in anoxic conditions is also a source of methane to the atmosphere, as verified by Rodriguez and Casper, (2017).

### *Turbidity increase*

With water level drawdown the bay becomes shallower and thus more prone to impacts of wind forming waves and sediment resuspension. The wave fetch in shallower water column reaches the bottom in areas where sediments were earlier settled during high water level (Selge, 2017). This sediment reenters the water column, enhancing water turbidity and impacting primary production in deeper regions.

### *Cylindrospermopsis raciborskii development*

*C. raciborskii* presence in Icó-Mandantes bay is steady and this cyanobacterium reacts readily to nutrients pulses (Burford et al., 2016). The load of nutrients facilitated by eroded margins rich in nutrients supports the massive growth of *C. raciborskii* that can compete with the debilitated *Egeria densa* stands by shading. Moreover, shading effects gives gradually more advantage in relation to

other algae species with lower growth rates. *C. raciborskii* is very aggressive by very adapted traits to the system, being a high competitor for nutrients and light.

#### *Cylindrospermopsis raciborskii* vs. *Egeria densa*

*E. densa* and *C. raciborskii* are two species with a high capacity of adaption and thus very invasive. They are mutual opponents as they have the same level of traits for competition – high affinity for P and intracellular P accumulation capacity, independence from N source and CO<sub>2</sub> affinity with possibility of bicarbonate assimilation. Water level changes promote ecological shifts and interchanging success of these species in the bay. Such a regime has already been observed in France with the exchange of turbid to clear water systems caused by *Egeria* and cyanobacteria (Dutartre et al., 1999).

## 6.3 Management tools

Overall, water level fluctuations in the reservoir were seen to be involved in a panoply of ecological processes in the bay and main stream. Directly and indirectly, it leads to poorer water quality and biodiversity and threatens the multiple ecosystem services of this water body.

Considering the water value in the semiarid northeast Brazil, oligotrophication of the system is very important for maintaining water quality and quantity. For that, constant water level, buffer biotopes construction and *Egeria densa* harvesting were the main three measures proposed in this work.

The outcomes of this study have repercussions on the management of the water of Itaparica reservoir and of the river watershed. This plan should be reevaluated considering the importance of the diverse aquatic functions of this reservoir.





---

## **7 Outlook**



This study, combined with other INNOVATE research on water quality, sediments processes and greenhouse gases emissions, contributed significantly for the increase of knowledge of semiarid aquatic systems, and of Itaparica reservoir in particular. Based on the data obtained in field campaigns and available monitoring data, knowledge on the system was built and allowed the identification of drivers for seasonal biogeochemical cycles. Nevertheless, the low number and duration of field campaigns and the limited data volume available from monitoring surveys of the reservoir prevented more detailed analyses of the system and a better perception of specific processes. Many questions came up along the research path which by their pertinence should be explored in the future for a comprehensive understanding of this aquatic system.

#### Future research

The present work opened a number of research lines and topics of interest which can contribute for a deeper understanding of the biodiversity and the spatial and temporal mechanisms behind ecological processes in Itaparica reservoir. These are related to biodiversity studies, nutrient cycling and restoration measures which can be approached as follows:

- 1) This study showed the importance of water level changes on the ecological shifts in Icó-Mandantes bay. In the future, it would be of interest to conduct analyses during the periods of water level rise and drawdown, as these were shown to be key points of system modification. These would include the first pulses of nutrients during decomposition of *Egeria densa* along water level drawdown. Besides, it would be important to quantify CO<sub>2</sub> emissions from desiccating stands.
- 2) INNOVATE research indicates that there are spatial and seasonal carbon limitation in the system. Accordingly, species registered in higher abundances were characteristic of systems with low DIC concentrations. The cycle of carbon in the reservoir seems thus to be a very important topic with high influence on primary production dynamics, species assemblages and GHG emissions.
- 3) Based on the knowledge obtained in this study, it is now clear that biweekly/monthly sampling for one year of phytoplankton and macrophytes stands survey would have been important to assess species succession and relation to nutrients availability.
- 4) Unfortunately, only monitoring data referring to years 2007-2010 was available for analyses. Data after this period would be important to compare with field campaigns data, and mostly importantly to analyze phytoplankton and water quality in the reservoir during drought period. According to the results, a higher concentration of cyanobacteria is expected in the main stream of the reservoir during this time. It is of high significance that environmental monitoring data of the reservoir becomes available to the public, at least to scientific institutions.
- 5) The harvesting of *Egeria densa* as restoration tool was suggested in this study. The calculation of the necessary amounts of biomass to be removed would be important for a cost effective intervention. This could be done, in similarity to other studies in temperate shallow lakes, using a model comparable to PC lake model, which was used to calculate removed P and evaluate long term effects of harvesting. Such a model in tropical lakes does not exist and would be beneficial for other applications too (Kuiper et al., 2017; Sachse et al., 2014).
- 6) Additionally, biomanipulation as a strategy of reservoir restoration is attractive, but much research is needed for a successful action plan. A better understanding on the food web would be achieved by analyzing fish and zooplankton communities (richness and grazing and reproductive patterns). This would help and support the decision making processes related to aquatic functions. Also examination of species with high value, endemic from São Francisco River should be used to see their potential on *Egeria densa* control. These findings would be

very important for *Egeria densa* growth control and in fostering growth of species with economical and ecological importance.

- 7) Diverse plant species developed in the margins of Icó-Mandantes during drought period. Their taxonomical classification and the assessment of their role in the ecosystem would be beneficial to increase information on endemic species of the semiarid, as only few studies are available on this topic. The information on the services they provide to the ecosystem is valuable as support for planning management programs.

