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Original Article

Systems ecology of watersheds of Itaqueri and Lobo rivers and Lobo/Broa reservoir (Itirapina, SP): "a new wine for an old bottle"

Ecologia de ecossistemas das bacias hidrográficas dos rios Itaqueri e Lobo e da represa Lobo/Broa (Itirapina, SP): "um novo vinho para um antigo recipiente"

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Abstract

In this paper the authors present and discuss the systems ecology of the watersheds and the reservoir (Lobo/Broa), located in Itirapina, SP, Brazil. This is a new approach to an ecosystem studied since 1971. An hierarquical organizing model is shown as well as the response of the biological communities to climate and inputs such as nutrient pulses. The biogeochemical cycles are discussed and the relationships of the hydrodynamicas of the reservoiir with spatial and temporal distribution of phosphorus, carbono and nitrogen are presented. The reservoir resilience to inputs and the "tipping point" theory are presented. Ecosystems services of watersheds and reservoir are described and their values are discussed. A new proposal relating economy/ecology is discussed.

Keywords: systems ecology, watersheds, reservoirs, economy, climate, ecosystems services, "tipping point".

Resumo

Neste trabalho os autores apresentam a ecologia de sistemas aplicada às bacias hidrográficas dos rios Itaqueri e Lobo e Represa da UHE Carlos Botelho (Lobo/Broa), Itirapina, SP Brasil. Esta é uma nova abordagem a um ecossistema em estudo desde 1971. O modelo de organização hierárquica, é demonstrado bem como são discutidas as respostas das comunidades biologicas e dos ciclos biogeoquímicos ao clima e impactos diversos. A relação entre a hidrodinâmica do ecossistema represa, e os ciclos biogeoquímicos é discutida. A resposta resiliente do reservatório e da comunidade biológica aos eventos climáticos e outros impactos – usos do solo, por exemplo- é discutida e a teoria do "*tipping point*" é apresentada. Os serviços ecossistêmicos e seus valores para a bacia hidrográfica e a represas são descritos. A relação ecologia/economia é destacada com uma nova proposta.

Palavras-chave: ecologia de ecossistemas, bacias hidrográficas, represas, economia, clima, serviços de ecossistemas, "*tipping point*".

1. Introduction

The watersheds of Itaqueri and Lobo rivers are a relatively small ecologically complex ecosystem (230km^2), located near the geographyc center of São Paulo State, Brazil (Latitude 22°15´S and Longitude 47°49´W) (Figure 1).

The climate is subtropical with a wet period (November to April), and a dry period (May to October). The average yearly temperatures are approximatelly 22 °C.

The natural vegetation of the watersheds are a "cerrado" a charactheristic savannah typical of central areas of Brazil; reforestation of *Pinus* sp and *Eucalyptus* sp, were introduced about 50 years ago in he watersheds.

The soils of the region are a mosaic of sandy type with some areas of red clay (Figure 2).

In 1971 an integrated study of the watersheds and the reservoir was started by the Department of Biological Sciences of the Federal University of São Carlos, and the Department of Hydraulics and Sanitation of the School of Engineering of University of São Paulo at São Carlos.

2. The Study Plan and the Development of Research

The starting point of the Project was established by Macagno (1970), who described the opportunity to establish in the region a Center of Ecological Engineering based on the integration of ***Engineering, Hydrology, Biology, Ecology*** in a unit in a effort to understand the ecosystem dynamics from the biogeofisiographyical approach.

The research plan established in 1971, stated three main objectives:

- Research per se to understand ecological dynamics with a system orientation.
- Research organization for a long term period.
- Capacity building including faculty associates, post doctorates fellows, students, international collaborators network.

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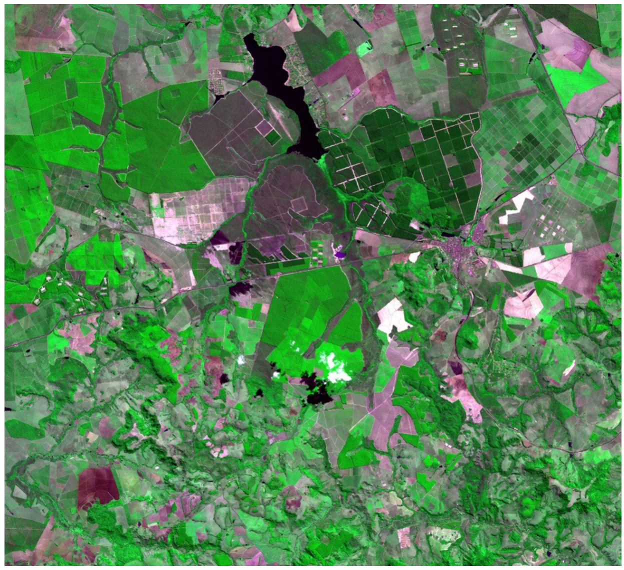

Figure 1. The watersheds of Itaqueri - Lobo rivers and the Lobo/Broa Reservoir.
(**Source:** Tundisi, 2017).

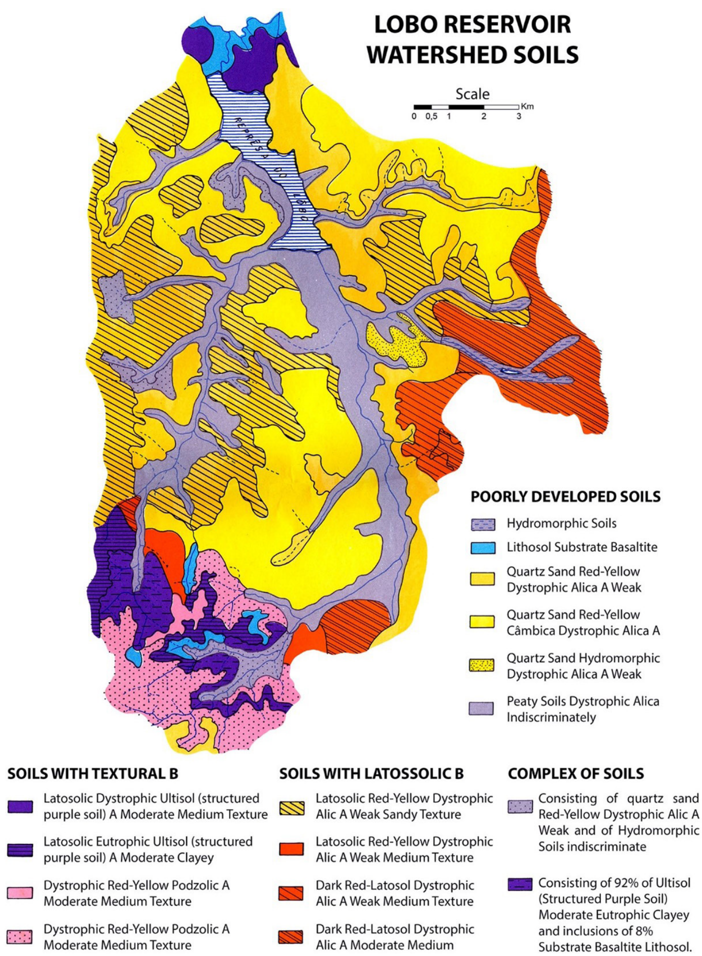

Figure 2. The mosaic of soils of the watersheds.
(**Source:** Sobral and Tundisi, 1986).

3. The System Ecology Foundation of the Project

As pointed out by Patten et al. (1994), every ecosystem is open: exchanges energy, matter and information with a dynamic process that includes biotic and abiotic factors. Systems ecology formalizes the open characteristics of the ecosystem with concepts of input/output and transformation of energy and cycling of matter (Margalef, 1995).

The responses of the system takes inputs, promotes X states into outputs and provides a functional and structural dynamics in time and space that will be represented in the diferent levels of habitats, transitional habitats and within habitats, each one with specific time and size scales. The modelling plan and the hierarchical organization of the ecosystem generally points toward the integration of knowledge of the watersheds and the reservoir to undestand the communities and their environment as a unit of coevolution (Patten, 1994).

4. Hierarchical Organizing Model

Lobo and Itaqueri watersheds are a spatial mosaic in which the heterogeneous distribution of habitats and communities reflects a non uniformity of the environment.

The hierarquical model of the watersheds is shown in Figure 3; this includes: a) the geographic region, wih a regional context and incorporate ***climate, meteorology, geology, soils, and hydrology***; b) the watershed ecosystem defines the área of the two ***sub basins of Itaqueri and Lobo rivers***.

In the reservoir itself (Reservoir from Hydroelectric Power Plant Carlos Botelho –Lobo/Broa) two compartments are distinguished: a open water compartment and a wetland compartment upstream reservoir (Figure 4).

Tables 1 and 2 shows the hierarchical organization of the watersheds and the reservoir.

In the Table 1 it is described the organization of the components of the ecosystems from the hierarchical point of view.

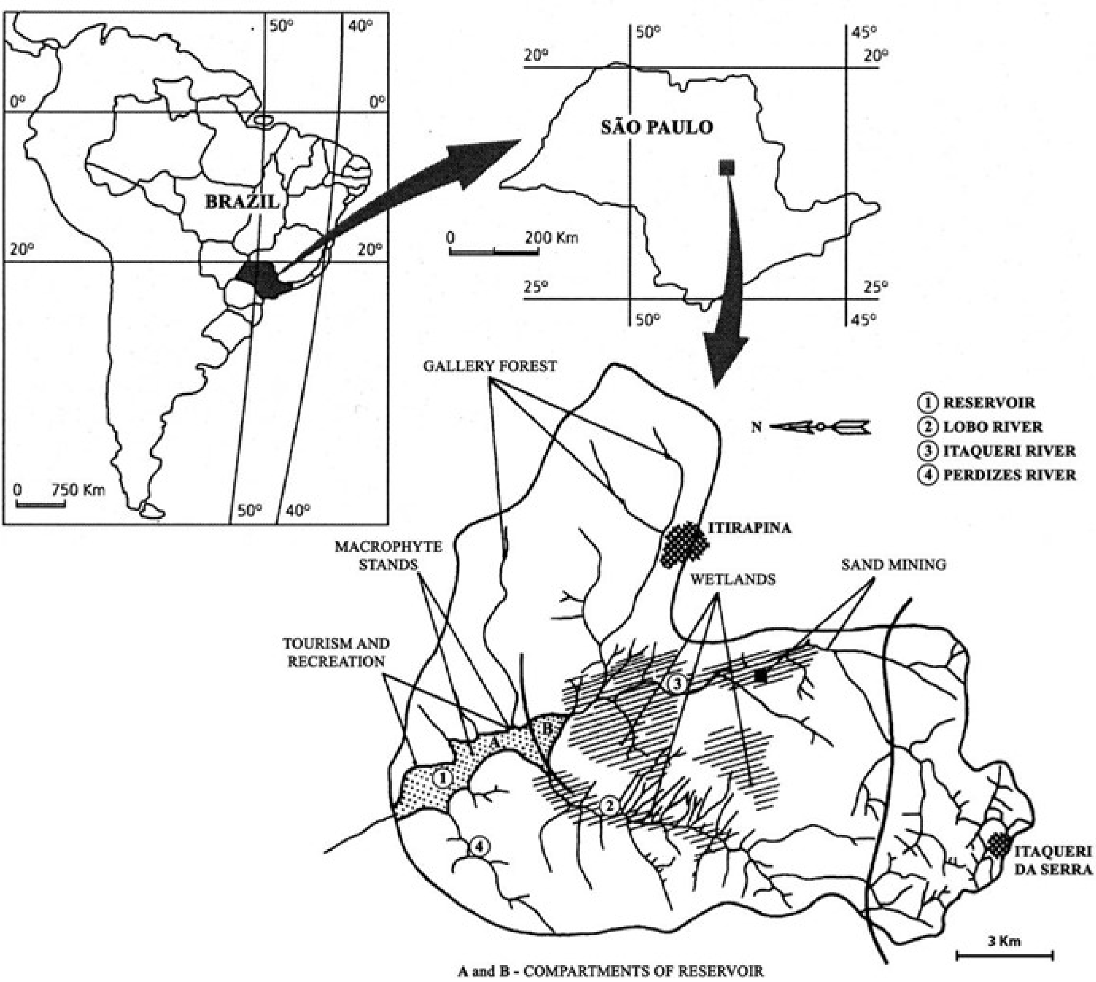

Figure 3. The location of the watersheds and the reservoir. (**Source:** Tundisi, 2017).

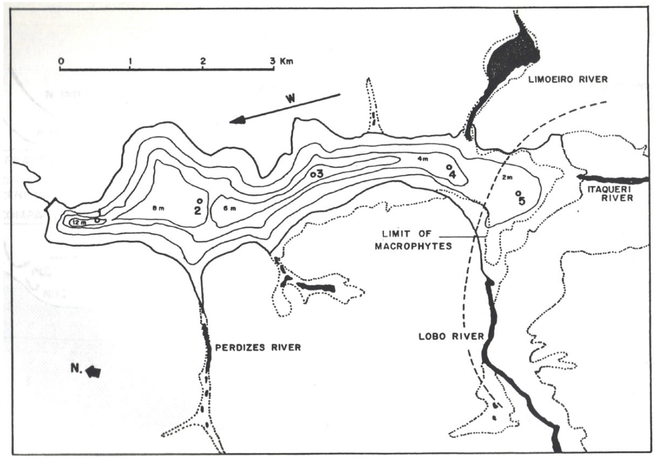

Figure 4. The reservoir of the Hydroelectric Power Plant Carlos Botelho (Lobo- Broa) with two compartments, main tributaries and morphometric characteristics.
Source: Tundisi (1977).

Table 1. Hierarchical model of the watershed ecosystem in diferent levels, in different time scale and size scale.

HABITATS	
LEVEL 0	Geographcal region
LEVEL 1	watershed, ecosystems
LEVEL 2	Habitats type: Savana, ("Cerrado") *Pinnus* spp, *Eucaliptus* spp
LEVEL 3	Habitats transitional: Lobo/Broa reservoir; rivers, wetlands
LEVEL 4	Habitats within: phytoplankton, zooplankton, macrophytes, fishes
LEVEL 5	Habitats within: Sediments; water interactions
TIME SCALE	
LEVEL 1	Years, centuries
LEVEL 2	Months, Decades
LEVEL 3	Hours, months, Year
LEVEL 4	Hours, Das, Months
LEVEL 5	Minutes, hours, days
SIZE SCALE	
LEVEL 1	km^2
LEVEL 2	hectars
LEVEL 3	hectars; m^2
LEVEL 4	cm^2; m^2
LEVEL 5	cm^2; m^2

Table 2. The Lobo/Broa reservoir hierarchical model.

LOBO/BROA RESERVOIR	
Compartment 1	Components:
CENTER OF RESERVOIR	Phytoplankton, zooplankton, fishes sediment, biogeochemistry, C:N:P cycles, water circultaion.
Compartment 2	Components:
UPSTREAM RESERVOIR	Phytoplankton, zooplankton, fishes, sediment, biogeochemistry, peat, C:N:P cycles.

The next step in the organization are the driving forces of the watershed and the other componentes of the ecosystem This is shown in description below.

- **Driving forces**: Climate, Hydrology, Soils, Management, Environmental disturbances
- **Mosaics of Vegetation**: Cerrado (Savannah Forest) *Pinus* spp *Eucalyptus spp.*
- **Timber Management**: for *Pinus spp and Eucalyptus spp.*
- **Soil Composition**
- **Soil Biogeochemistry**
- **Riparian Forest** –Terrestrial/Aquatic Ecotone
- **Impact**s: Fire /Deforestation (Affects): Soil Composition; Soil Biogeochemistry.

The mosaic distribution of vegetation spatially is the result of both environmental heterogeneity and recent disturbances by fires or timber exploitation. Logging can create patches of young three or empty spaces amid forests that can develop a secondary succession process in the vegetation with new niches being occupied. Posterdisturbance patches can therefore undergo succession. The degree of burn during fires can regress successional stages in the cerrado vegetation and destroy extensive áreas of introduced vegetation. Environmental disturbances of varying types and intensities determine the área of vegetation in the watersheds and the composition of this community. The impact of these disturbances of the terrestrial component on the aquatic ecosystems have yet to be determined.

The Hierarchical model for the Lobo/Broa reservoir is shown in Table 2.

The response of the reservoir to the external forcing functions such as cold fronts or other disturbances was in the direction of a re-organization of the system in terms of physical – circulation-rapid chemical changes in the biogeochemical cycles (for example in the sediment/water interactions), or in the succession of phyoplankton zooplankton. However due to the shallowness of the reservoir the response occurred but the feed back mechanisms forced the system to be near the original status (for example of biomass and organic matter production and decomposition).

