Aquatic systems in semi-arid Brazil: limnology and management

Ecossistemas aquáticos do semi-árido brasileiro: aspectos limnológicos e manejo

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Abstract: Aquatic systems in semi-arid Brazil include natural shallow lakes, artificial reservoirs and intermittent streams and rivers. These systems are distinctive features in the semi-arid landscape and comprise a range of associated systems functioning as an ever-changing mosaic of dry/wet patches. Lakes and reservoirs in semi-arid Brazil are subject to important periods of water shortages, whereas rivers and streams are characterized as highly variable and driven by the extremes of water flow and its absence. Within this view a catchment-scale approach must be used to create a holistic model to conceptualize and comprehend these aquatic systems, since the aquatic environment types in the semi-arid region of Brazil incorporate broader aspects within the catchment scale such as geomorphology, vegetation, climate and land use. This paper summarizes some of the information on the aquatic systems of the Brazilian semi-arid region and shows the importance of limnological studies in this region. It also attempts to establish perspectives for future research considering the catchment as a scale for surveying biological processes and limnological characteristics of the various aquatic systems. It is presented information on their overall structure and functioning, as well as characteristics of some biological communities, such as phytoplankton, periphyton, aquatic macrophytes, benthic invertebrates and fish. The importance of the understanding of eutrophication in reservoirs and the role of the dry phase in streams is emphasized, and information on possible actions of planning and management to improve water quality of reservoirs are presented.

Keywords: arid and semi-arid zones, aquatic biodiversity, reservoirs and intermittent rivers.

Resumo: Os ecossistemas no semiárido brasileiro englobam lagos rasos naturais, reservatórios artificiais e rios e riachos intermitentes. Estes sistemas são particularidades na paisagem do semiárida e compreendem uma grande variedade de sistemas associados, funcionando como um mosaico em constante mudança entre épocas de seca e chuva. Lagos e reservatórios no semiárido brasileiro estão sujeitos a importantes períodos de escassez de água, enquanto que os rios e riachos são caracterizados como altamente variáveis e impulsionados pelos extremos de fluxo de água e sua ausência. Dentro desta perspectiva uma abordagem em escala de bacia hidrográfica deve ser usada para se criar um modelo holístico para conceituar esses sistemas aquáticos, uma vez que os tipos de ambientes aquáticos na região semiárida do Brasil incorporam aspectos mais amplos dentro da escala de bacia hidrográfica como geomorfologia, clima, vegetação e uso da terra. Este artigo

sintetiza algumas das informações sobre os sistemas aquáticos da região semiárida brasileira e mostra a importância de estudos limnológicos nesta região. Ele também tenta estabelecer perspectivas para pesquisas futuras considerando a bacia hidrográfica como uma escala para levantamento de processos biológicos e as características limnológicas dos vários sistemas aquáticos. É apresentada informações sobre sua estrutura e funcionamento geral, bem como características de algumas comunidades biológicas, tais como o fitoplâncton, perifíton, macrofitas aquáticas, invertebrados bentônicos e peixes. A importância do entendimento da eutrofização em reservatórios e o papel da fase de seca em riachos são enfatizados, e informações sobre possíveis ações de planejamento e gestão para melhorar a qualidade da água dos reservatórios são apresentados.

Palavras-chave: zonas áridas e semiáridas, biodiversidade aquática, reservatórios e rios intermitentes.

1. Introduction

Arid and semi-arid zones represent a third of the land cover of the planet, encompassing about 61 million km² (Pimm, 2001; Leemans and Kleidon, 2002) and these areas are inhabited by a fifth of the world´s human population (Galbally et al., 2010). Such areas have been subject to increased of human population, various models of land use, water body eutrophication, natural water flow management and climatic changes. These factors impose important challenges for the conservation of biodiversity, maintenance of habitat integrity, food production and availability of drinking water for in arid and semi-arid systems worldwide (Brasseur et al., 2003; Solomon et al., 2007).

In addition, it has been estimated that semi-arid areas in the tropical region of the planet cover most of the developing countries, including Latin America, sub-Saharan Africa, India and southeastern Asia (Icrisat, 1998). Three great arid and semi-arid regions are represented in South America: the Guajira region, in northern Colombia and Venezuela; the dry diagonal of the southern cone, covering the Patagonia, Argentina, Chile and the Andes; and the semi-arid region of northeastern Brazil (Ab'Saber, 2003; Cavalcante and Salles, 2011).

Throughout the world the semi-arid regions are defined as transition zones between arid and sub-humid regions, where precipitation is lower that evaporation and the temperatures are high during warmer months. The semi-arid region of Brazil is defined and delimited based on three criteria (Brasil, 2005): 1) average annual precipitation lower than 800 mm; 2) aridity index below 0.5, which is calculated as the hydric balance between precipitation and evapotranspiration for the period between 1961 and 1990; and 3) chance of drought greater than 60%, based on the period between 1970 and 1990. Based on this classification, the Brazilian semi-arid region encompasses an area of 969.589,4 km², covering 11% of the country, and 1.132 municipalities and nine states (Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Bahia and Minas Gerais) (Figure 1).

Representing 70.6% of the northeastern region of Brazil, this semi-arid region is the most populated in the world. Furthermore, the Brazilian semi-arid possesses a range of climatic and geomorphologic characteristics that make this area distinct from other arid and semi-arid regions in the tropics. These characteristics are 1) high spatial and temporal variation in precipitation, 2) low thermal amplitude with temperatures above 25 °C throughout the year, 3) high potential evapotranspiration, leading to a deficit in the hydric balance during at least nine months of the year, 4) shallow and poorly structured soils 5) drainage catchments characterized by intermittently flowing streams and rivers and 6) decidual vegetal cover, termed "Caatinga".

Therefore, the conservation value of aquatic systems and their management in semi-arid regions are enhanced due to the dry nature of the environment, whereas the importance of the linkages between the aquatic systems must also be recognized. This paper summarizes some of the information on the aquatic systems of the Brazilian semi-arid region and shows the importance of limnological studies in this region. It also attempts to establish perspectives for future research considering the catchment as a scale for surveying biological processes and limnological characteristics of the various aquatic systems.

2. Management and Monitoring of Aquatic Systems at Catchment Scales

The catchment-scale approach has been used as a more holistic model to conceptualize and

comprehend aquatic systems, since aquatic environment types incorporate broader aspects within the catchment such as geomorphology, vegetation, climate and land use. These characteristics lead to the formation a mosaic of subsystems connected by biotic and abiotic processes (Smith and Petrere Junior, 2000; Schiavetti and Camargo, 2002; Brigante and Espíndola, 2003). The catchment basin also integrates structural and functional processes which in turn result from the interaction among geomorphology and social-economical issues across the drainage area. Therefore, in order to effectively understand and manage aquatic systems, the catchment area must be evaluated as a whole, being the ideal unit of study for identifying processes that sustain biodiversity at landscape levels, not only at local levels. This approach is desirable since the maintenance and/ or restoration of the aquatic systems incorporates a multiple-scale approach and given the history of human adaptation to the Brazilian semi-arid, the configurations of ecosystems and the social system should be taken into account in management and conservations plans for the catchment areas (Tundisi and Schiel, 2002; Tundisi, 2003; Maltchik and Medeiros, 2006).

Other important aspects that qualify the catchment area as the fundamental unit of study and management are: (i) the possibility of integrated solutions for local and regional development and solution of water and land conflicts (Tundisi and Matsumura-Tundisi, 1995); (ii) integration among decision makers, research institutions and land owners, to enhance sustainable development and (iii) development a data sets about the different aspects of the catchment (economic, social, morphological and biological) (Tundisi and Schiel, 2002; Tundisi, 2008). Furthermore, the study of river basins has been incorporating more theoretical frameworks such as the River Continuum Concept (Vannote et al., 1980); the Flood Pulse Concept (Junk et al., 1989); the Nutrient Spiraling (Newbold et al., 1982), as well as concepts associated with landscape ecology (Hansson et al., 1995; Thorp et al., 2006).

Within this view, a catchment area functions and interacts from a four-dimensional organization (Ward, 1989). Longitudinally, the interactions occur between processes up and down stream, including the tributaries and the main river channel, whereas laterally, processes and biota interact between the river and its floodplain. Vertically, the catchment presents important integration between

surface and sub-surface waters, resulting from geological and morphological processes that affect the degree of interaction between the upwelling and downwelling waters. The fourth dimension represents the temporal scale of functioning of the aquatic systems, including the structure and dynamics of the aquatic fauna and flora and their responses to flow variations. Catchment areas and their river systems have been seen as a continuous longitudinal gradient (Vannote et al., 1980) or as discontinuous stretches where biotic communities respond to local aspects of the landscape and that local communities are segregated structurally and functionally across the drainage basin. The later has been emphasized in the Uniqueness within the River Discontinuum (Poole, 2002) which proposes that river catchments are unique systems, being organized structurally and functionally in the catchment basin scale. In this case, the catchment would be formed by patches segregated across the catchment reaches and the dynamic of patches along the system would characterize the catchment area. Within this model, tributary and dams contribute to the segregation in the system leading to a mosaic of patches and creating a meta-structure of functional sub-systems (Medeiros et al., 2008).

It is important to note that aquatic ecological systems are complex, being necessary to consider the level of longitudinal organization of the catchment and the application of landscape models as tools for understanding these systems (Bunn and Arthington, 2002). A holistic view on how aquatic systems function and on how they are structured is fundamental to enable effective management and mitigation of the anthropogenic effects on waterways and catchments. A fundamental tool in this understanding is the monitoring of key processes and organisms which generate sensitive and effective indicators of system alterations and their consequences on biotic interactions. This in turn will lead to effective strategies to the use, management and conservation of aquatic systems (Cottingham and Carpenter, 1998; Likens, 2001; Tundisi, 2008).

3. Aquatic Systems in Semi-arid Brazil: Reservoirs and Intermittent Rivers

Aquatic systems in semi-arid Brazil include natural shallow lakes (Maltchik et al., 1999), artificial reservoirs (Barbosa, 2002) and intermittent streams and rivers (except for the perennial São Francisco River and artificially regulated rivers) (Maltchik and Medeiros, 2006). These systems are

distinctive features in the semi-arid landscape and comprise a range of associated systems functioning as an ever-changing mosaic of dry/wet patches.

Lakes and reservoirs in semi-arid Brazil are subject to important periods of water shortages. In this region, reservoirs present low outflow and high water residence time associated with a negative hydric balance and high temperatures during most of the hydrological cycle. This intensifies the accumulation and concentration of nutrients, making these systems considerably more vulnerable to eutrophication than reservoir in more humid areas. Eutrophication has been reported as a major issue leading to decrease in water quality (Bouvy et al., 2000; Costa et al., 2006; Eskinazi-Sant'Anna et al., 2007). Furthermore, reservoirs receive heavy loads of nutrients, as a consequence of high susceptibility to soil erosion, inputs of sewage from urban areas and inadequate land use and occupation. The poor quality of the water accumulated in such reservoirs severely restricts its use and aggravates the already scarce sources of water for human consumption.

