Reservoirs: Functioning, Multiple Use and Management

Tundisi, J. G., T. Matsumura-Tundisi, J. E. M. Tundisi, D. S. Abe, D. Vanucci, R. Ducrot
Institute International of Ecology

Abstract-Reservoirs are complex artificial ecosystems, oscillating with and responding to several impacts of climatological, hydrological and anthropogenic forcing functions. The functioning of the reservoirs, is thus related to the multiple impacts of climatological factors, to the interaction of climatology / hydrology with the natural functions of the watersheds and the reservoirs and to the multiple uses of the reservoirs. The impacts of multiple activities in the watersheds and reservoirs is well documented is many regions, and this is a background for management: predictive, integrated, adaptative and at the watershed level. In order to improve and enhance the multiple use of reservoirs an equilibrium of social and economic perspectives and innovative technological developments should be promoted. The integration of research, planning and management is a fundamental concern, in reservoir science and application. Since the forcing functions vary with latitude and multiple operational uses, the result is qualitative and quantitative differences in a reservoir or reservoir cascades. Therefore, several regional approaches to their management are required. Economic evaluation of the "services" provided by reservoirs should be performed in order to provide a realistic balance of the positive / negative impacts of their construction. Reservoirs in the Metropolitan Region of São Paulo represent special cases due to their strategic value in water supply and multiple uses.

1 Introduction

All the major hydrographic basins of South America have been impounded by the construction of large reservoirs. Initially built up with the objective of providing hydropower for energy supply, these artificial ecosystems were subjected in the course of time to multiple uses. The construction of large reservoirs (higher than 15 meter crest at the dam site) was intensified in the 30 years between 1950 and 1980. Particularly in Brazil dam construction strongly interfered with river functioning and hydrological cycles, producing many changes in the cycles themselves, in the biodiversity related to the rivers, and also in the hydrosocial cycle Several research papers (Junk and Melo, 1987; Tundisi, 1994a,b; Agostinho *et al.*, 1994; Tundisi *et al.*, 1999, 2003; Straskraba and Tundisi, 1999) showed the changes produced in natural systems by reservoir construction and also the multiple uses which they brought about or enhanced.

The size and complexity of the natural hydrographic network of South America undoubtedly influence the use of this valuable resource and the exploitation of the water resources. Construction of hydropower plants is one of many alternatives for exploiting the vast continental water supply in South America, and enhancing economic development and industrial build-up

2. Reservoirs as complex systems

A reservoir is only a component of three major ecological subsystems: the watershed and its hydrographic network, the reservoir itself, the outflow and the downstream river. These subsystems are closely coupled and the reservoir functioning depends on these interactions. Reservoirs as part of the watershed integrate detectors of the overall impact of anthropogenic activities carried out in the watershed, but they also reflect the state of conservation of the watershed if it is pristine, or degraded.

The levels of organization of watersheds as discussed by Vollenweider (1987) are:
1. Geological and climatological properties of the watershed;
2. Limnological properties of rivers, reservoirs, wetlands;
3. Water properties (water chemistry, hydrodynamics);
4. Anthropogenic impacts.

A reservoir is a fully interactive network among living organisms and their physical-chemical environment. As complex ecosystems, reservoirs present several characteristics which should be described: function and structure is determined by forcing functions such as climatological and hydrological factors; reservoirs are self-designing systems able to reorganize after dam closure; elements are recycled in the reservoirs; homeostasis is a result of interaction between chemical composition and biological functions; reservoirs have characteristic time scales and spatial scales; reservoirs have either artificial or natural pulse patterns; reservoirs have a complex network of biological components which interact with their hydrological regime and watershed inputs; and many reservoirs have a high degree of heterogeneity both in space and time.

Other factors that can add to the complexity of reservoirs are: age, morphometry, level of outlets and type of dam construction, and retention time.

The magnitude of reservoir response to the external climatological, hydrological and anthropogenic forcing depends upon the magnitude of the impacts and inputs and the size and volume of a reservoir. The time variability in reservoirs is a source of complex oscillations and the biota of the reservoirs, their food webs and the biogeochemical cycles respond to the oscillations with several transient organizations states. Therefore, the functional dynamics of the reservoirs are a complex process of input / output and varying degrees of responses to forcing functions. Reservoir forcing functions may be categorizes as climatological dependent through such agents as rainfall, wind, solar radiation. These functions are also operational, such as retention time, water level fluctuations, or water withdrawal. The forcing functions vary with latitude, and multiple operational uses, resulting in important qualitative and quantitative differences that produce various patterns of limnological and ecological functioning.

