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MEASUREMENT PLAN FOR THE DIAGNOSE OF AQUATIC ECOSYSTEMS

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Abstract – This paper is relating the effort to organize a pertinent measurement plan to analyze 2 aquatic ecosystems, a canal and a lake, where the issue is to improve the natural surviving of fishes for the benefit of local angling clubs.

The first case is a 4 century old canal, located in a castle, built from its very beginning for French king entertainment and trout rising; the issue is related to the massive introduction of new fishes every November which are disappearing during winter while trout, fishes very sensitive to pollutions, are surviving.

The second case is a more recent lake dedicated to fly fishing, where the issue is quite the opposite: introduction of trout is resulting, after a month, into a complete disappearance of these fishes while other alien species are still alive with a good reproduction rate. In both case there is no trace of dead bodies or other visual evidences of the changes.

The measurement plan is considering over 1000 different parameters that may explain the lethal for life situation of aquatic ecosystems and is creating a typology and hierarchy of these parameters to build a measurement sequence.

A set of abiotic specifications was created with a scale compared to Nisbet & Verneaux abiotic inventory of French lakes and rivers.

The paper will cover the different techniques used for that purpose and what we have learned to obtain reliable results for physical measurements (flow, laminar flow, volume and water renewal rate, temperature etc…), abiotic (pH, redox, conductivity, hardness, dissolved gas etc…), biotic index, and comparison to biological history (sclerochronology).

The presentation will show several tools we have developed for mass sampling, continuous surveillance and GPS driven measurements.

The conclusion will show the need for a systemic approach to integrate all these measurements into a consistent model for overall behavior and productivity prediction.

Keywords: ecosystem, aquatic, productivity.

1. INTRODUCTION

3 years ago we were involved in an aquatic ecosystem diagnose with an objective to find the actionable parameters to increase the overall fish productivity. We have chosen a scientific approach based on measurements of critical parameters. This first example, a 4 century old canal, looked very simple, like an open air aquarium with a long history of good operation; we were mainly supposed to detect what has changed to explain the disappearance, during winter, of most fishes massively introduced every November, while trout, fishes very sensitive to pollutions, are surviving.

During this investigation we have acquired more than 700 data points and added more parameters and measurement techniques every month. We had to face the issue in defining what is a critical parameter, what an acceptable value is, and how these data are correlated together within a specific chemical or biological cycle.

Later on we had to perform a quite similar analysis with a different situation: a lake for fly fishing where the objective is trout surviving but where only invasive species are still alive with a good reproduction rate. The situation was more complicated due to poor homogeneity of a lake requesting to refine and automate our sampling techniques.

Altogether, the main issues for such analysis was to organize a pertinent measurement plan, this is the aim of this paper.

We had 3 constraints for this project:

- An equipment budget limited to 10 k Euros in order to replicate the operation for other angling clubs facing the same issue.
- To use, whether possible, electrical measurements for mass sampling, on site surveys with temperature compensated sensors, continuous monitoring devices; taking into account the short life expectation of such instruments.
- To respect the regulations of the public parks where these ecosystems are located.

Definition of the mesurand

An ecosystem is a system formed by the interaction of a community of organisms with their physical environment; Fresh water lakes with slow-moving water, are called lentic ecosystem. Freshwater ecosystems contain 41% of the world's known fish species.

According to one author [1], an ecosystem can be compared to a car manufacturing plant with a main production line, production of fishes in our case, and several "supply chains" contributing to the main one (calcium, azoth, photosynthesis cycles, food chain etc..).

Productivity measurements

Productivity is measured in kg/ha (lake) or kg/km (river or canal); High productivity levels are between 250 and 500 kg/ha.

The standard method used to evaluate the number of fishes within an ecosystem is electrical fishing applied to representative area. However, using a 400 V DC under 2 A generator in water is a process reserved to a limited number of trained specialists and not adapted, for example, to a 2 meters depth canal. In addition, the profile may vary, (slope in the canal) and fish population may migrate according to the water temperature gradient. For this reason we have chosen an easier way to evaluate the situation by using the data from the volume of captures during the yearly angling competitions, taking place at same time at the same location using similar techniques.