Probably the average regular cycle of temperature, or the regular climate cycle contributed to this response. However the possible impact and feedback of the indirect effects should be considered. This was not measured but as discussed by Patten (2019), can be a fundamental regulating fator. The pulsing characteristics of the ecosystems were described in several papers and reviews (Tundisi et al., 2004; Tundisi and Matsumura-Tundisi, 2014).

5. The Biological Communities Succession and its Dynamics

The biological communities of this ecosystem are affected by the following processes:

i) In the terrestrial ecosystem fires during the dry period, (May to October), destroy natural vegetation and affects soil ecology and terrestrial biogeochemical cycles.

ii) In the aquatic ecosystems rivers and reservoir, the biological communities responds to the impacts of cold fronts (Tundisi et al., 2004, 2007), which change circulation patterns affecting distribution of phytoplankton and zooplankton communities, and interfering in the sediment /water interactions. Phosphorus inputs enhance eutrophication (Tundisi et al., 2015).

iii) Impacts on the fish communities are represented by the introduction of exoctic species that changed the food chain, resulting in the reduction of native species such as *Astyanax* spp, a zooplankton predator (Tundisi and Matsumura-Tundisi, 2022).

iv) Global changes impacts were due in 2013 /2014, to a extensive dry period and the accidental introduction of a cyanobacteria (*Cylindrospermopsis raciborskii)* which affected the biological community and increased the toxicity of the waters by releasing toxins. All multiple uses had to be stopped for several months.

6. The Biogeochemical Cycles

The cycles of Carbon, Phosphorus and Nitrogen in the reservoir are regulated and dependent upon:

i) The input of these elements as nutrients from the soil drainage during the rainfall season (November to April).

ii) The exchange of nutrients in the interaction of water / sediment.

iii) The production/decomposition processes of organic matter.

All these biogeochemical processes are a result of the oxidation/reduction situation of the water, the hydrodynamical processes and circulation.

iv) As the reservoir is a polimyctic ecosystem, the water column is well oxigenated and phophorus is forced to the sediment by the precipitation of ferric phosphate. During short periods of time in the deepest region of the reservoir (12 meters), episodes of anoxy occur liberating phosphorus to the water column.

v) The cycles of nutrients are also dependent upon the rates and processes of carbon fixation by phytoplankton and macophytes and peryphitic algae, and by the decomposition processes that differ at each compartment. The macrophyte compartment at upstream reservoir has a strong role in the cycles of these main nutrients in the whole reservoir. Mechanisms of secondary production and the fast production of rotifer biomass (Pelaez-Rodriguez & Matsumura-Tundisi, 2002) also have a role in the biogeochemical cycles. Primary production of organic matter from phytopplankton has an average of 150 $mgC.m^{-2}day^{-1}$ (Tundisi 1977).

vi) In a study of the reservoir hydrodynamics Granadeiro Rios (2003), demonstrated the strong interaction of the resrvoir hydrodynamics with the biogeochemical cycles and the nutrient distribution

The Figure 5 describes the dynamic flux of phosphorus within compartments, in the aquatic ecosystem (the Lobo/Broa reservoir).

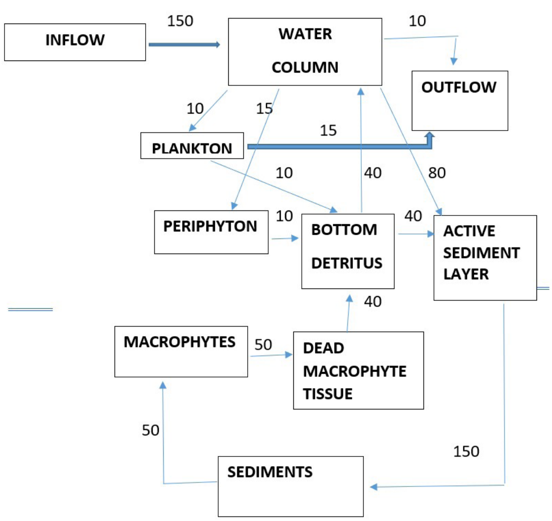

Figure 5. The dynamic flux of phosphorus within the diferent compartments of the aquatic ecosystem. The value of 150 is the overall initial total phosphorus input.
Source: Chalar and Tundisi (1999) and UNEP (2005).

