Water pollution in Zirahuen Lake (Michoacan, Mexico): Teaching-learning experience in a social and environmental chemistry approach

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TEACHING NOTES

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SUMMARY OF THE CASE STUDY

This case study is designed for higher education. We propose a time frame of eight sessions. During the first session, students are faced with a “Hook” dynamic, where they are given a situation in which a child from a specific community gets sick. Based on the symptoms, they must research which disease the child has. In the second session they are exposed to a general panorama of how environmental problems can be understood through the complex systems theory. In the third session they are asked to make a basic characterization of the social subsystem, and in the fourth session they must identify and present what are the possible interactions between different actors involved in the socio-environmental problem of Zirahuen Lake. In the fifth session they must carry out a characterization of the physical and chemical system, and study how the use of environmental spheres allows us to contextualize matter and energy flows promote the generation of waste that can then affect the surrounding environment. During the sixth session, the students identify the physicochemical parameters that determine the quality of different types of water. In the seventh session they integrate both characterizations (social and physicochemical) to identify and describe the socio-environmental problem found in Zirahuen Lake, and the importance of undertaking environmental problems as complex systems with defined structures and functions as well as positive and negative feedback loops that may or may not keep them in a state of dynamic equilibrium.

Students must have basic chemistry and social sciences knowledge to participate in this experience. We employ the framework on complexity and interdiscipline proposed by Rolando García et al. (2000).

This case study is presented as a teaching strategy to identify and take on an environmental problem from the paradigm of complex systems, the systemic analysis of environmental spheres and through interdisciplinary approaches.

The complexity paradigm is undertaken from the perspective of Zurlini (2007), who states that interaction between social and ecological systems has evidenced the need to have frames of reference that include these two spheres. The paper also discusses the characteristics of these complex systems: they are non-linear, hierarchical, self-organized, have multiple equilibrium points, they present no “ideal” stable states and they generally present a chaotic behavior, which makes them difficult to predict. Additionally, García (2006) establishes criteria to delimit and study complex systems, including their limits, the elements that compose them and their structure.

We propose using the theoretical framework proposed by Manahan (2012) in order to discuss the biophysical system. Here we must first define the environment, and after understanding this concept we can include five environmental “compartments” through which matter and energy can flow. The student can then understand that, in order to determine the impact of pollutants, it is necessary to study their transport and where in the environment they end up.

Finally, we worked with the integration of knowledge through a systemic analysis. Starting from the delimitation of the systems and subsystems that make up our study site, the functions of each

subsystem were defined as well as the interactions between the different subsystems. The pedagogic sequence led students through a gradual experience of understanding how complex systems are defined, answer questions about how they work, how knowledge is integrated, how environmental problems are approached, etc.00) to approach environmental problems.

INTRODUCTION

Hook: *A group of women arrive, looking desperate, from the Copandaro community. One of them enters the Morelia Children's Hospital screaming and holding a small three-year-old boy, weak and motionless in his mother's arms, with sunken eyes and dry mouth. He looks like a rag doll.*

The other women make way for her and she tearfully pleads with the ER nurse: "Please, do something, my boy is not responding!" Immediately she gets transferred to the first available exam room and the attending physician asks her what is wrong. She tells the doctor she has travelled from a remote community near Zirahuen Lake and that her son has had diarrhea for several days, loss of appetite and severe stomach pain. The doctor carefully examines the child and notices a slight yellowish hue on his eyes. After his exam, the doctor says: "Hmm, this is the fourth patient that has been brought from Copandaro with the same symptoms", to which the desperate mother replies: "Please doctor, tell me what is wrong with my boy!"

Copandaro is a small community located on the shore of Zirahuen Lake, in the state of Michoacan, Mexico. This community has about 400 inhabitants (INEGI, 2010) and water for local consumption is extracted directly from the lake. Several other communities surround the lake, including Agua Verde and Zirahuen. The latter is more urbanized and has a population of 15,000 people (INEGI, 2010).

The Zirahuen Lake watershed is an important source of water for agriculture and human consumption in nearby populations. It is an endorheic watershed and is contained mainly within the Salvador Escalante municipality, in the North-central part of the state of Michoacan. The main affluent is the Silencio River, also known as Arroyo La Palma, which originates in the eastern edge of the watershed and leads into the west part of the lake.

Vegetation in this region is composed of pine, oyamel, oak and cloud forests, as well as grasslands and aquatic plants. However, the last decades have seen significant hydric erosion and lake desiccation due to deforestation, over-grazing, inadequate agricultural practices in hillsides, overexploitation of aquifers and loss of water from tectonic movements (Bravo, 2009).

The main economic activities in the region are: Agriculture, intensive farming, forestry, copper and crafts industries, fishing and tourism due to its beautiful scenery (traditional and ecotourism; Paniagua et. al., 2010). The artisanal copper industry, tourism and the fast-growing avocado industry are particularly significant.

The town of Santa Clara del Cobre, located along the Silencio River, specializes in the production of diverse copper crafts. Several different supplies are required for the elaboration of these crafts, such as water, firewood and chemicals. A number of solid, liquid and airborne waste and by-products are generated during the production process. Unfortunately, waste management is inadequate, and most substances are dumped into the river. Together with insufficient drainage in the region, this has created a contamination problem: Limnological studies have found concentrations of copper in Zirahuen Lake (Ayala Ramírez et. al., 2010).

The shores of Zirahuen Lake are described as a secondary touristic destination, that is, most people visit the area because it is close to more important destinations such as Patzcuaro and Morelia.

Within the watershed, tourism represents a major economic activity for the towns of Santa Clara del Cobre and Zirahuen, mainly through the sale of crafts, food and some recreational activities in and around the lake (Paniagua et. al., 2010). However, the infrastructure for these services is precarious, and most of the waste they generate is poured into the lake along with the town's sewage.

Historically, the main economic activity in this region has been agriculture. Avocado cultivation was adopted towards the end of the 1990s, with which the production value of this sector went from around 30% to over 90% employing only a fourth of the agricultural land. During the same period, maize cultivation generated just under 1% of production value while using more than quarter of the total cultivated area (Paniagua et. al., 2010). Avocado cultivation has since expanded throughout the region and is one of the most profitable crops as one of Mexico's main exports.

Proliferation of avocado croplands has resulted in the loss of approximately 30% of the region's forest cover (Barsimantov & Navia, 2012) and has also caused social conflict. It is one of the main drivers of land privatization, as previously community-owned lands pass into private ownership (such transactions were prohibited until a constitutional reform that occurred in 1992). Faced with economic hardships and low yields from hillside agriculture, owners of lands adjacent to Zirahuen Lake have sold them to private avocado producers, which has generated division and conflicts amongst the region's inhabitants. Additionally, high water consumption for avocado crops has also made local people angry at what they perceived as excessive water pumping.

In 2013, this situation led inhabitants from Zirahuen, Copandaro and other lake towns to approach local and state authorities, as well as the academic sector, to communicate their concerns regarding the lake's change of color and excessive algal blooms. Copandaro inhabitants were particularly concerned because this is the only population that obtains water for human consumption directly from the lake. Michoacan's government responded by calling on the *Universidad Michoacana de San Nicolás de Hidalgo* to carry out a diagnostic on the condition of the lake, and by creating the Zirahuen Lake Watershed Commission through the National Water Commission (CONAGUA).

The results of the diagnosis performed by the state university showed that the lake's change in color and algae proliferation was due to eutrophication and an accelerated deterioration that could be reversed with adequate watershed management. They also established that the lake's water is not fit for human consumption and can be potentially toxic during certain months (Gómez Tagle, 2016). The newly created Zirahuen Lake Watershed Commission met twice between 2014 and 2016.