The multiple uses of watersheds and reservoirs produce many impacts in the biodiversity, water quality, hydrolofical cycle and water quality. These impacts are cumulative since they are incorporated in the functioning of the reservoirs and in their structure and function. For example, the accumulation and effects of heavy metals on the sediments and on the aquatic biota is a matter of concern not only for aquatic scientists but also for managers and decision makers. As the multiuse become more complex and diversified (Kennedy et al, 2003; Tundisi et al, 2003), more difficult is the task to remove impacts, recover watersheds and reservoirs. Costs of recovery will be difficult to evaluate if the reservoirs are large, dendritic and subject to dynamic activities resulting from changing economic exploitation of watersheds, and water quantity. Cumulative impacts are not only affecting the reservoir itself but the regional / local economy, human health and ultimately they impair multiple uses.

3. Urban reservoirs in the La Plata Basin and the Metropolitan of S. Paulo

A prominent feature of the water resources in the La Plata basin is the urban reservoirs for water supply of large populations. An outstanding example is the reservoir system for the S. Paulo Metropolitan region (although many other urban areas, from large to small towns, have the same pattern of water supply). The S. Paulo Metropolitan region has 26 large reservoirs, constructed in the last quarter of the nineteenth century and the twentieth century. These reservoirs, today located amidst a heavily populated and industrialized urban system, supply drinking water for 21 million inhabitants. The costs of treatment have increased in the last 10 years due to the many problems of eutrophication, toxicity and deforestation that affect the water quality and produce loss of biodiversity.

Many reservoirs are used for recreation, tourism and fisheries as well as for water supply. These activities were developed by the local communities over the years; the reservoirs are located in other municipalities, not in the S. Paulo town, and therefore there are problems of an institutional and political nature that interfere with their management. Despite efforts to introduce the watershed approach as a concept for management, the institutional and legal constraints are difficulties for implementation (Braga et al., 1998). The strategy for management of these reservoirs is focused on the following actions (Tundisi, 1990a, 1990b):

- Control of non-point sources of phosphorus and nitrogen (reforestation of watersheds, sanitary education of population),
- Treatment of wastewater to control eutrophication,
- Organization of a data bank, and
- Implementation of corrective and remediation actions at the watershed level, and technology for reservoir recovery (in-lake management), aeration, sediment isolation and phosphorus inactivation,
- Negotiations on the water uses and supply / demand should follow structural actions.

The cost of these actions is very high. For example, the estimated cost for the pollution abatement of Pinheiros River in S. Paulo town is US$ 100 million. It also requires an extensive period of preparation for institutional integration (federal, state and municipal institutions), involving negotiation at several levels. A great effort should be made for environmental and sanitary education, especially for populations near the reservoir, on the lake shore (Tundisi, 1993a, 1993b).

4. The integration of limnological research in the effort for sustainable water resource management: the challenges of reservoirs

Our understanding of the reservoirs as a unique class of epicontinental aquatic ecosystems is growing but far from complete (Kennedy *et al.,* 2003). The design and operation of the reservoir has limnological consequences and this provided a basis for a better knowledge of the link between engineering and limnology.

However the impact and role of reservoirs in the watersheds and the hydrological and hydrosocial consequences of their presence are still not well know and should require the integration of social, economic and environmental considerations in the management. For example what is the perception of the community about the reservoir pollution and eutrophication and the possible effects on their health and economic activities?

Reservoirs in urban regions and specially those located in the Metropolitan Region of São Paulo have an enormous and diversified impact on the economy and social organization in the region water availability, recreation, biomass exploitation are some activities that certainly will be affected by the deterioration of the reservoir water quality. The extent of this disruption in the cycle, produced by pollution and contamination, should be quantified and could provide limnologists with and insight capable to define the linkages between engineering and operation requirements, ecological outcomes and consequences and social aquatic resources (Robarts and Wetzel, 2000). Linking ecohydrology and hydrology is not and easy task and limnological studies are in the center of this linkage. Table 1 shows the engineering design of the parameters of reservoir location, morphometry, operation and its limnological implications.

A recent development on the knowledge of reservoir function and structure in the Metropolitan region of São Paulo and the role of limnological knowledge is given by the interaction of climatological forcing functions with the hydrography and vertical structure of the reservoirs. The vertical structure of these reservoirs is dependent on the wind force and duration and also on the input of solar radiation that supply energy to the water mass, besides the energy utilized for photosynthesis. During the cold fronts that affect the Metropolitan Region of São Paulo, wind force increases, solar radiation decreases and a process of vertical circulation is permanent changing the water quality and promoting a more homogeneous distribution of physical and biological variables in the system. After the passage of the cold front, wind force is low, solar radiation and surface heating increases and biological and chemical stratification occurs changing the water quality of the reservoirs and promoting the growth of cyanobacteria that further deteriorate the water quality increasing the costs of treatment. Therefore the cost of treatment of the water available for domestic use in the Metropolitan Region of São Paulo is related to the frequency and absence of the cold fronts. That affect this region during the whole year (Tundisi et al, 2004a,b).

Table 1. Engineering design considerations and limnological implications related to reservoir purposes

Reservoir Purposes	Design Considerations	Design-related Parameters	Limnological implications
Flood control Hydropower Navigation Water supply Irrigation Recreation Tourism Agriculture	Storage capacity Inflow volume Inflow seasonality Hydraulic head Volume Level of outlets Filling phase period	Geographic location • Incident solar radiation • Precipitation/evaporation • Geology and soil type Location within the watershed • Basin slope • Stream order • Drainage area • Surface area to drainage area ratio • Landuse Morphometry • Length to width ratio • Shoreline development • Surface area • Volume • Volume to surface area ratio • Mean and maximum depth • Surface elevation fluctuation • Outlet depth (s)	Material loading • Nutrient supply • Inorganic suspended matter Hydrology • Hydraulic retention • Advective transport Thermal budget • Water temperatures • Degree of stratification Light regime • Non-algal turbidity • Photic depth Mixing regime • Density currents • Mixing depth Material retention

Modified from Kennedy (1999).

5. New perspectives for reservoir management in the metropolitan region of São Paulo: changing strategies for the future

The management options and alternatives show in chapter 4 of this paper are one step in the overall strategy of management of reservoirs of the Metropolitan Region of São Paulo. Strategies that demand the implementation of only structural inputs in the management are not sufficient. By structural inputs we understand new channels, water transportation, technological plants. It is necessary a vast array of non structural inputs such as proposed in the NEGOWAT project: negotiations on supply / demand with the local communities, active participation of the public and a permanent increase of awareness in order to improve public understanding of the problem. (Tundisi, 2003b). The watershed concept in the management is in part adapted and accepted by the decision makers and managers but this has to be improved with institutional integration on the problem of water quality & quantity.

The effort for modeling the climatological / hydrological processes should thus be followed by the permanent implementation of scenarios of water quality and the economic impacts of water treatment.

For the future options and alternatives it is clear that the emphasis on treatment and production of water of good quality should be continuously pursued, however including a better protection of the water sources such as reflorestation, protection of forested areas and protection of wetlands. This would improve the water quality at the source promoting a decrease in the costs of treatment and a better water quality in the future (Ana, 2002).

The new strategies for reservoir management in the MRSP should also include efforts to promote a massive dissemination of information in order to include permanently the community in the process of management.

The costs of water treatment are due to a decrease in water quality at the source. This can be changed by a more elaborate process of watershed and water quality protection and conservation. The decrease of non point sources of impact is dependent on the community participation and awareness.

Reservoir "services" should be evaluated and this should be part of the new strategic approach to solve this complex problem in a complex context and region.

6. Conclusions

The management of natural or artificial ecosystems is now in a transition stage from reactive, local and sectorial to a predictive, at watershed level and integrated approach. The watershed as a unit for research, management and development of negotiations is now internationally recognized as a useful and well designed approach. At each watershed a local / regional data bank should provide a stronger basis for strategic planning. A strong link between data bank, research and management should be pursued. The evaluation of "services" of ecosystem structure and functions, the values of these "services" and their role on the local / regional society is another fundamental issue. For both Tietê / Cabeceiras and Guarapiranga basins, an effort into the sanitary education and environmental education of the population should help to improve the management process and the negotiations at the watershed level.

Considering this issue the "Water School" ("A Escola da Água") as proposed by Tundisi (2003a) is one of the tools that, if implemented, could help in the increase of awareness and participation

The need for restoration of aquatic ecosystems claim for a strong emphasis on "ecological design" (Palmer et al, 2004) that is the ability to restore the ecosystem at structural and functional levels. Restoring functions in reservoirs implies in the restoration of water quality and the necessary measures to improve watershed functioning, specially feedback systems and biodiversity.

Referências bibliográficas

Agostinho, A.A. et al. 1994. "Impacts of the Ichthyofauna on Reservoir and Biological Basis for its Management". Environmentall and Social Dimensions of Reservoir Development and Management in the La Plata River Basin. UNRCD, Nagoya, Japan, 135-148 pp.

ANA – Agência Nacional das Águas 2002. A evolução da gestão dos recursos hídricos no Brasil, Edição comemorativa do Dia Mundial das Águas. 64 pp.

Braga, B.; Rocha, O.; Tundisi, J.G. 1998. Dams and the environment: the Brazilian experience. Water Resources Development, v.14. 127-140 pp.

Junk, W.J. And Mello 1987. "Impactos Ecológicos das Represas Hidroelétricas na Bacia Amazonica Brasileira". Tumbingen Geographische Studien, 95: 375-387 pp.

Kennedy, R. H 1999. Reservoir design and operation: limnological implications and management opportunities. In: Tundisi, J.G. & Straskraba, M. (eds). Theoretical Reservoir Ecology and its application. Backhuys Publishers, the Netherlands. 1-28 pp.