The climate in the Brazilian semi-arid region is characterized by a mean annual precipitation ranging from 400 to 800 mm, with a rainy season usually occurring between January and July, but presenting wide spatial and temporal variation. In general, precipitation above 100 mm is reached only between February and May. The dry season (August to December) is marked by an almost complete lack of precipitation. The evaporation rate is estimated around 3 m.yr^{-1} (Bouvy et al., 1999).

The absence of precipitation during the dry period, and the continuous consumption of water throughout the year decrease continuously the water levels in man-made lakes from August to December. In dryer years some reservoirs can completely dry out. This strong reduction in the water level results in a series of modifications in the reservoir ecosystems, including salt and nutrient concentration (Bouvy et al., 1999). Due to the climatic conditions in the semi-arid region of Brazil, man-made lakes present long water residence time, being usually higher than one year (Bouvy et al., 1999; Eskinazi-Sant'Anna et al., 2007).

The man-made lakes from semi-arid Brazil are relatively shallow, with mean depth of aprox. 5 m, and turbid, with Secchi depth usually lower than 1 m (Bouvy et al., 2000; Eskinazi-Sant'Anna et al., 2007; Sousa et al., 2008). Water temperature is always high, with values greater than 23.5 °C, being the lower values observed between June and August. Due to the high water temperatures, diel stratifications can be formed in the water column (Bouvy et al., 1999; Dantas et al., 2008). Water pH values from reservoirs are usually above 8, and they also present high alkalinity values (>2000 µEq.L^{-1}), being the highest values observed usually in the dry season (Bouvy et al. 2000; Huszar et al., 2000; Eskinazi-Sant'Anna et al., 2007). These high pH and alkalinity values are related to high carbonate and bicarbonate concentrations naturally found in the aquatic ecosystems from the region, due the influence of soil type (Leprun, 1983). The man-made lakes present high electric conductivity values, usually greater than 300 µS.cm^{-1} (Bouvy et al., 2000; Eskinazi-Sant'Anna et al., 2007). In general, the variation in conductivity values is negatively correlated with water levels (Bouvy et al., 1999). At some occasions, such as droughts promoted by El Niño events, the electric conductivity values can reach values greater than 10.000 µS.cm^{-1} (Bouvy et al., 2000). Oxygen concentrations are generally above 4 mg.L^{-1} (Bouvy et al., 2000), and sometimes can occur vertical variation, with values decreasing with depth, yet not reaching anoxic conditions (Eskinazi-Sant'Anna et al., 2007).

Most municipalities of semi-arid Brazil do not present wastewater treatment. Thus, the total nutrient concentration is, generally high, the mean values of total nitrogen concentration being greater than 2500 µg.L^{-1} and the total phosphorus higher than 100 µg.L^{-1}, showing the high eutrophication levels in these aquatic ecosystems (Huszar et al., 2000; Eskinazi-Sant'Anna et al., 2007). Dissolved nutrient concentrations show high variability, but in general, they are relatively high. The mean concentration of reactive soluble phosphorus ranges between 15 and 37 µg.L^{-1}, and dissolved inorganic nitrogen between 87 and 107 µg.L^{-1}, with ammonium representing the larger contribution of nitrogen forms (Bouvy et al., 2000; Huszar et al.,2000).

Intermittent streams and rivers are distributed in most of the world´s semi-arid lands. Although not restricted to dry regions, intermittent rivers are characteristic aquatic systems in semi-arid Brazil. These systems are increasingly growing in focus of scientific and applied research as drylands expand (Tooth, 2000). Recent research in dryland river systems of Brazil indicates that the hydrological disturbances are the driving forces structuring biotic communities and that the spatial heterogeneity resulting from disturbance plays a major role in organizing communities spatially (Maltchik and Florin, 2002; Medeiros et al., 2008).

There are important reasons to study intermittent rivers in semi-arid Brazil. From a theoretical point of view the models that integrate biotic processes and function with form and geomorphology in dryland rivers are rare and general in nature, not being specific to intermittent systems. This occurs despite the fact that fluvial processes are significant agents of landscape erosion and deposition meaning that intermittent river systems can be active land-forming agents (Thomas, 2011). Furthermore, concepts specific to dryland rivers deal with channel behavior focusing on landform dynamics, whereas models that integrate biological communities on the other hand have been developed for small perennial temperate streams or large tropical systems, and are hardly applicable to intermittent streams (eg. Vannote et al., 1980; Junk et al., 1989).

From an applied standpoint, general conceptual models and theories are a basic tool for the understanding of intermittent rivers and are needed if research is to be reverted and applied to catchment management and conservation of biotic processes at landscape scale (Bunn and Arthington, 2002). This is critical since many intermittent rivers and streams are under the threat or already being influenced by flow regulation schemes and other human activities. In Brazil, these practices have been altering the integrity of these systems by modification of the riparian vegetation, introduction of exotic species of plants and animals, change in fire regime, vegetation clearing, sand and ore extraction, and water pollution by pesticides, urban and industrial waste (Leal et al., 2005). Water storage associated with farming irrigation, also deplete the quality of the already scarce water resources and increase the threat of soil salinization in the semi-arid region of Brazil. In other dry regions, such modifications have been associated with changes in morphology of river channels and decline in average annual flows and peak discharges, as well as decrease in channel size and meander and parafluvial zone width (Everitt, 1993), with important consequences to biotic integrity and processes.