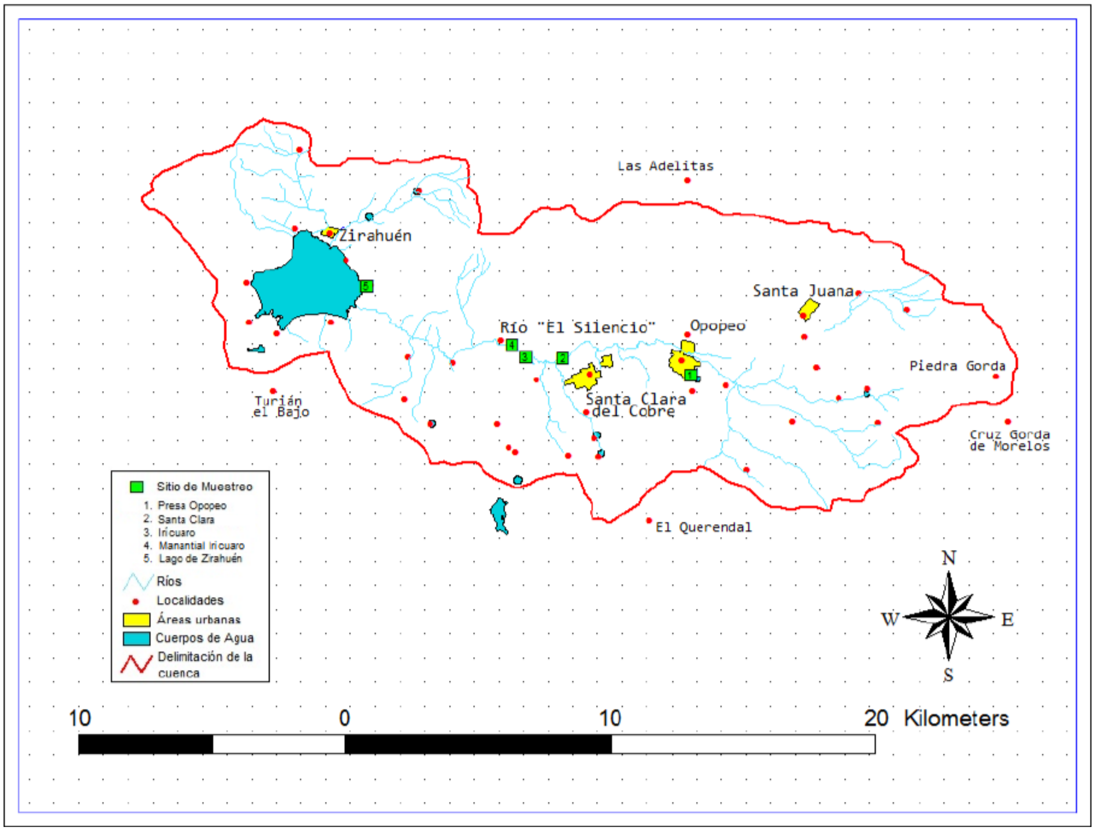

Figure 1. Map of the Zirahuen Lake watershed. Source: González Villareal & Flores-Díaz, 2014.

SESSION 1 (3 hours): WARM UP

This activity is designed to make the students interested in the case study and provide a general context about its location. Likewise, this session will allow students to identify the main sources of information provided by their institution, as well as the main Internet search engines. This session is intended to last three hours.

Lesson plan: This lesson is designed to introduce and interest the students in the proposed case study. It starts by reading the "hook" and the introduction to the study. After these readings the students are asked to split into teams and search online for the symptoms described in the hook and to try to figure out what disease corresponds to these symptoms. Afterwards, the teams share their results and write them on the board. The instructor then talks in more depth about Hepatitis A and its relationship to water contamination, and hands each team a map where they must locate key sites within the watershed of Zirahuen Lake in order to briefly contextualize the study site. After locating the community mentioned in the Introduction (Copandaro), the students will discuss where the outbreak of Hepatitis A may have originated. The instructor will give a brief explanations of previous studies related to water quality in Zirahuen Lake. During the last hour of this session there will be a visit to the campus library where the instructor will show the students all available resources to find information, as well as the main internet search engines.

As homework the students will perform a bibliographic and hemerographic search for studies related to Zirahuen Lake using key phrases such as "Zirahuen Lake pollution/contamination", "Zirahuen village", "economic activities in Zirahuen".

Materials:

- Projector
- Computer with internet access
- Printed maps of the study site
- A paper exposing the link between hepatitis and water pollution

Activities:

1. The students read the "hook" story (10 minutes).
2. Students form teams of four or five people and do a quick online search for diseases with the described symptoms. They record their findings in their notebooks (20 minutes).
3. A representative from each team mentions their findings and writes down on the board all possible diseases they identified (15 minutes).
4. The instructor briefly talks about the relationship between water polluted with *Escherichia coli* and hepatitis A in Mexico (PPT presentation) and comment on whether the teams found the correct diagnostic. Discuss the possible origin of the outbreak described in the introduction (30 minutes).
5. The instructor provides teams with a map (Figure 1) of the Zirahuen watershed and helps them locate the communities of Copandaro, Zirahuen, Agua Verde, Opopeo, Casas Blancas

and Santa Clara del Cobre. The Zirahuen Lake and the Silencio River must also be located (20 minutes).

6. After locating these places and listening to the possible causes of hepatitis A, the students must discuss what could be the problem faced by the village of Copandaro (15 minutes).
7. Students read the summary of the case study.
8. Explanation of library resources (1 hour).

Homework:

Read the following papers and answer these questions: Which characteristics define a complex system? What is an environmental problem?

- García, R. (2000). “Conceptos básicos para el estudio de sistemas”. En E. Leff (Ed.), *Los problemas del conocimiento y la perspectiva ambiental del desarrollo* (pp. 381–409). México: Siglo XXI Editores.

- Zurlini, G., Petrosillo, I., & Cataldi, M. (2008). “Socio-ecological System”. *Systems Ecology*, 4, 3264–3269.

Box 1. Lecture notes

Hepatitis A epidemiology in Mexico

The viruses of hepatitis A (VHA) and B (VHB) have been documented in Mexico since the 70th decade of the 20th century. VHA infection has a high incidence on children. In Mexico, the main risk factors for contagion on children under nine years of age include:

a) Residing in southern states
b) Living in rural communities
c) Belonging to low-income households
d) Having limited access to sanitary systems (drinking water and drainage)

In this country, hepatitis A infections are acquired through water or food polluted with fecal matter containing the virus. Like many developing countries, this infection is generally associated with deficient hygienic conditions.

As socio-economic class increases, cases of hepatitis A decrease, which shows that poverty and the associated lack of hygienic conditions is a risk factor for this infection.

Risk groups

The VHA virus is highly infectious and children are particularly vulnerable to contract the disease, while the adult population is more likely to develop further complications one infected. In Mexico, there is considerable incidence of this infection particularly in rural and/or indigenous populations.

Symptoms

According to the World Health Organization, the main symptoms of hepatitis A are:

- Fever
- Ache
- Loss of appetite
- Diarrhea
- Nausea
- Abdominal pain
- Dark urine color
- Jaundice (yellowish hue in skin and eyes)

Sources

WHO (2016). Hepatitis A. Retrieved from http://www.who.int/mediacentre/factsheets/fs328/es/

Panduro, A., Meléndez, G. E., Fierro, N. A., Madrigal, B. R., Zepeda-carrillo, E. A., Sc, M., & Román, S. (2011). Epidemiología de las hepatitis virales en México, *53*(2), 37–45.

Valdespino, J. L., Ruiz-gómez, J., Olaiz-fernández, G., Arias-toledo, E., Biot, I., Conde-gonzález, C. J., … C, D. (2007). Seroepidemiología de la hepatitis A en México. Sensor de inequidad social e indicador de políticas de vacunación. *Salud Pública de México*, *49*.

MODULE 1. ENVIRONMENTAL PROBLEMS AS COMPLEX SYSTEMS (1 session)

General learning goal (S-ESLG):
To identify the basic characteristic of a complex system and discuss why environmental problems can be considered complex systems.

