

REPORT LAGUNA DEL DIARIO

2014

Rehabilitation strategy of the lagoon ecological status





STEP 1

Harvesting of submerged
macrophytes



STEP 2

Control of nutrient input



STEP 3

Re-establishing an input
of seawater



The Experts



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The Experts



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Executive Summary

The Laguna del Diario is a highly modified coastal lagoon located in the Department of Maldonado that has experienced significant change resulting from anthropogenic activities over the last century. Of principal concern is the extensive eutrophication caused by a combination of: a) input of nutrients from the watershed; b) changes in land use (forestry and urbanization); and c) construction of the coastal highway (Rbla. C. Williman -- previously Ruta 10). The result has been the evolution of a nutrient-enriched, highly productive coastal lagoon that is undergoing rapid succession towards a filled wetland. Recent changes in water clarity in the seaward end of the lagoon have become a concern because of blooms of cyanobacteria, which may have human health implications. In addition, growth of emergent and submerged plants is restricting recreational uses of the lagoon.

A major study was initiated in 2008 by the Universidad de la Republica (Mazzeo *et al.* 2008) of the environmental setting of the lagoon, the processes of change since 1955, and the prospects for remediation. Three possible responses to the rapid rate of degradation of the lagoon were considered:

- ⇒ Control of submerged vegetation by mechanical harvesting.
- ⇒ Control of submerged vegetation combined with control of nutrient inputs.
- ⇒ Control of submerged vegetation and nutrient inputs combined with control of the internal load of nitrogen and phosphorus.

In order to assist local authorities to decide on an appropriate course of action, an agreement was reached between the Intendencia, the Universidad de la Republica and St Andrews University in Scotland, to establish an expert committee of scientists to examine the problem and advise on its resolution. This report is the output of that examination.

Any remediation option adopted should aim to achieve a number of conservation and management objectives:

- ⇒ To halt, and preferably reverse, the increasing eutrophication of the lagoon.
- ⇒ To maintain and possibly enhance its biodiversity.
- ⇒ To improve water quality in order to diminish public health concerns and to improve recreational potential.
- ⇒ To enhance the quality of the environment for residents and visitors alike.
- ⇒ To develop and support public awareness of the richness and aesthetic value of the lagoon.
- ⇒ To enhance the reputation of the Maldonado region as an exemplary and attractive destination for tourists.

The Expert Committee has considered four possible responses to the situation in the Laguna del Diario:

- I. The Null Option: to do nothing.
- II. To restore the connection between the lagoon and the coastal marine area (e.g. by supporting the highway on a bridge or installing a large culvert).
- III. To reduce the rate of eutrophication of the lagoon by decreasing the input of nutrients and sediments, and removing submerged and emergent plants.
- IV. To reverse the present trophic status by a combination of plant harvesting, nutrient input control, and possibly flushing of the seaward end of the lagoon with seawater.

Of these options, the Expert Committee recommends the more extensive intervention (IV above) as the only one that will sustain a long-term improvement in the environmental status of the lagoon, and that will provide a number of additional benefits for residents, visitors and the tourist industry, and the reputation of the region and the country.

The recommended option responds to the needs for short-term mitigation actions, preventing further degradation, and long-term remediation and recovery actions required for the conservation of Laguna del

Diario ecosystem health. Therefore, the recommended intervention is organized into successive steps, with key recommendations for every step in order to avoid inefficient or even negative results.

STEP 1 - Harvesting of submerged macrophytes has to be maintained and developed further by harvesting emergent macrophytes; this action allows removal of excess external and internal nutrient loading in the short term, while more effective interventions on the nutrient input and lagoon water retention time are designed and implemented. When nutrient input and water retention time are under control, re-establishing an equilibrium in the nutrient budget in the lagoon by harvesting of emergent and submerged macrophytes will most probably no longer be required. The harvesting activity has to take into account the following recommendations:

- ⇒ the role of submerged macrophytes on Laguna del Diario food webs has to be clarified in order to avoid negative impacts on biodiversity. Fishes, gastropods and birds are relevant herbivorous species contributing to both nutrient export from the lagoon, and lagoon biodiversity, which has to be protected while harvesting the macrophyte biomass;
- ⇒ macrophytes compete with phytoplankton for nutrients and light; harvesting has to avoid creating a competitive advantage for phytoplankton resulting in dominance of phytoplankton species that could potentially increase eutrophication and public health issues;
- ⇒ the role of emergent macrophytes for gastropod and bird reproduction in the Laguna del Diario has to be assessed to optimize the harvesting of emergent macrophyte biomass;
- ⇒ timing during the year and spatial extent of harvesting have to be planned taking account of the previous recommendations in order to maximize nutrient export from the lagoon;
- ⇒ use of removed plant biomass in energy production might be a solution to compensate the harvesting cost.

STEP 2 - Control of nutrient input through re-naturalization and management of the small stream entering the Laguna del Diario, and construction and management of artificial wetlands in the lagoon watershed. This action requires time to be fully realized but when the control is fully operational it will have strong and permanent positive effects on the health of the Laguna del Diario ecosystems. As regards this action, we recommend that:

- ⇒ the operation of nutrient input control is based on a model of the optimal nutrient load to the Laguna del Diario that results in a reduction in eutrophication while enhancing biodiversity in the lagoon ecosystem.

STEP 3 - Re-establishing an input of seawater in the Laguna del Diario, decreasing the water residence time and increasing the export of nutrients towards the sea. Timing and amount of seawater input in the lagoon have to be estimated and modelled taking into account the following recommendations:

- ⇒ stratification of freshwater and seawater in the lagoon has to be avoided in order to prevent the risk of hypoxia or anoxia of benthic sediments;
- ⇒ the potential effects of seawater input and increased salinity on the lagoon flora and fauna have to be monitored in order to avoid negative impacts.

In order to support the rehabilitation actions above the following things also need to be done:

- ⇒ During the course of the recovery intervention, consider the possibility of artificially oxygenating benthic sediments in areas showing signs of strong hypoxia or anoxia events.
- ⇒ Compile a comprehensive bibliography of reports and data sources regarding the Laguna del Diario.
- ⇒ Conduct baseline studies to fill in important ecological knowledge gaps in order to ensure that the results of the rehabilitation action are delivering the desired outcomes. Such studies include: diversity and distribution of benthic organisms; diversity and areal extent of emergent macrophytes; role of emergent macrophytes as fish and bird habitat; and sediment composition and properties.
- ⇒ Establish a network of monitoring stations to measure precipitation, surface and ground water levels to provide ongoing refinement of existing hydrological models.
- ⇒ Establish a water quality monitoring programme in order to deal with potential health issues.
- ⇒ Conduct a study of present trends in land use and watershed development.
- ⇒ Engage the local community in monitoring activities and enhance public education and awareness.

1. Problem Statement

The Laguna del Diario is a highly modified coastal lagoon located in the Department of Maldonado that has experienced significant change as a result of anthropogenic activities over the last century.

Of principal concern is the extensive eutrophication resulting from a combination of: a) input of nutrients from the watershed; b) changes in land use (forestry and urbanization); and c) damming the lagoon outlet for the construction of the coastal highway (Rbla. C. Williman -- formerly Ruta 10). The result has been the conversion of a previously small, probably intermittent lagoon or coastal stream into a lagoon that is rapidly becoming occluded by growth of macrophytes and accumulation of sediments. Recent changes in water clarity in the seaward end of the lagoon have become of concern because of blooms of cyanobacteria, which may have human health implications. In addition, growth of emergent and submerged plants is restricting recreational uses of the lagoon.

Natural water courses are ecosystem units that respond to both internal and external perturbations. The watershed (or catchment basin) of the Laguna del Diario extends over 43 km². Originally treeless, the basin was modified by extensive plantings of pines and

eucalyptus trees beginning in the 19th century. In the 20th century, urbanization around the city of Maldonado has progressively impacted the watershed, influencing both the input of nutrients and surface runoff. There were apparently no recorded observations of environmental concern immediately after the stream

throughout much of the lagoon. As a result of these concerns, a major study was initiated in (2005-2006) by the Universidad de la Republica (Mazzeo *et al.* 2008). The focus of the study was on the environmental setting, the processes of change since 1955, and the prospects for remediation.

