Global Review of Lake and Reservoir Eutrophication and Associated Management Challenges

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Through a sequence of working questions, the following sections outline a global review of eutrophication of lakes and reservoirs with associated management challenges. A short state-of-the art on remedial measures and feasible innovations to counterpart challenges enhances yardsticks of decentralization technologies, ecohydrology issues, suitable scenarios to societal goals, valuation of ecological services, trade-offs meaningful for human well-being and lessons learned for adaptive management. Consequently, those topics are addressed towards governance, management, research and capacity building in order to assist stakeholders through sustainable, accountable programs and win-to-win partnerships.

Eutrophication: a global problem

The growth of the human population in the first decade of the 21st century is estimated as 100 million persons/year. Considering the per capita production of 4g of phosphorus, 15g of nitrogen and 100g carbon, as biological oxygen demand we can get an insight into the eutrophication problems that humanity has to face on a global scale.

Human waste and wastewater from the human, agricultural and industrial activities will continue as permanent inputs into lakes, rivers, reservoirs, wetlands, coastal waters shallow lakes and coastal lagoons. The causes and consequences of eutrophication are well known, especially in temperate waters (Jeppesen et al 2005). Effects to understand the relationships of nitrogen and phosphorous loads and the functioning on lakes, reservoirs and rivers (see **Box 1**) under these stress conditions have been intensified in the last 20 years (Sutcliffe and Jones 1992; UNEP/IETC 2001).

Eutrophication is thus a global problem aggravated by contamination and other sources of pollution around the world. The consequences of the deterioration of the water bodies under eutrophication stress besides the usual and well known impacts on the biogeochemical and technological cycles in lakes and reservoirs (Reynolds, 1992) are also of an economical and social nature. These are not well measured or well discussed consequences, but eutrophication has large scale impact into the economy of entire regions as well as in the social context quality of life and human health (IETC 2001, Tundisi 2003).

Box 1. A short guide on global review of eutrophication

Increased input of nutrients, especially phosphorous, leads to an increased incidence of nuisance blooms of blue-green algae, leading to a increase of water turbidity, a building of organic and nutrient-rich sediments, loss of oxygen from the bottom waters of the lake which, in turn, accelerates nutrient recycling processes, and changes in the lake's food web structure. Secondary nutrient limitation of silica or nitrogen that results when phosphorus levels are elevated also leads to changes in the phytoplankton community and to the development of nuisance species of algae. Proliferation of macrophytes is associated with eutrophication, especially in shallow lakes, but these problems are not tied directly to excessive rates of nutrient loading. Although increases in nutrient levels enhance fish production, the loss of habitat, e.g., by sediment buildup, deoxygenation, undesirable proliferation of macrophytes, and food web simplification cause a shift from fish diversity to less desirable species, especially in more extreme cases of eutrophication. Stocking of exotics and overfishing exacerbate this problem. From a human use perspective these changes create numerous problems, i.e. fouling of boats and structures by algal growths, loss of aesthetic appeal, accessibility problems for swimmers and boaters because of macrophytes, economic damage to resort and property owners, and increased costs and technical difficulties of treating water for drinking purposes because of taste and odor problems and increased potential for trihalo-methane production. Once an oligotrophic lake has been made eutrophic, processes develop that may delay recovery after nutrient loadings have been decreased. If the hypolimnion becomes anoxic, recycling of phosphorous from the sediments is enhanced, in effect increasing the efficiency of use of the phosphorous input. During the eutrophic phase many changes may occur that will not be easily reversed by a reduction in nutrient supply, such a loss of desirable macrophyte, invertebrate, and fish species. Source: adapted from NRC (1992), Tundisi (2003)

Nutrient reduction is a necessary, but not always a sufficient, condition for reversal eutrophy. Point sources of nutrients are the primary cause of excessive loadings in some lakes, but nonpoint sources (urban and agricultural runoff) contribute most of the nutrient input to the majority of lakes. A further discussion is enclosed in the **Box 2** which depicts some of stresses. As consequence of this process, on the one hand, eutrophication produces a general reduction of possibilities of water use; thus, the importance of reservoirs and lakes can be compromised seriously as primary resources for socio-economic development.

On the other hand, biological processes in eutrophic environments increase productivity, either as fish yield or as proteins' source which could be positively regarded for developing regions. Thus, eutrophication involves increasing nutrient inputs resulting from natural or human activities. Since freshwater lakes or reservoirs become more eutrophied, some ways to foresight and prevent this problem was historically engineered through the reduction and control of nutrients inputs. Although this high-cost process is unquestionably necessary in most of the cases, it does not produce the expected improvement in a short-time –due to the necessary adaptation time of the environment to manage changes.

Where we go in terms of eutrophication

At the global scale since 1960 until 2005 the total amount of freshwater stored in reservoirs grew up four times. Although today's reservoir freshwater is three times bigger than in rivers, during the same period the total loadings of nitrogen doubled and phosphorous loadings tripled in water bodies. Because most of these water bodies are located in either tropical or subtropical regions, prospective challenges of how to handle with eutrophication growing is becoming a national level strategy, also in transboundary frameworks and programs.

This calls a plea to stakeholders at temporal and spatial scales. At temporal scales, the working hypotheses outlined throughout the following sections depict a summary of insights from eutrophication studies and water practices that ought to share a plurality of visions, analyses and projects worldwide. Those hypotheses gather up the scientific methods applied usually at short-term schedules, in compliance with global societal demands, at long-term, through demonstrative projects which put strengths in some guidance questions and policy adaptation with medium-term master plans.

At the spatial scales, associated management challenges from remedial measures and possible feasible innovations, either as structural or as non-structural ones, are outlined at main spatial scales: of the lake/reservoir and of the drainage basin. In real cases, these scales have a continuum of integrated scales of streams and rivers, wetlands and lake area. The characteristics and emergent properties are specific to each scale, but of common approach in terms of restoration and stakeholder's empowerment. Also, structural and functional characteristics should be assessed, as follows.

Structural features are water quality, geology and soil condition, hydrology, topography, morphology, flora and fauna, carrying capacity, food web support and nutrient availability.

Functional features gather factors of surface and ground water storage, recharge and supply, floodwater and sediment retention, transport of organisms, nutrients and sediments, humidification of atmosphere by transpiration and evaporation, oxygen production, nutrient cycling, biomass production, food web support, and species maintenance, provision of shelter for ecosystem users, detoxification of waste and purification of water, reduction of erosion and mass wastage, and energy flow. Most of them are related to intrinsic possibilities of restoring water-bodies.