---

## **8 Bibliography**



- Allan, J.D., Castillo, M.M., 2007. Stream Ecology: Structure and function of running waters, 2nd Edition. ed. Springer.
- Antunes, J.T., Leao, P.N., Vasconcelos, V.M., 2015. *Cylindrospermopsis raciborskii*: Review of the distribution, phylogeography, and ecophysiology of a global invasive species. *Front. Microbiol.* 6, 1–13. doi:10.3389/fmicb.2015.00473
- APAC, 2015. Agencia Pernambucana de Aguas e Clima (Agency of Water and Climate of Pernambuco) [WWW Document]. <http://www.apac.pe.gov.br>.
- Attygalla, N.W., Baldwin, D.S., Silvester, E., Kappen, P., Whitworth, K.L., 2016. The severity of sediment desiccation affects the adsorption characteristics and speciation of phosphorus. *Environ. Sci. Process. Impacts* 18, 64–71. doi:10.1039/C5EM00523J
- Azevêdo, D.J.S., Barbosa, J.E.L., Porto, D.E., Gomes, W.I.A., Molozzi, J., 2015. Biotic or abiotic factors: which has greater influence in determining the structure of rotifers in semi-arid reservoirs? 27, 60–77.
- Bakker, E.S., Hilt, S., 2015. Impact of water-level fluctuations on cyanobacterial blooms: options for management. *Aquat. Ecol.* 50, 1–14. doi:10.1007/s10452-015-9556-x
- Baldwin, D.S., Mitchell, A.M., 2000. The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river – floodplain systems: a synthesis. *Regul. Rivers Res. Manag.* 16, 457–467.
- Barbosa, J.E.L., Medeiros, E.S.F., Brasil, J., Cordeiro, R.S., Crispim, M.C.B., Silva, G.H.G., 2012. Aquatic systems in semi-arid Brazil: limnology and management. *Acta Limnol. Bras.* 24, 103–118.
- Batista, A.M. V, De Carvalho, F.F.R., Marques, C.A.T., De Medeiros, S.J.S., De Almeida, O.C., 2004. *Egeria densa* Hay Inclusion in Ration for Sheep. *Rev. Bras. Zootec.* 33, 1309–1315. doi:10.1590/S1516-35982004000500024
- Benson, B.B., Krause, D., 1984. The concentration and isotopic fractionation of oxygen dissolved in freshwater and seawater in equilibrium with the atmosphere. *Limnol. Oceanogr.* 29, 620–632.
- Bicudo, D.C., Fonseca, B.M., Bini, L.M., Crossetti, L.O., Bicudo, C.E.M., Araújo-Jesus, T., 2007. Undesirable side-effects of water hyacinth control in a shallow tropical reservoir. *Freshw. Biol.* 52, 1120–1133. doi:10.1111/j.1365-2427.2007.01738.x
- Bittencourt-Oliveira, M.D.C., Piccin-Santos, V., Moura, A.N., Aragao-Tavares, N.K.C., Cordeiro-Araujo, M.K., 2014. Cyanobacteria, microcystins and cylindrospermopsin in public drinking supply reservoirs of Brazil. *An. Acad. Bras. Cienc.* 86, 297–309. doi:10.1590/0001-3765201302512
- BMH, B.M. of H., 2011. Portaria 2914/2011. Diário Of. da União 1–16.
- Bormans, M., Marsalek, B., Jancula, D., 2016. Controlling internal phosphorus loading in lakes by physical methods to reduce cyanobacterial blooms: a review. *Aquat. Ecol.* 50, 407–422. doi:10.1007/s10452-015-9564-x
- Bornette, G., Puijalon, S., 2010. Response of aquatic plants to abiotic factors: a review. *Aquat. Sci.* 73, 1–14. doi:10.1007/s00027-010-0162-7
- Boschilia, S.M., De Oliveira, E.F., Schwarzbald, A., 2012. The immediate and long-term effects of water drawdown on macrophyte assemblages in a large subtropical reservoir. *Freshw. Biol.* 57, 2641–2651. doi:10.1111/fwb.12035
- Brasil, J., Attayde, J.L., Vasconcelos, F.R., Dantas, D.D.F., Huszar, V.L.M., 2016. Drought-induced water-level reduction favors cyanobacteria blooms in tropical shallow lakes. *Hydrobiologia* 770, 145–164. doi:10.1007/s10750-015-2578-5
- Burford, M.A., Beardall, J., Willis, A., Orr, P.T., Magalhaes, V.F., Rangel, L.M., Azevedo, S.M.F.O.E., Neilan, B.A., 2016. Understanding the winning strategies used by the bloom-forming cyanobacterium *Cylindrospermopsis raciborskii*. *Harmful Algae* 54, 44–53.

doi:10.1016/j.hal.2015.10.012

- Calijuri, M.C., Santos, A.C.A.D., Jati, S., 2002. Temporal changes in the phytoplankton community structure in a tropical and eutrophic reservoir ( Barra Bonita , S . P .— Brazil ). *J. Plankton Res.* 24, 617–634. doi:10.1093/plankt/24.7.617
- Carneiro, R.L., Pacheco, A.B.F., Azevedo, S.M.F.O., 2013. Growth and saxitoxin production by *cylindrospermopsis raciborskii* (cyanobacteria) correlate with water hardness. *Mar. Drugs* 11, 2949–2963. doi:10.3390/md11082949
- Carrillo, Y., Guarín, A., Guillot, G., 2006. Biomass distribution, growth and decay of *Egeria densa* in a tropical high-mountain reservoir (NEUSA, Colombia). *Aquat. Bot.* 85, 7–15. doi:10.1016/j.aquabot.2006.01.006
- Carvalho, F.T., Galo, M.L.B.T., Velini, E.D., Martins, D., 2003. Plantas aquáticas e nível de infestação das espécies presentes no reservatório de Barra Bonita, no Rio Tietê. *Planta Daninha* 21, 15–19. doi:10.1590/S0100-83582005000200027
- Casati, P., Lara, M. V, Andreo, C.S., 2000. Induction of a C(4)-like mechanism of CO(2) fixation in *Egeria densa*, a submersed aquatic species. *Plant Physiol.* 123, 1611–22.
- CHESF, 2011. Triannual report 2007-2010 Itaparica Reservoir.
- Cooke, G.D., 1980. Lake level drawdown as a macrophyte control technique. *J. Am. Water Resour. Assoc.* 16, 317–322. doi:10.1111/j.1752-1688.1980.tb02397.x
- Costa, I.A.S., Cunha, S.R.S., Panosso, R., Araújo, M.F.F., Melo, J.L.S., Sant’Anna, E.M.E., 2009. Dinâmica de cianobactérias em reservatórios eutróficos do semi-árido do Rio Grande do Norte. *Oecologia Bras.* 13, 382–401.
- Dellamano-Oliveira, M.J., Vieira, A.A.H., Rocha, O., Colombo, V., Sant’Anna, C.L., 2008. Phytoplankton taxonomic composition and temporal changes in a tropical reservoir. *Fundam. Appl. Limnol. / Arch. für Hydrobiol.* 171, 27–38. doi:10.1127/1863-9135/2008/0171-0027
- DEV L16, 1985. Deutsche Einheitsverfahren zur Wasser-, Abwasser- und Schlammuntersuchung (DEV) – Testverfahren mit Wasserorganismen – Bestimmung des Chlorophyll-a-Gehaltes von Oberflächenwasser (Systemnummer L16) – DIN 38412 Teil 16.
- Dörr, F.A., Pinto, E., Soares, R.M., Azevedo, S.M.F.O., 2010. Microcystins in South American aquatic ecosystems: Occurrence, toxicity and toxicological assays. *Toxicon* 56, 1247–1256. doi:10.1016/j.toxicon.2010.03.018
- Dromgoole, F.I., Brown, J.M.A., 1976. Quantitative grab sampler for dense beds of aquatic macrophytes. *New Zeal. J. Mar. Freshw. Res.* 10, 109–118. doi:10.1080/00288330.1976.9515602
- Dutartre, A., Haury, J., Jigorel, A., 1999. Succession of *Egeria densa* in a drinking water reservoir in Morbihan (France). *Hydrobiologia* 415, 243–247. doi:10.1023/A:1003864024365
- Dutra Júnior, W.M., Carvalho, D.M.D.S., Rabello, C.B. V, Ludke, M.C.M.M., De Almeida, G.H.N., Lima, S.B.P., 2009. The use of pondweed (*Egeria densa*) in pig feed. *Acta Sci. - Anim. Sci.* 31, 39–44. doi:10.4025/actascianimsci.v31i1.3587
- Elliott, J.A., 2010. The seasonal sensitivity of Cyanobacteria and other phytoplankton to changes in flushing rate and water temperature. *Glob. Chang. Biol.* 16, 864–876. doi:10.1111/j.1365-2486.2009.01998.x
- Espinosa-Rodríguez, C.A., Rivera-De La Parra, L., Martínez-Téllez, A., Gómez-Cabral, G.C., Sarma, S.S.S., Nandini, S., 2016. Allelopathic interactions between the macrophyte *Egeria densa* and plankton (alga, *Scenedesmus acutus* and cladocerans, *Simocephalus* spp.): A laboratory study. *J. Limnol.* 75, 151–160. doi:10.4081/jlimnol.2016.1397
- Feijoó, C., García, M.E., Momo, F., Toja, J., 2002. Nutrient absorption by the submerged macrophyte *Egeria densa* Planch.: Effect of ammonium and phosphorus availability in the water column on growth and nutrient uptake. *Limnetica* 21, 96–104.