Changes in the Laguna del Diario are the natural ecosystem response to human activities in the watershed, such as forestation and urban development

outflow was closed by a causeway constructed for the Rbla. C. Williman highway in 1955. The first notable beds of vegetation were recorded in 2001; by 2006 these had become dominant in the upper part of the lagoon, and extensive growth of submerged vegetation was evident

1.1 Existing knowledge

The study by the Universidad de la Republica outlined the geology and environmental setting of the Laguna del Diario, based upon existing, documented information, and on new research. The watershed is underlain by crystalline

bedrock, principally gneiss, overlain in most upland areas by alluvial deposits, and beneath the lagoon by lagoon-generated sediments. Thus, much of the surficial topography is composed of readily-erodible material that, when exposed, will wash down towards the lagoon. Much of the sediment input is derived from the basin, and may be associated with different land use practices, including farming. When land is cleared (e.g. during forestry or for construction), the potential also exists for significant amounts of silt to enter the lagoon, especially under flood conditions. Palaeolimnological studies, based upon a sediment core taken from the bed of the lagoon, have enabled a preliminary interpretation of the watershed changes over the last 5,300 years. Analysis of the core using ^{14}C enables dating of deeper and older sediments, whereas analysis using ^{210}Pb and ^{137}Cs allows interpretation of more recent events. The results indicate that a coastal lagoon existed in this location about 5,000 ybp, but for the last 4,000 years the watershed had mostly been occupied by a stream rather than a lagoon. Sedimentation rates in the lagoon have changed significantly: approximately 40 cm of sediment accumulated during the last 4,000 years, whereas almost 25 cm have settled over the most recent 60 years – i.e. since completion of the causeway. Chemical analyses of the core show that the organic matter signal rose significantly following the forestation of the watershed in the late 19th century, and that there has been a steady increase in both nitrogen and phosphorus in the sediments since the causeway was completed in 1955. Similarly, diatom fossils in the core indicate a shift from marine-brackish to freshwater-brackish species over the last 50-60 years.

Studies of the hydrological regime of the watershed were conducted between 1990 and 2005 based on information from La Dirección Nacional de Hidrografía. During that time, the lagoon water level varied between a maximum of 2.94 m above official datum and a minimum of 0.17 m. In general, the variation in water level is correlated with precipitation, except for periodic events of intense rainfall

during which much of the inflowing water overflows to the sea. Occasionally, drought conditions (e.g. autumn 2000) and human intervention have also changed the correlation between lagoon level and precipitation. Hydrological modelling by the Universidad de la República does not capture all of the observed variation in water levels because of limited information about the discharge of water at the seaward end of the lagoon, and difficulties of estimating both infiltration rates and human demand. In addition, the model has deficits that vary from 10,000 to 300,000 m^3/month compared with empirical data that are not accounted for by errors in estimating water withdrawals or infiltration rates. The modelling would be improved by the addition of more and better data, particularly through continuous monitoring of water levels in the lagoon, in the ground water in the watershed, and of discharges to the sea. The demand for effective hydrological modelling for planning rehabilitation of the lagoon ecosystem highlights the need for more comprehensive monitoring of the watershed.

Shallow lagoon ecosystems may exist in alternative states according to the nutrient regime, and are indicated especially by the clarity of the water. In one state, submerged and emergent vegetation sequester the available nutrients (especially phosphorus), competing effectively with

in turn control the phytoplankton by grazing. The alternative state, typically found in nutrient enriched (i.e. eutrophic) conditions, is dominated by phytoplankton – especially cyanobacteria that can capture nitrogen from the atmosphere – which leads to high productivity, high turbidity in the water, poor water quality, and major fluctuations in oxygen levels that may restrict or eliminate many species of fish and zooplankton.

The Mazzeo *et al.* (2008) study indicates that the Laguna del Diario illustrates both of these states. Following closure of the pre-existing outlet in 1955, sediments and nutrients arriving into the lagoon from the watershed were retained, enabling the growth of rooted aquatic plants, especially *Zizaneopsis bonariensis*, *Schoenoplectus californicus*, *Typha latifolia*, *T. dominguensis* and *Scirpus giganteus*, along the shoreline in the upper part of the lagoon. There appears to have been no monitoring of the growth of the emergent vegetation, but it is apparent that the rapid growth of emergent vegetation contributed to clarifying of the water by trapping incoming sediments and diminishing turbulence. Water quality remained high, enabling the lagoon to act as a source of drinking water in the 1970s. Beginning in 2003, there was a rapid growth of submerged vegetation throughout much of the lagoon, with

The harvesting of submerged macrophytes has shifted the lagoon ecosystem toward a phytoplankton-dominated community which has water quality and human health implications

phytoplankton in the water, and minimizing turbulence, leading to low turbidity. This state, which is commonly associated with low to moderate nutrient levels, exhibits a trophic cascade in which fish maintain effective control of zooplankton, which

the replacement of *Potamogeton pusillus*, which is tolerant of high turbidity, by *Myriophyllum quitense* and *Potamogeton illinoensis*, which are superior competitors under high transparency conditions. Coverage by

submerged plants reached essentially 100% of the open water lagoon area by 2006, minimizing vertical mixing of the water column and increasing surface temperatures. Harvesting of submerged plants commenced in 2006, and by 2007 *Myriophyllum* and *Potamogeton* were substantially reduced, especially over the seaward end of the lagoon.

The Laguna del Diario is presently a diverse and productive coastal ecosystem that will deteriorate in the future if no remediation actions are adopted

The combination of high organic productivity, shading, and reduced vertical mixing in the water column leads to great variations in oxygen saturation, with occasional supersaturation (>100%) near the surface and saturation deficits near the bottom. In the spring of 2006 there were instances of hypoxia and even anoxia in vegetated areas of the lagoon, with evidence of hydrogen sulphide production resulting from decomposition of organic matter near the bottom. With removal of the submerged vegetation, the differences in oxygen saturation between surface and bottom waters have diminished.

It is evident from water and sediment chemistry that the lagoon had become increasingly eutrophic over recent decades, reaching a hyper-eutrophic state in the spring of 2006. Substantial decreases in nitrogen and phosphorus concentrations following that time were associated with uptake by phytoplankton as the system shifted into a phytoplankton dominated state. Prior to 2006, the phytoplankton was dominated by diatoms, but in spring 2006 the community shifted to dominance by chlorophytes and cyanobacteria. Some of the latter are potentially toxic (e.g. *Oscillatoria limosa*,

Microcystis aeruginosa, and *Anabaena planktonica*), and therefore represent a public health issue. Similarly, removal of the submerged vegetation results in an order of magnitude increase in zooplankton abundance, the majority of which are small zooplankton rather than the larger species that are of interest to fish predators.

Examination of the fish fauna using a combination of survey techniques (e.g. gill nets, electrofishing) yielded 17 species, five of which are considered potentially fish predators, the others being primarily zooplankton feeders. Although numerically the plankton feeders were most abundant, the large potentially piscivorous species represented the majority of the biomass (between 62 and 82 %). The relatively high diversity of fish species appears to be related to the diversity of habitats, even though the lagoon is no longer open to the sea. Maintenance of such habitat diversity will be an important consideration for any rehabilitation strategy.

It is evident that considerable information does exist regarding the Laguna del Diario, and is summarized in the Universidad de la Republica document and in both published and un-published literature (e.g. master and PhD thesis) available. However, there is still a lack of knowledge after analysis of the existing literature and a need to update information that will have a bearing on the decision regarding rehabilitation of the lagoon. Particularly, we lack detailed information on the bird fauna of the lagoon, their temporal distribution and use of both space and food dimensions of the lagoon ecosystem; moreover, updated information of benthic

invertebrates and fish fauna abundance and distribution, following the ongoing changes in the lagoon ecological status and bird fauna composition and abundance are relevant to fine tune the design of any of the rehabilitation options that have been considered.

These gaps will need to be filled for a satisfactory resolution of the problem.

1.2 Preliminary options for rehabilitation

In their report, Mazzeo *et al.* (2008) considered three possible responses to the rapid rate of degradation of the lagoon:

1. Control of submerged vegetation by mechanical harvesting.
2. Control of submerged vegetation combined with control of nutrient inputs.
3. Control of submerged vegetation and nutrient inputs combined with control of the internal load of nitrogen and phosphorus.

These options were aimed primarily at halting the continued process of eutrophication of the lagoon, restoring water quality, and enhancing its potential use. Evidence from the study showed that simple mechanical harvesting shifts the trophic status of the lagoon, increasing turbidity and favouring blooms of cyanobacteria that represent potential health problems. Given the potential for rapid regrowth of macrophytes, this option has the risk that it may need to be continuous. The more extensive interventions (#2, 3 above) offer greater potential for halting and even reversing the eutrophication process, but would inevitably be more expensive, and similarly may have to be a continuing activity, with minimal financial return.

In order to assist local authorities to decide on an appropriate course of action, an agreement was reached between the Intendencia Departamental de Maldonado, the Universidad de la Republica and St Andrews University in Scotland, to establish an expert committee of scientists to examine the problem and advise on its resolution. This report is the output of that examination.

2. Conservation Issues and Objectives

This section will highlight the main conservation issues that need to be addressed in the restoration of the Laguna del Diario and the surrounding watershed, as well as highlighting the opportunities that this presents for the enhancement of local enjoyment and engagement in the stewardship and sustainable exploitation of the lagoon.

Throughout these considerations it is important to remember that all natural systems are dynamic and constantly changing and adapting to the prevailing conditions. The changes in the extent and condition of the lagoon over the last 60+ years are evidence of these natural processes that are driven by a range of forces including nutrient enrichment of the catchment, changes in water levels, previous management actions such as the permanent closure of the connection of the lagoon with the sea, and climate change pressures. It is possible to devise actions that will halt and reverse some of these changes that will help to restore the lagoon to a more open-water condition, but there is always the possibility that unforeseen pressures will act to confound any measures taken. Nevertheless, with the implementation of a sustainable management plan and appropriate monitoring there is every likelihood that the condition of the lagoon can be improved over time.