2. OVERALL SYSTEMIC DESCRIPTION

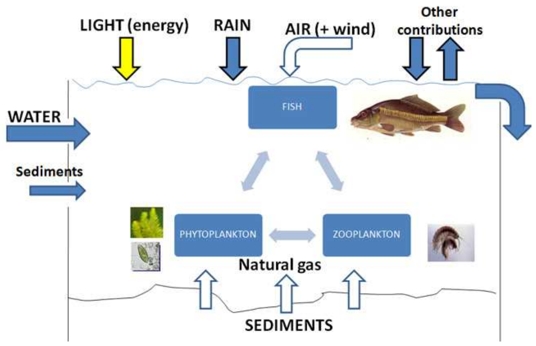

Fig. 1. Simplified systemic view of the ecosystem.

Figure 1 gives an overall systemic view of the ecosystem. Sunlight is providing energy for the development of phytoplankton (algae, macrophyte), this is feeding the zooplankton eaten by fishes. Waste from fishes is giving food to the phytoplankton, closing the loop. Water is provided by a main stream, few other sources and rain. Several gases are diluted in water from air via the wind, and sediments are generating natural gas via fermentation from anaerobic bacteria. The economy of this ecosystem relies also on the balance between chemical components given by the sources of water and the ones fixed within the dead organisms evacuated by the pouring system (deciduous leave).

Within the "other" components we can consider:

- Fishes added by angling clubs or removed by their members, food added to facilitate the catches,
- Surface water bringing soil components,
- Leave falling from surrounding trees and bringing toxic substances or adding an anaerobic layer to the sediments
- Water birds adding chemical components or parasites via their feces, or eating fishes
- Any pollution

This is a simplified view as there are multiple chemical cycles participating to the fabrication of nutriments.

An important question is to define at which level we have to place the lower limit of the ecosystem. The sediment layer is an integral part of our ecosystem and not only a physical limit of the water for the following reasons:

- Fishes like carps are digging into the sediments to find something to eat, such as worm clams and crawfishes; several fish species have a hibernation phase where they dig a refuge within the sediment that may be toxic for them,

- During winter, the surface water is cooler than the bottom, creating an ascending current which is making water muddy, mixing up the chemical component coming from sediments. The same mix up occurs when there is a tempest and when the lower depth (less than 1 meter) is shacked.

- The surface of sediments has an important role for bacteria development, acting as a recycling engine,

- The canal sediments are only removed twice a century; heavy metals like lead used for fishing can accumulate and influence the food chain,

Specialists of fisheries are recommending to consider the physical limit of the bottom at 30 cm and to perform mass sampling on the first 5 cm where the most active part of what they call the "precious laboratory" is active [2]. The argument is considering that aquatic plants, as opposed to terrestrial, are taking their nutriments within water and not from their roots. Therefore we can plan to perform most frequent sampling for the few 5 cm completed with some 30 cm sampling as sanity checks.

For the canal, the main stream is directly coming from spring sources; due to the extruded double stone walls for the flanges, there is no influence of surface water; same for trees which were planted 20 meters away but the contribution of the fishermen food is significant (about 2 tons per year).

For the lake, surface water is strongly contributed to turbidity as well as sediments coming from a river; trees are dropping their leave and pollens into water, their roots are destroying the banks; fly fishing is not bringing any food to the water.

3. OVERALL MEASUREMENT PARAMETERS

Any owner of freshwater aquarium knows that he can maintain fishes alive by filtering and renewing water adding oxygen, light, food and from time to time, or after an incident, controlling less than 10 parameters. NASA has popularized a sealed bottle with a shrimp to demonstrate that a well balanced ecosystem can survive without any external components but light [3].

Within an outdoor ecosystem the situation is more complicated because food is coming from the system itself, weather and plants are sources of oxygen and energy. Concerning our main medium, water, according to literature on fisheries, 23 parameters should be monitored for an optimum productivity [1]; about 350 industrial pollutants [4] may affect the life cycle balance, acting on fishes, zooplankton, phytoplankton, and recycling bacteria; The European Water Framework Directive has identified 33 priority substances and 8 other pollutants to be monitored [5]. Another organization, the French ANVAR, has integrated toxic natural substances within their inventory [6]. More recently researches have also shown the importance of 700 pharmaceutical wastes such as hormones, analgesic and psychotropic substances, even if they are metabolized or present in very small quantities [7] [8].