- Figueredo, C.C., Giani, A., 2009. Phytoplankton community in the tropical lake of Lagoa Santa (Brazil): Conditions favoring a persistent bloom of *Cylindrospermopsis raciborskii*. *Limnologia* 39, 264–272. doi:10.1016/j.limno.2009.06.009
- Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C.S., 2004. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annu. Rev. Ecol. Evol. Syst.* 35, 557–581. doi:10.1146/annurev.ecolsys.35.021103.105711
- Frau, D., Battauz, Y., Sinistro, R., 2017. Why predation is not a controlling factor of phytoplankton in a Neotropical shallow lake: a morpho-functional perspective. *Hydrobiologia* 788, 115–130. doi:10.1007/s10750-016-2991-4
- Gunkel, G., 2007. Contamination and eutrophication risk of a reservoir in the semi arid zone: Reservoir Itaparica, Pernambuco/ Bahia, Brazil, in: Sobral, G.G. & M. (Ed.), *Reservoir and River Basin Management. Exchange of Experiences from Brazil, Portugal and Germany*. pp. 81–95.
- Gunkel, G., Lima, D., Selge, F., Matta, E., Sobral, M., Calado, S., 2015a. Serviços de ecossistemas em reservatórios: produtos finais, capacidade e processos limitantes - exemplo de Itaparica, rio São Francisco, in: *Proceedings of XII Simpósio de Hidráulica E Recursos Hídricos Dos Países de Expressão Portuguesa*. Brasília, pp. 1–13.
- Gunkel, G., Lima, D., Selge, F., Sobral, M., Calado, S., 2015b. Aquatic ecosystem services of reservoirs in semi-arid areas: sustainability and reservoir management. *WIT Trans. Ecol. Environ.* 197, 1743–3541. doi:10.2495/RM150171
- Heo, W.M., Kim, B., 2004. The effect of artificial destratification on phytoplankton in a reservoir. *Hydrobiologia* 524, 229–239. doi:10.1023/B:HYDR.0000036142.74589.a4
- Hilt, S., 2015. Regime shifts between macrophytes and phytoplankton - concepts beyond shallow lakes, unravelling stabilizing mechanisms and practical consequences. *Limnetica* 34, 467–479.
- Holland, D.P., Pantorno, A., Orr, P.T., Stojkovic, S., Beardall, J., 2012. The impacts of a high CO<sub>2</sub> environment on a bicarbonate user: The cyanobacterium *Cylindrospermopsis raciborskii*. *Water Res.* 46, 1430–1437. doi:10.1016/j.watres.2011.11.015
- Hu, Z., Guo, L., Liu, T., Chuai, X., Chen, Q., Shi, F., Jiang, L., Yang, L., 2014. Uniformisation of phytoplankton chlorophyll a and macrophyte biomass to characterise the potential trophic state of shallow lakes. *Ecol. Indic.* 37, 1–9. doi:10.1016/j.ecolind.2013.10.007
- Huszar, V.L.M., Nabout, J.C., Appel, M.O., Santos, J.B.O., Abe, D.S., Silva, L.H.S., 2015. Environmental and not spatial processes (directional and non-directional) shape the phytoplankton composition and functional groups in a large subtropical river basin. *J. Plankton Res.* 37, 1190–1200. doi:10.1093/plankt/fbv084
- Huszar, V.L.M., Silva, L.H.S., Marinho, M.M., Domingos, P., Sant’Anna, C.L., 2000. Cyanoprokaryote assemblages in eight productive tropical Brazilian waters. *Hydrobiologia* 424, 67–77. doi:10.1023/A:1003996710416
- INNOVATE, 2017. INterplay among multiple uses of water reservoirs via inNOvate coupling aquatic and Terrestrial Ecosystems. [www.innovate.tu-berlin.de](http://www.innovate.tu-berlin.de).
- INPE, 2015. Instituto Nacional de Pesquisas Espaciais [WWW Document]. <http://sinda.crn2.inpe.br/PCD/SITE/novo/site/index.php>.
- IPCC, 2013. Summary for policymakers, in: Stocker, T. F., Qin, G. K., Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V.B. & P.M.M. (Ed.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assess Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 3–29.
- Janssen, A.B.G., Teurlinx, S., An, S., Janse, J.H., Paerl, H.W., Mooij, W.M., 2014. Alternative stable states in large shallow lakes? *J. Great Lakes Res.* 40, 813–826. doi:10.1016/j.jglr.2014.09.019
- Jeppesen, E., Brucet, S., Naselli-Flores, L., Papastergiadou, E., Stefanidis, K., Nöges, T., Nöges, P., Attayde, J.L., Zohary, T., Coppens, J., Bucak, T., Menezes, R.F., Freitas, F.R.S., Kernan, M.,

- Søndergaard, M., Beklioglu, M., 2015. Ecological impacts of global warming and water abstraction on lakes and reservoirs due to changes in water level and related changes in salinity. *Hydrobiologia* 750, 201–227. doi:10.1007/s10750-014-2169-x
- Jeppesen, E., Meerhoff, M., Jacobsen, B.A., Hansen, R.S., Søndergaard, M., Jensen, J.P., Lauridsen, T.L., Mazzeo, N., Branco, C.W.C., 2007. Restoration of shallow lakes by nutrient control and biomanipulation—the successful strategy varies with lake size and climate. *Hydrobiologia* 581, 269–285. doi:10.1007/s10750-006-0507-3
- Jorgensen, S.E., Tundisi, J.G., Matsumura-Tundisi, T., 2013. *Handbook of Inland Aquatic Ecosystem Management*.
- Junk, W.J., 1997. *The Central Amazon Floodplain: Ecology of a Pulsing System*. Springer-Verlag Berlin Heidelberg. doi:10.1007/978-3-662-03416-3
- Keitel, J., Zak, D., Hupfer, M., 2015. Water level fluctuations in a tropical reservoir: the impact of sediment drying, aquatic macrophyte dieback, and oxygen availability on phosphorus mobilization. *Environ. Sci. Pollut. Res.* doi:10.1007/s11356-015-5915-3
- Kimmel, B.L., Groeger, A.W., 1984. Factors controlling primary production in lakes and reservoirs: a perspective. *Lake Reserv. Manag.* 1, 277–281. doi:10.1080/07438148409354524
- Kleeberg, A., Heidenreich, M., 2004. Release of nitrogen and phosphorus from macrophyte stands of summer dried out sediments of a eutrophic reservoir. *Arch. für Hydrobiol.* 159, 115–136. doi:10.1127/0003-9136/2004/0159-0115
- Krolová, M., Čížková, H., Hejzlar, J., Poláková, S., 2013. Response of littoral macrophytes to water level fluctuations in a storage reservoir. *Knowl. Manag. Aquat. Ecosyst.* 1–21. doi:10.1051/kmae/2013042
- Kuiper, J.J., Verhofstad, M.J.J.M., Louwers, E.L.M., Bakker, E.S., Brederveld, R.J., van Gerven, L.P.A., Janssen, A.B.G., de Klein, J.J.M., Mooij, W.M., 2017. Mowing Submerged Macrophytes in Shallow Lakes with Alternative Stable States: Battling the Good Guys? *Environ. Manage.* 59, 619–634. doi:10.1007/s00267-016-0811-2
- Lara, I.C., Otalora, Z.R., Silva, R.L., 2009. Production of organic fertilizers with *Elodea* (*Egeria densa*) present in Fuquene Lagoon. *Rev. U.D.C.A. Actual. Divulg. Cient.* 12, 91–100.
- Lazzaro, X., 1987. A review of planktivorous fishes: Their evolution, feeding behaviours, selectivities, and impacts. *Hydrobiologia* 146, 97–167.
- León, J.G., Beamud, S.G., Temporetti, P.F., Atencio, A.G., Diaz, M.M., Pedrozo, F.L., 2016. Stratification and residence time as factors controlling the seasonal variation and the vertical distribution of chlorophyll- a in a subtropical irrigation reservoir. *Int. Rev. Hydrobiol.* 101, 36–47. doi:10.1002/iroh.201501811
- Lewis, W.M.J., 2002. Causes for high frequency of nitrogen limitation in tropical lakes. *Verhandlungen des Int. Verein Limnol.* 28, 210–213.
- Lewis, W.M.J., 2000. Basis for the protection and management of tropical lakes. *Lakes Reserv. Res. Manag.* 5, 35–48. doi:10.1046/j.1440-1770.2000.00091.x
- Lewis, W.M.J., 1996. Tropical lakes : how latitude makes a difference, in: Schiemer, F., Boland, K.T. (Eds.), *Perspectives in Tropical Limnology*. SPB Academic Publishing, pp. 43–64.
- Liboriussen, L., Jeppesen, E., 2009. Periphyton biomass, potential production and respiration in a shallow lake during winter and spring. *Hydrobiologia* 632, 201–210. doi:10.1007/s10750-009-9840-7
- Lopes, H., Sobral, M.C., Gunkel, G., Candeias, A.L., Melo, G., 2015. Spatial behaviour of chlorophyll-a in Itaparica Reservoir, Sao Francisco river. *Eng. Sanit. Ambient.* 20, 475–484.
- Lopes, H., Sobral, M.C., Gunkel, G., Candeias, A.L., Melo, G., 2013. Análise espaço-temporal da clorofila-a no reservatório de Itaparica por meio de imagens Landsat-TM., in: *Anais XVI Simpósio Brasileiro de Sensoriamento Remoto - SBSR*. Foz do Iguaçu, PR, Brasil., doi:online