Box 2. Stresses affecting lake and reservoirs – becoming globally threaten?
Common stresses affecting lakes and reservoirs include eutrophication from nutrient and organic matter loadings at local scales which provoke accumulated effects at long-term and global scales. Siltation from inadequate erosion control in agricultural, construction, logging, or mining activities is coupled with eutrophication; moreover, introduction of exotic species, acidification from atmospheric sources and acid mine drainage can aggravate trophic states. And contamination by toxic or potentially toxics metals such as mercury and organic compounds such as polychlorinated byphenyls (PCBs) and pesticides are common downstream human settlements. Chemical stresses are categorized according to source as (1) point sources, i.e. municipal wastewater, which generally are the easiest to identify and control; (2) non-point or diffuse sources such as urban and agricultural runoff from a lake's watershed; and (3) long-range atmospheric transport of contaminants, which is the most difficult to measure and control. These local stresses become cumbersome, because in the last century the intercepted continental runoff grew up 15 times as urban center intensified.
Source: adapted from Millennium Ecosystem Assessment (2005).

A review of restoration measures

In addition, physical changes both at the land-lake interface by draining of riparian wetlands, and hydrologic manipulations through damming outlets to stabilize water levels also have major impacts on the structure and functioning of lake ecosystems (NRC, 1992). Some emergent properties for restoration are (NRC, 1992; Mendiondo & Valdés, 2002): resilience, persistence, verisimilitude, likelihood and adaptive management. Some complementary definitions are enclosed in the **Box 3**, and their performance are broadly related to management actions.

Lake-and-reservoir restoration is a relative recent activity to attain global standards. Historically, the term *restoration* has been applied broadly in lake management to an array of actions aimed at improving lake conditions for designated human uses (e.g., contact, recreation, fishing, and water supply). Return of a lake to its pristine condition has note been an explicit goal of most lake restoration projects, although these actions often improve some aspects of a lake's ecological attributes. As such, most so-called lake restoration projects are actually *rehabilitation efforts*, and many are merely designed to manage (mitigate) undesirable consequences of human perturbations.

It is worth noting a distinction between methods that improve ecosystem structure and function (*restoration in the broad sense*) and methods that merely manage symptoms of stress. In the US, lake restoration began after 1970, primarily in response to problems of nutrient overenrichment (i.e. NRC, 1992).

For *long-term restoration*, it is essential to control the source of the problem. In the case of *eutrophication*, this means decreasing the loading of nutrients, particularly phosphorous, from various watersheds sources. In some cases, this also means that loadings of silt and organic mater must be decreased.

Control of external sources is sufficient to return some water bodies to their former conditions, but in many cases the changes in the lake have been so dramatic – major shifts in biota, loss of habitat, physical changes in bottom sediments, and lake hydrology— that merely turning off the loadings is not sufficient to improve water quality and ecosystem structure, at least in a reasonable time frame. *In-lake restoration* techniques must be employed.

Numerous methods have been developed to restore lakes or improve their conditions. Available methods range widely in *effectiveness, cost, frequency of use, and range* of applicability. Because eutrophication is the most widespread and longest-studied lake problem, more methods have been developed to restore eutrophic lakes than to address all other problems put together (NRC, 1992).

Limiting factors of eutrophication management

The common ability to assess the *effectiveness of management projects* and to compare the performance of restoration methods is severely limited by three factors:

- *continuous surveillance* of lake conditions for an adequate period of time before and after a restoration attempt has been done on relatively few lakes; sometimes, sufficient surveillance probably was done, but analysis and interpretation of data were not a part of the surveillance effort, or not readily available to others;

Box 3. Brief description of managing water system features from local to global scales

Resilience is the ability of the ecosystem to recover from perturbation or to attain a new equilibrium state after disturbance. Persistence, or self-sufficiency, is the ability of the system to undergo natural successional process or persist in a climax sere (a stage in ecological succession), without active human management; in short, *persistence* is the ability of the system to survive as a dynamic system, evolving in a manner and at a rate regarded as normal for that type of ecosystem at it particular stage of development (i.e. time between needed management intervention or units of management effort required). *Verisimilitude* is a broad characteristic of the restored ecosystem reflecting the overall similarity of the restored ecosystem to the standard comparison, be it prior conditions of the ecosystem or of a reference system. *Likelihood* is the ability of the system to produce non-linear, different responses within a confidence interval of possibilities, in front to the same perturbation input. *Adaptive management* is a characteristic of restoration programs to assess and survey measures in progressive ways in companion to natural reaction of system to changes in time and in space.

- *restoration projects* for lakes and reservoirs are usually considered to be *operational activities* rather than R&D projects; as a result they are designated to produce the desired effect (a restored water body) by whatever combination of methods seems likely to succeed; it is so usually not possible to determine which of several techniques used simultaneously actually produced the measured improvements, even if detailed monitoring is done;

- the *goals* of restoration projects are not always clearly defined, and it is difficult to judge the degree of success when clear objectives have not been set.

Lake restoration projects typically focus on restoring only one part (the lake) of a complex, connected stream-wetland-lake system within a watershed. When wetlands are considered at all in lake restoration projects, it is currently for diversion of nutrient-laden storm water runoff or sewage effluent into the wetland in an effort to obtain nutrient uptake by wetland vegetation. Such diversions may provide a temporarily lowering of nutrient loadings to lakes, but wetland flushing during high flow periods may result in little net annual retention of nutrients by the wetlands.

The impacts of diversion on wetland ecology generally are not taken into account in deciding whether to proceed with such project. Although many techniques are potentially available to restore degraded lakes, the science of lake or reservoir restoration is still *inexact*, and the outcome of applying a given technique to a particular lake is difficult to predict accurately.

Restoration technology for lakes and reservoirs can be advanced by ensuring that projects are monitored adequately so that the effects of various manipulations can been assessed properly. Some integrated techniques seem promissory (Mendiondo, 2000; Mendiondo & Valdés, 2002; Mendiondo et al, 2000a; 2000b), but further research should be developed to validate at different biomes.

Local Measures

The measures for eutrophication control could be structural, non-structural and a mix of them. High loading of nutrients to lakes and reservoirs produces algal blooms and other problems. In most cases, oxygen-demanding organic matter, silt, toxic materials accompany the nutrient loadings. **Table 1** shows a brief summary of restoration measures and their convenience to main problems affecting lakes and reservoirs. Restoration using the concept of ecoregions – a major determinant of lake and reservoir productivity is the steady-state, long-term average concentrations of nutrients, especially those that can be growth limiting, such as phosphorous, nitrogen, and silica. For instance, control of algal blooms consists, on the one hand, in:

- *nutrient source reduction* as actions towards diversion, product modification, removal of phosphorous from wastewater, interception of nonpoint sources of nutrients, best management practices, and dilution; or
- *in-lake methods* to reduce phosphorous concentrations and cycling as phosphorous inactivation, sediment skimming, sediment oxidation, deep-water discharge as well;
- *Management of symptoms* as biomanipulation, artificial circulation, algicides, among others.