This process starts from the position where the lagoon is considered to be in reasonable ecological status but is in need of some attention to ensure that the increasingly rapid rate of changes in extent and abundance of emergent and submerged macrophytes and increasingly frequent microalgal blooms are halted and subsequently reversed.

have catalogued certain elements of the lagoon's biodiversity but there is not a comprehensive up-to-date species list or habitat map of the lagoon and adjacent wetlands. The lagoon is already recognized as an important habitat for a wide range of bird species with around 150 different species having been seen in the area, and is recommended as a good site for bird watching. In order to be

The lagoon is recognized as an important habitat for birds (around 150 species) being recommended as a good site for bird watching

2.1 Biodiversity of Laguna del Diario

There have been a number of surveys undertaken over recent years that

able to plan a remediation strategy it is important that all relevant data are compiled in a single database and that a structured programme of

survey work is planned. This will not only be important to inform the detail of remedial action but also to act as a baseline from which changes can be measured in the future, based on the actions taken.

The identification of the lagoon as a key site within the Proyecto de Ordenamiento Territorial de la Aglomeración Central de Maldonado (San Carlos-Maldonado-Punta del Este) reinforces the need for urgent and positive action to help restore the overall balance within the lagoon. The regional plan recognizes the need for the area to be protected and acknowledged as a nationally important site. Uruguay is a signatory of the Ramsar Convention and it is recommended that careful consideration is given to the option of compiling a case for proposing the Laguna del Diario and its environs as a Wetland of International Importance under the convention.

Maintain / enhance the diversity of fish

A number of key targets can be identified, the precise definition of these to be agreed on the basis of the outcomes of the baseline survey:

- ⇒ Maintain/enhance the abundance and diversity of breeding and wintering birds.
- ⇒ Maintain / enhance the diversity of fish.
- ⇒ Reduce the extent of emergent macrophyte cover.
- ⇒ Reduce the abundance and extent of submerged macrophytes.

2.2 Water and waste management

The luxuriant growth of submerged and emergent macrophytes, and development of phytoplankton blooms in recent years are a clear indication of a nutrient enriched environment. The sources of this enrichment have already been

Maintain / enhance the abundance and diversity of breeding and wintering birds

discussed and there is a clear need to reduce the nutrient loading within the lagoon and its watershed in order to reverse the increasingly rapid expansion of the macrophytes and the loss of open water area.

The freshwater input to the lagoon comes from three main sources: rainfall, from two or three small streams, and from groundwater. The nutrient loading of these latter two sources is not clear but the most likely main source is through groundwater seepage from the expanding urban development around the lagoon. This can best be addressed by linking the majority of these houses to the new mains sewage system. The level of agriculture and stock densities around the lagoon are low and as such are not considered a major contributor of nutrients. The main source of nutrients is those recycled by the annual die-back of macrophytes and the subsequent accumulation of sediment on the lagoon bed. It is apparent that this accumulation of nutrient rich sediment has occurred at a rate of around 2.0-2.5mm per year over the last 60 years, i.e. since the connection to the sea was lost with the construction of the road at the seaward end of the lagoon. The loss of this connection has

Reduce the extent of emergent macrophyte cover

resulted in a situation where none of the sediment has been able to escape and hence has built up over the years. The key objective must be to reduce the nutrient loading within the lagoon and this can be achieved through a number of activities:

- ⇒ Reduction in the inputs to the lagoon through linking the various houses in the lagoon catchment area to the mains sewage system.
- ⇒ Continued cutting and complete removal of submerged macrophytes.
- ⇒ Cutting and removal of the emergent macrophytes at the end of the growing season.
- ⇒ Removal of the sediment that has built up over the last 60 years.
- ⇒ Reinstatement of a salt water flushing regime at the seaward end of the lagoon.

Reduce the abundance and extent of submerged macrophytes

- ⇒ Set targets can be associated with these activities:
- ⇒ A reduction in the nutrient loading in the water by agreed annual increments.
- ⇒ Removal through cutting of an agreed amount of submerged macrophytes from specified areas of the lagoon, and their immediate removal from the lagoon area.
- ⇒ A reduction in the sediment depth by an agreed amount.

- ⇒ Removal on an annual basis of a set area of the fringing emergent macrophytes.
- ⇒ A reduction in the frequency and extent of algal blooms.

2.3 Enhancement of public awareness and engagement

The process of restoration of the lagoon presents an excellent opportunity for engagement of the whole of the local community, not only in benefiting from the improved environment but also in being involved in the decision making process and the monitoring of the features of interest.

The opportunities for public awareness and engagement are considerable:

- ⇒ Establishment of a local ornithologists

- group to help monitor the bird populations.
- ⇒ Development of facilities to enhance the wildlife watching experience with the construction of hides and interpretation boards.
- ⇒ Involvement of local school children and inclusion of projects in the national curriculum.
- ⇒ Opportunities for collaborative projects between researchers from the national university based in Maldonado and institutes from other countries.
- ⇒ The development of a feeling of pride in their local environment.
- ⇒ Enhanced recreational opportunities, including sailing, kayaking, and angling.

- ⇒ Broad representation on the management group for the lagoon including local officials, researchers, members of the residents association, NGOs, user groups.
- ⇒ Promotion of the programme as a case study of best practice.



*Development of facilities
to enhance the wildlife
watching experience*

3. Opportunities

The need to address the continued degradation of the Laguna del Diarío also represents an opportunity to maximize the value of this highly productive and diverse ecosystem to the region of Maldonado

Tourism is an important contributor to the economy of both the Intendencia and the National Government, and the maintenance of a good environmental status is a critical element of the attraction of the area which has given Punta del Este a well known position as a top international summer resort .

According to latest official statistical (Uruguay XXI Institute) data, in 2013 2.8M tourists visited Uruguay, and spent U\$S 1,878M. Thus, foreign tourism is one of the most important contributions to the economy, representing 7% of the GNP and generating almost 100.000 jobs. Maldonado, through its main "Aglomeración Central San Carlos-Maldonado-Punta del Este" participates with roughly 42% of this economic activity.

Maldonado offers extremely attractive and diverse natural, easily interconnected sites within short distance: maritime beaches, rural spaces, hills, forests, lagoons and luxurious real estate developments. The Laguna del Diarío, strategically located

at the very entrance of the Maldonado Bay separated from the Río de la Plata by the main coastal causeway connecting Montevideo to Punta del Este continues to undergo a severe process of ecological degradation. This site daily offers to thousands of citizens and travellers alike, a unique view of one of the most imposing, beautiful coastal landscapes of Nature at its plenitude.

The lagoon continues to undergo succession, and unless management measures are put in place it will become progressively more eutrophic, resulting in a range of negative consequences such as foul aromas, increasingly frequent toxic algal blooms, and associated public health issues. These will act as a deterrent to tourists and to future development opportunities. On the other hand, an improved lagoon condition can have positive effects on the local economy.

Some of the positive benefits are outlined below:

- ⇒ A successful remediation result for the lagoon will enable the expansion of the existing recreational uses, which at present are restricted to a small water craft concession near the causeway at the seaward end of the lagoon. Swimming is periodically banned in this accessible part of the lagoon because of health concerns. If the lagoon recovers, these activities could be increased.
- ⇒ Because the lagoon is so productive, harbouring a wide variety of birds, for example, it would be simple to develop interpretative trails and observation points that would facilitate wildlife watching, and act as a positive inducement to visitors. Ecotourism is a growing economic activity worldwide and there are plenty of examples of successful ventures elsewhere that could help inform developments on

the lagoon. A successfully recovered lagoon would present an asset with the potential to attract visitors from a distance, especially if efforts were made to provide public education of the potential for recovery from environmental damage by providing descriptive panels, brochures, or guided tours.

⇒ National and regional policies aim to portray Uruguay as a country with a strong environmental conscience, as indicated by its support of international

conservation initiatives such as the Ramsar Convention. Clearly, a degraded Laguna del Diario does not support that image, whereas a recovered lagoon system can be used to send the message that Uruguayans care about their environment and are prepared to commit efforts to protect it.

⇒ The rehabilitation of damaged wetlands is of international interest, and considerable efforts are being made in other countries to that end.

The skills that will be developed among young professionals in Uruguay as a result of the rehabilitation of the Laguna del Diario will enable them to participate and assist other countries with similar problems, thus helping to raise the profile of the scientific community in Uruguay.

The rehabilitation of damaged wetlands is of international interest and considerable efforts are being made in other countries to that end



4. Rehabilitation options

The Laguna del Diario requires immediate rehabilitation interventions in order to improve water quality, stabilise its ecological status, maintain and improve the high biodiversity of plants and animals it is still hosting.

The previous sections of this report, dealing with the environmental and socio-economic context, have highlighted two key points:

- ⇒ the lagoon still supports a high diversity of plants and animals, particularly birds; but,
- ⇒ it is already showing signs of dis-equilibrium, that will drive it in time to a tipping point in its ecological status from which it will be very difficult to recover.

Accretion of bottom sediments (20-25cm in the last 60 years compared with 40cm in the previous 4000 years), expansion of emergent vegetation, increased growth of submerged vegetation as well as increasing nutrient concentration, are all signs of a lack of equilibrium in the lagoon between input and output of nutrients and organic matter.