- INPE, 6628-6635. ISBN: 978-85-17-00066-9.
- Loverde-Oliveira, S.M., Huszar, V.L.M., Mazzeo, N., Scheffer, M., 2009. Hydrology-driven regime shifts in a shallow tropical lake. *Ecosystems* 12, 807–819. doi:10.1007/s10021-009-9258-0
- Maltchick, L., Florín, M., 2002. Perspectives of Hydrological Disturbance As the Driving Force of the Brazilian Semiarid Ecosystems. *Acta Limnol. Bras.* 14, 35–41.
- Maltchick, L., Medeiros, E.S.F., 2006. Conservation importance of semi-arid streams in north-eastern Brazil: implications of hydrological disturbance and species diversity. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 16, 665–677. doi:10.1002/aqc.805
- Martins-Melo, F.R., Pinheiro, M.C.C., Jr, A.N.R., Alencar, C.H., Bezerra, F.S.M., Heukelbach, J., 2015. Spatiotemporal Patterns of Schistosomiasis- Related Deaths, Brazil, 2000–2011. *Emerg. Infectious Dis.* 21, 1820–1823.
- Matta, E., Özgen, I., Cabral, J., Candeias, A.L., Hinkelmann, R., 2014. Simulation of Wind-Induced Flow and Transport in a Brazilian Bay. *Int. Conf. Hydrosoci. Eng.*
- Matta, E., Silva, G.N., Lorenz, R., Gunkel, G., Hinkelmann, R., 2016. Estimation of water residence time in Icó-Mandantes bay using the TELEMAC-2D modeling system, in: *I Simpósio Da Bacia Hidrográfica Do Rio São Francisco*. Juazeiro-BA, pp. 1–8.
- Medeiros, L.C., Mattos, A., Lüring, M., Becker, V., 2015. Is the future blue-green or brown? The effects of extreme events on phytoplankton dynamics in a semi-arid man-made lake. *Aquat. Ecol.* 49, 293–307. doi:10.1007/s10452-015-9524-5
- Moura, M.A.M., Franco, D.A.S., Matallo, M.B., 2007. Manejo integrado de macrófitas aquáticas. *Biológico* 69, 31–39.
- Mowe, M.A.D., Mitrovic, S.M., Lim, R.P., Furey, A., Yeo, D.C.J., 2015. Tropical cyanobacterial blooms: a review of prevalence, problem taxa, toxins and influencing environmental factors. *J. Limnol.* 74, 205–224. doi:10.4081/jlimnol.2014.1005
- Mustapha, M.K., 2008. Effects of aquatic macrophytes on the limnology and utilization of Moro Reservoir, Ilorin, Nigeria. *J. Aquat. Sci.* 23, 49–56.
- Nogueira, M.G., 2000. Phytoplankton composition, dominance and abundance as indicators of environmental compartmentalization in Jurumirim Reservoir (Paranapanema River), São Paulo, Brazil. *Hydrobiologia* 431, 115–128. doi:10.1023/A:1011946708757
- Nogueira, M.G., Ferrareze, M., Moreira, M.L., Gouvêa, R.M., 2010. Phytoplankton assemblages in a reservoir cascade of a large tropical - subtropical river (SE, Brazil). *Braz. J. Biol.* 70, 781–793. doi:10.1590/S1519-69842010000400009
- O’Farrell, I., Izaguirre, I., Chaparro, G., Unrein, F., Sinistro, R., Pizarro, H., Rodríguez, P., de Pinto, P.T., Lombardo, R., Tell, G., 2011. Water level as the main driver of the alternation between a free-floating plant and a phytoplankton dominated state: A long-term study in a floodplain lake. *Aquat. Sci.* 73, 275–287. doi:10.1007/s00027-010-0175-2
- Oliveira, N.M.B., Sampaio, E.V.S.B., Pereira, S.M.B., Moura Junior, A.M., 2005. Regeneration capacity of *Egeria densa* in reservoirs in Paulo Afonso, Bahia. *Planta Daninha* 23, 363–369.
- Oliveira, R.J.F., De Carvalho, F.F.R., Batista, A.M. V, De Andrade, M.F., Silva Filha, O.L., De Medeiros, S.J.S., 2004. Effect of addition of *Egeria densa* on digestibility and nitrogen balance in growing goats. *Arch. Zootec.* 53, 175–184.
- ONS, 2015. Operador Nacional do Sistema Elétrico [WWW Document]. <http://www.ons.org.br/>.
- Pacheco, F.S., Soares, M.C.S., Assireu, A.T., Curtarelli, M.P., Abril, G., Stech, J.L., Alvalá, P.C., Ometto, J.P., 2015. The effects of river inflow and retention time on the spatial heterogeneity of chlorophyll and water–air CO<sub>2</sub> fluxes in a tropical hydropower reservoir. *Biogeosciences* 12, 147–162. doi:10.5194/bg-12-147-2015
- Padisák, J., Crossetti, L.O., Naselli-Flores, L., 2008. Use and misuse in the application of the