Box 4. Local ecological criteria for global successful measures
Water quality and human use criteria aided by use of simple trophic indices. The most widely used TSIs are those developed by Carlsson, based on Secchi disk transparency and on concentrations of total phosphate and chlorophyll a. An increase of 10 units in an index represents a doubling of algal biomass. Carlsson recommended that the indices be considered separately in evaluating trophic state. Lake morphometry plays a major role in determining the amount of “internal loading” of nutrients from the sediments to the water column. Shallow lakes, particularly those exposed to wind-induced mixing are likely to have high internal loading rates. Water residence time also plays a role in determining lake water column nutrient concentration. As water residence time decreases, the concentration of nutrients approaches the concentration in incoming streams or rivers, and sedimentation of nutrients becomes less a factor. Some controversies emerge about the success of restoration projects, as vested interests, different standard of evaluation, or duration of evaluation period. Finally, success will come whether some needs were addressed before as: continuous system restoration (river, floodplain, lake/reservoir), the setting of restoration goal(s), the recognition of needs for adaptive management and for improved assessments, and for high standard in assessing functional equivalency (restored versus natural systems). Source: adapted from NRC (1992) and Tundisi (2003)

Table 1. Summary of local lake/reservoir restoration measures of eutrophication with suitability ("yes") and unsuitability or uncertainties ("?") for the measure to each problem (adapted from NRC, 1992; Tundisi, 2003).

Structural measures	Eutrophication	Siltation	Acidification	Exotic Species	Toxic loads
Nutrient source reduction	yes	yes	yes	?	yes
Diversion	yes	yes	?	?	?
Land disposal	yes	?	?	?	?
Product modification	yes	?	?	?	yes
Wastewater treatment	yes	?	?	?	yes
Interception of nonpoint sources	yes	yes	yes	?	yes
Dilution	yes	?	yes	?	yes
Flushing	yes	?	yes	?	yes
In-lake methods	yes	?	yes	yes	yes
Alum treatment	yes	?	?	?	?
Sediment skimming	yes	?	?	?	yes
Sediment oxidation	yes	?	?	?	?
Deep-water discharge	yes	?	?	?	yes
Biomanipulation	yes	?	?	yes	?
Artificial circulation	yes	?	?	?	?
Biocides (algicides/herbicides)	yes	?	?	yes	?
Biocontrol agents	?	?	?	yes	?
Drawdown/sediment desiccation	yes	yes	?	?	?
Bioharvesting	yes	?	?	yes	?
Aeration	yes	?	?	?	?
Dredging	yes	yes	?	?	?
Liming	yes	?	yes	?	?

On the other hand, the control of aquatic macrophytes encompasses biological agents, water level drawdown, harvesting and herbicides. Finally, to low dissolved oxygen some procedures include hypolimnetic aeration and artificial aeration. Reduction of nutrient loadings and related inputs can be accomplished by (NRC 1992, Tundisi 2003):

- diverting point sources of nutrients or nutrient-laden streams out of the lake's watershed,
- modifying products to contain lower amounts of nutrients, mainly phosphorous;
- removing nutrients from wastewater in engineered treatment systems;
- intercepting nutrients in pre-lake impoundments as stormwater detention and retention ponds, natural or artificial wetlands;
- decreasing nutrient runoff from agricultural lands by "best management practices", and
- instituting land use and management controls.

Control methods for external sources of nutrients encompass different situations:

- stream or wastewater diversion;
- municipality wastewater treatement (i.e. tertiary treatment for N and P removal);
- product modification, i.e. legislative ban of phosphate in laundry detergents, slow release fertilizers);
- treatment of inflow streams, either as diversion (into wetlands; over upland vegetation) or in-stream methods (sedimentation/impoundment basins to remove particulate N and P; channel aeration; chemical precipitation; biotic harvesting).

The *land use practices* are discriminated by:

- *prospective zoning* (i.e. on-site storm at retention or detention regulations; setback and other shoreline restrictions on new constructions; restrictions on shoreline vegetation removal; restrictive zoning in watershed to minimize development; minimization of impervious areas in development; use of grassy swales instead of curb and gutter drainage);
- *best management practices*: runoff controls to change volume and peak flow through no or minimum tillage; winter cover crop; contour plowing and strip cropping; terraces; grassed outlets; vegetated borders on fields and along waterways; detention ponds;
- *treatment of urban runoff*, i.e. best management practices (BMP) as retention/detention basins; swirl concentrations; first flush diversion or low flow to sanitary sewers;
- *diversion* of runoff into wetlands; street sweeping or vacuuming; public education to

reduce litter accumulation, to control lawn fertilizer losses); or as treatment of agricultural runoff
- *nutrient loss controls*: timing and frequency of fertilizer applications, their amounts and types used; control in situ transformation of fertilizers to soluble forms; crop rotation with legumes; storage of manure during low temperature season.

Integrated measures

One cumbersome problem to control eutrophication is the complex nature of loadings coupled to the flow regimes draining to the water-bodies. **Figure 1** illustrates the example depicting in **Box 5** that several, equal possible scenarios of loadings are possible to various levels of organic matter production and with a wide range of circumstances. In short, several combinations of net productivity could attend dynamical, ecological conditions of river flows, especially depending upon water quality, becoming progressively more complex to be managed if only at the lake/reservoir scale. Another situation is to estimate future treatment costs of water withdrawals from lakes and reservoirs which river basin will be under climate or land-use change (see i.e. **Box 6** and **Figure 2**).

Ecological features of freshwater biodiversity in lake and reservoirs can be addressed over landscape continuity through structural and biological features of river corridors. This attempts to ecohydrological categories which are detailed in the **Appendix 1,** adapted from Mendiondo (2008). All these categories are ranked in accordance with principles of continuity, dynamics, resilience, vulnerability and diversity in departure of interactions among the drainage area, the floodplain and the river. In this table, several variables are defined in order to guide scientists and water practitioners during the analysis of basic data on field. In this way, the **Appendix 2** also points out an example of using the **Appendix 1** through an interaction matrix between parameters, as rows, and indicators through columns for urban biodiversity responses to environmental stimuli during flood pulses. In the **Appendix 2** the arrow direction points towards biodiversity increase, having three potential biodiversity responses to environmental stimuli: increase, decrease, and dual response.

Associated management challenges

How challenges could be converted into opportunities? Here is briefly depicted prospectives to envisage challenges into opportunities through yardsticks of technologies towards eco-hydrology, to long-term scenarios suitable to attain societal goals, to valuate of ecological services of lakes and reservoirs, their trade-offs meaningful for human well-being and lessons learnt for adaptive management. **Table 2** summarizes main questions for win-to-win partnerships ranging from global to local scales.