From a climatic viewpoint, semi-arid intermittent rivers and streams present rapid and strong correspondence to climatic changes and phenomena that occur in global scale (such as the El Niño-Southern Oscillation patterns), being accurate in forecasting of climatic patterns and acting as amplifiers global climatic changes (Molles and Dahm, 1990).

Intermittent streams are characterized by the extremes of flooding and drought. In arid and semi-arid lands, flooding is mostly associated with short flow events that vary in intensity, frequency and magnitude. In accordance to these criteria, Graf (1988) classified flooding in dry rivers as being seasonal, with multiple peaks, with a single peak and flash flooding. The type of flooding is the result of local and regional precipitation in a given hydrological cycle, flash flooding occurring in smaller river systems and seasonal flooding associated to larger basins. Droughts on the other hand, are longer events with specific phases also resulting from precipitation patterns. Typically, the period with no continuous surface water flow of an intermittent river can be separated into three phases. The "drying phase" occurs when continuous flow ceases, after the flooding period, and pools are formed in the river bed. During the "dry phase" (or dryness) there is no surface water. During the "rewetting phase", initial flow occurs with the onset of the flooding period (Stanley and Fisher, 1992).

Given the high spatial heterogeneity resulting from flooding and drought patterns and the temporal dynamics of water flow the aquatic fauna is subject to multiple scale processes. Two mechanisms have traditionally been proposed as capable of regulating biotic communities in such variable systems. Mechanisms involving deterministic processes incorporate the notion of equilibrium communities where diversity and composition of species are maintained avoiding competitive exclusion. Biotic interactions such as resource partitioning, predation and competition are major factors in this view. On the other hand, stochastic processes may also play an important role in biotic communities of intermittent streams. This is based in the idea that the physical habitat and chemical characteristics at local scales are rarely stable enough to allow communities to reach equilibrium. Therefore, community composition and diversity would be determined by species-specific responses to the unpredictable changes in the habitat rather than biotic interactions (Grossman et al., 1990). The dynamics between stochastic and deterministic mechanisms has been discussed and is yet to be established.

The recognition of intermittent streams as important sites of biodiversity and that their diversity is closely associated with natural patterns of flow and hydrological disturbances is, therefore, important for the conservation and management of these systems (Bunn and Arthington, 2002). This understanding will aid in the development of effective strategies for their conservation, otherwise

regulation and alterations in flow regime will increase fragmentation and favor loss or substitution of biotic communities. Therefore, it is clear that, for intermittent streams, a multiple-scale approach is needed for the understanding of processes at a landscape level, and that the preservation of physical processes that create and maintain aquatic variability ensures that the aquatic biota is able to colonize these systems.

4. Biological Communities and General Pattern

4.1. Phytoplankton community

The man-made lakes from semi-arid Brazil present, in general, high chlorophyll concentrations (mean values higher than 20 µg.L^{-1}), showing the eutrophic or hypertrophic conditions of those systems (Huszar et al., 2000; Barbosa et al., 2006; Eskinazi-Sant'Anna et al., 2007). The temporal pattern of phytoplankton biomass is determined by rain distribution throughout the year. According to Huszar et al. (2000) a temporal pattern comprises unimodal cycles with phytoplankton peaks occurring (i) during dry or wet periods; (ii) from the end of the dry period to the beginning of the rainy period; (iii) from the intermediate season until the rainy season, or even, (iv) during more than six months encompassing dry and rainy periods.

In general, Chlorophyceae is the most prominent group in terms of number of species. However, in terms of density, biomass and biovolume the phytoplankton community is usually dominated by Cyanobacteria, namely *Cylindrospermopsis raciborskii* (Woloszynska) Seenaya & Subba Raju (Bouvy et al., 1999, 2000; Huszar et al., 2000; Barbosa and Mendes, 2004; Panosso et al. 2007; Dantas et al., 2010; Vasconcelos et al., 2011). Toxic cyanobacterial blooms are common in man-made lakes of semi-arid region of Brazil, frequently causing human health threats (Molica et al., 2005; Costa et al., 2006). As an example, a dramatic case of human poisoning by cyanotoxins took place in the northeast of Brazil resulting in the death of 76 patients submitted to haemodialysis that used water from a reservoir colonized by cyanobacteria (Carmichael et al., 2001). This event and other alike have been referred as the Caruaru syndrome.

Although cyanobacterial blooms in reservoirs of semi-arid Brazil are mainly related to the eutrophic conditions of these systems, other factors may also contribute to the success of cyanobacteria, such as environmental constancy, annual rain deficit and lack of water renewal, high temperatures and pH, low N/P ratio, low ammonium concentration and absence of efficient predators (Bouvy et al., 1999, 2000; Huszar et al., 2000; Barbosa et al., 2010; Dantas et al., 2010).

4.1.1. Periphytic algae

The periphyton has been characterized as a complex array of microorganisms and organic detritus attached to natural or artificial substrates, which in turn may be dead or alive (Wetzel, 1983). Being predominantly composed by authotrophic algae, the periphyton plays an important role in the food web and exchange of matter between organic and inorganic components of the ecosystem (Lowe and Pan, 1996). Thus, the periphyton has the potential to influence the growth, development, survival and reproduction of organisms in aquatic systems (Campeau et al., 1994). Its potential as bioindicator for water quality and trophic status has been emphasized in many studies, mostly in small rivers and streams (Costa and Chellappa, 2000).