- phytoplankton functional classification: a critical review with updates. *Hydrobiologia* 621, 1–19. doi:10.1007/s10750-008-9645-0
- Pelice, F.M., Agostinho, A.A., 2006. Feeding ecology of fishes associated with *Egeria* spp. patches in a tropical reservoir, Brazil. *Ecol. Freshw. Fish* 15, 10–19. doi:10.1111/j.1600-0633.2005.00121.x
- Posselt, A.J., Burford, M.A., Shaw, G., 2009. Pulses of phosphate promote dominance of the toxic cyanophyte *Cylindrospermopsis raciborskii* in a subtropical water reservoir. *J. Phycol.* 45, 540–546. doi:10.1111/j.1529-8817.2009.00675.x
- Quilliam, R.S., van Niekerk, M.A., Chadwick, D.R., Cross, P., Hanley, N., Jones, D.L., Vinten, A.J.A., Willby, N., Oliver, D.M., 2015. Can macrophyte harvesting from eutrophic water close the loop on nutrient loss from agricultural land? *J. Environ. Manage.* 152, 210–217. doi:10.1016/j.jenvman.2015.01.046
- Ramos, Y.S., Pedroza, J.P., 2014. Áreas Degradadas Por Erosão Próximas Ao Reservatório Da Usina Hidrelétrica Luiz Gonzaga PE, in: XII Simpósio De Recursos Hídricos Do Nordeste. Natal- RN, pp. 1–10.
- Rangel, L.M., Silva, L.H.S., Rosa, P., Roland, F., Huszar, V.L.M., 2012. Phytoplankton biomass is mainly controlled by hydrology and phosphorus concentrations in tropical hydroelectric reservoirs. *Hydrobiologia* 693, 13–28. doi:10.1007/s10750-012-1083-3
- Reynolds, C.S., 2006. *Ecology of Phytoplankton*, 1st ed. Cambridge University Press.
- Rigosi, A., Rueda, F.J., 2012. Hydraulic control of short-term successional changes in the phytoplankton assemblage in stratified reservoirs. *Ecol. Eng.* 44, 216–226. doi:10.1016/j.ecoleng.2012.04.012
- Rodriguez, M., Casper, P., 2017. Green house gases emissions from a semi-arid reservoir in Northeast Brazil. *Reg. Environm. Chang. Spec. Issue Follow. ahead Large dams lesson Manag. water L. nexus.* (in press).
- Romo, S., Soria, J., Fernández, F., Ouahid, Y., Barón-Solá, A., 2013. Water residence time and the dynamics of toxic cyanobacteria. *Freshw. Biol.* 58, 513–522. doi:10.1111/j.1365-2427.2012.02734.x
- Sachse, R., Petzoldt, T., Blumstock, M., Moreira, S., Paetzig, M., Ruecker, J., Janse, J.H., Mooij, W.M., Hilt, S., 2014. Extending one-dimensional models for deep lakes to simulate the impact of submerged macrophytes on water quality. *Environ. Model. Softw.* 61, 410–423. doi:10.1016/j.envsoft.2014.05.023
- Sampaio, E.V.S.B., Oliveira, N.M.B., 2005. Use of aquatic plant (*Egeria densa*) as an organic fertilizer. *Planta Daninha* 23, 169–174.
- Sant’Anna, C.L., Azevedo, M.T.P., 2000. Contribution to the knowledge of potentially toxic Cyanobacteria from Brazil. *Nov. Hedwigia* 71, 359–385.
- Sant’Anna, C.L., Azevedo, M.T.P., Werner, V.R., Dogo, C.R., Rios, F.R., Carvalho, L.R., 2008. Review of toxic species of Cyanobacteria in Brazil. *Arch. Hydrobiol. Suppl. Algal. Stud.* 126, 251–26. doi:10.1127/1864-1318/2008/0126-0251
- Sarmiento, H., 2012. New paradigms in tropical limnology: The importance of the microbial food web. *Hydrobiologia* 686, 1–14. doi:10.1007/s10750-012-1011-6
- Scheffer, M., Jeppesen, E., 2007. Regime shifts in shallow lakes. *Ecosystems* 10, 1–3. doi:10.1007/s10021-006-9002-y
- Scholte, R.G.C., Carvalho, O.S., Malone, J.B., Utzinger, J., Vounatsou, P., 2012. Spatial distribution of *Biomphalaria* spp., the intermediate host snails of *Schistosoma mansoni*, in Brazil. *Geospat. Health* 6, 95–101.
- Selge, F., 2017. Aquatic ecosystem functions and oligotrophication potential of the Itaparica reservoir, São Francisco river, in the semi-arid Northeast Brazil. *Schriftenreihe Nr. 33. Papierflieger Verlag*

- Clausthal-Zellerfeld.
- Sherman, B., Whittington, J., Oliver, R., 2000. The impact of artificial destratification on water quality in Chaffey Reservoir. *Erg Limnol* 55, 15–29.
- Silva, L.H.S., Huszar, V.L.M., Marinho, M.M., Rangel, L.M., Brasil, J., Domingues, C.D., Branco, C.W.C., Roland, F., 2014. Drivers of phytoplankton, bacterioplankton, and zooplankton carbon biomass in tropical hydroelectric reservoirs. *Limnol. - Ecol. Manag. Int. Waters* 48, 1–10. doi:10.1016/j.limno.2014.04.004
- Soares, M.C.S., Huszar, V.L.M., Miranda, M.N., Mello, M.M., Roland, F., Lürling, M., 2013. Cyanobacterial dominance in Brazil: Distribution and environmental preferences. *Hydrobiologia* 717, 1–12. doi:10.1007/s10750-013-1562-1
- Soares, M.C.S., Marinho, M.M., Azevedo, S.M.F.O., Branco, C.W.C., Huszar, V.L.M., 2012. Eutrophication and retention time affecting spatial heterogeneity in a tropical reservoir. *Limnologica* 42, 197–203. doi:10.1016/j.limno.2011.11.002
- Soares, M.C.S., Marinho, M.M., Huszar, V.L.M., Branco, C.W.C., Azevedo, S.M.F.O., 2008. The effects of water retention time and watershed features on the limnology of two tropical reservoirs in Brazil. *Lakes Reserv. Res. Manag.* 13, 257–269. doi:10.1111/j.1440-1770.2008.00379.x
- Soares, M.C.S., Rocha, M.I.D.A., Marinho, M.M., Azevedo, S.M.F.O., Branco, C.W.C., Huszar, V.L.M., 2009. Changes in species composition during annual cyanobacterial dominance in a tropical reservoir: physical factors, nutrients and grazing effects. *Aquat. Microb. Ecol.* 57, 137–149. doi:10.3354/ame01336
- Sobral, M.C., Carvalho, R., Figueiredo, R.C., 2007. Environmental risk management from multipurpose use of reservoirs in semi-arid areas of São Francisco River, Brazil., in: Gunkel, G., Sobral, M.C. (Eds.), *Reservoirs and River Basins Management: Exchange of Experience from Brazil, Portugal and Germany*. Berlin, p. 279 pp.
- Sobral, M.C., Carvalho, R.M.C.M.O., Silva, M.M., Melo, G.L., 2006. Uso e ocupação do solo no entorno de reservatórios no semi-árido brasileiro como fator determinante da qualidade da água, in: 30 Congreso Interamericano de Ingeniería Sanitaria Y Ambiental 26-30 Nov. 2006, Uruguay.
- Søndergaard, M., Johansson, L.S., Lauridsen, T.L., Jørgensen, T.B., Liboriussen, L., Jeppesen, E., 2010. Submerged macrophytes as indicators of the ecological quality of lakes. *Freshw. Biol.* 55, 893–908. doi:10.1111/j.1365-2427.2009.02331.x
- Song, Y., Liu, L., Yan, P., 2006. A review on complex erosion by wind and water research. *J. Geogr. Sci.* 16, 231–341. doi:10.1007/s11442-006-1
- Talling, J., 1976. The depletion of carbon dioxide from lake water by phytoplankton. *J. Ecol.* 64, 79–121. doi:10.2307/2258685
- Tavares Junior, J.R., Lima, D., Candeias, A.L., Gunkel, G., 2017. Submerged macrophyte volume estimation in Itaparica Reservoir, Icó-Mandantes Bay, northeastern Brazil. *Reg. Environm. Chang. Spec. Issue Follow. ahead Large dams lessons Manag. water L. nexus* (submitted).
- Thomaz, S.M., Bini, L.M., 2003. *Ecology and Management of Aquatic Macrophytes*. Editora da Universidade Estadual de Maringá, Maringá. doi:10.1007/s13398-014-0173-7.2 (in portuguese)
- Thomaz, S.M., Carvalho, P., Padial, A.A., Kobayashi, J.T., 2009. Temporal and spatial patterns of aquatic macrophyte diversity in the Upper Paraná River floodplain. *Brazilian J. Biol.* 69, 617–625.
- Thomaz, S.M., Chambers, P.A., Pierini, S.A., Pereira, G., 2007. Effects of phosphorus and nitrogen amendments on the growth of *Egeria najas*. *Aquat. Bot.* 86, 191–196. doi:10.1016/j.aquabot.2006.10.004
- Thomaz, S.M., Esteves, F.A., Murphy, K.J., Santos, A.M.D., Caliman, A., Guariento, R.D., 2008. Aquatic Macrophytes in the Tropics: Ecology of Populations and Communities, Impacts of Invasions and Human Use, in: Del Claro, K., Oliveira, P.S., Rico-Gray, V. (Eds.), *Tropical*