Associated management challenges are crucial at rivers, creeks and swamps connected to lakes and reservoirs, highly dependant on budgets and payment of environmental services. For instance, in South American cases the average specific cost of biodiversity restoration project in upper areas should be up to US$ 2.5 million km^{-2} of drainage area of river basin (Mendiondo, 2008b). For this case, the average amount of environmental services of subtropical rivers draining to reservoirs are estimated from 28 to 33 million US$ km^{-2}. This figures point restoration projects as a small amount in comparison with the benefits from lakes and reservoirs. Project costs vary in a wide range in dependence with the efficiency, the methods used and the usage to evaluate costs per unit drainage area or per river's unit length. Enhancement and rehabilitation costs differ from restoration or renaturalization ones (Mendiondo, 1999). Enhancement-biodiversity projects cost ca. 3 U$ million km^{-1} of river length and 1.5 km^{-2} of drainage basin. Conversely, restoration projects rise to 25 U$ million km^{-1} of river, and renaturalization can rise to more than 90 U$ million km^{-1} of river (Mendiondo, 2006). All these costs support investment and maintenance during the half life of the project to increase functions at floodplain ecotones. These costs should be fully compared with costs and efficiencies of water treatment of eutrophication removal and, mainly, with management frameworks suited with stakeholders of the river basin. General speaking, the higher river drainage area, the lower specific costs per capita. This outlines needs for hydrosolidarity trade-offs through implementing river basin association to compensate the strong degradation at upland areas with societal management capacity at lowlands.

Thus some measures could be better addressed through demonstrative pilot projects which help on developing and setting a framework of sound lake management for a continuing related research agenda with policy and decision makers, lake users, senior executives, Government officials, NGOs, researchers and those who are involved in lakes & reservoirs. **Table 3** depicts one example of a demonstrative pilot project based upon "Water for Life" premises.

Box 5 – Merging loadings and discharges to control eutrophication of lakes/reservoirs

Complentary to floods, the low-flow analysis of scenarios at river basins draining to a water-body **(Figure 1)** is addressed comparing the duration of permanency (abscissa axis), average *chlorophyll* balance of Productivity-to-Respiration ratio (*P/R*, in right ordinates) and specific discharges (left ordinates). This chart is adequate to every size of river basin draining to a lake or reservoir and could be used to make inferences about the sources of loads, either autochtonous or allochtonous of the river. Indirectly, it also could be envisaged towards linking minimum flow needs of rivers to maintain various equally possible states of in-stream biodiversity. In this figure, left ordinates, with solid lines, depict the specific discharge of permanency curve with excedance probability in the abscissas. Right ordinates outline different scenarios of specific *chlorophyll*-a loadings, related to the catchment area of the river, in correspondence with the same probability values. The first scenario, with bold dotted lines, is related to *chlorophyll-a* productivity higher than respiration ($P / R > 1$) derived from the mixing process of fitobenthos and alloctonous loads incorporated into the main flux of the river and during flood passages. Conversely, during medium to low flows, the second scenario (with double continuous line) shows a quasi steady-state, or quasi "lentic equilibrium", without connection of the main river with adjacent floodplain. In this second scenario of **Figure 1**, the net flux of *chlorophyll-a* remains constant (≈ 0.05 mg s^{-1} Km^{-2}) between 25% to 90% of permanency curve that corresponds to specific discharges ranging from 15 to 5 L s^{-1} Km^{-2}). For this scenario, a decrease of net *chlorophyll-a* flux is expected for discharges expected to occur for lower than $Q_{90\%}$, because of possible anoxic conditions and low radiation inputs. When lentic behavior is persistent in time, without floodplain connections to river channel, a general drop of *chlorophyll-a* net flux is expected for a new, third scenario (with double, non-continuous line). This novel situation is characterized by a moderate reduction of the *P/R* ratio but with high photosynthesis rates yet. However, if this situation persists with low photosynthesis rates, the *P/R* ratio would maintain values below previous ones and consuming autoctonous organic matter, as showed in the fourth scenario of **Figure 1**.

Source: Mendiondo (2008)

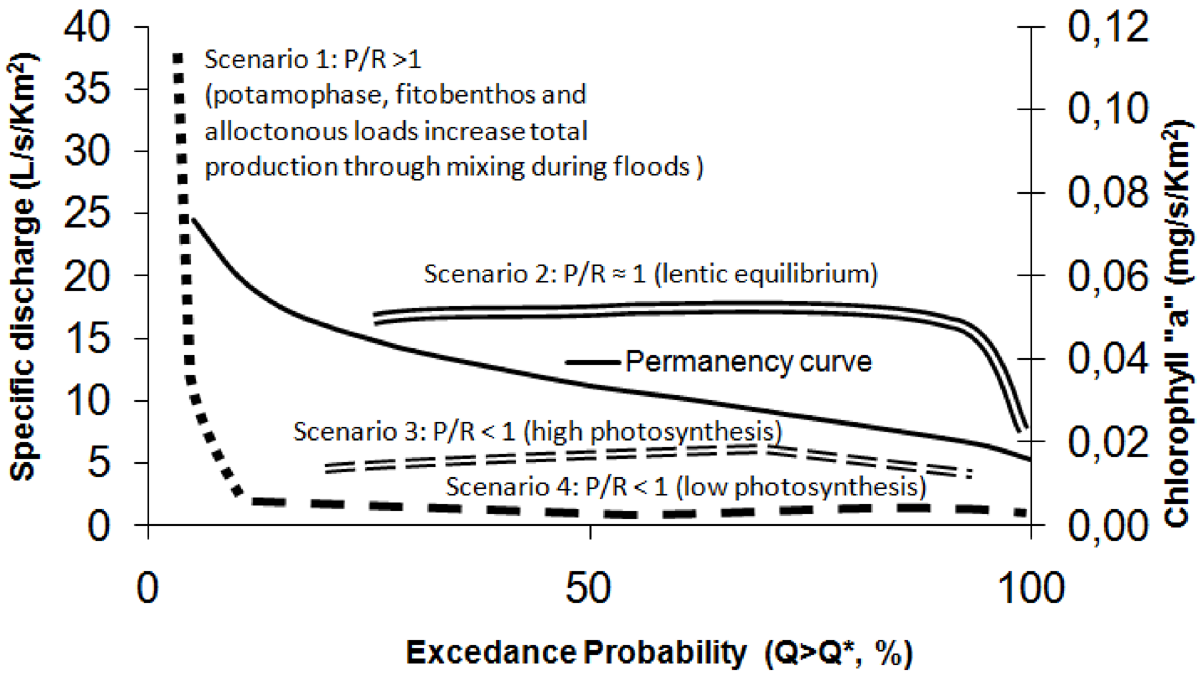

Figure 1- Flow analysis scenarios of river basin draining to a reservoir and with potential consequences to trophic index, with discharge permanency (at abscissa axis), scenarios of average *chlorophyll-a* balance of Productivity-to-Respiration ratio (four scenarios, at right ordinates) and specific discharges of permanency curve (continuous line, at left ordinates). Source: Mendiondo (2008)

Box 6. Treatment costs of water withdrawn from lakes/reservoirs under long-term change