However, studies describing the periphytic communities in Brazil are recent, and so are the one developed in the semi-arid region of the country. This is most likely due to the lack of specialists in the subject in this region. In the state of Paraíba, the first attempts to study periphytic communities were made by Batalla and Watanabe (1993) surveying the Gramame and Mamuaba reservoirs. Despite that, the first published research from Paraíba on a refereed paper was the work from Maltchik et al. (1999), which described ecological aspects of periphytic algae in an intermittent stream.

At present, research on periphytic communities has been increasing as a result of investments of the Long-Term Ecological Program (PELD) in the Caatinga, which resulted in a book chapter (Dantas and Barbosa, 2005) comparing ficoperiphyton across different substrate types in lentic systems and six monographic works and a master´s dissertation on the topic of periphytic algae.

4.1.2. Aquatic macrophytes

The overall dynamics of aquatic macrophytes is one of the most important aspects in their study. The basic patterns of spatial and temporal distribution of aquatic plants are explained by the physiological relations between plants and environmental conditions, as well as the tolerances and competitive abilities allowing growth at different levels of resource availability along environmental gradients.

General patterns of distribution of the aquatic macrophytes are related with light and nutrient availability, temperature, pH, alkalinity, salinity, discharge, water level, and geomorphology. Nevertheless, the biotic and abiotic variables interact to establish populational and individual patterns (Menendez and Peñuelas, 1993; Bini et al., 1999; Henry-Silva et al., 2010; Barendregt and Bio, 2003; Henry and Costa, 2003; Neiff and Poi de Neiff, 2003). It is noteworthy that aquatic plants are susceptible to different levels of chemical and physical disturbances that occur in catchment areas, such as dredging, mining, domestic and industrial waste pollution and alterations in water levels (Mackay et al., 2003; Thomaz et al., 2003; Ferreira et al., 2005; Pedro et al., 2006).

Forty species of aquatic macrophytes distributed across 22 families and 33 genera were observed for the Apodi/Mossoró (RN) river basin by Henry-Silva et al. (2010). Poaceae and Cyperaceae were the richest taxa. The most frequent growth form were amphibian (42.5%), with 17 species, emergent (27,5%), free floating (12,5%), submersed rooted (10,0%) and floating leaved (7,5%). The submersed rooted *Hydrothrix gardneri* and *Ceratophyllum demersum* were observed in great abundance and frequency in the Santa Cruz do Apodi reservoir, especially near net cages for tilapia (*Oreochromis niloticus*) growth. The free floating *Eichhornia crassipes*, *Pistia stratiotes* and *Salvinia auriculata*, commonly occurred in reaches crossing urban areas. It has been established that the richness of aquatic macrophytes is similar to that observed in other drainage basins across Brazil, and proposed that given the large number of reservoirs in semi-arid Brazil, the survey and monitoring of aquatic macrophytes is important, especially in the drainages that will receive waters from the São Francisco river transposition.

4.1.3. Benthic invertebrates

The first studies on benthic macroinverebrates in semi-arid Brazil, deal mostly with the taxonomy and distribution of specific taxa, such as Mollusca (Abílio et al., 2007). In reservoirs studies relate the biology and ecology of macroinvertebrates in the littoral sediment and associated with aquatic macrophytes (Abílio et al. 2005a, b, 2006; Abílio and Watanabe 1998, 2000, Brito-Junior et al. 2005, Souza and Abílio, 2006). It is important to mention that such studies frequently record the presence of the Planorbidae *Biomphalaria straminea*, the

intermediate host for the human parasitic trematode *Schistosoma mansoni*.

The benthic macroinvertebrate fauna in Brazilian semi-arid streams is rich when compared with other dry systems, comprehending mostly insects, annelids and mollusks. Among the insects, Chironomidae is a very abundant taxa contributing with most of the individuals of the benthic fauna. Gomphidae, Libellulidae, Gerridae, Pleidae, Corixidae, Dytiscidae and Hydrophylidae are also common in Brazilian intermittent streams. Magnitude of flooding strongly influences the macroinvertebrate composition, by increasing the number of families after low-magnitude flooding and decreasing their numbers after floods of greater magnitude. Even though the resistance of benthic macroinvertebrates to higher-magnitude flooding is low, Chironomidae are highly persistent. Among the benthic macroinvertebrates, the insects have been reported as the first colonizers after flooding. These are mostly the aquatic adults capable of flight which emerged prior to flooding (Maltchik and Silva-Filho, 2000; Maltchik and Medeiros, 2006).

4.1.4. Fish

Diversity of fish species in Brazilian semi-arid streams is greatly affected by the extremely variable flows (Maltchik and Medeiros, 2001). These hydrological disturbances create a range of habitats that enable coexistence of species and are likely to reduce exclusion by competition. Studies indicate that diversity, food resources and reproductive activity are partitioned among species across temporal and spatial scales. Furthermore, the spatial heterogeneity created by different hydrological phases, and the environmental variations within these phases are important factors in the maintenance of a rich and variable fish community, while decreasing prolonged dominance of species. The dry periods lead to the formation of pools in the river bed with different sizes and degrees of permanence. Such habitats enhance the resilience of fish after flooding, since many species use them as reproductive sites (Medeiros and Maltchik, 2001). The larger temporary and semi-permanent pools act as safe habitats and reduce mortality associated with flood and drought disturbance. Fish populations at these habitats probably function as metapopulations enabling persistence of fish across stream reaches and other bodies of water by dispersal migration when the wet phase commences.

This natural dynamics has been threatened by the expansion of water resource development in

semi-arid Brazil. Increasing pressure for drinking and irrigation water has led to water resource development policies which emphasize construction of large dams, barrages, artificial channels and, more recently, large-scale inter-basin water transfers. Efforts to manage flow appropriately to allow water storage and biotic integrity are virtually inexistent and/or hampered by limited scientific information on the ecological processes driving stream flora and fauna. Human occupation in this region and the strategies adopted for land use and forest management has led to changes in local climate and the intensification of arid conditions (Leal et al., 2005). Furthermore, long-term programmes of introduction of exotic species of fish contribute to the deterioration of the natural biodiversity .

Conservation values of aquatic systems in drylands are enhanced given the dry nature of the surrounding environment (Williams, 1999). Brazilian semi-arid streams provide a range of services, from socio-economic to ecological. The most important issues in the conservation of these streams are their recognition as providers of such services. Failure to recognize the importance of the ecological processes and the link between natural hydrological disturbances and biodiversity, will lead to the extinction of species and the loss or disruption of natural patterns diversity and species distribution. To be effective, conservation and management efforts in semi-arid streams of Brazil will need to understand and maintain key ecosystem processes and their drivers (e.g. hydrological disturbance, river–riparian zone interactions), as well as dispersal pathways and their associated refugia. These agents have been pointed as the most important aspects that enable resilience of the aquatic fauna and maintain their biodiversity and processes (Maltchik and Medeiros, 2006).

5. Using Limnological Knowledge in Environmental Planning and Managing: a Study Case for Reservoirs in the Semi-arid Region of Brazil

Man-made reservoirs in semi-arid Brazil present important limnological characteristics. These systems are prone to have their trophic status increased to eutrophic or hypereutrophic during dry periods, resulting from high evaporation and concentration of nutrients (Crispim et al., 2000; Barbosa, 2002). This is aggravated by their small size and depths leading to long water retention time. The Long-Term Monitoring Program (PELD/ Caatinga) has been monitoring several reservoirs

in semi-arid Brazil, in order to understand their structure and functioning. The monitoring of the Taperoá II reservoir has shown that the water quality has improved throughout the study period. Observation of the precipitation chart (Figure 2) reveals an increase in rainfall since 2004, causing more frequent spill outs and decreasing the water retention in the reservoir. This has led to the regression of the trophic status during the dry periods. An important response to this process has been observed to zooplankton, which decreased their peaks of maximum densities.

It has been observed in the Taperoá II reservoir high densities of *Moina minuta* (Cladocera, Crustacea) in the beginning of the wet period. During this phase this species dominates the water column, but shortly after it decreases in numbers leaving ephippia in the sediment (Crispim et al*.,* 2003). This species is known to require large amounts of food (phytoplankton) and its densities can reach greater values in eutrophic waters (Vieira, 2007; Medeiros et al., in preparation). At the beginning of the rainy period algae densities are lower but their growth is rapid (Barbosa, 2002), providing food in significant quantities. The analysis of the effect of *M. minuta* on algal growth and the comparison with the foraging rates of the calanoid copepod *Notodiaptomus cearensis* and the rotifer *Brachionus urceolaris* showed that *M. minuta* presents higher feeding rates (twice as much compared with *N. cearensis* and ten times the rates of *B. urceolaris*), regardless of the amount of food provided. Nevertheless, *B. urceolaris* showed greater foraging in the presence of greater amounts of food, whereas *N. cearensis* showed greater foraging in the presence of lower food amounts. These results show that, the quality of the food available not being considered, some species of zooplankton may have their foraging rates inhibited depending on the amount of food available in the water. This explains, at least in part, the segregation in species composition among reservoirs with different levels of eutrophication.