- Biology and Conservation Management. EOLSS, Oxford, pp. 27–60.
- Thomaz, S.M., Mormul, R.P., Michelan, T.S., 2015. Propagule pressure, invasibility of freshwater ecosystems by macrophytes and their ecological impacts: a review of tropical freshwater ecosystems. *Hydrobiologia* 746, 39–59. doi:10.1007/s10750-014-2044-9
- Tortajada, C. (Ed.), 2016. Increasing Resilience to Climate Variability and Change. The Roles of Infrastructure and Governance in the Context of Adaptation. Springer Singapore.
- Transposition Project, I. of the S.F. river, 2007. Programa 22. Monitoramento da qualidade da água e limnologia.
- Tundisi, J.G., Matsumura-Tundisi, T., Abe, D.S., 2008a. The ecological dynamics of Barra Bonita (Tietê River, SP, Brazil) reservoir: implications for its biodiversity. *Brazilian J. Biol.* 68, 1079–1098. doi:10.1590/S1519-69842008000500015
- Tundisi, J.G., Matsumura-Tundisi, T., Tundisi, J.E.M., 2008b. Reservoirs and human well being: new challenges for evaluating impacts and benefits in the neotropics. *Brazilian J. Biol.* 68, 1133–1135.
- UFPE, 2012. Programa de Monitoramento de Qualidade de Água e Limnologia do Projeto de Integração do Rio São Francisco com as Bacias Hidrográficas do Nordeste Setentrional – PBA 22. 2009-2011. Recife, PE.
- Velini, E.D., Correa, M.R., Tanaka, R.H., Bravin, L.F., Antuniassi, U.R., Carvalho, F.T., Galo, M.L.B.T., 2005. Avaliação operacional do controle mecânico de plantas aquáticas imersas no reservatório de Jupia. *Planta Daninha* 23, 277–285.
- Vivian, L.M., Marshall, D.J., Godfree, R.C., 2014. Response of an invasive native wetland plant to environmental flows: Implications for managing regulated floodplain ecosystems. *J. Environ. Manage.* 132, 268–277. doi:10.1016/j.jenvman.2013.11.015
- Wang, Y.W., Zhao, J., Li, J.H., Li, S.S., Zhang, L.H., Wu, M., 2011. Effects of calcium levels on colonial aggregation and buoyancy of *Microcystis aeruginosa*. *Curr. Microbiol.* 62, 679–683. doi:10.1007/s00284-010-9762-7
- Wetzel, R.G., 1983. Opening remarks, in: Wetzel, R.G. (Ed.), *Periphyton of Freshwater Ecosystems*. Dr W. Junk Publishers, The Hague.
- Wu, Z., Shi, J., Li, R., 2009. Comparative studies on photosynthesis and phosphate metabolism of *Cylindrospermopsis raciborskii* with *Microcystis aeruginosa* and *Aphanizomenon flos-aquae*. *Harmful Algae* 8, 910–915. doi:10.1016/j.hal.2009.05.002
- Yarrow, M., Marin, V.H., Finlayson, M., Tironi, A., Delgado, L.E., Fischer, F., 2009. The ecology of *Egeria densa* Planchon (Liliopsida: Alismatales): A wetland ecosystem engineer. *Rev. Chil. Hist. Nat.* 82, 299–313.
- Zehnsdorf, A., Hussner, A., Eismann, F., Röncke, H., Melzer, A., 2015. Management options of invasive *Elodea nuttallii* and *Elodea canadensis*. *Limnol. - Ecol. Manag. Inl. Waters* 51, 110–117. doi:10.1016/j.limno.2014.12.010
- Zohary, T., Ostrovsky, I., 2011. Ecological impacts of excessive water level fluctuations in stratified freshwater lakes. *Inl. Waters* 1, 47–59. doi:10.5268/IW-1.1.406

---

## **9 Annex**





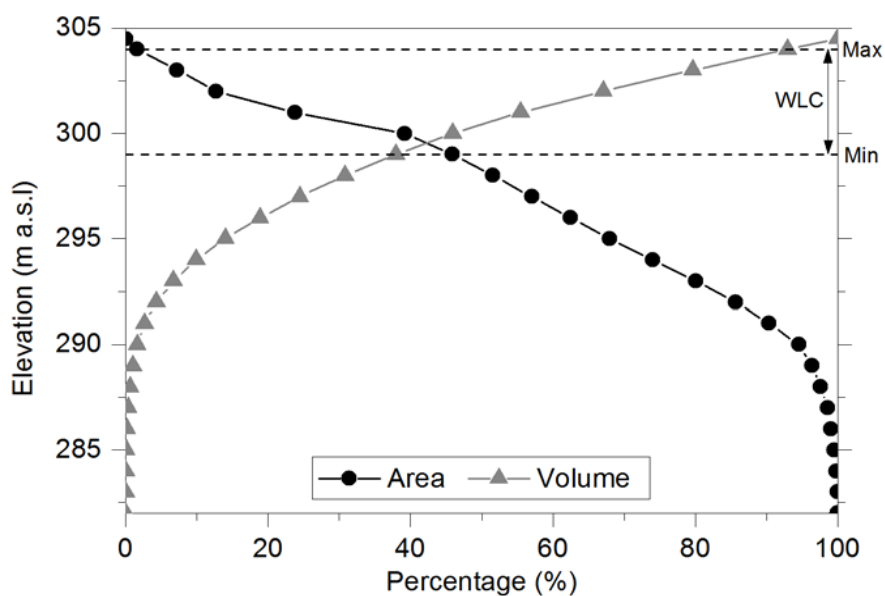
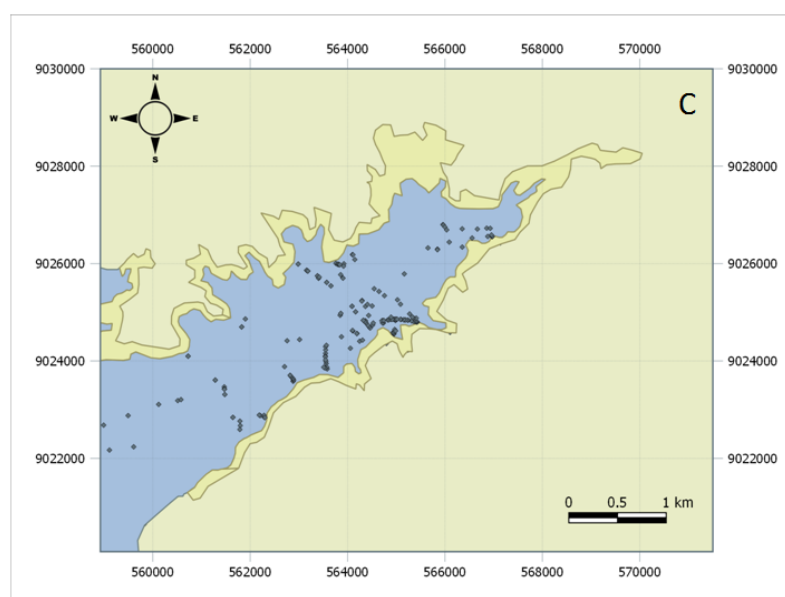
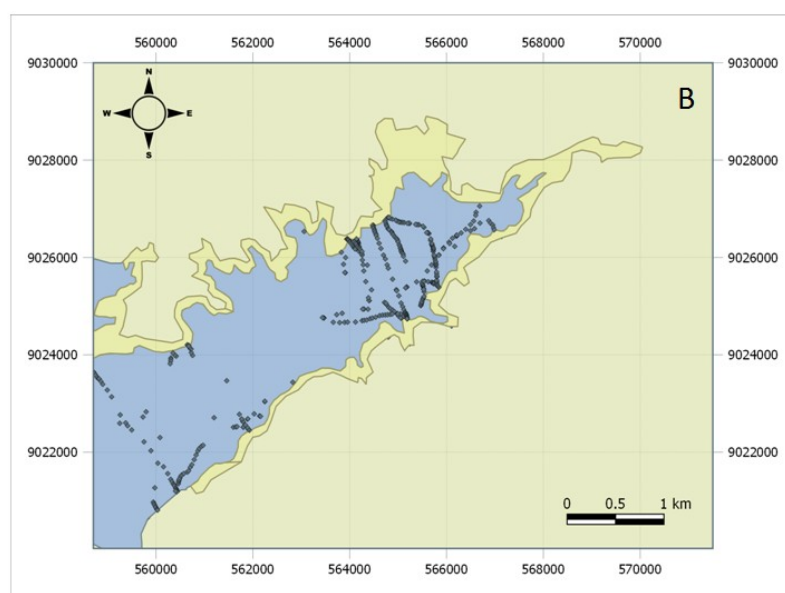
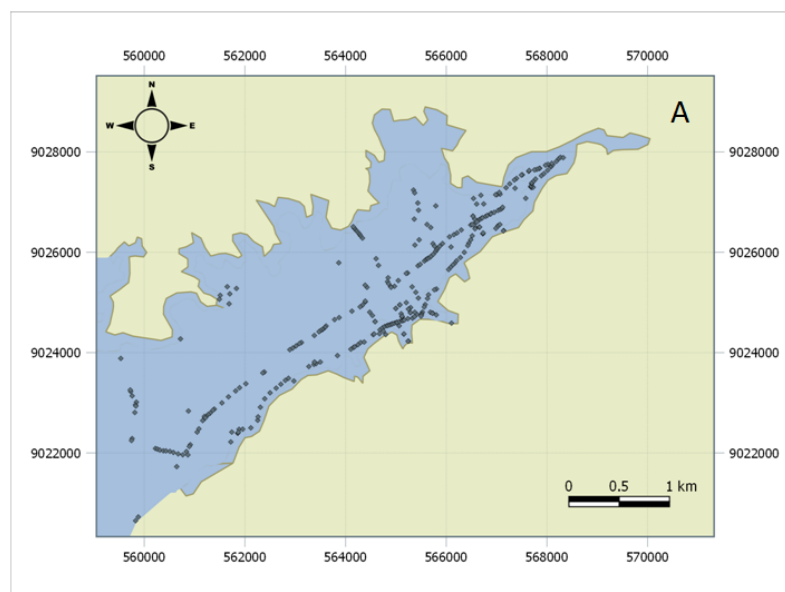