Progressive loadings from rivers have persistent effects in trophic states which impact the future treatment of water withdrawn from lake and reservoirs. These impacts could be addressed as the relative, nominal change in treatment costs, i.e. the percentile difference of treatment costs between two comparing periods related to the previous situation and for each time scale of the scenario. For instance, in **Figure 2** are depicted two long-term scenarios, both of them related to nominal treatment cost of year 2000 and towards year 2025, 2050 and 2100. The first scenario (upper chart) points the expected effect of the long-term climate change, and without land-use change in the upper river basin draining to the water-body, in the treatment cost of water withdrawn and for different technologies of nitrogen and phosphorous removal ranging from lower to higher efficiency methods: stabilization ponds, natural/artificial wetlands as well as flocculation and denitrification. The second scenario (bottom chart) is the expected treatment cost of water withdrawn for no climate change, but with land-use conversion at the long-term between two scenarios: food and energy security, i.e. ethanol boom and cash-crops, in comparison with ecotechnologies and payment for environmental services. Source: Mendiondo (2008a)

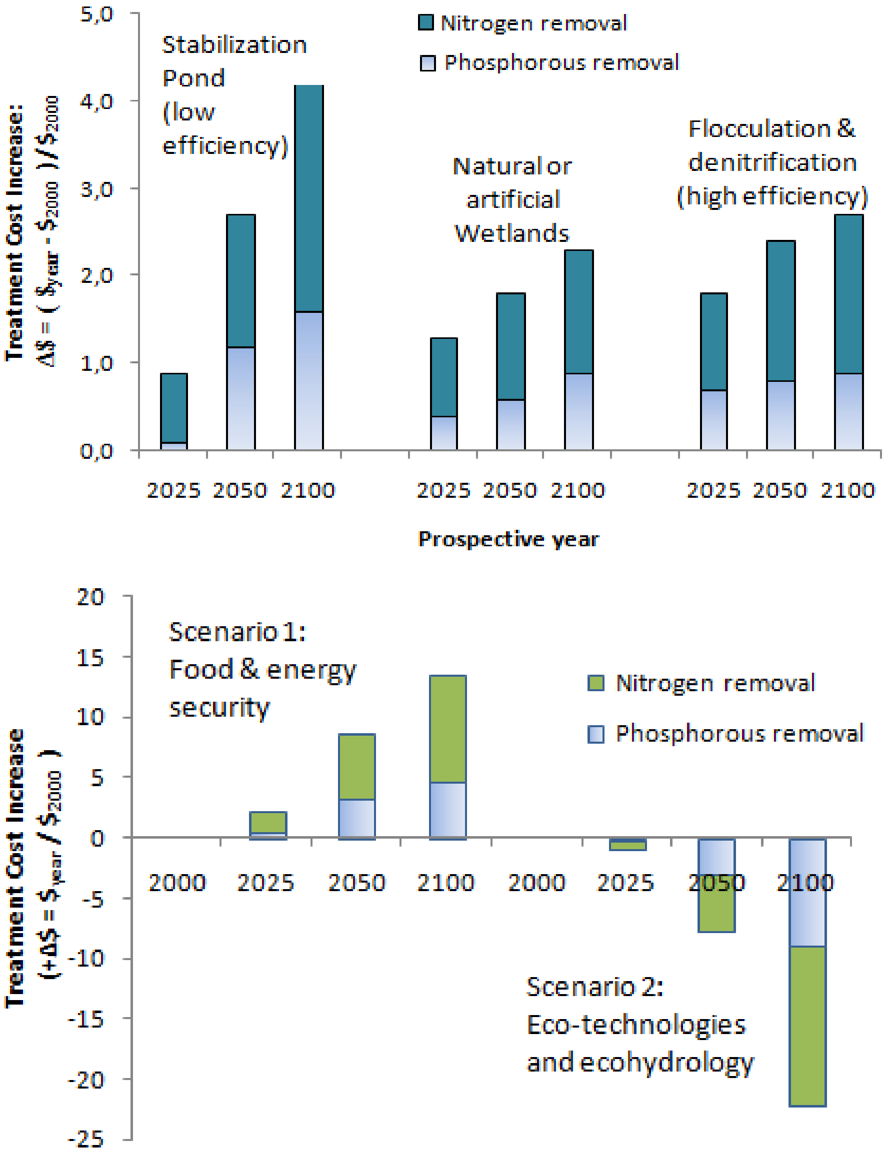

Figure 2. Nominal treatment costs (ordinates) expected for water withdrawn of water-body with different trophic situation affected by long-term scenarios of time (abscissa) from only climate change (upper chart) or only land-use conversion (bottom chart). Source: Mendiondo (2008,a)

Table 2. Associated global management challenges for stakeholder's empowerment

Keypoint	Working questions and hypotheses
Innovation	• What decentralized innovations are achievable to maintain the eco-hydrology of the system "drainage basin & water body" as dynamic as developed? • How could in-flow river needs help "catching" nutrients on basin floodplains to mitigate downstream eutrophication of lakes/reservoirs?
Scenarios	• What consistent scenarios are suitable to attain goals of reducing eutrophication? • How will the global change through scenario land-use assessment affect eutrophication of lakes and reservoirs?
Ecological Services	• How the ecological services of lakes and reservoirs could to be valuated? • How do the degradation of ecosystem services at the basin (draining to a lake/reservoir) cause significant harm (i.e. eutrophication) to human well-being?
Trade-offs	• How ecological services are meaningful for the human well-being?
Lessons learnt	• How past experiences "are"/ "should be" learned in perspective?
Transboundary governance	• What yardsticks on eutrophication should underpin sustainability for stakeholder conflicts, especially at trans-boundary river basins? • Would 'hydrosolidarity' become a way to transboundary problems of eutrophication? • Would potential pressure water conflicts make eutrophication accelerate at most?
Management costs	• Which risks are to be coped with to avoid jeopardizing accountability? • What insurance devices do cope with eutrophication risks at the long term through feasible programs of early-warning? • How could we propose protocols for regional water plans to better manage reservoirs under, or in progress of, eutrophication at a global change? • Could we regionalize the specific costs of today and future water demands on reservoirs/lakes under progressive eutrophication? • How does adaptive policy collaborate to maintain water quality at reservoirs (to decrease eutrophication)?
Research	• How does it integrate eutrophication mitigation measures addressing ecohydrology? • How does floodplain play as retention basin of nutrient loads? • How to relate trophic factors with ecohydrology of floodplains?
Capacity Building	• Where should ecosystem services empower the less resilient groups? • How could early-warning systems assess the water "compromise" on incoming flows to lakes and reservoirs?
Pilot projects	• What right actions to what most sensible audience?

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Outlook

Further agenda of global review of lake and reservoir eutrophication should focus on some detailed management challenges, as follows: (1) the cost of eutrophication abatement, (2) the differences of eutrophication in temperate and tropical regions, (3) the emergence of ecohydrology and ecotechnology opportunities, and (4) the social and economic influences of eutrophication to human well-being.