7. Discussion

The ecological dynamics of the watersheds and the reservoir are influenced by the climate temporal changes, as a result of the geographical position of the ecosystem and the sub tropical climate. Furthermore human activities such as soil uses and other disturbances such as fires and nutrient input resulting from wastewater efluents are also a forcing function.

The response of the biological communities to the climate, soil, nutrient inputs and global changes are the succession of species, their temporal and spatial distribution and the rates of production/decomposition (Rodriguez and Matsumura-Tundisi, 2000).

As Margalef (1995), pointed out organisms and ecosystems conserve the information and their main characteristics.The periodic changes in the biological communities incorporate this conservation ability of structure and function.

The scales of motion relevant for the maintenance, distribution, succession, population dynamics and species composition of planktonic assemblages vary in time and space. Motion in rivers, reservoirs, and lakes covers a wide spectrum of spatial and temporal scales (Reynolds, 1984, 1992).

In the case study of Lobo/Broa reservoir the diferences between the impact of cold fronts and the relatively calm period with low wind force during summer are remarkable and fundamental for the succession of phytoplankton and zooplankton. Mixing, light penetration and photosynthetic behaviour were measured by Tundisi (1977). The interaction between the rate of vertical transport of algae through the underwater light gradient are very important for the growth capacity of phytoplankton. Equaly important is the frequency and duration of hydraulic events.

In conclusion the scale of fluid motion at Lobo/Broa reservoir are key to the natural selection of phytoplankton. Motile species survive the impacts of motion and stability of environmental gradientes due to the capacity to self regulate their position. (Banse, 1976). Non motile species such as the diatom *Aulacoseira itálica* are dependent of the wind action for resuspension and growth in the euphotic zone (Lima et al., 1978).

The horizontal gradient of phytoplankton and zooplankton at Lobo/Broa reservoir, is therefore a result of the characteristics of the two compartments and the hierarchical organization of the eosystem.

This sets up an entire difference of food chain organization and nutrient cycles with time scales from minutes to hours and days and space scales of centimeters, meters and kilometers.

New organization processes occur during the temporal changes and the ecosystems (watersheds, rivers, reservoirs) are approaching the "tipping point" (Sensu: Schaeffer, 2014) but return near the original organization after some period of time.

Exergy expresses the biomass of the system and the amount of genetic information incorporated in it. Accordingly to Jorgensen and Svirezhev (2004), ecosystems attempt to develop towards a high level of exergy and away from the thermodynamic equilibrium. The determination of exergy at this ecosystem measured by Periotto and Tundisi (2013) showed that, despite temporal changes there was maintained a high level of exergy. This is reflected in the resilience of the watersheds, rivers, reservoir (Tundisi et al., 2012).The currency for the economy of nature is energy and matter. The result of this energy input is a niche structure biosphere permanently adapted to changing biophysical conditions (Patten, 2016) and maintainig the maximum distance from the thermodynamic equilibrium and the rate of transivity that is the capability of operating transactional networks. This is dependent upon the degree of conectivity of the nodes (biological and nutrient nodes). The strong is the conectivity as a result of a coevolution process, the strong is the resilience of the ecosystem and its capacity to return near the original state (Figure 6).

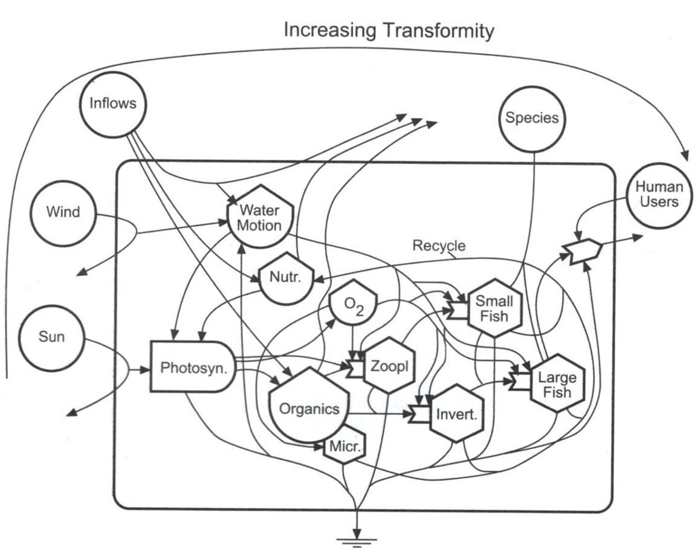

Figure 6. The Reservoir of UHE Carlos Botelho (Lobo/Broa). The conceptual organization based in Odum (1983).

Figure 7. The management plan for the Hydroeletric Power Plant Reservoir (Lobo/Broa). Source: Matsumura-Tundisi and Tundisi (2018).

An optimal biosphere requires maximization of energy and matter storage and flow which is in alignement with the growth of economics and ecological services and their values The extensive network synergism is not visible because the long and diffuse network distances (Odling-Smee et al., 2003). Therefore to be away from the thermodynamic equilibrium pays off in terms of energy conservation and biodiversity and network transactional interactions ;this has an economic component related to ecosytem services and economy (Fath and Patten, 1998). The link between ecological dynamics, conservation and economy in this case is clear. The conservation of the ecosystem functions and the economy (as ecological services) is the key to the management.

8. Management Implications and the Ecological Dynamics of the Ecosystem

i) *The maintenance of a spatial heterogeneity* of the ecosystem is fundamental to induce and stimulate an adequate response to the forcing functions.The riparian vegetation of the rivers maintains the water quality in good conditions but also provides organic matter to invertebrates and fishes improving aquatic biodiversity and enhancing biomass growth.

ii) *Since phosphorus is the main limiting fator to be controlled,* the input of phosphorus to the reservoir should be reduced at a minimum level. The efluents of the wastewater treating station should be strongly reduced to improve dissolved phosphorus control and avoid eutrophication (Gonzalez Rivas, 2020)

iii) *Control of fisheries the introduction of exoctic species, and the use of aquatic sports*. Since the reservoir is a shallow ecosytem the mixing taking place during extensive aquatic sports performances may disturb the sediment and releases suspended matter and dissolved substances to the water column. The regulation and control of introduction of exoctic species will retain original biodiversity sustaining resilience.

iv*) Educate users of the reservoir* to control the water quality, solid wastes and plant new threes;organizing field trips and field seminars is a very good option. Information to schools is also important.

v) *Education of the population to avoid fires during the dry period is essential.*

vi) *Maintain a strict well designed and frequent* monitoring system for water quality and very advanced protocol standards for sanitation.

Economic benefits to the local and regional human population can be obtained with these conservation and protection measures (Tundisi et al., 2008; Luz-Agostinho et al., 2009).

Figure 7 desccribes the integrated management plan for the Watersheds and the Lobo/Broa reservoir.

9. Ecological Services of the Ecosystem

Periotto and Tundisi (2013), realized a detailed study on the range and value of services provided by the Itaqueri- Lobo watersheds and the Lobo- Broa reservoir. The conceptual input for this research was given by Constanza et al. (1997) and the Millenium Ecosystem Assessment (2003) approach.

The list of services resulting from the survey in this research is as follows:

• Gas regulation ($CO_{2;}CH_{4;}N_{2;}$H2S);
• Regulation of the regional climate;
• Regulation of the water flow preventing flood;
• Ater resrvation at the surfasse;
• Retention os sediments;
• Fixation of solar energy (Photosynthesis);
• Retention of nutrientes (Phosphorus and Nitrogen);
• Maintenance of habitats for reproduction;
• Maintenance and enhancing biodiversity;
• Food production (fish, fisheries);
• Genetic and medicinal resources;
• Aquaculture – fish production;
• Environmental education services;
• Aquatic Sports;

• Cultural values;
• Spiritul values;
• Scientific research;
• Energy production;
• Recreation;
• Tourism.

The human well being resulting from these services is: recreation, tourism,aquatic sports, sports fisheries, water reservation, energy production,better human health, increase of jobs and general services and enhancing biodiversity. The overall value of services resulted in U$ 45.000/hectare/year as a result of investments in recreation, tourism, aquatic sports, construction of residences, and other facilities including investments in Science and Technology.It is clear that the ecological services provided were due to the persistence of biological growth, energy flow and resilience of the ecosystem (Tundisi et al., 2008). Growth in money flow as a consequence of ecological services mirrors matter and energy flow in ecosystems. Capital accumulation as monetary profit in economics (as ecosystem services!) is expressed as the standing stock and biodiversity of natural capital in ecology (Patten, 2019).

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