Understanding Socio-Groundwater Systems: Framework, toolbox, and stakeholders' efforts for analysis and monitoring groundwater resources

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Supervised by
Prof Dr Claudia Binder and Prof Dr Wolfram Mauser

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En México aprendemos a resolver problemas, no a publicar papers.

All the effort put in this doctoral thesis is especially dedicated to my mother Nelia Maldonado Echeverria.

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List of Abbreviations and Definitions

APU	Animal Production Unit. Total weight of pigs / 100
Aquifer	Term used for describing a porous geological formation that contains water at full saturation and permits water to move through it under ordinary field conditions
Average Annual Precipitation	Average value of annual rainfall as reported for country –wide measurements over several years
Biodigestor	Anaerobic reactor that converts wastewater into clean water and natural gas
CANACOME	National Chamber of the Industry Sector (Cámara Nacional de Comercio de Mérida)
CBC	Community-based conservation
CICY	Yucatan Center for Scientific Research (Centro de Investigación Científica de Yucatán)
CINVESTAV	Center for Research and Advanced Studies (Centro de Investigación y de Estudios Avanzados)
CIR-UADY	Center for Regional Research – University of Yucatan (Centro de Investigaciones Regionales - Universidad Autónoma de Yucatán)
CDI	National Commission for the Indigenous Peoples Development (Comisión Nacional para el Desarrollo de los Pueblos Indígenas)
CONAGUA	National Water Commission (Comisión Nacional del Agua)
CONANP	National Commission of Natural Protected Areas (Comisión Nacional de Áreas Naturales Protegidas)
COTASMEY	Technical Committee for the Study of the Groundwater System in Yucatan (Comité Técnico de Aguas Subterráneas de la Zona Metropolitana de Yucatán)
CONCITEY	Yucatan Council of Science and Technology (Consejo de Ciencia, Innovación y Tecnología del Estado de Yucatán)
CPR	Common-pool resource
ECA's	Units for water culture (Espacios de la Cultura de Agua)
FIUADY	Faculty of Engineering, University of Yucatan (Facultad de Ingeniería, Universidad Autónoma de Yucatán)
Humidity	% of water contained in a product, *e.g.*, tortilla
IGRAG	International Groundwater Resources Assessment Centre
Indemaya	Yucatan Institute for the Maya Culture Development (Instituto para el Desarrollo de la Cultura Maya del Estado de Yucatán)
INEGI	National Institute of Statistics and Geography (Instituto

Nacional de Estadística y Geografía)

JAPAY	Water Supply Company of Yucatan (Junta de Agua Potable y Alcantarillado de Yucatán)
LGBM	Local Groundwater Balance Model
MFA	Material Flow Analysis
MM	Mental Models
Nixtamal	Raw corn mass that has undergone alkaline hydrolysis with $Ca(OH)_2$, and thoroughly washed with water
Patio	Local family gardens in Yucatan usually containing plants and vegetables for own consumption
PO	Participant observation
Precipitation unit	1 mm = 10 m^3 ha^{-1}
Repda	Registry of Aquifer Users (Registro de Usuarios del Acuifero)
SDG	Sustainable Development Goals
SSY	Ministry of Health of Yucatan (Secretaría de Salud de Yucatan)
Sagarpa	Ministry of Agriculture, Livestock, Rural Development, Fishing and Food (Secretaría de Agricultura, Ganaderia y Desarrollo Rural, Pesca y Alimentacion)
Sedesol	Ministry of Social Development (Secretaría de Desarrollo Social)
SEDUMA	Ministry of Urban Development and Environment of Yucatan (Secretaría de Desarrollo Urbano y Medio Ambiente, Yucatán)
Semarnat	Ministry of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales)
Sefotur	Ministry of Tourism of Yucatan (Secretaría de Fomento Turístico)
Septic tanks	Tanks that are used as means of disposal of domestic sewage especially in rural areas.
Tortilla	Flat corn bread made of maize, *i.e.*, from nixtamal
UE	Underwater exploration
UNESCO	United Nations Education, Scientific and Cultural Organization
YPA	Yucatan Peninsula Aquifer

List of publications

The content of this thesis is based on four scientific journal papers. At the time of writing, three have been accepted for publication.

I. López-Maldonado, Y. 2014. "Towards an Understanding of the Human-Environment System of Mayan Communities: Knowledge, Users, Beliefs and Perception of Groundwater in Yucatan". *The Digital Library of the Commons. Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis.* Indiana University. URL: http://dlc.dlib.indiana.edu/dlc/handle/10535/9408

II. Lopez-Maldonado, Y., Batllori-Sampedro, E., Binder, C., and Fath, B. 2017. "The Local Groundwater Balance Model: Stakeholders Efforts to Address Groundwater Monitoring and Literacy". *Hydrological Sciences Journal*. DOI: 10.1080/02626667.2017.1372857. Available at: http://dx.doi.org/10.1080/02626667.2017.1372857

III. Lopez-Maldonado, Y., and Berkes, F. 2017. "Restoring the environment, revitalizing the culture. Cenote conservation in Yucatan, Mexico". *Ecology and Society*. Accepted

IV. Lopez-Maldonado, Y., and Batllori-Sampedro, E. 2017. "Groundwater Literacy: Bridging the gap between science, policy makers and society". *Water Resources Research* (*manuscript in preparation*).

In this thesis, these papers are referred to by author names and Roman numbers. Additionally, the following publications, related to the topic of this thesis, were co-authored during the PhD studies:

- Lopez-Maldonado, Y. "Understanding couple human-groundwater systems. The case of the past -and contemporary- Mayas of Yucatan Mexico." *Proceedings of the II Open Conference of the Programme on Ecosystem Change and Society 2017, Oaxaca, Mexico.*

- Lopez-Maldonado, Y. "Everyone in our community, at some point, will lose". The inequalities of groundwater between society and ecosystems: The case of the Mayan area of Yucatan, Mexico". *Proceedings of the Resilience Conference 2017*, Stockholm, Sweden.
- Lopez-Maldonado, Y. "Groundwater monitoring requires groundwater knowledge: The transdisciplinary socio-groundwater toolbox". *The Swedish Water Management Conference*, 16-17 May 2017, Gothenburg, Sweden.
- Lopez-Maldonado, Y. & Binder, C. 2016. "The Local Groundwater Balance Model". *Proceedings of the 12th Kovacs Colloquium*, UNESCO Headquarters, Paris International Hydrological Prize and Tison Award Ceremony (Hydrological inputs for water-related SDGS implementation: knowledge, data, indicators, tools & innovations). 15 June 2016, Paris, France.
- López-Maldonado, Y. "Groundwater sustainability: Narrowing the gap between science, policy and society". *Proceedings of the 2016 World Water Week*. 28 August – 2 September 2016, Stockholm, Sweden.
- López-Maldonado, Y. "The early identification of human drivers affecting groundwater resources. Developing a Material Flow Analysis of the Geohydrological Reserve zone in Yucatan, Mexico". *International Institute for Applied Systems Analysis Final Young Summer Program Report.* 1 June - 30 August 2015, Laxenburg, Austria. URL: http://www.iiasa.ac.at/web/scientificUpdate/2015/cb/Maldonado-Lopez-Yolanda.html
- Lopez-Maldonado, Y. and Binder, C. "The early identification of the human drivers affecting groundwater system in Yucatan, Mexico using Material Flow Analysis". *Proceedings of the 42nd International Association of Hydrologist AQUA2015*. Organised by the UNESCO International Hydrological Programme (IHP) and the Rome-based United Nations' Food and Agriculture Organization (FAO). 12 - 19 September 2015, Università degli Studi di Roma "La Sapienza", Rome, Italy.
- López-Maldonado, Y. "Groundwater common pool resources in Yucatan, Mexico**:** Understanding commonisation processes - and anticipating decommonisation – in the cenotes of the Mayan Area". *Proceedings of the*

International Association of the Study of the Commons Conference 2015. 25-29 May 2015, University of Edmonton, Edmonton, Canada.

- López-Maldonado, Y. and Batllori-Sampedro, E. "Why mapping groundwater matters?" *Proceedings of the Mapping Water Bodies from Space 2015 Conference. European Space Agency*. 18 - 19 March 2015, Frascati, Italy.

Two bachelor's theses were supervised and published related to this thesis:

- Dörflinger, M. 2014. Thesis Title: "Stoffflussanalyse des Wasserverbrauchs in Haushalten in Yucatán, Mexiko" (Material Flow Analysis of the Water Usage in Households in Yucatán, Mexico). Bachelorarbeit at Ludwig-Maximilians Universität München, Fakultät für Geowissenschaften, Human-Environment Research Group. Munich, Germany, 2014.
- Neidhardt, L. and Utz, A. 2016. Title: "Modeling groundwater pollution. The case of the ring of cenotes in Yucatán/Mexico". Human Geography and Sustainability – Monitoring, Modeling, Management. Ludwig-Maximilians Universität München, Fakultät für Geowissenschaften, Human-Environment Research Group. Munich, Germany, 2016.

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Yolanda Lopez Maldonado

Summary

Understanding Socio-Groundwater Systems: Framework, toolbox, and stakeholder efforts for analysis and monitoring groundwater resources

Yolanda Lopez Maldonado Doctor of Philosophy September 2017

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Problem

Groundwater, the predominant accessible reservoir of freshwater storage on Earth, plays an important role as a human-natural life sustaining resource. In recent decades there has been an increasing concern that human activities are placing too much pressure on the resource, affecting the health of the ecosystem. However, because groundwater it is out of sight, its monitoring on both global and local scales is challenging. In the field of groundwater monitoring, modelling tools have been developed for improving insights into groundwater characteristics, dynamics, and patterns in the hydrological cycle. Although models are accessible, the drawbacks are: they are not always locally affordable, data are not always reliable, and stakeholders are not included. Global assessments are important, but problems might be exacerbated if we do not examine groundwater from another perspective by considering that its related problems are largely local. An example of this is the groundwater system in Yucatan, Mexico, a place where groundwater is the only source of freshwater for the population and where inhabitants have to deal with pollution problems, salt intrusion, biodiversity loss and resource degradation. Consequently the water situation can quickly reach critical conditions and even small disturbances may have dramatic consequences.

Goal

The goal of this research project is to *"develop a research toolbox for understanding and developing a monitoring system for socio-groundwater systems. The toolbox includes a transdisciplinary methodology to develop a Socio-Groundwater model, to investigate factors that influence the way in which groundwater resources are managed, to support monitoring efforts and approaches to contribute to groundwater literacy"*. The work described in this thesis deals with the design of the framework, characterization and modelling of the system by (i) developing a model by analyzing the relevant fluxes of the groundwater system, (ii) eliciting the stakeholders mental models, their values regarding groundwater use and management, and (iii) proposing a groundwater toolbox to integrate different methods with environmental activities for a better groundwater resource management.

Methods

This thesis is part of a larger project organized in three phases: development of the framework, the toolbox and monitoring. Five different, interrelated, methodologies for system analysis have been developed and employed, including: 1 material flow analysis (to quantify groundwater flows associated with present-day economic sectors), 2 mental models (to analyze stakeholders' risk perception regarding groundwater pollution, by eliciting mental models), 3 underwater exploration (to obtain insights about current status of local wells and sinkholes), 4 community-based conservation (to integrate local values, beliefs and perceptions into groundwater

conservation), 5 environmental activism (to directly involve stakeholders in local well clean-ups, and community events). These methods were developed in a transdisciplinary process with stakeholders spanning sectors including: NGOs, local communities and policy makers.

Analysis and results

We analyzed, in a unique way, groundwater in Yucatan, Mexico, where no other sources of freshwater exist. Applying system analysis and bringing local and scientific knowledge, we adapted our framework and methods to understand socio-groundwater systems. Data was obtained from a range of different sources: literature, national and local statistics, stakeholder's workshops, expert opinions, expert consultation, local interviews, and estimations. Investigation of flows by applying MFA helped us to develop the first Local Groundwater Balance Model. The results from this revealed:

a) high wastewater emissions into the aquifer (*ca*. 6.4 hm^3 $year^{-1}$). Wastewater ranges from grey water to wastewater with high concentrations of organic matter (*i.e.*, discharges from pig farms) and alkaline discharges (*i.e.*, tortilla industry);

b) all wastewater emissions are discharged directly into the aquifer without treatment;

c) poor recycling practices (<1%, relative to the total water emissions).

Mental models of local members and experts were elucidated and discrepancies were found regarding risk perceptions. The results revealed that experts' conceptions were rather unclear and incomplete, based on characteristics of the system. They described fluxes erroneously, vaguely, and depicted unclear flows representing the system. Experts perceive a clear connection with pollution and related health risks. Locals described groundwater as clean drinking water, originating from rainfall, but stored in the ocean. They described fluxes erroneously and they were not aware of the concept of groundwater stored in a porous medium. The local population did not see any connection between pollution (*i.e.*, use of pesticides) and health related risks. Overall, the mental models did not overlap since locals did not have a clear understanding of their influence on the system whereas experts did.

Interviews revealed a profound sense of loss of local and traditional knowledge, a strong desire to learn about groundwater, to restore cultural practices and to revitalize local values. Contemporary governance status and regimes of the cenotes are mostly mixed or unclear. Community respondents did not seem to associate contamination of cenotes and the governance regime, and what that might imply for stewardship responsibilities. Interviewees did not understand that all cenotes are part of a single interconnected groundwater system, and cultural values did not seem to be considered. Speleological records obtained during underwater explorations evidenced current hotspots of pollution due to bad waste disposal local practices. Cenotes explored indicated bad waste disposal practices in open-illegal dumping. Through sinkhole clean-ups, locals were aware of groundwater sensitivity, hazardous materials associated with human activities (*i.e.*, agriculture) and this provided insights into local pollution sources. We collected *ca*. 400 kg of plastics and solid waste from just one of the cenotes explored. Plastic bags, cups, cans and cigarette butts were amongst the top ten items collected. Direct involvement with policy makers, experts and locals was found to be key to guide and validate the project stages in an iterative process, and simultaneously narrowed the gap between science, policymaking and society towards groundwater sustainability.

Conclusions

In the study of the groundwater system in Yucatan, we found that technical solutions to groundwater problems are of importance; however, local stakeholder involvement is crucial. We agree with the relevance of models, but we offer a much more comprehensive view and approach to local groundwater problems since we involved stakeholders during the research process. This is a reliable and versatile methodology that meaningfully contributes to groundwater sustainability and literacy. It can be adapted to the specific social, economic, political, and environmental setting of different regions. A real transformation is required in how we value, manage and characterize groundwater systems since hydrological-only models and single-discipline approaches seemed to have failed. The proposed toolbox, framework and approaches help to identify the patterns of changes in biosphere leading to changes in inequality, as a driver of resource use patterns. To implement SDG 6, our toolbox specifically supports the following Targets 6.3, 6.4, 6.5, and 6.6 (a & b) by: facilitating examination of hotspots of pollution, distribution of flows of hazardous substances, minimizing release of chemicals, ensuring sustainable withdrawals, revealing water extraction trends and sectors with major consumption, strengthening participation of local communities, and safeguarding the ecosystem by recognizing traditional ecological knowledge as an informal norm of monitoring. Our results support the current global monitoring framework of SDG 6, by acknowledging the importance of community participation and that groundwater literacy is essential to effectively address SDG 6 and its water related targets.

Zusammenfassung

Understanding Socio-Groundwater Systems: Framework, toolbox, and stakeholder efforts for analysis and monitoring groundwater resources

Yolanda Lopez Maldonado Doctor of Philosophy September 2017

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Problem

Grundwasser ist das wichtigste zugängliche Speicherreservoir für Süßwasser auf der Erde. Es besitzt eine zentrale Bedeutung als lebenserhaltende Ressource für die Menschen und die belebte Natur. In den letzten Jahrzehnten wächst die Sorge über den Druck, den die menschlichen Aktivitäten auf diese Ressource ausüben, wodurch die Funktionsfähigkeit des Ökosystems gefährdet wird. Da allerdings das Grundwasser unsichtbar ist, verändert sich dessen Erfassung sowohl auf globaler wie auch lokaler Ebene. Im Bereich des Grundwassermonitorings wurden Werkzeuge der Modellierung entwickelt, welche die Einblicke in die Eigenschaften, die Dynamik und in den Wasserkreislauf des Grundwassers erhöhten. Obwohl diese Modelle zugänglich sind, sind auch Nachteile und Schwierigkeiten zu konstatieren: Sie sind nicht immer vor Ort bezahlbar; Daten sind nicht immer zuverlässig; und einige Interessengruppen sind nicht beteiligt. Globale Beurteilungen sind zwar wichtig, aber die Probleme können sich noch verschärft, wenn das Grundwasser nicht auch aus einer Perspektive betrachtet wird, welche den konkreten lokalen Bezug der Probleme berücksichtigt. Um zu einer Überwindung dieser Probleme beizutragen wird in der vorliegenden Arbeit am Beispiel der Grundwassernutzung in Yukatan das komplexe Zusammenwirken von sozialen und natürlichen Systemen in einem Raum mit geophysikalisch wie auch kulturell einzigartigen Bedingungen untersucht.

Ziel

Das Ziel des Forschungsvorhabens ist es, einen Forschungs-Werkzeugkasten für das Verständnis und die Entwicklung eines Monitoringsystems für Sozio-Grundwasser-Systeme zu erarbeiten. Die Toolbox beinhaltet eine transdisziplinäre Methodik zur Entwicklung eines Sozio-Grundwasser-Modells, eine Untersuchung der Faktoren, welche die Art und Weise beeinflussen, in der Grundwasserressourcen verwaltet werden, die Unterstützung von Bestrebungen des Monitorings sowie Ansätze, welche zu Grundwasserkenntnissen beitragen. Die vorliegende Arbeit beschäftigt sich mit der Entwicklung eines Rahmens zur Charakterisierung und der Modellierung des Systems, indem (i) ein Modell entwickelt wird, das die relevanten Flüsse des Grundwassersystems analysiert, (ii) die mentalen Deutungsmuster und die Werte der Interessensgruppen bezüglich der Grundwassernutzung- und Regulierung herausarbeitet und (iii) ein 'Werkzeugkasten' vorgeschlagen wird, der verschiedene Methoden der Umweltnutzung integriert und so zu einem besseres Management der Grundwasserressourcen beiträgt.

Methodischer Ansatz

Wir verwenden fünf verschiedene, miteinander verbundene Methodologien: 1) Materialflussanalyse: um Grundwasserströme im Zusammenhang mit den gegenwärtigen Wirtschaftssektoren zu analysieren; 2) Den Ansatz der strukturellen

mentalen Muster, um die unterschiedliche Risikowahrnehmung der Interessensgruppen bezüglich der Verschmutzung des Grundwassers infolge der mentalen Modelle herauszuarbeiten; 3) Unterwassererkundung, um Einblicke bezüglich des aktuellen und tatsächlichen Status der örtlichen Brunnen und Dolinen zu erhalten; 4) Gemeinschaftsorientierte Ansätze, um lokale Werte, Überzeugungen und Wahrnehmungen in Maßnahmen zum Grundwasserschutz zu integrieren; 5) Umweltaktivismus, um beteiligen Akteure direkt in die lokalen Sanierungsmaßnahmen und Community-Events einzubinden. Diese Methoden werden in einem transdisziplinären Prozess mit den Beteiligten (NGOs, kommunale Gemeinden und politische Entscheidungsträger) entwickelt.

Analyse und Ergebnisse

Untersucht wird das Grundwasser auf der Halbinsel Yukatan in Mexiko, einem einzigartigen Gebiet, wo keine anderen Süßwasserressourcen vorhanden sind. Methoden der Systemanalyse und lokale und wissenschaftlichen Erkenntnisse über dieses Gebiet werden in einer integrierten Perspektive zusammengeführt. Die Daten stammen aus verschiedenen Quellen: Literatur, nationale und lokalen Statistiken, Stakeholder-Workshops, Gutachten, Expertenberatung, lokale Interviews und Schätzungen. Untersuchung über Strömungen durch die Anwendung einer Grundwasserflussanalyse ermöglichten es, ein erstes Modell der Wasser-Balance zu entwickeln und die Schmutzwasseremissionen in die Grundwasserspeicher zu erheben. Die Ergebnisse zeigen:

a) hohe Abwasseremissionen im Grundwasser (ca. 6.4 hm^3/Jahr). Die Abwässer reichen von Brauchwasser bis hin zu Abwässern mit hohen Konzentrationen an organischen Stoffen (z.B. Einleitungen aus der Schweinehaltung) und alkalische Einträge (d.h. Tortilla-Industrie);

b) alle Abwasseremissionen fließen direkt ohne Behandlung in das Grundwasser;

c) geringe Recyclingmengen (<1 %, bezogen auf die gesamten Wasseremissionen). Die mentalen Modelle der lokalen Akteure und Experten wurden erfasst und Diskrepanzen in Bezug auf die Risikowahrnehmung gefunden. Die Ergebnisse machen deutlich: Die Vorstellungen der Experten waren ziemlich unklar und unvollständig bezüglich der Eigenschaften des Systems? Sie beschreiben Ströme fehlerhaft und diffus und beschreiben unabhängige Flüsse, um das System darzustellen. Die Experte sehen einen eindeutigen Zusammenhang zwischen der Verschmutzung und den damit verbundenen gesundheitlichen Risiken. Die Einheimischen beschrieben Grundwasser als sauberes Trinkwasser, das vom Regen gespeist wird, aber im Ozean eingelagert ist. Sie beschreiben Flüsse in unzulänglicher Weise und haben keine Kenntnisse von dem Konzept, dass das Grundwasser in einem porösen Medium gespeichert wird. Die lokale Bevölkerung sieht keinen Zusammenhang zwischen der Verschmutzung (z. B. Einsatz von Pestiziden) und gesundheitlichen Risiken. Insgesamt betrachtet überschneiden sich die mentalen Modelle nicht, da die Einheimischen kein klares Verständnis von ihrem Einfluss auf das System haben, während dies bei den Experten der Fall ist.

Die Interviews haben ebenso einen tiefes Gefühl des Verlusts des lokalen und traditionellen Wissens deutlich gemacht, sowie ein starkes Verlangen mehr über das Grundwasser zu erfahren, die kulturellen Praktiken wiederzugewinnen sowie die lokalen Werte wiederzubeleben. Es scheint, dass der gegenwärtige Regulierungsweise der Cenotes alle vier Formen dieses Regime umfasst, aber meistens in vermischter oder unklarer Weise. Die Befragten der Gemeinden scheinen die Verschmutzung der Cenotes und die Regulierungsweisen nicht miteinander zu verbinden und wissen nicht, was dies für die Führungsaufgaben impliziert Die Antworten deuten darauf hin, dass die Befragten nicht verstehen, dass alle Cenotes Teil eines einzigen zusammenhängenden Grundwassersystems sind und die kulturellen Werte scheinen nicht berücksichtigt zu werden. Die untersuchten Cenotes machen Praktiken der Schmutzwassereinspeisung mit offen-illegalen Entsorgungsweisen erkennbar. Die am stärksten kontaminierten Standorte sind diejenigen mit offenem Zugang. Wir sammelten ca. 400 kg Kunststoffe und feste Abfälle aus nur einem der erkundeten Cenotes. Plastiktüten, Becher, Dosen, Zigarettenkippen waren die am meisten gesammelten Gegenstände. Durch die Erkundung von unterirdischen Gewässern in Höhlensystemen wurden aktuelle Hotspots der Umweltverschmutzung aufgrund der schlechten Praktikern der Müllentsorgung vor Ort belegt. Die Interviews enthüllten das tiefe Empfinden eines Verlusts von lokalem und traditionellem Wissen sowie einen starken Wunsch, mehr über das Grundwasser zu lernen, die verlorengegangene kulturellen Praktiken wiederzugewinnen und lokale Werte neu zu beleben. Durch Säuberungsaktionen in den Dolinen entwickelte die Einheimischen ein Bewusstsein für die Gefährdung des Grundwassers durch die menschlichen Aktivitäten (insbesondere Landwirtschaft) und diese lieferte Einsichten über die Ursachen der lokalen Verschmutzung. Die direkte Beteiligung von politischen Entscheidungsträgern, Experten und Einheimische war ein entscheidender Schlüssel, um die Projektphasen in einem iterativen Prozess zu validieren und zugleich die Differenzen zwischen Wissenschaft, Politik und Gesellschaft zu verringern und Wege für eine nachhaltigere Nutzung des Grundwassers zu erschließen.

Schlussfolgerungen und Hauptaussagen

Technische Lösungen für Grundwasserprobleme sind von Bedeutung; jedoch ist ebenfalls die Einbindung von lokalen Stakeholder von entscheidender Wichtigkeit. Wir betonen zwar ebenfalls die Relevanz von Modellen, bieten aber einen umfassenderen Ansatz zur Betrachtung der lokalen Grundwasserprobleme an, indem wir die Beteiligten während des Forschungsprozesses einbeziehen. Dies ist eine zuverlässige und vielseitige Methodologie mit wesentlicher Bedeutung für den Erhalt der Nachhaltigkeit des Grundwassers. Dies kann auf die spezifischen sozialen, wirtschaftlichen, politischen und ökologischen Bedingungen verschiedener Regionen angewendet werden. Eine echte Transformation ist hinsichtlich der Art und Weise erforderlich, in der wir Grundwassersysteme bewerten, managen und charakterisieren, da die Anwendung von einfachen hydrologischen Modelle und isolierten Ansätze von Einzeldisziplinen fehlgeschlagen sind. Notwendig ist die Entwicklung umfassender, soziale und ökologische Dimensionen integrierender Modelle.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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To my family for all the support during the years. I sustain myself with the love of my family.

To Josué. My love for you will always be there.

Preface

This PhD thesis is based on research carried out from March 2013 to March 2017 at the Department of Geography, Research and Teaching Unit in Human-Environment Relations, Ludwig Maximilian University of Munich (LMU). This work is part of a larger project whose structure reflects the close cooperation among science, policy makers and society. The project group consists of scientific management by Yolanda Lopez-Maldonado, co-management and supervision by Prof. Dr Claudia Binder, LMU, and Dr Eduardo Batllori-Sampedro, Head of the Ministry of Environment in Yucatan (Seduma), as co-authors, and the involvement of three bachelor students from LMU. Furthermore, it involved accompanying groups consisting of members and regional representatives of associations and organizations of different sectors in Yucatan, Mexico, and more than 200 stakeholders.

The work was primarily founded by the National Council of Science and Technology (Conacyt) Mexico (PhD scholarship No. 312243), and by the Potsdam-Institute fur Klimafolgenforschung e.V., Germany. Fieldwork expenses were covered by the Rachel Carson Center for Environment and Society, LMU, Munich, and the Canada Research Chairs.

The research was principally developed at LMU, and included three field trips to the study area in Mexico (June-December 2014, March 2015 and June 2017), a short (4 months) research stay at the Natural Resource Institute of the University of Manitoba (March-June 2015) under the direct supervision of Prof. Fikret Berkes, a Young Scholar Summer Program (June-August 2015) at the International Institute for Applied Systems Analysis, Advanced Systems Analysis Group, Laxenburg, Austria, under the supervision of Prof. Brian Fath, and a Young Scientists Scholar Program at The Beijer Institute of Ecological Economics, the Royal Swedish Academy of Sciences (May-June 2016; May-June 2017) under the supervision of Prof. Carl Folke and Prof. Anne-Sophie Crépin.

Chapter 1. General Introduction

1.1. Groundwater systems in karst

Water is a resource that is constantly circulating in the hydrological cycle and its domain spans several temporal and spatial scales. It evaporates, it changes from liquid to gas or recondenses as a liquid (Oki & Kanae, 2006), but ultimately reverts to liquid water. At the deepest and lower level of the cycle, groundwater has become associated with the highest and most valuable resource for societies due to the ecosystem services it provides. This characteristic makes groundwater an extremely complex and important coupled human-natural life-sustaining resource (Gleeson, Wada, Bierkens, & van Beek, 2012; Richey et al., 2015).

Its importance resides in that much of the freshwater located below the land's surface supplies water to billions of people, thus playing an imperative, if not unique, role in energy, food security, human health, and ecosystems (Gleeson, Befus, Jasechko, Luijendijk, & Cardenas, 2016). Groundwater feeds springs, streams, supports wetlands, maintains soil stability, and contributes to serving human water needs (Giordano, 2009; Gleeson et al., 2016; Morris et al., 2003; Sophocleous, 2002), and accounts for as much as 33% of total water withdrawals worldwide (Siebert et al., 2010).

In groundwater systems, water enters the surface by infiltration and contributes to aquifer recharge (Giordano, 2009). Groundwater flows vertically and horizontally through the aquifers at rates that are influenced by geological and chemical processes (Figure 1.1). Water slowly flows from soil to underground reservoirs, which acts as a filter creating a source for drinking water (Giordano, 2009). However, several factors influence the recharge and infiltration processes, particularly the characteristics of the soil, such as karst terrains (IGRAC, 2015).

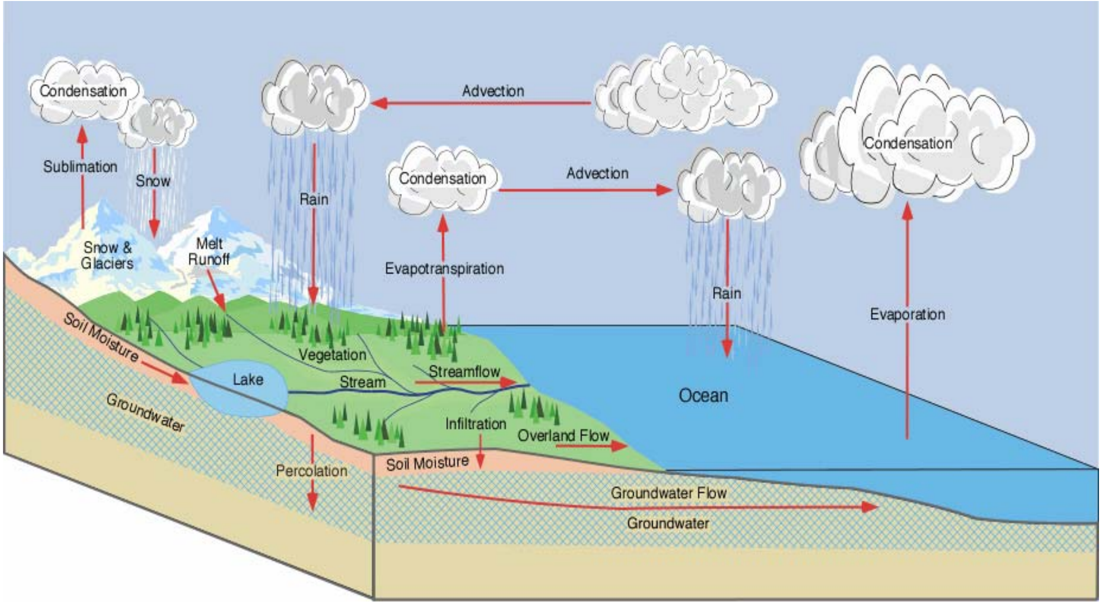


Figure 1.1. The hydrological cycle where water is moving between subsystems, including groundwater (Image from https://www.un-igrac.org).

Karst refers to landforms that are produced primarily by the dissolution of rocks (Winter, Harvey, Franke, & Alley, 1998). Groundwater systems in karst terrains are characterized by channels, dolines, caves, natural wells, and sinkholes or similar depressions. However, they are more highly vulnerable to pollution and a range of environmental impact problems than any other terrain due to the difficulties associated with the development of subterranean networks, and due to the impacts of human activities (Ford & Williams, 2007).

One characteristic of karst aquifers is their individuality - means that every karst system is different and requires the development of specific approaches bearing in mind local contexts (Ford & Williams, 2007). Considering this and the rapid movement of water that might transport contaminants quickly into the system enhancing water pollution, water-quality problems that might be localized can become regionalized. Thus, groundwater karst systems require particular protection and application of specific methods for their investigation (IAH, 2017) (Figure 1.2).

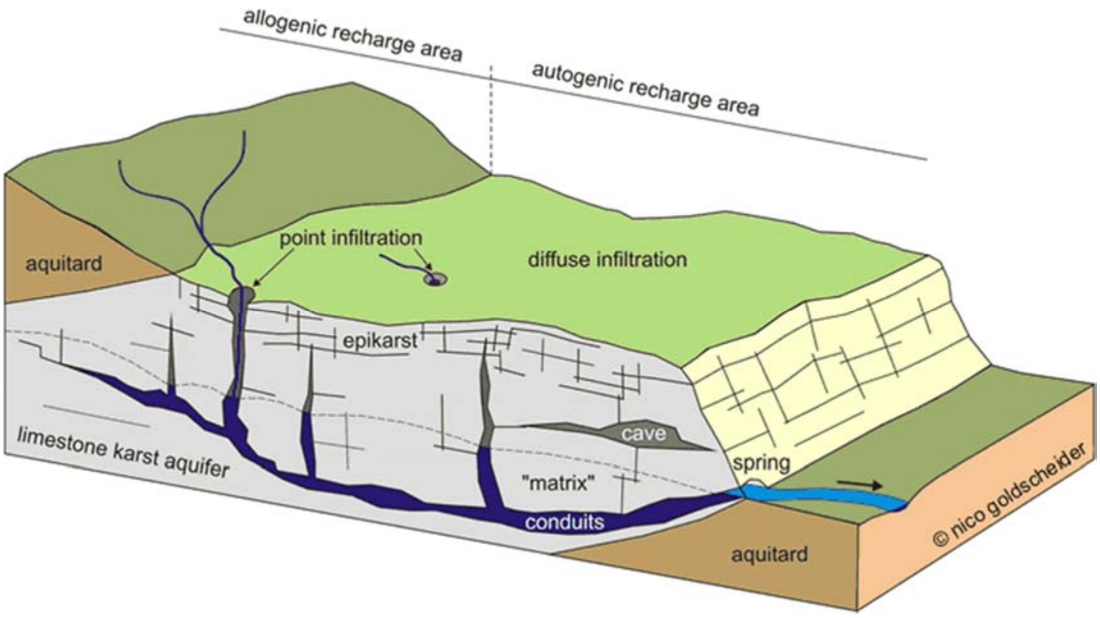


Figure 1.2. Illustration of a karst aquifer. Figure from (http://karst.iah.org/karst_hydrogeology.html)

Karst aquifers are potential sites for hazardous and poor solid waste disposal practices. Contaminants, such as pesticides or faecal bacteria, might enter and reach directly the aquifer directly without filtration. Thus, karst aquifers are difficult to manage and understand due to the complex nature of the resource, which makes preventive measures or remedial processes difficult and sometimes unrealistic.

Groundwater systems exist in many regions of the world (IGRAC, 2015). Three Mexican states, Yucatan, Campeche and Quintana Roo, constitute the Yucatan Peninsula, and share the Yucatan Peninsula Aquifer (YPA). Fed by one of the world's largest karst aquifers, the YPA is the only source of water supply in the Yucatan state (González-Herrera, Sánchez-y-Pinto, & Gamboa-Vargas, 2002). However, as these areas have different economic structures and processes, groundwater problems are not the same.

The groundwater system in Yucatan, Mexico provides an excellent case for the study of local scale groundwater problem in karst terrains without any influence of surface water. However, previous research has primarily concentrated on the hydrogeology of the study area, whereas the social system has received little to no attention (Table 1.1). Thus, the need for scientific data to enable understanding of groundwater systems and their conservation is clear.

Table 1.1. Previous research in the hydrogeology of the groundwater system in Yucatan, Mexico.[a]

Region	Discipline	Issue	Reference
Yucatan	Geophysics	Experiments and insights about extra-terrestrial impact of a meteor	(Alvarez, Alvarez, Asaro, & Michel, 1980)
Yucatan Peninsula	Geology	**Karst characteristics and dynamics**	(Gaona-Vizcayno, Gordillo-de Anda, & Villasuso-Pino, 1980)
Yucatan	Hydrology	Chemical constraints on groundwater management, regional groundwater supply, policies, past studies in the Yucatan area	(Back & Lesser, 1981)
Quintana Roo	Geochemistry	Studying the dynamics of the systems by linking geochemistry and hydrology	(Stoessell, Ward, Ford, & Schuffert, 1989)
Yucatan Peninsula	Geology	Geomorphology of the Yucatan Peninsula, analysis of topographic maps	(Lugo-Hubp, Aceves-Quesada, & Espinasa-Pereña, 1992)
Yucatan	Hydrology	Hydrogeology, vulnerability of the aquifer, groundwater pollution	(Steinich & Marín, 1997)
Yucatan	Geophysics	Karst features, characteristic of the impact structure of the meteor	(Connors et al., 1996)
Yucatan	Hydrology	Hydrogeological reserve, karst, drinking water quality	(Oscar A Escolero, Marin, Steinich, & Pacheco, 2000)
Yucatan	Hydrology	Conceptual model of the aquifer, geological features	(Villasuso & Méndez Ramos, 2000)
Yucatan	Hydrology	Biological characteristics of cenotes, water samples	(Schmitter-Soto et al., 2002)
Yucatan	Hydrology	Groundwater management, hydrogeological reserve, karst characteristics	(O. A. Escolero et al., 2002)
Yucatan	Oceanography	Cenotes, isotopic composition, conductivity, depth of groundwater	(Socki, Perry, & Romanek, 2002)

Yucatan	Hydrology	Groundwater-flow model	(González-Herrera et al., 2002)
Yucatan	Geochemistry	Water hydro geochemistry in wells, groundwater management	(Cabrera Sansores et al., 2002)
Yucatan	Geology	Determination of dispersivity and dissolution conduits, karst characteristics	(Graniel-Castro, Carrillo-Rivera, & Cardona Benavides, 2003)
Yucatan Peninsula	Hydrology	Groundwater flows, hydric balance, geohydrology	(Cervantes-Martínez, 2007)
Yucatan	Hydrology	Sulphates in the groundwater, pollution, karst characteristics, fertilizers, dilution	(Graniel Castro, Pacheco Medina, & Coronado Peraza, 2009)
Quintana Roo	Hydrology	Groundwater discharge, water quality, coral reefs vulnerability, pollution	(Hernández-Terrones et al., 2011)
Quintana Roo	Hydrology	Karst pollution, herbicides, coastal area, groundwater-coastal interaction	(Metcalfe et al., 2011)

[a] Groundwater in Yucatan has been documented mostly from the natural science disciplines.

Following the pathways of groundwater circulating from the environment through its consumption by completely or partially dependent societies and back to water, we can consider groundwater as a continuous common resource, given the high degree of interaction between the society with the ecological system. However, for understanding hydrological processes within the hydrological cycle needs to be also viewed at a wide range of approaches and scales (Winter et al., 1998).

For example, at global scale, groundwater residence times (stocks) can be important for geological processes, but groundwater ages are often inconsistent with social-local timescales. At local scale, human activities commonly affect the distribution, quantity, and quality of groundwater systems making them susceptible to contamination and producing global long-term impacts. These have many consequences in the short and long run: wells become less productive and eventually run dry, groundwater becomes more expensive, aquifers may become exhausted, and ecosystems may be affected. However, since groundwater is used as a common resource, its management represents more a significant societal challenge (Alley, Healy, LaBaugh, & Reilly, 2002; Vrba & van der Gun, 2004). This is principally because the interaction of our societies with this resource is also rapidly changing (Montanari et al., 2013) and the speed of the resource self-regulatation often overcomes the ability of users and institutions to respond effectively.

1.2. Groundwater as a common-pool resource

Historically, societies declined as their natural resources also declined, especially when the resource is a common-pool resource. Common Pool Resources (CPR) are resources that are held in common and for which exclusion is difficult and joint use involves subtractability (Berkes, Feeny, McCay, & Acheson, 1989; Gardner, Ostrom, & Walker, 1990; Ostrom, 2009). Groundwater is a CPR because groundwater exploitation by one user reduces resource availability for others (Ostrom, Burger, Field, Norgaard, & Policansky, 1999).

Groundwater is particularly degraded in places where tit is open access or governed by top-down approaches. In a groundwater common pool situation, when the resource is open access, sometimes this can generate severe free-riding problems since the water extraction of individual agents affects everyone (Levin et al., 2013). From an economic perspective, groundwater is also classified as a CPR subjected to the “tragedy of the commons” wherein users have no incentive to limit extraction to a socially desirable level, resulting in depletion (Aeschbach-Hertig & Gleeson, 2012; Ostrom, 1990; Theesfeld, 2010).

Groundwater systems are in fact more often contaminated than depleted due to several factors including: salinization, highs amounts of nutrients and pesticides, dissolved and non-aqueous chemicals, natural contamination, population growth, urbanization, pumping of groundwater for human use, and in general, due to the lack of effective groundwater governance and unsustainable use (Giordano 2009, Foster 2003). The paradox of groundwater is that despite its critical importance (Famiglietti, 2014), most of the major aquifers in the world are experiencing rapid rates of depletion and pollution (Konikow, 2011).

Moreover, the social and ecological interactions are often difficult to observe and measure, and commonly have been ignored in policies and other considerations, generating conflicts and becoming drivers of inequality. In the case of Yucatan, the environmental consequences of a "groundwater free for all" combined with the fact that groundwater is often poorly monitored and managed (a very common practice in developing countries (Famiglietti, 2014; IGRAC, 2015)), and that local high-resolution statistical data is not available, the population is confronting a greater groundwater risk than is currently recognized.

The understanding, monitoring and management of aquifers is very difficult due to their diversity in uses and users, fuzzy boundaries, irregularities in the development of the information, and uncertainties in their hydrogeological characteristics. Thus, reliable groundwater data are imperative for making knowledge-based and appropriate decisions (van der Gun, 2012). Without understanding the complexity of the groundwater system in Yucatan, countering groundwater depletion, lack of protection, and poor collective cooperation will be unsuccessful.

1.3. Groundwater as a Social-Ecological System

Groundwater is embedded in complex social-ecological systems (SES). It is composed of multiple subsystems with internal variables; they are relatively separable but intermingled producing outcomes and feedbacks (Levin et al., 2013; Ostrom, 2009). Human societies are also complex systems with their own internal variables and subsystems (*e.g.*, institutions or ways of managing such systems). Understanding these complex interactions should encompass a SES approach emphasizing the linkages between environmental (the hydrological cycle) and human systems (the society), the identification of variables, the interactions and outcomes among them, their subcomponents, as well as the socioeconomic and political settings and how they affect, and have affected, each other.

Understanding social and ecological interactions represents a major challenge in the exploration of theories and current frameworks, but also requires methodological adaptations since isolated disciplines do not produce adequate results to characterize groundwater as one socio-groundwater system. A comprehensive perspective of these interactions may be the first step toward an effective water resource management and policy process, since management of one single component is not effective. In view of these difficulties, and considering that these systems have been threatened with a double jeopardy –depletion and degradation-, what is needed is a knowledge-based, common understating of the resource as a one socio-groundwater system.

1.4. Groundwater and the duality of its investigation methods

Natural systems –and all humanly used resources- are not limited to physical systems since they are connected to other cycles, such as biochemical cycles, leading to interactions and interdependencies among them and related to socio-economic and governance systems, such as groundwater systems (van der Gun, 2012). However, due to the interconnectedness with further cycles, the analysis of groundwater as a one socio-groundwater system remains limited. New research is needed to characterize the heterogeneity of social processes with the hydrological cycle, their interlinkages at different spatial and temporal scales, and from transdisciplinary approaches by involving modeling, analytical and management perspectives.

Groundwater shows double interactions, consisting of feedbacks between hydrological and social processes across different spatial and temporal scales. Storage, flows and infiltration, occurs as part of the hydrological cycle, but extractions and pollution, are caused by external social influences, which are shaped by long-term dynamics. This duality of groundwater systems also results in a duality of investigation methods from different disciplines (Table 1.2).

Although the multiple approaches and despite the methods described in Table 1.2 the investigations did provide crucial information about the hydrological cycle, they might overestimate data significance, thus being poor at local --or even regional scales. Similarly, data about the social aspects of water use are not easily available (Fan, 2015; Gleeson et al., 2010; Oki & Kanae, 2006; Wada, 2016). Thus, a combined experimental and theoretical effort is needed to help us to conceive and understand them conjunctively, as “one socio-groundwater system”.

Table 1.2. Investigation methods commonly used to understand hydrogeology of karstic aquifers (Table adapted from (Goldschneider & Drew, 2007)).

Group	Method	Applications	Drawbacks	Social system
1	Geological methods	Aquifer geometry Flows Hydraulic properties	Lack of data	Not included
2	Geophysical methods	Geologic structures Location of conduits	Similar characteristics in different places	Not included
3	Speleological methods	Direct observation Mapping of conduit networks	Inaccessible	Not included
4	Hydrological methods	Water balances Storage characteristics Degree of karstification	Fuzzy boundaries Complexities on karst	Not included
5	Hydraulic methods	Hydraulic parameters Flows Water table variations	Scale-dependency of hydraulic properties Turbulent conduit flow	Not included
6	Hydro chemical methods	Contamination Mixing of water Water rock interactions	Variability Event-based sampling and monitoring	Not included
7	Isotopic methods	Origin and mixing of water Matrix Water-rock interactions	Input function not know Ambiguities in data	Not included
8	Artificial tracers	Flow paths and catchments Transit times	Limited applicability in regional systems with long transit times	Not/partially included

1.5. Groundwater literacy

Groundwater systems are among the most complex and widely accessible freshwater ecosystems, but also the most acutely susceptible to rapid change and depletion. Thus, sustainable groundwater resource management requires good knowledge of the functioning of the systems. As modelling is still one of the most promising tools for groundwater understanding, as demonstrated by recent advances in this regard (Alcamo et al., 2003; Oki & Kanae, 2006; Wada, van Beek, & Bierkens, 2012), its combination and use with methods for the analysis of both social and ecological systems remains important.

Whilst some models and tools are accessible, they are not always locally affordable, data might not be reliable and they do not tend to consider or to influence local knowledge. In addition, in most countries, the data available are poor, unreliable, patchy, outdated, or inaccessible (Theesfeld, 2010). For example, hydrogeologists use analytical methods and computer modelling to assess groundwater systems. Models are usually based on mathematical equations, require global hydrological data, and are essentially centered on large-scale patterns and processes (Fan, 2015). Some of them are focussed on multiple climate projections and consider future global scenarios (Haddeland et al., 2014). Since some of these models might overestimate data, it is important to examine groundwater from another perspective by considering the social system that impact on it.

Good groundwater management also depends on how we use, manage and value the resource (Gleeson, Alley, et al., 2012). Successful monitoring and management often calls for a clear understanding of the groundwater system or groundwater literacy defined here as: *the knowledge of the users about the resource and some of its attributes, and their perception and valuation of their impacts in the system*. We argue that communities need to develop appropriately their monitoring tools appropriately and to produce information to use and monitor groundwater resources properly. Likewise, scientists and policy makers need to consider local conditions, knowledge, and norms to build local scale models since groundwater problems are largely local (Giordano, 2009; Gleeson et al., 2016).

In view of the above evidence, and with an imminent global water crisis (World Economic Forum, 2016), understanding groundwater characteristics is essential for better control, assessment, and comprehension of this unpredictable system. We agree that monitoring, sound aquifer knowledge, and calculation or modelling behaviour are needed in a framework to set objectives and policies (Custodio, 2002). However, groundwater monitoring remains difficult since common and well-established methods for the analysis of groundwater systems and water balances typically require synthesis of the corresponding previous (and often not reliable) databases (Fan, 2016) and they often do not include stakeholders.

These limitations highlight the importance of studies considering the duality of groundwater systems as one socio-groundwater system, and of alternative and simple procedures to groundwater modelling in order to get better and more reliable results. By exploring how local groundwater management is currently organized in a rural setting, we have developed a research toolbox for understanding and developing a monitoring system for socio-groundwater systems. This toolbox includes a transdisciplinary methodology to develop a socio-groundwater model, and to contribute with groundwater literacy.

1.6. Summary and Scope of Thesis

Due to the importance of understanding of the social system as a key component of the hydrological cycle, more reliable, affordable, simple, and easy-to-understand methods and approaches are demanded. Thus, this project takes into account the impacts of human activity as one of the most influential factors causing environmental degradation of groundwater resources. The goal is to develop a research toolbox to understand and develop a monitoring system for socio-groundwater systems. The toolbox includes a transdisciplinary methodology to develop a Socio-Groundwater model. Here we present the most important methods of the toolbox, discuss the advantages, drawbacks and limitations of the individual methods developed during this research, and present a case study analysing a local groundwater basin as a one socio-groundwater system.

We focus on the extensive environmental problems with common pool groundwater resources in the Mayan area of Yucatan in Mexico where groundwater caves account for the majority of karst groundwater flow (Gondwe et al., 2010). In Yucatan these groundwater caves with plenty of freshwater are called cenotes (from the Mayan word *d'zonot*, (Worthington, 1993)) from which societies extract water for several uses. At present, this common groundwater reservoir remains as the main and only source of freshwater for the population, and the natural wells from which water can be obtained. Currently there are more than two million people withdrawing water from this source, and thus maintaining the quality and quantity of water is critical for all. Nevertheless, demand for water is growing, and inhabitants have to deal with water problems. Knowledge about the location, properties, users and values of those groundwater caves, including the community management and uses of the available water, is consequently crucial to understand it as one socio-groundwater system.

This thesis is based on the results from 4 different papers. It includes an introduction to groundwater systems (**Chapter 1**) and the scope of the work. In **Chapter 2**, the goals and research questions are provided. Subsequently, in **Chapter 3**, the framework and approach is described (**Publication I**). The study area and the main methods used in the research for the development of the toolbox, are presented in **Chapter 4**, and explained in further detail in **Publication II**, **Publication III** and **Publication IV**. In **Chapter 5**, the main results obtained with the development and application of the toolbox are presented. **Chapter 6** features a discussion of perspectives for groundwater management which are provided based on the findings of the research and future research directions are outlined. Some concluding remarks are provided in **Chapter 7** to summarise the thesis.

Chapter 2. Goals and research questions

Given the drawbacks related to the absence of effective methods to facilitate the analysis of groundwater resources as a socio-groundwater system, the ultimate goal of this thesis is: "***to develop a research toolbox to understand and develop a monitoring system for socio-groundwater systems. The toolbox includes a transdisciplinary methodology to develop a Socio-Groundwater Model, to investigate factors that influence the way in which groundwater resources are managed, to support monitoring efforts and approaches to contribute to groundwater literacy"***. The thesis is organized in three phases, and the following objectives and research questions are defined:

Phase 1: Analysis of the natural system

A system analysis approach was implemented to analyze the local-scale hydrology of the study area in order to find out the relevant characteristics of the system and to overcome the lack of reliable data. The following objectives were addressed:

1. To physically characterize the groundwater system of the area using data collected through literature review, expert consultation, interviews, estimations – *i.e.*, the main relevant fluxes, the main extractors, etc.
2. On the basis of the collected data, to develop a conceptual hydrological model of the study area with the stakeholders.
3. To develop a numerical model to describe the system with the aim of producing relevant results for solving future groundwater resource problems in the study area.

Workshops, interviews and expert consultation were used to address the following research questions:

- How is the natural system structured?
- What are the total inputs, outputs and groundwater flows in the aquifer?

- How does the resulting Local Groundwater Balance Model (LGBM) support groundwater literacy and future groundwater monitoring?

All the questions of Phase 1 were resolved in **Publication II** of this dissertation.

Phase 2: Analysis of the social system

The elicitation of mental models is necessary to establish agreements and common understandings in natural resource management problems faced by stakeholders in the study area. In this phase the objectives are:

1. To elicit stakeholder's mental models.
2. To characterize present-day local values regarding groundwater management.
3. On the basis of the collected data, to analyze how the scientific community assimilate local knowledge in the study area in relation to groundwater resources.

Using data collected through workshops, informal conversations and interviews, speleological and underwater exploration, the following research questions were addressed:

- What is the structure and content of the mental models of the scientific community -or experts, and the local population, regarding the use and management of groundwater? Are those mental models fragmented? Are the mental models shared?
- How does the local population conceptualize the socio-groundwater system? How does their understanding of the system diverge from that of experts? What role does local knowledge play in the eyes of experts?
- What are the present-day meanings, understanding and values of the system for the local population? Is it feasible, and what are the prospects of adopting a biocultural approach for conservation of cenotes in Yucatan?

All the questions of Phase 2 were resolved in **Publication III** of this dissertation.

Phase 3: Analysis of the Socio-Groundwater System at local level

Declines in groundwater availability, deterioration of global groundwater quality, population growth and rising quality of life, increasing demand for water, along with drawbacks of existing methodologies for analysis of the system, all contribute to far greater levels of stress on our crucial groundwater resources. Thus, a more reliable, straightforward, and versatile methodology to meaningfully contribute towards groundwater sustainability, including a deep understanding of the SES interactions in socio-groundwater system, is required. The objectives in this phase are:

1. To characterize in a particular framework the social-groundwater system of the study area.
2. To provide a research toolbox to analyze the socio-groundwater system in Yucatan which contributes to groundwater literacy.
3. On the basis of the obtained data, to provide support for a more strategic management or implementation of the SDG 6 at local level.

Therefore, the relevant research questions are:

- Can the transdisciplinary Socio-Groundwater toolbox be applied to study the example of demand and use of groundwater resources in the region, even with the lack of reliable data?
- What is needed to implement the SDG 6 in the case of the groundwater system in Yucatan?

The conceptual framework and the questions of phase 3 were resolved in **Publication I** and **IV** of this dissertation.

Chapter 3. The framework

3.1. Framework outline

To study the example of the socio-groundwater system in Yucatan, Mexico, we need a particular framework within which to work. **Chapter 1** provides a comprehensive review of a systematic framework of ecological and social information needed to understand complex groundwater systems. Our study is set up in the Social-Ecological Systems framework (Ostrom, 2007, 2009) since it can be applied to the relatively well-defined domain of a common-pool resource situation, according to rules and procedures determined by an overarching governance system (Anderies, Janssen, & Ostrom, 2004). We chose this framework since it seems to be the only framework that treats the social and ecological systems in almost equal depth (Claudia R. Binder, Hinkel, Bots, & Pahl-Wostl, 2013). As such, this chapter is devoted to exploring this framework, with the aims to analyzing the ecological system (to determine their characteristics and natural conditions), and the social system (according to the local context and conditions).

The multi-level framework, as developed here, involves both the human components of the system (operations, rules, policies and laws), the biophysical components of the ecosystem and the system knowledge pertinent to the dynamics of environment and resource use (Figure 3.1). The underlying understanding is that groundwater problems in the study area are the result of different forces and a complex network of situations and concerns dictated by hydrological conditions, spatial and demographic patterns, complex political economy dynamics, technical considerations, and local circumstances. Five dimensions are defined in the framework (Table 3.1). The model in Figure 3.1 below illustrates the five elements of the socio-groundwater system in Yucatan.

Table 3.1. The five dimensions for the case of the socio-groundwater system in Yucatan, Mexico.[a]

Entry	System	Description
1	Natural	It refers to the groundwater system of Yucatan, Mexico
2	Resource units	It refers to the freshwater moving in the aquifer
3	Social	It refers to the Maya (those with a historical continuity in resource use practice) and non-Maya society who inhabit the Yucatan State
4	Users	It refers to the large number of users in Yucatan that use and depend completely in the resource
5	Governance	It refers to the government systems that control the rules of use of the cenotes and the resource in question
6	Knowledge system	It refers to the cumulative body of knowledge of the local population, the practice, and belief, evolving by adaptive processes, handed down through generations by cultural transmission, about their relationship with their environment

[a] Based on the Social-ecological system framework (Ostrom, 2009) and the Adaptive Co-management Approach (Berkes, Colding, & Folke, 2000).

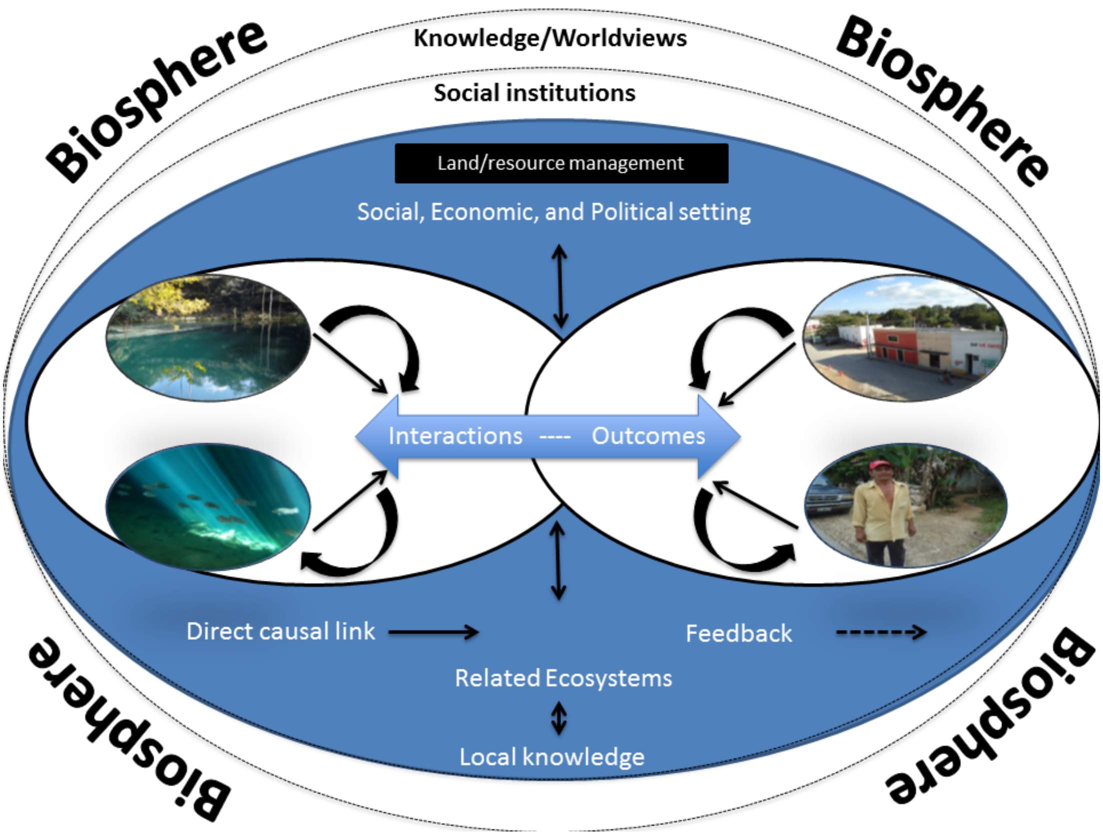


Figure 3.1. The multilevel framework showing the main components of the Socio-Groundwater System in Yucatan. Based on the Social-Ecological System Framework (Ostrom, 2009) and the Adaptive Co-management Approach (Berkes et al., 2000).

The interactions among the three major components in the framework: the natural (groundwater system), the social (users and uses) and the knowledge system (values and perceptions), are shown in Figure 3.1. Here, the knowledge system is a key element that represents the societal values and preferences, which tend to be shaped by the long-term dynamics of the human-water interrelationships. The underlying understanding is that if social and ecological systems are approached as complex systems, it makes sense to include the worldviews and knowledge of the people who use the resource since this seems fundamental of being able to effectively address current groundwater problems. The framework emphasises that resource knowledge or, in this case, groundwater literacy, can be one of the possible approaches towards solutions. It is based on the premise that the inclusion of local knowledge can support more coherent and effective decision-making, and better facilitate follow-up and monitoring.

3.2. Combination of methods for the study of socio-groundwater systems

In this thesis we propose a toolbox developed by and for the stakeholders to understand, develop and implement analysis and monitoring system of current environmental conditions of socio-groundwater systems. The toolbox includes a transdisciplinary methodology to develop a socio-groundwater model, to investigate factors that influence the way in which groundwater resources are managed, to support monitoring efforts and approaches to contribute to groundwater literacy. The toolbox combines five methodologies; for each component of the framework specific methods were developed and implemented. The Material Flow Analysis method (MFA), and the elicitation of Mental Models (MM) of the actors involved, together with speleological and underwater exploration (UE), community-based conservation (CBC) and cenote clean-ups were combined with the aim of understanding the groundwater systems problems in the case of a local aquifer in Yucatan.

MFA is a method to analyze and understand the flows and exchanges of material and energy with the environment (Baccini & Bader, 1996). It has become a useful tool for resource management especially in developing countries, including its applicability to investigate hazardous materials for environmental risk assessment in water bodies (Palmquist & Hanæus, 2005). The application of MFA allows for data analysis and setting up of monitoring concepts.

'Mental models' are internal and personal representations of a specific domain of knowledge (Schnotz, 2001; Vosniadou, 1994; Vosniadou & Brewer, 1992). It is a construction resulting from a personal perspective of the world. To correctly diagnose local community members preconceptions, experts should be aware of their own mental models and should have an adequate comprehension of the groundwater system that is scientifically accepted. Thus, elicitation of local members preconceptions and mental models of the stakeholders can be seen as a crucial step in the process of achieving groundwater literacy in the case of Yucatan.

Voluntary compliance with regulatory provisions is strongly linked with mental models, which when ignored leads to poor groundwater management (Theesfeld, 2010). Traditions and local knowledge shape these mental models. Thus, we characterized and surveyed traditional local knowledge and values, to interpret feedback from the environment in order to see how this guides the direction of resource management in the study area. Through a biocultural approach we describe local strategies in biocultural conservation, the impact of these activities and opportunities for developing own rules-of-use of the resource in question (Maffi & Woodley, 2010; Stephenson, Berkes, Turner, & Dick, 2014). We argue that in Yucatan, local knowledge, ethnic cultural values, and local actions might also be decisive factors in the success of groundwater management options. Biocultural conservation was implemented to bridge the gap between scientific conservation and local and indigenous values.

Since most of the caves and cenotes explored are largely hidden from view and not apparent, it is important to perform speleological exploration to find and document the places (Kambesis, 2007). Photography, drawings, maps and video documentation were implemented and this might serve as a baseline for future cave research in the study area.

Chapter 4. Methodology

4.1. Study zone

Yucatan is located in the southeast portion of Mexico and is within the hydrological unit area of the Yucatan Peninsula Aquifer, which includes the states of Yucatan, Campeche and Quintana Roo. The total area of Yucatan is 124,409 km^2 and the population is nearly 2.1 million inhabitants (INEGI, 2015). The aquifer is karstic and unconfined, except in the coastal zone (Figure 4.1).

Figure 4.1. Map of Yucatan showing the Geohydrological Reserve (green zone), the municipalities (black dot) and cenotes explored (red dot). Source: Own work.

The landscape in the study area is defined by a highly permeable karstic soil. Two consequences of that are the notable absence of rivers or permanent freshwater resources within the area and a high number of sinkholes or natural wells (locally called cenotes). With more than 2000 cenotes within the Yucatan state, and around 400 groundwater cenotes in the study area, groundwater is the only source of freshwater for the population. National and international institutions such as The UNESCO Biosphere Reserve Program, the Ramsar Convention and The Mesoamerican Biological corridor have recognized the scientific, cultural and historical importance of the area.

In the study area, it is easy to locate groundwater caves and cenotes or natural sinkholes due to the calcareous soil, from which societies extract water for several uses. However, increasing demands on this resource, combined with changing land use practices, aging infrastructure and tourism pose significant threats to the system. Some problems are contamination with high levels of organic matter, faecal organisms, chemical compounds and detergents, etc. in both, rural and urban areas (Pérez Ceballos & Pacheco Ávila, 2004).

The study area also contains diverse habitats, vegetation zones, cenotes and aguadas that are part of a Geohydrological reserve (Pacheco Ávila, Calderón Rocher, & Cabrera Sansores, 2004), a priority area for environmental protection established in 2014 with the aim to secure the provision of water for the metropolitan region (Table 4.1). In the Reserve there are thirteen municipalities and all of them are part of the recharge zone of the Ring of Cenotes[1]. The aquifer is highly permeable, and therefore untreated sewage reaches the aquifer quickly (Oscar A. Escolero et al., 2005). The months with highest temperatures are July and August, whereas the lowest temperatures are in December and January (Villasuso & Méndez Ramos, 2000). Rainfall is reflected as a non-uniform spatial distribution (CONAGUA, 2012).

[1] The Ring of Cenotes is an important and unique feature of the Yucatan Peninsula's hydrogeology: this unit is formed by a complex system of >2000 sinkholes (locally called cenotes) that cover approximately 5 km arc wide with a radius of 90 km in the Yucatan state (Perry et al., 1989). The Ring is product of a large meteor impact 65 million years ago, which fractured the surface layers of the Earth's crust and led to the ring alignment of the aquifer outcrops (Pope, Ocampo, & Duller, 1993; Sharpton et al., 1992).

Table 4.1. List of the communities part of the GR zone, and selected for the study of the socio-groundwater system in Yucatan.

Entry	Community	Population[a]	Cenotes reported[b]	Cenotes explored	Methods
1	Acanceh	15,337	11	1	UE
2	Timucuy	6,833	5	1	UE
3	Seye	9,276	3	1	UE
4	Cuzama	4,966	68	3	MM/Interviews
5	Homun	7,257	114	1	UE
6	Tecoh	16,200	128	2	MFA
7	Tahmek	3,609	2	-	Interviews
8	Hoctun	5,697	3	-	Interviews
9	Hocaba	6,061	4	-	CBC
10	Xocchel	3,236	1	-	PO
11	Sanahcat	1,619	20	-	CBC
12	Huhi	4,841	22	4	Clean-ups
13	Tekit	9,884	31	1	MM

[a] For the year 2010 (Source: http://www.beta.inegi.org.mx/app/areasgeograficas).
[b] Officially reported on the public database (Source: http://www.seduma.yucatan.gob.mx/cenotes-grutas/censo-cenotes.php).

The groundwater system of Yucatan is a suitable for setting for a study to address groundwater common pool issues since property rights are not well defined and where groundwater management has evolved from long surviving traditional common institutions but which at at one point they were absent (**Publication III**).

4.2. Research procedure

Management of groundwater not only requires improved understanding of water flow patterns, but also the social process impacting on it, and thus getting stakeholders involved was crucial. A system approach was implemented and developed during the different project stages, illustrated in Figure 4.2.

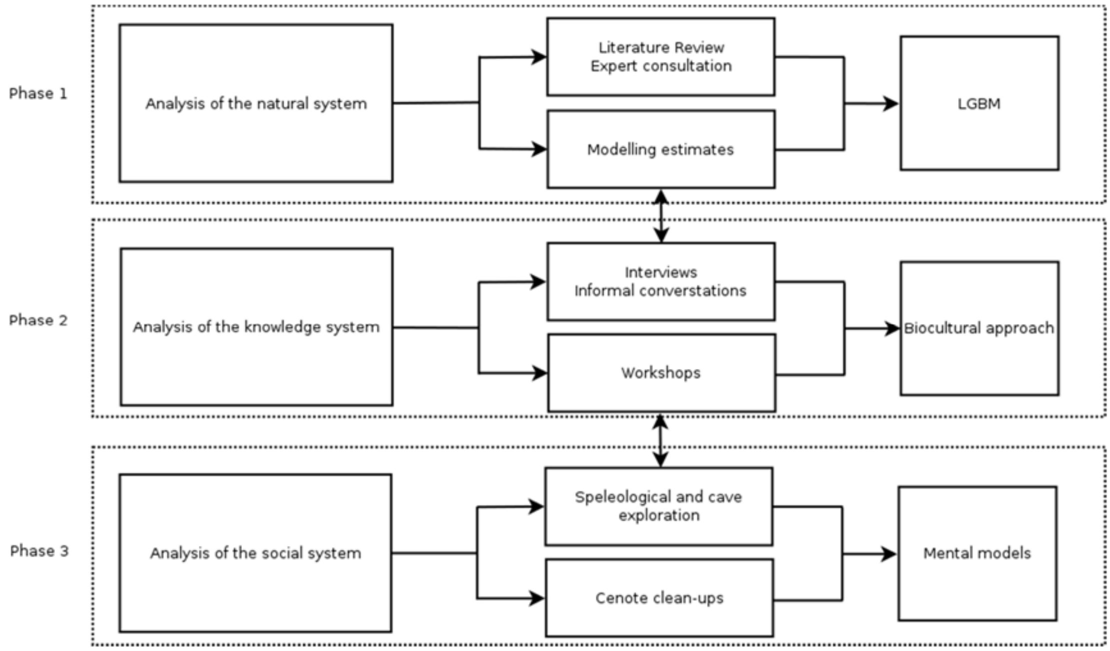


Figure 4.2. Research project stages for the analysis of the socio-groundwater system in Yucatan, Mexico.

4.3. The Transdisciplinary Socio-Groundwater toolbox

The available methods in groundwater system analysis include hydrological and geophysical approaches, as well hydraulic techniques. In this project we applied five different, interrelated, methodologies from both the social and natural sciences, illustrated in Figure 4.3.

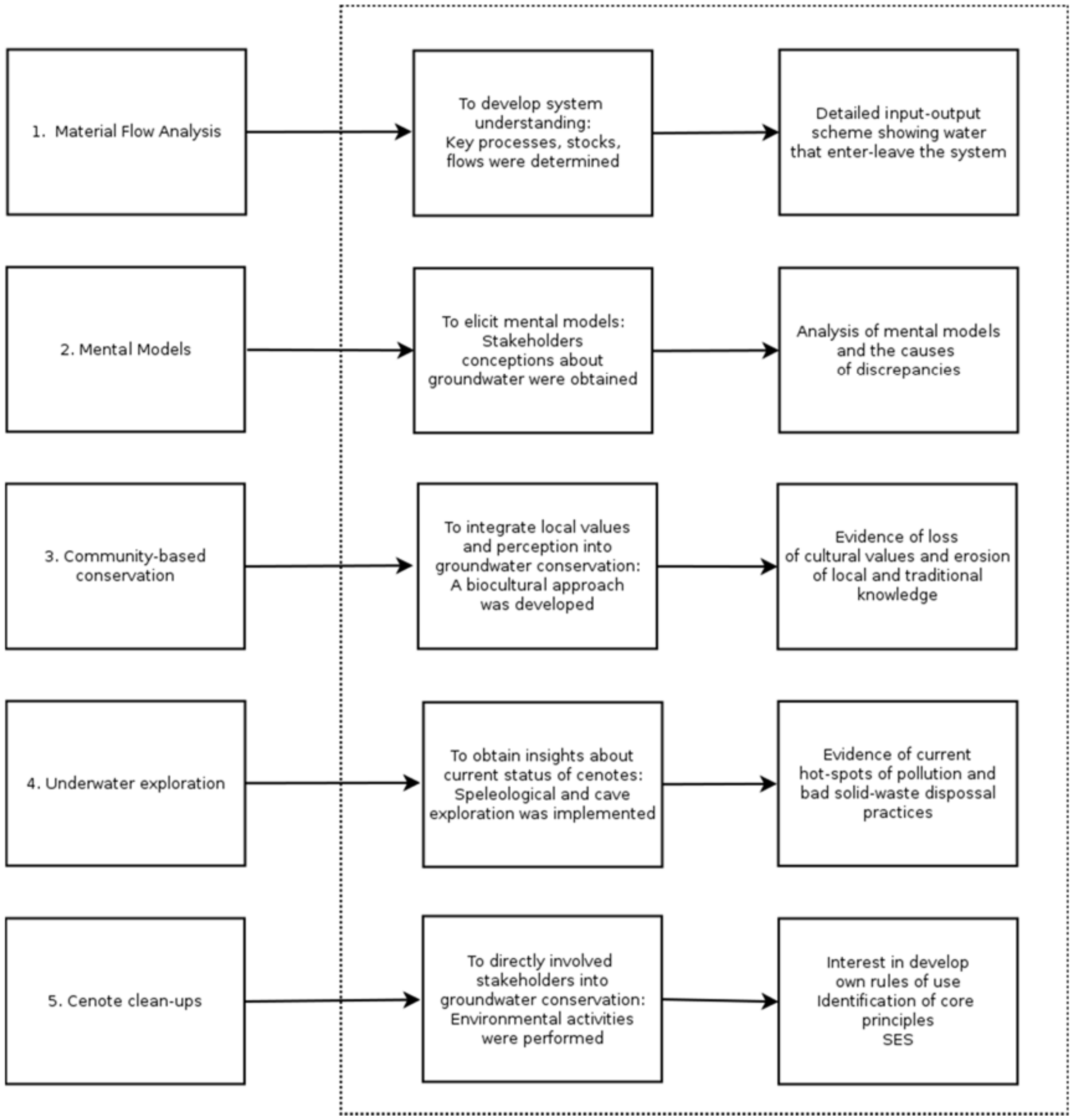


Figure 4.3. Summary of the transdisciplinary socio-groundwater toolbox developed for the case study of the groundwater system in Yucatan.

4.3.1. The Material Flow Analysis Method for the groundwater system in Yucatan

The Material Flow Analysis (MFA) method was applied to quantify groundwater flows associated with present-day economic sectors. By using applied system analysis, mass balance, estimations and current published data, the flows were accounted for. Information from a variety of institutions and sources, including the water sector, water supply company and local communities, etc. was collected. We started with the creation of an initial system analysis of the defined study area as described in section 2.1, based on expert opinion. Then, the stakeholders were asked to (i) develop the system analysis, (ii) provide data on the flows and related sources, and, (iii) validate results in an iterative process by comparing the initial diagrams. Based on these data the LGBM was elaborated and related to a regionalized groundwater balance. Inputs and outputs to the aquifer were depicted using STAN software. The five steps to construct the LGBM are:

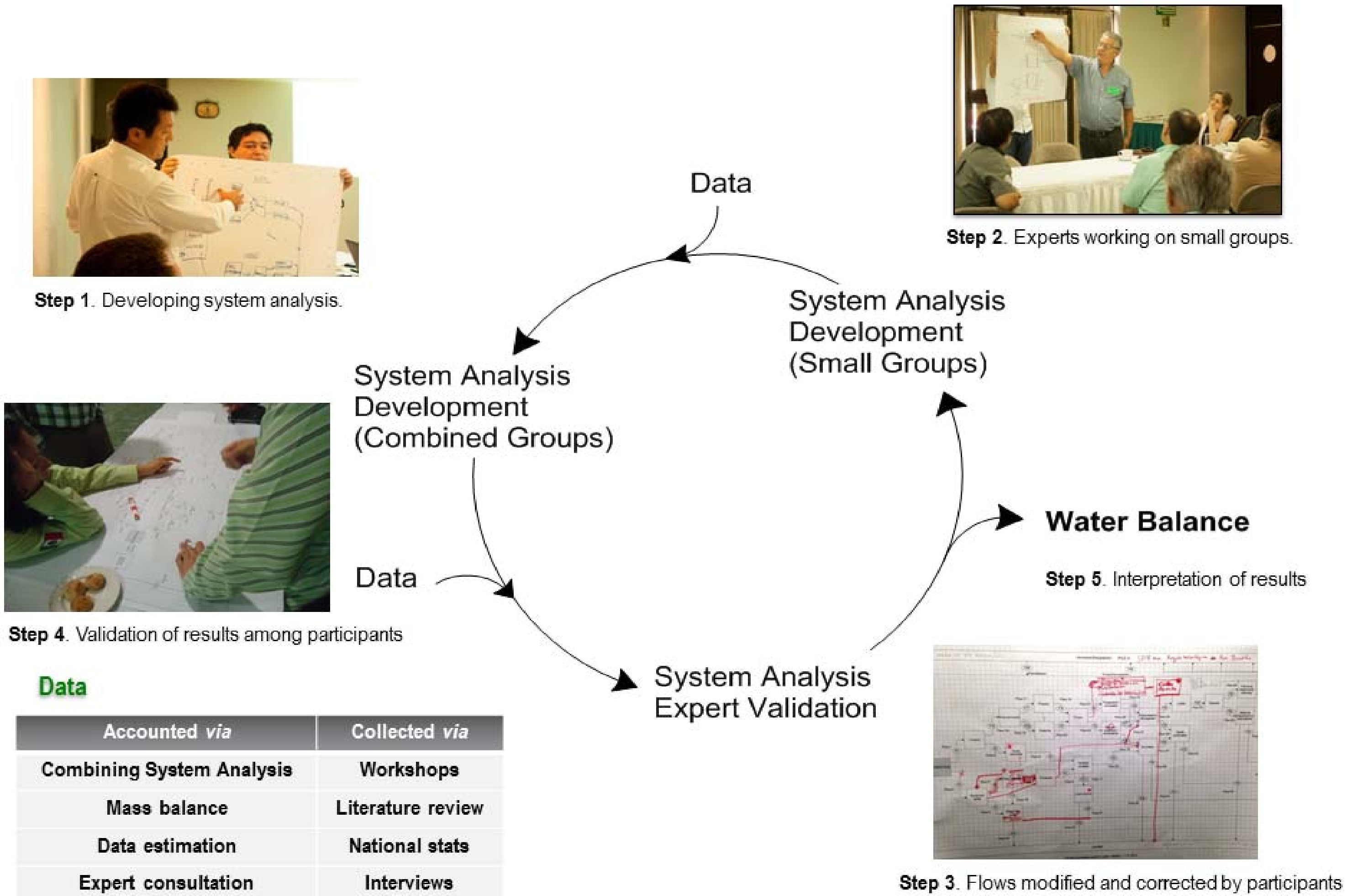
System boundary definition: In the first step, a system boundary was defined in space and time (Baccini & Bader, 1996; C. R. Binder, Schertenleib, Diaz, Bader, & Baccini, 1997). The hydrological system boundary is the GR zone in Yucatan, which includes thirteen municipalities located within the Ring of Cenotes, whereas the aquifer and atmosphere were located outside the system boundary. The flows of groundwater into, out of, and through the system boundaries were analyzed. The municipality of Tecoh (16,200 inhabitants) was selected as the study area to apply the method. Tecoh is part of the recharge zone of the GR zone and receives pollutants from intensive agriculture, particularly from southern parts of the state (Polanco Rodríguez et al., 2015). The same processes selected for the system analysis were used for the water balance with the analysis conducted for the year 2014.

Identification of relevant flows, processes, and stocks: Five relevant processes: extraction, distribution, uses, treatment and recycling were identified, defined and validated in workshops with stakeholders working within the water sector. The stakeholders were given the first draft of the system analysis, which was previously developed by the authors as described in step 1. Stakeholders were asked whether the processes and flows identified were in their experience correct. Following this, they were asked to fill in missing information, values, and were also the basis knowledge for all the flows (For a detailed overview of the system analysis approach used during the research process see Supplementary Material of **Paper II**). Five processes (extraction, distribution, uses, treatment, and recycling) were identified and a total of 39 flows were established. Groundwater was the substance used for the water balance.

Substance flow diagrams: In the third step, we developed substance flow diagrams by combining system analysis from the gathering of local and scientific knowledge.

Water balance: In the fourth step, the water balance was estimated. The water supply company, Junta de Agua Potable y Alcantarillado de Yucatan (JAPAY), supplies water to 90% of the urban households in the region. Rural households are water self-sufficient but receive technical support from JAPAY. In addition to this, municipalities also receive water for a main pumped source that consists of legal concessions available for those who want to extract water for several uses from the aquifer. Tecoh, similarly to the other 105 state municipalities of Yucatan, has only one main water source: the groundwater system. This also means that water can be extracted from local wells and stored in tanks without a concession from Conagua (National Water Commission). Groundwater is pumped directly to the households, and this transportation process has an estimated efficiency of 60%. In general, most rural households also extract water from their own wells, locally called *pozos*. Calculations were made considering one year (2014) since it was the year with most available and reliable statistical data. We estimated the groundwater balance as the sum total of inputs, stocks, and output flows. First, we selected primary sources of information about the total extracted water volume based on national and regional statistics. Expert consultation was made to get local data as proposed by some authors (Gleeson, Wada, et al., 2012). We then calculated flows at local scale and the associated outputs (see Supplementary Material of **Publication II**).

Interpretation of results: In the fifth step, the results obtained were interpreted and the method was adapted to be applied in further sectors (*e.g.*, the livestock and industry sector). With the aid of Sankey diagrams within each sector, obtained using STAN software (Cencic & Rechberger, 2008), the Sankey flows depicted the directed outputs of the human system to the aquifer and thus indicated how human activities influence the system. The steps for the development of the first Local Groundwater Balance Model are presented in Figure 4.4.



Accounted *via*	Collected *via*
Combining System Analysis	Workshops
Mass balance	Literature review
Data estimation	National stats
Expert consultation	Interviews

Figure 4.4. Five steps for the development of the Local Groundwater Balance Model.

4.3.2. The Mental Model-building process

Mental models (MM) were elicited to analyze stakeholders' views about the groundwater system and their conceptions of the related groundwater pollution problems. For the application of the MM two groups of participants were selected: 1) a group of experts from different fields of expertise and disciplines (*e.g.*, hydrologists and geographers etc.) (n=10), currently working in the water sector, and 2) a group of local members (*e.g.*, NGO's, divers, members of young committees, members of local associations) (n=10) making specific related decisions regarding groundwater use and management. The two groups attended workshops designed by the author in order to ensure that the two groups were comparable and equivalent in terms of the topic for discussion. Group 1 (experts) was selected during the workshop for the elaboration of the LGBM. The members from the group 2 (locals) were selected by using the 'snowball technique'.

The two groups completed a specially designed interview to determine their existing knowledge about groundwater: the basic function, boundaries and questions about the features of the system. We used informal conversations and asked the participants to give a description of their understating of groundwater, and to draw a sketch of their ideas concerning groundwater flows and occurrence in nature. Subsequently we used the results to elicit their mental models. The interviews comprised a two-hour session with each participant by the author. Questions about the connectivity of the system, the porous media, among others, where developed in order to support stakeholders to create a mental representation of the system, which includes information about its shape, characteristics and dynamics. The questionnaires were developed through extensive work with valuable help from a second researcher (Psychologist) from the study area, and designed to provide information about knowledge of certain concepts related to the resource in question. This researcher checked the questions for adequacy and format. After asking some of those questions (*e.g.*, How the groundwater system function? How does rain become groundwater?) and eliciting drawings (*e.g.*, Could you draw the groundwater system?) we implemented discussion, and informal conversations related to solving pressing groundwater problems in the region (*e.g.* water management, pesticides, agriculture, etc.). Drawings were used to explore mental models of the participants, and block diagrams were used to explore participants understanding of the concepts of fluxes and groundwater occurrence. Given that stakeholders of group 2 are exposed to the information provided by group 1, we considered it important to ask questions which had the potential to test the usefulness of this information. Each interview was taped and transcribed.

Informal conversations were conducted with the two groups to explore how they constructed their ideas about the water cycle, the distribution of groundwater, the movement of water under the ground, pollution, etc. Following previous research (Reinfried, 2006; Vosniadou, 1994; Vosniadou & Brewer, 1992) we tried to see if we could find evidence in the way experts and locals conceptualize groundwater systems. The mental model building process is presented in Table 4.2.

Table 4.2. The mental model-building process for the case of the socio-groundwater system in Yucatan.

Phase	Experts activities	Local members activities
Preparation	Selection of a group of experts working on the water sector. Ascertains views from the literature	Selection of a group of local members in the community
Elicitation of experts mental models	Interviews during workshops with this group to elicit their mental models	Interviews during workshops with this group to elicit their mental models
	Drawings	Drawings
Elicitation of local members mental models	Graphic representation of experts mental models	Use of graphic representation of experts mental model to elicit local members mental models
Relational model	Relational model of the interactions participants with respect to the specific issue	Relational model of the interactions participants with respect to specific issue
Comparison and interpretation to find discrepancies	Articulate and compare the experts mental models within their group	Interpretation of local members mental models and compare them with experts ones to find discrepancies

4.3.3. A biocultural approach for conservation

A biocultural approach for community-based conservation (CBC) was implemented to integrate local values, beliefs and perceptions into groundwater conservation efforts. In dealing with the erosion of both natural and cultural values in Yucatan, we adopted the concept of community-based conservation, *i.e.*, resource management or biodiversity protection by, for, and, with local communities. Primary data were collected through a triangulation of four methods: (a) participant observation, (b) open-ended interviews, (c) discussions with stakeholders and authorities, and (d) underwater exploration of cenotes, in addition to hydrological findings reported elsewhere. Secondary data were also used, including exhaustive review of karst inventories and official reports from the Ministry of Environment of Yucatan (SEDUMA, 2014). More than 400 reports were analyzed to determine cultural elements and human-made karst modifications. We used literature sources for background, along with ethnographic descriptions of the communities. This large dataset made it possible to develop an interview guide and to test our questions.

Fieldwork and interviews were developed during different stages from 2014 to 2017, over a period of 10 months. We applied the snowball technique in order to interview local people in the communities. Participants from various agencies and sectors were interviewed, including members and experts of the water sector (*e.g.*, the National Water Commission, the water supply company), socioeconomic sectors (*e.g.*, members of the maize industry, representatives of the livestock sector), experts from local institutions (*e.g.* members of the Technical Committee for the Study of the Groundwater System in Yucatan), and local members. Interviews of 21 experts working in different sectors provided representative data to examine local opinions of this group. The interviews also included local people from the communities in the study area and around the perimeter of the reserve, allowing comparisons on groundwater and cenote issues to be made between those living near Merida, the capital of Yucatan State, and those living in rural areas. One community in the state of Campeche was also included to provide an example of how opinions in that region differed from opinions in Yucatan. In relation to the total sample of 109 participants, we ensured that this sample was regionally representative.

We designed and carried out two workshops, one with a group of experts and one with locals. For the interview process, a group of experts was selected (Technical

Committee for the Study of the Groundwater System in Yucatan), based on their previous experience of groundwater and cenote issues. The Units for Water Culture (ECA) members were convened by invitation with the support of the Ministry of Health of Yucatan. We implemented informal conversations and interviews with the participants. The objectives were to investigate how people ascribed meaning to cenotes in Yucatan and to explore possible solutions about how cultural and spiritual values could be recognized for a better groundwater management. Interviews included general socio-demographic questions about participants such as gender and age, and one specific section related to the significance of cenotes. Interviews were elaborated based on the findings during the revision of the SEDUMA reports. The interview stage was followed by informal conversations that were valuable since they allowed a robust understanding of how cenotes are perceived by participants.

Overall, the project focused only on communities that had not been previously explored by SEDUMA (2014). Twelve cenotes in the Reserve, including caves, were explored in November and December 2014. The communities were selected based on their geographic location (located in the perimeter of the Reserve). We visited some families, which have cenotes in their gardens (*patios*) and carried out informal conversations for information about how they took care of their cenotes. Overall, all the cenotes were registered mapped and video-recorded; speleological drawings, which included formations, biodiversity and ancient cultural material, were made with the support of local divers. The precise locations of the sites explored are not revealed. There have been few archaeological cave surveys and projects in the area, including the studies performed in the SEDUMA database. Using SEDUMA survey of cenotes in the area as baseline, cenotes were explored and the results obtained complemented SEDUMA reports including videos, photos, interviews, drawings and reference books and papers than can be used for further research in the area.

A case study approach was used (Yin, 2009). We explored the communities, carried out participant observation in two of them and conducted interviews (N=109) with 69 local Maya people, 21 academics, three government officials, one tourism operator, two cave divers and 13 others working in different water related sectors. These were complemented by informal conversations with a wider range of people. We used our previous knowledge of the area, and snowball technique to identify community leaders and representative participants. We asked about current knowledge of cenotes near the community, since in most cases local people did not know exactly where the cenotes were located but did know that they existed. We held informal conversations with underwater explorers to get information of cenotes from a speleological point of view. We asked about photos or cave material that informants considered as illustrations of cultural importance of cenotes. In the communities we began by asking local members about Mayan words they used to describe water quality. We asked questions about current knowledge of cenotes near the community, since in most cases local people did not know exactly where the cenotes were located, but they did know that they existed. The transcripts of interviews were analyzed for themes that occurred frequently.

4.3.4. Speleological and underwater exploration

We performed underwater exploration and speleological prospecting to gain insights into the current status of local wells and sinkholes in terms of pollution. Speleological prospection was performed in order to produce detailed cave maps to illustrate the geometry of the cave and the karstic conduit networks. Speleological records obtained provided information about architectural formations and possible cultural material of importance. Exploration has been ongoing in the area over the past 5 years, although despite this progress, a complete understanding of the complex cave network is not yet fully realised. Thus, a systematic documentation of the selected caves was necessary to understand the geology of the area. We consulted the SEDUMA surveys, trip reports, and used this information to plan our exploration. Narrative descriptions about caves and passages were also obtained. For the speleological prospection, vertical and horizontal progression techniques were applied (Cuenca Rodriguez et al. 2010).

Geomorphological characteristics, hydrological factors, presence of biodiversity and cultural traces, as well as pollutants were noted. Cenotes were classified in relation to current use, visible pollution, presence of cultural material and governance regime using an “index card” system (Figure 4.5) (**Publication III**), and to obtain information related to the institutional system, legislation, governance and policy regulations of the sites explored since some of the information found during fieldwork did not overlap with the information published on scientific literature. The equipment used in the exploration was provided by SEDUMA.

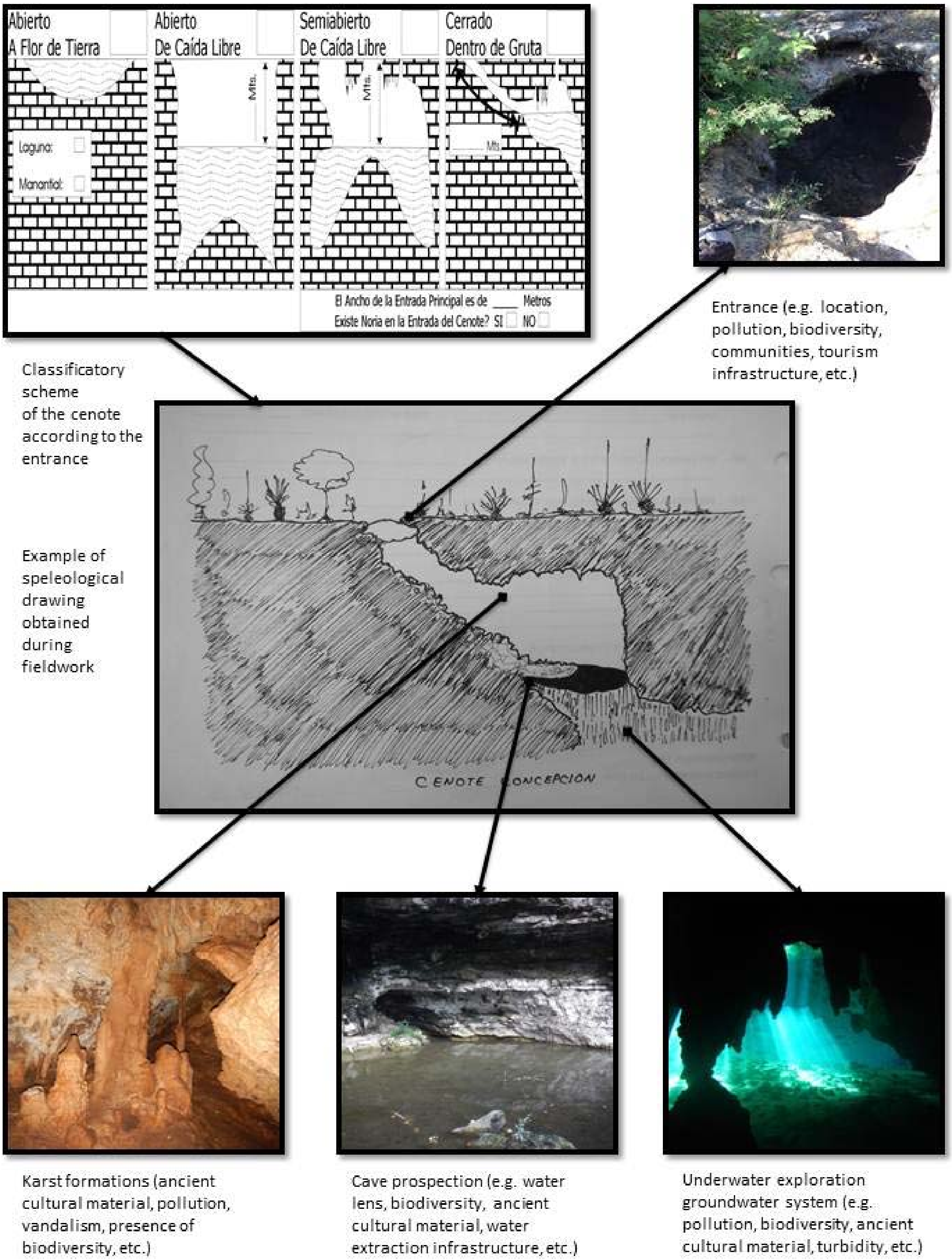


Figure 4.5. Example of the "index card" system developed for the speleological and underwater exploration. Source: own work.

4.3.5. Cenote clean-ups

Some activities were designed and implemented in the study area to directly involve stakeholders in local well clean-ups, and community events with the aim to examine their interest in developing their own rules of use. Working at a variety of sites, we conducted cenote inspections by tagging and photographing pollution problems, which were monitored in conjunction with local members to assess current conditions of the caves. Before clean-ups, we first identified sites in the study area that could be cleaned and we picked those locations that were also safe and accessible to local community members. We then contacted local authorities to get the necessary permission. We asked municipal authorities for support to collect the trash and recyclables we collected, as well as to encourage and convoke stakeholders to get involved. During clean-ups, stakeholders were divided into groups in order to affectively address the goals. After clean-ups: the trash was weighed, collected and photos were taken for future monitoring (Figure 4.6).

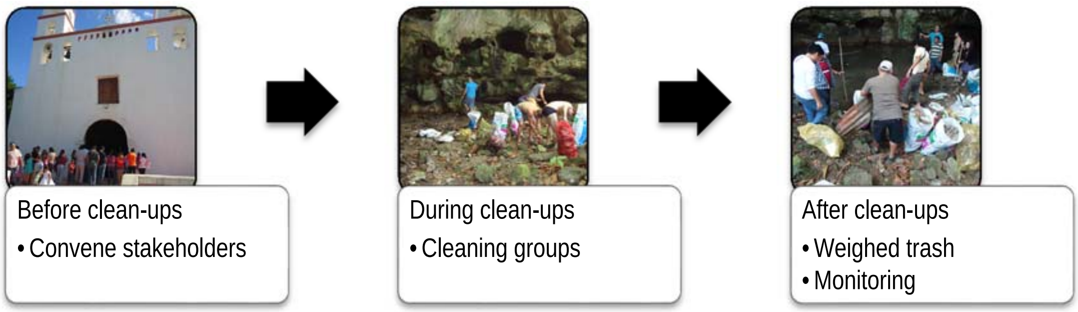


Figure 4.6. The process for cenote clean-ups developed for the case of the socio-groundwater system in Geohydrological reserve in Yucatan, Mexico. Source: own elaboration.

4.4. Data sources

The study used both primary and secondary data. Data were obtained from different sources: literature, national and local statistics, stakeholder's workshops, expert opinions, expert consultation, local interviews and estimations, underwater and speleological exploration, karst inventory and the review of reports. Primary data were collected from June to December 2014 and December 2015 to February 2016 through participant observation, semi-structured interviews, workshops and focus group discussion with stakeholders. Informal conversations and interviews were applied and involved representatives of stakeholders spanning sectors: state officials involved in the governance and management of the Reserve, practitioners (*e.g.*, community leaders, members of NGOs, experts and underwater explorers. Review of available published data was performed as well as analysis of national and local statistics, karst surveys and research fieldwork reports in the area. Records about groundwater uses, extractions and distribution of the water supply company (JAPAY) were studied. Literature and information at the country level were reviewed including national policies, reports, yearbooks and scientific publications. Online interviews were performed to consult experts and members from the water sector (Krueger, Page, Hubacek, Smith, & Hiscock, 2012). We used expert open-ended interviews and informal conversations with stakeholders, as well as *in situ* observations in the selected municipality (Creswell, 2003). For the speleological prospection, vertical and horizontal progression techniques were applied (Cuenca Rodríguez et al., 2000). Overall, fieldwork and interviews were developed during different stages from 2012 to 2016 and over a period of 10 months. We applied the snowball technique in order to interview local people on the communities. We developed workshops with the COTASMEY and with representatives of CONAGUA (e.g. members of the Units for Water Culture (ECAs)[2] in Yucatan.

[2] The ECAs are part of a Federal program established by CONAGUA in 2002 with the aim of promoting and strengthening community participation in water related issues and to promote good uses of the resource among the population. In Yucatan, during the fieldwork phase there exists 79 ECAs comprising 80 municipalities (considering that more than 2 ECAs can be found in urban centres and large communities).

Chapter 5. Results

In this chapter the most relevant results obtained during the different research phases are presented. Complete details are provided in the publications section.

Results are grouped in six major headings according to each methodology: 1) development of the first Local Groundwater Balance Model (LGBM) with stakeholders throughout the application of MFA, 2) elicitation of mental models of experts and local population to conceptualize the socio-groundwater system, 3) adopting a biocultural approach for groundwater conservation, 4) local scale underwater and speleological exploration of cenotes and karst caves, and 5) cenote and sinkhole clean-ups to directly involve stakeholders.

5.1. Development of the first Local Groundwater Balance Model with stakeholders

The development of the first Local Groundwater Balance Model allowed us to physically characterize the groundwater system structure of the area and to develop a conceptual hydrological model with the stakeholders. The following research questions were addressed: How is the natural system structured? What are the total inputs, outputs and groundwater flows in the aquifer? How does the resulting Local Groundwater Balance Model supports groundwater literacy and future groundwater monitoring?

In this section we show, how, in a transdisciplinary process, the data scarcity problem can be overcome and a LGBM can be developed. Over 50 stakeholders from more than 15 disciplines and groundwater related sectors (scientists, policy-makers, NGOs, students, divers and local members) were involved in obtaining a groundwater balance for the selected Municipality (Tecoh in Yucatan, Mexico). The results of the application of the LGBM are presented in the following order: 1) System analysis including relevant flows, processes and stocks, 2) Water balance, and 3) the interpretation of substance flows including inputs, outputs and total flows within the system.

5.1.1. System analysis

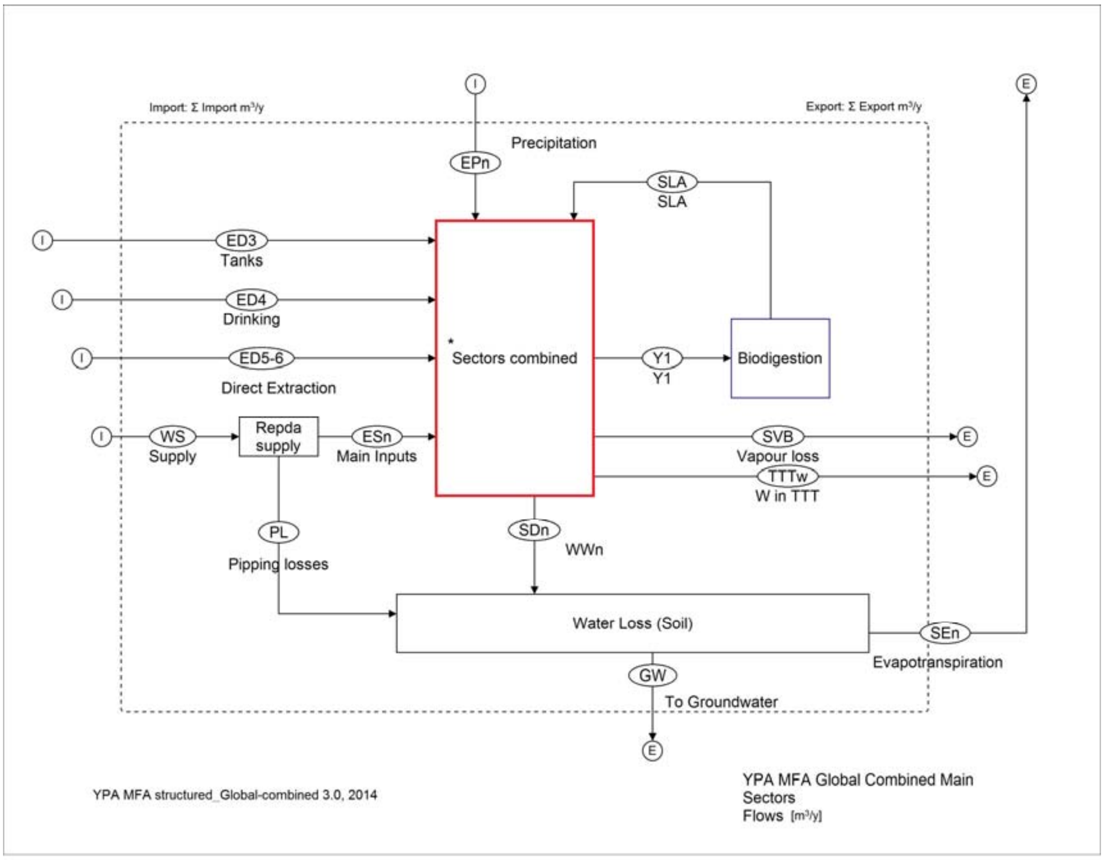
Figure 5.1 illustrates the system analysis for the Municipality of Tecoh, Yucatan, in the reserve zone for the year 2014. The system is composed of 5 relevant processes: extraction, supply/distribution, uses/consumption by all the sectors, treatment/management (*e.g.*, biodigestion) and recycling. Our model also includes water losses estimated through soil percolation. Input flows to the system are: precipitation and water inputs from the ocean; the major output flows are evaporation and groundwater discharges.

5.1.2. Modelling procedure

The model was set up for the year 2014 by using STAN 2.0. It starts with the groundwater storage component, which accounts the subterranean flow. Then fluxes of groundwater for each sector were calculated simultaneously. Each sector was modelled and described by applying the steady-state overall mass balance equation (1):

$$\sum E_i - \sum S_i = 0 \tag{1}$$

Where E_i is the i^{th} input flow, and S_i is the i^{th} output flow.



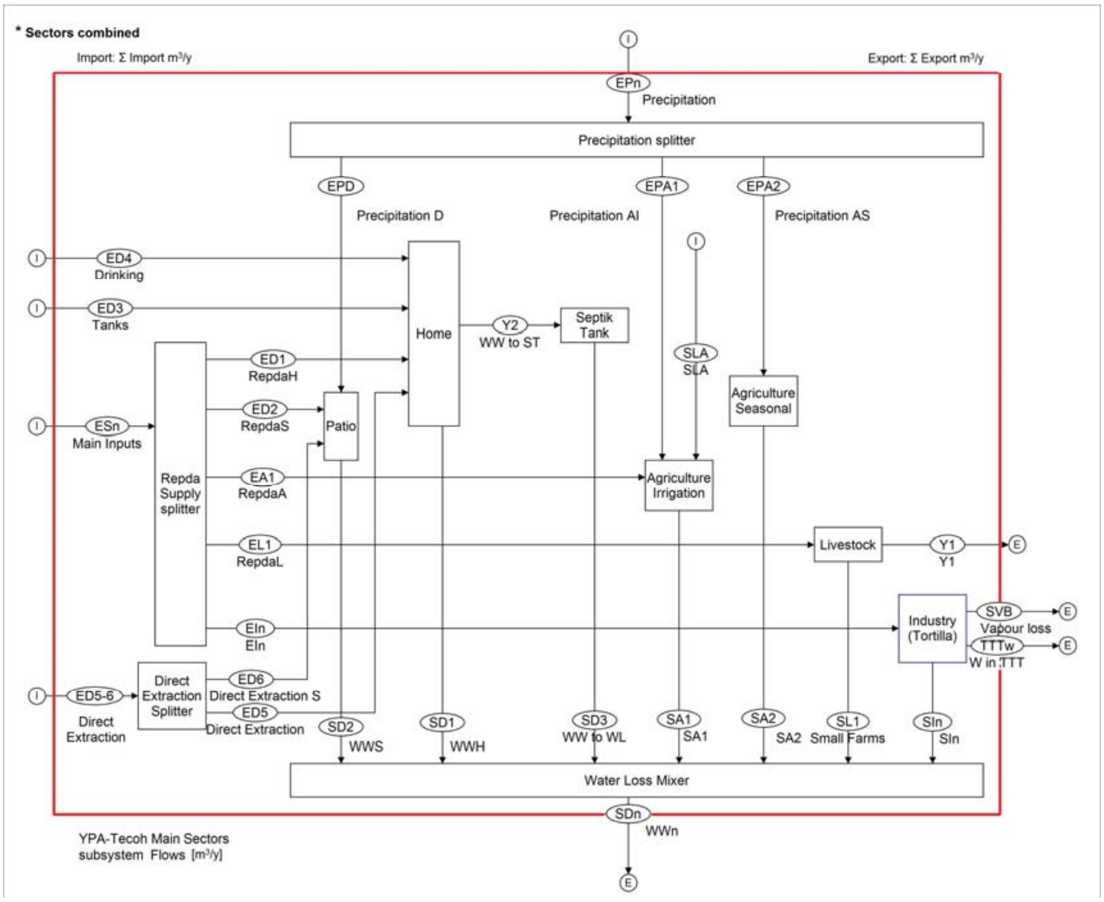


Figure 5.1. System analysis for the Municipality of Tecoh with all sectors. For definitions of the flow abbreviations see **Publication II**.

Water enters the system through precipitation (*Precipitation*), by the water supply company JAPAY (*Repda supply*) which draws groundwater directly from the system, as well as imports of water and direct extractions from private wells located on rural and urban households (*Direct Extraction*), drinking water bottles (*Drinking*) and tanks (*Tanks*) which serve as additional collected private groundwater extractions. During the potable water transport (*Main Inputs*) for its distribution from the *Repda supply* to the consuming sectors, a quantity of water is lost due to damage in the pipes. Water is consumed by households (accounted as *Home*, and *Patio*, *vide supra*), agriculture (accounted as *Agriculture Irrigation*, and *Agriculture Seasonal*, *vide supra*), livestock (*Livestock*), and industry (*Industry Tortilla*), summarized under *Sectors combined* in Figure 5.1. Water is either treated in a biodigestion plant (*SLA*), retained within a commodity (*e.g.*, tortillas) (*Vapour loss,* and *W in TTT*), directly sent to the groundwater (*To Groundwater*) or lost through evapotranspiration (*Evapotranspiration*).

5.1.3. Water mass balance

Figure 5.2 shows the numerically solved water mass balance. It accounts for Tecoh municipality in the Reserve zone for the year 2014. The total amount of water entering the system is 32,217,002 m^3 $year^{-1}$, whereas the largest input flow is precipitation accounting for 77.6% of the inputs, followed by *Repda supply* 15.8%, *Tanks* 4.4%, *Direct Extraction* 2.2%, and less than 0.001% for *Drinking*.

A quantity of 17,633,000 m^3 $year^{-1}$ from the *Precipitation* reaches agricultural soils (*Agriculture Seasonal* and *Agriculture Irrigation*) and provides 91.2% of the water needed in this sector. Three sources of water are used for irrigation (*Agriculture Irrigation*): from precipitation (*Precipitation AI*), Repda (*Repda A*), and a small contribution from a recycled source (*SLA* from *Biodigestion*) (as seen in Figure 5.2). However, they only account for 9.5% of the total water supply. Consumption of water from households (*Home* and *Patio*) and pig farms (*Livestock*) account for 10.5% and 0.4% of the total water consumed, respectively.

The largest output flow is evaporation (*Evapotranspiration* and *Vapour loss*) accounting 80% of the water leaving the system. From all water consumed, less than 0.04% (*Y1*) of the wastewater is treated and re-used in another subsequent process (*SLA*). The rest of the wastewater from Households (*WWH* and *WWS*), septic tanks

(*WW to WL*), agricultural outputs (*SA1* and *SA2*), pig farms (*Small Farms*), and tortilla industry (*SIn*) flow into the aquifer without any treatment. It was stated that the different sectors contribute as follows to the contamination of the aquifer: the agricultural and livestock sector, which might contain high concentrations of pesticides and organic matter (*i.e.*, discharges from pig farms) accounting for *ca*. 19.4 hm^3 $year^{-1}$, followed by tortilla industry (high pH, alkaline discharges) accounting for *ca*. 5,700 m^3 $year^{-1}$. The flows of wastewater from households to the aquifer amount to *ca*. 11.3 hm^3 $year^{-1}$. As mentioned above all wastewater emissions are discharged directly into the aquifer without treatment as demonstrated by the poor treatment and recycling practices (<1%, relative to the total waste water produced).

5.1.4. Interpretation of substance flows

Results revealed: a) high wastewater emissions into the aquifer (*ca*. 6.4 hm^3 $year^{-1}$). Wastewater ranges from grey water to wastewater with high concentrations of organic matter (*i.e.*, discharges from pig farms) and alkaline discharges (*i.e.*, tortilla industry); b) all wastewater emissions are discharged directly into the aquifer without treatment; and c) poor recycling practices (<1%, relative to the total water emissions).

When considered by sectors, flows displayed the following characteristics:

Household: In the household sector the major consumption is represented by water storage in tanks (*Tanks*). This volume is approximately 3 times larger than that from direct extraction from wells (*Direct extraction H*) and 1.5 times larger than that from the Repda water supply (*RepdaH*). Septic tanks (*WW to ST*) eventually provide some treatment to wastewater emissions from Households (*Home*), but our results clearly show that this water is discharged to the aquifer and is not used in another subsequent process. In the Household sector (*Home*) 75% of the wastewater goes to septic tanks (*Septic Tank*) and the remainder is discharged directly into the aquifer (*WWH*).

Agriculture: Results show that 60% of all input water is used for agricultural practices. The model does not consider irrigation based on seasonal periods. Note that the treated water (<1%, from *Biodigestion*, *see above*) is used for irrigation (*SLA*).

Livestock: One peculiarity is the livestock sector, where small farms generate 10 times more wastewater than the larger farms. It is noticeable that discharges from small farms (*Small farms*) are also direct outputs into the aquifer without treatment. In contrast, wastewater from large farms (*Y1*) is treated in Biodigestors (*Biodigestion*), after which this water is reused (*SLA*) in other subsequent process (*Agriculture Irrigation*). Small farm process output (*Small Farms*) and wastewater emissions from the tortilla industry (*SIn*) are minor flows (3.8% and 0.02%, relative to the total wastewater flows to the aquifer, respectively), but they are discharged directly into the aquifer without any treatment.

Industry: During workshops, participants were more concerned about the industry sector (*Industry*). They were aware of the challenges faced due to the lack of data about the processes involved and local and regional statistics. For these reasons and the lack of data for the industry sector in general, we selected the tortilla industry to illustrate this sector partly because it is possible to carry out an estimation of the water involved in the entire production process by considering statistical information and the residual, or virtual, water contained in tortillas, and because it is well known from previous unpublished reports (González Barrera, 2005) and interviews with experts, that these effluents are heavily contaminated. In contrast to domestic, livestock, and agriculture, water mass balance for the tortilla industry was obtained by considering its production processes, *i.e.*, alkaline hydrolysis, nixtamal washing, and baking. Virtual water in tortilla final products was considered only as an example and starting point for the calculations. More details about the flows, definitions, and calculations can be found in the Annexes. Importantly, albeit the total water consumption of this sector represents 0.023% from the total water input in the balance, all the outputs from the sector constitute a 77% (*SIn* relative to *EIn*, ca. 5,700 m^3 $year^{-1}$) of wastewater with high pH and high content of organic matter, and this water is directly discharged into the aquifer.

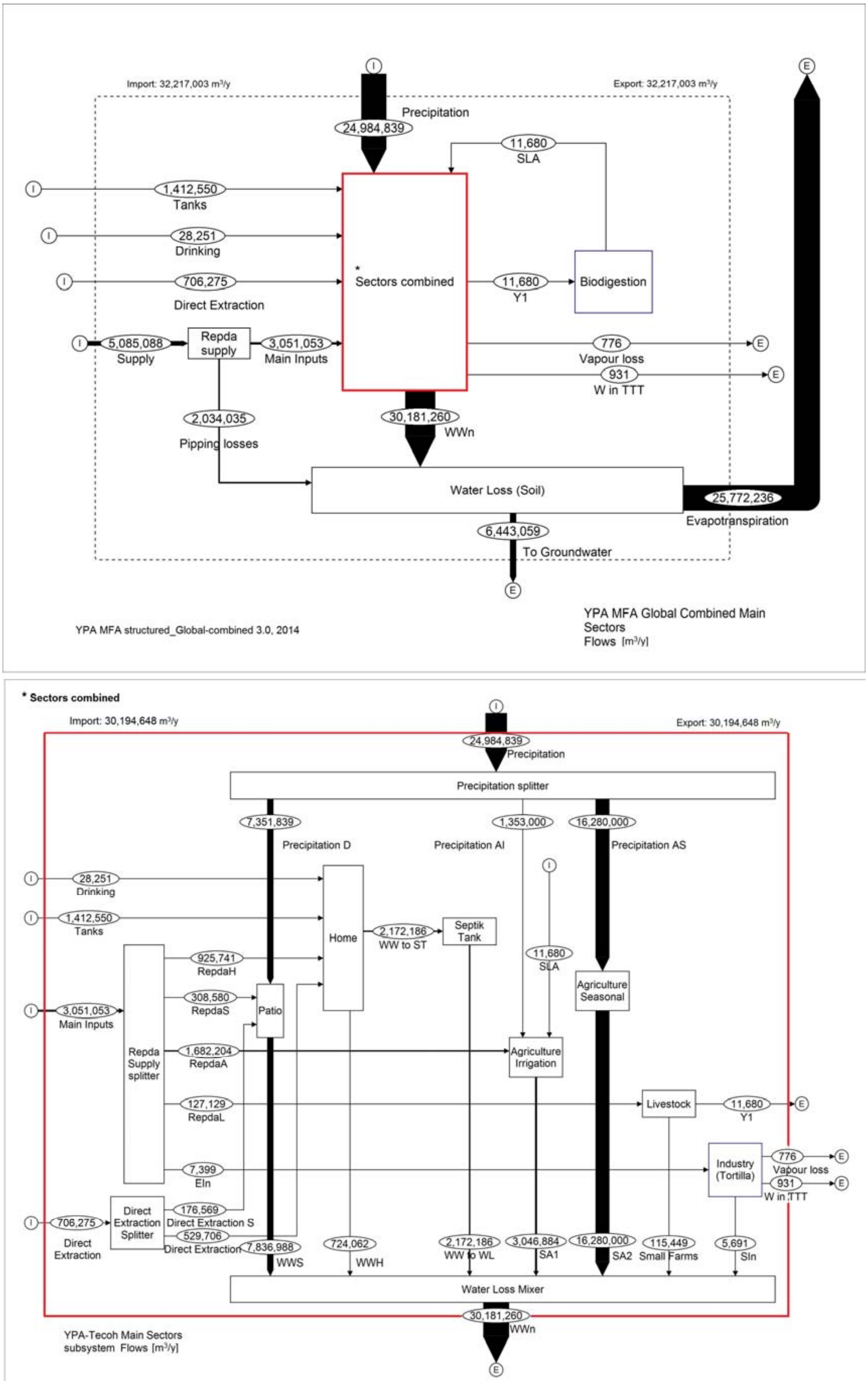


Figure 5.2. Numerically solved water balance for the Geohydrological Reserve, Municipality of Tecoh 2014.

5.1.5. Use of this thesis results at local-scale: Application of the Local Groundwater Balance Model to overcome the lack of reliability of data.

An important result of obtaining water balances and the hydrological modelling of the study area is that some flows have been assessed for the first time regarding specific sectors. From this it is clear that groundwater quality in the area is the more critical problem, combined with the lack of reliable data. The modelling results show that the LGBM can be used in the study area to overcome this.

Focusing in groundwater management, the goal is to protect groundwater quality. The LGBM delineated in **Publication II** is useful for accounting the flows of specific socio-economic sectors, in order to determine main extractors and hotspots of pollution. To exemplify this, we selected the industry sector (tortilla industry) due to the lack of published data and because we wanted to demonstrate that virtual water can be also calculated. Figure 5.3 shows the three steps for the tortilla industry (maize/corn).

Figure 5.3. The maize tortilla industry process in Mexico: Hydrolysis, washing and baking (Images adapted from: http://www.tortillaworld.com/manufacturers).

Within this sector it was necessary to account the input, losses and main flows used in the tortilla production and as part of the general water balance. Tortilla industry wastewater calculations were obtained according to available data for tortilla consumption per capita (Figure 5.4). We took a look of the wastewater generation in this industrial system.

Table 5.1. Known data for the Industry sector.

Entry	Quantity	Unit	Source	Variable Definition
Total population (Tecoh)	16,200	inhab	(INEGI, 2015)	*TP*
Average tortilla consumption per capita	0.35	kg	(Domínguez Espinosa & Pacho Carrillo, 2003)	*TTC*

Table 5.2. Transfer Coefficients for the Industry sector.

Entry	Definition	Value
c4	Content of water per tortilla (humidity)	0.45
c5	Content of water in nixtamal (humidity)	0.5
c6	Water for Hydrolysis (or Washing per maize mass unit)	0.75
c7	Additional water to make tortillas (in Baking)	0.25 L/kg nixtamal

Total amount of water at the end of the tortilla process, TTTw, was calculated from the known values of tortilla consumption per capita, TTC, and tortilla humidity, c4:

$$TTTw = c4 * (TTC * TP * 365) \quad (2)$$

$TTTw = 0.45\ (0.35\ \text{kg inhab}^{-1}\ \text{day}^{-1} * 16200\ \text{inhab} * 365\ \text{day})$

$\boldsymbol{TTTw = 931{,}298\ \text{kg}}$

Therefore, the mass balance of tortillas TTTs, corresponding to the non-water constituents that do not change over the entire tortilla-making process:

$TTTs = 0.55\ (0.35\ \text{kg inhab}^{-1}\ \text{day}^{-1} * 16200\ \text{inhab} * 365\ \text{day})$

$TTTs = 1{,}138{,}253\ \text{kg} = Y4s$

Flow Y4 as input to Baking process is known as “Nixtamal”(Y4) and contains 50% humidity:

$Y4s = Y4w$ (50% nixtamal humidity)

$\mathbf{Y4w = 1{,}138{,}253\ kg}$

Therefore:

$$Y4 = Y4w + Y4s \tag{3}$$

$Y4 = 2{,}276{,}505$ kg

Additional water needed for Baking process EI3, is related to the amount of nixtamal Y4, and defined by c7:

$$EI3 = c7 * Y4 \tag{4}$$

$EI3 = 0.25 * 2{,}276{,}505$ kg

$\mathbf{EI3 = 569{,}126\ kg}$

Water used for both Alkaline Hydrolysis and Nixtamal Washing processes, EI1 and EI2, respectively, is related to the amount of nixtamal Y4, and defined by c6:

$$EI2 = 3 * Y4s \tag{5}$$

$EI2 = 3 * 1{,}138{,}253$ kg

$\mathbf{EI2 = 3{,}414{,}758\ kg}$

Likewise,

$$EI1 = EI2 \tag{6}$$

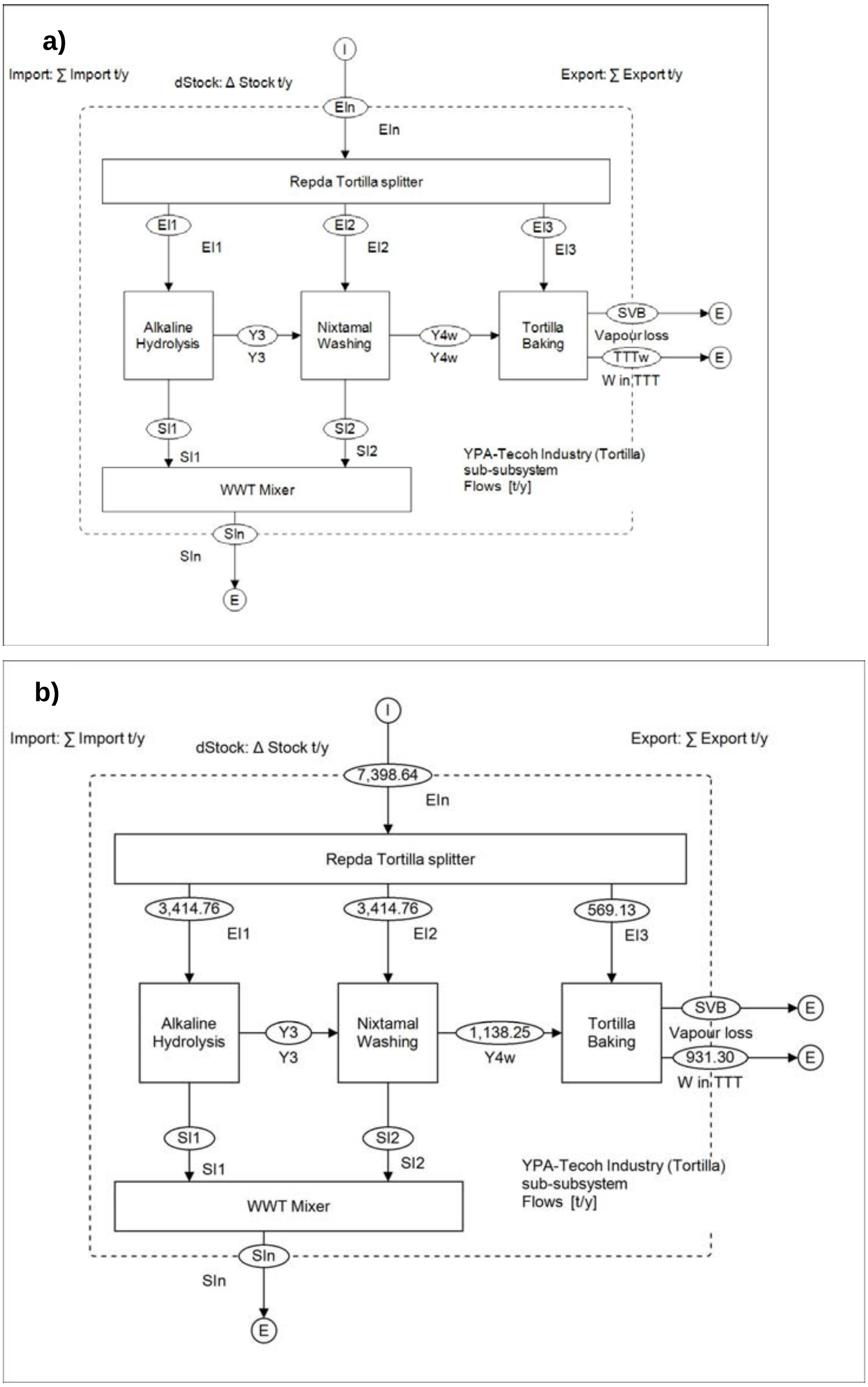


Figure 5.4. System analysis of Tortilla industry sector considered for MFA construction (as *Industry (Tortilla)* from the *Sectors combined* subsystem) showing a) System analysis, and b) System analysis after data inputs taken from available and calculated data sources.

Thus, these calculated flows from known data were used as data input for the constructed MFA in the STAN software (Cencic & Rechberger, 2008). Numerically solved mass balance containing all calculated flows are provided in the Annexes.

5.2. Conceptualizing the socio-groundwater system *via* Mental Models

In the case of the social system, the elicitation of mental models and characterization of present-day local values regarding groundwater was necessary to analyze how the scientific community assimilate local knowledge in the study area in relation to groundwater resources. During this phase the following research questions were addressed: What is the structure and content of the mental models of the scientific community -or experts and local population, regarding the groundwater system? Are those mental models fragmented? Are the mental models shared? How does their understanding of the system diverge from that of experts?

5.2.1. Mental Models of experts

Our first basic assumption is that there is a lack of knowledge on the area's hydrogeology and groundwater flow patterns and, in general, of the dynamics and functions of the aquifer. We argue that MM of experts regarding the system are originated *via* formal acquired knowledge. Overall, for both groups, definitions of the system were poor and incomplete, and the understandings of the resource were also different among the members of each group. An initial review of experts' answers and drawings revealed interesting erroneous assumptions and ideas regarding the natural system. Experts' conceptions were rather unclear, based on characteristics of the system. Since drawings are effective at capturing mental representations (Schwartz & Ibaraki, 2011) results obtained with the drawings highlight the fact that MM of experts are incomplete. For example, half of the experts (n=5) described fluxes erroneously and diffuses, and they were not able to explain how the system functions or some of its characteristics. Experts, for example, depicted correct boundaries, but they only depicted unrelated flows representing the system (Figure 5.5). Correct concepts, flows and layers were clear and correct for only two experts, who unsurprisingly are hydrologists. They also perceive a clear connection with pollution and related health risks.

5.2.2. Mental Models of locals

Local members use experts models to help formulate their own mental models, thus it is crucial to analyze how they conceptualize the system and to what extent their understanding of the system diverge from those of experts. In general, locals described groundwater as clean drinking water, originating from rainfall, but being stored in the ocean. All the participants in this group (n=10) described fluxes erroneously and they were not able to explain how the system functions or some of its characteristics (similarly as described above). This group depicted incorrect boundaries, unrelated flows and they were not aware of the concept of groundwater stored in a porous medium. Drawings also revealed interesting results regarding the lack of awareness of boundaries of the system. Results also suggested that the local population do not see any connection between pollution (*e.g.*, use of pesticides) and health related risk. Participants believed that there are possible solutions in the case of pesticide contamination but they referred this as a solution in which education and the complete society should be involved. In general, MM of the local population differed significantly from the group of experts since their conceptions were incorrect. Importantly, whilst experts MM are in general incorrect, locals MM are also incorrect but they do not have a clear understanding of their influence on the system whereas experts do.

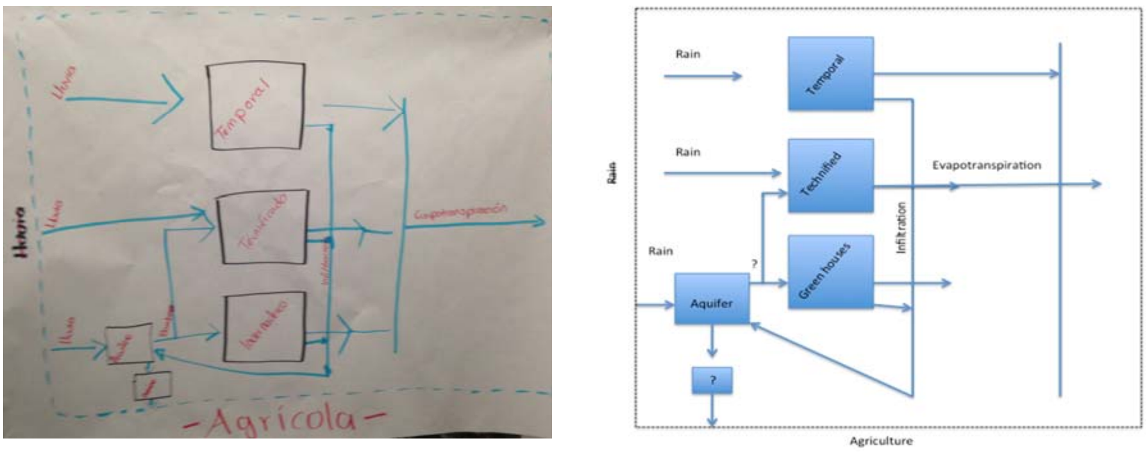


Figure 5.5. Example of experts drawings illustrating unclear flows, boundaries and features representing the system.

Overall, the local population and experts conceptualize the socio-groundwater system differently. In terms of related risk, both groups gave no clear statement about the current situation regarding pollution problems in Yucatan. They provided fewer concerns about health, and differences in values also occur between the two groups. Questions about the water quality were asked and participants provided ambivalent responses. The majority of experts (n=8), for example, viewed water quality as a non- desirable and vulnerable to contamination, but their answers were somehow vague and inconsistent as stated by one interviewee:

"Water quality in Yucatan is desirable. However, for drinking water purposes, water must be complied with environmental regulations, including official norms such as NOM 127 […]. We comply with all the norms except with the issue of chlorination […]. Which is the only requirement for disinfection. I consider water as desirable and undesirable because chlorine will not be in the extracted water, it will be in the piped water". (Interview, Head of the water supply company, male, 53 years old)

All participants were asked what they believed is the more crucial factor affecting the system. Table 5.3 shows some responses. All the participants referred pesticides as one of the more pressing problems for the society. It is noteworthy that all the experts working within the government sector were ambiguous as to whether to respond or not due to conflict of interests with their jobs. The participants view the groundwater problem of Yucatan mainly in relation to planning and management but consider this as a task of governmental agencies. This is most evident in the way responses were provided with regard to pesticides and bad solid waste disposal practices. Lack of information and aging water infrastructure was also mentioned. They described the development process of the Yucatan state as the process of unsustainable use of water bodies: *"as the population grows, the infrastructure is getting obsolete and old".* (Interview, policy-maker, male, 32 years old).

Table 5.3. Example of the different perceived factors affecting the groundwater system as mentioned by the participants.[a]

Organization	**Origin**[b]	**Water quality**[c]	**Factors affecting the groundwater system**[d]	**Problems**[e]	**Possible solution**	**Responsible**[f]
CICY	*Subterranean water 100%*	No desirable (due to the karstic nature of the soil)	Open defecation, old septic tanks, agricultural activities, bad solid waste disposal practices, limestone dissolution, saline intrusion	"*Quality monitoring is implemented by JAPAY. The quality for standards is between 20–40 m depth. While water there is good, we do not sample other zones where we know is already contaminated*"	Depending of contaminant, more investment on research	Municipalities, and Conagua
JAPAY	*Absolutely from the rain*	Desirable (exception: the chloride levels)	Wastewater discharges without treatment, dead animals on the streets and plastic pollution	*"… Not all people have access to scientific studies. Educated people know more about it because the information is very technical […]"*	It is a local phenomenon	Conagua
Pig farmers association	*From the aquifer*	No desirable and desirable depending on the area and the part of the	Pollution problems due to the characteristics of the karstic soil in the area	**No answer**	Hire specialist to teach how to change bad practices	Government and society

		aquifer				
Indemaya	*"Subterranean water, from the sinkholes"*	Desirable but in a short-term to become No-Desirable)	Lack of awareness or interest, farmers	*"Farmers do not have the necessary information, they don't know the risks; lack of technical assistance in organic agriculture management"*	Water treatment, to reduce the amount of chemical products to be disposed in wastewater	No one will be responsible
Cinvestav	*"Water consumed throughout Yucatan comes or is distributed from the ring of cenotes, which comes from the sea. Water in Yucatan is extracted from the soil, from the aquifer"*	No desirable	Pollution, Hurricanes	*"The lack of information is the problem. Policy-makers don't share the information with us…"*	Water flows are static through channels and cenotes	Government and water institutions
UADY	*"Potable –drinking water-, is generated from the hydrological cycle, from the aquifers"*	Desirable	Agricultural practices, industries without regulation, tourism services, salt intrusion	*"Daily wastewater discharges from industry and households directly to the aquifer"*	It will be cheaper to prevent than to remedy	Authorities and population

UADY-Anthropology	*"From the underground but is generated from the rain (absorbed by the surface of Yucatan)"*	Desirable	Wastewater discharges, intensive use of chemical substances for agriculture, wastewater from pig farms	*"The problem is that our freshwater bodies can gradually become scarce and poor"*	We will need an emergency system of purification	Government and water system managers
CIS-Hideyo Noguchi	*"From cenotes and sinkholes in rural areas"* *"From deep wells in urban areas"*	Desirable. However, water from wells and cenotes is No desirable. Potable water (provided from JAPAY) is No desirable	Poverty, lack of application of environmental regulations, bad management of agrochemicals and pesticides, high density of sinkholes, deforestation	*"Low education levels in rural areas, low risk perception and that we don't trust on policy makers and on each other"*	Intervention between authorities, government, academic sector, society, etc. is needed	The state and federal agencies

[a] Source: Author's interviews June-December 2014.
[b] Question: Where does the water for human consumption in Yucatan come from?
[c] Question: How do you consider the water quality in Yucatan?
[d] Question: Which factors (natural or human) can affect the water quality in Yucatan?
[e] Question: Which problem do you consider is crucial for the water quality in Yucatan?
[f] Question: Who is responsible for solving the groundwater problems in Yucatan?

The results obtained with the MM provide a basis for identifying origins of misunderstandings between the two groups. Government agencies, researchers and specialists (*e.g.*, members of the Cotasmey) have different opinions on whether and how they could solve pressing water related problems. It is interesting to note here how the idea of who will be responsible to provide possible solutions was perceived by the interviews. In general, MM of the group of local members differed significantly from the group of experts, and that the differences could be related to the lack of inclusion of local population into management plans. Overall, MM of experts do not consider cenotes embedded in one socio-groundwater system. They perceive cenotes as a part of the hydrological cycle but the social system is often not considered. Additionally, experts do not include local knowledge on groundwater management plans.

Drawings of the participants could be differentiated into groups based in the following categories (Table 5.4). Correct hydrogeological concepts: in this group the groundwater features consists of water flows and boundaries located in an interconnected porous media. False or partially correct: participants depicted correct flows, channel, boundaries, undefined openings like caves and other features but they place them in the wrong places or missed important details. Unclear or inadequate: participants depicted flows and characteristics that were ambiguous and difficult to understand. Diffuse: participant depicted groundwater features and included more information than that that was requested.

Nevertheless how much is what the experts and local population knows, or do not know, about their actions and how the system functions are affecting the health of the groundwater system? Results shows that people are more worried about the activities in the cenotes than they are informed about the details of the interrelated environmental problems. Locals for example mentioned tourism as one of the main problems caused by people but pesticides, for example, were not even cited. Experts, on the other hand, are clear on exactly what natural or human actions are leading to groundwater problems but they were not able to mention how much does the local population know about the problems. Overall, they do not know about environmental regulations in the area, policies, decision-making processes, or how to address some of the problems in question. Experts also do not know about what information is crucial to communicate to the local people and they were not aware about the updated environmental regulations. In general, none of the participants mentioned that individual changes seem fundamental to effectively address current groundwater problems.

Table 5.4. Example of some responses of experts and local members about the groundwater system in Yucatan.[a]

Data[b]	Expert's mental model	Locals mental models
General conceptual drawing	Correct	False
Identification of boundaries	Unclear	False
Fluxes	Diffuse	False
Idea of water stored in a porous media	Correct	False
Idea of cenotes are interconnected within the system	Clear	False
Idea of society as a part of the system	No/society not considered	No/society not considered
Idea of contamination and health related risk	Clear	Unclear/No idea

[a] Drawings could be differentiated into groups related to the questions about characteristics of the aquifer such as function, boundaries, users, etc.
[b] Not all the questions are included in this table.

5.3. Adopting a biocultural approach for groundwater conservation

Technical solutions to environmental problems such as groundwater contamination are of importance. However, information alone is not usually sufficient for change since cultural values and meanings are also necessary towards solutions. Focusing on the case of Yucatan, we addressed the following research questions: What are the present-day meanings, understanding and values of the system for the local population? What role does local knowledge play in the eyes of experts? What are the prospects of adopting a biocultural approach for conservation of cenotes in Yucatan and is it feasible?

One way to understand how the Maya people “appropriate” and value nature is through an analysis of how they ascribe meaning to it. Although it is possible to find cenotes all over Yucatan, past research efforts concentrated on a few places close to archaeological zones. We documented unrecorded cenotes, including some caves and aguadas, and carried out clean-up and other activities with the young. Given the significance of cenotes in the past, it might be anticipated that indigenous people would emphasize social and cultural values. Nevertheless, the cultural and spiritual importance of cenotes did not come up in the list of current uses, implying that utilitarian values are in the forefront. Participants gave priority to functional values of cenotes mainly as a source for water used in cattle ranching, agriculture and tourism.

Given that some protected areas have been established (Yalahau Lagoon and the Reserve) in the study area, one might expect to find joint management and conservation-compatible human activities. However, the presence of reserves does not seem to have motivated sustainable resource use and cultural practices. For example, protected areas were not identified well by any of the interviewees, and neither were archaeological zones associated with cenotes. There was no consensus regarding current management and what else can be done to protect them. The alarming decline in water quality was frequently mentioned. Fifty-two participants reported that, prior to the mid-1990s, they could drink water directly from the pozos (wells), but presently they did not because they could become sick. One interviewee said:

"In the past 25–30 years, we used to drink water from our pozo […]. Nowadays water is not drinkable and that is the reason why we prefer to buy bottled water." (Informal conversation, farmer, male, 50 years old)

Interviews with local stakeholders were performed in order to collect information on governance. As cenotes and the Yucatan groundwater basin are commons, we classified governance according to the terms used in the commons literature (Ostrom, 1990). Table 5.5 summarizes the governance regime of cenotes in Yucatan.

Table 5.5. Governance of the cenotes in Yucatan.[a]

No.	Regime	Description	Notes
1	*State property*	When the cenote is owned by government authorities	Some responsibilities may be shared with the community
2	*Private property*	When an individual owns a cenote on their private land	Water in Mexico belongs to the nation. The owner owns the cenote, the cave but not water
3	*Collective property* or *ejido*[b]	When the cenote is owned by *ejido* members	They are different from communal land by being an endowment granted by the government to an organized group of farmers with no land
4	*Open-access*	When the cenote does not have well-defined property rights	Is open to everyone and all uses

[a] According to Lopez-Maldonado and Berkes 2017.
[b] Ejidos are common-use lands and lands intended for housing and urban infrastructure (Jones & Ward, 1998; Torres-Mazuera, 2009).

It appears that the contemporary governance status of cenotes includes all four of these regimes but is largely mixed or unclear. What used to be communal property under communal care in ancient times has become mostly unmanaged state property verging on open-access. In effect, cenotes have been decommonized (Lopez, 2015) into open-access, suffering from degradation, the usual consequence of open-access (Ostrom, 1990). Community respondents did not seem to associate contamination of cenotes and the governance regime, and what that might imply for stewardship responsibilities. Cenotes used for tourism activities are managed according to environmental regulations, but there is a lack of regulation for other cenotes. One member of a tourism cooperative observed:

"We are six members in this cooperative. The land and cenote does not belong to us, the Ejido members donated all. We can use the cenote and the land for the next 30 years and then we need to move or to extend the agreement. We can do whatever we want, but we need to follow government rules. For example, we cannot use pesticides around the cenote and we cannot modify the entrance of the cave, nor add lamps […]." (Interview, member of tourism cooperative, female, 56 years)

Evidence of ancient sacredness of groundwater in the Yucatan Peninsula is everywhere. Many of the cenotes explored contained ancient Maya pottery, fire pits, human and animal remains below the water table. Furthermore, the SEDUMA database contains references to ceremonies and some cave systems being considered as sacred routes. Sacredness appears to be understood by some, but certainly not all, of the respondents. Indigenous respondents perceived cenotes as the abode of deities and spirits, and that cenotes were primarily used for rituals in the past.

"In the past, cenotes were sacred but not all of them now. There are some of them that can serve to [carry out] ceremonies such as the Cha-Chaac (ceremony for the God *Chaac*) *but they are few and it is not easy to reach them [the cenotes]"* (Interview, beekeeper, male, 50 years)

We interviewed participants about the current importance of cenotes. We used the example of one cenote in Yucatan (the Sacred Cenote of the archaeological zone in Chichen Itza) to exemplify the concept of sacred. We asked if they can tell why the cenote *Sagrado* in Chichen Itza is called "Sacred", and what the Mayas from the past used to do with the water of that cenote. Did they think that cenotes we have today are the same cenotes the Mayas used in the past? We asked the participants to explain and expand on each response. We then asked if they think sacred cenotes still existed in Yucatan. Questions about supernatural agencies in local people's beliefs were also explored. We asked about *Aluxes* (the name given to a spirit in the mythological Maya tradition). Most participants, including experts, seemed to have some belief in the *Aluxes*. One respondent mentioned:

"The Sacred cenote in Chichen Itza is sacred because it was important for the Mayan ceremonies […]. The water was used to support the needs of the population. The other cenotes in Yucatan are the same cenotes as those in the past because they require a lot of time to form. However, present cenotes are contaminated" (Interview, housewife, female, 35 years).

Interestingly, 89 respondents rejected the idea that cenotes continue to represent sacred places but they did mention that they believed in the importance of the cenote in Chichen Itza and in *Aluxes* as protectors and caretakers of the cenotes.

This suggests that the link between sacredness and cenotes has been broken, even for some who acknowledged spiritual powers:

"I don't know the cenotes and I've never been into a cave but I know that there exists some spirit that inhabits there and protects the entrance of the cenote." (Informal conversation, student, male, 20 years)

According to some respondents, loss of respect for cenotes may be related to the erosion of sacredness across generations. Knowledge of cenotes as sacred natural sites was no longer being transmitted to younger generations. One diver member of a local NGO working on the protection of cenotes noted:

"The problem is the lack of education among the younger people, between 15 to 24 years old. As explorers of caves and cenotes, we always find beer bottles, spirit bottles, condoms, graffiti, etc. I do not believe that older people visit cenotes and do all of these things. Besides, it is difficult to access some of these sites and not everyone has the skills to descend [into the cenotes]. The young people have to be involved more in the tasks of protection and conservation." (Informal conversation, cave diver, male 24 years)

We recorded information on current management, legends, and (where possible) rituals or ceremonies. Some of the legends were consistent with the idea that all cenotes once had names and spiritual guardians or "owners". Some interviewees seemed to know of the ancient institution of cenote guardians, spiritually powerful humans or animals. Twenty-four interviewees mentioned that the guardian of the cenote is a snake. None of the respondents themselves were guardians. One interviewee said: "In order to be a guardian you have to have knowledge and special powers as *X'menes* (Mayan healer) used to have. No one has it now, it is something which someone was born with".

In interviews and participant observation in the one community in Campeche State, we found that population still practiced some water-oriented ceremonies. We interviewed local members and found a profound sense of respect to cenotes. However, we also found high density of pesticide bottles in the area and evidence of high levels of solid waste (mainly plastics) contamination, suggesting lack of knowledge of their impact on the groundwater system and the consequent environmental effects.

Overall, cenotes were assessed according to specific characteristics including accessibility and safety. Some cenotes were considered unsafe places by about half of the respondents. Seventy-eight of the interviewees reported being afraid of entering into a cenote, and almost all the participants (N=101) said they would only visit them for recreation. People believed cenotes were dangerous places because of vandalism, drug and alcohol use, hazardous species that inhabit dark places (*e.g.*, spiders and snakes), or because underwater streams can cause drowning.

Results show that responses of local members related to contamination since they explained that quality of groundwater was not suitable for human consumption in some cenotes - but not in all of them. Impact of human activities was widely recognized as one of the most influencing factors that cause environmental degradation of these ecosystems in the area. However, responses indicated that interviewees did not understand that all cenotes are part of a single interconnected groundwater system and cultural values did not seem to be considered.

The role that local people could play in the management of cenotes came up for discussion during informal conversation with experts working on the water sector but mainly regarding contamination. For example, the Reserve was so designated because of the quality of water. However, some cenotes in the Reserve have been reported contaminated with pesticides (Polanco Rodríguez et al., 2015). Toxic contamination was not reflected in the understanding of participants regarding water quality, and pesticides were not mentioned as a potential factor affecting groundwater, even though in five of the cenotes explored some bottles of pesticides were found. One interviewee said:

"We used to live here in the ranch and we did not have another [source of] water to drink. We had to drink water from the cenote. We never got sick because water was sacred and it was always clean." (Interview, Municipal authority, male, 43 years)

Distributed speleological and underwater exploration in the area were carried out to investigate central management questions such as the current uses of cenotes and the local cultural values that people ascribe to the resource. Evidence of cultural importance of groundwater was everywhere. As described above, numerous cenotes explored contained ancient Maya pottery, fire pits, human and animal remains below the water table. However, results obtained during the interviews revealed a profound sense of loss of local and traditional knowledge, but also a strong desire to learn more about groundwater. Cultural values were not well reflected in the interviews. Values, beliefs, and meanings regarding cenotes seem to have declined. Cenotes have been suffering of an erosion of human value systems, including the way people perceive nature, and the environmental change implications. Indicators of these changes in values were evident during the interviews. One woman reported having a *pozo*, which she considered far more important to her than a cenote:

"We have pozos in our houses. All here in the village have their own pozo, therefore why are we going to take care of cenotes if what we use comes from the pozo. I better take care of my pozo because I take water from it". (Interview, ECA member, female, 43 years)

An erosion of human value systems and associated environmental damage have also negatively impacted on biodiversity and habitats of endemic species, including blindfish (*Thiplyasina pearsei*, *sak-ay* in Mayan) and the blind swamp eel (*Ophisternon infernale*). Worth mentioning that many cavernicolous species are listed as Threatened on the IUCN Red List, mainly from adverse impacts of human activities. Participants mentioned that the impact on biodiversity in cenotes was due to the introduction of invasive species such as tilapia (*Oreochromis mossambicus*), water extraction, demolition of cenotes and natural areas to construct tourist facilities and roads, direct human consumption of cenote water, abandonment of ceremonies associated with sacred beliefs, wastewater discharges, and solid waste disposal.

Results from interviews and informal conversations indicated a failure of knowledge transmission of cenotes as sacred sites. More than the half of the respondents (N=62) expressed a strong desire to learn about cenotes, to restore cultural practices and to revitalize values of sacred places. Overall, interviews and informal conversations revealed a profound sense of loss of local and traditional knowledge of uses and practices (*e.g.*, rainwater harvesting) and a lack of self-recognition as custodians. According to the testimony of many elders who have witnessed tremendous change over the past years, these responses indicated the loss of meaning and value among the local population. Interviewees identified threats to the cenotes, lack of interest in preservation, and changes in water quality but little consensus was found regarding the significance of cenotes, how to better protect them, and what trade-offs may be involved.

Cenotes have become a major tourist attraction, posing threats such as loss of respect. The designation of the Geohydrological Reserve, meant as a conservation measure, has had the impact of increasing tourism, compounding problems through modifications of cenotes, for example, to improve tourist access. Paradoxically, those cenotes are less contaminated with plastics and better preserved, since the local population is interested in tourism income. Complementary results obtained are provided in Publication **III**.

5.4. Local-scale exploration of cenotes and karst caves

All the plausible hydrological methods illustrated in Table 1.1 show that none of them include stakeholders. Thus, exploration and measurements were carried out over the cave system in the study area to determine the usefulness of speleological exploration with the support of local stakeholders in detecting caves in the geology of Yucatan. Finding out the precise location and properties of caves was crucial in order to determine the characteristics and patterns of caves, including hotspots of pollution.

Cave records obtained during speleological and underwater explorations evidenced current hotspots of pollution due to bad waste disposal local practices, the current and real local use of the system and some insights on the biodiversity in the area. During the speleological fieldwork twelve cenotes and more than twenty caves were explored. Information regarding the size of the cave, the presence of several caves in the vicinity, shape and depth were obtained (Lopez-Maldonado 2015, unpubl. report).

Most of our findings were correlated with the location of caves known from local stakeholders. However, determining exact cave locations did not appear possible without the support of local stakeholders. The cave system explored clearly evidenced bad management practices and loss of important endemic biodiversity. One explanation for this may be the lack of interest of local authorities in preserving the sites but also due to the lack of knowledge of the resource. For example, seven of the cenotes explored indicated bad waste disposal practices (currently some places are used as open-illegal dumping sites). Interestingly, the most contaminated sites are those that are *open access* (when a sinkhole or well does not have well-defined property rights and is open to everyone, Table 5.5).

Informal conversations helped us to get some insights on the governance regimes, uses and activities performed in the cenotes. Wastewater discharges from farms were found in two of the cenotes and illegal extraction in five of them. It is interesting to note that during our speleological prospections we found pesticides bottles in the interior of five of the caves. In terms of biodiversity, Blindfish (*Typhliasina pearsei*) (*Dama Blanca Ciega* in Spanish, or *Sak-ay* in Maya), Blind Swamp Eel (*Ophisternon infernale*) (*Anguila Ciega* in Spanish), and Langostino (*Creseria moreley*) were reported in the cenotes by local divers. Results suggest that speleological and underwater exploration methods can be used to determine the precise location and characteristics of caves, and to use the data to perform robust modelling estimates. However, the nature of the medium surrounding caves remains to be determined.

5.5. Cenote and sinkhole clean-ups to meaningfully contribute to groundwater sustainability

Although the soil is effective in removing some substances before they reach groundwater supplies, the direct flow of pollutants and contaminants remains as a critical problem in the study area. After performing cave exploration and showing that we were able to locate caves in the study area with the stakeholders, the next step was to implement cenote clean-ups in the sites we found most contaminated. We designed and implemented activities in the communities for this study and conducted informal conversations with stakeholders in order to analyze their interest in developing their own rules of use. During our fieldwork phase (2014) we collected *ca*. 400 kg of plastics and solid waste from only one of the cenotes explored. This is interesting considering that in one community it is possible to find more than 4 cenotes (up to 128, Table 4.1) where water is extracted for human consumption. In most cases, the wells and caves are being used as illegal public waste dumps. Plastic bags, cups, cans, cigarette butts seems to be out of control, and other materials found were pesticide bottles and herbicides bags. We found that, due to the lack of collaboration and interaction between agents, this ecosystem is declining and management at inappropriate scales has created both biological and social problems. As an example, the top 10 items collected on the sinkholes are presented on Table 5.6.

Table 5.6. Top ten items collected during cenote clean-ups.[a]

Number	Item
1	Broken glass (mainly beer bottles)
2	Plastic cups
3	Plastic bags
4	Bottle cans (and the rings)
5	Cigarette butts
6	Plastic bottles (mainly beverages)
8	Expanded polystyrene products
9	Personal care and hygiene products
10	Pharmaceutical items

[a] Example of other items found: one old refrigerator, bicycle spare parts, livestock skull, pesticide containers (as mentioned in text).

Through sinkholes clean-ups, locals were made awater of groundwater sensitivity, hazardous materials associated with human activities (*i.e.*, agriculture) and this provided us with key insights of the sources of local pollution. However, their interest in participation was somehow diffuse. Apparently the stakeholders were not fully interested in participating in the clean-ups, but the direct involvement with policy makers, experts and divers was key to promote collaboration and interaction between them and the local stakeholders. Interviews also revealed considerable confusion about the role of local and regional institutions, as well as diffuse understanding on what they should or not should do, in relation to the plastic and wastewater pollution problems (Figure 5.6). For example, we asked who should be in charge of cleaning the plastics and solid waste, and locals perceived that this activity should rely on the government and not the society. Common phrases obtained on this regard were:

“Why should I myself clean-up the cenote if the responsible authorities in our community don’t do their job?”

Still, and in terms of the natural system, the reality is that the local population do not have enough knowledge of groundwater: where it comes from, how long it has been there, how much they have, which limits their capability to effectively address groundwater challenges. On the basis of the above results and observations, and considering all the other factors that might jeopardize the resource in the short-long term, this suggests that knowledge of the people about the resource, and the establishment of a connection *via* emotion or shared value, such as responsibility for protection concerning the resource, is fundamental to be able to effectively motivate action.

Figure 5.6. Before (left) and after (right) cenote clean-up, Municipality of Huhi (Images Lopez, Y. Dec. 2014).

5.6. Use of the Transdisciplinary Socio-Groundwater toolbox for better groundwater resource management

The previous sections have summarized the results that answer the objectives stated in **Chapter 2**. Those results will not be repeated here. Instead this section focuses on the general advantages of the presented transdisciplinary approach applied to study the groundwater in the study area, as well as on how the results of the research can be applied for future monitoring.

When studying sensitive ecosystems on data scarce areas, as the one investigated in this thesis, it is convenient to use and combine data from different sources. To address current local problems such as groundwater management, a transdisciplinary approach is needed.

Combining five methodologies from different disciplines, the toolbox was developed with the aim to provide research tools for stakeholders to understand, develop and implement analysis and monitoring of current environmental conditions. The development of the toolbox in this study provided information on hydrology of the region, the social factors impacting on it, local values, the interest in develop own rules of use, and current status of the system.

The use of the toolbox ensures data from different sources that can be generated or be collected *in situ* by the stakeholders. Likewise, water data can be collected but also obtained from experts working in the water sector, and this information can be shared with local members. In the case of Yucatan, this crosscheck of information was valuable because information tended to be patchy and often not shared among sectors. The approach used in the present study of involving experts and local population improved data-collection efficiency, given fewer uncertainties and more robust results.

Thus, the toolbox can be used to identify specific, measurable and action-oriented indicators for monitoring, to support the development of intervention strategies to ensure the success of the SDG 6. Two topics will be analyzed: the use and applicability of the LGBM at local scale, and the importance of transdisciplinary approaches in current groundwater monitoring efforts.

Chapter 6. Discussion

This chapter describes the relevance of this research, its representativeness, and the issues that remain open for further research and policy implications. The main contribution is summarized in the following aspects:

6.1. Relevance of the methods used in the Transdisciplinary Socio-Groundwater toolbox

This research contributes to find out and develop specific methods, as well the advantages and disadvantages of their combination, instead of hydrological models alone, particularly when they are implemented in local contexts and in developing countries. After a substantial literature review of previous studies, a more effective, and easy-to-implement-by-stakeholders methodology was developed in consideration of the lack of reliable data in developing countries. Using a variety of methods from the social and the natural sciences, the toolbox was developed in a transdisciplinary process.

6.1.1. Gaining groundwater literacy *via* the LGBM

Groundwater in Yucatan is needed for almost all purposes, including health, food and industrial production. Thus, groundwater pollution may have different origins and be generated by different wastewater. With little coordination among users and government, its monitoring can be a challenge. In **Publication II**, we analyzed the natural system, including main socioeconomic sectors, different uses and users, and the related flows. Building on local monitoring efforts, the data scarcity problem was overcome and the LGBM developed.

The LGBM was elaborated by quantifying flows and distribution of groundwater in a local aquifer. We accounted for the flows and characterized the system. However, the ultimate goal was to involve stakeholders in its elaboration in order to influence their knowledge of the resource, *i.e.*, groundwater literacy. This work focuses on the ways that people act upon and understand, information about a range of environmental problems in a local groundwater basin in Yucatan.

The relevance of this work is that people are not aware of the fact that their day-to-day activities have been having an effect in the resource in question. Many, for example, do not have a clear understanding of the system and its analysis is a challenge due to the scientific approach involved, even if described in simple terms. Thus, understanding and managing groundwater resources can be a challenging task for decision makers and others with a professional background in water studies. Identifying major flows by applying system analysis and tendencies with the stakeholders helped us to understand the system dynamics and to influence local groundwater literacy. The LGBM helps the stakeholders to explore, develop, represent, and use this information to assess human impacts, and this can be the basis for future groundwater management in the region.

Recognizing the importance of community participation and groundwater literacy is essential to address effectively SDG 6 and its water related targets: "Ensure availability and sustainable water management of water and sanitation for all". To implement groundwater monitoring, it is crucial that data collection, analysis, and dissemination involve stakeholders and government. Current mechanisms in this regard range from household surveys to global earth observations. However, this does not tend to influence the knowledge of the users since most of the surveys and specialists collect the data on particular fields. The LGBM, for example, provides a systematic framework to identify relevant stakeholders and consider their participation in the decision making process since we included social science methods. The elaboration of the LGBM included a wide range of stakeholders across sectors and levels of government, and offered the possibility to involve local people.

Investigation of flows and development of the first LGBM in Yucatan, revealed high wastewater emissions into the aquifer (*ca*. 32 hm^3 $year^{-1}$) that could be expected from anthropogenic sources. The obtained results showed that flows and pollution sources, even in a small and well-defined system such as the Reserve zone, are difficult to determine.

The Integrated Monitoring Guide for SDG 6 suggests that it is necessary to collect data from different locations in both urban and rural settings in order to capture the full range of scenarios needed for national estimates. However, in general, data are obtained through detailed questionnaires filled in by experts and consultants who collect information, though this can generate high levels of uncertainty. It is also recommended that organizations and institutions should be consulted for the assessments including those officials responsible for sanitation, and external agencies and organizations responsible for regulation or licensing treatment services. Nevertheless, these data still remain a part of global and regional estimates and include some sectors in particular.

As proposed by the Integrated Monitoring guide for SDG 6, it is possible to obtain data from databases of institutions, ministries, and establishments typically involved but the absence of reliable data in Latin-American countries might generate uncertainties that can be crucial when calculating the flows (C. R. Binder et al., 1997). In Yucatan for example, ownership of data is a critical issue since current water management does not overlap and some information is not published in scientific literature and therefore lacks credibility in some sectors (according to Espejo, W., Head of the Water Supply Company, personal communication, 19th December 2014).

Our results provide critical insights for future analysis since they do not depend on the (scarce) published data: we obtained them through workshops with stakeholders and with a combination of research tools from a variety of disciplines. Although uncertainties and gaps persist, our results are clear: the LGBM allows the identification and assessment of the human induced flows affecting the quality of groundwater resources of an individual local aquifer with more precision, together with the society, while demonstrating that this model can influence groundwater literacy.

6.1.2. Insights gained with Mental Models

In Yucatan, groundwater is currently the main source of freshwater for the population but knowledge of the state of the system is limited. The MM method supports the understating of local knowledge, motives and values of the population. Results obtained *via* interviews and informal conversations with stakeholders show that crucial information about the system (*e.g.*, precise location, quantity, main fluxes and function) was poorly understood by the majority of the participants. Identifying major flows, by applying system analysis and tendencies with the stakeholders, helped us to understand the system dynamics and to also influence their groundwater literacy. Those results might help to explore, develop, represent and use this information to assess human impacts and this can be the basis for future groundwater management in the region.

Likewise, there are specific educational targets for the local population. For example, locals did not show any concern about possible risks than can contribute to the total or partial contamination of the aquifer. In general, they did not perceive adverse effects to the health or environment. Notions about the form and functioning of the system were not well defined by this group; however, they developed alternative notions regarding the dynamics of the system. These ideas might have had their origin in a set of interrelated beliefs about groundwater based on interpretations of daily observations, cultural information, and Mayan worldviews.

The utility of MM is evident when we analyze that the lack of groundwater system understanding is persistent in all of the interviews, and seems to influence the way in which water quality is perceived. Overall, we conclude that the ecological perception of the system possessed by experts and locals arises from the classification of biophysical elements, together with their spatial and temporal relations, and is not perceived as a socio-ecological system. Therefore, many rules for its management cannot be developed from the dynamics of biophysical and cultural environments.

6.1.3. Biocultural approach for conservation: Achieving conservation while addressing erosion of cultural values

Current conservation strategies in Yucatan do not combine cultural values with groundwater and biodiversity conservation. Likewise, current government policies do not mesh well with cultural values and the possibilities of cultural revitalization; thus, there is a lack of biocultural appreciation (Maffi & Woodley, 2010). Even though communities may no longer hold, or even know about their traditional belief systems, they seem to be interested in protecting the system. However, without an appreciation of traditional cultural and current practices, it would be difficult to understand how contemporary conservation can foster transformative change. Cenotes are linked to individual and community wellbeing, but their values have been eroded and culture and traditions lost as motivators.

Additionally, communal values have been largely replaced by individual values. Communities will benefit from conservation action, but no individual seems to have sufficient incentive to act alone. Using commons theory terminology, there is a collective action problem (Ostrom, 1990). However, there may be ways to motivate local communities by involving their knowledge, beliefs and values to enable community-based conservation, which in turn benefits communities and society as a whole, solving the collective action problem.

What are the prospects for using community-based conservation strategies to protect cenotes and thus Yucatan's groundwater resources? Elements of such an approach may include the following: First, there is a need for cultural revitalization to restore the connection of people to cenotes. Second, a biocultural approach needs to replace the government's conventional expert-based, regulation-driven conservation. Third, the governance of cenotes has to be thought of by restoring community ownership and communal responsibility of cenotes where feasible, through devolution of government authority. Fourth, an on-going educational campaign at all levels, but especially aimed at school children and youth, is needed to transmit knowledge and values about cenotes. To operationalize a biocultural approach, cenotes must be understood from an indigenous perspective by including current values and local knowledge (Samakov & Berkes, 2016). Indigenous knowledge should be integrated into hydrological management plans and be recognized at the policy level. Community-based conservation represents grassroots interests and the control of cenotes by communities provides local incentives to protect them. Education is a necessary component of a successful biocultural conservation program, especially to supplement the weak intergenerational transmission of cultural values of cenotes. Education is needed at all levels and sectors: the youth, local people, government officials, industry representatives and educational institutions themselves.

Likewise, there are specific educational targets for community people and others. It was found that, even though groundwater is currently the main source of freshwater for the population, crucial information about the state of the system (*e.g.*, precise location, function, quality, quantity, etc.) is limited and poorly understood (**Publication II**). For example, the meaning of polluted water and interconnected groundwater system was not apparent in the language or the imagery of the interviewees. What they did describe was more like an idealized, historical single cenote as a continuous aquatic “clean” underworld without considering that cenotes are interconnected. The lack of groundwater system understanding is persistent in all of the interviews, and seems to influence the way in which water quality is perceived. There can be no clearer sources of information regarding the importance and sacredness of cenotes than the importance of recognizing and revitalizing ancient Maya wisdom to help protecting groundwater and the society that depends on it. Thus, it is emphasized that the importance of groundwater literacy: the knowledge of the users about the resource and its attributes, and the perception and valuation of impacts on the system (**Publication II and III**).

6.1.4. Underwater and speleological exploration

Conservation of cenotes can be considered as a commons problem, specifically as a multilevel commons problem because each cenote is part of the larger hydrological system. It is not possible to consider each cenote as an isolated resource: water extraction or pollution of each cenote has repercussions for all (or nearly all) other cenotes, pozos and the groundwater system as a whole. Multilevel commons require a matching multilevel governance system (Berkes, 2007). During underwater exploration we found that cenotes were important manifestations of culture and cultural diversity of the Maya. This, in turn, can be important for a revalorization of current belief systems, worldviews and local knowledge involved. Our evidence also suggests that most of these sites are geographically completely isolated, and that insufficient recognition of cenotes as important cultural and spiritual natural sites both by governments and the locals is affecting the resource which at present is unsustainably used. In general, management strategies for cenotes do not include indigenous peoples in decision-making processes and this can be correlated with the amounts of pollution found. The loss and modification of the cenotes and the groundwater system in general in the region over the past decades requires strengthening conservation, technical and local efforts.

6.1.5. Cenote clean-ups: Local actions for global solutions

We performed cenote clean-ups and speleological exploration in some of the communities. The results obtained provided us key insights into the source of local pollution (*e.g.,* bad solid-waste disposal practices, water-debris problems), and helped us strategize how to stop pollution in its tracks. However, we gained insights on the overall lack of interest within the population to develop their own rules of use and to act according the notion of taking care of the resource in question. Although technical solutions are of importance, managing and protecting groundwater systems requires a whole network of public and private actors: communities, governments, industry associations, private owners, NGOs, educational institutions.

6.1.6. To what extend can the toolbox bridge the gaps between science, policy-makers and academia?

The contribution of this thesis is to propose a toolbox to analyze groundwater resources as socio-groundwater systems. The toolbox helps to identify and analyze the main characteristics of both the social and ecological system on a sensitive environmental setting. As the first toolbox to analyze socio-groundwater systems, our study shows that it is possible to generate a more robust approach to solve groundwater local problems and that those solutions can be developed in a transdisciplinary process by involving stakeholders.

Because data are often not reliable in developing countries, this toolbox might help to obtain the first estimations and water balances, and together with stakeholders, develop with this to develop a strategic management plan to make decisions. The main characteristics of the toolbox are described in Table 6.1.

Table 6.1. Characteristics of the Transdisciplinary Socio-Groundwater toolbox.

Characteristic	Description
Aim	To develop a research toolbox to understand and develop a monitoring system for socio-groundwater systems. The toolbox includes a transdisciplinary methodology to develop a socio-groundwater model, to investigate factors that influence the way in which groundwater resources are managed, to support monitoring efforts, and approaches to contribute to groundwater literacy
Basis	Material flow analysis, mental models, speleological and underwater exploration, community-based conservation, clean-ups
Framework	Social-Ecological System framework (Ostrom, 2009) and the Adaptive Co-management approach (Berkes et al., 2000)
Discipline	Natural and social sciences
Analysis of natural system	The toolbox includes a transdisciplinary methodology to develop a socio-groundwater model (the LGBM), which characterizes the system structure and dynamics: flows, boundaries, initial conditions
Analysis of social system	The toolbox helps to identify stakeholders and their perceptions regarding the system
Analysis of knowledge system	The toolbox characterizes local perceptions and cultural values of the Maya population in relation to the resource
Availability	The toolbox and interrelated methods are published in open access journals but also shared with the stakeholders who voluntarily involved in the research and members working in the water sector
Guidance	The toolbox structure is explained in the scientific literature. We use diagrams and graphic representations of each steps in order to make the process more understandable
Knowledge required	Knowledge is generated during workshops with stakeholders
Equipment required	Use of STAN (free software) facilitates the calculation but this can also be performed with other software and by using pen and paper
Substance	It is specially designed for groundwater but can also include virtual water calculations
Efficiency	The model is successful in producing the desired results and in influencing groundwater literacy
Accuracy	By developing the LGBM it is possible to produce precise results since they can be validated by stakeholders working in the water sector during workshops
Literacy	The toolbox involves stakeholders during the complete process, thus it is possible to establish conditions to enable stakeholders to

	develop and use their knowledge so they can take responsibilities and to take actions towards solutions
Affordability	It is specially designed in a local context with stakeholders in order to be affordable
Reliability	The degree to which the results can be depended on to be precise is high since data was obtained from different sources including scientific literature, interviews, informal conversations, and validated during different research stages

The proposed toolbox complies with all the criteria required for the analysis of socio-groundwater systems in karstic terrains with the inclusion of local stakeholders. However, it is important to consider that we performed some of the methods in one community and a larger case study should be considered to validate the results. In addition, even though this research was initially thought to be local in scope, it is possible to regionalize the approach.

6.1.7. Use of the thesis results at global-scale: Stakeholders monitoring efforts and the Sustainable Development Agenda 2030

To date, hydrological issues are playing a key role in the implementation of the goals in which water has a cross-cutting role linked to many other Sustainable Development Goals (SDGs) set in the 2030 Agenda for Sustainable Development. With a dedicated water goal (SDG 6), the need for data integration and monitoring remains essential to guarantee the success of all the water related targets. To "Ensure availability and sustainable management of water and sanitation for all", according to the SDG 6, there is a need to monitor eight different interrelated targets globally. At present, there are several global tools and initiatives for water monitoring (WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation/JMP, and UN-Water Global Analysis and Assessment of Sanitation and Drinking Water/GLAAS). A prerequisite for the implementation of these initiatives is to have a thorough knowledge of the system and simultaneously a consistent database, usually collected at a country and global scale worldwide (UN-Water, 2016). However, this is not the case in less developed countries where databases are not often reliable.

Hydrological modelling in the case of the Reserve zone in Yucatan was carried out to investigate central management questions such as the extent of the groundwater catchment, flows, uses, main socio-economic sectors, etc. However, the hydrological role of the system obtained with extensive revision of literature could not be determined from global data sets. Therefore, local scale hydrological modelling, elicitation of MM, and cave exploration were chosen as methods to investigate the possible contribution to global or regional monitoring, while considering local actions.

Existing monitoring initiatives such as country-based data to analyze the structure of a local system, the relevant flows, and the main socio-economic sectors, combined with the results of the toolbox, were used to identify hot-spots of pollution, the distribution of flows, to reveal water extraction trends and sectors with major consumption, and to strength stakeholder participation. A summary of the main SDG 6 targets and indicators that were addressed with the development and application of the LGBM is provided in Table 6.2.

Table 6.2. Summary of the SDG 6 targets for global monitoring that can be addressed with the LGBM.[a]

Goal 6 targets	Type and level of data required	Drawbacks	LGBM contribution
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water	Global and National statistics	Data (*e.g.*, chemical and faecal contamination) do not cover all countries immediately	LGBM facilitates examination of hotspots of pollution and distribution of flows of hazardous substances
6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying attention to the needs of women and girls and those in vulnerable situation	National estimates adjusted for global comparison (*e.g.*, administrative, population and environmental data can be combined to estimate safe disposal or transport of excreta when no country data are available)	Data will not cover all countries Deficiencies on infrastructure for collection and transport are difficult to consider	LGBM facilitates examination of the amount of wastewater treatment process in specific economic sectors (*e.g.*, industry) Calculations considering deficiencies on infrastructure can be made throughout expert consultation and during workshops to calculate error margins
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and at least doubling recycling and safe reuse globally	Data will come from sources combining utility and regulator data for off-site and household survey questions and measurements relating to onsite treatment supplemented by estimates where no reliable national data exist	Data (*e.g.*, safe disposal and treatment) remain scarce and might not be available in all countries Information is usually not shared among water institutions and society, leading to conflicts among institutions and users	LGBM facilitates the identification of the human induced flows affecting groundwater quality and the amount of water that it is recycled within the system LGBM supports monitoring at different points of the water body revealing different pollution trends LGBM promotes participation and transdisciplinary approaches to

		Households surveys do not influence knowledge of society	contribute towards the lack of sharing information among the interested stakeholders LGBM influence the user's knowledge
6.4 By 2030, increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	Global datasets from AQUASTAST-FAO on water withdrawals in different sectors at national (hydrological units) and global level International datasets on water availably and withdrawals from different sectors	Recognition of main sectors, flows and their distribution is a requisite but data is available for some countries only and gaps tend to proliferate Regional and climatic conditions can limit results Difficulty to obtain accurate, complete and up-to-date data Potentially large variation of subnational data Lack of account of seasonal variations in water resources Absence of consideration of water quality and its suitability for use Double counting when	LGBM facilitates the monitoring process of groundwater availability and withdrawals and promote improved allocations between users by revealing water extraction trends Lack of tax declaration and local data can be overcome Data on volumes of withdrawn and distributed water can be estimated and complement those obtained from the municipal supply utilities records (JAPAY) Estimation of water withdrawals by sector can be possible Indicator 6.4.2 concerning the level of water stress can be achieved by collecting data regarding the ratio between total freshwater withdrawn by all major sectors

		conflicting sources of information Deficiency of tax declaration (influencing datasets) Difficulties in defining level of water stress (*e.g.*, in Yucatan quality, not quantity, seems the main problem)	
6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	National surveys, regional and global estimates can be aggregated from national data	Spatial data and global database for freshwater treaties and transboundary basins are available as well as regional ones but uncertainties on groundwater resources exist Current operational arrangements do not tend to consider groundwater basins Water resource management do not tend to consider all users	LGBM support the involvement and participation of stakeholders and local communities in the development and application of the results in improving water and sanitation management LGBM is based on system analysis and can be used to estimate transboundary water flows and this might improve the level of cooperation LGBM can be implemented in adjacent states that share the groundwater basin

6.6 By 2020, protect and restore water-related ecosystems, including mountains, forest, wetlands, rivers, aquifers and lakes	Data from National sources, Global datasets (*e.g.*, groundwater volume, wetland extent) are needed Ground-based surveys	Temporal gaps exist Collection of data still needed Data available only for some countries only	LGBM can be used to monitor and to track changes over time in the extent of wetlands and the groundwater table in the region, and to determine the quantity of water within the system
6.a By 2030, expand international cooperation and capacity-building support to developing countries in water and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater, treatment, recycling and reuse technologies	National sources Global datasets Global compilations	Difficult to know how much local administrative units depends on external support or to what extend external grants or loans are coordinated by the government	LGBM ensure the direct participation of stakeholders and facilitate the identification of weaknesses in water-related activities, the amount of water that is recycled, the efficiency of the system, the available programmes and technologies. The identification of those factors might help stakeholders to apply for external grants or support in coordination with government LGBM facilitates the promotion of good practices and use efficiency and stimulates water recycling
6.b Support and strengthen the participation of local communities in improving water and sanitation management	Data for global and regional surveys Data can be disaggregated on urban/rural sanitation; urban/rural drinking water-water and hygiene promotion	There are not well-defined established and operational procedures for participation of local communities in water and sanitation management	LGBM facilitate the identification of relevant stakeholders LGBM promotes the meaningful involvement of local communities and relevant stakeholders in the development of the monitoring tool LGBM strongly influence groundwater

		It is difficult to ensure participation of users and to assess this through surveys	literacy

[a] From **Publication II**.

To implement SDG 6, the LGBM specifically supports the following Targets 6.3, 6.4, 6.5, and 6.6 (a & b). Using the example of Target 6.3, the indicator 6.3.1 addresses the proportion of all wastewater generated that is safely treated at source or through a treatment plan before it is discharged into the environment. In the case of Yucatan and particularly in rural areas, the percentage of the population with safely treated wastewater is uncertain since some households do not have a treatment facility, a septic tank, or latrine pits, and inhabitants do not tend to handle (or are not allowed to) and re-use the wastewater (*e.g.*, as an agricultural input). The LGBM shows that, despite a portion of wastewater reaching a treatment plant, the rest remains untreated and the emissions are outputs discharged directly into the environment. As already suggested by several studies, these emissions come with a variety of contaminants such as: organic matter, pesticides, pharmaceuticals, etc. (Metcalfe et al., 2011). With the development of the LGBM it would be possible to determine the flows of those substances within a particular pre-defined system.

But what is needed to fully implement SDG 6 in the case of Yucatan? Our results demonstrate that with the toolbox it is possible to implement the SDG 6 since we:

1) Approached the implementation of SDG 6 in an integrated transdisciplinary way.

2) Strengthened coordination among stakeholders at all levels, including local communities in the study area.

3) Developed comprehensive strategies to raise awareness of the natural and cultural significance of the socio-groundwater system by involving local members and Mayan elders and by understanding how population ascribe meaning to the resource.

4) Improved groundwater literacy, including traditional knowledge, by acknowledged local knowledge as an informal way of monitoring by involving stakeholders in the complete process.

5) Promote transdisciplinary research among scientific disciplines to make information less patchy during the development of workshops.

Overall, the toolbox proved to be effective in the understanding, characterization and modelling of socio-groundwater systems, however, its implementation should involve stakeholders.

6.2. Representativeness of the case study

This is a reliable and versatile methodology to meaningfully contribute with groundwater sustainability. It can be adapted to specific social, economic, political and environmental setting of different regions. However, in this research the modelling was applied to only one of the communities selected (Tecoh, Yucatan) although it can be extrapolated to any other community with similar characteristics. Furthermore, this model does not take into account rivers or surface water, and thus it does not evaluate their possible influences on the system. Similarly, transfer coefficients must be calculated and calibrated.

6.3. Policy implications

As our project is intended to also be used by policy makers, our results could be easily implemented to plan the transition process for better groundwater management within the region. The model can be a useful tool for resource management considering poor data and it is aimed at knowledge integration as key for understanding socio-groundwater systems. The ideas proposed here may guide the adoption of a new approach towards a better groundwater resource management.

In policy terms, for example, the LGBM might provide policy relevant guidance to government and environmental authorities for implementing measures intended at mitigating impacts on the resource. The model provides a starting point for detailed analysis of the effect of anthropogenic emissions on natural groundwater processes. This is critical for policy and management implications, particularly in a place where no other sources of freshwater exist. Monitoring at each step and by particular socioeconomic sectors of the chain helps to capture the hotspots generated by users, including the fraction of water that is reused or treated. Our confidence is attained not only due to mathematical equations but also from results obtained during stakeholder workshops. This will support a future groundwater balance for the complete region by adapting particular parameters into the model.

6.4. Future research

The toolbox could be extended in the following directions: 1) to model the flux of hazardous substances within the system under different scenarios, 2) to incorporate the dynamic nature of decision-making into modelling, 3) to include stakeholders from additional sectors (*e.g.*, textile industry, etc.). Monitoring, back-casting, and modification of resource with future research data are highly recommended.

The toolbox can be adapted to specific regions, can be used to address methodological challenges for monitoring and can contribute with the achievement of the 2030 Development Agenda. The LGBM can be built on existing monitoring frameworks and statistical standard definitions, classifications and treatment categories such as AQUASTAT and SEEA.

This thesis also contribute to the literature on commons theory, traditional knowledge and worldviews for natural resource management, especially where the local community is a joint manager (Berkes, 2012; Borrini-Feyerabend, Kothari, & Oviedo, 2004). Thus, further research on this field is also recommended.

Chapter 7. Conclusions

7.1. Where are the key environmental problems and how the toolbox can contribute towards solutions?

Because of the topography and a comparatively high annual precipitation, Yucatan possesses an extensive network of groundwater rivers forming natural sinkholes that are locally called cenotes. Over the years local communities have traditionally used many of these ecosystems despite the fact that water resources are property of the Nation and their management is the government's duty. This situation gave rise to a co-management regime involving a great number of actors with different interests. However, this management is always under discussion due to the overexploitation of these resources, and the lack of coordination between government and users. In Yucatan absence of clearly defined property rights, failure by governmental agencies to efficiently support local community development and the increasing pollution issues are the most common problems. The vast population who use and manage the resource are highly dependent on it because is the only available source of freshwater. Pollution and impacts on this resource due to human activities such as tourism and agriculture are increasing the vulnerability of the groundwater system, making the community vulnerable as well. The need to secure groundwater future and protect it against pollution and related problems is crucial.

This thesis started with the idea that groundwater resources are social-ecological systems because they are interconnected. Thus, the case of Yucatan as an integrated social-ecological system was analyzed by applying natural and social science methodologies. Many of the results obtained in this thesis showed that human actions are responsible for the majority of the drivers that impact the socio-ecological system and thus the analysis of the social system as part of the natural system is crucial. The case of groundwater CPR in Yucatan shows the interplay between natural and social factors, provides some lessons in commons management, and draw attention to the importance of local scale issues. All those problems are crucial and equally important, and the solution should involve a multilevel approach. Rural communities may focus on financial income and livelihoods, experts in the understanding of the system, and policy-makers in the resolution of conflicts. All the perspectives might be different but they need to overlap. Thus, this thesis documents the fragility of groundwater resources in Yucatan, Mexico and provides a toolbox to analyze it as a socio-groundwater system. The work focuses on the design of a toolbox to investigate complex socio-groundwater systems with an emphasis on an integrated, transdisciplinary approach. The toolbox is based on a combination of methods and empirical evidence. In order to design a toolbox that can combine as many desired methods from different disciplines, an appropriate framework was required. A detailed description of the framework was presented in **Chapter 3** (fully explained in **Publication I**). These methods are closely related, featuring groundwater systems interactions, better understanding of feedbacks, and preferential resource conservation, all of which were observed experimentally. The key steps are the characterization of the natural system, by obtaining the first local groundwater balance, the elicitation of mental models, followed by underwater and cave exploration, community conservation and, ultimately, the development of clean-ups to directly involve stakeholders. The combination of those methods proved to be a very efficient route for the analysis of both, the social and the ecological system, for support groundwater monitoring and to contribute with groundwater literacy.

For example, it is known that quantifications of the flows require continuous data or long-term predictions, and water balances often require sophisticated hydrological methods. To overcome this, applying hydrological modelling as a method enables the estimation of a groundwater balance and the development of the first LGBM. Our system approach addressed current gaps in groundwater management since the MFA method was implemented and a water balance over a recently declared hydrological protected area was developed.

The elicitation of MM and data from interviews, informal conversations, and estimations enabled better interpretation of the LGBM results. The analysis of MM was implemented in order to understand the stakeholders' perceptions of the system. Experts must be aware of their MM and must have a clear understanding of the relevant concepts on the dynamics of the aquifer –and the system- that is scientifically accepted. This is because this information can influence the MM of the local population. Locals have to understand and know the nature of the groundwater system, how it is formed, stored, contaminated and how their actions influence the resource. They should understand that the system connects with everything in the hydrological cycle. This will be possible through the integration of MM and LGBM results. The results can be used as a baseline to find inconsistencies on information, and if the mental models of experts are shared with the society. The MM provided a basis for identifying the origins of misunderstandings among the stakeholders, and led to the conclusion that society has its own conceptions and understandings about the local hydrological cycle but that conceptions do not overlap. Thus, without a correct understanding of groundwater occurrence in the environment (its formation, use, implications of contamination, etc.) it is not possible to take action to protect groundwater.

In Yucatan, as problems and population develop, communities, and almost all stakeholders, are less able to find solutions. The problem is probably because the society is never considered as part of the system, and because the local population is not allowed to take at least some control of the resource in question. In addition, the information is not shared among stakeholders and the assessments, monitoring and regulatory controls are insufficient for this case.

For example, in the case of the communities included in this research, high levels of pollution, combined with the lack of support from environmental authorities and poor local participation represent a serious problem. Furthermore, environmental and government regulations are diffuse, the system dynamics are not well understood by the users, and management of the resource tends to exclude collective arrangements. Thus, water can be extracted without any regulation, despite the fact that this is a protected area. Hence, the issue of groundwater literacy is crucial: users need to understand the resource, develop their own tools for management and monitoring, engage more and keep informed about environmental regulations.

7.2. Cenotes for the Maya

Global solutions to environmental problems such as groundwater contamination are of importance; however, local involvement is also significant towards these solutions. Community-based conservation has been considered as one of the biocultural approaches to conservation embedded within social-ecological systems (Gavin et al., 2015). Action is needed for culturally appropriate protection of cenotes. Local traditional communities should encourage, revival and recognize the current values of cenotes as important sacred natural sites. They should work together to face the threats affecting them and encourage young generations for their preservation. In the case of Yucatan, and because cenotes are interconnected, they cannot be managed as isolated entities. Similarly, cenotes are part of a millennial culture and cannot be managed in isolation from that culture. Even though culture and environment are no longer closely coupled in current Yucatec Maya society, cenotes cannot be managed and understood without recognizing the values and knowledge of local communities. Thus, there is a need for revitalization and recognition of cenotes as sacred natural sites. Communities are the most appropriate actors to initiate collective action, with support from a network of other stakeholders, to reverse threats and encourage stewardship in younger generations.

Commons theory does not explicitly recognize the revitalization of indigenous cultures and social norms as essential for commons management. However, the present case shows that groundwater conservation in Yucatan cannot come solely from government regulation and privatization. It may be better initiated by the revitalization of community values and norms, as in this case, the recognition of cenotes as important cultural and spiritual natural sites. The social enforcement of respect for cenotes and groundwater restores individual incentives to act in ways that benefit communities and society. Hence, restoring cultural values is the way communities can foster conservation and solve the collective action problem (Nyborg et al., 2016). Through such collective action, individuals, as well as the community, can derive social and economic benefits from conservation, consistent with commons theory (Berkes, 2004).

The revitalization of cultural values, and the protection of the cenotes in general, needs to be supported by at least three other community-based conservation strategies, as detailed in the previous section: (a) the adoption of a biocultural approach to replace government's conventional sectoral or discipline- and expert-based, regulation-driven conservation; (b) governance reform to restore community ownership and communal responsibility for cenotes through devolution of government authority; and (c) an on-going educational campaign at all levels to transmit knowledge and values about cenotes. Strengthening of community culture and knowledge is important also for maintaining the ecological integrity of cenotes, as these sites need to be conserved as reservoirs of biodiversity. This is one potential area of cooperation between local and scientific knowledge (Wild & McLeod, 2008). Traditional ecological knowledge or indigenous knowledge is a source of biological information and ecological insights for conservation (Berkes, 2012). However, until recently, inclusion of indigenous knowledge into planning was not even considered. Conservation of protected areas should be designed to work with local people (Borrini-Feyerabend et al., 2004). Moreover, if social and ecological systems are going to be approached as integrated complex systems, there is a need to develop a model of conservation that takes into account the complexity of Maya society and the complexity of the groundwater system, and the relationships between the two as a social-ecological system (Berkes, 2004). Naturally there is always cultural change and loss of some values, changing the ways in which groundwater is used -- but these values can also change still further - toward conservation. Such changes would necessarily involve deliberation and mutual learning among the people engaged (Berkes & Turner, 2006).

The main driving forces behind the growing interest in the protection of cenotes are human activities, development, and environmental impacts. There is potential for the recognition of the importance of cultural values in Yucatan groundwater conservation. Internationally, efforts have been made, and methods and approaches developed, in order to assess the cultural values of indigenous communities regarding their ecosystems (Oviedo & Janrenaud, 2007). However, the present study clarifies the need for the inclusion of indigenous thinkers, policy makers and local people in the understanding of those values, traditions and beliefs.

Cenotes were important manifestations of culture and cultural diversity of the Maya. This, in turn, can be important for a revalorization of current belief systems, worldviews and local knowledge involved. Our evidence suggests that most of these sites are completely isolated, and insufficient recognition of cenotes as culturally important sites, both by governments and the locals are affecting the resource, and cenotes being used unsustainably at present. In general, management strategies of cenotes do not include indigenous peoples in decision-making processes. The loss and modification of the cenotes and the groundwater system in general requires strengthening conservation, technical and local efforts.

This work also emphasizes the development and use of additional methods and local actions, including speleological exploration and clean-ups as the most effective way for groundwater management and conservation, and demonstrates the potential of our approach as a successful manner to contribute with groundwater literacy.

7.3. Final remarks

Our results confirm that the toolbox has significant potential for the analysis of a range of groundwater-related problems. The combination of current methods with the development of novel approaches for this purpose, and the need to develop simple, non-expensive routes to solve pressing groundwater problems, make this toolbox fully suitable to be applied to other regions with similar characteristics.

This work is of importance, both from a scholarly and an applied point of view, as it deals with an environmentally sensitive groundwater basin. It is worth that more than 200 stakeholders were involved for the design and implementation of our toolbox, acknowledging local knowledge, rather than encouraging these knowledge systems to become "more scientific". With this we confirm that more efforts are needed to fully understand the fact that any effort to solve real world problems should first engage with local communities, beginning from the perspective of local actions, community efforts, and the respect of local knowledge. For the future the toolbox can be used by the stakeholders to i) identify the human induced flows affecting groundwater quality, ii) monitor water availability and withdrawals, iii) promote improved allocations between users, iv) stimulate water recycling, traditional rainwater harvesting practices and efficient use, v) detect hot-spots of pollution, vi) determine precise location and characteristics of the cave system, including cultural values and biodiversity, vii) perform cenote clean-ups in the communities, and viii) influence groundwater literacy.

The methods applied for the analysis of both systems are consistent with current methods, but our toolbox helps to ensure the success of the SDG framework. It should be noted that the elements of analysis involved in the socio-groundwater system mechanisms could also be fragmented for further analysis. It should also be noted that our toolbox provides a sound basis for the design of interventions, communications and educational programs in Yucatan. The thesis results support the groundwater literacy and thus will facilitate the future management of groundwater.

Chapter 8. References

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Annexes

Publication I

López-Maldonado, Y. (2014). “Towards an Understanding of the Human-Environment System of Mayan Communities: Knowledge, Users, Beliefs and Perception of Groundwater in Yucatan”. The Digital Library of the Commons. Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis. Indiana University. URL: http://dlc.dlib.indiana.edu/dlc/handle/10535/9408

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

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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.

<<<INSERT FIGURE 1 ABOUT HERE>>>

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.

<<<INSERT TABLE 1 ABOUT HERE>>>

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.

<<<INSERT FIGURE 2 ABOUT HERE>>>

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).

<<INSERT TABLE 3 ABOUT HERE>>

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.

<<INSERT TABLE 4 ABOUT HERE>>

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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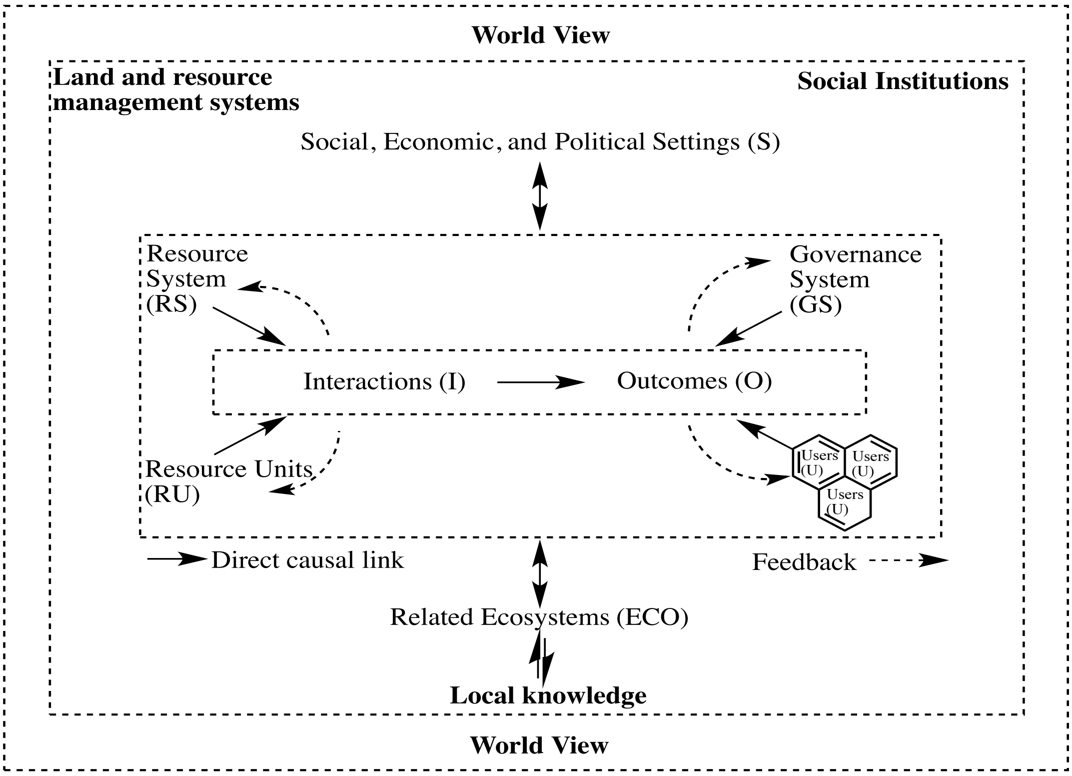

Figure 1. Based in Social-Ecological System Framework (Ostrom 2009; Ostrom 2007) and the Adaptive co-management approach (Berkes et al. 2003; Folke 2007; Folke et al. 2005).

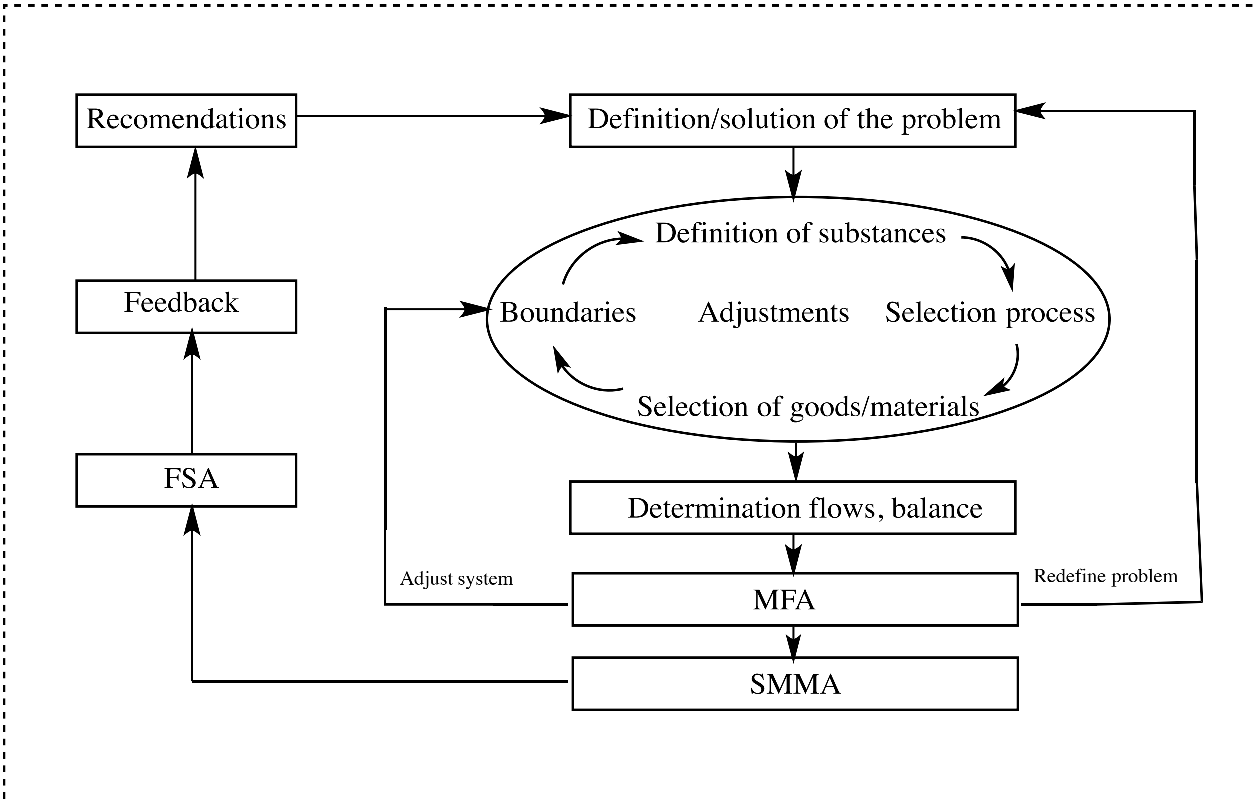

Figure 2. The research process departs from the identification of the problem by analysing the current state of the system and leads through a complete analysis and definition of boundaries, substances, actors and related process for the development of the MFA and SMMA, which finally leads to the solution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

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Local groundwater balance model: stakeholders' efforts to address groundwater monitoring and literacy

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Local groundwater balance model: stakeholders' efforts to address groundwater monitoring and literacy

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ABSTRACT
Understanding groundwater systems is crucial to ensure their monitoring and protection. Global groundwater models and predictive tools exist to better understand them. In view of scarce groundwater data, especially in developing countries, the question of how to model these systems and make them usable for groundwater management is crucial. Herein, we demonstrate how a transdisciplinary process can overcome the data scarcity problem and lead to the development of a local groundwater balance model (LGBM). Over 50 actors from more than 15 disciplines and groundwater-related sectors were involved for the case of Yucatan, Mexico. Results revealed high wastewater emissions to the aquifer discharged without treatment and poor recycling practices. The method can be adapted to specific regions, can be used to address methodological challenges for monitoring, and can contribute to the achievement of the 2030 Development Agenda by addressing Sustainable Development Goal 6-related Targets (6.3, 6.4, 6.5, 6.6(a, b)).

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1 Introduction

1.1 Groundwater: our complex common-pool resource

Groundwater is an important common-pool resource that plays a unique role for human and ecological health and supports the freshwater needs of up to two billion people (Gleeson *et al.* 2012b, Richey *et al.* 2015). Indeed, groundwater has been described as a key, strategic, socially important, primary, life-sustaining resource (Custodio 2002, Giordano 2009, Richey *et al.* 2015). However, groundwater management represents a societal challenge, since problems of universal importance tend to occur at different levels and scales (e.g. human–hydrological and local–global) (Sophocleous 2002, Gleeson *et al.* 2016). Understanding groundwater characteristics and dynamics is crucial for its monitoring and protection, which require data and cross-scale approaches to support communities to address urgent local environmental challenges.

In recent decades, there has been increasing concern as human activities are placing excessive pressure on groundwater resources (Döll and Fiedler 2008, Vermooten and Kukuric 2009, Van Loon *et al.* 2016, Wada 2016). This has caused a reconsideration of groundwater as one of the major future concerns for humanity, and for it to be included in global agendas, publications (both scholarly and popular), and large-scale policy recommendations on the subject, where past water-related targets were missing (UN-Water 2016, World Economic Forum 2016). In addition, as these concerns grow, the urgent need to ensure availability and sustainable management of water and sanitation for all remains crucial.

To date, hydrological issues are playing a key role in the implementation of the goals set in the 2030 Agenda for Sustainable Development, in which water has a cross-cutting role linked to many other Sustainable Development Goals (SDGs) (UN-Water 2016). Water is inter-related to almost all remaining SDGs, making it a challenge to assess, monitor and support their implantation. Thus, with a dedicated water goal (SDG 6) on the sustainable development agenda, the need for data integration and monitoring remains essential to ensure the success of all the water related targets (UN-Water 2016).

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1.2 Groundwater monitoring requires groundwater knowledge

To monitor and enhance our understanding of groundwater and its problems, global models and monitoring initiatives exist (Sood and Smakhtin 2015, Wada 2016). These models and initiatives have mostly been applied for understanding global hydrological processes; hence, their use and applicability to local groundwater systems is unclear. In view of data scarcity, mostly in developing countries, a key challenge is how to model these systems and make them usable for better groundwater monitoring and consequent management.

Good groundwater management depends on how we use, manage and value the resource (Gleeson *et al*. 2012a). Successful monitoring and management often calls for a clear understanding of the groundwater system or groundwater literacy, defined here as: the knowledge of the users about the resource and some of its attributes, and their perception and valuation of their impacts in the system. We argue that communities need to develop their monitoring tools appropriately and to produce information to use and monitor groundwater resources properly. Likewise, scientists and policy makers need to consider local conditions, knowledge and norms to build local-scale models, since groundwater problems are largely local (Giordano 2009, Gleeson *et al*. 2016). However, it remains unclear how hydrologists, for example, can apply their results at a local scale and how they can significantly contribute towards groundwater literacy.

The objective of this study is to develop a local groundwater balance model (LGBM) by quantifying flows and distribution of groundwater in a local aquifer, and to influence groundwater literacy with the involvement of more than 50 stakeholders. Recognizing the importance of community participation and groundwater literacy is essential to address SDG 6 and its water-related targets effectively: "*Ensure availability and sustainable water management of water and sanitation for all*". We use the example of Yucatan, Mexico, where groundwater is the only source of freshwater for the population, where water demands and problems are growing, and groundwater data remain limited. The LGBM could be used to determine the human-induced flows affecting groundwater quality, to monitor water availability and withdrawals, and to promote improved allocations between users. The LGBM is complementary to current assessment methods such as the groundwater footprint method (GFM) (Gleeson *et al*. 2012b) and the regional water balance (RWB) (Binder *et al*. 1997), and it can be used to address methodological challenges for monitoring.

For developing the LGBM the following research questions were addressed: (1) How is the natural system structured? (2) What are the inputs, outputs, and groundwater flows in the system? (3) Which human factors might induce groundwater pollution at a local scale? (4) How can the information obtained with the LGBM be used at a local scale?

We show how the LGBM was developed, by involving stakeholders, and this can be taken as a platform for groundwater monitoring following a ladder approach. The results shows that, for the implementation of SDG 6, the LGBM specifically supports Targets 6.3, 6.4, 6.5 and 6.6(a and b).

2 Methods

2.1 Case study region

Yucatan is located in southeast Mexico and is in the hydrological unit area of the Yucatan Peninsula Aquifer, which includes the states of Yucatan, Campeche and Quintana Roo. The total area of Yucatan is 124 409 km^2 and the population recorded in 2015 was 2 097 175 inhabitants (INEGI 2015). The aquifer is karstic and unconfined, except in the coastal zone (Bauer-Gottwein *et al*. 2011). The soil characteristics and the high permeability influence the amount of rainfall that can directly enter the aquifer. Permeability helps water to flow through the rocks and precipitation infiltrates into the subsurface. This phenomenon has had strong effects in the resource, especially the formation of the connected underground channels and sinkholes that are widely spread throughout the area. Within the study area, the agriculture sector is the main water consumer. Current aquifer problems are high levels of organic matter, fecal organisms, residual chemicals such as detergents and pesticides, etc. in both rural and urban areas (Pérez Ceballos and Pacheco Ávila 2004, Bauer-Gottwein *et al*. 2011). With the interest in developing a possible solution for the groundwater crisis in the region, a priority area for environmental protection was established in 2014: the Geohydrological Reserve (GR) zone (Pacheco Ávila *et al*. 2004). Its aim was to create a zone in order to secure the provision of water for the metropolitan region. The creation of the GR zone comprises five lines that facilitate water management and protection in the region of incidence. Its aim is to encourage the local population in the development of actions that might generate economic benefits, while achieving conservation and restoration of ecosystems: (a) economic

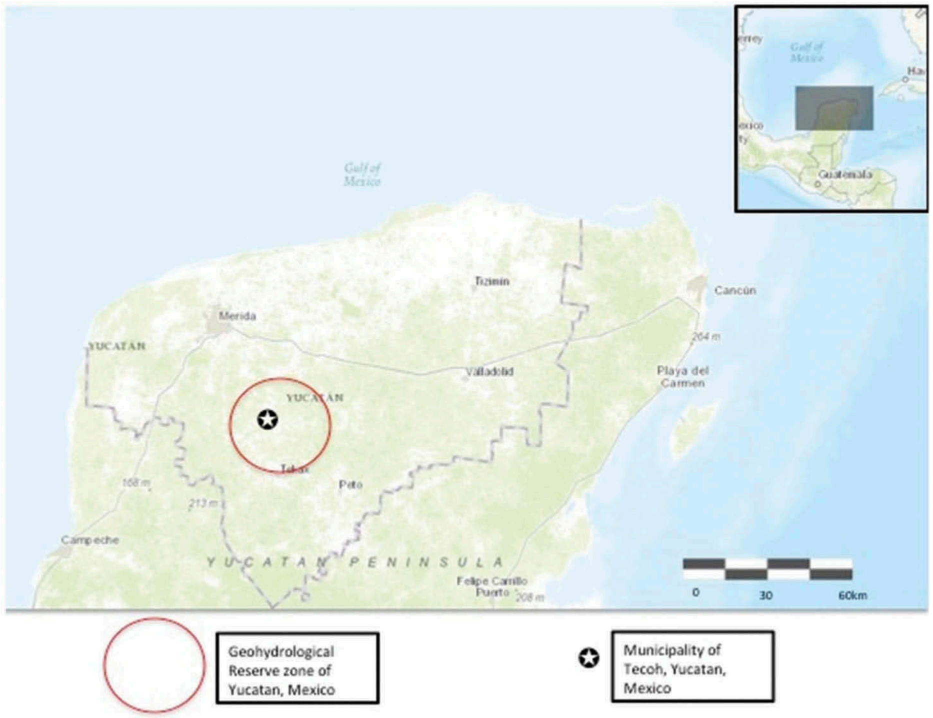

Figure 1. Location of the Geohydrological Reserve in Yucatan, Mexico.

valuation of environmental services; (b) restoration and conservation of cenotes; (c) improvement of groundwater quality through integral waste management processes; (d) development of studies for sustainable resource management; and (e) improvement of ecosystems services and water provision for the whole population.

Groundwater storage and flow occur in a karst aquifer with major cave systems, where groundwater flow is dominated by turbulent conduit flow (Graniel *et al.* 1999). The quality of groundwater is threatened in the Yucatan karstic region in general due to high population growth, tourism infrastructure, coliform concentrations, and a high density of nutrients. Nitrogen and phosphorus concentrations of anthropogenic origin through sewage percolation threaten the resource. The GR zone consists of 13 municipalities and is located within the Ring of Cenotes (Perry *et al.* 2009) (Fig. 1). The municipality of Tecoh was selected as a case study due to the availability information for the year 2014 in relation to other local municipalities. Further descriptions of the Ring of Cenotes, the groundwater context and a general description of the study area are available in the Supplementary Material.

2.2 Model overview

The LGBM, as proposed here, was developed to obtain a water balance and to assess local-scale groundwater impacts. This will allow users to monitor the local groundwater system in an integrated manner and thus support the implementation of SDG 6. The LGBM was developed in five steps in an iterative process (Fig. 2).

For developing the model, we employed the material flow analysis (MFA) method (Baccini and Bader 1996, Brunner and Rechberger 2004) because it assisted us to analyse, understand and visualize the flows and exchanges of materials and energy with the environment (Ayres and Ayres 2002). It quantifies flows that raise environmental and health risk concerns (Huang *et al.* 2012). In general, MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It is a helpful tool to understand flows, stocks and processes of the human activities and the environment. One crucial characteristic of MFA is that it can serve as a basis for sustainable regional material management and for developing monitoring programs (Binder 2007).

The MFA method has also been used to investigate hazardous materials for environmental risk assessment in water bodies such as lakes, rivers and reservoirs (Palmquist and Hanæus 2005, Schaffner *et al.* 2009, 2010, Chèvre *et al.* 2013). We followed five different steps according to the MFA procedure to build the LGBM (Baccini and Bader 1996).

To the best of our knowledge, there is no previous similar study in the literature; thus, for the

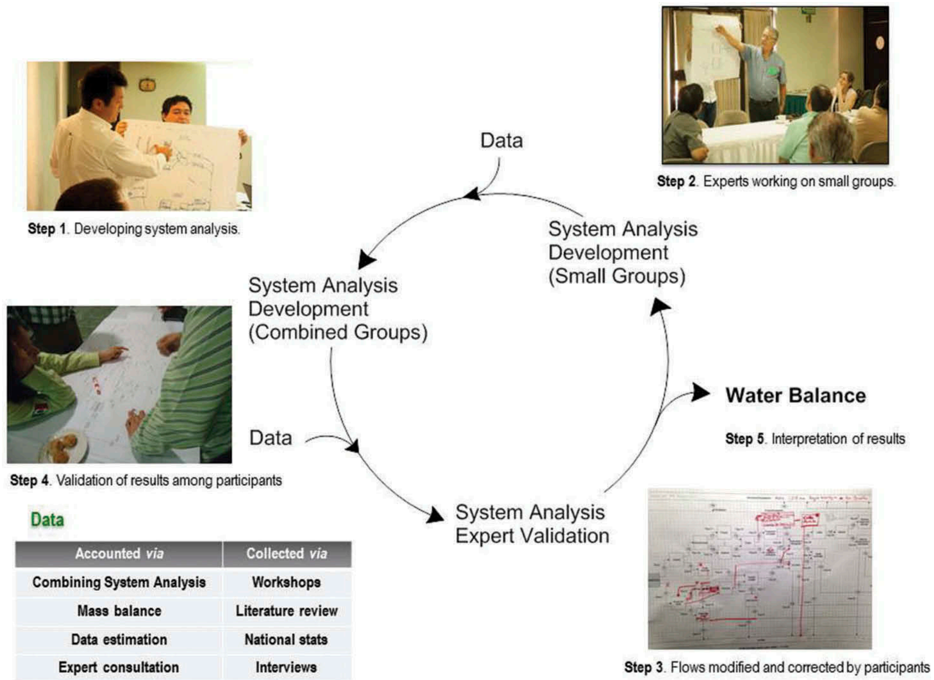

Figure 2. Five steps for the development of the local groundwater balance model.

development of the MFAs and the sets of diagrams, we started with the creation of an initial system analysis of the defined study area, as described in Section 2.1, based on expert opinion (see Supplementary Material). Then, the stakeholders were asked to (i) develop the system analysis; (ii) provide data on the flows and related sources; and (iii) validate results in an iterative process by comparing the initial diagrams. Based on these data, the LGBM was elaborated and related to a regionalized groundwater balance. We accounted for groundwater human-induced flows by combining system analysis, mass balance, data estimation, and expert and public consultation. The five steps to construct the LGBM are:

(1) **System boundary definition**: A system boundary was defined in space and time (Baccini and Bader 1996, Binder *et al.* 1997). The hydrological system boundary is the GR zone in Yucatan, which includes 13 municipalities located within the Ring of Cenotes, whereas the aquifer and atmosphere were located outside the system boundary. The flows of groundwater into, out of and through the system boundaries were analysed. The municipality of Tecoh (16 200 inhabitants) was selected as the study area to apply the method. Tecoh is part of the recharge zone of the GR zone and receives pollutants from intensive agriculture, particularly from southern parts of the state (Polanco Rodríguez *et al.* 2015). The same processes selected for the system analysis were used for the water balance, with the analysis performed for the year 2014.

(2) **Identification of relevant flows, processes and stocks**: Five relevant processes: extraction, distribution, uses, treatment and recycling, were identified, defined and validated in workshops with stakeholders working within the water sector. The stakeholders were given the first draft of the system analysis, which was previously developed by the authors as described in Step 1. Stakeholders were asked whether the processes and flows identified were, in their experience, correct. Following this, they were asked to fill in missing information (numerical values), which were also the basis knwoledge for all the flows. (For a detailed overview of the system analysis approach used during the research process see Supplementary Material.). Five processes were identified and a total of 39 flows were established. Groundwater was the substance used for the water balance. The aquifer and atmosphere were located outside the system boundary.

(3) **Substance flow diagrams**: We developed substance flow diagrams by combining system analysis from the gathering of local and scientific knowledge.

(4) **Water balance**: The water balance was estimated. The water supply company, Junta de Agua Potable

y Alcantarillado de Yucatan (JAPAY), supplies water to 90% of the urban households. Rural households are water self-sufficient, but they receive technical support from JAPAY. In addition to this, municipalities also receive water for a main pumped source, which consists of legal concessions available for those who want to extract water for several uses from the aquifer. Tecoh, similar to the other 105 state municipalities, has only one main water source: the groundwater system. It also means that water can be extracted from local wells and stored in tanks without a concession from Conagua (National Water Commission). Groundwater is pumped directly to the households, and this transportation process has an estimated efficiency of 60%. In general, most rural households also extract water from their own wells, locally called *pozos*. Calculations were made considering one year (2014), since it was the year with the most available and reliable statistical data. We estimated the groundwater balance as the sum total of inputs, stocks and output flows. First, we selected primary sources of information about the total extracted water volume based on national and regional statistics. Expert consultation was made to get local data as proposed by Gleeson *et al.* (2012a). We then calculated flows at local scale and the associated outputs (see Supplementary Material).

(5) **Interpretation of results**: The results obtained were interpreted and the method was adapted to be applied in further sectors (e.g. the livestock and industry sectors). With the aid of Sankey diagrams within each sector, obtained using STAN software (Cencic and Rechberger 2008), the Sankey flows depicted the directed outputs of the human system to the aquifer and thus indicated how human activities influence the system. One essential characteristic of this tool is that any substance or material can be represented by arrows, whose widths are shown proportionally to the flow quantity and the transfers between processes (Schmidt 2006). Uncertainty values were not considered in the model due to the lack of sufficient data (uncertainties of only two out of 39 flows are known).

2.3 The local groundwater balance model

There are four sectors in the model: (1) industry, (2) agriculture, (3) livestock and (4) households, and five relevant processes (Table 1). The model starts with the groundwater storage component, which accounts for the subterranean flow. Then fluxes of groundwater for each sector are calculated simultaneously.

2.4 Data sources

In Tecoh, and most of the Yucatan's 106 municipalities, time series data on social and natural resources are very poor in terms of coverage, accuracy and duration. This may be due to government terms and the related changes in governmental parties. Hence, data were obtained and derived from different sources: literature, national and local statistics, stakeholder workshops, expert opinions and consultation, and local interviews (Table 2). Literature and information at the country level were reviewed, including national policies, reports, yearbooks and scientific publications. Online interviews were performed to consult experts and members from the water sector (Krueger *et al.* 2012). We used expert open-ended interviews and informal conversations with stakeholders, as well as *in-situ* observations in the municipality selected (Creswell 2003).

In addition, interviews and expert consultation were obtained during workshops performed in 2014. Stakeholders working in the water sector were asked about data regarding specific sectors and the system analysis was validated with representatives from regional and local level. More than 50 stakeholders were involved (for further characteristics of the interviews

Table 1. Definition of processes for the water balance.

Process	Description
Water extraction	The process of taking water from any part of the aquifer (includes private extractions that are not reported in water statistics)
Water supply/distribution	Delivery of water to final users plus net abstraction of water for own final use (self-supply)
Water uses/consumption	The part of water withdrawn and extracted from the aquifer for use in specific sectors
Wastewater treatment/ management	Management of volume of domestic, commercial and industrial effluents, and storm water runoff, generated within urban or rural areas
Water recycling	Re-use of water in any other sub-process

Table 2. Data sources to characterize to obtain a groundwater balance.

Type of data	Source, year	Model component	Accounted via	Collected via
Groundwater characteristics (fluxes, structure, main economic sectors)	Expert consultation and scientific publications, 2014, 2015, 2016	Groundwater dynamics, assessment, input, outputs, stocks	Combining system analysis	Workshops
Climatic data	National, regional and local statistics (CONAGUA Climatic station), 2014	Inputs and outputs groundwater balance	Meteorological Department, Government of Yucatan	Literature review
Population	INEGI (2015)	Household and agricultural sector	Survey of Yucatan Irrigation and Water statistics	National statistics
Livestock	REPDA Archives – CONAGUA, 2014, 2015	Animal husbandry	Census of livestock and agricultural production, expert consultation, data estimation	Interviews, literature review
Industry	INEGI and CANACOME 2014	Water extraction rates	Census of industrial production, water extraction, expert consultation, data estimation	Interviews, literature review
Agriculture	INEGI, SAGARPA, Indemaya, 2014	Crop and water requirements for irrigation	Census of agricultural production, expert consultation, data estimation	Interviews, literature review

see Supplementary Material). The scientific community were actively involved in general discussions and exchanged opinions with other sectors by stimulating and valorizing contradictory ideas. Stakeholders were able to develop strategies and possible solutions for the problem of groundwater monitoring in the region. Along with the LGBM, interviews with members and experts working in the water sector, NGOs and stakeholders other than the former group of stakeholders were performed. With this we promoted the engagement of the population and developed on existing methodologies towards a monitoring built on stakeholders' efforts.

As shown in Table 2, we determined the most representative socio-economic sectors from data obtained during workshops, statistics and literature. To obtain information about groundwater extraction from wells located in rural households, we interviewed members from the water sector. Simplifications and assumptions were made to determine groundwater extractions more accurately for the year 2014, since extractions might occur due to the large number of rural household wells. Data regarding the number of local wells were obtained through interviews and local expert consultations. The transfer coefficients of each process were established from diverse data sources (described in the Supplementary Material).

2.5 Modelling procedure

The model was set up for the year 2014 using STAN 2.0. It started with the groundwater storage component, which accounts for the subterranean flow. Then fluxes of groundwater for each sector were calculated simultaneously. Each sector was modelled and described by applying the steady-state overall mass balance equation:

$$\sum E_i - \sum S_i = 0 \quad (1)$$

where E_i is the ith input flow and S_i is the ith output flow.

3 Results

We show how, in a transdisciplinary process, the data scarcity problem can be overcome and a LGBM can be developed. Over 50 stakeholders from more than 15 disciplines and groundwater related sectors (scientists, policy makers, NGOs, students, divers and local members) were involved in obtaining a groundwater balance for the Municipality of Tecoh in Yucatan, Mexico.

The results of the application of the LGBM are presented in the following order: (1) system analysis including relevant flows, processes and stocks; (2) water balance; and (3) the interpretation of substance flows including inputs, outputs and total flows within the system.

3.1 System analysis

Figure 3 illustrates the system analysis for the Municipality of Tecoh GR zone for 2014.

Input flows to the system are precipitation and import of drinking water; output flows are evaporation

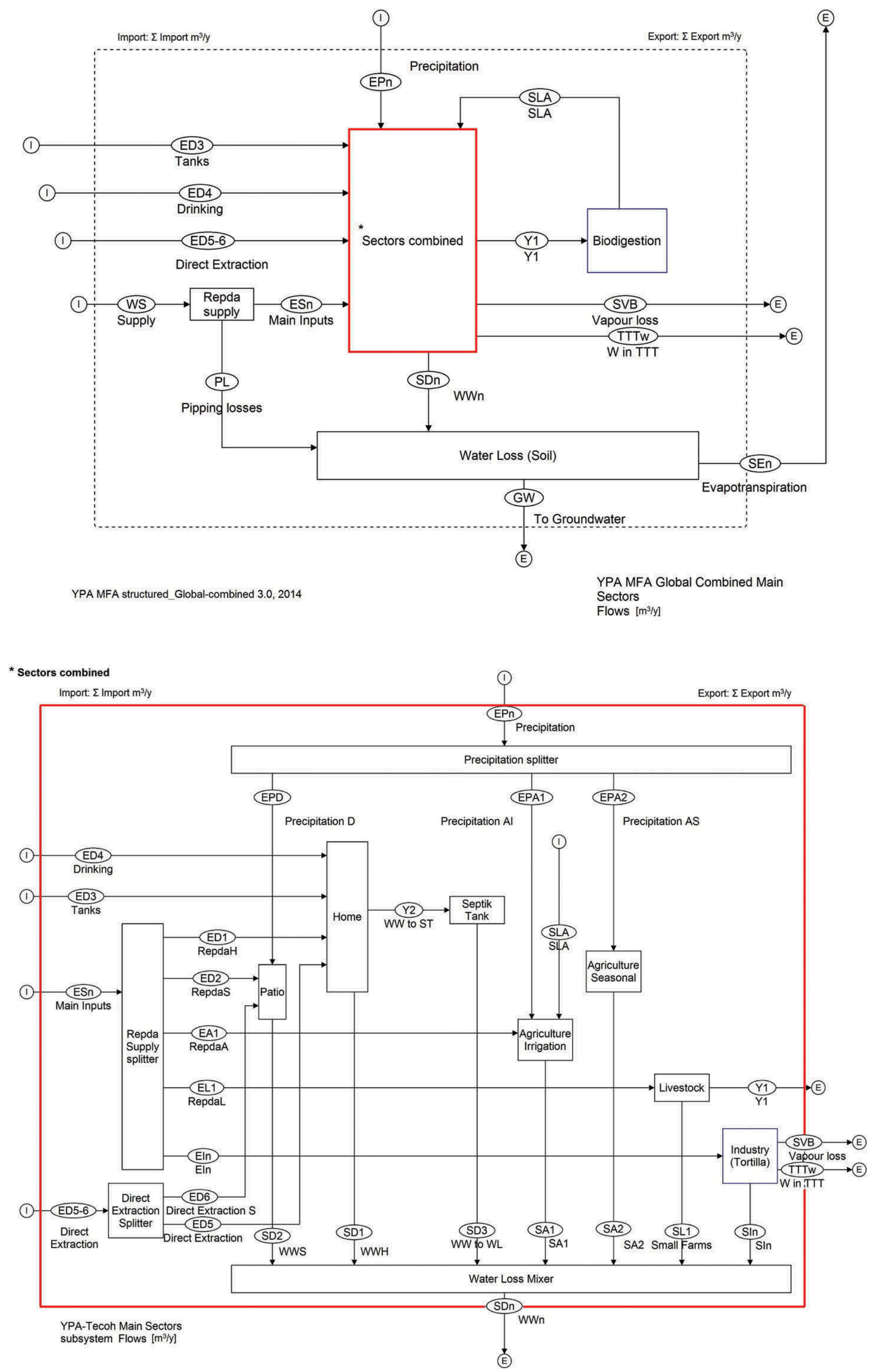

Figure 3. System analysis for the Municipality of Tecoh with all sectors. For definitions of the flow abbreviations see Supplementary Material.

and groundwater discharges. The system is composed of five relevant processes, as listed in Table 1: extraction, supply/distribution, use/consumption by all the sectors, treatment/management (e.g. biodigestion) and recycling. Our model also includes water losses estimated through soil percolation. Input flows to the system are precipitation and water inputs from the ocean; the major output flows are evaporation and groundwater discharges.

Water enters the system through precipitation (*Precipitation*), by the water supply company JAPAY (*Repda supply*), which draws groundwater directly from the system, as well as imports of water and direct extractions from private wells located on rural and urban households (*Direct Extraction*), drinking water bottles (*Drinking*) and tanks (*Tanks*), which serve as additional collected private groundwater extractions. During the potable water transport (*Main Inputs*) for its distribution from the *Repda supply* to the consuming sectors, a quantity of water is lost due to damage in the pipes. Water is consumed by households (accounted as *Home* and *Patio*, see below), agriculture (accounted as *Agriculture Irrigation* and *Agriculture Seasonal*, see below), livestock (*Livestock*) and industry (*Industry (Tortilla)*), summarized under *Sectors combined* in Figure 3. Water is either treated in a biodigestion plant (*SLA*), retained within a commodity (e.g. tortillas) (*Vapour loss*, and *W in TTT*), sent directly to the groundwater (*To Groundwater*), or lost through evapotranspiration (*Evapotranspiration*).

3.2 Water mass balance

Figure 4 shows the numerically solved water mass balance. It accounts for Tecoh municipality in the GR zone for the year 2014. The total amount of water entering the system is 32 217 002 m^3 $year^{-1}$, whereas the largest input flow is precipitation, accounting for 77.6% of the inputs, followed by *Repda supply* 15.8%, *Tanks* 4.4%, *Direct Extraction* 2.2%, and less than 0.001% for *Drinking*.

A quantity of 17 633 000 m^3 $year^{-1}$ from the *Precipitation* reaches agricultural soils (*Agriculture Seasonal* and *Agriculture Irrigation*) and provides 91.2% of the water needed in this sector. Three sources of water are used for irrigation (*Agriculture Irrigation*): from precipitation (*Precipitation AI*), Repda (*Repda A*), and a small contribution from a recycled source (*SLA from Biodigestion*) (as seen in Fig. 4). However, these sources only account for 9.5% of the total water supply. Consumption of water by households (*Home* and *Patio*) and pig farms (*Livestock*) accounts for 10.5 and 0.4% of the total water consumed, respectively.

The largest output flow is evaporation (*Evapotranspiration* and *Vapour loss*) accounting for 80% of the water leaving the system. From all water consumed, only less than 0.04% (*Y1*) of the wastewater is treated and re-used in another subsequent process (*SLA*). The rest of the wastewater from households (*WWH* and *WWS*), septic tanks (*WW to WL*), agricultural outputs (*SA1* and *SA2*), pig farms (*Small Farms*), and the tortilla industry (*SIn*) flow into the aquifer without any treatment. It was stated that the different sectors contribute as follows to the contamination of the aquifer: the agricultural and livestock sector, which might contain high concentrations of pesticides and organic matter (i.e. discharges from pig farms) accounting for approx. 19.4 hm^3 $year^{-1}$, followed by the tortilla industry (high pH, alkaline discharges) accounting for approx. 5700 m^3 $year^{-1}$. The flows of wastewater from households to the aquifer amount to approx. 11.3 hm^3 $year^{-1}$. As mentioned above, all wastewater emissions are discharged directly into the aquifer without treatment, as demonstrated by the poor treatment and recycling practices (<1%, relative to the total wastewater produced).

3.3 Interpretation of substance flows

The results revealed (a) high wastewater emissions into the aquifer (approx. 6.4 hm^3 $year^{-1}$); wastewater ranges from grey water to wastewater with high concentrations of organic matter (i.e. discharges from pig farms) and alkaline discharges (i.e. tortilla industry); (b) all wastewater emissions are discharged directly into the aquifer without treatment; and (c) poor recycling practices (<1%, relative to the total water emissions).

When considered by sector, flows displayed the following characteristics:

- **Household**: In the household sector the major consumption is represented by water storage in tanks (*Tanks*). This volume is approximately 3 times larger than from direct extraction from wells (*Direct extraction H*) and 1.5 times larger than from the Repda water supply (*RepdaH*). Septic tanks (*WW to ST*) eventually provide some treatment to wastewater emissions from households (*Home*), but our results clearly show that this water is discharged to the aquifer and is not used in another subsequent process. In the household sector (*Home*) 75% of the wastewater goes to septic tanks (*Septic Tank*) and the remainder is discharged directly into the aquifer (*WWH*).

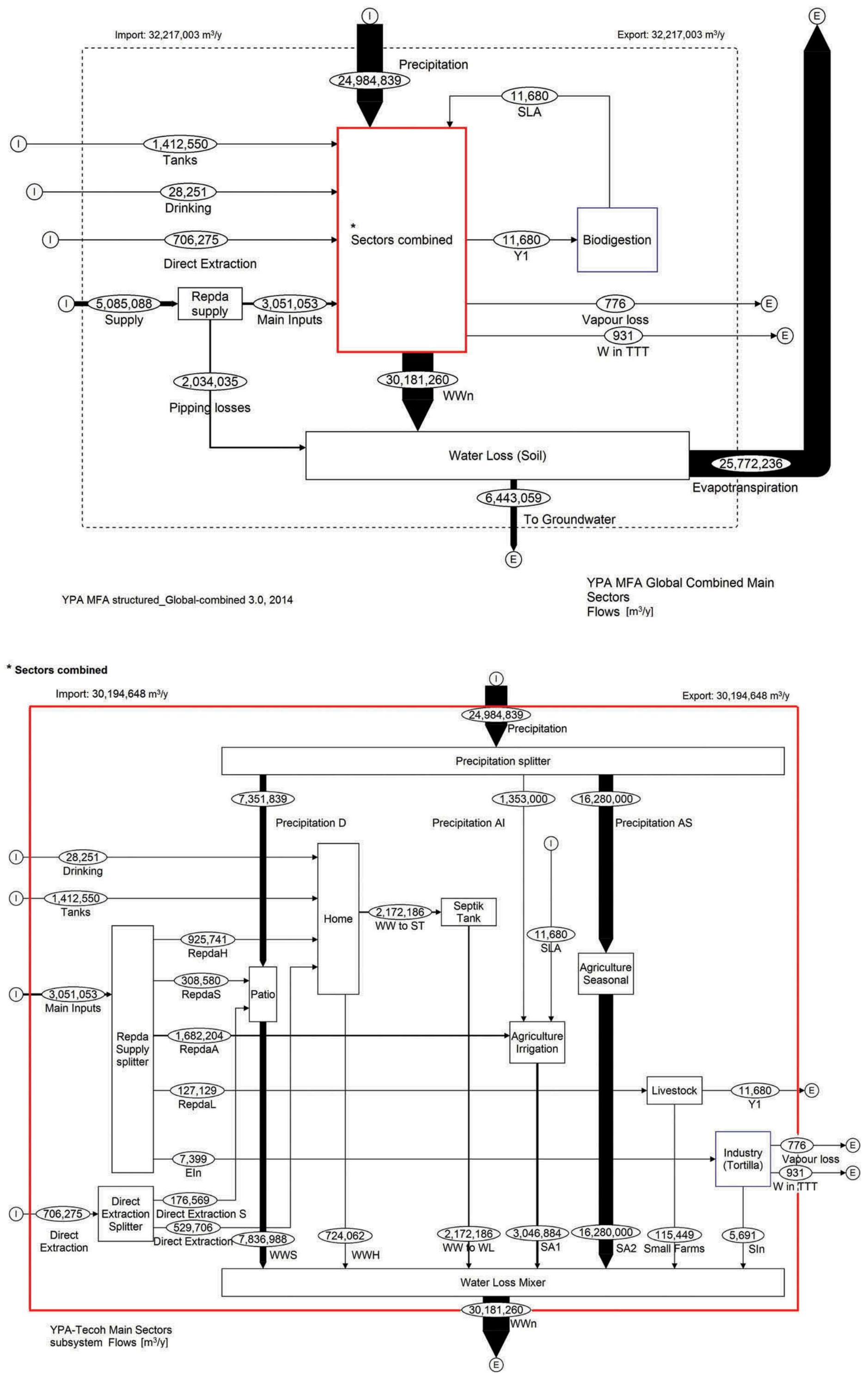

Figure 4. Numerically solved water balance for the Geohydrological Reserve, Municipality of Tecoh 2014. For definitions of the flow abbreviations see Supplementary Material.

- **Agriculture**: The results show that 60% of all input water is used for agricultural practices. The model does not consider irrigation based on seasonal periods. Note that the treated water (<1%, from *Biodigestion*, see below) is used for irrigation (*SLA*).
- **Livestock**: One particularity is the livestock sector, where small farms generate 10 times more wastewater than the larger farms. It is noticeable that discharges from small farms (*Small farms*) are also direct outputs into the aquifer without treatment. In contrast, wastewater from large farms (*Y1*) is

treated in biodigestors (*Biodigestion*), after which this water is reused (*SLA*) in other subsequent processes (*Agriculture Irrigation*). Small farm process outputs (*Small Farms*) and wastewater emissions from the tortilla industry (*SIn*) are minor flows (3.8% and 0.02%, relative to the total wastewater flows to the aquifer, respectively), but they are discharged directly into the aquifer without any treatment.

- **Industry**: During workshops, participants were more concerned about the industry sector (*Industry*). They were aware of the challenges faced due to the lack of data about the processes involved and local and regional statistics. For these reasons and the lack of data for the industry sector in general, we selected the tortilla industry to illustrate this sector, partly because it is possible to carry out an estimation of the water involved in the entire production process by considering statistical information and the virtual water contained, and because it is well known from previous unpublished reports and interviews with experts, that these effluents are heavily contaminated. In contrast to domestic, livestock and agriculture, the water mass balance for the tortilla industry was obtained by considering its production processes, i.e. alkaline hydrolysis, nixtamal washing, and baking. Virtual water in tortilla final products was considered only as an example and starting point for the calculations. More details about the flows, definitions and calculations can be found in the Supplementary Material. Importantly, albeit the total water consumption of this sector represents only 0.023% from the total water input in the balance, all the outputs from the sector constitute 77% (*SIn* relative to *EIn*, approx. 5700 m^3 $year^{-1}$) of wastewater with high pH and high content of organic matter, and this water is directly discharged into the aquifer.

4 Discussion

Groundwater in Yucatan is needed for many purposes, including health, food and industrial production. Thus, groundwater pollution may have different origins and may generate different wastewater. With little coordination among users and government, its monitoring can be a challenge. In this paper, we analysed, in a unique way, groundwater resources, in a place where no rivers exist on the surface. Our approach was to analyse the main socioeconomic sectors including different uses and users. Built on local monitoring efforts, the data scarcity problem was overcome and the LGBM developed. The LGBM supports the current global monitoring framework of SDG 6 and contributes towards groundwater literacy.

4.1 The LGBM as a coherent mechanism for monitoring

Investigation of flows and development of the first LGBM in Yucatan revealed high wastewater emissions into the aquifer (approx. 32 hm^3 $year^{-1}$), which could be expected from anthropogenic sources. The data obtained are interpreted as reflecting:

(1) Extraction of groundwater: this process represents a central issue in the system since there are currently several gaps in water extraction regulations. The LGBM corroborates that significant volume is extracted directly by individual pumping from wells for domestic uses.
(2) Rapid recharge of rainwater: rainwater circulates in the system, but this water is not collected for further use.
(3) Recycling: despite the poor recycling practices, the recycled wastewater final emissions are also directed into the aquifer (<1%, relative to total water emissions).
(4) Management of groundwater: results from the model regarding uses illustrate the disparity among sectors and show the main extractors and polluters; however, due to the complexity of the household sector this requires further investigation.
(5) Rapid rainwater recharge is an important event, as can be seen in the model. The agricultural sector may circulate some hazardous substances present in open areas, at least during rainy seasons.
(6) This study also indicates that there is a poor wastewater treatment infrastructure, which leads to a generalized introduction of pollutants into the aquifer.

The obtained results, even in a small and well-defined system such as the GR zone, show that flows and pollution sources are difficult to determine. Our results provide critical insights for future analyses since they do not depend on published data: we obtained them through workshops with stakeholders and with a combination of research tools from a variety of disciplines. Although uncertainties and gaps persist, our results are clear: the LGBM allows the identification and assessment of the human-induced flows affecting the quality of groundwater resources of an individual local aquifer with more precision, together with the society, while demonstrating that this model can be combined with other methods (such as MFA) and include virtual water calculations.

The LGBM could be extended in the following directions: (i) model the flux of hazardous substances within the system under different scenarios, and (ii) incorporate the dynamic nature of decision making into modelling. Monitoring, back-casting and modification of resources with future research data are highly recommended.

4.2 Step-by-step: local monitoring of SDG 6

To "*Ensure availability and sustainable management of water and sanitation for all*", according to SDG 6, there is a need to monitor eight different inter-related targets globally. At present, there are several global tools and initiatives for water monitoring (WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation/JMP, and UN-Water Global Analysis and Assessment of Sanitation and Drinking Water/GLAAS). A prerequisite for the implementation of these initiatives is to have a thorough knowledge of the system and simultaneously a consistent database, usually collected at a country and global scale worldwide (UN-Water 2016). However, this is not the case in less-developed countries, where databases are not often reliable.

Groundwater monitoring is often a difficult task due to the cost, complexity and unpredictable nature of the system. In the case of Yucatan, a coherent framework for monitoring groundwater from a local perspective is required. To pursue global or national monitoring, while considering local actions and monitoring efforts, the LGBM combines existing monitoring initiatives such as country base data to analyse the structure of a local system, the relevant flows, and the main socio-economic sectors.

The obtained results can be used by the involved stakeholders to (i) identify the human-induced flows affecting groundwater quality; (ii) monitor water availability and withdrawals; (iii) promote improved allocations between users; and (iv) stimulate water recycling, traditional rainwater harvesting practices and use efficiency.

A summary of the main SDG 6 targets and indicators that can be addressed with the development and application of the LGBM is provided in Table 3. To implement SDG 6, the LGBM specifically supports the following Targets 6.3, 6.4, 6.5, and 6.6(a and b) by facilitating examination of hotspots of pollution and distribution of flows of hazardous substances; minimizing release of chemicals; ensuring sustainable withdrawals; revealing water extraction trends and sectors with major consumption; strengthening participation of local communities; and protecting the ecosystem. As an example, in the case of Tecoh, concentrations of 6.5 ppm of α-lindane and 10.9 ppm of δ-lindane were found directly in water from local wells and sinkhole samples in an area with 724 agricultural production units (approx. 4000 hectares) (Polanco Rodríguez *et al.* 2015). These values are above the permitted concentration limits, according to Mexican norms. It is reasonable to assume that further substances could also be found in the surrounding area. With the development of the LGBM, it would be possible to determine the flows of those substances within a particular pre-defined system.

Using the example of Target 6.3, the indicator 6.3.1 addressed the proportion of all wastewater generated that is safely treated at source or through a treatment plan before it is discharged into the environment. In the case of Yucatan, and particularly in rural areas, the percentage of the population with safely treated wastewater is uncertain, since some households do not have a treatment facility, a septic tank or latrine pits, and inhabitants do not tend to handle (or are not allowed to) and re-use the wastewater (e.g. as an agricultural input). The LGBM shows that, despite a portion of wastewater reaching a treatment plant, another portion remains untreated and the emissions are outputs discharged directly into the environment. As already suggested by several studies, these emissions come with a variety of contaminants such as organic matter, pesticides, pharmaceuticals, etc. (Metcalfe *et al.* 2011).

From a water quality and environmental perspective, this is remarkable because it might bring critical problems to the population's health and biodiversity. In policy terms, the LGBM might provide policy-relevant guidance to government and environmental authorities for implementing measures intended to mitigate impacts on the resource. Although there are suggestions for the use of tools and methodologies to validate and verify the treatment data, including geospatial information and Earth observations (UN-Water 2016), their applicability in groundwater systems remains complex. Recent technologies such as GRACE (NASA 2016) are appealing for this geospatial monitoring purpose, but its global applicability is yet to be implemented.

The Integrated Monitoring Guide for SDG 6 suggests that it is necessary to collect data from different locations of both urban and rural settings in order to

Table 3. Summary of SDG 6 targets (UN-Water 2016) for global monitoring that can be addressed with the LGBM.

Goal 6 targets	Type and level of data required	Drawbacks	LGBM contribution
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water	Global and national statistics	Data (e.g. chemical and faecal contamination) do not cover all countries immediately	LGBM facilitates examination of hotspots of pollution and distribution of flows of hazardous substances
6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying attention to the needs of women and girls and those in vulnerable situation	National estimates adjusted for global comparison (e.g. administrative, population and environmental data can be combined to estimate safe disposal or transport of excreta when no country data are available)	Data will not cover all countries Deficiencies on infrastructure for collection and transport are difficult to consider	LGBM facilitates examination of the amount of wastewater treatment process in specific economic sectors (e.g. industry) Calculations considering deficiencies on infrastructure can be made throughout expert consultation and during workshops to calculate error margins
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and at least doubling recycling and safe reuse globally	Data will come from sources combining utility and regulator data for off-site and household survey questions and measurements relating to onsite treatment supplemented by estimates where no reliable national data exist	Data (e.g. safe disposal and treatment) remain scarce and might not be available in all countries Information is usually not shared among water institutions and society, leading to conflicts among institutions and users Households surveys do not influence knowledge of society	LGBM facilitates the identification of the human-induced flows affecting groundwater quality and the amount of water that it is recycled within the system LGBM supports monitoring at different points of the water body revealing different pollution trends LGBM promotes participation and transdisciplinary approaches to contribute towards the lack of sharing information among the interested stakeholders LGBM influences the user's knowledge
6.4 By 2030, increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	Global datasets from AQUASTAST-FAO on water withdrawals in different sectors at national (hydrological units) and global level International datasets on water availability and withdrawals from different sectors	Recognition of main sectors, flows and their distribution is a requisite but data are available for some countries only and gaps tend to proliferate Regional and climatic conditions can limit results Difficulty to obtain accurate, complete and up-to-date data Potentially large variation of sub-national data Lack of account of seasonal variations in water resources Absence of consideration of water quality and its suitability for use Double counting when using conflicting sources of information Deficiency of tax declarations (influencing datasets) Difficulties in defining level of water stress (e.g. in Yucatan, quality, not quantity, seems the main problem)	LGBM facilitates the monitoring process of groundwater availability and withdrawals and promotes improved allocations between users by revealing water extraction trends Lack of tax declarations and local data can be overcome Data on volumes of withdrawn and distributed water can be estimated and complement those obtained from the municipal supply utility records (JAPAY) Estimation of water withdrawals by sector can be possible Indicator 6.4.2 concerning the level of water stress can be achieved by collecting data regarding the ratios among total freshwater withdrawn by all major sectors
6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation, as appropriate	National surveys, regional and global estimates can be aggregated from national data	Spatial data and global database for freshwater treaties and transboundary basins are available as well as regional ones, but uncertainties on groundwater resources exist Current operational arrangements do not tend to consider groundwater basins Water resource management tends not to consider all users	LGBM supports the involvement and participation of stakeholders and local communities in the development and application of the results in improving water and sanitation management LGBM is based on system analysis and can be used to estimate transboundary water flows and this might improve the level of cooperation LGBM can be implemented in adjacent states that share the groundwater basin

(*Continued*)

Table 3. (Continued).

Goal 6 targets	Type and level of data required	Drawbacks	LGBM contribution
6.6 By 2020, protect and restore water-related ecosystems, including mountains, forest, wetlands, rivers, aquifers and lakes	Data from national sources, global datasets (e.g. groundwater volume, wetland extent) are needed Ground-based surveys	Temporal gaps exist Collection of data still needed Data available only for some countries	LGBM can be used to monitor and to track changes over time in the extent of wetlands and the groundwater table in the region, and to determine the quantity of water within the system
6.6a By 2030, expand international cooperation and capacity-building support to developing countries in water and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater, treatment, recycling and reuse technologies	National sources Global datasets Global compilations	Difficult to know how much local administrative units depend on external support or to what extent external grants or loans are coordinated by the government	LGBM ensures the direct participation of stakeholders and facilitate the identification of weaknesses in water-related activities, the amount of water that is recycled, the efficiency of the system, the available programmes and technologies. The identification of those factors might help stakeholders to apply for external grants or support in coordination with government LGBM facilitates the promotion of good practices and use efficiency and stimulates water recycling
6.6b Support and strengthen the participation of local communities in improving water and sanitation management	Data for global and regional surveys Data can be disaggregated on urban/rural sanitation; urban/rural drinking water-water and hygiene promotion	There are no well-defined established and operational procedures for participation of local communities in water and sanitation management It is difficult to ensure participation of users and to assess this through surveys	LGBM facilitates the identification of relevant stakeholders LGBM promotes the meaningful involvement of local communities and relevant stakeholders in the development of the monitoring tool LGBM strongly influences groundwater literacy

capture the full range of scenarios needed for national estimates. However, in general, data are obtained through detailed questionnaires filled in by experts and consultants who collect information, but this can generate high levels of uncertainty. It is also recommended that organizations and institutions should be consulted for the assessments, including officials responsible for sanitation, external agencies and organizations responsible for regulation or licensing treatment services. Nevertheless, these data still remain a part of global and regional estimates and include some sectors in particular.

As proposed by the Integrated Monitoring Guide for SDG 6, it is possible to obtain data from the databases of typically involved institutions, ministries and establishments, but the lack of reliable data in Latin-American countries might generate uncertainties that would be crucial when calculating the flows (Binder *et al.* 1997). In Yucatan, for example, ownership of data is a critical issue, since current water management does not overlap, and some information is not published in scientific literature and lacks credibility in some sectors (according to W. Espejo, personal communication, 19 December 2014).

4.3 The LGBM supports groundwater literacy

A more systemic understanding of the scale interdependencies of water systems is needed globally. In Yucatan, groundwater is currently the main source of freshwater for the population, but knowledge of the state of the system is limited. Results obtained via informal conversations with stakeholders during workshops show that crucial information about the system (e.g. precise location, quantity, main fluxes and function) was poorly understood by the majority of the participants. Identifying major flows, by applying system analysis and tendencies with the stakeholders, helps us to understand the system dynamics and to influence their groundwater literacy. The LGBM helps to explore, develop, represent and use this information to assess human impacts, and this could be the basis for future groundwater management in the region.

To implement monitoring of SDG 6 it is crucial that data collection, analysis and dissemination involve stakeholders and government. Current mechanisms in this regard range from household surveys to global Earth observations. However, these tend not to influence the knowledge of the users, since most of the surveys and specialists collect data on particular fields. The LGBM provides a systematic framework to identify all of the relevant stakeholders and consider their participation in the decision-making process, since we include social science methods. The elaboration of the LGBM included a wide range of stakeholders across sectors and levels of government.

Workshops were crucial because stakeholders were able to interact, share data and be involved in the same degree of participation. Through this overall participation, the first groundwater model was developed and every step of its construction was validated. Our estimates are consistent with previous estimates conducted decades ago within the region (Villasuso and Méndez Ramos 2000), but our analysis is stronger since information was obtained directly from stakeholders currently working in the water sector.

Whereas the methodology for determining hydrological flows and water balances on aquifers and water bodies is already internationally standardized within proper methods (Molden 1997), and that global groundwater models do not consider the impact of socioeconomic forces on hydrology, several uncertainties still remain (Chahine 1992, Sood and Smakhtin 2015). Through cooperation, our results demonstrate how it is possible to work together and to simultaneously narrow the gaps between science, policy making and society.

Our case is completely different so far in terms of obtaining more empirical results, which in turn might contribute towards more real solutions. We argue that groundwater models can contribute to the speed of data processing; understanding characteristics of global groundwater resources, their distribution, volumes and fluxes; and scrutinizing the interrelated human impacts. However, the rate at which we decide to take local actions and to find alternatives to effectively address groundwater problems is crucial. The LGBM offers the possibility to involve local people and work towards groundwater literacy. We collected data during different fieldwork research stages from 2013 to 2017 and validated them during workshops with experts working in the water sector and the local population. The novelty of this work is that our complete methodology produces systematically useful results, strengthens participation of local communities, and recognizes local knowledge as an informal norm of monitoring. Interviews and informal conversations with experts and locals were carefully designed, which guarantees a certain structure in the answers. This provides the opportunity for interviewees to freely respond and to make use of their knowledge on particular topics. The interviews provided information that can be compared with data published in the literature, so its validity and reliability can also be anticipated. In our case, participants were able to develop, use and share their own knowledge to start to solve their own problems.

Gleeson *et al.* (2012a) proposed that multigenerational goals (50–100 years) for water quantity and quality be set for many aquifers. Additionally, short-time policy horizons should be implemented by back-casting for pre-established sustainable goals. Thus, we agree with the importance of models; however, communities can no longer wait for models to solve urgent water problems. The practical aim is simple: models can help to make predictions of the hydrological cycle to support environmental management, and, furthermore, they can meaningfully contribute towards solutions if they involve stakeholders.

5 Conclusions

Yucatan has a large aquifer that is shared by local communities. In several of them, the situation can be seemingly positive with no current reported pollution or water use conflicts. However, groundwater requires detailed analysis and planning, and this applies to areas related to several users and uses, particularly those that are vulnerable to contamination.

Sustainable Development Goal 6 is about drinking water, and drinking water in Yucatan is obtained mainly from groundwater. Large global-scale modelling is crucial in evaluating groundwater resources. Analysing groundwater using a local groundwater balance model provides a starting point for detailed analysis of the effect of anthropogenic emissions on natural groundwater processes. This is critical for policy and management implications, particularly in a place where no other sources of freshwater exist. Monitoring at each step and by particular socioeconomic sectors of the chain helps to capture the hotspots generated by users, including the fraction that is reused or treated. Our confidence is attained not only due to mathematical equations but also from results obtained during stakeholder workshops.

Systematic development of knowledge of the groundwater system is necessary. However, despite a deficient knowledge base, the analysis must be started using the current available knowledge of the local population and the different sectors. The LGBM has been useful in raising concerns over the environmental destination of hazardous materials. It indicates that perhaps it is not enough to know about the potential hazards of those substances, and that moving them from the different compartments may cause future consequences. The visual representation of inflows, outflows, abstraction and returns will support the understanding of the system and thus will facilitate the future management of groundwater. As our project is related to policy makers, our results could easily be implemented to plan the transition process for better groundwater management within the region.

Our results are innovative and constitute a versatile methodology that can be applied in regions with similar characteristics. The method can be a useful tool for resource management considering poor data and it is aimed at knowledge integration as key for understanding social–ecological systems. The ideas proposed here may guide the adoption of a new approach towards better groundwater resource management. This will support a future groundwater balance for the complete region by adapting particular parameters into the model. We agree with the importance of models, but we offer a much more favorable view of a systems-analytical approach to groundwater resources.

The LGBM can be adapted to specific regions, can be used to address methodological challenges for monitoring, and can contribute to the achievement of the 2030 Development Agenda. The LGBM can be built on existing monitoring frameworks and statistical standard definitions, classifications and treatment categories such AQUASTAT and SEEA.

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Research

Restoring the environment, revitalizing the culture: cenote conservation in Yucatan, Mexico

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ABSTRACT. Cenotes are sinkholes through which groundwater may be accessed from the Yucatan Peninsula Aquifer. Historically and culturally, cenotes are also important cultural and spiritual natural sites for the Maya, but they have been contaminated and degraded. We ask the following: What are the present-day meanings, understanding, and values of cenotes for the Maya? Is it possible to adopt a cultural approach for conservation of cenotes in Yucatan? Participant observation, interviews with stakeholders, and underwater exploration in cenotes were used to obtain data. Results indicate that cenotes often retain some spiritual meaning for people but not as important cultural, spiritual, or sacred sites. Little consensus was found regarding the significance of cenotes and how best to protect them. Informants noted changes in water quality, and identified the threats to cenotes including tourism, poor solid waste management, contamination, and deficiency of interest in preservation. Lack of accurate knowledge was a problem: informants did not seem to understand that cenotes are interconnected through the groundwater system. The Yucatan case illustrates how loss of cultural values can be linked to environmental quality and resource degradation. Conversely, it can be argued that cultural revitalization in indigenous communities has the potential to bring back community-based conservation.

Key Words: *cenotes; community-based conservation; groundwater; Mayas; sacred natural sites; Yucatan*

INTRODUCTION

Groundwater in Yucatan is not simply a hydrological resource. Historically it had elements of sacredness perhaps related to the fact that it was an essential resource in an area without rivers. It has since lost much of its sacredness and over the decades has become contaminated. In this paper we deal with groundwater-related issues in Yucatan, and suggest that the way to improve conservation is through the inclusion of cultural values and renewed spiritual connections between people and their environment. Understanding cultural values, belief systems, and meanings are often necessary toward solutions; looking at nature with awe and reverence fosters sensitivity to the environment (Wild and Macleod 2008).

The notion of cultural connection to nature is mediated through sacred natural sites in various parts of the world. Sacred sites are areas of land or water having special spiritual significance to peoples and communities, and may include mountains, hills, forests, groves, rivers, lakes, lagoons, islands, springs, and caves (Oviedo and Jeanrenaud 2007, Thorley and Gunn 2008, Wild and McLeod 2008). They are the oldest protected areas of the planet, constitute biodiversity hotspots, and are useful for conservation (Dudley et al. 2009, Metcalfe et al. 2010). However, sacred natural sites are subject to a diversity of threats, including culture change, which can lead to loss of spiritual values. Protecting sacred sites is especially critical in indigenous communities, since these places constitute unique social-ecological landscapes, a source of cultural identity (Oviedo and Jeanrenaud 2007, Samakov and Berkes 2016).

In dealing with the erosion of natural and cultural values in Yucatan and their possible restoration, we adopt the concept of community-based conservation, that is, resource management or biodiversity protection by, for, and with local communities, recognizing the coexistence of people and nature, as distinct from protectionism, and the exclusion of people from nature (Western and Wright 1994). The most appropriate theory for the analysis of community-based conservation is commons theory, whereby conservation at the local-level, under local institutions, may be seen as one part of a multilevel commons problem (Cash et al. 2006). Yucatan groundwater, as a commons, is a resource important at multiple levels from local to international (Berkes 2007). It fits the Ostrom et al. (1999:278) definition of a commons or common-pool resource: those "in which (i) exclusion of beneficiaries through physical and institutional means is especially costly, and (ii) exploitation by one user reduces resource availability for others." The Yucatan groundwater issue can be considered a collective action problem: a group of people, such as a community or society, would benefit from a certain action, but no individual has sufficient incentive to act alone (Ostrom 1990).

Yucatan has a large aquifer that is shared by local communities. In our exploration, community-based conservation in the Yucatan case requires a biocultural approach that considers both biophysical and social-cultural aspects of conservation (Maffi and Woodley 2010, Gavin et al. 2015). Community-based conservation has received increasing attention in recent years, partly because of the recognition that conservation efforts should address human needs, and that such efforts should not rely only on the government (Borrini-Feyerabend et al. 2004, Berkes and Turner 2006). The groundwater case in Yucatan illustrates the complexity of the problem, and how a biocultural approach can be used to support water resources, biodiversity, and local values, and foster environmental restoration and cultural revitalization.

The inclusion of spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences helps the protection of sacred natural sites (Wild and McLeod 2008). Both cultural and spiritual values of ecosystems relate to the importance of indigenous worldviews, knowledge, and traditions often manifested in the form of respect and tribute to local

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wisdom (Verschuuren and Furuta 2016). Environmental problems cannot be solved by rational arguments alone, they also require emotional engagement (Anderson 1996). Hence, indigenous knowledge and traditional worldviews may help to preserve sacred natural sites through the emotional involvement of people with their environment.

In Yucatan, most groundwater research has focused on its hydrology and environmental problems (Hernández-Terrones et al. 2011, Polanco-Rodríguez et al. 2015). This is of importance since successful monitoring and management often calls for a clear understanding of the groundwater system. For example, Lopez-Maldonado et al. (2017), found that high wastewater emissions are discharged to the aquifer without treatment. Wastewater range from grey water to wastewater with high concentrations of organic matter, i.e., discharges from pig farms, and alkaline discharges, i.e., tortilla industry; all wastewater emissions are discharged directly to the aquifer without any treatment; despite rapid recharge of rainwater circulating in the system, this water is not collected for further use, and poor recycling practices (< 1%, relative to the total water emissions). The results also illustrate disparity among sectors, and conflicts among the main extractors and polluters. However, we contend that there is another aspect of this issue: the relevance of local cultural values. The integration of local values and revitalization of sacred natural sites can lead to better groundwater management.

Yucatan is an area of places of cultural and environmental significance, most of them water-related, including traditional sacred natural sites such as human-made monuments, springs, landscapes, and caves (Healy 2007). The land of the Yucatec Maya, one of the largest groups of indigenous peoples in Mexico, has permeable limestone formation (karst), which results in precipitation quickly seeping into the groundwater. There are no surface rivers in Yucatan, but only groundwater in the form of a large, extensive aquifer that underlies most of the State of Yucatan plus parts of two adjoining states. Rain enters the karstic platform and percolates quickly down through the porous limestone to form underground channels. The aquifer in Yucatan is reachable from the surface through thousands of sinkholes, locally called cenotes (from the Mayan word *ts'onot*; Huntington 1912) and aguadas. In Yucatan, aguadas are not as well defined as the cenotes. Some are artificial and some are natural. The natural ones can be permanent or exist during the rainy season. The artificial ones were apparently built by the Maya to conserve water during the dry season. Most of the aguadas are shallow compared to the cenotes. Aguadas were a common water resource in the southern Maya Lowlands where they originated from collapse or dissolution of cenotes (Akpinar-Ferrand et al. 2011).

Cenotes are all types of karst features including caves and springs, can vary in size from the very small to interconnected cave systems, and can be found on land and inshore marine areas. In principle all cenotes in Yucatan are connected; however, it is possible that, because of sedimentation, some ducts were filled and cenotes become isolated (E. Batllori-Sampedro, Ministry of Environment Yucatan, *personal communication,* 7 December 2016). In some cenotes nature itself can be sacred, while in others sacredness can be conferred by connections with ancestral spirits, human-made structures, or sacred histories (Brady et al. 1997). The Maya have a particular cosmology and worldview, which gives shape to current cultural values. For the Maya, cenotes were sacred sites and one of the most important elements for the survival during the dry season (Scarborough 1998, Medina-Elizalde and Rohling 2012, Turner and Sabloff 2012).

Thus, the groundwater system was (and still is) a critical common-pool resource (Ostrom 1990) with multiple values, shared by communities over a large area. Cenotes, as accessible water points from the aquifer, played a major role in religion, politics, and subsistence, provided fish, clay for pottery, and stalactites to build altars, and were associated with rituals and ceremonies displaying water symbolism (Dunning et al. 1997). They were thus set aside as religious sites, as places inhabited by spirits (MacLeod and Puleston 1978, Lucero 1999, Lucero et al. 2011). Cenotes needed to be culturally protected and evidence of this can be found throughout the entire Mayan zone. In some places, they continued to be protected even after the Spanish Conquest.

For Yucatan's present population of nearly two million (INEGI 2012), groundwater is the only major source of freshwater. However, even though local people possess values and some knowledge about water, they continue to have a heavy impact on the resource including wastewater discharges and poor solid-waste disposal practices. Problems include water resource scarcity and pollution due to development, biodiversity loss, and resource degradation (Hernández-Terrones et al. 2011, Metcalfe et al. 2011, Lopez-Maldonado et al. 2017; Fig. 1).

Fig. 1. Cenotes in Yucatan suffer from poor solid waste disposal practices (before and after cenote clean-ups in the fieldwork phase) Photos: Y. Lopez-Maldonado.

Despite progress on hydrological and environmental studies, cultural values and social aspects of cenotes are not well documented. As a way of approaching groundwater conservation, we explore how local meanings can support protection. We seek further understanding of current values that communities themselves consider as important. The Yucatan case serves to elucidate a conservation approach that considers present-day meanings and local community values. Concepts including sacred natural sites (used here in the wider nonreligious sense), and revitalization of cultural traditions are used to define community-based conservation of sacred natural sites as the act of maintaining, safeguarding, and sheltering environmentally and culturally important places by integrating conservation and local cultural values that give meaning to the local people. The aim is to recognize the cultural and spiritual aspect of nature in the local context, even if those values may not be recognized by the whole community.

Focusing on a selected area in Yucatan, the paper deals with two interrelated research questions: What are the present-day meanings, understandings, and values of cenotes for the Maya people? What are the prospects of adopting a biocultural approach for community-based conservation of cenotes in Yucatan?

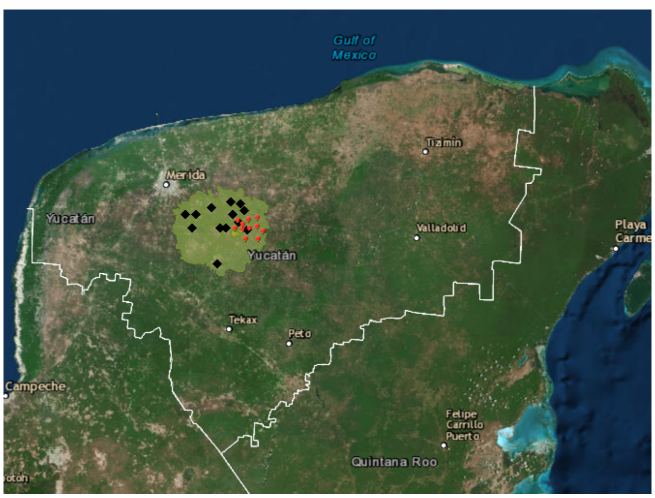
METHODS

Study area

Ecological context

Three Mexican states, Yucatan, Campeche, and Quintana Roo, are found in the area of the Yucatan Peninsula Aquifer. The aquifer comprises thirteen hydrogeological units, four of these are located in Yucatan, including the Ring of Cenotes, a unique water system formed by a meteor impact 65 million years ago (Hildebrand et al. 1991). The Ring has been recognized as a Ramsar site, and tentatively included in the list of the UNESCO World Heritage sites (SEDUMA 2014). Our case study was the Geohydrological Reserve zone located within the Ring in Yucatan (Fig. 2). The Ring encompasses a Natural Protected Area, the Yalahau Lagoon. Several groundwater caves, or cenotes, account for the majority of karst groundwater flow. The cenotes are mostly used for human consumption and their distribution is usually controlled by rainwater recharge, extractive uses (water for irrigation, farms, and fields, hotels, industries), and discharges into the sea. The study area contains diverse habitats and vegetation zones, and cenotes and aguadas that are part of a Geohydrological Reserve (Pacheco-Avila et al. 2014), a priority area for environmental protection established in 2014 with the aim to secure the provision of water for the metropolitan region.

Fig. 2. Map showing the Geohydrological Reserve zone in Yucatan, Mexico, and the cenotes explored (precise locations are not given).



Cultural context

In the Reserve there are 13 municipalities. All of them are in the recharge zone of the Ring of Cenotes, within which is located the city of Merida and its metropolitan zone. The area has the majority of cenotes in Yucatan State, and important historical and cultural characteristics that come from the time of the ancient Mayas. The Mayan communities that developed in this region were closely related to the use of the cenotes as a source of fresh water; that is why archaeological and cultural sites can be found associated to the majority of these cenotes.

There is past and present archaeological evidence of the importance of sacredness of cenotes in the Mayan area (Brady et al. 1997, Prufer and Dunham 2009). The importance of the water to the Maya is simple: everything seems to be related to water and the underworld, where supernatural beings live, where the souls of the dead go, and where ancestors reside (Bonnafoux 2011). Historically, practices and culture were water-rainfall oriented (Lucero 1999, Lucero et al. 2011). Archaeological sites with such evidence provide signal of long-term spiritual connection and cultural importance. Recently, a cenote was found under the main structure of El Castillo in Chichen Itza, one of the greatest Maya centers of Yucatan, (UNAM 2015; Fig. 3). This suggests that the cenotes in the Mayan area were culturally valued and respected in the past.

Fig. 3. Photo of “El Castillo” in Chichen Itza, one of the greatest Maya centers of Yucatan. The arrow indicates the approximate location below the pyramid where the cenote was found. Photo: Y. Lopez-Maldonado.

Political context

Despite the economic importance of cenotes, there is no particular law that regulates its management in Mexico’s federal legislation. The National Water Commission (CONAGUA) links the federal, state, and municipal governments for the exploitation of national waters by providing concessions and permits for groundwater extraction to public or private persons. However, in terms of management, municipalities are independent because they only receive technical advice from the local water supply company (JAPAY) (L. Caceres, Department of Culture for Water, National Water Commission, *personal communication,* 29 December 2014). Most rural households own *pozos* (wells), meaning that water can be extracted from all local wells without a proper concession. This creates conflicts among users related to issues of ownership or problems with boundaries, extraction, and pollution.

It is estimated that there are between 400–450 cenotes in the study area and they are interconnected (J. Ruiz, Department of Karst, Ministry of Environment Yucatan, *personal communication,* 12 December 2014) out of an estimated 2000 cenotes and caves in Yucatan State. The total is uncertain because some of them have been recorded under different names, and multiple entrances to one site have often been recorded as separate sites. The Ring is perhaps the best-surveyed zone, but a full inventory is not available. Efforts began in 1996 to establish a standardized data collection bridging biological, archaeological, and land use aspects (SEDUMA 2014). The Ring contains mostly hydrological information, despite the fact that cenotes hold ancestral values as well.

The Maya depended exhaustively on groundwater resources for the provision of water. Thus, they had to design, build, and control their own water sources since ancient times (Huntington 1912, Scarborough and Gallopin 1991, Dunning et al. 1997, Scarborough 1998). Sacred places were related and shaped by water rituals, including those connected to the *Dios Chaac* (Water God; Veni 1990, Scarborough 1998). This implies detailed resource knowledge and a belief system that reflects the intimate relationship between water and people. However, none of the existing literature explicitly integrates that knowledge and present-day values or practices associated with cenotes in a clear way. To do this properly, we think that papers that include indigenous scholars as coauthors are especially important (Johnson et al. 2016). We speculate that through participatory action, linking indigenous and local knowledge with modern scientific and technical approaches, and revitalization of values can provide support to monitor, interpret, and care for groundwater ecosystems.

Study methodology

Primary data were collected through a triangulation of four methods: (a) participant observation, (b) open-ended interviews, (c) discussions with stakeholders and authorities, and (d) underwater exploration of cenotes, in addition to hydrological findings reported elsewhere. Secondary data were also used, including exhaustive review of karst inventories and official reports from the Ministry of Environment of Yucatan (SEDUMA 2014). More than 400 reports were analyzed to determine cultural elements and human-made karst modifications. We used literature sources for background, along with ethnographic descriptions of the communities. The large dataset made it possible to develop an interview guide and to test our questions.

Overall, fieldwork and interviews were developed during different stages from 2014 to 2017, over a period of 10 months. We applied the snowball technique to interview local people in the communities. We developed workshops with representatives of the water sector and with members of the Communitarian Spaces for Water Management (ECAs) in Yucatan. The ECAs are part of a Federal program established by CONAGUA in 2002 with the aim to promote and strengthen community participation in water related issues and to promote good uses of the resource among the population. In Yucatan, during the fieldwork phase there were 79 ECAs in 80 municipalities (considering that more than two ECAs can be found in urban centers and large communities).

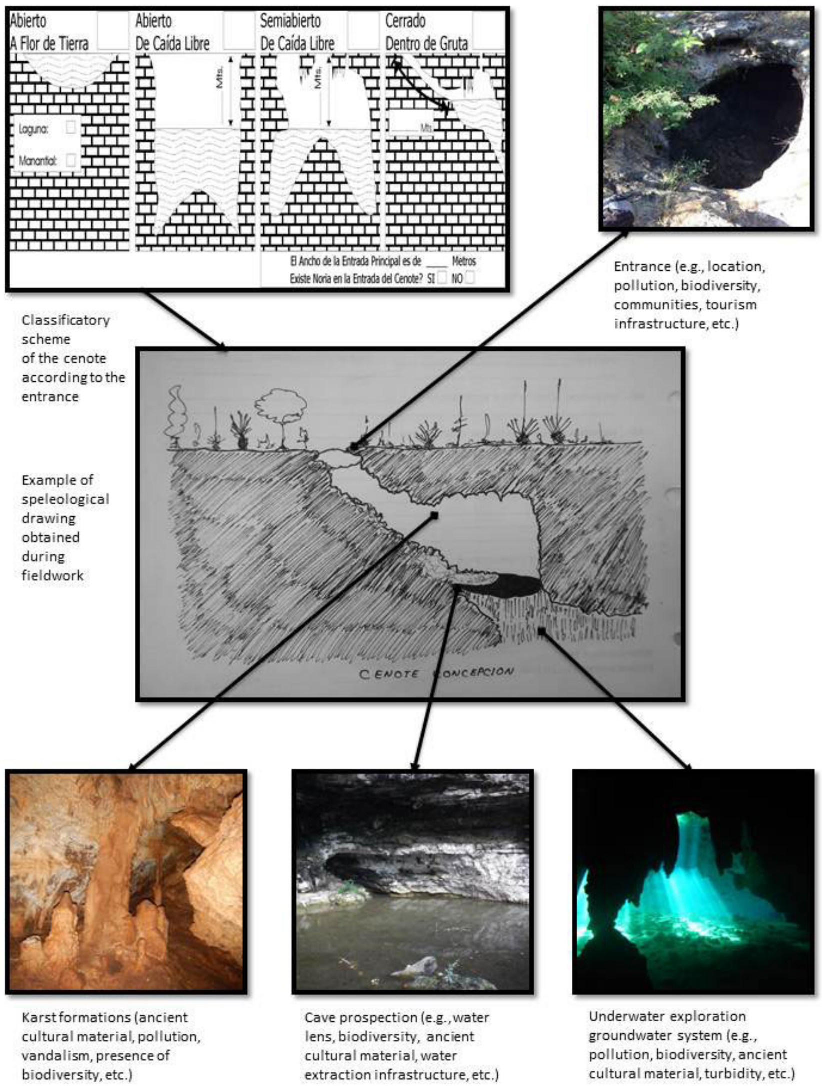
Participants from various agencies and sectors were interviewed, including members and experts of the water sector (e.g., the National Water Commission, the water supply company), socioeconomic sectors (e.g., members of the maize industry, representatives of the livestock sector), experts from local institutions (e.g., members of the Technical Committee for the Study of the Groundwater System in Yucatan), and local members. Interviews of 21 experts working in different sectors provided representative data to examine local opinions of this group. The interviews also included local people from the communities in the study area and around the perimeter of the reserve, allowing comparisons on groundwater and cenote issues to be made between those living near Merida and those living in rural areas. One community in the state of Campeche was also included to provide an example of how opinions in that region differed from opinions in Yucatan. In relation to the total sample of 109 participants, we ensured that the sample was regionally representative.

We carried out two workshops, one with a group of experts and one with members of the ECAs. For the interview process, a group of experts was selected (Technical Committee for the Study of the Groundwater System in Yucatan), based on their previous experience of groundwater and cenote issues. ECA members were convened by invitation with the support of the Ministry of Health. We implemented informal conversations and interviews with the participants. The objectives were to investigate how people ascribed meaning to cenotes in Yucatan and to explore possible solutions about how cultural and spiritual values could be recognized for better groundwater management. Interviews included general socio-demographic questions about participants such as gender and age, and one specific section related to the significance of cenotes. Interviews were developed based on the findings during the revision of the SEDUMA reports. The interview stage was followed by informal conversations that were valuable because they allowed for a robust understanding of how cenotes are perceived by participants.

Overall, the project focused only on communities that had not been previously explored by SEDUMA (2014). Twelve cenotes in the Reserve, including caves, were explored in November and December 2014. The communities were selected based on their geographic location (located in the perimeter of the Reserve). We visited some families, which have cenotes in their gardens, and carried out informal conversations for information about how they took care of their cenotes. Overall, all the cenotes were registered, mapped, and video-recorded; speleological drawings, which included formations, biodiversity, and ancient cultural material, were made with the support of local divers. The precise locations of the sites explored are not given. There had been few archaeological cave surveys and projects in the area, including the studies performed in the SEDUMA database. Using the SEDUMA survey of cenotes in the area as baseline, cenotes were explored and the results obtained complemented SEDUMA reports including videos, photos, interviews, drawings, and reference books and papers than can be used for further research in the area.

A case study approach was used (Yin 2009). We explored the communities, carried out participant observation in two of them, and conducted interviews (N = 109) with 69 local Maya people,

Fig. 4. Example of information obtained to create the index cards used to explore cenotes.



21 academics, 3 government officials, 1 tourism operator, 2 cave divers, and 13 others working in different water related sectors (Table 1). These were complemented by informal conversations with a wider range of people. We used our previous knowledge of the area and people, and snowball technique to identify community leaders and representative participants. We asked about current knowledge of cenotes near the community, because in most cases local people did not know exactly where the cenotes were located but did know that they existed. We held meetings with underwater explorers to get information from a speleological point of view, and asked for photos or cave material that informants considered as illustrations of sacredness. In the communities we began by asking local members about Mayan words they used to describe water quality and if they considered some cenotes sacred or not. The transcripts of interviews were analyzed for themes that occurred frequently. We include here some quotes recorded during fieldwork. A detailed list of the organizations represented can be found in Table 2.

Table 1. Age and gender details of informants.

	< 25 years old	25–60 years old	> 60 years old	All
Women	26	20	5	51
Men	27	22	9	58
Total	53	42	14	109

Speleological records obtained during cave explorations provide information about architectural formations and possible past uses such as rituals or ceremonies. Geomorphological characteristics, hydrological factors, presence of biodiversity, and cultural traces, as well as pollutants were noted. For the speleological prospection, vertical and horizontal progression techniques were applied (Cuenca Rodríguez et al. 2010). Cenotes were classified in relation to current use, visible pollution, presence of cultural material, and governance regime using an index card system (Fig. 4).

Table 2. Organizations represented in the interviews, and their roles and responsibilities, in the analysis of the cenotes in Yucatan.

Organization	Responsibilities	Participants
Ajau (NGO)	User association	1
Autonomous University of Yucatan	Research on Hydrology and Hydraulics	3
Cámara de la Industria del Vestido de Yucatán	User association	1
Center for Research and Advanced Studies Mexico (Dept. of Human Ecology and Dept. of Applied Physics)	Research and coordination	2
Center of Scientific Research of Yucatan (Water Science Unit)	Research and coordination	1
CIR-UADY (Health, Environment and Development Unit)	Research	1
Colectivo Na' Lu' Um (NGO)	User association	3
CONAGUA	Environmental Authority	2
CONANP (Natural Protected Areas)	Environmental Authority, coordination	1
Consultores en Agua Potable, Alcantarillado, Geohidrología & Hidráulica Costera, I.C.	Consultancy	1
Technical Committee for the Study of the Groundwater System in Yucatan	Implementation, planning, research, and management for the Yucatan aquifer, support to river basin organization of the Yucatan Peninsula	10
ECAs (Communitarian Spaces for water culture)[†]	Community members who promote and strengthen participation in water related issues and good uses of the resource	68
Ecologistas Subacuaticos (NGO)	Environmental activism (community activities, cenote clean-ups)	2
Indigenous Development Center	Implementation	1
Local Livestock Association of Pig Farmers of Merida	User association	1
Local water supply company	Service provider, coordination of the local sewage system, support for local communities in water issues	1
Maize industry sector	User association	1
Ministry of Environment in Yucatan	Environmental Authority	2
Ministry of Health	Environmental Authority	2
Municipality representatives	Coordination, implementation, planning	4
Organismo de Cuenca Península de Yucatán	Coordination, implementation, planning	1

[†] 65 participants from rural communities and 3 from the city of Merida.

RESULTS

Results are grouped under three major headings: (i) present-day uses of cenotes in the area, (ii) contemporary meanings and values of cenotes for the local population, and (iii) changes in values for recognition of cenotes as sacred natural sites, an indication of the potential for community-based conservation in the area.

Present-day uses of cenotes

One way to understand how the Maya people appropriate and value nature is through an analysis of how they ascribe meaning to it. Although it is possible to find cenotes all over Yucatan, past research efforts concentrated on a few places close to archaeological zones. We documented unrecorded cenotes, including some caves and aguadas, and carried out clean-up and other activities with the young (Fig. 5). Given the significance of cenotes in the past, it might be anticipated that indigenous people would emphasize social and cultural values. Nevertheless, as can be seen in Table 3, sacredness of cenotes did not come up in the list of current uses, implying that utilitarian values are at the forefront. Participants gave priority to functional values of cenotes mainly as a source for water used in cattle ranching, agriculture, and tourism. Table 3 also includes notes on visible pollution, presence or absence of ancient cultural material from underwater exploration, governance regime according to interviews, and biodiversity values from SEDUMA reports.

Fig. 5. Example of some of the activities performed during the project, (a) cenote clean-ups with community members, (b) workshops with members of the ECA, and (c) speleological and (d) underwater exploration (Photos: Lopez, Y.).

Given that some protected areas have been established (Yalahau Lagoon and the Reserve) in the study area, one might expect to find joint management and conservation-compatible human

Table 3. Characteristics and common uses of cenotes explored in the Geohydrological Reserve Zone.

No.	Name[†]	Current use	Level of Pollution	Cultural material	Governance Regime[‡]	Biodiversity (common and scientific name)	Comments and remarks[§]
1	La Noria	Cattle farming	High	Yes	Ejido Open access State property	Bagre (*Rhamdia guatemalensis*) Langostino (*Creaseria morleyi*) Ramon (*Brosimum alicastrum*) Huano (*Sabal Mexicana*)	Future plans for ecotourism
2	Huhi	Not in use	High	No	State property Open access		Open dumpsite
3	Concepcion	Agriculture	High	No	Ejido Open access	Bagre (*Rhamdia guatemalensis*)	Clandestine open dump site
4	Papaya	Not in use	Low	Yes	Open access, State property Not specified	Bagre (*Rhamdia guatemalensis*) Waxim (*Leucaena leucocephala*)	Clandestine open dumpsite
5	La Peinada	Not in use	Low	Yes	Ejido Open access State property	Langostino (*Creaseria morleyi*) Henequen (*Agave fourcroydes*)	Future plans for ecotourism
6	Uxutún	Cattle farming, apiculture	High	Yes	Ejido Private property	Tilapia (*Oreochromis mossambicus*) Bagre (*Rhamdia guatemalensis*)	Future plans for ecotourism Pesticide bottles found
7	Saktún	Apiculture	Low	Yes	Ejido Private property	Langostino (*Creaseria morleyi*) Bagre (*Rhamdia guatemalensis*) Serpiente coral falsa (*Sibon sartorii*) Chaya (*Cnidoscolus chayamansa*) Piñuela (*Bromelia pinguin*)	Future plans for ecotourism
8	Mudzuy	Agriculture Cattle farming Human consumption	High	Yes	Ejido Private property	Bagre (*Rhamdia guatemalensis*) Mojarra (*Cichlasoma urophtalmus*) Tilapia (*Oreochromis mossambicus*)	Pesticide bottles and a gallon containing diesel found, gasoline spill
9	Torcaza	Agriculture	High	Yes	Ejido Private property	Ceiba (*Ceiba speciosa* (L.) Gaertn) Ramon (*Brosimum alicastrum*)	Herbicide bottles found Recommended for ecotourism
10	Tixcacal Quintero	Agriculture Cattle farming	Medium	No	Ejido State property	Langostino (*Creaseria morleyi*) Chaya (*Cnidoscolus chayamansa*)	Recommended for ecotourism
11	No name	Agriculture Cattle farming	High	Yes	Ejido Private property Open access	Langostino (*Creaseria morleyi*)	Recommended for ecotourism
12	Xtohil	Agriculture Cattle farming	Low	Yes	Ejido Open access	Langostino (*Creaseria morleyi*) Pich (*Enterolobium cyclocarpum*)	Construction of a main road will close the entrance of the cenote

[†] The name of the communities and precise location of the cenotes are not included to protect the cultural material found.
[‡] According to the responses obtained during the interviews with stakeholders.
[§] As reported in the SEDUMA database and responses obtained during the interviews with authorities and stakeholders.

activities. However, the presence of reserves does not seem to have motivated sustainable resource use and cultural practices. For example, protected areas were not identified well by any of the interviewees, and neither were archaeological zones associated with cenotes. There was no consensus regarding current management and what else can be done to protect them. The alarming decline in water quality was frequently mentioned. Fifty-two participants reported that, prior to the mid-1990s, they could drink water directly from the *pozos* (wells), but presently they did not because they could become sick. One interviewee said the following:

> *In the past 25–30 years, we used to drink water from our pozo […]. Nowadays water is not drinkable and that is the reason why we prefer to buy bottled water.* (Informal conversation, farmer, male, 50 years old).

We collected information on governance. Because cenotes and the Yucatan groundwater basin are commons, we classified governance according to the terms used in the commons literature (Ostrom 1990): (1) state property: when the cenote is owned by government authorities; some responsibilities may be shared with the community; (2) private property: when an individual owns a cenote on their private land; (3) collective property or *ejido*: when the cenote is owned by *ejido* members; and (4) open-access: when the cenote does not have well-defined property rights and is open to everyone and all uses. *Ejidos* are common-use lands and lands intended for housing and urban infrastructure. They are different from communal land by being an endowment granted by the government to an organized group of farmers with no land (Jones and Ward 1998, Torres-Mazuera 2009).

It appears that the contemporary governance status of cenotes includes all four of these regimes but is mostly mixed or unclear (Table 3). What used to be communal property, under communal care, in ancient times has become mostly unmanaged state property verging on open-access. In effect, cenotes have been decommonized (Lopez-Maldonado 2015) into open-access, suffering from degradation, the usual consequence of open-access (Ostrom 1990). Community respondents did not seem to associate contamination of cenotes and the governance regime, and what that might imply for stewardship responsibilities. Cenotes used for tourism activities are managed according to environmental regulations, but there is a lack of regulation for other cenotes. One member of a tourism cooperative observed the following:

> *We are six members in this cooperative. The land and cenote does not belong to us, the Ejido* members donated all. We can use the cenote and the land for the next 30 years and then we need to move or to extend the agreement. We can do wherever we want, but we need to follow government rules. For example, we cannot use pesticides around the cenote and we cannot modify the entrance of the cave, nor add lamps […]. (Interview, member of tourism cooperative, female, 56 years old).

The role that local people could play in the management of cenotes came up for discussion during informal conversation with experts working on the water sector but mainly regarding contamination. For example, the Reserve was so designated because of the quality of water. However, some cenotes in the Reserve have been reportedly contaminated with pesticides (Polanco-Rodríguez et al. 2015). Toxic contamination was not reflected in the understanding of participants regarding water quality, and pesticides were not mentioned as a potential factor affecting groundwater, even though in five of the cenotes explored, pesticide bottles were found. Chemical pollution challenges some of the responses indicating that water clarity was the essential criterion for considering a cenote as sacred or not, and suggests that water in cenotes has lost much of its former sacredness. One interviewee said the following:

> *We used to live here in the ranch and we did not have another [source of] water to drink. We had to drink water from the cenote. We never got sick because water was sacred and it was always clean.* (Interview, Municipal authority, male, 43 years old).

Respondents were asked how they characterized the water in the Mayan language, because linguistics often provides insights into local perceptions; the way in which a resource is named and categorized helps to understand their knowledge system. Responses were diverse and confusing: concepts such as clean, transparent, turbid, stinky, or with sacred powers such as pure water were mentioned. Interviewees used over 20 different terms for water (Table 4). However, they were not able to express a particular idea for *agua contaminada* or *agua sucia* (Spanish for contaminated or polluted water). Participants recognized the presence of virgin water or *Sujuy Ja'* in some cenotes but they did not mention the use of this water for healing or as sacred water. Nine out of 25 used the term *Ja'* when referring to clean water in a cenote, but indicated that this water was not suitable for human consumption. Twelve out of 109 mentioned the term *Eek Ja'* as water that is not suitable for drinking, but they did not connect this concept to contamination (Table 4). These mixed results are consistent with the regional database in which more than 50% of the cenotes were registered as contaminated (SEDUMA 2014). Interestingly, more than the half of the group of experts (N = 21) were not able to define any of the Maya terms.

Table 4. Selected terms and ideas expressed regarding the concept of water.

Maya	English	Spanish
Ja'	Drinkable water	*Agua para beber*
Luuk'	Mud	*Fango, lodo*
Boombil Ja'	Water containing substances (e.g., gasoline)	*Agua con substancias*
Boox Ja'	Black water	*Agua negra*
Ch'a ch'alkil Ja'	Oily water	*Agua aceitosa*
Ch'e'en Ja'	Water from a well	*Agua de pozo*
Ch'ooch' Ja	Salty water	*Agua salada*
Ch'ujuk Ja'	Fresh water	*Agua dulce*
Chaltun Ja'	Limestone/calcareous water	*Agua de laja*[†]
Chokoj Ja'	Warm water	*Agua caliente, tibia*
Eek Ja'	Turbid/blurry water	*Agua turbia*
Eek' Ja'	Black water	*Agua negra*
K'ook'ol	Impure water	*Agua impura*[‡]
Ki'irits Ja'	Dingy water	*Agua cubierta de polvo*
Óomil Ja	Foamy water	*Agua espumosa*
Tóos lu'umbil Ja'	Dusty water	*Agua con polvo*
Tu' Ja	Stinky water	*Agua hedionda*
Saasil Ja'	Clean water	*Agua limpia*
Siis Ja'	Cold water	*Agua fria*
Sujuy Ja'	Virgin/pure water	*Agua virgen, pura*
Ts'ono'ot Ja'	Water from a cenote	*Agua de cenote*
Ya'as Ja'	Greenish water	*Agua verdosa, verde*[§]
Yoom Ja'	Scummy water	*Agua espumosa*

[†] *Laja* in Yucatan is a common, natural limestone found underneath the soil (0.3 to 2.5 cm).
[‡] Impure water refers to water with additional innocuous compounds. However, in the Mayan native vocabulary it refers to water that has lost its main healing properties.
[§] Indigenous people recognized the Spanish concept for contaminated water (agua contaminada) but they did not have a native Mayan word for it.

Participants were perceptive to contamination because they explained that quality of groundwater was not suitable for human consumption in some cenotes, but not in all of them. Responses indicated that interviewees did not understand that all cenotes are part of a single interconnected groundwater system and cultural values do not seem to be considered.

Contemporary meanings and values

Evidence of ancient sacredness of groundwater in the Yucatan Peninsula is everywhere. Many of the cenotes explored contained ancient Maya pottery, fire pits, human and animal remains below the water table. Furthermore, the SEDUMA database contains references to ceremonies and some cave systems being considered as sacred routes. Sacredness appears to be understood by some, but certainly not all, of the respondents. Indigenous respondents perceived cenotes as the abode of deities and spirits, and that cenotes were primarily used for rituals in the past.

> *In the past, cenotes were sacred but not all of them now. There are some of them that can serve to [carry out] ceremonies such as the Cha-Chaac (ceremony for the God Chaac) but they are few and it is not easy to reach them [the cenotes].* (Interview, beekeeper, male, 50 years old).

We interviewed participants about the current importance of cenotes. We used the example of one cenote in Yucatan (the Sacred Cenote of the archaeological zone in Chichen Itza) to exemplify the concept of sacred. We asked if they can tell why the cenote *Sagrado* in Chichen Itza is called "Sacred", and what the Mayas from the past used to do with the water of that cenote. Did they think that cenotes we have today are the same cenotes the Mayas used in the past? We asked the participants to explain and expand on each response. We then asked if they think sacred cenotes still existed in Yucatan. Questions about supernatural agencies in local people's beliefs were also explored. We asked about *Aluxes* (name given to a spirit in the mythological Maya tradition). Most participants, including experts, seemed to have some belief in the *Aluxes*. One respondent mentioned: "The Sacred cenote in Chichen Itza is sacred because it was important for the Mayan ceremonies […]. The water was used to support the needs of the population. The other cenotes in Yucatan are the same cenotes as those in the past because they require a lot of time to form. However, present cenotes are contaminated" (Interview, housewife, female, 35 years).

Interestingly, 89 respondents rejected the idea that cenotes continue to represent sacred places but they did mention that they believed in the importance of the cenote in Chichen Itza and in *Aluxes* as protectors and caretakers of the cenotes. This suggests that the link between sacredness and cenotes has been broken, even for some who acknowledged spiritual powers:

> *I don't know the cenotes and I've never been into a cave but I know that there exists some spirit that inhabits there and protects the entrance of the cenote.* (Informal conversation, student, male, 20 years old).

According to some respondents, loss of respect for cenotes may be related to the erosion of sacredness across generations. Knowledge of cenotes as sacred natural sites was no longer being transmitted to younger generations. One diver member of a local NGO working on the protection of cenotes noted the following:

> *The problem is the lack of education among the younger people, between 15 to 24 years old. As explorers of caves and cenotes, we always find beer bottles, spirit bottles, condoms, graffiti, etc. I do not believe that older people visit cenotes and do all of these things. Besides, it is difficult to access some of these sites and not everyone has the skills to descend [into the cenotes]. The young people have to be involved more in the tasks of protection and conservation.* (Informal conversation, cave diver, male, 24 years old).

We recorded information on current management, legends, and (where possible) rituals or ceremonies. Some of the legends were consistent with the idea that all cenotes once had names and spiritual guardians or "owners." Some interviewees seemed to know of the ancient institution of cenote guardians, spiritually powerful humans or animals. Twenty-four interviewees mentioned that the guardian of the cenote is a snake. None of the respondents themselves were guardians. One interviewee said "In order to be a guardian you have to have knowledge and special powers as *X'menes* (Mayan healer) used to have. No one has it now, it is something that someone was born with."

In interviews and participant observation in the one community in Campeche State, we found that the population still practiced some water-oriented ceremonies (see Video). We interviewed local members and found a profound sense of respect for cenotes. However, we also found high density of pesticide bottles in the area and evidence of high levels of solid waste (mainly plastics) contamination, suggesting lack of knowledge of their impact on the groundwater system and the consequent environmental effects.

Overall, cenotes were assessed according to specific characteristics including accessibility and safety. Some cenotes were considered unsafe places by about half of the respondents. Seventy-eight of the interviewees reported being afraid of entering into a cenote, and almost all the participants (N = 101) said they would only visit them for recreation. People believed cenotes were dangerous places because of vandalism, drug and alcohol use, hazardous species that inhabit dark places, e.g., spiders and snakes, or because underwater streams can cause drowning.

Changes in values regarding cenotes as sacred natural sites

Values, beliefs, and meanings regarding cenotes sacredness seem to have declined. Although some ancient Maya indigenous beliefs still exist, cenotes have been suffering from an erosion of values, including the way people perceive nature and environmental change implications. Indicators of these changes in values were evident during the interviews. One woman reported having a *pozo*, which she considered far more important to her than a cenote:

> *We have pozos in our houses. All here in the village have their own pozo*, therefore why are we going to take care of cenotes if what we use comes from the *pozo*. I better take care of my *pozo* because I take water from it. (Interview, ECA member, female, 43 years old).

Value and environmental change also impacted biodiversity and habitats of endemic species, including blindfish (*Typhliasina pearsei*, *sak-ay* in Mayan) and the blind swamp eel (*Ophisternon infernale*). Participants mentioned that the impact on biodiversity in cenotes was due to the introduction of species such as tilapia (*Oreochromis mossambicus*), water extraction, demolition of cenotes and natural areas to construct tourist facilities and roads, direct human consumption of cenote water, abandonment of ceremonies associated with sacred beliefs, wastewater discharges, and solid waste disposal.

Results from interviews and informal conversations indicated a failure of knowledge transmission of cenotes as sacred sites. More than the half of the respondents (N = 62) expressed a strong desire to learn about cenotes, to restore cultural practices, and to revitalize values of sacred places. Overall, interviews and informal conversations revealed a profound sense of loss of local and traditional knowledge of uses and practices, e.g., rainwater harvesting, and a lack of self-recognition as custodians. According to the testimony of many elders who have witnessed tremendous change over the past years, responses indicated the loss of meaning and value among the local population. Interviewees identified threats to the cenotes, lack of interest in preservation, and changes in water quality. But little consensus was found regarding the significance of cenotes, how to better protect them, and what trade-offs may be involved.

Cenotes have become a major tourist attraction, posing threats such as loss of respect. The designation of the Geohydrological Reserve, meant as a conservation measure, has had the impact of increasing tourism, compounding problems through modifications of cenotes, for example, to improve tourist access. Paradoxically, those cenotes are less contaminated with plastics and better preserved because the local population is interested in tourism income.

DISCUSSION: A BIOCULTURAL APPROACH TO CENOTE CONSERVATION

Current conservation strategies in Yucatan do not include cultural values in groundwater and biodiversity conservation efforts. Likewise, current government policies do not mesh well with cultural values and the possibilities of cultural revitalization; thus, there is a lack of biocultural appreciation (Maffi and Woodley 2010). However, the Ring of Cenotes (and the Reserve) is on the tentative list of the UNESCO World Heritage Site, providing international recognition of the biocultural significance of the area. Findings of ancient cultural material such as pottery, figures, animal and human bones during our fieldwork are consistent with previous results of archaeological research in Yucatan State (Andrews 1981), as in entire Mesoamerica (Healy 2007, Prufer and Dunham 2009). Even though communities may no longer hold, or even know about, their traditional belief systems, they seem to be interested in protecting these sites. However, without an appreciation of traditional cultural and spiritual practices, as well as current practices, it would be difficult to understand how contemporary conservation can foster transformative change toward environmental stewardship.

Cenotes are linked to individual and community well-being, but their values have been eroded and sacredness, as a motivator, lost. As well, communal values have been largely replaced by individual values. The quotations about wells makes this clear (why worry about "cenotes if what we use comes from the *pozo*"). Communities will benefit from conservation action, but no individual seems to have sufficient incentive to act alone. Using commons theory terminology, there is a collective action problem (Ostrom 1990, Nyborg et al. 2016). However, there may be ways to motivate local communities by involving their knowledge, beliefs, and values to enable community-based conservation, which in turn benefits communities and society as a whole, addressing the collective action problem.

What are the prospects for using community-based conservation strategies to protect cenotes and thus Yucatan's groundwater resources? Elements of such an approach may include the following. First, there is a need for cultural revitalization to restore spiritual connection of people to cenotes. Second, the consideration of the integrated social-ecological system through a biocultural approach needs to replace government's conventional sectoral, expert-based, regulation-driven conservation. Third, the governance of cenotes has to be revised by restoring community ownership and communal responsibility for cenotes where feasible through devolution of government authority. Fourth, an ongoing educational campaign at all levels, but especially aimed at school children and youth, is needed to transmit knowledge and values about cenotes. We expand on each of these points.

First, cultural revitalization is necessary because it supplies the emotional engagement to conserve (Anderson 1996). Cultural revitalization can go hand in hand with ecosystem restoration, as seen in some indigenous areas in the United States, such as the Nisqually Tribe of Washington State (Grossman 2010) and elsewhere (Maffi and Woodley 2010). However, cultural revitalization is not an easy process; it has to start from the bottom-up. Through disempowerment and dispossession brought about by colonization, it has become difficult for indigenous peoples to relate to their environment. In many areas however, indigenous peoples search for personal and spiritual meaning. As reservoirs of meaning and identity, sacred natural sites can represent important ways for establishing relations with the environment (Oviedo and Jeanrenaud 2007, Wild and McLeod 2008). For example, Huicholes of northern Mexico continue to live their everyday and ceremonial lives according to ancestral practical knowledge. They perform ancient ceremonies and rituals in the desert region called *Wirikuta*, where their ancestors reside and manifest themselves as rocks, mountains, animals, or plants (Myerhoff 1974, Neurath 2003). Their local and traditional knowledge frame the way in which they interact with nature.

Cenotes are seriously contaminated (Metcalfe et al. 2011, Polanco-Rodríguez et al. 2015), but our results indicate that the local people perceive contamination in a different way from scientific understanding. The linguistic classification of water (Table 4) reflects local knowledge, and the terms for different perceptions of "water" are helpful to deepen the analysis of how to improve water management to go from an undesirable to a desirable state. For example, cenotes were considered as sources of "virgin water" in the past, and there is archaeological evidence for this belief (Andrews 1981, Prufer and Dunham 2009). However, contemporary people have noticed a distinct deterioration in the quality of water and say that it is very difficult to find sources of virgin water. Instead, there is a rich terminology for bad water instead of drinkable *Ja'*. Cultural revitalization, in the form of people reclaiming ownership of their culture and recognizing the value of virgin and drinkable water, can provide the impetus for reversing the degradation trend. Restoring and revitalizing the present-day meanings of cenotes and good water can help reconnect ancient and present Maya wisdom, along with a better understanding of water contamination.

Second, we need to recognize different values of conservation and ask, what kind of conservation? People in Yucatan believe in protecting cenotes for cultural and spiritual reasons, conservationists seek to protect groundwater ecosystems and biodiversity, and government authorities want to protect the aquifer. However, these interests do not seem to overlap as they should, as if we were dealing with three separate conservation objectives. Bringing these objectives together requires a biocultural approach (Gavin et al. 2015). Our findings indicate that authorities do not recognize the potential of sacred sites for biodiversity conservation, and that local knowledge is not used alongside scientific knowledge.

To operationalize a biocultural approach, cenotes must be understood as integrated social-ecological systems from the indigenous perspective, including current values and local knowledge (Samakov and Berkes 2016). Local and indigenous knowledge should be integrated into hydrological management plans and be recognized at the policy level. Further studies on cultural values regarding cenotes are needed for fuller documentation and better understanding. Sacred natural sites located in protected areas should be integrated into the planning processes. Similarly, cultural values could be integrated into tourism planning to safeguard against excessive loss of spiritual characteristics due to commercialization and commodification of cenotes.

Third, these considerations raise the question of governance. Inconsistent water governance regimes, laws, and policies, as well as local practices, pose huge problems for cenote conservation. In general, management strategies for groundwater or cenotes do not include indigenous peoples in the decision-making process. However, the biocultural approach to conserve biodiversity and cultural diversity together highlight the need to include local voices in decision making. Current governance of cenotes is complex because some of them are under state management, others under the control of communities, and some of them are private. Most of them are under mixed regimes or simply open-access. In 10 out of the 12 cenotes explored, there was still some *ejido* governance (Table 3) and this signals an opportunity for community-based conservation and local stewardship. However, this also might indicate a potential for confrontations and problems with cenote water use and land use rights (Oswald-Spring and Sanchez-Cohen 2011).

Conservation of cenotes can be considered as a commons problem, specifically as a multilevel commons problem (Berkes 2007) because each cenote is part of the larger hydrological system. It is not possible to consider each cenote as an isolated resource: water extraction or pollution of each cenote has repercussions for all (or nearly all) other cenotes, aguadas, *pozos*, and the groundwater system as a whole. Multilevel commons require a matching multilevel governance system (Berkes 2007). Community-based conservation represents grassroots interests, and the control of cenotes by communities provides local incentives to protect them.

Taking the long view, community-based conservation, if it could be instituted, reverses the historic trend of decommonization whereby cenotes had been turned into open-access over the colonization period (Lopez-Maldonado 2015). Community-based conservation would restore cenotes as locally controlled commons, a commonization process (Nayak and Berkes 2011). Restoration of local control can be a support tool for cultural revitalization and help stimulate local values of sacred sites. Community-based conservation is not in conflict with state conservation; it is complementary. The combination of different levels of management allows for governance pluralism and social justice in the restoration and use of the resource.

Cenotes on private lands or those controlled by tourism interests have been effectively privatized. But they are still part of a hydrological system and require oversight by public institutions at municipal, state, and national levels. Managing and protecting cenotes from a holistic perspective, as commons, probably requires the cooperation of a whole network of public and private actors: communities, governments, industry associations, private owners, NGOs, and educational institutions. Typically in a multilevel commons situation, these actors may be connected with vertical and horizontal linkages, in which vertical links connect across levels (e.g., municipal - state - national) and horizontal links connect within levels, such as a cluster of communities that communicate and learn from one another (Berkes 2007).

Fourth, education is a necessary component of a successful biocultural conservation program, specifically to supplement the weak intergenerational transmission of cultural values of cenotes. Education is needed at all levels and sectors: the youth, local people, government officials, industry representatives and educational institutions themselves. As a primary objective, cenotes can be used for educational purposes at various levels for preserving local knowledge, and making sacred sites a core for community conserved areas. Integrating cultural and natural values of past and present Maya culture into a focal point can help establish a benchmark for cultural identity, whereby expressions of culture, including ceremonies, dances, and songs can be preserved.

Hence, cenotes can be used to highlight indigenous Maya knowledge and to legitimize the importance of sacred values. As known from elsewhere (Verschuuren and Furuta 2016), ancient sites often retain at least a residual spiritual meaning for people, even if original belief systems have been much eroded. Conservation may build on such values, and the elaboration of these indigenous values can be used to educate the larger society (Zurba and Berkes 2014). Cenotes are being promoted for tourism development, and communities are interested in tourism income. However, none of the interviewees raised the possibility of using cenote tourism to educate society. Protection is more pertinent if the spiritual aspect of the site is considered as significant in itself, a useful lesson for the dominant society. This can be a call to protected area managers, landowners, government authorities, locals, and other stakeholders to recognize the importance and legitimacy of sacred values embedded in cenotes.

Likewise, there are specific educational targets for community people and others. Lopez-Maldonado et al. (2017) found that, even though groundwater is currently the main source of freshwater for the population, crucial information about the state of the system, e.g., precise location, function, quality, quantity, etc., is limited and poorly understood. For example, the meaning of polluted water and an interconnected groundwater system was not apparent in the language or the imagery of the interviewees. What they did describe was more like an idealized, historical single cenote as a continuous aquatic “clean” underworld without considering that cenotes are interconnected. This lack of groundwater system understanding was persistent in all of the interviews, and seemed to influence the way in which water quality was perceived. There can be no clearer sources of information regarding the importance and sacredness of cenotes than the importance of recognizing and revitalizing ancient Maya wisdom to help protect groundwater and the society that depends on it. Thus, Lopez-Maldonado et al. (2017) emphasized the importance of groundwater literacy: the knowledge of the users about the resource and its attributes, and the perception and valuation of impacts on the system.

CONCLUSIONS

Cenotes are sinkholes through which people access water from the Yucatan Peninsula Aquifer. Because cenotes are interconnected, they cannot be managed as isolated entities. Similarly, cenotes are part of a millennial culture and cannot be managed in isolation from that culture. Even though culture and environment are no longer closely coupled in current Yucatec Maya society, cenotes cannot be managed and understood without recognizing the values and knowledge of local communities. Thus, there is a need for revitalization and recognition of cenotes as sacred natural sites. Communities are the most appropriate actors to initiate collective action, with support from a network of other stakeholders, to reverse threats and encourage stewardship in younger generations.

Commons theory does not explicitly recognize the revitalization of indigenous cultures and social norms as essential for commons management. However, the present case shows that groundwater conservation in Yucatan cannot come solely from government regulation and privatization. It may be best initiated by the revitalization of community values and norms, in this case, the recognition of cenotes as sacred sites. The social enforcement of respect for cenotes and groundwater restores individual incentives to act in ways that benefit communities and society. Hence, restoring cultural values is the way communities can foster conservation and solve the collective action problem (Nyborg et al. 2016). Through such collective action, individuals themselves, as well as the community, can derive social and economic benefits from conservation, consistent with commons theory (Berkes 2004).

The revitalization of spiritual values needs to be supported by at least three other community-based conservation strategies, as detailed in the previous section: (a) the adoption of a biocultural approach to replace government's conventional sectoral or discipline- and expert-based, regulation-driven conservation; (b) governance reform to restore community ownership and communal responsibility for cenotes through devolution of government authority; and (c) an ongoing educational campaign at all levels to transmit knowledge and values about cenotes.

Strengthening of community culture and knowledge is important also for maintaining the ecological integrity of cenotes because sites need to be conserved as reservoirs of biodiversity. This is one potential area of cooperation between local and scientific knowledge (Wild and McLeod 2008). Traditional ecological knowledge or indigenous knowledge is a source of biological information and ecological insights for conservation (Berkes 2012). However, until recently, inclusion of indigenous knowledge into planning was not even considered. Conservation of protected areas should be designed to work with local people (Borrini-Feyerabend et al. 2004). Moreover, if social and ecological systems are going to be approached as integrated complex systems, there is need to develop a model of conservation that takes into account the complexity of Maya society and the complexity of the groundwater system, and the relationships between the two as a social-ecological system (Berkes 2004). Naturally there is always cultural change and loss of some values, changing the ways in which groundwater is used. But these values can also change still further, toward conservation. Such changes would necessarily involve deliberation and mutual learning among the people engaged (Berkes and Turner 2006).

The main driving forces behind the growing interest in the protection of cenotes are human activities, development, and environmental impacts. There is potential for the recognition of the importance of cultural values in Yucatan groundwater conservation. Internationally, efforts have been made and methods and approaches developed to assess the cultural values of indigenous communities regarding their ecosystems (Oviedo and Jeanrenaud 2007). However, the present study makes clear the need for the inclusion of indigenous thinkers, policy makers, and local people in the understanding of those values, traditions, and beliefs.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/9648

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Publication IV

Lopez-Maldonado, Y., and Batllori-Sampedro, E. 2017. “Groundwater Literacy: Bridging the gap between science, policy makers and society”. *Water Resources Research* (in revision)

Publication V

Lopez-Maldonado, Y. 2017. "Everyone in our community, at some point, will lose". The inequalities of groundwater between society and ecosystems: The case of the Mayan area of Yucatan, Mexico. Proceedings of the Resilience Conference. Stockholm, Sweden. August-July 2017.

Abstract

Groundwater is needed for almost all life-sustaining purposes and contributes to the health of many ecosystems, but many issues remain critical: pollution, overexploitation. Groundwater is a socio-ecological system where uses and users are interconnected, and possibly conflicting, becoming in many cases drivers of inequality that can propagate: 1) through either the social system, or 2) through the biosphere. To exemplify this, we use the case of Yucatan, in Mexico, a place where no rivers on the surface exist. Aspects of affordability, availability and accessibility to water tend to capture these inequalities and calls for the recognition of human rights to safe drinking water and sanitation. Groundwater supplies drinking water for the complete population; almost all users are allowed to take water from any part of the aquifer and the related water bodies for use in industry, agriculture or for their human needs. Due to population growth, increased urbanization, and unsustainable use, the groundwater system is threatened with a double jeopardy -depletion and degradation. Evidence shows that, indirectly, through unlimited groundwater extraction –and its consequent pollution-, some sectors are the main extractors and polluters resulted into greater inequity. That puts indigenous population and poor communities, at a disadvantage: only about 40% of rural households receive potable water, versus about 68% of those living in urban areas, and with the highest incomes. This contributes to decrease productivity of provision of water services, biodiversity loss, threatening food security, livelihoods, and the integrity of ecosystem services in general. However, and despite the local communities often feel the harmful effects of groundwater degradation disproportionally, the complete population is currently embedded in the vicious circle of overexploitation process of the natural capital. The aquifer represent the buffer by making freshwater available even during dry seasons. However, water resident times might also influence inequalities from the biosphere

in the future (i.e. natural changes on the hydrological cycle -precipitation, evaporation, infiltration, runoff, might affect the ecosystem, which in turn will affect livelihoods and economic growth). Both inequalities in the freshwater systems must be avoided since threshold behavior at local and regional scales, can generate feedbacks to the processes that do have large-scale thresholds affecting important mechanisms for maintaining the resilience of the Earth system as a whole.

Publication VI

Lopez-Maldonado, Y. 2017. Groundwater monitoring requires groundwater knowledge: The transdisciplinary socio-groundwater toolbox. Proceedings of the Havs-och vattenforum (The Swedish Water Management Conference): From Source to See. Gothenburg, 16-17 May 2017.

Available at:
https://www.havochvatten.se/download/18.4017b8c415bb1778a7fcf6c8/1494398898074/Programkatalog2017.pdf

Abstract

Groundwater is an extremely complex coupled human-natural life-sustaining resource. Its importance resides in that much of the freshwater located below the land's surface, supplies water to billion of people playing a unique role in human health and ecosystems. As a consequence, it is more widely accessible and also most acute to rapid change and depletion. Still, groundwater systems are difficult to monitor since it is out of view, and it is intimately link to the social system. In view of data scarcity mostly in developing countries, a key challenge is how to understand, monitor and model these systems and make the results usable for better groundwater management. To date, hydrological issues are playing a key role in the implementation of the goals in which water has a crosscutting role linked to many other Sustainable Development Goals (SDG's) set in the 2030 Agenda for Sustainable Development. With a dedicated water goal (SDG 6), the need for data integration and monitoring remains essential to guarantee the success of all the water related targets. According to SDG 6, there is a need to monitor eight different interrelated targets globally. At present, several global tools and initiatives for water monitoring exist. A prerequisite for their implementation is to have a thorough knowledge of the system and a consistent database, usually collected at a country and global scale worldwide. Nevertheless, this is not the case in less developed countries where databases are not often reliable. This calls for a clear understanding of the groundwater system - or groundwater literacy - defined here as: the knowledge of the users about the resource, some of its attributes, and their perception and valuation of

their impacts in the system. To overcome this, we develop a transdisciplinary socio-groundwater toolbox for a better groundwater resource management. We use the example of Yucatan, Mexico, where groundwater is the only source of freshwater for the population, where water demands and problems are growing, and groundwater data remain limited. We applied five different, interrelated, methodologies: 1) material flow analysis: to quantify groundwater flows associated with present-day economic sectors; 2) mental model approach: to analyze stakeholders' risk perception regarding groundwater pollution, by eliciting mental models; 3) underwater exploration: to obtain insights about current and real status of local wells and sinkholes; 4) community-based conservation: to integrate local values, beliefs and perceptions into groundwater conservation; 5) environmental activism: to directly involve stakeholders in local well clean-ups, and community events. These methods were developed in a transdisciplinary process with stakeholders spanning sectors. To implement SDG 6, our toolbox specifically supports the following Targets 6.3, 6.4, 6.5, and 6.6 (a & b) by: facilitating examination of hotspots of pollution, distribution of flows of hazardous substances, minimizing release of chemicals, ensuring sustainable withdrawals, revealing water extraction trends and sectors with major consumption, strengthen participation of local communities, and safeguarding the ecosystem by recognizing traditional ecological knowledge as an informal norm of monitoring. Our results support the current global monitoring framework of SDG 6; by acknowledging the importance of community participation and that groundwater literacy is essential to effectively address SDG 6 and its water related targets.

Publication VII

Lopez-Maldonado, Y. & Binder, C. (2016). "The Local Groundwater Balance Model".

Published in: Proceedings of the 12th Kovacs Colloquium15 June 2016, UNESCO Headquarters, Paris International Hydrological Prize and Tyson Award Ceremony (Hydrological inputs for water-related SDGS implementation: Knowledge, data, indicators, tools & innovations). Paris, France.

Publication VIII

López-Maldonado, Y. (2016). "Groundwater sustainability: Narrowing the gap between science, policy and society".

Published in:
Proceedings of the 2016 World Water Week". Stockholm, Sweden. 28 August – 2 September 2016.

Abstract

Highlights of the work

Groundwater problems occur in different ways and depending on the aquifer. To assess them, global and regional estimates and models exist. However, some models overestimate data, uncertainty and results can be poor at local scales. Models are important, but how scientist can meaningfully contribute with groundwater sustainability without considering local involvement?

Introduction and objectives

Groundwater has been described and qualified as a key, strategic, socially important, life-sustaining, out of view, unpredictable, hidden, common-pool and vulnerable resource. Because it is out of view, it is difficult to monitor at both, global and local scales. Modeling tools have been developed towards solutions to groundwater environmental problems. Although models are accessible, drawbacks are: they are not always locally affordable, data is not always reliable, and local key stakeholders are not included. Global assessments are important, but problems might be exacerbated if we do not examine groundwater from another perspective considering that its related problems are largely local. The aim was to develop a transdisciplinary socio-groundwater toolbox by applying a local-transdisciplinary approach.

Methodology approach – description and discussion of the approach of the study

I applied four different, interrelated, methodologies at the social-groundwater system interface: 1) groundwater flow analysis which uses numerical models to quantify in

groundwater flows associated with present-day economic sectors; 2) mental model approach to analyse experts (local members) and non-experts' risk perception regarding groundwater use and management, by eliciting their mental models; 3) underwater exploration made with the support and suggestions of local divers help us to obtain insights about the current and real use and status of local wells and sinkholes; 4) bio-cultural approach for conservation to form an idea of the importance for the local population; 5) Environmental activities to implement local wells-cleanups, make school presentation, and participate in community events. All those methods were develop in a transdisciplinary process including numerous workshops with stakeholder's spanning sectors such as: NGO's, local communities and policy makers.

Analysis and results – clear and understandable statements on which we can assess the value added of the proposed paper

Combining system analysis with mass balance, current published data, estimations, workshops, etc. we adapted our framework by bring local and scientific knowledge. Data was obtained from different sources: literature, national and local statistics, stakeholder's workshops, expert opinions, expert consultation, local interviews, and estimations. Investigation of flows by applying groundwater flow analysis help us to develop the first water balance and to revealed wastewater emission to the aquifer. The mental model method allows to find the current misunderstanding between a researchers and experts of the water sector and local members regarding groundwater problems in the region. Speleological records obtained during underwater explorations inform us about cave formations, biodiversity and current hotspots of pollution due to bad solid waste disposal local practices. Interviews revealed a profound sense of loss of local and traditional knowledge, and a strong desire to learn more about groundwater, to restore cultural practices and to revitalize the local values. Through local involvement and volunteering environmental activities, we cleanup local wells. Results are important for the policy making process since we analyze, in a unique way, groundwater resources in place where no other sources of freshwater exist. All those ideas we may guide the adoption of a new approach towards groundwater sustainability.

Conclusions and recommendations

Technical solutions to environmental problems such as groundwater contamination are of importance; however, local involvement is significant towards solutions. What level of scientific involvement is necessary, and how can communities make decisions to ensure solutions for groundwater conservation, at a time when local approaches are scarce? A real transformation is required in how we value, manage and characterize groundwater systems since only hydrological models and single-disciplines approaches have seem to be failed. We agree with the importance of models, but we offer a much more favourable view since we involve stakeholders in the development process. This is a versatile, reliable and more efficient methodology to meaningfully contribute with groundwater sustainability. It can be adapted to specific social, economic, political and environmental setting of each region.

1.3. Groundwater systems and the linkages to the 2030 Sustainable Development Agenda

To date, hydrological issues are playing a key role in the implementation of the goals in which water has a crosscutting role linked to many other Sustainable Development Goals (SDG's) set in the 2030 Agenda for Sustainable Development. With a dedicated water goal (SDG 6), the need for data integration and monitoring remains essential to guarantee the success of all the water related targets (UNGA 2015).

The vision formulated in terms of water resources pictures a world with water and sanitation for all. One challenge in this regard is the fact that groundwater is more widely accessible and also most acute to rapid change and depletion. To balance competing uses and users in an equitable manner while maintaining water quality and ensuring health ecosystems if the dynamic interface between the social and the ecological systems remains critical.

According to SDG 6, there is a need to monitor eight different interrelated targets globally. At present, several global tools and initiatives for water monitoring exist. A prerequisite for their implementation is to have a thorough knowledge of the system and a consistent database, usually collected at a country and global scale worldwide.

Goal 6 addresses the issues relating to drinking water, sanitation, hygiene, and quality and sustainability of water resources worldwide.

Publication IX

López-Maldonado, Y. (2015). "The early identification of human drivers affecting groundwater resources. Developing a Material Flow Analysis of the Geohydrological Reserve zone in Yucatan, Mexico". International Institute for Applied Systems Analysis Final Young Summer Program Report. Laxenburg, Austria.

Published in:
Final Young Summer Program Report. International Institute for Applied Systems Analysis, Laxenburg, Austria. June -August 2015
Available at http://www.iiasa.ac.at/web/scientificUpdate/2015/cb/Maldonado-Lopez-Yolanda.html

Abstract

Groundwater systems constitute the predominant accessible reservoir of freshwater storage on Earth. When studying interconnections of groundwater with society, problems arise. Successful groundwater resource management relies on models that effectively capture these interactions. In Yucatan, Mexico, effects of a meteor impact 65 million years ago dominate the geomorphology forming a complex groundwater system that is the only source of freshwater for the population. In this place, water demands are growing, and inhabitants have to deal with water problems; however, groundwater data remain limited. Because it is necessary to quantify groundwater flows to secure water for the future, the case of the Yucatan groundwater system was modelled using Material Flow Analysis (MFA). MFA is a method to analyse flows and exchange of materials and energy with the environment. It is an instrument for the early recognition of environmental problems and prediction of future environmental loadings. The study quantifies groundwater flows associated with present-day economic sectors (industry, agriculture, cattle, and household consumption); a range of physical characteristics of the related flows and environmental impacts of human activities (extraction, uses, recycling, and final disposal) are examined. MFA was constructed by applying systems analysis. Combining this with mass balance and based on current data and estimations, we traced processes and sectors, and accounted for the flows. As our results do not only

depend on literature, and since MFA has not been previously carried out in Yucatan, thus, it was necessary to enlist stakeholder workshops, statistical data, and expert opinion. Assumptions were made when data were unavailable. MFA show what parameters have to be considered to identify human drivers affecting groundwater and to detect red-points. Results reveal the freshwater resource supply, demand balance and relevant flows. Knowing that some of those flows have a high pH, content of organic matter, pesticides and further pollutants, the MFA shows that they are directly discharged to the aquifer in considerable volumes. Less than 0.04% of wastewater is treated and reused; recycling constitutes less than 1% of total wastewater emissions; 75% of the wastewater in households goes to septic tanks and the remaining is discharged directly to the aquifer. Main wastewater inputs to the aquifer are from households, septic tanks and agriculture. On the industry sector the majority of the water consumed (77%) is used as water for process but they are directly discharged to the aquifer. Therefore, criteria must be biased according to local interest to determine the most sustainable solution and to serve as a basis for a long-term strategic planning. MFA can be applied in regions with similar characteristics and different environmental management states.

Publication X

Lopez-Maldonado, Y. & Binder, C. (2015). “The early identification of the human drivers affecting groundwater system in Yucatan, Mexico using Material Flow Analysis”. Proceedings of the “42nd International Association of Hydrologist AQUA2015”. Organised by the UNESCO International Hydrological Programme (IHP) and the Rome-based United Nations’ Food and Agriculture Organization (FAO). Held at La Sapienza University, Roma. September 12-19, 2015.

Published in:
Proceedings of the “42nd International Association of Hydrologist AQUA2015”. La Sapienza University, Rome. September-May 2015.

Publication XI

López-Maldonado, Y. (2015). "Groundwater common pool resources in Yucatan, Mexico: Understanding commonisation processes - and anticipating decommonisation – in the cenotes of the Mayan Area" Proceedings of the International Association of the Study of the Commons 2015 Conference. University of Edmonton, Edmonton, Canada.

Published in:
International Association of the Study of the Commons 2015 Conference. University of Edmonton, Edmonton, Canada. May 2015. Session: Framing commons as a process: Exploring the concepts of commonisation and decommonisation for theory, policy and practice of Governance.

Abstract

All groundwater exploitation made by societies results in some decline in the quality of aquifer water (Wada et al. 2010). In this paper we present the analysis of groundwater common pool resources in the Mayan area of Yucatan, Mexico. Due to the karstic and highly permeable soil of Yucatan, is easy to find groundwater systems, which forms 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). 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). Because the cenotes were the source of water that supported a considerable population, particular emphasis is given to the interactions of communities and institutions related to the use and management of those resources. We define common pool groundwater resources based on two attributes according to Ostrom (2009): the difficulty of excluding beneficiaries and the subtractability of us. We then adapt this definition to the local context of the Mayan area and present characteristics of groundwater resources located there in regard to their ecological and institutional significance and as an early recognition of the possible process of commonization

and decommonization. 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 analysing at regional scale groundwater management problems in a very sensitive resource based-dependent society in the area. By using the orientation of transdisciplinary approaches to pursue a case study of groundwater resource development and management, emphasis is given to the strategies, which people can follow in seeking to solve a common problem through communitarian actions that cannot be solved by individual private actions.

Publication XII

López-Maldonado, Y. & Batllori-Sampedro, E. (2015). "Why mapping groundwater matters?" Groundwater caves from Space in the Circle of Cenotes in Yucatan, Mexico (ID: 16/1.5:12). Proceedings of the Mapping Water Bodies from Space 2015 Conference. European Space Agency. Frascati, Rome, Italy.

Published in:
Mapping Water Bodies from Space Conference. European Space Agency (ESA-Esrin) 18 - 19 March 2015. Frascati, Rome, Italy
http://due.esrin.esa.int/mwbs2015/index.php

Abstract

Due to the karstic and highly permeable soil of Yucatan, in Mexico, is easy to find groundwater caves plenty of fresh water. Groundwater storage and flow occur in a regional karst aquifer with major cave systems, where groundwater flow is dominated by turbulent conduit flow. 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. More than 2000 groundwater caves have been estimated along the region. 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. Furthermore, all data on cenotes remains limited. Some efforts began in 1996 to establish a standardized cenote data collection methodology bridging biological, archaeological, and land use aspects for use by local persons, explorers, and visiting interested persons. However, data from past and current satellites is needed and knowledge about those water bodies, is consequently crucial to understand groundwater-human interactions. From the space those cenotes are visible, interspersed with other water bodies like poljes and aguadas. This project aims to establish a georeferenced surface karst inventory of groundwater bodies situated principally in the area called Circle of Cenotes, located in the state of Yucatan, Mexico. As a unique hydrologic region in the world, formed due to the impact of a large meteor Circle Cenotes, this region was considered the ideal location

to develop the project. Mapping groundwater bodies, or cenotes, will not only expedite direct exploration of the subterranean rivers but may also provide the basis for a quantified data of groundwater extraction. Mapping will also contribute to water and waste management by generating data for several purposes at local and regional scale in a very sensitive resource based dependent society.

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CONTACT INFORMATION

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EDUCATION

2013-2017 **Ludwig-Maximilian University of Munich, Rachel Carson Center for Environment and Society, and Department für Geographie Lehrstuhl für Mensch-Umwelt-Beziehungen; Munich, Germany.**
PhD, Geography. Expected: May 2017 Thesis "**Understanding Socio-Groundwater Systems: Framework, toolbox, and stakeholder efforts for analysis and monitoring groundwater resources".** Supervisor Prof. Dr. Claudia Binder. Funded by the National Council of Science and Technology (Conacyt) Mexico.

2009-2011 **Center for Research and Advanced Studies of the National Polytechnic Institute (Cinvestav-IPN), Department of Human Ecology; Merida, Yucatan, Mexico.**
MSc, Human Ecology. Funded by the National Council of Science and Technology (Conacyt) Mexico.

RESEARCH EXPERIENCE

2013-onwards **Researcher, *Ludwig Maximilian University of Munich/Technical University of Munich, Department of Geography, Human-Environment-Relations***; Munich, Germany.
- *Wissenschaftlerin. Mensch-Umwelt-Beziehungen* Group. *Prof. Claudia Binder*

2016 **Research scholar, The Beijer Institute of Ecological Economics, The Royal Swedish Academy of Science:** Stockholm, Sweden (2016 - 2019).

2015 **Research scholar, International Institute for Applied Systems Analysis (IIASA):** Laxenburg, Austria. (3 months, Jun-Sept 2015).
- Advanced System Analysis Research Group. Prof. Brian Fath

2015 **Visiting PhD Researcher, *University of Manitoba, Natural Resources Institute***; Winnipeg, Manitoba, Canada. (3 months, Feb-Apr 2015).
- Community-based Resource Management Research Group. Prof. Fikret Berkes.

2011 **Visiting MSc Researcher, *Autonomous University of Barcelona, Department of Geography***; Barcelona, Spain. (5 months, Jan-May 2011).
- Tourism and Socioeconomic Dynamics in Rural Areas Research Group. Prof. Gemma Cànoves

2012 **Museography Adviser.** Yucatan, Mexico. (*ad honorem* for 8 months, Feb-Sep 2012)
- Researcher.

2011-2012 **Research Assistant, *Centre for Research and Advanced Studies of the National Polytechnic Institute (Cinvestav-IPN), Department of Human Ecology***; Merida, Yucatan, Mexico.
- Researcher, Laboratory of Research and Community Participation (LRCP) (6 months, Sep-Feb) Dr. Teresa Castillo-Burguete and Federico Dickinson-Bannack.

PUBLICATIONS

- López-Maldonado, Y. & Berkes, F. (2017). "Restoring the environment, revitalizing the culture: Cenote conservation in Yucatan, Mexico". Ecology and Society.
- Lopez-Maldonado, Y., Batllori-Sampedro, E., Binder, C., & Fath. B. (2017). "Local groundwater balance model: stakeholders' efforts to address groundwater monitoring and literacy". Hydrological Science Journal. DOI: 10.1080/02626667.2017.1372857
- Lopez-Maldonado, Y. (2017). "Understanding couple human-groundwater systems. The case of the past -and contemporary- Mayas of Yucatan Mexico." *Proceedings of the II Open Conference of the Programme on Ecosystem Change and Society, Oaxaca, Mexico.*
- Lopez-Maldonado, Y. (2017). "Everyone in our community, at some point, will lose". The inequalities of groundwater between society and ecosystems: The case of the Mayan area of Yucatan, Mexico". *Proceedings of the Resilience Conference*, Stockholm, Sweden.
- Lopez-Maldonado, Y. (2017). "Groundwater monitoring requires groundwater knowledge: The transdisciplinary socio-groundwater toolbox". *Proceedings of the Swedish Water Management Conference*, 16-17 May 2017, Gothenburg, Sweden.
- Lopez-Maldonado, Y. & Binder, C. (2016). "The Local Groundwater Balance Model". Proceedings of the 12th Kovacs Colloquium15 June 2016, UNESCO Headquarters, Paris International Hydrological Prize and Tison Award Ceremony (Hydrological Inputs For Water-Related SDGs Implementation: Knowledge, Data, Indicators, Tools & Innovations) Paris, France.
- López-Maldonado, Y. (2016). "Groundwater sustainability: Narrowing the gap between science, policy and society". Proceedings of the 2016 World Water Week". Stockholm, Sweden. 28 August – 2 September 2016.
- López-Maldonado, Y. (2015). "The early identification of human drivers affecting groundwater resources. Developing a Material Flow Analysis of the Geohydrological Reserve zone in Yucatan, Mexico". International Institute for Applied Systems Analysis Final Young Summer Program Report. Laxenburg, Austria.
- Lopez-Maldonado, Y. & Binder, C. (2015). "The early identification of the human drivers affecting groundwater system in Yucatan, Mexico using Material Flow Analysis". Proceedings of the "42nd International Association of Hydrologist AQUA2015". Organised by the UNESCO International Hydrological Programme (IHP) and the Rome-based United Nations' Food and Agriculture Organization (FAO). Held at La Sapienza University, Roma. September 12-19, 2015.
- López-Maldonado, Y. (2015). "Groundwater common pool resources in Yucatan, Mexico: Understanding commonisation processes - and anticipating decommonisation – in the cenotes of the Mayan Area" Proceedings of the International Association of the Study of the Commons 2015 Conference. University of Edmonton. Edmonton, Canada.
- López-Maldonado, Y. & Batllori-Sampedro, E. (2015). "Why mapping groundwater matters?" *Proceedings of the Mapping Water Bodies from Space 2015 Conference*. European Space Agency. Frascatti, Italy.
- López-Maldonado, Y. (2014). "Towards an Understanding of the Human-Environment System of Mayan Communities: Knowledge, Users, Beliefs and Perception of Groundwater in Yucatan". *The Digital Library of the Commons. Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis*. Indiana University. URL: http://dlc.dlib.indiana.edu/dlc/handle/10535/9408
- López-Maldonado, Y. & Castillo-Burguete, T. (2013). "Communitarian initiatives on cultural heritage: preservation, achievements and challenges". *British Archaeological Reports, International Series 2551*, 141-149.
- López-Maldonado, Y. (2012). "Coastal tourism in Yucatan and its effects on the environment" [in English and Spanish]. *E-News Bulletin. Gulf of Mexico Large Marine Ecosystem*. 3(7), 6-10. URL: http://iwlearn.net/iw-projects/1346/newsletters/gom-lme-e-news-bulletin-july-2012
- Ayuso, J.I. & López-Maldonado, Y. (2012). "Dance and cultural transformations on the Yucatecan jarana. An overview through two decades" [in Spanish]. *Proceedings of the National Institute of Anthropology and History of Mexico*. (in press).

- López-Maldonado, Y. & Castillo-Burguete, T. (2011). "Environment, diversification and tourism in the coastal community of Sisal, state of Yucatan, Mexico". *Proceedings of the 4th International Conference Advances in Tourism Economics*, (on CD). Lisbon, Portugal.
- López-Maldonado, Y., Pech-Jiménez, N., Benítez, E. & Castillo-Burguete, T. (2011). "Sustainability, tourism & love: Perceptions of mangrove on the coast of Yucatan state, Mexico". *Proceedings of the 4th International Conference Advances in Tourism Economics*, (on CD). Lisbon, Portugal.
- López-Maldonado, Y. & Castillo-Burguete, T. (2011). "Women in community management of historic heritage on the coast of Yucatan, Mexico. A human ecology perspective". *Book of Abstracts of the XVIII International Conference of the Society for Human Ecology: Human Responsibility & Environmental Change: Planning, Process, and Policy*, pp 44 (on CD). Las Vegas, Nevada, USA.
- López-Maldonado, Y. & Castillo-Burguete, T. (2010). "Cultural tourism in a coastal community of Yucatan. Case study" [in Spanish]. *Topofilia, Revista de Arquitectura, Urbanismo y Ciencias Sociales*. 2(1). URL: http://topofilia.net/lopez-castillo.pdf.

PARTICIPATION IN CONFERENCES

- Invited to participate in "**The Inner Dimensions of Climate Change. A Contemplative Retreat for Young Ecologists in Europe"**. During COP23 UNFCCC Climate Change Summit. Bonn, Germany. November 10-15, 2017.
- Oral presentation at the "**II Open Conference of the Programme on Ecosystem Change and Society"***,* Oaxaca, Mexico*. November 5-10, 2017.*
- Invited oral presentation at the **"Resilience Conference"**, Stockholm, Sweden. August 20-23, 2017. Organised by the Stockholm Resilience Center.
- Invited oral presentation at the "**Swedish Water Management Conference"**. Gothenburg, Sweden. May 16-17, 2017, Organized by the Swedish Agency for Marine and Water Management.
- Invited poster presentation "**12th Kovacs Colloquium"**. 15 June 2016, UNESCO Headquarters, Paris International Hydrological Prize and Tyson Award Ceremony (Hydrological Inputs For Water-Related SDGs Implementation: Knowledge, Data, Indicators, Tools & Innovations) Paris, France.
- Invited oral presentation at the **"2016 World Water Week"**. Stockholm, Sweden. Aug 28- Sept 2, 2016. Organised by the Stockholm International Water Institute.
- Paper presentation at the **"Transformations of the Earth. International Graduate Workshop in Environmental History"**. Beijing, China. May 18 – 23, 2016. Organised by the Rachel Carson Center for Environment and Society, Ludwig Maximilian University of Munich, Germany, and the School of History, Renmin University of China, Beijing, China.
- Invited oral presentation at the **"26th British Cave Research Association"**. Cave Science Symposium, Manchester, UK. Oct 31- Nov 1, 2015. Sponsored by Environmental Geology & Geotechnical Consultants.
- Poster presentation at the **"42th International Association of Hydrologist AQUA2015".** Organised by the UNESCO International Hydrological Programme (IHP) and the Rome-based United Nations' Food and Agriculture Organization (FAO). Held at the La Sapienza University, Roma. September 12-19, 2015.
- Invited oral presentation at the 15th Biannual Global Conference **"International Association for the Study of the Commons"**, to be held at Edmonton, Canada. May 25-29, 2015. Funded by the Indigenous Biocultural Exchange Fund, supported by the Christensen Fund.
- Poster presentation at the Workshop **"Mapping Water Bodies from Space 2015"**. European Space Agency (ESA-ESRIN). Frascati, Italy. Mar 18-19, 2015. URL: http://due.esrin.esa.int/mwbs2015/
- Oral presentation **"Why (ground) water matters?"** in the 4th Global Environments Summer Academy, at University of Bern. Bern, Switzerland. Aug 13, 2014.
- Oral presentation **"Towards an understanding of the Human-Environment System of Mayan communities: Knowledge, users, beliefs, and perception of groundwater in Yucatan"** in the 5th Workshop

on the Ostrom Workshop, at The Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis, Indiana University. Bloomington, Indiana, USA. Jun 18-21, 2014.

- Oral presentation **"Social-Ecological systems in Mayan communities: A scientific and traditional knowledge perspective of groundwater management"** in the 3rd International Science and Policy Conference on the Resilience of Social & Ecological Systems, at Resilience Alliance Network. Montpellier, France. May 4-8, 2014
- Poster presentation "**Interest of inhabitants of Sisal, Yucatan on the community development as a tourist centre through the use and management of its cultural and natural heritage**" in the 54º International Congress of Americanists *Building Dialogues in the Americas*. Symposium 477 *Ibero American Cultural Heritage: Conservation, Management and Sustainability*, held at University of Vienna, Vienna, Austria. Jul 15-20, 2012.
- Poster presentation "**Dance heritage in Yucatan. Yucatec jarana and its transformation from a dancer perspective**" in the 54º International Congress of Americanists *Building Dialogues in the Americas*. Symposium 477 *Ibero American Cultural Heritage: Conservation, Management and Sustainability*, held at University of Vienna, Vienna, Austria. Jul 15-20, 2012.
- Oral presentation **"Communitarian initiatives on cultural heritage preservation: Achievements and challenges"** in the 1st Municipal Congress of Museums and Heritage Spaces in Mexico held at Merida City Museum, Merida, Yucatan, Mexico. Jan 26-27, 2012.
- Oral presentation **"Women in community management of historic heritage on the coast of Yucatan, Mexico. A Human Ecology perspective"** in the XVIII International Conference of the Society for Human Ecology *Human Responsibility & Environmental Change: Planning, Process, and Policy*, in Las Vegas, Nevada, United States of America. Apr 20-23, 2011. (Travel grant funded by Yucatan Fund).
- Oral presentation **"Human Ecology research results communication to participating groups on the coast of Yucatan, Mexico"** in the XVIII International Conference of the Society for Human Ecology *Human Responsibility & Environmental Change: Planning, Process, and Policy*, in Las Vegas, Nevada, United States of America. Apr 20-23, 2011 (Funded by the National Council of Science and Technology Mexico).
- Oral presentation **"Environment, diversification and tourism in the coastal community of Sisal, State of Yucatan, Mexico"** in the 4th International Conference Advances in Tourism Economics, held at Universidade Lusiada de Lisboa, Lisbon, Portugal. Apr 14-15, 2011. (Travel grant funded by Conacyt-Mexico).
- Oral presentation **"Sustainability, tourism & love: Perceptions of mangrove on the coast of Yucatan State, Mexico"** in the 4th International Conference Advances in Tourism Economics, held at Universidade Lusiada de Lisboa, Lisbon, Portugal. Apr 14-15, 2011. (Travel grant funded by Conacyt-Mexico).
- Oral presentation "**Cultural tourism in a coastal community of Yucatan. A case study**" in the 3rd International Colloquium *Cities of Tourism: Places, Practices and Representations in the New Tendences*, held at Universidad de Sonora, Hermosillo, Sonora, Mexico. Oct 7-8, 2010 (Funded by the National Council of Science and Technology Mexico).

WORKSHOPS AND SHORT COURSES

- **"IUCN Best Practice Guidelines Workshop"**. Specialist Group: Cultural and Spiritual Values of Protected Areas of the IUCN, World Commission on Protected Areas. Jun 1 -10, 2016. Vilm, Germany.
- **"Transformations of the Earth. International Graduate Workshop in Environmental History"**. Beijing, China. May 18 – 23, 2016. Organised by the Rachel Carson Center for Environment and Society, Ludwig Maximilian University of Munich, Germany, and the School of History, Renmin University of China, Beijing, China.
- **"Mapping Water Bodies from Space 2015"**. International Workshop about mapping from space organized by the European Space Agency (ESA-ESRIN). Frascati, Italy. Mar 18-19, 2015. URL: http://due.esrin.esa.int/mwbs2015/

- "**Global Environments Summer Academy**". International workshop about Social-Ecological Interactions organized by Global Diversity Foundation and Universität Bern. (Grant: GESA). Bern, Switzerland. Jul 17-Aug 15, 2014.
- "**Transformation Processes and their Meaning for the Sustainability Transition**". International workshop organized by Regional Studies Association Research Network, University of Westminster, Universität St Gallen, Leibniz Institute of Ecological and Regional Development, Worcester Polytechnic Institute. (Travel grant: RSA). London, United Kingdom. Oct 9-10, 2013.
- "**Interactive Visualization Tools for Socio-Environmental Data**". International workshop organized by National Socio-Environmental Synthesis Center, University of Maryland. (Travel grant: University of Maryland). Annapolis, Maryland, USA. Aug 15-16, 2013.
- **"Silent Spring: Chemical, Biological and Technological Visions of the Post-1945 Environment"**, International workshop organized by the Birbeck College, University of London and the University of York. Held at London, United Kingdom. Jun 7, 2013. (Travel grant by Centre for Modern Studies at the University of York and Arts and Humanities Research Council Collaborative Skills Development Grant).
- "**2nd International workshop on governance for the Gulf of Mexico**". Organized by: United Nations Industrial Development Organization (UNIDO), Universidad Veracruzana, Gulf of Mexico Large Marine Ecosystem, National Oceanic and Atmospheric Administration, Comisión Nacional de Áreas Naturales Protegidas, Secretaría de Medio Ambiente y Recursos Naturales, Harte Research Institute at Texas A&M University. Attendance funded by United Nations Industrial Development Organization. Veracruz, Mexico. Aug 2011 (Funded by UNIDO).

AWARDS

2017 Award. The Inner Dimensions of Climate Change. A Contemplative Retreat for Young Ecologists in Europe. Bonn, Germany. During COP23 UNFCCC Climate Change Summit.

2017 Grant. Resilience conference 2017. Stockholm, Sweden.

2017 Beijer Young Scholar 2017. The Beijer Institute for Ecological Economics. The Royal Swedish Academy of Science (Kungul. Vetenskaps-Akademien). Stockholm, Sweden.

2016 Grant. World Water Week Stockholm (SIWI) 2016. Stockholm, Sweden.

2016 Grant. IUCN Best Practice Guidelines Workshop. Specialist Group: Cultural and Spiritual Values of Protected Areas of the IUCN, World Commission on Protected Areas. Vilm, Germany.

2016 Beijer Young Scholar 2016. The Beijer Institute for Ecological Economics. The Royal Swedish Academy of Science (Kungul. Vetenskaps-Akademien). Stockholm, Sweden.

2015 Young Scientist 2015. Young Scientist Summer Program. International Institute for Applied System Analysis, Laxenburg, Austria.

2015 Stipendien, Young Scientist Summer Program. Potsdam-Institut for Klimafolgenforschung e.V. (PIK Germany).

2015 IBEX Award Recipient. The Indigenous Biocultural Exchange Fund supported by the Christensen Fund.

2014 Fellow at the Global Environments Summer Academy on Socio-ecological Interactions in a Dynamic World (GESA). