Towards an understanding of the Human-Environment System of Mayan communities. Knowledge, users, beliefs and perception of groundwater in Yucatan

By
Yolanda Lopez-Maldonado
Ludwig Maximilian University of Munich

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Abstract

Human-Environment Systems emphasises the linkages between environmental (e.g., natural resources) and human systems (e.g., society). The major goal of this project is to methodically investigate Human and Environmental Systems in contemporary Mayan communities in Mexico as a case study, by combining natural and social science approaches. The background of the project is the increasing production of scientific literature addressing the importance of groundwater ecosystems for the provision of services to societies and the rapid change and degradation of the groundwater in the area. Particular emphasis in the Yucatan Peninsula aquifer case will be given to the interactions of communities and institutions related to the use and management of groundwater and to the understanding of feedbacks concerning human induced changes in this ecosystem. Nowadays, the aquifer is threatened by anthropogenic activities including tourism, agriculture and solid waste disposal degrading the capacity of this resource. The aim is to develop a framework to study the dynamic relationships between groundwater and social processes to enhance our understanding of the systems and to develop an empirically-based simulation model by involving institutions and stakeholders. We will include both biophysical processes and associated human behaviours of local members by considering the decision-making of actors who influence the ecosystem, their interactions, roles and perceptions. In a broad sense, the use of system analysis and the analysis of traditional Mayan knowledge will be investigated to find solutions for the groundwater problem and to foster regional development in contemporary Mayan society.

Keywords: Human-Environmental Systems, Mayan communities, Groundwater

INTRODUCTION

The present study is part of a project that involves the analysis of complex environmental problems regarding groundwater. The problems we are referring to are associated to a particular case study in the Mayan area of Yucatan, in Mexico. In this place, where groundwater is the only source of freshwater, the inhabitants have to deal with water problems such as resource scarcity, groundwater pollution, climate change, biodiversity loss, and resource degradation. This study investigates the linkages between environmental and human systems by considering the interaction of Mayan communities, their own knowledge, uses, beliefs and perceptions, with the understanding of the dynamics of the groundwater system in Yucatan, Mexico. The major goal is to methodically investigate human and environmental systems (HES) in contemporary Mayan communities as a case study, by combining natural and social science approaches and by developing a framework for the understanding of the systems and to answer the research questions addressed. In this paper, we synthesize the major findings about the characteristics of HES in order to show practical values of studying these complex relations in Mayan contemporary society.

The author of this article has been working for two years in the understanding of the complex groundwater-human interactions in Yucatan. Since much of the work about the analysis of the social and ecological systems tries to be so elaborate, this work was set up in the context of the Social-Ecological Systems framework (SES), also called human environment systems (Turner & Sabloff 2012), initially proposed by Ostrom (Ostrom 2009; Ostrom 2007). In this paper, we refer to SES as the multilevel system that provide services to societies and where subsystems such as a resource system, resource units, users, and governance systems are relatively separable but interact to produce outcomes at the SES level, which in turn feed back to affect these subsystems and their components, as well other larger or smaller SES (Ostrom 2009; Berkes et al. 2003).

In this paper, we use some definitions in order to avoid misunderstanding. For example, we use the term HES (Scholz 2011; Binder et al. 2013) to refer to our analysis of the relations of the human and the ecological system in the Mayan society. Traditional ecological knowledge is considered here according to the definition proposed by Berkes (Moller et al. 2004; Berkes et al. 2000) as a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission. We also define groundwater management as proposed by Belkin (Belkin 2000) as: all planned activities that assess and affect the quality and quantity of phreatic water.

After briefly summarizing the motivation of this work, this article provides an overview of the initial findings that have been made in order to develop a framework for the study of groundwater resources in Yucatan, Mexico. The framework developed here is still in the beginning phase and still intricate, particularly for people who are not familiar with the Mayan society and the geographical characteristics of the area in which this civilization still develops. However, we are convinced that it is crucial to first establish a common methodology in the management of groundwater resources. To delineate a framework and to establish this common language, as the basis for theoretical and empirical analyses of groundwater in different contexts, we firstly present a brief description of the study case, the area, and then we introduce the specific objectives and research questions of the project that will guide the study. Finally, we present the methodology, some preliminary results and reflections.

The case

Groundwater systems unquestionably constitute the predominant reservoir of freshwater storage on Earth (Foster & Chilton 2003). The problems of contamination of these water bodies by human activities exist at many levels and all over the world (Anon n.d.). These problems pose serious triggers an intense debate regarding the potential environmental and human health effects (Wada et al. 2010; Vermooten & Kukuric 2009; Foster et al. 2002). In regions with frequent water stress or remarkable water problems and large aquifer systems groundwater is often used as an additional water source (Döll 2009; Foster et al. 2002). However, the situation is different in places where groundwater is the only source of fresh water for the population. One clear example of this case is the groundwater system in the Yucatan Peninsula, in Mexico, that has one of the world's largest karst aquifers in the world, which takes up approximately most of the total area (138,000 km^2) of the peninsula (CONAGUA 2011).

The Yucatan Peninsula is divided in three states: Yucatan, Campeche and Quintana Roo. In the case of Yucatan, groundwater is the only source of water supply of its nearly two million inhabitants (CONAGUA 2011) and also the physical environment creates a set of hydrogeological constraints to future economic and social development (Doehring & Butler 1974).

All groundwater exploitation made by societies results in some decline in the quality of aquifer water (Van Weert et al. 2009; Wada et al. 2010; Döll 2009; Morris et al. 2003; Anon 1984). In the case of Yucatan, this is also influenced by the calcareous nature of the soil that confers it characteristics of high porosity and permeability causing rapid rainwater evaporation and infiltration. In the area, the aquifer is susceptible to several problems like salt intrusion from the sea towards the interior of the basin, contamination derived from an inadequate waste disposal, climate change, and natural hazards. Consequently, water situation there can quickly reach critical and vulnerable conditions and even small disturbances may cause dramatic consequences. So far, groundwater demands and groundwater pollution problems are still growing in the area (Metcalfe et al. 2011; Delgado et al. 2010; Hernández-Terrones et al. 2010; Perry et al. 2009).

According to the prevailing published literature the groundwater in the area is partly contaminated and this situation is affecting large parts of the Yucatan Peninsula. For example, several authors (Bauer-Gottwein et al., 2011; Beddows, Smart, Whitaker, & Smith, 2007; Escolero et al., 2005) reported cases of seawater intrusion into the freshwater aquifer. Groundwater is contaminated especially by tourism activities, industry and agriculture (Gondwe et al. 2010; Metcalfe et al. 2011; Bauer-Gottwein et al. 2011), but particularly, wastewater and bad solid disposal poses potential risk to the inhabitants.

In Yucatan, groundwater management data are generally scarce. Existing data on the region primarily focus on hydrogeology (Beddows et al. 2007; Hernández-Terrones et al. 2010; Gondwe et al. 2011); archaeology (Veni 1990; van Hengstum et al. 2010); geology (Perry et al. 1989; Lugo-Hubp et al. 1992); urban planning (Pacheco et al.

2001) and geochemistry (Escolero et al. 2005; Garing et al. 2013; Perry et al. 2009). However, there is a lack of studies that include the management and the views of local people, their knowledge, uses, beliefs and perception of groundwater in Yucatan. Only one reported work addressed the management and uses of groundwater in the area (Perry et al. 2003)

Considering that groundwater resources management have been playing an important role in the economy of Mayan society, at past and present, by helping communities to survive dry seasons (Faust & Bilsborrow 2000), this project takes into account the impacts of human activities as one of the most influencing factors that cause environmental degradation of this ecosystem.

Hence, even though numerous studies in this regards have improved our understanding of the human-society interactions, we are still looking for improving research accomplishments on the comprehension of HES in groundwater-based societies: (1) It should become clear what framework can be used for the analysis of the interactions between society and the ecological dimension of groundwater, but also considering the perception and knowledge of the actors involved; (2) a suitable framework should be developed in order to support research regarding groundwater by considering the drivers affecting the system; (3) it should become clear what parameters and possible components has to be considered in order to develop a model that reflects the diversity of human behavior of Mayan society and that clearly provides insights of the systems in question. Thus, and due to the complex nature of groundwater management, comprehensive human-environment data are required. For achieving the goals of this project a combination of methods and the development of a framework that considers the current situation of the groundwater in the study area, the actors, and the strategies for groundwater management is required.

Human environment systems in Mayan communities

The framework

In the study of the human and environment systems, the development of a coherent analysis of complex, nested systems operating at multiple scales is a challenge (McGuinnis & Ostrom 2012). To help us to understand and model the relations between these two systems is important to have an adequate framework within which to work. In the case of the Mayan society, the analysis requires a holistic approach – which can only be achieved if it considers: (1) a deep understanding of the dynamics of the natural system, (2) the analysis of actors who use the resources, including their interdepencies; and (3) the study of their perceptions, knowledge and beliefs.

There are different approaches or frameworks (Social ecological system, Human environment system, etc.) (Binder et al. 2013) to know how the human and social system can be analyzed (Turner et al. 2003; Ostrom 2009; Scholz 2011). In the case of the Mayan area, extensive literature and experience has been gained since the interest for the analysis of HES (G. Haug, D. Gunther, L. Peterson, D. Sigman, K. Hughen 2003; Liu et al. 2007; Toledo et al. 2003; Diamond 2005). The analysis of HES in the Maya society, and the processes involved, are crucial to get furthering comprehension, and to find solutions, for complex environmental processes. For example, in the case of groundwater, the analysis of HES is important for the understanding of the characteristics of the natural system. So far, knowledge of those interactions is essential for the sustainable management of these resources.

Understanding those relations in Maya society is a clear example of why those complex problems cannot be analyzed with disciplinary approaches alone. This is because the dual view of the HES relations is not shared by all cultures (Scholz 2011), including the Maya. To understand how a complex society like the Maya (Turner 2010; Turner & Sabloff 2012) interact with the environment, is important to determine in our analysis how these interactions are crafted and sustained. Here we call upon a well-established definition of a framework to provide clearly the concepts and terms that may be used to explain those relations.

Nevertheless, all of the models mentioned cannot be completed yet if we see that the integration of local perception and knowledge is missing. In writing this paper we notice that first, none of the existing frameworks explicitly integrates human perception in a clear way. Second, the frameworks presented here have been developed by scholars from multiple disciplines that tends to focus on their own fields of study without recording, measuring, controlling or even thinking of other variables that might account or affect the interactions within the systems (Ostrom 2009). Third, we think that frameworks that include non-academics as co-authors and participants are especially important for the sustainable management of natural resources. The different ways of thinking, worldviews and the ways in which scholars and practitioners might use those frameworks, inclusion of indigenous knowledge and local practices, and the different ways of thinking and practice are also of special interest.

Of particular relevance in this case is the SES framework (Ostrom 2009; Ostrom 2007) that can be applied to a relatively well-defined domain of common-pool resource management situations in which resource users extract resource units from a resource system, and provide for the maintenance of that system, according to rules and procedures determined by an overarching governance system (Anderies et al. 2004). We focus our interest because the SES framework seems to be the only framework that treats the social and ecological systems in almost equal depth (Binder et al. 2013). However, and since the ecological knowledge does not function in an isolated way (Berkes et al. 2003; Berkes & Turner 2006) because is embedded in local social norms; we decided to adapt the SES framework by including the spiritual component regarding the water management in the Mayan society (Figure 1).

In this paper we do not completely address in detail the belief or spiritual component of traditional knowledge that underlie the world view in which the Mayan knowledge is embedded. Thus, the framework needs to comprise knowledge, concepts, and approaches from various disciplines. In this sense, the rational departs from the idea that groundwater problems, caused from human activities, could easily increase and this will affect the groundwater quality. Extensive use of groundwater resources without considering local needs and without the understanding of the transport and flow of pollutants would also decrease the quality of fresh water and would affect the ecosystem. Thus, improving our understanding of groundwater dynamics, including flows, processes and stocks, and knowledge about actors, their beliefs and perceptions of the ecosystem would support a more sustainable development of the aquifer in the area. We postulate that the integration of methods will help to gain furthering understanding of the system and to develop strategies for a better management.

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The need for an integrative framework to analyze human-groundwater interactions

In this paper, we present an approach to integrate a material flow analysis (MFA) of groundwater and the analysis of the actors' perceptions and worldviews by the application of Structural Mental Model Approach (SMM), for a sustainable management of the groundwater system in Yucatan, Mexico. We argue that the sustainable use of groundwater resources requires a full understanding of the aquifers' characteristics, which involves a clear definition of flows, aspects and sources that contributes with its depletion and pollution (human activities, industry, etc.), as well as the identification of actors involved, their perceptions, discrepancies, believes and traditional knowledge (rituals, ceremonies, etc.) related.