Specific goals:
- Identify the limits, elements and structure of the case study: Contamination in Zirahuen Lake.
- Identify the characteristics of the case study's basic sub-systems: Physicochemical and social.

Skills (SLO):
- Students will be able to identify, characterize and classify the elements that make up the study system.
- Students will be able to identify the agents, both social and physicochemical, that relate to the contamination of Zirahuen Lake.

SESSION 2 (2 HOURS): Systematic vision of the case study

Lesson plan: The goal of this session is to establish a common conceptual framework about what is a complex system, and discuss why an environmental problem should be treated as a complex system. After reading García (2000) and Zurlini et al. (2008), the students (aided by the professor) will generate a collective definition of "environmental problem" and establish what the environmental problem of Zirahuen Lake is. In teams of four or five, the students will delimit their study system (limits, elements and structures according to García, 2000) and try to identify interactions between two subsystems: social and biophysical. This activity must be guided by the key question: Which biophysical, chemical and socio-economic factors are causing the contamination of Zirahuen Lake? The information given in the Introduction can be used for this activity.

Materials:

- Projector
- PPT presentation about environmental problems as complex systems
- Sheets of paper
- A copy of the introduction to the case study for each team

Activities:

1. As a group, the students will share their answers to the homework questions. The teacher will annotate relevant answers on the board (20 minutes).
2. The instructor offers a summary of the main ideas included in the readings about what is a complex system, what are their components and characteristics (see Box 2) (20 minutes).

3. Considering the student's homework and the instructor's explanation, the class will propose a definition of "environmental problem" and establish what is the environmental problem in Zirahuen (20 minutes).
4. Students will split into teams and define the study system as a "complex system". To do this they must define the limits and elements (according to García, 2000) of the study system. It must be emphasized that they will find at least two subsystems: social and biophysical. To clarify this process, a guiding question may be established, such as: Which biophysical, chemical and socio-economic factors are causing the contamination of Zirahuen Lake? It may also be helpful for students to read the Introduction to this case study again (1 hour).
5. Each team will hand out a one-page explanation where they point out the limits of the study system, its components (elements) and structure (relationships between elements).

Homework:

Perform a bibliographic and hemerographic search for studies related to Zirahuen Lake using key phrases such as "Zirahuen Lake pollution/contamination", "Zirahuen village", "economic activities in Zirahuen".

Box 2. Lecture notes

ENVIRONMENTAL PROBLEMS AS COMPLEX SYSTEMS

Both García (2000) and Zurlini et al. (2007) refer to natural ecosystems as systems that will, inevitably, interact with social systems, especially through human communities' exploitation of natural resources to satisfy their production necessities. Therefore, the actions of social systems determine the function and structure of natural systems (Zurlini et al., 2007), which frequently constitutes a problem as this endangers ecosystems and the benefits they provide to humans.

García (2000) and Zurlini et al. (2007) provide a model to study the "problematic" interactions between natural ecosystems and social systems. While García talks about a "Complex Global System" and Zurlini et al. describe the study of "Socio-ecological Systems", we will refer to them simply as "Complex Systems".

Generally speaking, this complex system is built out of two large and mutually-influencing systems: ecological and social. On one hand, you can talk about a natural system that, among other things, provides renewable and non-renewable resources that are necessary to sustain the productive activities of human societies. On the other hand, a social system characterized by socio-economic and cultural processes constitutes the main driver of change for natural systems.

Main characteristics of a complex system

For Zurlini et al., Socio-ecological Systems are:

a) Non-linear: the system cannot be understood simply by isolating its components
b) Hierarchical: its elements are related through a hierarchy
c) Internal causality: they are self-organized systems
d) Dynamic stability: there are no single points of system equilibrium
e) Multiple stationary states: there is no "ideal" state of system stability
f) Catastrophic behavior: they may suffer unpredictable, unforeseen or discontinuous changes
g) Chaotic behavior: it is difficult to predict future states.

García describes complex systems as "a representation of a *snapshot* of reality, conceptualized as an *organized totality* (hence a system), where elements are not separable and, therefore, cannot be studied separately" (García, 2000: 21). Amongst the characteristics of complex systems mentioned by this author we have:

a) Heterogeneity of their components: the nature of each element is different, in this case: biophysical elements and social elements
b) Interdefinability if their elements: mutual definition between components
c) Non-linearity: the relationships between elements are complex and dialectic
d) Hierarchy: the total system is organized hierarchically
e) Non-disciplinary: the problems presented by these systems cannot be solved by one single discipline of knowledge.

The study of complex systems

García (2006) gave this name to the set of elements that describe interaction processes between natural ecosystems and social systems. These include biophysical, social, economic and associated political processes.

This model establishes some basic criteria to delimit this type of system in such a way that allows for their study, which are:

Limits: This includes geographic and spatial limits, as well as the delimitations of other elements, for example: specific economic activities, cultural groups, types of land ownership, etc. This step helps us identify clearly what

Elements: This concerns the definition of the units that make up our study system, as well as the types of relationships between them. In this case study we propose an analysis based on the types of economic and social activities found in the watershed: Agriculture (industrialized and for self-consumption), tourism, local crafts and the regulation of public functions. In the same way we identify the relationships between these elements, especially in terms of demands, waste generation and responsibility over the contamination of the lake (see Figure 2).

Structure: As we have seen, interactions with other elements are an important part of what characterizes each element of the complex global system. García points towards the need to identify how these interactions take place, for which it is necessary to identify their "historicity". This shows us the structuring process of the system. In this part of the exercise, we do not intend for the students to research at depth the relationships between economic activities in the region. It will be sufficient for them to point out their importance in the region's economic development.

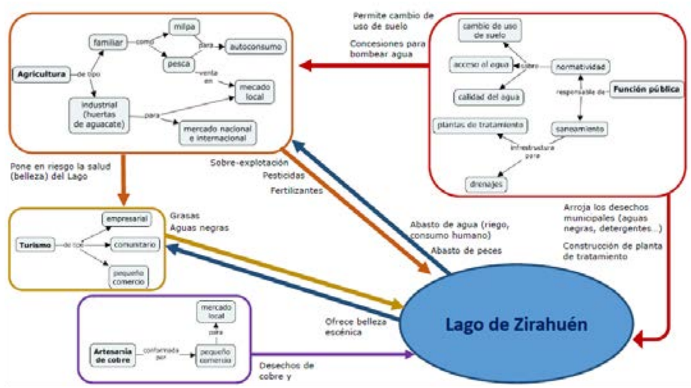

Figure 2. Example of the construction of a complex system for the "Contamination Problem of Zirahuen Lake". Created by the authors.

Sources:

García, R. (2000a). Conceptos básicos para el estudio de sistemas. In E. Leff (Ed.), *Los problemas del conocimiento y la perspectiva ambiental del desarrollo* (pp. 381–409). México: Siglo XXI Editores.

García, R. (2000b). El conocimiento en construcción. De las formulaciones de Jean Piaget a la teoría de los sistemas complejos. España: Gedisa.

García, R. (2006). *Sistemas complejos*. España: Gedisa.

Zurlini, G., Petrosillo, I., & Cataldi, M. (2008). Socioecological System. *Systems Ecology*, *4*, 3264–3269. Retrieved from http://www.elsevier.com/locate/permissionusematerial.

MODULE 2. BASIC CHARACTERIZATION OF THE SOCIAL SUB-SYSTEM (2 sessions)

General learning goal (S-ESLG):

Identify and classify the economic activities and interests of the main actors involved in the contamination problem of Zirahuen Lake.

Specific goals (learning objectives):

- Identify and classify the main economic activities developed around the study site and their relationship with the waste generated that contaminates Zirahuen Lake.
- Characterize the social actors involved in the case study according to their activities and economic interests.
- Identify the interactions between social actors and the physicochemical environment.

Skills (SLO):

- Students will be able to identify and illustrate the relationship between the economic activities developed around the study site and the generation of wastes that pollute the lake.

SESSION 3 (2 HOURS). Characterization of the socio-economic activities developed around the study site.

Lesson plan: The objective of this lesson is for the students to identify and classify the main economic activities that are carried out around the study site. This exercise will allow the student to find relationships between economic activities and the generation of waste that contaminates the Zirahuen Lake. The exercise will be carried out in teams and will require scientific and journalistic information about the study site, as well as the #1 work sheet. The lesson will be divided into two stages: first, each team will identify, classify and characterize the main social actors involved in the case study; second, the teams will share their results and attempt to come up with one consensual classification of the social actors.

Materials:

- Information (scientific and journalistic papers) gathered as homework
- One copy of the Introduction of this case study
- One copy of the #1 work sheet for each team.

Activities:

1. Students will split into the same teams that were previously allocated and use the information they found as homework to characterize the social actors involved in the study system (1 hour). This information must be organized in the following way (see student handout):
   a) Category: They must determine whether it is a State-owned public institution (for example, CONAGUA, the local government, the state's government, etc.), a private

institution (avocado commercialization companies) or a working class (farmers, craftsmen or other workers).

b) Main economic activity: Here they will identify if this is a primary, secondary or tertiary economic activity, as well as its intensity and scale.
c) Natural resources required for their economic activity: Water, soil, firewood, minerals, etc.
d) Environmental impact (waste) of their economic activity: Agrochemicals, fertilizers, soil degradation, deforestation, etc.
e) Power hierarchy for decision-making (high, medium or low).

2. The teams share their results with the class and try to establish a consensual characterization of all the actors (1 hour). We suggest:
   a) Small-scale growers of maize or avocado
   b) Copper craftsmen
   c) Avocado industry
   d) Local touristic sector (food sales, boat rides)
   e) National Water Commission (CONAGUA)
   f) Municipal government
   g) Population in general

   Note: It is unlikely that the "population in general" will be identified as an actor, since they are not immediately related to an economic activity. If this happens, it is important to include this actor and describe it as mentioned above. This actor is particularly important because they produce black and greywater from their domestic activities, and these are discharged into Zirahuen Lake and its tributaries.

Box 3. Lecture notes

Stakeholder analysis

This technique for mapping key actors in a system is a widely used strategy, also known as social mapping or sociograms. One of its main objectives is to elaborate conceptual schemes that help us to "represent the social reality in which we are immersed, understand it as fully as possible […] to know its actions and their reasons and perspectives for the immediate future" (Tapella, 2007: 2).

These schemes are centered on the relationships between subjects involved in our research problem, which allows us to recognize:

- The social relationships between involved actors
- Densities and discontinuities in these relationships
- Roles and decision-making power of the actors involved with regards to the problem being studied
- The actors'necessities and expectations
- Conflicts of interest between actors.

For this case study:

- Identify the actors involved from the economic activities they carry out in the region.
- Identify the relationship between economic activity, demand for natural resources and waste generation.
- Identify the "structure" of the complex system under study (see Box 2).
- Evaluate the viability of specific solutions.

For this session, the instructor can draw on the following papers:

Olander, S. (2007). Stakeholder impact analysis in construction project management, (March), 277–287. https://doi.org/10.1080/01446190600879125

Tapella, E. (2007). *El mapeo de Actores Claves. Documento de trabajo del proyecto "Efectos de la biodiversidad funcional sobre procesos ecosistémicos, servicios ecosistémicos y sustentabilidad en las Américas: un abordaje interdisciplinario". Universidad Nacional de Córdoba,*. Córdoba.

SESSION 4 (2 HOURS). Interactions between social actors in the study site

Lesson plan: Using a matrix (see the student handout), students will identify the interactions between social actors, distinguishing what each actor can offer to the rest and what they receive from others. With this matrix the student will be able to identify the density of the relationships between actors (the greater the number of interdependent relationships, the greater the density), as well as the points where conflict could arise between actors and the obstacles that may complicate establishing a solution to the environmental problem. At the end of this session, the students will be given basic advice on constructing conceptual maps: the final activity will be to create a map explaining the socio-environmental problem in Zirahuen Lake.

Materials:

- Student manual
- Computer with Internet access

Activities:

1. After splitting into the same teams, students will produce an interaction matrix where they will describe the type of relationship between pairs of identified actors in each intersection (45 minutes). They must distinguish between what the actor provides (positive or negative resource) and what they receive from the rest of the actors. What each actor provides will be written in the direction of the columns (vertical) and what they receive in the direction of the lines (horizontal). For example:

Actors - Receive

Actors - Provide

Interactions	**Actor 1** **Small-scale farmers**	**Actor 2** **Copper craftsmen**
Actor 1 **Small-scale farmers**		Small-scale farmers have no direct relationship with craftsmen
Actor 2 **Copper craftsmen**	Waste from the copper industry travel along the Silencio River and reach Zirahuen Lake. Indirectly this waste can reach crops through irrigation	

2. Teams share the results of their interaction matrix (30 minutes), emphasizing the relationships that can lead to conflict between actors and how this could complicate solving the environmental problem.
3. Teams write down some conclusions about the previous discussion (15 minutes).

4. The instructor explains that, using all the information generated so far, each team must now construct a conceptual map explaining "The socio-environmental problem of Zirahuen Lake" (30 minutes). To create this map, students should consider the following instructions:
   a) Represent two subsystems: **social** (characterization of the actor's economic activities and the waste these generate) and **physicochemical** (characterization of the pollutants present in Zirahuen Lake, chemical reactions and transport pathways).
   b) Write a maximum of three words per box.
   c) All boxes must be linked using short phrases.
   d) Write a 1-page explanation of your map (be aware that the map should be self-explanatory).

   We suggest that students use Cmap Cloud (https://cmapcloud.ihmc.us/) to elaborate their map.

MODULE 3. CHARACTERIZATION OF THE BIOPHYSICAL SYSTEM (3 SESSIONS)

General learning goal (S-ESLG):

Students will identify the interactions between the five environmental spheres where environmental problems occur. From a systemic perspective, they will work on identifying, stating and understanding and environmental problem, will indicate the physicochemical components that make up the Zirahuen Lake system and will delimit the different subsystems implicated in Zirahuen's environmental problem.

Specific goals (learning objectives):

- Students will analyze the environment as a system composed of five environmental spheres.
- They will discuss how matter and energy flows between different environmental spheres can help characterize a system and define its structure and behavior.
- Students will reflect about the importance of understanding the time horizon or time scale where the problem is analyzed and where it takes place. They will discuss how these temporal considerations affect the management of a dynamic system.
- Students will identify the subsystems that make up the environmental problem in Zirahuen.
- They will identify the main flows of energy and matter between environmental spheres.

SESSION 5 (2 HOURS). Characterization of environmental spheres

Lesson plan: The goal of this lesson is for students to learn about the five environmental spheres approach (atmosphere, hydrosphere, anthroposphere, geosphere and biosphere) and how energy and matter flow between them. This way of approaching environmental problems is based on systems analysis and it evidences the complexity and plurality of time horizons involved in the water contamination problem outlined in this case study.

Students will read Chapter 1 of the Introduction to Environmental Chemistry book by Stanley Manahan (2011) and discuss how the definition of environmental chemistry contributes to understanding the complexity of analyzing a multi-dimensional system, its structure, function and the possibilities for intervention to mitigate the potential effects of an environmental problem.

The definition of environmental chemistry is proposed as the study of the sources, reactions, transport, effects and destination of chemical entities in water, soil, air and living beings. The class can discuss the differences between this and "green chemistry", and students learn the importance of geo-chemical cycles.

They will review and discuss concepts such as contamination, chemical destination and transport of pollutants.

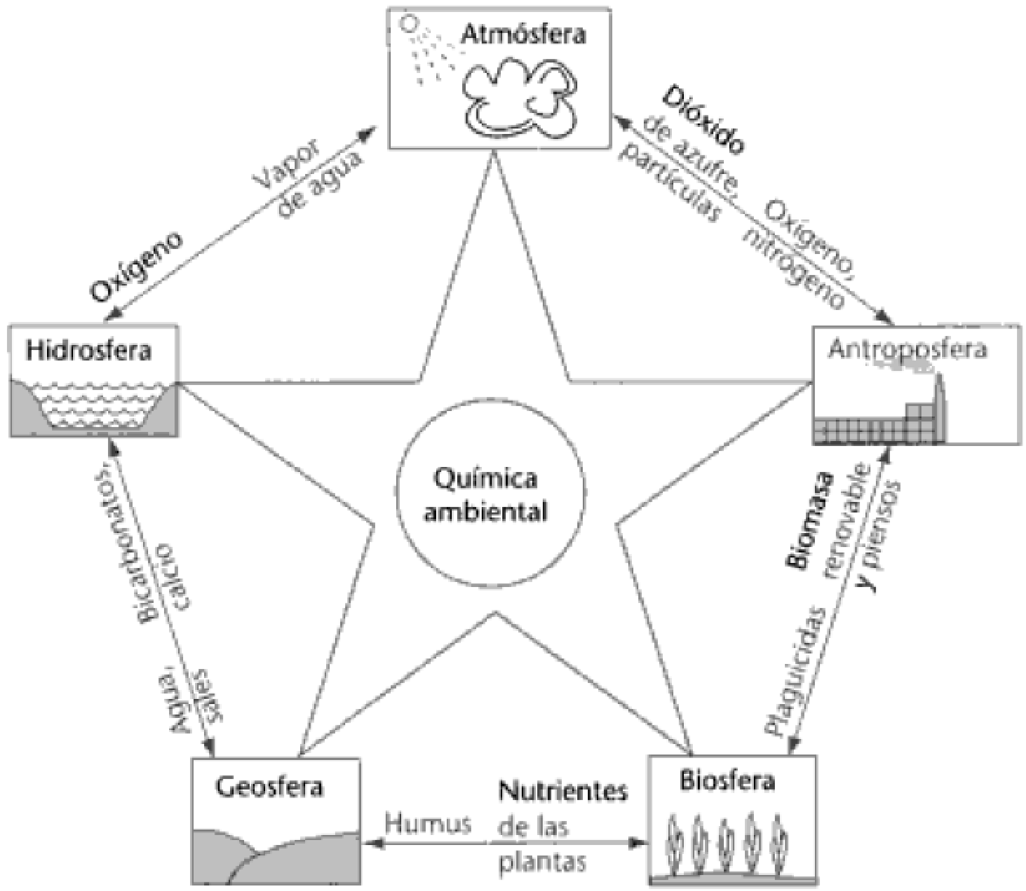

Figure 3. The five environmental spheres and their exchange of energy and matter.

Materials:

- Chapter 1 of Environmental chemistry: the sustainable chemical science. 2011. Stanley E. Manahan. Introducción a la Química ambiental, Editorial Reverté, UNAM. 1-29. Mexico, DF. Universidad Nacional Autónoma de México.
- Diagram of the environmental spheres, adapted from Manahan, 2011.
- Computer.

Activities:

1. In teams of three, students will carry out the "balancing tubes" activity to understand that the response of the system will depend on where we are observing it. If we look at the base of the system it will be difficult to understand how it works, which factors give it balance and which ones modify its structure. If we look above the system, we will lose sight of what the system is, what are its elements and how they interact to keep it balanced. Finally, if we look at the top of the system, we will have a better perspective and will understand how it moves, what its elements are, how they react to movement or some external factor, which

movements are soft enough go the system to bear without losing its structure and function, and which are strong enough to take it to a new point of equilibrium.

Homework:

1. Read Chapter 1 of the Introduction to Environmental Chemistry book by Stanley E. Manahan.
2. Answer the following questions:
    a) What role does environmental chemistry play in analyzing environmental problems? Inadequate production and use of chemical products have caused environmental damages in recent years. Different areas of knowledge must attempt to understand environmental problems and propose viable solutions that consider society, the environment and the economy. Environmental chemistry contributes to understand, identify, explain, prevent and mitigate problems between humans and the environment. Green chemistry aims to diminish the negative effects of the practice of chemical science and engineering. It minimizes risks and the use of non-renewable resources.
    b) What are the environmental spheres?
    c) What are the characteristics of the environmental spheres?
    d) What is environmental chemistry?
    e) Explain what the different environmental spheres exchange in terms of matter and energy, and how you think this interaction contributes to how we approach environmental problems.

SESSION 6 (2 HOURS). Physical and chemical parameters of water quality

Lesson plan: Students will split into groups of three and discuss how the properties of water affect the structure and behavior of this liquid in the different media where it is found in nature. They will analyze what it means for water to behave the way it does with regards to its intensive and extensive properties: density, boiling point, freezing point, specific heat, evaporation heat, solvent characteristics, etc.

Students will relate water's physicochemical properties to the hydric cycle, the mechanisms through which water is used and distributed as well as the proportion of different types of water found on planet Earth. Finally there will be an explanation on the difficulties associated to solving conflicts that arise from the use and distribution of water, as well as the possible types of contaminants that may be found in different types of water.

Box. 4 Lecture notes

Water contaminants

a) Distribution of water
b) Uses
c) What is a contaminant?
d) What are potential contaminants?
e) What are the typical concentrations in municipal residual waters?
f) Basic measurable parameters (depending on the type of water it is necessary to analyse certain parameters, not all)
g) Examples

Which are the sources that can contaminate water bodies?

Municipal, industrial and agricultural waste

How do we know when water is contaminated?

There is no way of knowing just by looking at it. The typical composition of residual water is: Water (90%) and solids (10%). Within these solids, we find 70% organic compounds (proteins, carbohydrates, fats) and 30% inorganic (sands, salts and minerals).

Potential contaminants:

When does a substance become a contaminant?

Main contaminants of water:

- **Heat.** It affects the properties of water and can generate bacterial growth, some of which can be pathogens and cause problems. The parameter we can measure is temperature. Heat has an impact on density, viscosity and oxygen availability. Water temperature depends on a number of factors such as altitude, weather, topography and depth. Residual waters are usually between 23-25°C.
- **Alkalinity/acidity.** This property allows water to neutralize some substances. The measurable parameter is pH, which gives us the degree of alkalinity or acidity. The range of pH that can sustain life is between 6.5 and 8.5. The pH affects biological processes and vital structures, intervenes in the motility of heavy metals and solubility of other substances. The conditions around the sampled site must be analyzed, including land use and any industrial processes, to determine the type of analysis. It is necessary to consider a systemic approach.
- **Organic matter.** Mainly from municipal waste. Organic matter is a normal part of water ecosystems: bacteria use it and transform it to obtain energy. It is measured through COD and BOD. The official Mexican standard (NOM) plans to change parameters in favor of industrial companies.

Materials:

- **Solids.** They affect light penetration in the water column, changing water color and reducing the amount of available radiation. It is necessary to consider the surrounding population and the journey the water takes to reach a body of water, as this greatly affects water quality.
- **Fats and oil.** They interfere with gas exchange between water and the atmosphere, not allowing the free movement of oxygen into the water or CO_2 from water to the atmosphere. They also affect light penetration.
- **Detergents.** These substances are good for cleaning because they are emulsifiers and break water's surface tension. In the US, around 450 million tons of detergent are consumed each year.
- **Nitrogen/phosphorus.** These nutrients cause trouble when they are present in excessive amounts, producing eutrophication (dense growth of algae). This in turn reduces light penetration, creates an excess of organic matter and of the bacteria that use it, which eliminates oxygen creating anoxic conditions that kill fish and other animals. Toxins produced by algae can be lethal, and can have harmful effects on brain and liver in local inhabitants. Eutrophication also changes the smell and taste of water. In the Cuitzamala system they have serious problems with algae.
- **Heavy metals.** Cadmium, lead and mercury can affect organisms depending on their concentration. Cd, for example, can irreversibly damage the metabolism of calcium, and if inhaled can lead to chronic lung diseases. The case of Minamata, Japan (1956) can be mentioned here.
- **Persistent organic pollutants (POPs).** They can remain in nature for long periods of time, even indefinitely. They include insecticides, fungicides, herbicides, dioxins and furans.
- **Emergent contaminants.** These are non-regulated contaminants, that may be candidates for future regulation depending on current research about their health and environmental impacts.
- **Microorganisms.** These can become a problem when found in excessive numbers or when they have an adverse effect. Some bacteria are used as indicators of water quality, such as *Shigella* and *E. coli*.

Food for thought: What is happening in the water system we are analyzing? Chemistry gives us tools to understand problems related to water in different presentations.

Final question: It is important to manage waste, but is it more important to reduce our consumption of resources and thus reduce the amount of waste that ends up in all different systems (water, soil and air)?

- Chapter 2 of the Introduction to Environmental Chemistry book by Stanley E. Manahan: Chemistry of the Hydrosphere
- A flip chart so that teams can add their contribution to the group project
- Markers
- Tape

Activities:

- Students will form teams of three and each team will choose one of the following aspects to determine water quality in Zirahuen Lake: design of the sample points to take water samples in the lake; the necessary materials to take the water samples; techniques for taking water samples in the different sample sites; conditions for storage and transport of the water samples; techniques for testing water quality and determining physical and chemical parameters of water, both in the field and in a lab; elaborating the format that students will use to take field notes on water samples to properly document the process.

- Teams will research what they must prepare for their chosen sampling activity and hand out a report outlining the complete methodology using information from all participating teams. This report will be discussed in class and a decision will me made regarding the number of samples that will be taken and the key sampling sites on the lake.

Homework: All students must read Chapter 2, Chemistry of the Hydrosphere. They will then answer the following questions as a group:

a) If 100Kg of cane sugar ($C_{12}H_{22}O_{11}$) are accidentally dumped into the Zirahuen Lake, which is saturated with oxygen at 25°C, how many liters of lake water will be contaminated to the point of eliminating all dissolved oxygen through biodegradation?
b) How does the thermal stratification of a body of water affect its chemistry?
c) Make a diagram showing the relationships between aquatic life and chemistry, including the following: autotrophic organisms, producers, heterotrophic organisms, decomposers, eutrophication, dissolved oxygen and biochemical demand for oxygen.

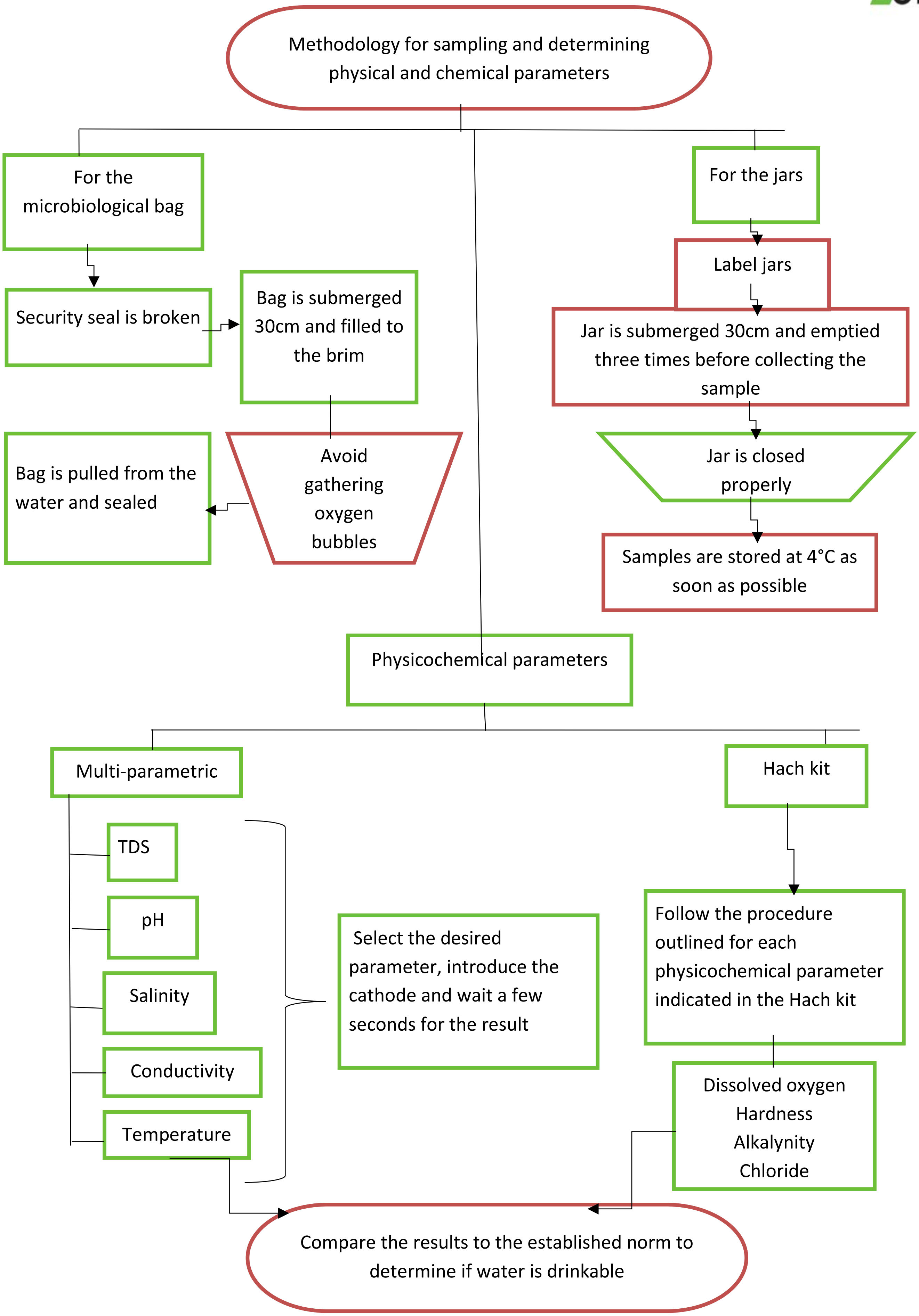

Figure 4. Flow diagram outlining the methods for taking water samples.

SESSION 7 (2 HOURS). The usefulness of data bases for water quality analyses in Zirahuen

Lesson plan: Students will analyze the physicochemical and water quality parameters obtained in the field, to determine which of the samples meets the standards established in the official Mexican norms. They will compare results found in the different types of water they collected to study the range of each parameter and the reasons for this behavior.

Materials:

- Data base with results of the analyzed water samples
- Computer
- Statistical analysis software

Table 1. Data base showing the results of the microbiological analysis and physicochemical parameters obtained in water samples from Zirahuen Lake.

#control	PROCEDENCIA	F.MUESTREO	F.ANALISIS	HORA	COLOR	OLOR	T.AMB oC	T.AGUA o C	pH campo
LMAU 279	Presa Opopeo UNAM	18/09/14	19/09/14	12:15	s/color	no	no	20.0 oC	
LMAU 280	Pileta Santa Clara del Cobre UNAM	18/09/14	19/09/14	13:30	turbia	no	no	20.0 oC	
LMAU 281	Manantial La Estrella UNAM	18/09/14	19/09/14	14:50	s/color	no	no	20.0 oC	
LMAU 282	Lago de Zirahuen, Capitania de Puerto, UNAM	18/09/14	19/09/14	10:38	s/color	si	no	20.0 oC	8.38
LMAU 283	Lago de Zirahuen, Agua Verde, UNAM	18/09/14	19/09/14	11:38	s/color	si	no	20.0 oC	8.47
LMAU 284	Lago de Zirahuen, Copandaro, UNAM	18/09/14	19/09/14	12:07	s/color	si	no	20.0 oC	8.44
LMAU 285	Manantial el Carrizal, UNAM	18/09/14	19/09/14	11:20	amarillo	si	25.0 oC	20.0 oC	7.34
LMAU 286	Junta de Manantiales Zirahuen UNAM	18/09/14	19/09/14	13:05	amarillo	si	22.0 oC	20.0 oC	7.83
LMAU 287	Pozo casa de Sr. Paz por la iglesia UNAM	18/09/14	19/09/14	14:12	s/color	no	22.0 oC	20.0 oC	6.5
LMAU 288	Planta de Tratamiento de Santa Clara UNAM	18/09/14	19/09/14	11:47	café	si	no	20.0 oC	7.51
LMAU 289	Rio del Silencio, UNAM	18/09/14	19/09/14	15:00	s/color	no	no	20.0 oC	6.76
LMAU 290	Rio del Silencio, puente parcela escolar UNAM	18/09/14	19/09/14	14:07	gris	no	no	20.0 oC	7.22
LMAU 291	Rio del Silencio, puente de la palma UNAM	18/09/14	19/09/14	13:05	gris	no	no	20.0 oC	7.3
LMAU 292	Desembocadura en el lago de Zirahuen (rio del	18/09/14	19/09/14	14:44	café	si	no	20.0 oC	7.22
LMAU 293	Manantial Iricuaro	18/09/14	19/09/14	11:10	s/color	no	no	20.0 oC	
LMAU 294	Manantial Iricuaro	18/09/14	19/09/14	12:15	turbia	si	no	20.0 oC	
LMAU 295	Manantial Iricuaro	18/09/14	19/09/14	13:15	turbia	si	no	20.0 oC	

Activities:

- Teams will review the results obtained for each parameter.
- They will determine the headings for each column on the data base.
- They will specify the units used to report each parameter.
- Teams will experiment with different types of graphs to find the one that better shows the behavior of their data and the differences between water samples.

Homework:

- Suggest different types of graphs to analyze the water quality data. Observe tendencies in the data using dispersion diagrams, frequency graphs, etc.
- Discuss which is the best option to represent the behavior of the data and the results of the water quality analysis.
- Use made-up data to familiarize yourself with the graphing process.
- Argue which type of graph better shows the differences between measured parameters in different types of water.

- Identify the importance of using statistical analysis software to report the results obtained from water sample analysis.
- Discuss the way in which the characteristics of different types of water found throughout Zirahuen determine how this resource is used and how it is perceived by the surrounding communities.

MODULE 4. INTEGRATION

SESSION 8 (2 HOURS). Presentation of the final product

General learning goal (S-ESLG):
To identify the social, biophysical and chemical components involved in the environmental problem observed in Zirahuen, as well as the interactions between them.

Specific goals (learning objectives):
- To distinguish the biophysical, chemical and social components related to water quality in Zirahuen Lake.
- Explain the interactions between these components.

Skills (SLO):
- Students will be able to identify and illustrate the heterogeneity of components related to water quality in Zirahuen Lake.
- They will be able to identify social and physicochemical drivers involved in the contamination of Zirahuen Lake and explain their interactions using conceptual maps.
- Students will be able to identify different components of an environmental problem and establish interactions between them, understanding in depth the complexity of the system.

Lesson plan: This session is designed for students to integrate all the information they obtained in the previous modules regarding characterization of the socio-environmental and physicochemical system. They will be asked to construct a diagram where they indicate the socio-environmental problem of Zirahuen Lake. They must identify social actor, socio-economic activities related to each actor, water quality parameters, the main sources of contamination, motility of contaminants, affected population and normativity. From the experience acquired and work done in the previous discussion sessions and classroom activities, the students will be able to face the challenges of integrating information from two areas of knowledge to characterize contamination in the lake. They will be able to discuss how to study complex systems, the benefits of using a systemic approach on study systems and how this approach gives us elements to integrate information and determine the structure and function of our system.

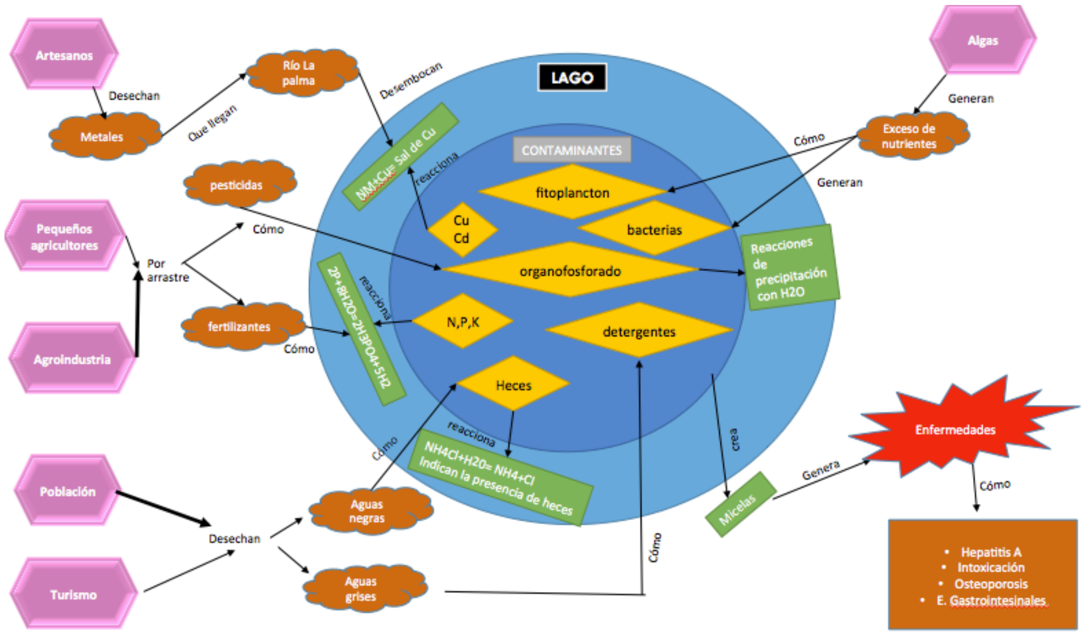

Figure 5. Example of a diagram characterizing the socio-environmental problem of Zirahuen Lake, such as may be produced by the class.

Materials:

- Flip chart
- Markers

Activities:

In teams of three, students will choose the role they wish to represent during the activity: presenting the environmental problem of Zirahuen.

Homework:

- Make a conceptual map where you explicitly place the subsystems and elements that make up the Zirahuen Lake system.
- Each team must explain how relationships occur between social and physicochemical components: how does the interaction between these subsystems get us closer to understanding the socio-environmental problem of Zirahuen Lake as a whole?

Supporting materials on "Role play practices":

https://www.mindtools.com/CommSkll/RolePlaying.htm http://www.businessballs.com/roleplayinggames.htm

Discussion:

This sequence of activities was a guide for the students to be able to identify an environmental problem. From the first two modules, students learnt to identify the components of the socio-environmental system as well as the physicochemical system. Students understood that environmental problems are complex, and being able to separately describe two subsystems helped them understand which elements are required for the identification, understanding and solving of environmental problems.

They found it very difficult to integrate information. They had a first encounter with the challenges of teamwork, the importance of having effective communication tools, of listening and making compromises during an ongoing work.

Each team was able to highlight the main arguments through which people justify their actions, how their socio-economic activities use natural resources and produce waste, and how this waste has consequences on their surrounding environment.

When characterizing the social and biophysical subsystems, students were able to identify the economic activities and interests of the main actors involved in the contamination problem of Zirahuen Lake. They defined the environmental spheres where different issues occur, such as trash generation, disposal of substances into the lake, fertilizer and pesticide application in adjacent croplands, deforestation, social conflict, etc.

Using this case study to approach the environmental problem of Zirahuen Lake allowed them to have a well-grounded experience and to continually reflect on it. We not only considered the generation of knowledge as a cognitive process, but we promoted skill development by incorporating knowledge and content. The case study was used as a real point of reference for the students to remember and use the elements discussed in class to give meaning to what they learnt on each stage. Students had an active role, where the activities' design required them to be involved in constructing the experience.

We worked from the premise that knowledge is part and product of the cultural context where it is developed and used. We were clearly able to observe that "content" was not the most important aspect during the acquisition of knowledge, that is, focusing on "what" instead of "how" does not allow student to gradually incorporate the different elements of a system. When approaching complex problems it is necessary to work in conjunction with the content for an authentic learning experience, making it cohesive, significant and propositional, letting the student structure his/her thought process, dosing information so that they can focus on the process of building and integrating the elements needed to approach an environmental problem. This way, there can be a lasting thought process that incentivizes dialog and debate, and we build knowledge from the ground up.

The case study represented a highly effective tool during the teaching process, as it allowed us to: gradually evaluate students; establish rules within the group; build knowledge at different levels to promote generalization processes and knowledge transfer; develop social, cognitive, perceptive and emotional skills; provide gradual and growing understanding of the complexity of the system, where the student always has an active role in building their own thought process.

There were multiple challenges during the case study, including: teamwork; maintaining a clear and orderly sequence of activities where instructor and students have clear learning objectives in each module; maintaining the students' attention and concentration throughout the sessions; promoting autonomous thinking; maintaining motivation and a positive learning environment; maintaining balance during the moments of student-teacher interaction; considering the previous knowledge of each student, their preconceptions and context to gradually works toward integration and coherence; making sure students did not perceive knowledge as fragmented, thus contradicting the objective of this integrative process. Finally, the time challenge was also key. It is important to be very clear in the last session to achieve the objective of having the student experience the process of integration of knowledge.

Some difficulties were inherent to talking about complex problems. The main challenge is the fact that the elements we considered to approach this environmental problem are the ones that give meaning to the pedagogical experience, and in this case the context is a reality that is very close to the students. There are also challenges when integrating knowledge, generating mental processes and activities where the student can gradually build an understanding of an environmental problem, and also eventually in proposing solutions to mitigate this problem.

The case study is an effective tool for identifying, understanding and solving environmental problems. During this experience, students showed interest in working as a team and they maintained a perceptive, critical and thoughtful attitude that allowed them to study complex systems in depth. The systemic analysis was a useful strategy for students to transition from smaller to greater complexity of thought.

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APPENDIX I. GUIDE FOR DISCUSSING THE WATER QUALITY REPORTS

“Water quality in Morelia: the importance of determining physicochemical and microbiological parameters”

All the results from the water samples’ analysis must be compared to the official Mexicans norms (NOM).

What happens when we get to the field? All the material must be properly labeled with the precise location of the sample, date, time and serial number. Bring a 2L plastic pitcher.

Field parameters: pH, salinity, temperature, conductivity, dissolved oxygen. The data-logger must be properly calibrated. Samples must be taken directly from the pitcher. Each time the pitcher is used to collect water it must be closed, shaken, sampled and then dumped so that no residues remain that can interfere with the analysis. The pH measurements obtained in the field should correspond to those taken later at the lab. The samples must be preserved on ice. Temperature is extremely important, as the state of Michoacan has many locations where thermal waters can reach up to 60°C. Environmental temperature is also important because it affects microbial activity within the body of water, and affects the levels of dissolved oxygen. Salinity accounts for 60% of conductivity, and in turn, conductivity depends on salts and minerals present in the water. It is important to follow a logical geographical sequence when sampling.

Time of day: Bodies of water tend to have aquatic plants growing in them, particularly with eutrophication. During the light stage of photosynthesis there will be greater concentrations of oxygen dissolved in the water, whereas during the dark stage there will be fewer dissolved oxygen. Therefore, if you sample at 6am the levels of dissolved oxygen will be low. Solar radiation will also affect microbial activity.

Water color: When water has dissolved solids, such as clays, it acquires a characteristic color. Color can also come from other sources such as decomposing organic matter or residues from mining processes.

Types of analyses: Physical, chemical, organic, heavy metals, bacteriological. If different parameters are studied from the same sample, they must contain the same information. Samples can be taken to specialized laboratories for analysis.

Are NOMs determined for each parameter of per water source?

Temperature NOM: NOM-AA-007

Conductivity NOM: NOM-AA-093-SCFI-2000

When we have very small conductivity values it means we are dealing with natural residual or industrial water. If water is very shallow, it can present high conductivity (for example in Cuitzeo).

The city of Morelia receives water from Mintzita, treatment plants and wells. Rio Grande has permissible levels. Certain ranges of values indicate that water should not be used for human consumption, such as conductivity between 2,000 and 3,000 microS/cm and solids between 1,400 and 2,100 ppm. When aquifers are very old (containing fossil water), they tend to be more than 1Km deep and the water is harder (more mineralized).

Water is greatly used in agriculture. Some plants are very sensitive to the amount of salts (carbonates and bicarbonates) present in the water, especially when grown in greenhouses.

The main factors influencing the concentration of dissolved oxygen are temperature, salinity, chlorides and atmospheric pressure. Higher salinity or presence of chlorides prevents phytoplankton from reproducing properly, and these organisms generate an important amount of dissolved oxygen.

Microbiological contaminants: The Federal Law has ecological criteria for water quality according to the parameters of chemical oxygen demand (COD) and TDS (total dissolved solids).

Alkalinity and hardness: Alkalinity is defined as the capacity of water to precipitate soap. It is based on the presence of Mg and Ca ions. The related NOM is NMX-AA-072-SCFI-2001. Alkalinity is important because it can help neutralize pollutants: if there is more precipitation, there is neutralization, maintaining pH at optimal levels and supporting daily fluctuation of CO_2 levels. Alkalinity can be classified as very weak, weak, strong or very strong. There are different tests for alkalinity including phenolphthalein and methyl orange. Hardness depends on concentrations of $CaCO_3$ and can range from soft water to very hard water.

How do CO_3 and HCO_3 originate? Soils are naturally enriched from the drag of these compounds.

BOD, COD and TOC: Their values will depend on the type of water and its characteristics. BOD and COD are used to determine the amount of organic matter present in bodies of water, especially those that come from residual water discharge from municipal and non-municipal sources.

Biochemical oxygen demand (BOD): This parameter determines the amount of available organic matter. The sample is placed in a Wrinkler jar and oxygen is injected. It is incubated to allow microorganisms to develop and use the oxygen that is dissolved in the water as well as the organic matter. You then measure the amount of oxygen that was consumed. Toxic substances can affect the BOD by preventing microorganisms from using oxygen. If we have a BOD of 3mg/L in a stream of 40,000L/s then the oxygen concentration will be >6mg/L and fish can live here. But if we have a BOD of 15mg/L in a stream of 2,500L/s then only certain aquatic species can survive here because the dissolved oxygen is 4mg/L. If we have a BOD of 60mg/L in a stream of 400L/s then our concentration of dissolved oxygen will be <2mg/L and only carps can survive here.

Chemical oxygen demand (COD): This parameter measures the total amount of organic matter. It measures the amount of oxygen needed to oxidize the organic matter found in a sample under high temperature conditions (148°C), adding H_2SO_4 and allowing digestion for two hours. COD is always about 40% higher than BOD.

Total organic carbon (TOC): This parameter is critical to quantify pollution. Its value is around half the BOD value.

Phosphorus and nitrogen: They arrive at water bodies through residual waters and runoff. Nitrogen is degraded differently depending on the type of compound that contains it (amino acids, urea or nitrates). Agricultural, industrial or domestic activities can produce contaminants that may reach subterranean waters. It is important to determine the presence of P and N because these create ideal conditions for microorganisms to reproduce. Water turns green, oxygen levels increase during the day and fall rapidly during the night. Other organisms do not survive.

Total dissolved solids (TDS): It is a multi-parametric indicator that is determined in the laboratory. If we have TDS<1,000ppm then we have freshwater, and TDS>2,000ppm is seawater.

Total soluble solids (TSS): It is defined as the residue retained by a filter of pore size 0.45-2µm dried at a temperature of 105°C. It can be compared to the turbidity parameter.