Facing such challenge we have to focus on our main objective which is fish abundance and to identify substances and their quantity lethal for species or slowing down their development and proceed by elimination, from natural to anthropogenic contributions.

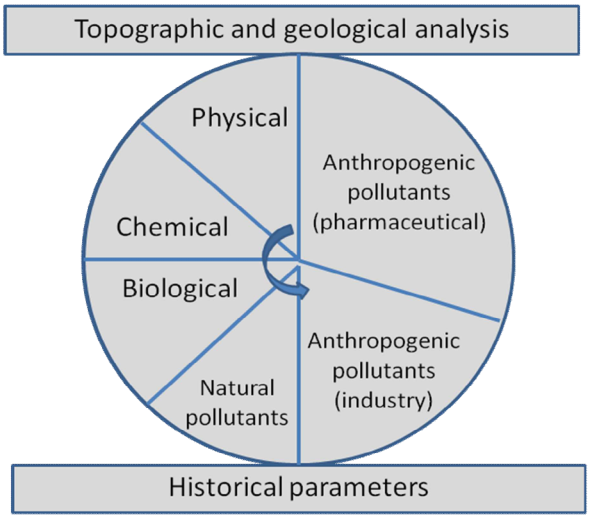

Fig. 2. Proposition for measurement classification.

We have segmented the measurement plan into several categories and recommend starting with a geological and topographic analysis to eliminate a maximum number of parameters.

For example, our 2 ecosystems are located within public parks where, from more than a decade, there was a “green” approach (no more use of artificial fertilizers, pesticides herbicides or fungicides); our investigation for these pollutants should be limited to long life substances buried within sediments, such as atrazine.

Next step is to perform:

- Physical measurements: to evaluate the water renewal rate, the laminar flow, the temperature influence on dissolved oxygen and fauna reproduction,
- Chemical measurements: they are supposed to reflect the local geology; they help to identify lethal components like ammoniac,
- Biotic measurements: we need to evaluate the biomass providing food to fishes and directly linked to the productivity of the site (micro invertebrates), or reducing eutrophisation by production of oxygen via photosynthesis (aquatic plants),
- Natural pollutant evaluation: natural gas having a lethal effect at low concentration limit like methane (2 mg/L), hydrogen sulfide (0.002 mg/L) and cyanobacteria (1µg/L),
- Anthropogenic pollutants from industry processes; each type of industry is producing a set of predictable wastes affecting water [4],
- Anthropogenic pollutants from pharmaceutical industry; these are products usually metabolized at local level; they can affect elements like reproduction or vigilance in front of predators; they can end up with the eradication of species sensitive to these components.

The study can be completed by an historical analysis to identify any assigned cause of change (temperature evolution, bio accumulation of lethal substances, history of growth).

4. MEASUREMENT SPECIFICATION

The traditional metrology approach is to define tolerances for each measurement type and to build a surveillance dashboard with an alert system when limits are reached. The Collège Français de Métrologie has recommended the use of EWMA control charts for this purpose [9].

Unfortunately, ecosystems are also ruled by Darwinian adaptation laws and species can accommodate of very different environments. The recent European approach is to divide areas into river basins with their own sets of specifications mainly based on geology.

For our project we have used the Nisbet and Vernaux study as guidance [10]; they have performed a qualitative inventory of 1200 aquatic locations in France using 16 water quality parameters; this work is quite old but a good starting point to identify acceptable limits for a specific area.

For pollutants acceptable level, the limits are expressed in average lethal concentration (LC_{50}) which is the average value causing 50% death of the population over a specified period. In practice available data are not so rigorous: either we have detailed information on specific species [11], or a collection of partial experimental observation on small populations [3]; concentration limits vary according to species, therefore we can speak about estimates and have to focus on the weakest link of the life cycle. Recently, the LC_{50} concept was discussed as most pollutants are present in a cocktail format.

5. HOMOGENEITY AND SAMPLING

To make sure our measurements are representative, we have to consider 4 components:

- the geographical position of the water samples, often translated into a color on a map,
- the depth of the sample which can give significant differences (thermoclines for temperature, anaerobic zone for dissolved oxygen etc..),
- the time of the year. We have observed a temperature variation is superior to 20 °C over the 4 seasons the level of water may vary accordingly,
- the identification of short term variations for several parameters: only one hour with a dissolved oxygen level below 4 mg/L is able to kill most of the fauna; the reproduction phases depend on the temperature profile (heating degree days) and can result in multiple spawning,

no spawning at all or a shift within the prey-predator sequence.