In this regard, the protection of groundwater bodies and connected ecosystems has caused that scholars start to focus on methodologies and to establish a common language for the investigation in this sense, e.g. the flows of groundwater, geology of the groundwater reservoirs, hydrological patterns, etc. (Gondwe et al. 2010; González-Herrera et al. 2002; Delgado et al. 2010; Connors et al. 1996). At the same time some authors have suggested that the application of methods to gain understandings of the physical processes occurring in the ecosystems could be improved by combining these methods with those from the social sciences to make the results more relevant for policymakers (Binder & Schöll 2010; Binder 2007).

For example, groundwater pollution in Yucatan is not usually well detected and is not direct, since in most cases the pollution must pass through a layer (or several layers) of the soil (Bear & Cheng 2010). Sometimes this process also involves chemical and physical transformations of material or substances including dilution, mixing, adsorption, absorption, evaporation, biological degradation, etc. Despite of the existence of a body of research indicating that the soil is effective in removing toxic substances before they reach groundwater supplies (Hess 1999), the direct flow of pollutants and contamination of groundwater from human activities, however, remains controversial.

One insight from an earlier study (Binder et al. 2003; Binder 2007) was that the combination of MFA and methods from social science (e.g. SMMA) would support the application of MFA results for managing material flows. In summary, the main idea of is that a method is needed to analyze the relationship among social structure, including culture and social norms, individual decisions, and material consequences. This implies the need for filling this gap and to consider that other aspects of the social system should be included in the investigations in order to provide better results with dealing with natural resource management.

The Material Flow Analysis

Because the amount of a particular substance entering the groundwater ecosystem and the overall effect of its eventual high concentration on the aquifer and living organisms is always unclear, we propose the development of a MFA. This method can be applied in order to identify not only the significance of a given source depending on the toxicity of a particular substance, but also how much this substance enters the aquifer, and whether or not this remains in the system in a toxic form (Baccini & Brunner 2012).

In general, a MFA is one of the most helpful tools to analyze and understand the flows and exchange of materials and energy with the environment (Baccini & Brunner 2012; Ayres & Ayres 2002). It provides excellent information of the flows, stocks and processes to understand the human activities and the environment (Anon n.d.). Is also useful method for supporting environmental policy (Bouman et al. 2000). In the case of groundwater in Yucatan, the MFA can be applied to investigate the amount of a particular substance entering a particular system (in this case groundwater) and the overall effect of high concentrations (e.g. on the users of the aquifer and other living organisms). For example, in groundwater systems, wastewaters from households are combined with industrial discharges and urban runoff. Other activities, like agriculture, also contribute with substances to the groundwater. Thus, the management of groundwater resources requires improved understanding of water flow patterns, dynamics of the resource, and the social processes that impact on it, for which a range of diverse types of data is required.

In the case of the groundwater in Yucatan, several authors have proved that high levels of pollutants in groundwater are of concern because they can increase the salinity levels and pose significant related problems like health risk. The problem is bigger if we do not know how much of these pollutants enter the aquifer and whether they stay on it and if they affect the population who use the resource. In order to overcome this, it was envisaged that the application of a MFA would be beneficial for the understanding of the groundwater dynamic system and the interaction with other processes such as human activities.

Conversely, at the methodological level, the MFA can be difficult at the moment of the application of the results in the decision-making process (Binder 2007). For that reason, and discussing the advantages and disadvantages of the combination of methods, one important question is: how the results of the MFA can support local members to overcome groundwater problems in the area? Since the identification and analysis of actors, their interdepencies and perceptions, seems a promising approach for studying problems in environmental sciences, specific emphasis in the Yucatan Peninsula aquifer case will be given to the interactions of communities and institutions related to the use and management of groundwater.

The Structural Mental Model Approach

Psychological approaches such as surveys, experiments and interventions for changing behavior affecting material flows are mostly used for explaining agents' behavior (Binder & Schöll 2010). SMMA allows to get understating of the perception of local members in the context of groundwater pollution problems and to compare the differences in risk perception with experts (Schoell & Binder 2009). In the case of the groundwater in Yucatan, Mayan society depends on their ability to cope with risk affecting the quality of freshwater. People there must act and take decisions regarding their health, safety and environmental risks. Those decisions can be linked to water bodies' protection choices and also decisions regarding the perception of environmental risk (including their perception of risk for themselves and risk to other persons), emotional concerns about groundwater quality, and the differences between the perceptions of experts working in the water sector.

Especially in indigenous communities, the gap between the worldviews of experts and the members of indigenous groups is wide different and confusions are still happening. This is mainly due to the cultural interpretation and the lack of inclusion of indigenous knowledge in the analyses of the ecological systems. To get this information, various factors have to be considered, including local member's perception, their system understanding, the social norms (Feola & Binder 2010), but also the cultural values and traditional knowledge. The SMMA has been applied in diverse fields of research (Binder & Schöll 2010), but none of them have been developed in societies with a complex traditional ecological knowledge, such as the Maya.

The approach presented here will be developed by considering the discrepancies in the perception of risk between experts and indigenous local members. Specifically, this approach will consider the analysis of social and cultural characteristics of the society and will take into account how indigenous people organize and communicate about their environment. We are interested in get some insights about how ecological science can play a complementary role in the social science and vice versa and how the traditional knowledge can be intermixed.

Combining the MFA and SMMA for the Yucatan groundwater case

Here, we propose an approach to integrate both methods, MFA and SMMA, for a better understanding of the human environment system of Mayan communities in Yucatan in order to find solutions for the groundwater problem. We aim to contribute to these research challenges by providing a framework that can be used for the analysis of social-groundwater systems. In the Yucatan groundwater case we are interested in the analysis of three main issues regarding groundwater management as follows: (i) identification of the weak point in the ecosystem and we will represent this in a clear visible way, (ii) identification of the perception of actors involved, including their interdepencies, knowledge and beliefs regarding the system, and (iii) development of future scenarios (FS).