First, a problem that has not been considered for a long time is the cost of abatement or eutrophication control for feasible water treatment costs. Considering structural and non structural measures eutrophication control has a considerable economic component derived specially in the construction of infrastructure as waste water treatment, plants, channels, etc and organization of watershed or river basi committees and their functioning. Therefore when controlling eutrophication, it is necessary to consider these costs, the technology used and the institutional governance not only at the lake/reservoir scale but also at the draining catchment area. If transboundary situations appear, innovation and negotiation are mandatory.

Table 3. Example of a demonstrative pilot program to control and mitigate eutrophication of urban reservoir. Last line of the table depicts interval of costs of each phase related to total project budget. Source: adapted from Mendiondo & Tundisi (2007) and Mendiondo (2008b)

Main Action	(1) Concept Paper & Kick-off Policy Workshop	(2) Lifetime of Reservoir through Technical Assessment on Water Security	(3) Value of Ecosystem Services	(4) Emergency Actions and Short-term Mitigation Strategies	(5) Policy Workshop & Feedback Dialogue on Water Security Goals	(6) TORs: Terms of Reference on Security & Eutrophication of 'Water for Life'
Detailed actions and products	(1.1) Publishing the Whole Strategy in a Participative Workshop with Stakeholders and Decision-makers (1.2) "Water Security for Life"; Motivation; Problems; Lessons Learned; Stakeholders; Goals (1.3) Reflection: Goals of "Water for Life: 2010, 2020, 2030, 2050, 2100", Actions; Challenges; Chances; Testimonies (1.4) Tutorial for next phases	(2.1) In situ diagnosis of social, economical, physical, biological chemical, cultural and institutional variables. (2.2) Integrated Models of: society, ecology, sedimentology, economics (insurance), global change, hydrology (2.3) Scenarios: institutional, environmental arrangements and water security feasible at the long-term (2010 – 2100)	(3.1) Water Security with Value of Ecosystem Services of: Supporting Provision; Regulation; Cultural (3.2) Permission of Services for Security, Life; Health; Social; Human Well-Being (3.3) Willingness to Pay and Prices of Services for: Conflict Resolution and Trade-offs	(4.1) Structural Measures: ecotechnology and eco-hydrology towards Ecosystem Services Valorization (4.2) Non-Structural Measures for Maintaining Services until year 2010: Tax Incentives; Insurances; Monitoring; Early Warning; River Association; Public-Private Partnerships; Education & Training (4.3) Protocol of Institutional Empowerment, Governance, Policies and Adaptive Management until 2010.	(5.1) Strategic, Multi-Sector & Participative Goals "2010, 2020 e 2030" (5.2) Strategic Management at the Long-Term; Integrated Goals; Identification of Stakeholder (old and new); Selection of Indicators and Variables (5.3) Implementation of Initial Policies; Assessment of Sets of Indicators; Methodology of Hierarchy of Priorities	TORs of Demonstrative Projects (scenarios, goals, and actions): Strategic Management; Institutional Empowerment; Risk Mitigation & Conflict Reduction Funding; Incentive-driven Policies; Social Inclusion; Early Warning; Sustainable Urbanization Structural Measures Capacity building
Budget cost (%)	2 to 5	20 to 40	10 to 12	20 to 35	4 to 8	8 to 10

Second, the causes and consequences of eutrophication of lakes and reservoirs are approximately the same in temperate and tropical lakes and reservoirs. However, the responses of temperate waters differ in function of water temperature, diversity, seasonality and succession of species of the aquatic biota of these regions. This makes difficult to introduce methods of eutrophication control developed in temperate regions to the tropical systems, especially when considering in lake or reservoir management technology. Trophic dynamics and role of fishes in tropical warm waters differ considerably as stated by Jeppensen et al (2005). Therefore techniques of biomanipulation to control eutrophication in temperate lakes many not apply directly to tropical lakes. Therefore, it is necessary to develop a strong research program on mechanisms of functioning of tropical lakes and reservoirs under eutrophication stress (Starling, 1993, Arcifa et al 1995; Tundisi & Tundisi, 2008).

Third, the progress of eutrophication of continental and coastal waters in the last 25 years was very fast with consequences on the functioning of lakes and reservoirs worldwide. Economic and social consequences of eutrophication have bean dealt with in some regions, but is necessary an effort to include these approaches (IETC 2001) in the next steps to attempt to solve the problem. The control of the eutrophication process starts in the watershed and the ecotechnological and ecohydrological technologies for this control is an essential action. Without a watershed control with new and cheaper techniques it will be impossible to delay the consequences of eutrophication.

Finally, another emerging approach related to eutrophication and its control is the epidemiological studies related to global impacts on human health especially related with toxins from algal blooms and their health consequences to megacities and human settlement.

Acknowledgements

This short term report is prepared under the contract from International Lake Environment Committee Foundation, Shiga, Japan for developing contents for training classes for lake basin managers under JICA (Japan International Cooperation Agency) Project. The views expressed and any errors are entirely those of the author and do not necessarily conform to policy viewpoints by the contacted individuals and institutions.I thank Dr. Masahisa Nakamura, Professor, and Research Center for Sustainability and Environment, Shiga University for his interest in the author's presentation and Dr Thomas Ballatore, ILEC, for their kind invitation and helping comprehension.

Sources of literature and content

1. Arcifa, M.S., Starlinf, F.L.R.M., Sipúba-Tavares, L. & Lazzaro, x. 1995. Experimental Limnolgy, pp.257-280. In: J.G. Tundisi, C.E.M. Bicudo & T. Matsumura-Tundisi (eds). Limnology in Brazil. Brazilian Acad. of Sci and Brazilian Limnol. Soc., São Paulo.

2. Benndorf, J. 1995. Possibilities and limits for crontolling eutrophication by biomanipulation. Int. Rev. Ges. Hydrobio. 80: 519-534.

3. Bernhardt, Von H. Clasen, J., Hoyer, O. & Wilhelms, W. 1985. Oligotrophication in lakes by means of chemical nutrient removal from the tributaries. Its demonstration with the Wahnbach Reservoir. Arch. Hydrobiol. Suppl. 70: 481-533.

4. Branco, C.W.C., Rocha, M-I., Pinto, G.F.S. & Gômara, Filippo, R. D. 2002. Limnological features of Funil Reservoir (R.J., Brazil) and indicator properties of rotifers and cladoceran of the zooplankton community. Lakes & Reservoirs: Research and Management 7: 87-92.

5. Brookes, A., Shields Jr., F. D. 1996. River channel restoration: guiding principles for sustainable projects. Chichester: Wiley.

6. Callisto, M., Serpa-Filho, A., Oliveira, S.J. & Esteves, F.A. 1996. Chironomids on leaves of *Typha domingensis* in a lagoon of Rio de Janeiro State (Brzail). Stud. Neotrop. Fauna & Environm. 31: 51-53.