Fig. A - 1 Hypsographic curve of Icó-Mandantes bay for the bay bottom area and bay volume regarding water level elevation (Selge, 2017).

Table A - 1 Water depth categories information including area covered (in km<sup>2</sup>) by *Egeria densa* in each sampling season in Icó-Mandantes bay.

Water depth category (m a.s.l.)	Water depth in HWL (m)	Water depth in LWL (m)	Area covered by <i>Egeria densa</i> (km <sup>2</sup> )			
			Sep 2012	Mar 2013	Oct 2013	Jun 2014
> 303	0	-	0	-	-	-
303-302	1	-	0,78	-	-	-
302-301	2	-	1,56	-	-	-
301-300	3	0	3,32	0	0	0
300-299	4	1	1,47	1,47	1,01	1,28
299-298	5	2	1,14	1,27	1,12	1,24
298-297	6	3	1,10	1,21	0,85	1,21
297-296	7	4	1,00	0,72	1,27	1,24
296-295	8	5	0,23	0,39	0,84	0,90
295-294	9	6	0,00	0,07	0,23	0,26
294-293	10	7	0,00	0,00	0,00	0,00
< 293	> 11	> 8	0,0	0,00	0,00	0,00



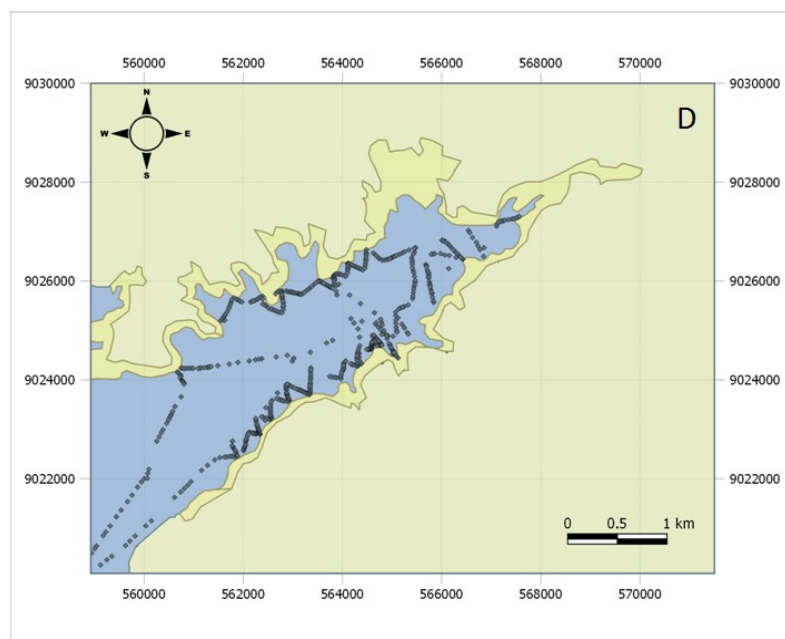


Fig. A - 2. Sampling points in acoustic survey of macrophytes distribution and biomass in the four field campaigns: A) September 2012; B) March 2013; C) October 2013; D) June 2014.

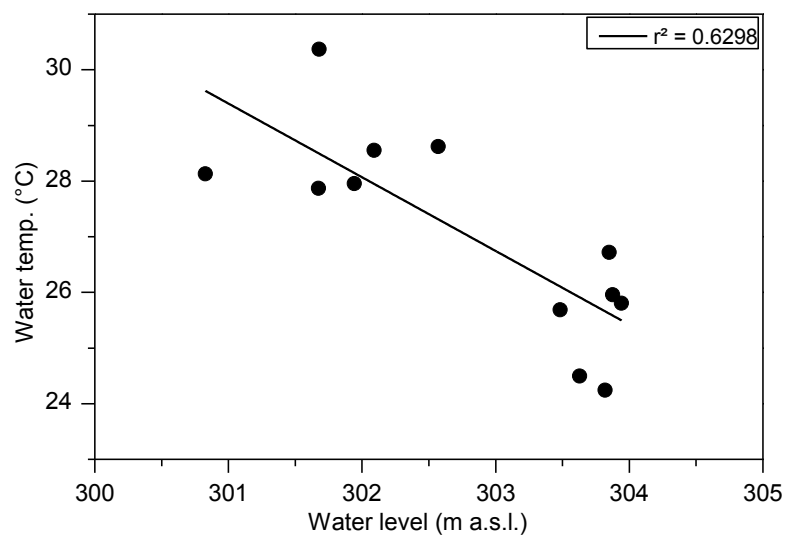


Fig. A - 3 Relationship between surface water temperature and water level in Itaparica reservoir.