Because our interest is to understand HES regarding groundwater and to build the appropriate framework, in this paper we discuss the value of the combination of MFA and SMMA by taking the Yucatan state as a case study. In order to address the main issues mentioned above we will combine those methodologies to answer the following research questions:

1. How are the social and the ecological systems, and their dynamics conceptualized?
2. To what extent the perceptions, knowledge and traditions related to the groundwater management are included in the analysis of those interactions and to what extent are treated equally with respect to analytical depth?
3. How the inclusion of behaviors, decisions, and perception of local members will influence the ecosystem (e.g., water quality, irrigations, other practices) and how this factors will influence the quality of life?

The study area

Yucatan Peninsula

The peninsula is characterized by the absence of rivers on the surface (Table 1).

Groundwater storage and flow occur in a regional karst aquifer with major cave systems, where groundwater flow is dominated by turbulent conduit flow (Bauer-Gottwein et al. 2011). The Yucatan state has a population of two million inhabitants (Anuario estadistico de Yucatan 2012. Instituto Nacional de Estadistica y Geografia 2012). Due to the karstic and highly permeable soil of Yucatan, is easy to find groundwater caves plenty of fresh water. In the area there are thousands of these caves, called cenotes, from the Maya word ts'onot that means sinkhole, in which societies extract water for several uses (Worthington 1993). Knowledge about community management and uses of those water bodies, is consequently crucial to understand groundwater-human interactions. Thus, the Yucatan groundwater system provides a good example for the study of these interactions by analyzing at regional scale groundwater management problems in a very sensitive resource based-dependent society in the area.

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Property

In Mexico, water resources are property of the nation and their management is the government's responsibility. Nevertheless, some cenotes in Yucatan are private property or are located in ejidos, a collective landholding regime. In the case of the groundwater in Yucatan, major parts of the cenotes are located on private households, who own and possess those groundwater caves. This shared-management situation gave rise to a co-management regime between authorities and communities (Berkes 2004). This term refers to a continuum of arrangements involving various degrees of power and responsibility-sharing between the government and the local community (Berkes & Turner 2006; Moller et al. 2004). These problems are mainly related to the interaction among multiple uses and users of the resource. For example, water management in Yucatan is not yet based on a participatory approach but on expert knowledge guiding management decisions. Local inhabitants are mainly informed of government strategies results and, just few sometimes, in consultation processes.

Historical groundwater-Mayan interactions

There are some societies that are otherwise very unlike. The Maya is an example of this and of the induced collapse, exacerbated by the overuse of natural resources in a non-sustainable way (Turner & Sabloff 2012; Diamond 2005). Nevertheless, a very complex traditional ecological knowledge and general worldview of the use of natural resources in Yucatan have significantly shaped the human-environment conditions in the region, in particular groundwater resources. Several authors have attempted to improve the understanding of complex processes underlying the Maya collapse, and the interactions of this society with nature (Turner & Sabloff 2012; Turner 2010; Dearing et al. 2010). But, if the demise of the Mayan populations was the result of complex HES, then what are those relations, at present, and how they are conceptualized? In this project we start from the bottom of the problem in order to identify the current methods that can be used for the analysis of the human and environment relations in order to address the research questions.

First of all, as there is evidence that Maya population had a high relation with those traditional practices (Turner et al. 2003; Faust & Bilsborrow 2000; Weiss-Krejci &

Sabbas 2002), the linkages and relations direct our attention to the understanding of the dynamics of the ecosystem and to the actors on the human system. However, we believe that the inclusion of the traditional ecological knowledge and the identification of all the actors that use the resource requires more than a fundamental understanding of the dynamics of the natural environment.

Worldview includes basic beliefs pertaining to religion and ethics, and structures observations that produce knowledge and understanding (Berkes et al. 2000). For example, in the case of Yucatan, a region where most of the inhabitants are indigenous, with a specific worldview where humans are part of an interacting nature that encourages a harmonious relationship between environment and society, ancient practices related to water are still conserved. Those practices are still strongly related and shaped by rituals and religious procedures, including those connected to the Dios Chaac (refers to the water God in Mayan culture). The symbolic treatment is by far the most important ritual linked to this god nowadays. The religion and culture was water oriented and the Mayan practices, rituals and ceremonies were primarily in the name of Chaac (Veni 1990; Munro-Stasiuk & Manahan 2010; Scarborough 1998). One example of this is the Cha Chaac ceremony, in which Mayan pray to the God Chaac to bring rain and where a ceremonial white corn drink, is offered to “los vientos” (the winds). The importance of the influence of Chaac to the Maya of Yucatan is simple as state elsewhere: without rain there is no corn, and without corn there is no life (Love 2011).

The Maya area of the Yucatan Peninsula was also a difficult environment in which to make a living (Lucero 2002). Because the absence of rivers, the Maya was one of the few early civilizations to use a groundwater supply extensively (Back & Lesser 1997). In the area, the cenotes and natural groundwater caves were the source of water that supported a considerable population (Perry et al. 1989). However, much of what is linked to water imagery, rituals and ceremonies is associated with water symbolism. In the case of the rituals in the study area, they were the prescribed activity that regularly provided aspects of meaning for religion or ideology to the Mayan society (Demarest 1997). We know with a lot of uncertainty some of the rituals developed in the past of the Mayan society, however, present-day rituals, still reveal valuable information about water use, and their interactions with nature.

Considering that groundwater resources management have been playing an important role in the economy of Mayan society, and that sustainability can be achieved through the complementary use by scientists of local and traditional ecological knowledge for joint resource management (Moller et al. 2004), this project takes into account the impacts of human activities as one of the most influencing factors that cause environmental degradation of these ecosystems in the area.

METHOD

Procedure

In order to fulfill the gaps, we propose a coherent framework that can be used when analyzing those coupled systems. The development, application or use of a framework allows to identify the elements to consider for the analysis of HES (Binder et al. 2013; Ostrom 2009). In the case of groundwater of Yucatan, in order to address the research questions we suggest the development of the framework in three steps (Figure 2). The primary step in this case is that we limited ourselves to the SES framework because it provides a better understanding of decomposable, multitier SES derived from systematic research (Dietz et al. 2003).

Our first basic assumption is that there is a lack of knowledge of the dynamics and functions of the aquifer but also there is a lack of inclusion of local knowledge and perception when elaborating the framework. After this, we analyzed the available information about groundwater in order to develop a database. Hence, we also suggest the inclusion of literature of both, biophysical processes and associated human behaviors.

In a second step, to gain some insights regarding the accumulation of material or hazardous substances, and to identify the potential sources of pollution, we suggest the implementation of the MFA. This is because most approaches for the analysis of contamination problems on groundwater resources have a strong tendency to blind human activities because they tend to focus more on hydrological aspects. The MFA will serve as a tool to represent the dynamics of the system and to identify the problematic points. The results obtained with the MFA will support the application of a second method, the Structural Mental Model Approach (SMMA).

In a third step, and by considering the soil-groundwater interactions, the inclusion of qualitative techniques constitutes an important issue for the analysis of groundwater pollution problems in the area. In this stage the SMMA will support the assessment of local perception, knowledge and for the identification of discrepancies in the perception of local members and experts. A fourth step, the combination of MFA and the SMMA will be investigated to find solutions for the future of the ecosystem. This will be possible throughout the development of future scenarios within the participants. Here we add the importance to give some feedback of the results obtained to the participants that support the development of the framework.

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Sources of information

In the Yucatan case, the analysis of this research begins by determining the primary influential elements that affect groundwater quality in the area. For doing so, we suggest the analysis of available information about groundwater in the study area and the selected communities. For this case and in a first step, statistical data, papers published and second sources of information have been also found. We selected those studies that have been focus in groundwater pollution problems and we synthesized the results of our analysis in a common table including factors and themes found (Table 2). This synthesis consists of three major components: region of the study, discipline and issue discussed.

Step I
Designing the Material flow analysis of groundwater

From a conceptual point of view the MFA and SMMA will combine concepts emerging from the balance of mass and concepts from psychological cognition perspectives, respectively. The conceptual framework of the MFA provides a systemic perspective of the groundwater in the area. It depicts, in one hand, the inputs, material and substances entering the system and consequently the stocks, related processes and outputs. On the other hand, it shows the weak points of the system. In the Yucatan case, our interest resides in three main questions: which materials or substances (inputs – outputs) and stocks are associated with environmental impacts of human activities in groundwater resources in the study area? Which material flows are relevant and substantial for the complete groundwater system? Which flows and stocks (or substances) are critical or can be taken as indicators for sustainability?

Within the region, for example, we suppose that the source of contamination is secondarily treated sewage. Here we will identify the direct outputs into the groundwater. Wastewater is further processed in local treatment plants and transferred to households. Some water is evaporated, whereas some residues are disseminated to the aquifer. Landowners also use some water for their gardens and animals. These will be helpful to get some insights about how much water is used by private households, how much is evaporated or what are the substances that disseminate to the aquifer. We assume that this example can be used with other processes influencing groundwater in order to develop the complete MFA.

Factors examined for their potential influence on contaminants in groundwater should be included; factors related to hydrogeology, land use, water use, natural and artificial recharge, groundwater travel time, and general chemical characteristics of water in the aquifer should also be integrated in the MFA. In other words, the model will include the most important sources and factors affecting groundwater. The aim is to illustrate all the processes occurring along a flow path from the land to the groundwater. For the development of the MFA we will explicitly focus in the analysis of the flux of water in order to identify the weak point of the system. The system boundary, processes including stocks, goods and flows will be established.

Step II
Implementing the Structural Mental Model Approach

Because the challenge is to know how the knowledge and values of different parts of society can be efficiently linked to scientific knowledge (Scholz 2011) and how environmental information can support communities to anticipate rebound effects, in a second phase, we will investigate the perception of local members and non local people living in the study area, but also the perception of experts in the water sector. This will be possible with the application of SMMA. A conceptual point of view of this method combines concepts emerging from psychological cognition perspectives (Binder 2010). The framework consists mainly in those factors affecting local members' mental models, their perceptions and their decisions.

Some of the questions to address in this step are: who are the main actors involved and what are the interdependencies? What are the local and expert's discrepancies of mental models of risk perception of groundwater pollution and what are the causes for these discrepancies? The investigation in this case will include only residents (male and female) of Yucatan. This is because we want to know the perception of changes in groundwater resources through time. Hence, we will analyze the risk perception of participants. Some variables to include in the analysis are perception of risk for oneself and risk to other persons, emotional concerns, etc. (Table 3).

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We will construct a standardized questionnaire and some interviews to get some insights about their perceptions and concerns about the groundwater situation. This will be assessed by questions such as their knowledge on groundwater contamination (current knowledge and desire for further information). Some questions regarding the understanding of concepts such as resilience, sustainability and groundwater can also be included. In the beginning two groups will be specified on the basis of map of the region. The people 'cenotes-group' (living in or in a close proximity of groundwater caves), and the people 'off cenotes-group' (living some distance away, without easy access to groundwater caves or cenotes but with contaminated aquifer) (Table 4). As the pollution problems probably decreases with the distance from the industrial and urban zone, people will be also informed about this and they will know the differential degree of pollution. Other information is the average time spent in the village, if they own a cenote, etc. At this point, a clear and visible representation of the problem is required. The selected communities and related actors will be asked if there is more than one source of contamination that affects the aquifer. Consequently, a final step in the application of SMMA is the identification of the social networks of actors involved. Hence, we propose the analysis of the interactions, connectivity and the degree they feel and perceive these discrepancies. A first overview of the actors involved should be considered. A further characterization of the actors is also needed.

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Step III

Future scenario development

In the case of the groundwater in Yucatan, the main question to address at the third step is if it is possible to predict future scenarios with Mayan local members. At this phase, by integrating MFA and SMMA, we suggest the development of those scenarios by applying Formative Scenario Analysis (FSA). This method provides a planned process to construct scenarios that include the same specifying information on a fixed set of variables (Scholz & Tietje 2002). We propose the definition of different levels of development for each impact factor then, the scenario can be defined. We recommend in this step the inclusion of actors and interested parties. A further step is the feedback of results to the communities involved.