For the canal we have performed an homogeneity test for dissolved oxygen, a parameter well reflecting changes; the canal was divided into 20 equal segments and series of 5 measurement were taken; an ANOVA test shows that the sampling is homogeneous at 90% confidence level to be compared to reference material [12] requiring a 95% confidence level. Several other physical and chemical parameters were also successfully tested and we were confirmed that the canal is behaving like a large open air aquarium. Further tests were showing that depth has little effect on the results of dissolved oxygen and temperature gradient.

The lake had a different behavior and we were forced to develop another strategy with mass sampling using a GPS driven remote controlled miniature boat to automate the survey.

For biological parameters there is no homogeneity; when the water is clear, it is obvious that our ecosystems are presenting a succession of poaches of life and desert areas.

The French AFNOR national standard for biotic index (to count “taxon” or unit from a standard taxonomy) states that it is not suitable for canals and lakes [13]. So we have to refer to another standard for the measurement of macrophyte to define our sampling plan [14].

These biotic and biologic standards have introduced several concepts to address sampling areas or representative habitat:

- “facies” which is homogeneous flow and granulometry area (mainly for rivers)
- Hydrobiological station : segment where the length is substantially equal to 10 times the width;

There are also recommendation to increase the surface when the number of taxon are below a threshold (5%).

If the AFNOR standard is requesting 8 samples, the trend is to increase this number to 12. For large rivers some protocols were developed with up to 100 samples to cover banks, middle river and sediments. Floating taxon are also taken into account; the sampling operation must take place out of exceptional hydrological events; the fact that micro invertebrates population has a reproduction peak in spring and that many macrophytes have deciduous leave is not taken into consideration.

Sampling within the food chain and bio accumulation

According to the position of species within the food chain, the pollutant concentration can drastically increase and be lethal for the fauna even if the dilution in water can be considered as negligible and in the noise level of most instrumentation. Study of pollution with mercury shows that a pike can concentrate 40 000 times the water level (from 0.1 ppb to 4 ppm) [11]. Therefore, these substances called bioaccumulative, are better quantified by sampling the concentration level in the flesh of fishes rather than dilution level in water

6. GPS BASED SAMPLING

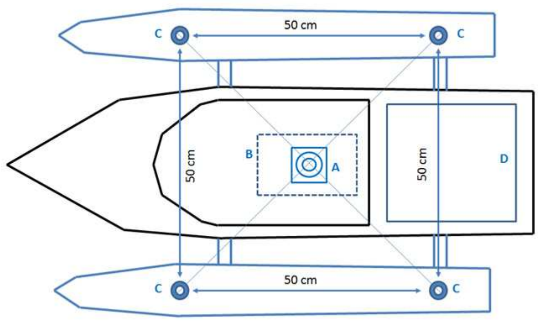

Fig. 2. Catamaran designed for mass sampling; A: GPS receiver; B: submarine camera; C: collimation lasers; D: Data acquisition system.

For the canal, a quick way to evaluate the surface of water is to use Google Planimeter, an accurate method for such a geometric and stable figure; but for a lake, due to bank erosion (sediments deposits, surface rain and galleries created by crawfishes) the geometry is changing every year and the map supporting this application may reflect a very old version of its contours. We have tested a data acquisition system equipped with a GPS antenna and were surprised by accuracy, quickness and cheapness of this solution; not only the accuracy is better than expected (1 meter instead of 15) but the survey of 40 points is taking less than one hour including the GIS (Geographic Information System) data processing. This allows to address the issue of homogeneity using mass sampling. For this reason we have built a GPS based measurement solution for several parameters dependent upon geography such as depth (bathymetry) and macrophyte evaluation (algal coverage).

The portable Vernier data logger we have used is equipped with 4 channels accepting direct reading of 12 water quality transducer and a multitude of other parameters with an electrical output, for a load below a kilogram [15].

The boat was designed for easy transport in a backpack and constructed around a commercial 70 cm RF piloted unit; where we have added 2 dismountable floaters to increase the stability and to handle 4 collimation lasers, limiting the pictures of the lake bottom to a 50cm x 50cm area; the propulsion is electrical and based on 2 small turbines avoiding water perturbation; energy is provided by a 4Ah battery for propulsion and a 2Ah for measurement devices such as the 40 kHz sonar with analog output and other circuitries. As such device is too light to handle a computer, we had to find a simple way to synchronize the picture with the GPS data; this is done by moving the boat every 2 minutes allowing 1 minute stabilization and acquiring the measurement data together with a time stamped picture.

Such process gives a 3 hours autonomy, enough to perform a set of samples within stable conditions; transducers candidates for such measurements require 1 minute stabilization time, which excludes some ORP transducers and ISEs (Ion Selective Electrode) devices.

7. MEASUREMENT METHODS AND EQUIPMENT

As mentioned before we have chosen to use, when possible, electrical equipment.

Here are the pros and cons of this approach:

Advantage:

- Higher resolution and accuracy,
- Most sensors used on site are temperature compensated which is necessary when dealing with water temperature span of 20°C over the year,
- Most equipment are offering 3 to 5 meters cables to measure below the surface,
- Instruments having large data memory and several hours of autonomy,
- USB output are becoming more common for a quick transfer to computer (CSV or text file format),
- GPS antenna input in some cases,
- Miniature and cheap data loggers allow long term surveillance of parameters like temperature or conductivity.

Inconvenient:

- Most transducer electrodes are protected from the direct contact of water via a membrane, a gel or an osmotic mechanism. This slows down the setup time (for example ORP - Oxidation Reduction Potential - transducers may request 30 minutes for stabilization),
- Very fragile probes, subject to contamination by contact with natural oil or sediments; the life expectation is between 6 months to 3 years depending on the nature of water measured; storage must keep the probe humid; a redundancy of equipment for periodic cross check is recommended.
- Many sensors have to be calibrated prior to use in lab conditions (25°C) using reference solutions, one per parameter; more recent equipment allows to use a unique solution to calibrated a multi-parameters head.
- Each manufacturer has his own protocol to program the instrument and perform data acquisition
- Many ion selective electrodes have a non linear response and require a very low an very high concentration calibration solutions with a risk to contaminate the reference material
- Most transducers have no specification for pressure so their use for different depth requires preliminary tests

Colorimetric methods are more robust as there is no direct contact between water and the measurement device. However the reference material has only 2-3 years life expectation.

For biological parameters we are using a microscope with a LCD screen and a camera; this allows to compare the taxon (invertebrates, algae, bacteria etc…) to reference data base libraries. Adding to the microscope an XY table with micrometer vernier facilitates scalimetry.

8. ABIOTIC MEASUREMENTS

After a topography analysis we are able to eliminate a maximum of anthropologic pollutants and to trace the origin of water for geological consistency.

The next step is to measure the volume of water mainly to get an idea of the water renewal rate and identify eutrophisation risks. Other benefits are the surveillance of water level, sediments deposits and erosion.

Our 2 ecosystems are slow moving water reservoirs, which means very small flows to measure; at this point we were able to find suitable locations to measure over 0,3 m^3/s, but we need also to evaluate the laminar flow bringing oxygen and food to plants, macro invertebrates, fish eggs etc… far below our current equipment sensitivity. A modified ultrasonic flow meter is under construction for this purpose.

Temperature is a very important parameter because it varies more than 20°C over the seasons, having an impact on dissolved oxygen, fish reproduction and survival. After destruction of one of our devices by water mussels, we have installed several permanent temperature data loggers within copper containers, a very efficient antifouling metal. With an hourly data acquisition the battery is able to work a couple of years, however, for security reasons we swap these devices every 3 months.

Water conductivity is another important parameter because its fluctuations allow to detect changes in water composition. At the beginning of the 20th century, using a Kohlrausch bridge, geologists were not only able to measure the resistance of one cubic centimeter of water, but also to trace back the origin of this water by combination of individual resistances in sources, wells, rivers etc.. We have designed a simple miniature resistance data logger based on this method to measure conductivity the same way than temperature. The main variation of conductivity for the canal was observed at the end of winter when one meter of ice and snow was suddenly mixed with spring water (the contribution of rain is usually below 5 %).

Turbidity is coming from the presence of unicellular algae, associated to high pH and temperature (canal) and from sediments and surface water (lake). Turbid water reduces macrophytes growth, production of oxygen by photosynthesis and development of vegetal food and support for fish eggs. We have used a portable turbidity meter, as well as a Secchi disk for relative measurements; after several tests we have preferred to use a modified lux meter able to measure the amount of light reaching the macrophytes 2 or 3 meters below the surface. This is more convenient to understand the growth of aquatic plants.

Dissolved Oxygen is a critical parameter and can be lethal below 5 mg/L. The measurement is quite simple as calibration is performed on site using the value of dissolved oxygen in air (20.9 mg/L at sea level). For the canal we have observed a permanent oversaturation of dissolved oxygen due to the wind (always over 10 mg/L). In such situation we can consider this parameter under control without further investigation. For the lake we have found values below 6 mg/L requesting additional parameters measurement such as biological and chemical oxygen demand, identification and count of macrophytes with their photosynthesis specifications, turbidity variations etc…

pH and ORP were found stable over the seasons. For the canal, the 16th century technology, used lead for most hoses;

if the pH moves below 7, the protective calcium coating is eroded and lead starts to mix with water.

For calcium, carbon and azoth cycle measurement we have used colorimetry. The effort to use ammoniac concentration increase to detect the death of fishes was not successful due to low sensitivity of our method.

Natural gas was detected within the canal sediments using pellistor based portable devices; it may explain death of buried fishes during winter. However, the quantification and evolution of these gases was quite a challenge (figures like ppm per cubic meters of sediments). We had to face the issue of sub ppm evaluation of anaerobic and volatile gas with different density. This is still work in progress.

9. BIOTIC MEASUREMENTS

Our first need was to evaluate the amount of natural food available within the ecosystem to support a fish population and to increase reproduction. One of the original concept of biotic index (Tuffery & Verneaux-1967) was very close to our objectives, but later on this indicator moved to a water quality and pollution evaluation [13]. The trend now is also to perform a relative measurement according to an ideal river basin and record the water quality progresses. We have started to perform these measurements using a Surber net on eight samples of 1/20 m^2 each, done separately in eight distinct habitats. As there are potentially 152 taxon to recognize we had to create our own data base with detailed information about critical species such as plecoptera markers of good water quality and asellus aquaticus, marker of bad water quality.

For macrophyte, our first samples shown that we had to deal with a couple of species over the 151 vegetal taxon of the standard; therefore, the decision was taken to picture the bottom of the canal and the lake with our sampling boat to follow the evolution of aquatic plants rather than performing 100 surveys over 50 meters segments.

10. HISTORICAL RECORDS MEASUREMENTS

The 2 ecosystems we have to diagnose have a long record of good performance, up to 4 centuries for the canal and a decade for the lake; therefore it make sense to analyze historical records to find what has changed and when.

Due to the multitude of activities requesting temperature recording such as airports weather stations, heating stations, etc.. it is quite easy to get the climate history of the area (up to 25 years for the canal, 10 years for the lake) and to identify abnormal climatic situations able to explain the variations in fish populations.

Sclerochronology, history of growth printed within the scale growth lines allows to measure the accidents within the fish life. During a spring viremia episode we were able to sample few scales of 10 years old carps dead bodies for this purpose [16].

Toxycology applied to fish flesh, allows also to identified the presence of bio accumulative substances slowing down the species development.

11. CONCLUSION

By a careful analysis we were able to reduce the 1000 potential measurement parameters to a few manageable items.

We have selected few parameters for continuous monitoring over the 4 seasons either because they are critical (dissolved oxygen, temperature, natural gas) or because they are the sentinels announcing changes in the nature of water (conductivity).

To resolve the issue of poor homogeneity of lakes, we have put in place an automated mass sampling solution using and RF controlled boat embarking water quality data acquisition systems and a GPS antenna.

However, the model of our ecosystem is quite poor. Today we are unable to predict, for example, the overall changes in fish productivity after pouring a ton of calcium within water. There are partial answers to this question; research has developed quantified calcium and azoth cycle, temperature profiles to trigger fish spawling, and fish population models [17] but not, to our knowledge, the overall quantified model of an aquatic ecosystem.

Our next step will be to use a closed aquarium to understand several of these natural cycles affecting our cases study; such as development of natural gas and their effect on fauna and flora (canal), participation of macrophytes and sediments to the production and absorption of oxygen (lake).

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