Therefore, the rapid decrease in densities of *M. minuta* after its peak can be explained by the consumption of food at rates too high, leading to densities of prey items too low to sustain the entire populations of this cladoceran. Furthermore, this is reflected in the water transparency, which is greater soon after the blooms of *M. minuta*, characterizing a period of clearer waters, the clear water phase (Figure 3).
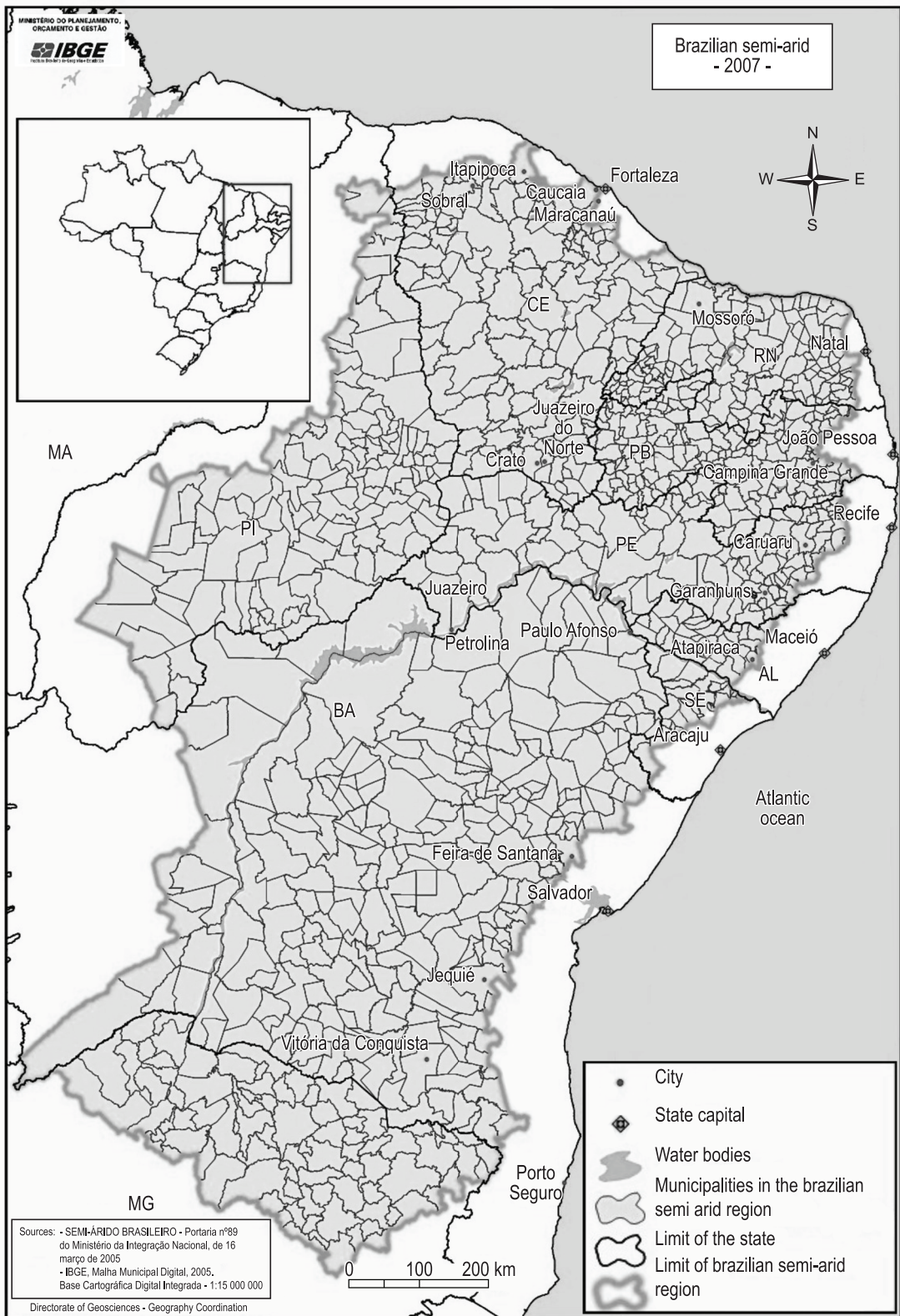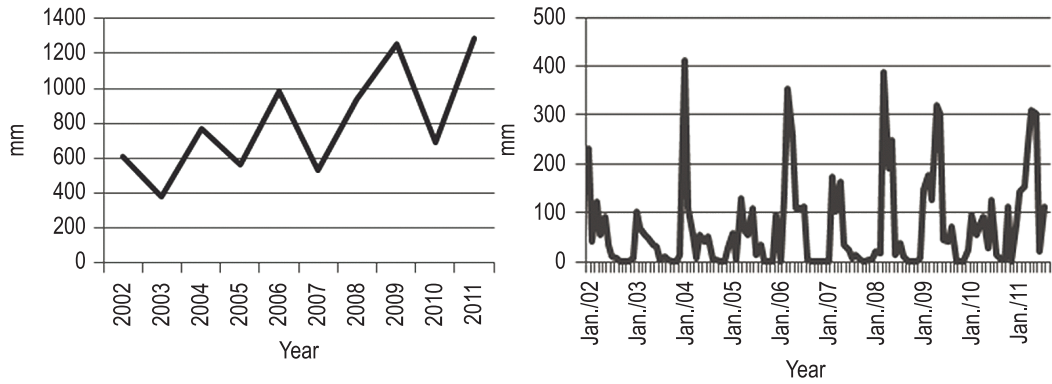
Figure 1. Delimitation of Brazilian semi-arid (source: Brasil, 2005).

Associated with the better water quality, after the effect of the presence of *M. minuta* in the water column, it was observed the increase in the abundance of other species such as the Cladocera *Ceriodaphnia cornuta* and *Diaphanosoma spinulosum* and the Calanoid Copepod *N. cearensis*. However,

Figure 2. Annual and monthly cumulative precipitation in the Taperoá municipality (semi-arid Brazil) from 2002 to 2011.
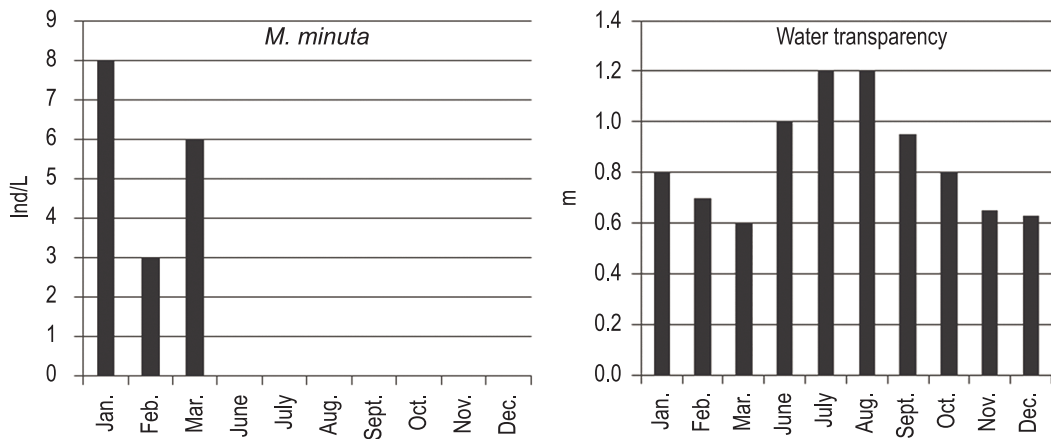
Figure 3. Densities of *M. minuta* and the water transparency in the Taperoá II reservoir.

these species are not able to control the algal growth as effectively as *M. minuta* and are eventually replaced by the Rotifera which starts to appear in greater richness as the Ciclopoid Copepod. *M. minuta* can, therefore, be seen as a key species in such reservoirs, enabling the presence of others that succeed it. From a management point of view, the presence of this species can help increase the quality of the water (at least regarding transparency and microalgae growth) in reservoirs in semi-arid Brazil by controlling the density of the phytoplankton. Interestingly, *M. minuta* has been observed again in the end of the dry period when the water is getting eutrophic again, but it does not show the same levels of density observed in the beginning of the hydrological cycle. This indicates that food may not be appropriate at this period or some other factor may be affecting the densities of the species.

Crispim et al. (2009) observed that the presence of a biofilm in the substrate enhances the removal of phosphates and nitrogen from the water, this biofilm

being more efficient than the absorption made by aquatic macrophytes such as the *Eichornnia crassipes*. The latter was in turn more effective in the removal of nitrogen than phosphorus. Nevertheless, associated with the presence of phyto- and zooplankton, the macrophyte cover is essential to the maintenance of larger predators like fish and their eggs. For instance, Montenegro et al., (in preparation) observed in the Taperoá II reservoir that the ichthyoplankton was more associated with macrophyte stands than with other areas of the reservoir.

On the other hand, exotic species of fish, such as the *Oreochromis niloticus* has playing a negative role in these systems since it competes with native species (Figueredo and Giani, 2005) and constructs nests in deeper areas of the reservoirs releasing nutrients to the water. Furthermore, studies in reservoirs show this species as a planktivore (Montenegro, 2007) that can control zooplankton populations and enable the growth of phytoplankton, contribution to water turbidity and eutrophication. This species

has been introduced to increase fishing and food availability to human populations, but this has not been effective since *Oreochromis niloticus* does not reach larger sizes in eutrophic environments.

With this limnological knowledge the management and planning for resource use in semi-arid Brazil, reservoirs must take into account the effects of biotic factors in their water quality. Since the richness of fish has been associated with the water quality of the reservoirs it is important that the conditions that promote fish richness and water quality are maintained. Also, incentives to remove exotic species and prevention of their introduction should be considered by decision makers and managers. Associated with that, is the fact that some species of Cladocera reach greater sizes (and higher reproductive rates) in the presence of invertebrate predators and the opposite in the presence of vertebrate predators (Crispim, 1998). Thus, in lower densities of vertebrate visual predators, invertebrate predators (Copepoda Ciclopoida or insect larvae) can contribute to the control of phytoplankton by allowing greater sizes and reproductive rates of cladocerans.

Furthermore, the maintenance of macrophyte stands, and their management, may increase water quality, by removal of nutrients and increase in richness of fish and invertebrate species, such as Cladocera, Rotifera, Copepoda, Molusca and Insecta. The importance of macrophyte stands also includes their use as foraging and shelter for eggs and young individuals.

The presence of substrata that allow the establishment of a biofilm is an important element in the reduction of nutrients in the water. The use of artificial substrata for the establishment of this biofilm is important. Given that, the biofilm represents food for consumers, the nutrients removed from the water would be transferred to fish and invertebrates increasing their biomass and sustaining larger and more diverse communities. This biofilm requires less management than macrophytes, for instance, that need to be removed when in large quantities. Such approach would also be important in cases where fish are being farmed in enclosures, since the nutrients produced by farming can be absorbed or removed by bioremediation.

An important characteristic of Brazilian semi-arid reservoirs is that they dry out after long dry periods. In such cases, the removal of the excess sediment in the bottom of these dry reservoirs should be preferred as opposed to dredging, when there is still water available. This nutrient rich sediments removed could be used as fertilizer by local farmers and at the same time preventing these nutrients to be released in the water.

Therefore, eutrophication in Brazilian semi-arid reservoirs can be mitigated by taking relatively simple actions, associated with the control of nutrient inputs through the drainage basin and management of local biotic processes in order to increase the quality of the water in these systems.

6. Final Considerations

Increased in human population growth in semi-arid Brazil and the associated expansion of water resource development may be regarded as the major threats to ecosystem integrity and loss of biodiversity. Eutrophication and pollution are important factors affecting biodiversity in reservoirs, whereas promotion of lenthic conditions by construction of dams and large-scale inter-basin water transfers are important threats to the intermittent stream biodiversity. Associated to that numerous human activities threaten the biotic integrity and biodiversity in aquatic systems of semi-arid Brazil such as sand and ore extraction and land-use practices that alter the riparian vegetation of water bodies, introduction of exotic species of plants and animals and vegetation clearing.

In northeastern Brazil these threats are enhanced by the dry nature of the environment and the recurrent droughts (Tundisi, 2003). These factors, coupled with the current patterns of global climate change are very likely to intensify the semi-arid conditions and caused further loss of diversity. Therefore, effective conservation and management efforts in semi-arid Brazil need to start by generating knowledge on the processes that maintain ecosystem diversity at catchment scale and on the importance of pathways for organisms and diversity and their associated refugia.

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