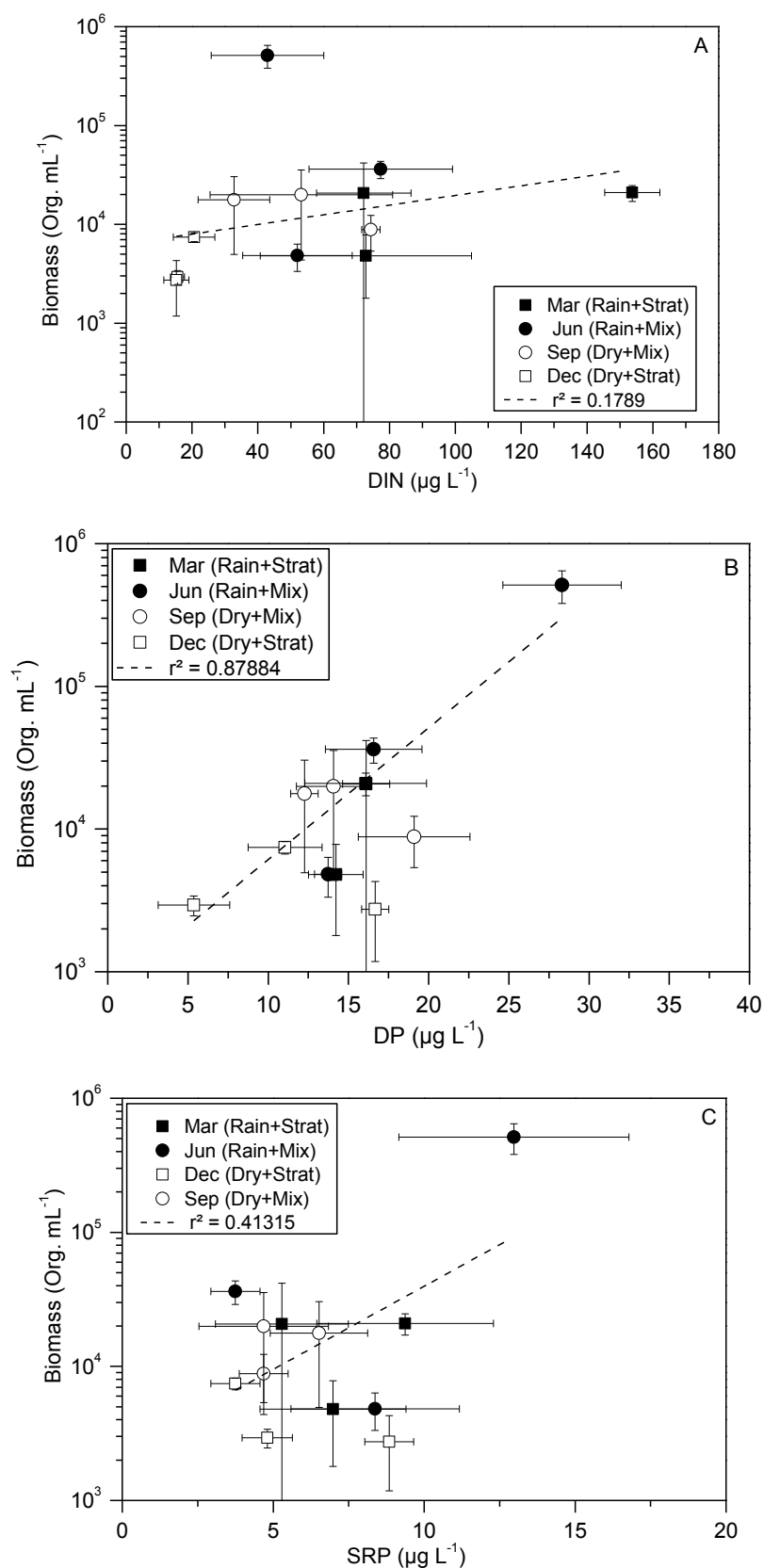


Fig. A - 4 Correlations of nutrients concentrations and phytoplankton concentration in Itaparica reservoir in the different sampling seasons. A) dissolved inorganic nitrogen (DIN); B) dissolved P (DP); C) soluble reactive phosphorus (SRP). Symbols and error bars represent mean and standard deviation, respectively, of phytoplankton concentration and nutrient concentration in sampling stations in the lower middle stretch of the reservoir (ITA 06, ITA 08 and ITA 09).

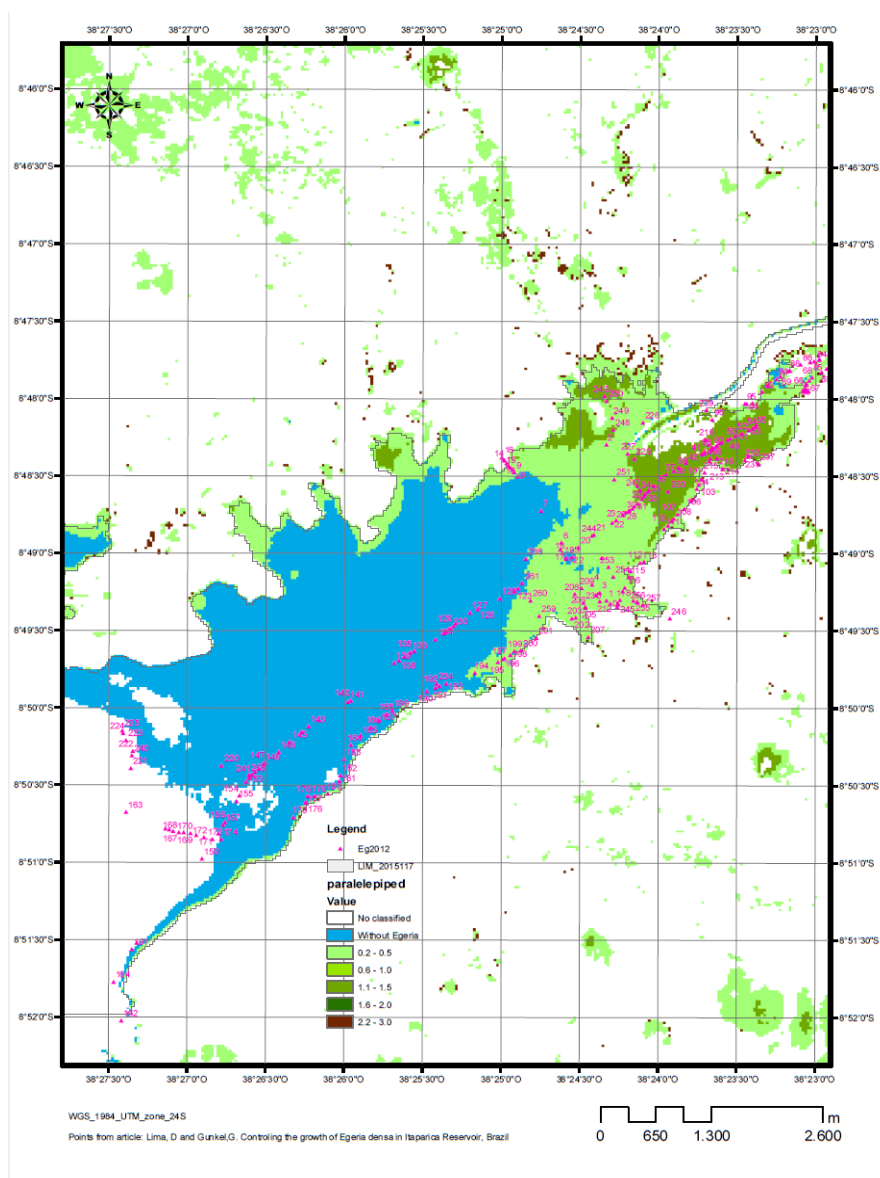


Fig. A - 5 Preliminary results of remote sensing analyses to determine *Egeria densa* distribution in Icó-Mandantes bay.





Fig. A - 6 Examples (A-I) of the biodiversity of terrestrial vegetation in the margins of Icó-Mandantes bay after almost 2 years of constant water level.