The recovery of an equilibrium level of

nutrient and organic matter dynamics in the Laguna del Diario ecosystem, while maintaining and possibly increasing the current level of biological diversity and overall quality of the cultural landscape, is a prerequisite and of the highest priority of every rehabilitation option.

- ⇒ restoring the connection between the lagoon and the coastal marine area, the breaking of which is one of the most important causes of the current high rate of sediment accretion in the lagoon; and

A recovered equilibrium in nutrient budgets, while maintaining biological diversity, is a prerequisite and the highest priority of every rehabilitation option

Following the results of a detailed study of the Laguna del Diario ecosystem by the Universidad de la Republica (Mazzeo *et al.* 2008), two major rehabilitation options, potentially complementary, have been raised:

- ⇒ increasing nutrient and organic matter export from the lagoon and decreasing nutrient and organic matter input.

In this section, taking into account the

options and targets highlighted in section 2.2 of the present report, we analyse, evaluate and discuss advantages and disadvantages of these rehabilitation options, as well as of the null option to 'leave as it is', and draw preliminary conclusions on their comparative and absolute adequacy to solve the socio-ecological problems posed by current conditions and the expected trajectory of the Laguna del Diario ecosystem.

All rehabilitation options focused on the recovery of the functioning equilibrium of the ecosystem in the Laguna del Diario have the following requirements:

- ⇒ actions leading to physical alteration of the lagoon surface and transition zone – such as berm construction or stream-bed modifications causing habitat loss, increased siltation and altered hydrological regime, are completely prevented;
- ⇒ rehabilitation actions are fully consistent with local and national environmental legislation and with the local territorial and developmental plans; and
- ⇒ rehabilitation actions address the need for adaptation to global climate change and/or mitigation of its effects even though in south-east South America climate changes are expected to be small in the next 25-50 years¹.

the concept of a 'cultural ecosystem' that incorporates concepts of desired ecosystem state(s), ecosystem services and social benefits promoting sustainable development and human well-being.

The stabilization of the coastal dune, the permanent interruption of the connection between the Laguna del Diario and the coastal marine area, and the change in land use with urbanization and its associated degradation of the physical environment, are strong directional changes that will drive the ecosystem to rapid degradation and collapse. The current rates of sediment accretion and macrophyte invasion of previous open water spaces are driving the Laguna del Diario to an intermediate condition of a shallow and small anoxic pond, that would eventually lead to the final state of a terrestrial ecosystem. The time scale for the complete collapse is still long (i.e. 100-150 years) while signals of progressive degradation and shift from the desired state [high quality of both ecological and cultural landscapes and high level of provisioning and recreational services (*sensu* Reid, Mooney *et al.*, 2005. - Millennium Ecosystem Assessment) (Convenio de restauración y conservación sustentable del la Laguna del Diario y su cuenca, 2007 – unpublished document)] are already detectable.

components of society. Degradation of the ecosystem will occur at an increasingly fast rate; collapse will eventually occur, and the highly valuable ecosystem services of the Laguna del Diario will disappear. According to the available estimate of the value of lagoon ecosystem services (Costanza *et al.*, 1997) the collapse of ecosystem services in the Laguna del Diario will cause an estimated loss of hundreds of thousands of dollars per year.

4.1.3 Overall evaluation

Simply the null option is not tenable and has to be rejected. The ecological, cultural and socio-economic costs of not undertaking any rehabilitation action are considered unacceptable.

4.2 Option 2 - Restoring the connection between the lagoon and the coastal marine area

Lagoons are multi-dimensional ecotone ecosystems between land, inland water and the sea, characterized by strong internal gradients mainly driven by the hydraulic forces of tide, waves and river discharge (Basset *et al.*, 2013). According to the absolute and relative strength of hydraulic forces lagoons are classified as either leaky or restricted or choked (Kjerfve, 1994).

Option 1 - Null option - Leave as it is

4.1. Option 1 - Null option – leave as it is

The option 'leave as it is' is based on the hypothesis that the Earth is a self-regulating system (i.e. Gaia Hypothesis; Lovelock, 1979) and ecosystems have strong potential for adaptation and resilience. However, this hypothesis is not consistent with

¹ IPCC-WG1, 2013; 1°C-1,5°C increase in temperature, 20%-30% possible increase in precipitation (high uncertainty).

4.1.1 Advantages

The only advantage of the null option 'leave as it is', is that it does not involve (at the moment) any additional cost for the management of the lagoon.

4.1.2 Disadvantages

The overall disadvantage of the null option is that it will ultimately cause ecological and economic costs to all

Prior to construction of the highway across its mouth, the Laguna del Diario was a typical choked lagoon being closed at the seaside by a sand bar, which was made open from time to time either by wave or by freshwater pressure. This condition is suggested by the data on sediment accretion over the last 4000 years, which increased after the consolidation of the sand bar with the construction of Ruta 10 (source: Mazzeo *et al.* 2008). In the

current conditions with the water level in the Laguna del Diario consistently higher than high tide level (source: Mazzeo *et al.* 2008), the connection between the lagoon and the sea is maintained only as an output of the lagoon to the sea, being managed in order to dampen the oscillations of the water depth in the lagoon exporting the excess freshwater to the sea.

According to both typology and history of the lagoon ecosystem, restoring the connection between the lagoon and the sea is a clear re-naturalization action, which can be performed in different ways. Here, we consider in detail two of them, which we may call structural re-naturalization and functional re-naturalization, respectively, since they have different advantages and disadvantages. The former requires an intervention on the sandbar below Ruta 10 (or on Ruta 10) to re-open the mouth of Laguna del Diario and leave it to follow the natural sand bar behaviour of a choked lagoon. The latter requires hydraulic intervention of pumping sea water into the lagoon through existing pipes and leaving it to go back to the sea from a gate at the bottom of the sand bar system; it does not modify substantially the infrastructure currently constituting the Laguna del Diario outlet to the sea, simply moving the gate of current connection from the surface to a deep water level.

4.2.1 Option 2a -Structural re-naturalization

The action of reconnecting the lagoon and marine ecosystems is possible, but it will require building a bridge or a large culvert below Ruta 10 and leaving the sedimentation processes and the hydraulic forces to close and open the new lagoon mouth periodically. This action will change the current ecological status of Laguna del Diario, since the lagoon surface will drastically decrease and largely oscillate between periods of free exchange with the sea and periods of closure. Consequently most abiotic parameters as well as most structural and functional components of the lagoon will follow these oscillations.

Option 2 - Restoring the connection between the lagoon and the coastal marine area

4.2.1.1 Advantages

The Laguna del Diario will recover its original status of a choked lagoon and in the opening periods tide will remove excess sediment from the lagoon and guarantee good ecological conditions. In the period of interrupted communication with the sea the ecosystem will undergo a progressive change toward more freshwater conditions but the current eutrophic conditions will be prevented by the relatively short temporal scale of the process or by artificial opening of the sand bar if eventually required.

4.2.1.2 Disadvantages

Since the water level of the Laguna del Diario is currently 1.0m-1.5m higher than average sea level, in the opening period the lagoon will almost completely disappear leaving the system as a small tidal stream. Most of the current flora and fauna, including the particularly rich bird fauna will also be drastically reduced in abundance and diversity and suffer a change in species composition due to changes in salinity. Lagoon surface and salinity oscillations will prevent a shift in land use of the reclaimed land and will adversely affect the high level of biodiversity that currently characterizes the Laguna del Diario. In addition, the action would be very expensive due to the work required for the construction of the bridge on Ruta 10 to replace the current causeway.

4.2.2 Option 2b -Functional re-naturalization

The reconnection of the lagoon with the sea can be achieved without changing drastically the existing hydraulic output of the Laguna del Diario by introducing an artificial input of seawater at the seaward end of the lagoon. Since seawater

is heavier than freshwater it tends to sink below freshwater, creating haline meromictic conditions; consequently, it will be required to shift the lagoon water outflow from the surface to the bottom layer of the Laguna del Diario in order to remove this layer. This solution has already been addressed in the available studies and documents (Mazzeo *et al.* 2008) in a different context and reconsidered here in order to achieve water circulation at the seaward end of the lagoon that will influence water circulation in the entire Laguna del Diario.

4.2.2.1 Advantages

The functional re-naturalization of the lagoon will provide a number of positive implications for the overall ecological status of the Laguna del Diario that can be summarized in terms of two main aspects:

- ⇒ nutrient and organic matter budgets; and
- ⇒ biodiversity and ecosystem functioning.

As regards the first point, the input of seawater, which is more oligotrophic (i.e. has less nutrients in it) than the lagoon water, will serve to decrease the concentration of nutrients in the lagoon, increase water circulation, and decrease the water residence time. Moreover, output of bottom layer water will increase the removal both of nutrients and organic matter and remove bottom seawater layers, thus preventing or mitigating stratification. The effect of organic matter removal is likely to be local, but considering the increased water circulation due to the bottom water output, it will gradually affect most of the lagoon habitats.

As regards the second point, the seawater

input will also recreate a natural slight salinity gradient in the Laguna del Diario, creating new habitats, new niche spaces and conditions for more species to coexist in the lagoon. Therefore, overall biodiversity is expected to increase due to increased habitat heterogeneity.

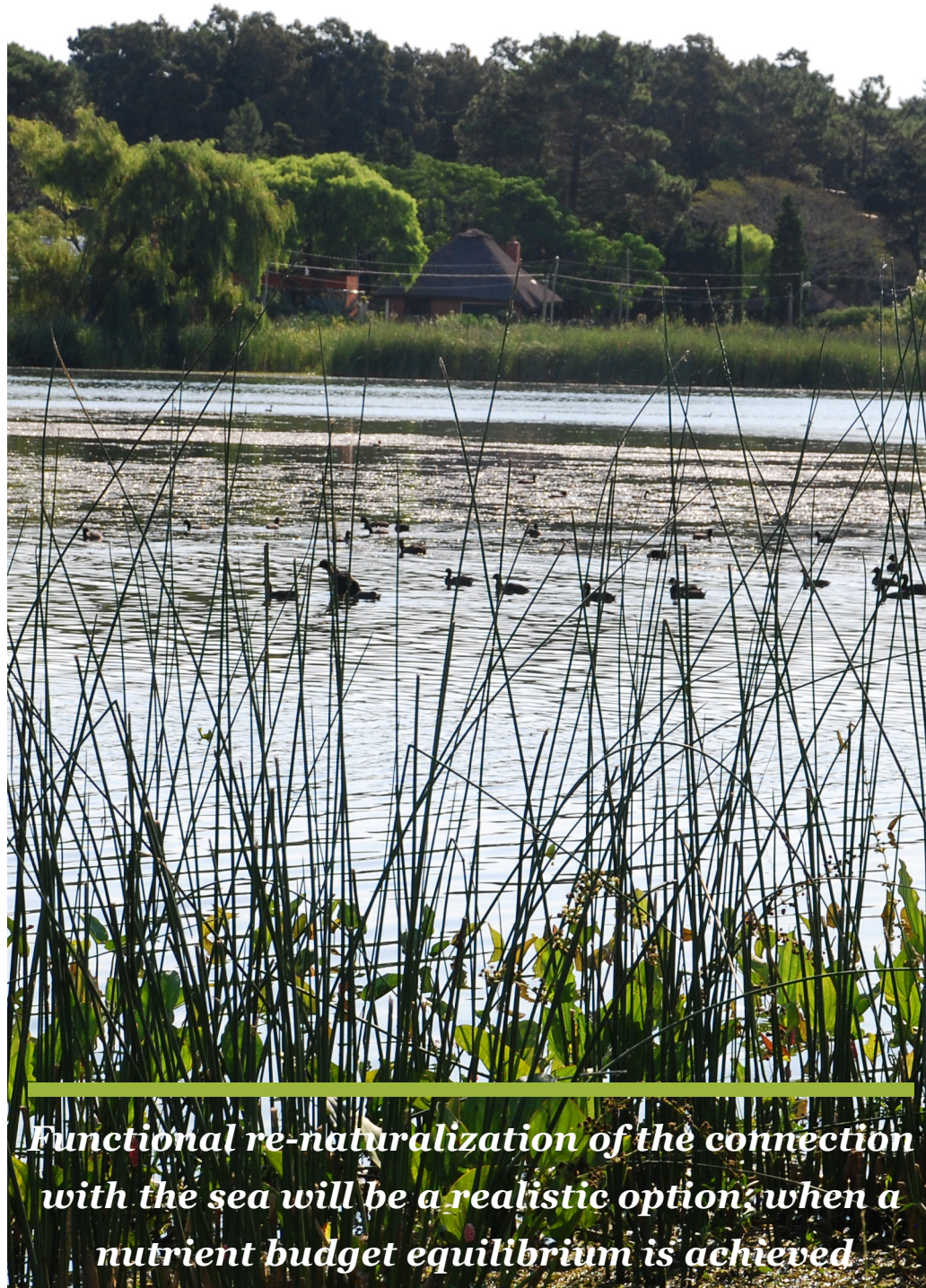
4.2.2.2 Disadvantages

The functional re-naturalization has costs related to the pumping station needed for introducing seawater into the lagoon and to restructuring the infrastructure connecting the lagoon with the marine environment in order to have the output of the water from the bottom layer. In order to quantify these costs it is necessary to analyse the possibility to adapting the existing pumping station of the old waste water treatment plant that is close to the seaward end of the Laguna del Diario. The functional re-naturalization will take time to export sediments to the neighbouring marine ecosystem at a scale larger than local and will constitute a risk of causing meromictic conditions due to the stratification of freshwater over a heavier seawater level; it would cause de-oxygenation of the sediment, release nutrients and increase eutrophication. However, this risk can be minimized by creating mixing conditions at the seawater input and modelling and managing water circulation and input-output balance.

4.2.3 Overall evaluation

Structural re-naturalization of the Laguna del Diario is a rehabilitation option that will produce much more negative impacts than positive effects at the ecosystem and landscape level. Therefore it has to be rejected.

Functional re-naturalization is a realistic rehabilitation option, which will have positive impacts on nutrient dynamics, increasing the nutrient output, and on biodiversity. However, the effectiveness of functional re-naturalization of the connection of Laguna del Diario with the sea on the ecological status of the lagoon cannot be fully evaluated in absence of clear assessments of the nutrient and organic matter



Functional re-naturalization of the connection with the sea will be a realistic option, when a nutrient budget equilibrium is achieved

inputs and estimates of nutrient input scenarios in the next decades. The re-naturalization action might be too weak to compensate in the short or in the long term for nutrient and organic matter inputs, simply slowing down the eutrophication problem while not solving the problem.

4.3 Option 3 - Increasing nutrient and organic matter export from the lagoon and decreasing nutrient and organic matter input

The impact of lagoon eutrophication on overall ecosystem status has been well described in the scientific literature (e.g. Zaldivar *et al.*, 2007) as well as the related risks of state transition towards undesirable states (e.g. Orfanidis *et al.*, 2008). Recovery from eutrophication is a two step process of re-balancing inputs and outputs of nutrients and organic loads and reducing overall nutrient availability. The time required and pathways of change are uncertain due to ecosystem hysteresis (Scheffer *et al.*, 2001; Reynolds, 2002)

Reduction of nutrient input is achieved through integrated actions:

- ⇒ Elimination of domestic waste water inputs.
- ⇒ Control and reduction of external point inputs from rivers, streams and groundwater.
- ⇒ Improved landscape management of diffuse sources.
- ⇒ Control and reduction of internal inputs.

It is not possible nor convenient, or even wise, to target controlling and reducing all external inputs of nutrients and organic matter. The allochthonous

leaf litter input from natural woodlands in the drainage basin is an example of 'green input', not susceptible to reduction; however, these diffuse 'green' inputs at least require quantification.

Nutrient and organic matter outputs from lagoon ecosystems commonly occur through:

- ⇒ Lagoon's connection with the sea.
- ⇒ Food chain dynamics and predation by terrestrial and marine organisms.
- ⇒ Amphibian and insect life cycles.

The last two mechanisms, which extract nutrients from the Laguna del Diario, describe the pathways through which lagoon ecosystems export nutrients towards the terrestrial and marine ecosystems, but the flux of nutrient they can involve in the Laguna del Diario is likely to be too low for achieving a balance in the nutrient and organic matter budget in the lagoon with the current conditions. However, increased nutrient export can be achieved, keeping and possibly enhancing these natural outputs. Other actions that can increase nutrient and organic matter outputs are through the management of submerged and emergent vegetation and removal of bottom sediments.

The documents already available on the rehabilitation of the Laguna del Diario have considered three integrated actions to achieve a balance between input and output of nutrients and organic matter in the Laguna del Diario and jointly decrease the inputs. These proposals are already stated in Section 1 of this report and take into consideration the management of submerged vegetation and organic

sediments. Here, we integrate them with the management of emergent vegetation and present an analysis of their advantages and disadvantages in the context of all the components affecting nutrient and organic matter dynamics of Laguna del Diario.

4.3.1 Option 3a - Control of submerged and emergent vegetation by mechanical harvesting

Mechanical harvesting of submerged and emergent vegetation is one of the most common means of nutrient management in freshwater lakes and lagoon ecosystems. Human exploitation of macroalgae and seaweed differs worldwide largely influenced by local culture (Harnedy and Fitzgerald, 2013). The plant material removed from the lagoon might give additional benefits by using it in energy producing processes. However, since the chemical composition of submerged vegetation varies with species, habitats, maturity and environmental conditions (Ito and Hori, 1989), the management choice concerning the optimized approach to be adopted for the use of algae biomasses have to be evaluated on a case by case basis after a complete physical-chemical screening of tissues.

Management of submerged vegetation requires consideration of a few key issues that might result in negative cascading effects:

- ⇒ Submerged vegetation represents a significant proportion of lagoon productivity and affects critical components of food webs. Key herbivorous species in the Laguna del Diario include fishes, birds and gastropods, which also contribute

Option 3 - Increasing nutrient and organic matter export from the lagoon and decreasing nutrient and organic matter input

to export of nutrients and organic matter from the lagoon.

- ⇒ Submerged vegetation competes with phytoplankton for nutrients and these interactions could potentially be affected by managing submerged vegetation biomass; a shift from submerged vegetation to phytoplankton in large areas of the lagoon is likely to drive a transition of the ecosystem status to a less desirable one and to a lower equilibrium level.
- ⇒ Submerged vegetation is sensitive to turbidity, which might be increased by harvesting, reinforcing the risk highlighted in the previous point.

As regards emergent vegetation, the best time to harvest riparian vegetation is during the early growing stages in spring and early summer, when vegetative growth is at its fastest (Bartoli and Viaroli, 2006), and in late summer and early autumn, just before the end of the growing season and the start of plant senescence.

Management of the emergent vegetation also requires consideration of a few key issues that might result in negative cascading effects:

- ⇒ Littoral vegetation is a nesting habitat important for different species of birds. Harvesting the vegetation requires a programme of plant removal that is designed on the temporal and spatial scales necessary to accommodate bird nesting activity.
- ⇒ Littoral vegetation is also a key habitat for insect hatching and snail reproduction. Both these functions have to be considered and protected in the plant cutting activity. This point needs to be seriously considered in Laguna del Diario, where the snail – snail kite interaction is a main pathway of nutrient output through food web interactions.

4.3.1.1 Advantages

The advantages of this action are clear: i.e. the removal of submerged and emergent macrophyte biomass increases the output of both nutrients and organic matter from the lagoon ecosystem.

Moreover, harvested plant biomass can be used for biofuel production and other types of energy production. There is good understanding of the energetic efficiency of the oil extraction process from microalgal artificial cultures (Mata *et al.*, 2010) due to the high lipid content in unicellular species (Spolaore *et al.*, 2006; range from 4% to 20% dry weight). In contrast, few data have been collected on the efficiency of extraction from macroalgae and phanerogams. In spite of that, macroalgae are naturally growing in coastal eutrophic ecosystems producing great quantities of biomass without any human effort (Lenzi *et al.*, 2003; Bastianoni *et al.*, 2008; Giovani *et al.*, 2010).

The advantages obtainable from the use of such resources are twofold:

- ⇒ The exploitation or 'cultivation' of submerged and emergent macrophyte biomasses avoids ecological, economical and energetic costs resulting from lagoon degradation and eventually lagoon collapse.
- ⇒ Energy recovery from macrophyte biomass offers the chance to transform a notable cost (the management of macroalgal and reed biomasses) into income. A large proportion of extractable oils from macroalgae is used for the production of bioethanol (Borines *et al.*, 2013; Tan *et al.*, 2013) and biodiesel (Belarbi *et al.*, 2000; Chisti, 2007). Concerning bioethanol, several studies were performed to optimize production from macroalgae including optimization of biomass pre-treatments to improve production efficiency.

4.3.1.2 Disadvantages

Management of submerged and emergent macrophytes needs to take into consideration the few issues raised at the beginning of this section. The only disadvantage of a properly undertaken macrophyte management process is the need for repeating the action not only throughout the year but for subsequent years until a positive result is reached. Without control of the inputs, the action of removal of lagoon vegetation biomass has an intrinsic risk of producing only partial results. The harvesting actions have a cost, and repeating the actions over years requires a prolonged engagement of the funding administration or funding donors.

4.3.2 Option 3b - Control of submerged and emergent vegetation combined with control of nutrient inputs

The control of nutrient inputs is a key management priority whenever land use in the watershed of inland water basins, such as freshwater lakes and lagoons, involves increasingly widespread and impacting human activities. Dealing with the Laguna del Diario, which has a relatively small watershed, characterized by streams and creeks rather than large rivers, and with a still relatively low density of urban settlements, nutrient removal can be achieved with the following actions of re-naturalization or 'green nature-manipulation':

- ⇒ Management of the waterways, with removal of excess organic matter accumulation from the streambeds and increasing the stream discharge into the lagoon with possible positive effects on water residence time.
- ⇒ Re-naturalization of the terrestrial vegetation along the stream corridors and control of agricultural and farming practices in order to minimize the diffuse discharge of nutrients into the Laguna del Diario.

Comparative analysis of the rehabilitation options 2 and 3

⇒ Creation of artificial controlled wetlands along the waterways such as reed beds to control and reduce organic matter transport to downstream lagoon ecosystems.

4.3.2.1 Advantages

This option will drive the system towards recovering a balance between input and output of nutrient and organic matter.

4.3.2.2 Disadvantages

It adds the costs of building controlled wetlands in the drainage basin and management of the streams and other smaller waterways to the costs of harvesting submerged and emergent vegetation. This action is a permanent action requiring long term investments for the operational costs, which are anyway pretty low when compared with the investment costs.

4.3.3 Option 3c - Control of submerged and emergent vegetation and nutrient inputs combined with control of the internal load of nitrogen and phosphorus

In both freshwater lakes and lagoons when the control of external nutrient and organic matter inputs does not sufficiently drive the ecosystem back to a more desirable and less eutrophic state, the control of the internal loads becomes an operative alternative or complementary action to be followed. According to the physiographic characteristic of the specific ecosystem considered and to its actual ecological status different actions are available.

For the Laguna del Diario, three main actions can be considered:

⇒ Dredging surficial sediments, by using mobile platforms sucking up sediments with high performance pumps and operating at the low depth characteristic of the Laguna del Diario.

⇒ Building a new artificial bottom layer, burying the nutrients and organic matter in the actual lagoon sediment beneath an impermeable artificial layer.

⇒ Oxygenating sediments in the most critical area of the lagoon with the same techniques/equipments used in inland intensive fish farms.

Each one of these actions has advantages and disadvantages that need to be analysed with respect to the characteristics of the specific ecosystem considered. Therefore, we weigh these actions here with reference to the Laguna del Diario ecosystem.

4.3.3.1 Advantages

Controlling the internal load through the first two actions (dredging, sealing off the bottom sediments), in addition to the management of the plant biomass and the control of the external inputs will have an immediate effect on water quality; however, it might also have negative effects on biodiversity, which will be discussed in the next section. The third action will produce positive effects on water quality but over a longer time span.

4.3.3.2 Disadvantages

All three actions have costs that need to be added to those already considered for plant biomass management and control of the external inputs. The costs vary greatly between actions, being highest for the reconstruction of a lagoon

bottom sediment layer and lowest for the oxygenation of selected lagoon areas that are more prone to hypoxia or anoxia events. The operational costs of the oxygenation action can be greatly reduced if the required electricity is achieved using solar energy. The cost of dredging depends on the area and depth of the dredging activity; but the vertical distribution of the nutrients in the sediments has to be considered carefully in order to avoid creating effects opposite to those desired. Moreover, dredging and building a new bottom sediment layer are invasive activities, affecting the bottom layer production of both microscopic producers and submerged plants that currently sustain an impressive diversity of fauna. Both activities require the detailed modelling of the Laguna del Diario food web structure to inform the intervention; in case of building a new bottom sediment layer, detailed modelling is required also to restore the benthic communities

4.3.4 Overall evaluation

Option 3 describes several critical actions that would enable the recovery of a high and desirable ecological status for the Laguna del Diario. Detailed comments on the methodological procedures suggested in order to minimize the risk of failure and optimize an adaptive management process will be described in the following sections. Control of the internal nutrient load would be useful to accelerate the process of rehabilitation and would need to be implemented after the first signs of recovery are observed. We suggest consideration is given to dredging of particularly vulnerable areas as a second option. Building a new bottom layer over the existing

REHABILITATION OPTIONS	ADVANTAGES			RISKS			COSTS		
	Env	Soc	Eco	Fai	Dam	Unc	Inv	Ope	Ove
Restoring connection with the sea									
a Structural re-naturalisation	Medium			High	High	High	High		High
b Functional re-naturalisation	High	High				High	High	High	High
Restoring nutrient balance and reducing loads									
a Harvesting lagoon vegetation	High	High	High	Medium			High	High	High
b Reducing external inputs	High	High		Medium			High	High	High
c Reducing internal inputs	High			Medium	High		High	High	High
c1 Dredging	High			Medium	High			High	High
c2 Burying sediments	High	High		Medium	High	Medium	High		High
c3 Oxygenating sediments	High	High		Medium			High	High	High

HIGH
MEDIUM
LOW
V. LOW

Table 4.1 – Comparative analysis of the potential rehabilitation options for the Laguna del Diario ecosystems. The darkness of the colours are proportional to the value for the respective category of advantages, risks or costs.

sediment is not an option required for the Laguna del Diario.

4.4 Comparative analysis of the rehabilitation options 2 and 3

A synthetic comparison of advantages, risks and costs of the different rehabilitation options considered at Sections 4.2 and 4.3 is given in Table 4.1.

In the definition and planning of the intervention for the rehabilitation of the Laguna del Diario advantages, risks and costs of the different potential options have to be comparatively analysed considering both short and long-term responses of the ecosystem. Short term positive effects of the planned intervention are required in order to prevent further degradation of the Laguna del Diario ecosystems thus avoiding the need for more drastic and expensive rehabilitation interventions in the future. The rehabilitation strategy needs to focus on the long term recovery of new equilibrium conditions allowing the achievement of high quality ecological conditions (environmental advantage of the intervention (ENV in Table 4.1)) as well as of desired ecosystem status (social advantage (SOC in Table 4.1))

and getting benefits from ecosystem services (economic advantage (ECO in Table 4.1)). Among the risks, the possibility that the intervention fails to meet its objectives (FAI in Table 4.1), that damages are directly or indirectly caused to the ecosystems determining new dis-equilibrium conditions (DAM in Table 4.1) and the level of uncertainty of the ecological dynamics determined by the intervention (UNC in Table 4.1) have to be carefully considered. Finally, investment (INV in Table 4.1), operational (OPE in Table 4.1) and overall (OVE in Table 4.1) costs of the intervention have to be considered. In the light of short and long term advantages, different types of risks and costs, the null option has to be rejected and an intervention needs to be planned in the short term. One of the rehabilitation options taken into consideration in the present report, i.e. the structural re-naturalization of the connection of the Laguna del Diario with the sea, has also to be rejected. The construction of a new outlet of the lagoon, structurally reconnecting it to the ocean, will cause extensive changes in the Laguna del Diario ecosystem and takes the ecosystem far from the desired status for the current socio-economic context of the area

(high risk of failure in bringing social and economic advantages to the area). In fact, when the connection is open to the sea, the Laguna del Diario will lose most of its surface area, with negative cascading effects on carrying capacity and energetics, organization and biodiversity. When the outlet is closed, the Laguna del Diario will recover almost completely its current surface area and carrying capacity, while recovering at a slower rate and with a degree of hysteresis its organization and biodiversity. Therefore, Laguna del Diario will recover its natural structural and functional oscillation according to the open/closed conditions of the outlet characteristic of a choked lagoon (*sensu* Kjerfve, 1994). Such a lagoon behaviour conflicts with the socio-economic desired status of a healthy ecosystem with high and 'visible' biodiversity, flagship species and stable equilibrium conditions at a much shorter temporal scale of the dynamic equilibrium conditions of choked lagoons, particularly when the lagoon surface area oscillates drastically between open and closed conditions.

Establishing a functional connection of the Laguna del Diario with the

sea, with an artificial circulation of marine water at the seaside end of the lagoon potentially will bring significant advantages both in the ecological condition of the Laguna, by decreasing the water turnover time and, consequently, reducing the negative effects of nutrient load and increasing habitat heterogeneity with cascading positive effects on overall lagoon biodiversity. However, it has to be clear that it would be an ecosystem level manipulative experiment that has not yet been performed in any lagoon ecosystem elsewhere; artificial lagoons, planned as mitigation actions for addressing sea-level rise risks include options of functional connection with the sea similar to that considered here. As a manipulative ecosystem level experiment, changing average salinity of the Laguna del Diario and salinity gradients, there are risks of chaotic dynamics within the ecosystems, which can be estimated but not minimized, particularly if it would be the first and only rehabilitation intervention in the Laguna del Diario, requiring extensive inputs of marine water to decrease

nutrient levels in the Laguna and increase water turnover rate. The probability of success of an intervention of functional re-naturalization of the connection of Laguna del Diario with the sea will be much higher if controlled small scale experiments were to be performed when the status of the Laguna is already undergoing significant improvements due to intervention actions on nutrient balance and loads.

In setting priorities among the rehabilitation options proposed in sections 4.2 and 4.3 and listed in Table 4.1, a major issue is ensuring short-term positive responses required to avoid further degradation of the Laguna del Diario ecological status while setting up the infrastructural components of the interventions producing long-term positive responses. Harvesting plant biomass in the Laguna del Diario provides positive environmental and societal responses with operational costs that can be partially covered by economic rewards from using the exported plant biomass. Therefore, the comparative analysis of the proposed

rehabilitation options indicates as a first priority optimizing the current on-going harvesting of submerged macrophytes and extending it to emergent macrophytes. However, harvesting plant biomass needs integrative actions on nutrient input in order to achieve a nutrient balance in the Laguna del Diario, while the overall nutrient loads decrease.

The rehabilitation options including reduction of nutrient loads, both external and internal, produce long-term positive effects on the environmental conditions of the Laguna del Diario. Among the options described in section 4.3 and listed in Table 4.1, the reduction of external nutrient inputs has the strongest environmental and societal advantages, since the characteristics of the Laguna del Diario watershed allow substantial reduction of the external nutrient inputs with the intervention listed at section 4.3.2. Moreover, these types of intervention have only very reduced and hypothetical risks of failure and no risks at all of negative implications on biodiversity and ecosystem functioning.



Lagoon restoration presents an excellent opportunity for engagement of the whole local community

The integration of harvesting plant biomass in the Laguna del Diario and reducing external inputs represent a consistent solution to reverse the current degraded conditions of the Laguna del Diario towards a less eutrophic equilibrium in the nutrient budget and a more desirable ecological status. Therefore, more drastic intervention in the lagoon ecosystem aimed at reducing the internal nutrient inputs does not seem to be required. In fact, both dredging locally the areas with the highest organic content of sediments and covering the bottom sediments with a new artificial bottom layer have strong impacts on the benthic communities, including both benthic flora and fauna, with risks of short term further deterioration of the environmental status of the lagoon. Moreover, they require expensive investment or operational costs. Only mechanical sediment oxygenation might be a feasible option to accelerate and reinforce the short-term positive ecosystem level responses to plant biomass harvesting. Mechanical sediment oxygenation is achievable in the Laguna del Diario, which is shallow enough to respond positively, and might substantially reduce the flux of nutrients, particularly phosphorous, from sediments in areas with high concentration of organic matter in the surficial sediment layers.

A proposal for the rehabilitation of the Laguna del Diario, integrating different options along a defined time scale of intervention, is given in the 'Recommendation' section of the present report.

5. Research & Monitoring

The need to understand the changes taking place in the Laguna del Diario system is acute. Although past research has revealed a great deal about the lagoon, its basin and its features, there is still a great deal that is not known about the processes under way and the rates at which these are changing.

In order to enable development of a sound adaptive management plan to rehabilitate the lagoon, and to adapt to future climate change it is critical to fill these knowledge gaps. It requires a combination of research investigations, which may be of relatively short duration, and longer-term monitoring to track the processes of change and the effectiveness of remediation. This section outlines some of the principal needs, and indicates where feasible the agency or personnel that might be recruited for the purpose.

5.1 Information database

The Universidade de la Republica report is based upon a review and analysis of pre-existing research endeavours together with new, targeted research conducted for the assessment. It is highly probable that other historical data exist in government reports, data banks, and research documents that would amplify the existing scientific and socio-economic

knowledge base. In order to maximize the value of past efforts, and to avoid unnecessary duplication, a short-term project should be conducted to search for and record existing sources of data. This is a suitable project for university students.

the data available to make use of its predictive potential are limited. A particularly important element relates to groundwater, which contributes to the lagoon by seepage, but is also part of the domestic supply. The contribution of groundwater to the

***Rehabilitation of the Laguna
requires that existing knowledge
gaps regarding ecosystem properties
and processes be filled by additional
research and monitoring***

5.2 Hydrological regime

The Universidade de la Republica has developed a model that attempts to describe the flows of water (surficial and groundwater) into and out of the lagoon. While the model itself is sound,

lagoon undoubtedly varies in different parts of the watershed, and its future role is expected to change under the influence of climate changes. Similarly, the inflowing surface water channels convey varying amounts of freshwater, sediments and nutrients into

Understanding and interpretation of the process of rehabilitation requires a comprehensive ecosystem model

the lagoon, especially following storms, but these are not monitored. A network of piezometers, weirs, precipitation gauges, etc., either monitored using modern sensors, or by periodic visits, would provide the data needed to run the hydrological models effectively, and support future management decisions. This would make a suitable collaborative project between university researchers and Intendencia personnel.

5.3 Sediment regime

Present information about the sediments in the lagoon is extremely sparse, based substantially upon a single mid-channel core. Knowledge of the present sediment load, its properties (e.g. contaminants, structure, mobility, etc.), is critical for assessing the remediation needs, no matter which remediation option is adopted. A more comprehensive survey of deposited sediments in the lagoon is required. The Universidade de la Republica has the equipment and personnel to conduct this task.

5.4 Water quality

As shown by the Universidade de la Republica report, water quality can change rapidly under the influence of ecosystem shifts, seasonal and weather changes, and remediation efforts. Monitoring of water quality is a crucial element in any adaptive management remediation scheme. Present monitoring activities related to public health issues need to be maintained, but also enhanced in terms of frequency of sampling and number of locations. Parameters of concern include: coliform bacteria, potentially toxic algae, nutrient concentrations, pH, alkalinity, sediment concentration, etc. This activity would fit within the mandate

of Intendencia personnel, but since the data are valuable for other than public health reasons, a collaborative project with the Universidade de la Republica is called for.

5.5 Land use

The problems of the lagoon are related to continuing changes occurring in land use in the watershed: particularly increasing urbanization, transportation, tourism, farming, etc. These activities – including an infilling project by one land owner on the south shore of the lagoon – represent progressive threats to the stability of the lagoon ecosystem, and the success of any rehabilitation efforts. Uncontrolled and unauthorized construction or changes in land use need to be eliminated. At present it is not clear to us (the Expert Committee) if the trends in changing land use are being monitored and, if so, whether the data are sufficiently well known and utilized to provide effective forecasting of future conditions that would affect the sustainability of the lagoon ecosystem. If not, such a study, followed by periodic reviews, needs to be done. This might be achieved by Intendencia personnel alone, or in collaboration with University researchers.

5.6 Flora

While recent research conducted by the Faculty has aimed at providing an inventory and biomass estimates for submerged vegetation, it does not appear that the same has applied to the emergent vegetation. Work on the submerged plants needs to be continued, to monitor both the effects of cutting and of any other remediation efforts. Similar surveys are required for the reed beds that currently occupy a large fraction

of the original lagoon. Removal of some of the accumulated sediments and organic matter in the emergent vegetation areas will help to reduce the accumulated organic matter and nutrient load in the lagoon (potentially reversing the present trend of continuing increase), increase habitat diversity, and enable better management of water exchange. Monitoring of emergent vegetation can be done by aerial or satellite photography (e.g. Tassi *et al.*, 2007), using drones, or more economically by field surveys. In the latter case, non-government organizations could be involved in annual surveys, increasing awareness and involvement in the lagoon and any rehabilitation processes.

The Universidade de la Republica document provides no information on the floral diversity of the emergent vegetation. This needs to be remedied with a short term, multi-seasonal study that would form the basis for planning longer term rehabilitation strategies.

Algal populations need to be monitored regularly because of their short life cycles, rapid response to environmental conditions, and public health concerns. The preliminary investigations reported by the Universidade de la Republica need to be continued, including periodic measurements of productivity.

5.7 Fauna

The study of the Universidad de la Republica, and associated published papers and unpublished documents, such as reports and thesis, produced by the university research teams provide a good knowledge base for evaluating the ecological status and the key drivers of current status in the Laguna del Diario, as has been made clear by the previous sections of this report. However, new knowledge and updated information is required to describe the conservation potential of the different options and describe the pathways of change and the remediation potential of the lagoon as a whole. High priority subjects are: updating fish population and distribution study; design of a seasonal monitoring programme using nets,

traps, and electrofishing techniques for all regions of the lagoon; updating the survey of benthos and a stratified sampling design for long term monitoring; and, particularly, design and implementation of a bird monitoring programme.

Monitoring programmes for fish and birds could provide good opportunities for recruitment of community members and development of citizen science projects.

5.8 Ecosystem interactions

Understanding and interpretation of the process of rehabilitation of a eutrophic lagoon system requires a comprehensive ecosystem model. Many of these exist, whose purpose is to describe for example food web interactions, population responses to environmental changes (etc.), but these have not been applied to Laguna del Diario. It will take several years to acquire the field data needed to populate the models, but the objective of achieving a holistic understanding of ecosystem processes requires that this be done. It will enable management agencies to assess the progress and measure the success of rehabilitation actions.

5.9 Socio-economic implications

Changes in lagoon productivity and diversity will create economic opportunities and costs. A principal reason for selecting the appropriate option for rehabilitation of the Laguna del Diario is to enhance it as an asset in support of the tourist industry of the Maldonado region – or at least to minimize the potential negative effect if the present process of degradation were to continue. Rehabilitating the lagoon, maintaining its productivity and biodiversity, will have a general benefit for the tourism industry as a whole, but it is difficult to define or quantify that benefit precisely. However, a rehabilitated lagoon will probably become a centre of new forms of recreational use; bird watching, swimming, boating etc., and may well support development of accommodation facilities (e.g.

hotels) nearby. In order to assess the economic benefits of this activity, which will offset some of the costs of

rehabilitation, it is recommended that a study of potential socio-economic benefits be conducted immediately.



***Rehabilitating the lagoon,
maintaining its productivity
and biodiversity, will have
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tourism industry as a whole***

6. Recommendations

The fundamental recommendation is to establish a remedial action programme to reverse the present process of eutrophication by controlling nutrient inputs, enhancing nutrient export, and removing some of the existing nutrient load in the lagoon. These actions (described in option 3 above) will be achieved mainly by harvesting existing submerged and emergent macrophytes, possibly supplemented by dredging and/or flushing with seawater.

The recommended intervention is organized into successive steps, with key recommendation for every step in order to avoid inefficient or even negative results.

STEP 1 – Harvesting of submerged macrophytes has to be maintained and further developed in connection with the harvesting of emergent macrophytes; this action allows removal of excess external and internal nutrient loading in the short term, while more effective intervention on the nutrient input and lagoon water retention time are designed and implemented. When nutrient input and water retention time is under control, re-establishing an equilibrium in the nutrient budget in the lagoon by harvesting of emergent and submerged macrophytes will most probably no

longer be required. The harvesting activity has to take into account the following recommendations:

⇒ ecological knowledge on submerged macrophyte-based food webs already exists in the Laguna del Diario (e.g., Mazzeo *et al.* 2008; Vianna; unpublished thesis); nevertheless, the role of submerged macrophytes on

Laguna del Diario food webs has to be further clarified in order to avoid negative impacts on biodiversity. Fishes, gastropods and birds are relevant herbivorous species contributing to both nutrient export from the lagoon, and lagoon biodiversity, which have to be protected while harvesting the macrophyte biomass;

The recommended intervention is organized in two successive steps with key recommendation for each of them in order to avoid negative outcomes

The objective is a high quality environment with high biological diversity providing recreational and aesthetic benefits to the region

- ⇒ macrophytes compete with phytoplankton for nutrients and light; harvesting has to avoid creating a competitive advantage for phytoplankton resulting in dominance of phytoplankton species that could potentially increase eutrophication and negative effects;
- ⇒ the role of emergent macrophytes for gastropod and bird reproduction in the Laguna del Diario has to be assessed to optimize the harvesting of emergent macrophyte biomass;
- ⇒ timing during the year and spatial extent of harvesting have to be planned taking account of the previous recommendations in order to maximize nutrient export from the lagoon;
- ⇒ use of removed plant biomass in energy production might represent a solution to compensate the cost of harvesting.

STEP 2 – Control of nutrient input through re-naturalization and management of the small stream entering the Laguna del Diario, and construction and management of artificial wetlands in the lagoon watershed. This action requires time to be fully realized but when the control is fully operational it will have strong and permanent positive effects on the health of the Laguna del Diario ecosystems. As regards this action, we recommend that:

- ⇒ the operation of nutrient input control is based on a model of the optimal nutrient load to the Laguna del Diario that results in a reduction in eutrophication while enhancing biodiversity in

the lagoon ecosystem;

- ⇒ a plan for land use change and urban development in the watershed basin of Laguna del Diario is implemented with management and policy actions aimed at ensuring environmental sustainability and the achievement of good ecological status for the lagoon ecosystem.

STEP 3 - Re-establishing an input of seawater in the Laguna del Diario, decreasing the water residence time and increasing the export of nutrients towards the sea. Timing and amount of seawater input in the lagoon have to be estimated and modelled taking into account the following recommendations:

- ⇒ stratification of freshwater and seawater in the lagoon has to be avoided in order to prevent the risk of hypoxia or anoxia of benthic sediments;
- ⇒ the potential effects of seawater input and increased salinity on the lagoon flora and fauna have to be monitored in order to avoid negative impacts.

In order to support the rehabilitation actions above the following things also need to be done:

- ⇒ Compile a comprehensive bibliography of reports and data sources regarding the Laguna del Diario.
- ⇒ Conduct baseline studies to fill in important ecological knowledge gaps in order to ensure that the results of the rehabilitation action are delivering the desired outcomes. Such studies include: diversity and distribution of benthic organisms; diversity and areal

extent of emergent macrophytes; role of emergent macrophytes as fish and bird habitat; and sediment composition and properties.

- ⇒ Establish a network of monitoring stations to measure precipitation, surface and ground water levels to provide ongoing refinement of existing hydrological models.
- ⇒ Establish a water quality monitoring programme in order to deal with potential health issues.
- ⇒ Conduct a study of present trends in land use and watershed development.
- ⇒ Engage the local community to assist with monitoring activities and enhance public education and awareness.

All of these recommendations are aimed at the long term rehabilitation of the lagoon ecosystem. The objective is to induce changes in the lagoon that will eventually yield a sustainable, high quality environment that exhibits high biological diversity, and provides recreational and aesthetic benefits to the region. Because of the dynamic nature of natural ecosystems, making any change has an inherent risk of initiating unexpected ecological responses, as illustrated by the growth of cyanobacteria following harvesting of submerged plants. Consequently, such changes need to be selected on the basis of the best available scientific information, and then modified as necessary over time as monitoring of important ecosystem indicators indicates that the desired outcomes are, or are not, being achieved. The approach is one of adaptive management, in which the final, desired outcome can only be achieved by intelligent adaptation of the rehabilitation measures as the rehabilitation process unfolds. If successful, there is every reason to expect that the costs of rehabilitation will eventually be paid back by the socioeconomic benefits achieved.

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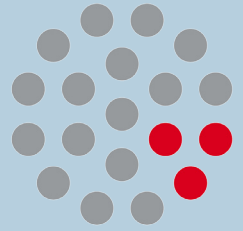


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