Kennedy, R. H.; Tundisi, J.G.; Straskrabova, V.; Lind, O.T. & Hejzlar, J. 2003. Reservoirs and the limnologist's growing role in sustainable water resource management. Hydrobiologia 504: xi-xii.

Palmer et al 2004. Ecology for a crowded planet. Science Vol. 304. 1251-1252 pp.

Robarts, R. & Wetzel, R.G. 2000. The looming global water crisis and the need for international education and cooperation. SIL News 29: 1-3 pp.

Straškraba, M.; Tundisi, J.G. 1999. Reservoir water quality management. ILEC. (Guideline series n.9). 129pp.

Straskraba, M. E Tundisi, J.G. 2000. Diretrizes para o gerenciamento de lagos. Gerenciamento da Qualidade da água de represas. V. 9. 258pp.

Tundisi, J.G. 1990a. Limnologia no século XXI: perspectivas e desafios. São Carlos: Instituto Internacional de Ecologia, 24pp.

Tundisi, J.G. 1990b. Perspectives for Ecological Modelling of Tropical and SubTropical Reservoirs in South America. Ecol. Modell. 52: 7-20 pp.

Tundisi, J.G. 1993a. The environmental impact assessment of lakes and reservoirs. In: Salánski, J.; Itsvánovics, V. (Eds.). Limnological bases of lake management: proceedings of the ILEC/UNEP int. training course. Tihany, Hungray; 38-50pp.

1993b. Man-made lakes: theoretical basis for reservoir management. Verh. Internat. Verein. Limnol., v.25; 1153-1156pp.

Tundisi, J.G. 1994 a. Regional approaches to River basin management in La Plata: An Overview. In: UNCRD (ed) Environmental and Social Dimensions of Reservoir Development and Management in the La Plata River Basin. Nagoya, Japan. 1-6 pp.

1994 b. Tropical South America: Present and Perspectives. In: Margalef, R. (ed). Limnology Now: A Paradigm of Planetary Problems. Amsterdan. Elsevir. 353 – 424 pp.

Tundisi, J.G.; Matsumura-Tundisi, T.; Rocha, O. 1999. Theoretical basis for reservoir management. In: Tundisi, J.G.; Straškraba, M. (Eds.). Theoretical reservoir ecology and its applications. Brazilian Academy of Sciences, International Institute of Ecology, Backhuys Publishers.505-528pp.

Tundisi, J.G. 2003. Água no século XXI: enfrentando a escassez. RIMA/IIE. 248 pp.

Tundisi, J.G. 2003a. Ciclo hidrológico e gerenciamento integrado. Ciência e Cultura, temas e tendências. Gestão das Águas. Vol. 55, no. 4. 31-32 pp.

Tundisi, J.G.; Matsumura-Tundisi, T.; Rodríguez, S.L. 2003b. Gerenciamento e recuperação das bacias hidrográficas dos rios Itaqueri e do Lobo e da Represa Carlos Botelho (Lobo-Broa). IIE, IIEGA, PROAQUA, ELEKTRO, 78pp.

Tundisi, J.G.; Matsumura-Tundisi, T.; Arantes Junior, J.D.; Tundisi, J.E.M.; Manzini, N.F. And Ducrot, R. 2004 a. The response of Carlos Botelho (Lobo, Broa) Reservoir to the passage of cold fronts as reflected by physical, chemical and biological variables. Brazilian Journal of Biology 64(1). 177-186 pp.

Tundisi, J.G.; Abe, D.S.; Matsumura-Tundisi, T.; Sidagis-Galli, C.; Tundisi, J.E.M. 2004b. Water quality and greenhouse gas production in hydroelectric reservoirs. Greenhouse Gas Emission from Hydropower Reservoirs and Water Quality (Editors – Luiz Pinguelli Rosa; Marco Aurélio dos Santos; José Galizia Tundisi) – COPPE-UFRJ. 109 -119 pp.

Vollenweider, R.A. 1987. Scientific concepts and methodologies pertinent to lake research and lake restoration. Swiss. J. Hydrol., v.49, n.2; 129-147pp.

Acknowledgements

The authors express their thanks to FAPESP (PIPE Project no. 00/007379-5, "Desenvolvimento de sistemas de suporte à decisão no gerenciamento de reservatórios e abastecimento público e hidroelétricas") to FINEP – CTHIDRO ("Estudo comparado da Represa Luis Eduardo Magalhães (TO) e Barra Bonita (SP) com a finalidade de desenvolver Modelos de Gestão dos Recursos Hídricos") to NEGOWAT ("Faciliting negotiations over land and water conflicts in Latin American periurban upstream catchments: combining agent based modeling with role game playing") for financial support for research in reservoir limnology and management.