7. Cooke, G. D., Wech, E. B., Peterson, S. A. & Newroth, P. R. 1993. *Restoration And Management of Lakes and Reservoirs.* Boca Raton, Florida: Lewis Publishers.

8. Crisman, T. L. & Beaver, J. R. 1990. applicability of planktonic biomasipulation for managing eutrophication in the subtropics. Hydrobiologia 200/201. 177-185.

9. Hansson, L. A., Annadotter. H., Bergman. E., Hamrin, S. F., Jeppesen, E., Kairesalo, T., Luokkanen, E., Nilsson, P.-Å., Søndergaard, M. & Strand, J. 1998. Biomanipulation as an application of food chain theory: Constraints, synthesis and recommendations for temperate lakes. Ecosystems 1: 558-574.

10. Jeppesen, E., M., Søndergaard, N. Mazzeo, M. Meerhoff, C. Branco, V. Huszar & Flavio Scasso, 2005: Lake restoration and biomanipulation in temperate lakes: relevance for subtropical and tropical lakes. Chapter 11 in: (Ed. M.V. Reddy), Tropical eutrophic lakes: their restoration and management: 331-359.

11. Legendre, L. 2004. Scientific Research and Discovery: Process, Consequences and Practice. In:

O.Kinne (ed) Excellence in Ecology.Oldendorf/LUHE 235pp.

12. Lewis, W.M. Jr. 1996. Tropical lakes: how latitude makes a different. In: F. Schiemer & K.T. Boland (eds) Perspectives in tropical limnology, pp. 43-64. SPB Academic Publishing bv, Amsterdam, The Netherlands.

13. Mendiondo, E M 1999. Towards the Renaturalization of Riparian Areas in South America Through an Interdisciplinary Approach In: 1999 Deutscher Tropentag, Berlin, Oct. 1999, ATSAF Proceedings, Berlin.

14. Mendiondo, E M (2006) Experiences and lessons in urban river restoration, Invited Talk, In: 4th International Conference on Safe Water and Health, Rio de Janeiro, RJ, 2006.

15. Mendiondo E M (2008a) Loading report of Thematic Project - Projeto Temático – *Internal Report* ,.In: M C Calijuri FAPESP Final Report 02/13449-1. EESC/USP, São Carlos, SP

16. Mendiondo E M 2008b. Challenging issues of urban biodiversity related to ecohydrology, *Braz. J. Biol.,* 68 (4, Suppl.): 983-1002, 2008

17. Mendiondo, E. M. 2000. Eco-hydraulics Integrated eco-hydraulics options for the recovery of life and safety in aquatic environments In: Maione, U., B. M. Lehto, R. Monti (eds.) *New Trends in Water & Environ. Eng. For Safety & Life*, Balkema:Rotterdam

18. Mendiondo, E. M.; Valdes, J. B. 2002. Strategies for sustainable development of water resources systems. In: 2nd Int. Conf. New Trends in Water & Environ. Eng. For Safety & Life: Eco-Compatible Solutions for Aquatic Ecosystems 2002, Capri, Italy, *Proceedings*, 2002.

19. Mendiondo & Tundisi 2007. Eutrophication in Lakes and Reservoirs: Remedial Measures and Prospective Research. In *International Colloquium of Lakes and Reservoirs*, 2007, Putrajaya, Malaysia. Key-note paper. Putrajaya: NAHRIM / ASM, National Hydraulic Research Institute of Malaysia / Academy of Sciences Malaysia.

20. Mendiondo, E.M., Neiff, J.J., Depettris, C.A., 2000a. Eco-hydrology of wetlands aided by remote sensing, In: Maione, U., B. M. Lehto, R. Monti (eds.) *New Trends in Water & Environ. Eng. For Safety & Life*, Balkema:Rotterdam

21. Mendiondo, E.M., Clarke, R. T., Toensmann, F.2000b. River restoration, discharge uncertainties & floods, In: Toensmann & Koch (eds.) *River Flood Defense*, Kassel: Herkules, Vol. II, (G) p.141-152.

22. Millennium Ecosystem Assessment (2005). Ecosystems and Human Well-Being: Synthesis, Island Press (Millennium Ecosystem Assessment Series)160 pp.

23. Moss, B. 1990. Engineering and biological approaches to the restoration from eutroplication of shallow in which aquatic plant communities are important components. Hydrobiologia 200/201: 367-377.

24. NRC – National Research Council. 1992. Restoration of aquatic ecosystems. National Academy of Sciences of U.S. Washington: National Academy Press.

25. Petts, G. , Calow, P. 1996. River restoration: Selected extracts from the rivers handbook. Oxford: Blakwell Science

26. Reynolds, C.S. 1992. Eutrophication and the management of planktonic algae: what Vollenweider couldn't tell us. In: Eutrophication: Research and application to water suplly. 4-29p. In: Freshwater biological association. 217pp.

27. Riemann, Bo., Søndergaard. 1986. Carbon Dynamics in Eutrophic, Temperate Lakes. Elsevier Science Publishers B.V.284pp

28. Sas, H. (Ed.). 1989. *Lake restoration by reduction of nutrient loading. Expectation, experiences, extrapolation.* Acad. Ver. Richardz Gmbh.,

29. Sutcliffe, D.W. & Jones, J.G. (Ed). 1992. Eutrophication: Research and application to water suplly. In: Freshwater biological association. 217pp.

30. Thomaz, S.M. & Bini, L.M. 2003. Ecologia e manejo de macrófitas aquáticas. EDUEM, Maringá, pp. 341.

31. Tundisi, J. G. 2003. Água no século XXI: enfrentando a escassez. São Carlos: RiMa Artes e Textos. v. 1, 248 pp.

32. Tundisi & T M Tundisi 2008 Limnology (in Portuguese), Oficina de Letras, São Paulo, 634p.

33. UNEP, IIE, World Bank, UNESCO, ANA, ANEEL. 2001. Planejamento e Gerenciamento de Lagos e reservatórios: Uma abordagem integrada ao problema de Eutrofização (edição em português), UNEP-IETC, Série de Publicações Técnicas, v. 11, são Carlos, 385 pp.

34. UNEP/IETC, 2001. Lakes and Reservoirs: Water quality, The Impact of Eutrophication. Lakes and Reservoirs, vol.3, Newsletter and Technical Publications (Series UNEP - Division of Technology, Industry, & Economics)

Appendix 1- Ecohydrological categories for sustainable river management to reduce eutrophication at lakes and reservoirsw (from Mendiondo, 2008b)

Category	Continuity	Diversity	Dynamics	Resilience	Vunerability
Interaction	Drainage area ↔ river	Drainage area ↔ river	Drainage area ↔ floodplain	Floodplain ↔ river	Floodplain ↔ river
Indicator **[Definition]**	Indicator associated to number and extension of drainage network and frequency of floodplain inundations, regarded to river perenization and integration processes between surface and ground-waters and auto-depuration at macro-scale.	Quantification of permanently-flooded areas with respect to potential flood areas, as an indicator of proportion of internal lentic systems which potentially exchange nutrients, energy and information with the main river channel.	Non-linear mechanisms of multivariate processes of nutrients, of information and of energy transferred under either limnophase or potamophase stages.	Potential recovery capacity to attain a new system equilibrium under inputs of matter, energy and information	Risk analysis and management of flood prone areas with factors of: hazard (return period), vulnerability (indirect costs of loss or excess of ecosystem service) and exposition (relative location inside flooplain to main river channel).
Variable **[dimension]**	***X1***: number of draining sub-basins per unit of main river channel length [No./km] ***X2***: density of drainage streams per unit area [km/km^2] ***X3***: frequency of occurrence of complete inundation of flooplain [No./decades] ***X4***: fraction of permanent, shallow water pools inside floodplain [km/km^2, %] ***X5***: relation of potential wetted perimeter of maximum floodplain cross-section and river channel wetted perimeter [m/m, %]	***X6***: quotient of instantaneous flooded areas, with regard to total floodplain area [km^2/km^2, %] ***X7***: fraction of total floodplain area and upslope drainage basin area [km^2/km^2, %] ***X8***: number of different land-uses per unit of floodplain area [No/km^2]	***X9***: quotient of maintenance time of flooded areas after the occurrence of maximum discharge and the duration of flood pulse [min./min., %] ***X10***: fraction of inundation duration above bankfull water level and total flood pulse [min./min, %]	***X11***: time rate of the difference of primary production, between preserved and degraded areas at floodplain, [g Biomass/hours] ***X12***: time rate of river flow per water level (i) before, and (ii) after flooding [m^3/s/m] ***X13***: dimensional surface of loops of primary production indicator versus total water level ***X14***: dimensional surface of loops of primary production indicator versus water levels above inundation floodplain terrace	***X15***: difference of primary production 'during' and 'after' maximum water inundation, in relation with primary production 'before' inundation [g/g, %] ***X16***: changes of permanency flows of Q5% and Q95%, from urban impacts [m^3/s] ***X17***: change of probability values of 95%, from urban impacts [Probability], ***X18***: multiplication of mean velocity times water level height [m^2/s]

Appendix 2- Interaction matrix between parameters (rows) and indicators (columns) for biodiversity responses to environmental stimuli during flood pulses at uplands (defined in Appendix 1) which control lake and reservoir eutrophication downwards. Arrow direction points towards biodiversity increase.

Parameter (dimensions)	**Category and indicators**																	
	Continuity					***Diversity***			***Dynamics***		***Resilience***				***Vulnerability***			
	X1↑	***X2↑***	***X3↑***	***X4↑***	***X5↑***	***X6↑***	***X7↑***	***X8↓***	***X9↑***	***X10↕***	***X11↑***	***X12↕***	***X13↕***	***X14↕***	***X15↕***	***X16↓***	***X17↓***	***X18↓***
Q95%	**+ +**	**+ +**	**?**	**+**	**+**	**+ +**	**+**	**?**	**+ +**	**- -**	**+ +**	**w/r**	**?**	**?**	**?**	**-**	**- -**	**-**
Q50%	**+**	**+**	**?**	**+/-**	**+/-**	**+**	**+**	**?**	**+**	**-**	**+**	**w/r**	**+/-**	**?**	**?**	**+/-**	**?**	**+/-**
Q05%	**+/-**	**+**	**+ +**	**+/-**	**-**	**+/-**	**-**	**+/-**	**+/-**	**+**	**+/-**	**+;-**	**+/-**	**+/-**	**-**	**+/-**	**?**	**+**
Q01%	**+/-**	**+/-**	**+**	**-**	**- -**	**-**	**- -**	**+/-**	**-**	**+ +**	**-**	**++;--**	**-**	**-**	**- -**	**+**	**+**	**+ +**
EC (µS/cm)	**-**	**-**	**-**	**+/-**	**+/-**	**+/-**	**-**	**+ +**	**+/-**	**+/-**	**-**	**- ; +**	**-**	**-**	**-**	**-**	**+**	**-**
DOC (mg/L)	**-**	**-**	**-**	**+/-**	**-**	**-**	**-**	**+**	**-**	**+/-**	**?**	**- ; ?**	**-**	**-**	**?**	**-**	**+**	**-**
BOD (mg/L)	**-**	**-**	**-**	**+/-**	**+/-**	**+/-**	**-**	**+**	**+/-**	**+/-**	**-**	**- ; +**	**-**	**-**	**-**	**-**	**+**	**-**
N-tot (mg/L)	**+/-**	**+**	**-**	**+/-**	**+**	**+/-**	**+/-**	**+**	**+**	**-**	**+**	**+ ; -**	**?**	**?**	**?**	**+**	**+ +**	**+/-**
P-tot (mg/L)	**+**	**+/-**	**-**	**+/-**	**+**	**+/-**	**+/-**	**+**	**+**	**-**	**+/-**	**+ ; -**	**?**	**?**	**?**	**+ +**	**+ +**	**+/-**
Biomass(g/m^2)	**+/-**	**+/-**	**-**	**+**	**+**	**+/-**	**+**	**+/-**	**+**	**-**	**+**	**+ ; +**	**+**	**+/-**	**-**	**- -**	**-**	**-**
ISS (mg/L)	**+**	**+**	**+**	**-**	**-**	**+**	**-**	**+**	**-**	**+**	**-**	**+ ; +**	**?**	**?**	**?**	**+**	**+ +**	**+**
OSS(mg/L)	**+**	**+**	**+**	**+/-**	**-**	**-**	**-**	**+**	**-**	**+**	**-**	**+ ; +**	**+/-**	**?**	**+**	**+**	**+**	**?**
TSS(mg/L)	**+**	**+**	**+**	**-**	**- -**	**+/-**	**- -**	**+ +**	**- -**	**+ +**	**- -**	**+ ; +**	**+/-**	**?**	**?**	**+ +**	**+ +**	**+**

Notation: *Q95%*: river flow discharge of expected permanency of 95% of annual river regime duration; *EC*: electric conductivity; *DOC* : dissolved organic carbon; BOD: biological organic demand; *N-tot*: total nitrogen; *P-tot*: total phosphorous; *ISS*: inorganic suspended solids; *OSS*: organic suspended solids; *TSS*: total suspended solids.
Biodiversity responses to environmental stimuli '↑: increase', ' ↓: decrease' , ' ↕: dual response'; **Interactions expected**: ' + : positive, '+ +: high positive' , ' - : negative, '- - : highly negative' , ' +/- : mixture' ,' x ; x : rising limb , recession of flooding', '? : indeterminate', 'w/r': without relation