PRELIMINARY RESULTS

Potential risk identified

Table 2 provides the main approaches and issues of studies developed in the area. In this section we also present an overview of the main potential risks for groundwater and some issues regarding HES that were identified in the literature:

1. The contamination of aquifers is mainly influenced by the lack of integration of disciplines working in the water sector.
2. The contamination of groundwater from spills, leaks, and the disposal of inadequately treated wastewater still being a critical problem in this regards.
3. The accumulation of pesticides in soil still unclear. No reliable data in the region or studies about the flow of those substances was found.
4. Is also unclear the level of (over) extraction of water resources for high-volume hydraulic fracturing that could induce water shortages or conflicts with other water users, particularly in the cenote region or in places with few of those groundwater caves.
5. The flow of materials, research and resource requirements have been rather constant over the last decades, thereby population, their needs and requirements, and pollution problems has increased.
6. The problem composition of groundwater is characterized by the high pressure and impacts of human activities in the area.
7. A considerably high precipitation and filtration rate increases the direct material potential inputs of the aquifer. Example of this is the waste from animal feeding and ranching in the area.
8. Use of pesticides has increased significantly during the last 30 years mainly due to the implementation of the 'Plan Chaac" in the south region of the Yucatan state. The plan was citrus founded by the Inter-American Development Bank and was oriented to orange production in order to meet the demand of Florida in the offseason from other areas.

<<INSERT TABLE 2 ABOUT HERE>>

Why is important the development of the MFA of groundwater of Yucatan?

This paper focuses on the material flow analysis of the groundwater system, by including and explaining the interests, perceptions and drivers of actors and experts. With respect to investigation of groundwater system, we found that various approaches have been applied in the case of the aquifer in Yucatan. We present here the reported data within the three states (Table 5).

<<INSERT TABLE 5 ABOUT HERE>>

We found that the interaction between the social system and the ecological system has been not considered and most of these studies have been looking just at one side of the interplay between groundwater and society. Hence, there is a need to understand how both systems influence each other and to know how the community perceives those influences. We also found that the use of MFA in groundwater has not been carrying out by so far, this led to understanding of the influence of pollutants due to human activities and reduce the possibility to involve other parameters. The current draft of the MFA in the case of groundwater in Yucatan has been developed in an interactive design process including students, government, NGO's and online meetings with representatives from experts working in the water sector. So far, is crucial to consider all these factors during the development of the framework in order to prevent biases.

Why is important to implement the SMMA in Mayan communities?

In order to cover all the perspectives in this study, one of the first steps was to identify the relevant experts and local members for the application of the SMMA. For this, we selected experts according the different fields of expertise and people working in the water sector. Locals were selected according the level of interaction with groundwater resources. After the first scan of the information at hand regarding the main characteristics of actors, the definition of the roles has to be considered.

After doing this, we propose to gain some insights into the dynamics of the social system regarding risk perception. With support of some facilitation (NGO) we will implement some workshops with participants in order to allow them to fully represent the dynamics, characteristics and processes of the ecosystem that have been vague to them since decades. Here is where we suggest to include also the cultural factor and the traditional ecological knowledge in order to design local members' interviews. Then all the responses should be analyzed and the statements compared. Furthermore, during this step the participants should point out the priorities to consider for the solution of the problems regarding groundwater. After doing this, the SMMA would also provide insights into the misunderstanding of the different ways of thinking and practice when comparing indigenous local members with non indigenous.

Proposed next steps

The integration of both methods will support the implementation of the next step to consider in this research. This consists mainly in the establishment of agreements within the group and to determine the strategies and measures with the actors involved and the development of the future scenarios. We suggest the implementation of participatory processes to support the process for a sustainable groundwater management. However, from the issues previously discussed other questions emerge: (i) how can we easily conceptualize the traditional ecological system in our framework; (ii) how can local indigenous people support the construction of this framework. An interesting research question here would be to what extent the traditional ecological knowledge can be incorporated in the analysis of the groundwater problem in Yucatan or in other social-ecological system case. Thus, a further analysis and research process for improving groundwater management have to be made by the parties involved.

DISCUSSION

The value of the combination of MFA and SMMA for a sustainable groundwater management

In Yucatan, system analysis and system understanding are relevant for the sustainable management of groundwater resources. However, is crucial to fulfill some of the gaps that are still missing:

1. Specify a detailed framework for further system understanding regarding the flows of pollutants in groundwater.

2. Include in an equal depth the analysis of both systems.

The groundwater framework has been developed with the integration of the insights generated in a dual perspective of the groundwater resource problems in Yucatan. This is because the author as a member of a Mayan community and scholar, try to provide information about how the Mayan social-ecological systems interactions represents an excellent example of the consequences to society of human impact on an environmentally sensitive area. One constrain is when trying to integrate the ecological knowledge and concepts of local members. Those can increase the complexity and require a profound understanding of the needs of the population and a variety of visions and perspectives of the problem.

The further development of the framework will address this challenge by continuing along the following route: the framework should be used to develop policies and water management guidelines for the groundwater in terms of both, society and the ecosystem. The framework should be used to specify the importance of the inclusion of the perception, knowledge, needs and believes of the population. The results of the MFA should be used to describe the structural characteristics (and requirements) for the sustainable management of groundwater resources. The framework can then be applied to other groundwater pollution situation in different context and case studies. This will facilitate a mutual exchange and learning and weak points in the structure of the systems can be identified and highlighted. To facilitate this, a database will be developed in order to include the relevant aspects from the MFA. Mayan groundwater management practices based on traditional ecological knowledge, and understanding the mechanisms behind them, may contribute with the sustainable management of these resources.

These points are important for an effective framework development. That is, actors can be identified, their perceptions can be considered for further discussion and the hazardous materials and substances can be identified or estimated. The development of the MFA allows for a clear simple representation of the system from the perspective of the participants and actors in the water sector and provides thus, with the basis for the development of future scenarios. However, in our framework is also crucial a deep integration of local practices such as ceremonies and rituals. We consider that the integration of MFA and SMMA provides a basis for the development of a new integrated framework to study the HES in the Mayan society and that goes beyond the analysis of the biophysical environment.

REFLECTIONS

Those of us who work in environmental topics know about the difficulties that we should confront to deal with complexity of environmental problems. We need a better understanding of the HES derived from the analysis of both, past and present societies, which have demised or perished as result of complex systems interactions in order to learn and to move towards a sustainable science (Clark & Dickson 2003). In a broad sense, this case study illustrate that the use of system analysis and the analysis of traditional Mayan knowledge allows to investigate and to find solutions for the groundwater problem in order to foster regional development in contemporary Mayan society. The main issue here is that actor inclusion is needed and strategies and measures have to be implemented in the water supply and demand sector.

A complete framework for the assessment of HES in Mayan population is not an easy task given the complexity of this society and due to the several factors, processes and feedbacks operating there. The difficulties we found are mainly those related with global processes and the long time perspective in which Mayan culture is analyzed. This general framework will provide a useful tool for the analysis of the HES and to assess the gaps and the objectives of this research. Thus we search for for additional information and understanding for the potential uncertainties that might be encountered.

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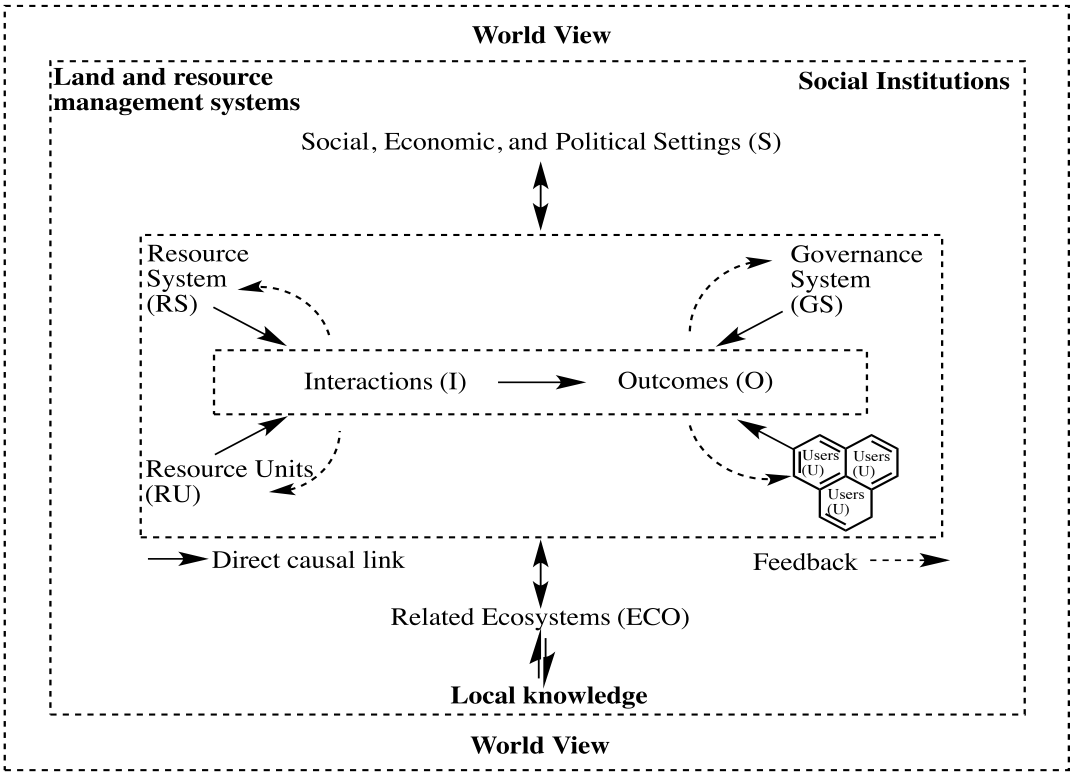

Figure 1. Based in Social-Ecological System Framework (Ostrom 2009; Ostrom 2007) and the Adaptive co-management approach (Berkes et al. 2003; Folke 2007; Folke et al. 2005).

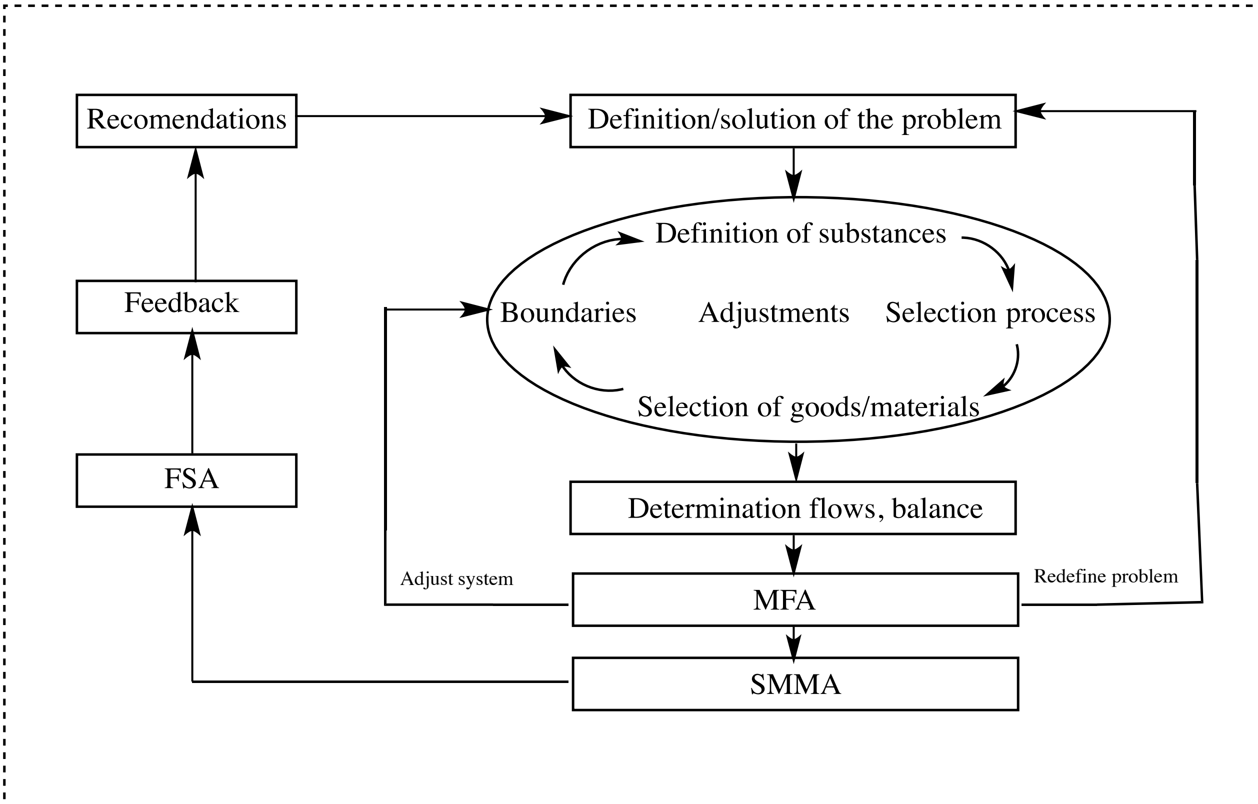

Figure 2. The research process departs from the identification of the problem by analysing the current state of the system and leads through a complete analysis and definition of boundaries, substances, actors and related process for the development of the MFA and SMMA, which finally leads to the solution in an iterative process (Source: own elaboration).

Table 1. Hydro geographic characteristics of the Yucatan State

Surface streams	Groundwater aquifers	Cenotes
Total absence	Frequent and bulky, form a system of communicating vessels that flow to the sea. Groundwater depth ranging from 2 to 3 meters (coastal strip) up to 130 meters (southern tip)	Located in the centre and northwest of Yucatan. Formed by a total or partial collapse of the limestone dome; locally are called: cenotes, rejolladas or aguadas

(Source: Duch Gary Jorge. *La Conformación Territorial del Estado de Yucatán.* 1988. Adapted from INEGI, 2013)

Table 2. Synthesis of current research

Step	Issues	Method	Current state
1	Current knowledge about groundwater, statues and trends	MFA[a]	Finished
2	Assumptions and calculations (data not reported)	MFA	In process
3	Development of the conceptual model	MFA	In process
4	Identification of actors	SMMA[b]	Finished
5	Definition and weighting of the Individual Capitals	SMMA	Currently planning
6	Analysis of the Livelihood Dynamics	SMMA	Currently planning
7	Definition of the Social Capital (Actor Network)	SMMA	Not started
8	Development of scenarios and feedback	FS[c]	Not started

[a]MFA: Material Flow Analysis. [b]SMMA: Structural Mental Model Approach. [c]FSD: Future Scenarios

Table 3. Examples of tools to be used for interviews

Group	Example of tools	Issues
Experts	Questionnaires, surveys, informal conversations	Risk perception, local capital
	Complete MFA with inputs, outputs, statistics and data about current research body in the groundwater sector	Current knowledge of the system
Local members	Photographs about their social capital, pictograms, semi-structured interview	Risk perception, local capital
	Clear and simplified MFA, videos about groundwater pollution problems,	Current knowledge of the system, desire for further information

Table 4. Data sources for the development of the SMMA

Group	Description	Issues for discussion
Cenote	Local or non-local people living in or in a close proximity of groundwater caves. Owners of cenotes	Groundwater uses, perception of pollution problems
Off cenote	Local or non-local people living some distance away, without easy access to groundwater caves or cenotes but using freshwater from the aquifer	Problems of groundwater, possible influences on the ecosystem, relevance of implementation of programs (e.g., sustainable management, political regulations)
Experts	Local or non-local people working, researching or studying water problems. People working at the governmental level, NGO's, cooperatives	Results from MFA, perception of risk, structure of regulation, strategies for improving regional groundwater management, future perspectives

Table 5. Reported groundwater data in the Yucatan peninsula

Region	Discipline	Issue	Reference
Yucatan	Geography	Description of the cenotes and Mayan communities	Cole 1910
Yucatan Peninsula	Geophysics, geology	Experiments and insights about extraterrestrial impact of a meteor	Alvarez et al., 1980
Yucatan	Geology	Cenotes formation, karst characteristics, description of formation of caves	Gaona-Vizcayno, Gordillo-de Anda and Villasuso-Pino 1980
Yucatan	Hydrology, geography, anthropology	Chemical constraints on groundwater management, regional groundwater supply, policies, past studies in the Yucatan area	Back and Lesser 1981
Quintana Roo		Studying the dynamics of the systems by linking geochemistry and hydrology	Stoessell et al., 1989;
Yucatan Peninsula, Yucatan	Geology, Geography		Perry, Velazquez-Oliman, Socki 1990
Yucatan Peninsula	Geology	Geomorphology of the Yucatan Peninsula, analysis of topographic maps	Lugo-Hubp, Aceves-Quesada and Espinasa-Perenia 1992
Yucatan	Hydrology, Geophysics	Hydrogeology, vulnerability of the aquifer, groundwater pollution	Marin and Perry 1994
Yucatan	Geophysics	Karst features, characteristic of the impact structure of the meteor	Connors, Hildebrand, Pilington et al., 1996
Yucatan	Hydrology, Urban Planning	Hydrogeological reserve, karst, drinking water quality	Escolero, Marin, Steinich et al., 2000
Yucatan Peninsula	Hydrology	Conceptual model of the aquifer, geological features	Villasuso and Mendez-Ramos 2000
Yucatan	Hydrobiology	Biological characteristics of cenotes, water samples	Schmitter-Soto, Comin, Briones et al., 2002
Yucatan	Hydrology	Groundwater management, hydrogeological reserve, karst characteristics	Escolero, Marin, Steinich et al., 2002
Yucatan	Oceanography	Cenotes, isotopic composition, conductivity, depth of groundwater	Socki, Perry and Romanek 2002

		caves	
Yucatan	Hydrology	Groundwater-flow model	Gonzalez-Herrera, Sanchez-y-Pinto, Gamboa-Varga 2002
Yucatan	Hydro geochemistry	Water hydro geochemistry in wells, groundwater management	Cabrera-Sansores, Pacheco-Avila, Cuevas-Sosa et al., 2002
Yucatan	Geography, Geology	Determination of dispersivity and dissolution conduits, karst characteristics	Graniel-Castro, Carrillo-Rivera, Cardona Benavides 2003
Yucatan Peninsula	Hydrogeology	Geological characteristics, karst, geophysical structures	Perry, Velazquez-Oliman and Socki 2003
Yucatan	Ecology	Coastal lagoons, groundwater-coastal interaction, water quality, eutrophication	Herrera-Silveira 2006
Yucatan Peninsula	Geohydrology	Groundwater flows, hydric balance, geohydrology	Cervantes-Martinez 2007
Yucatan	Geohydrology	Sulphates in the groundwater, Pollution, karst characteristics, fertilizers, dilution	Graniel-Castro, Pacheco-Medina and Coronado-Peraza 2009
Quintana Roo	Hydrology, Geology	Groundwater discharge, water quality, coral reefs vulnerability, pollution	Hernandez-Terrones, Rebolledo-Vieyra, Merino-Ibarra et al., 2011
Quintana Roo	Hydrology, Ecology	Karst pollution, herbicides, coastal area, groundwater-coastal interaction	Metcalfe, Beddows, God-Bouchot et al., 2011
Quintana Roo	Hydrology	Groundwater model, porosity, catchment groundwater area, water management	Gondwe, Merediz-Alonso, Bauer-Gottwein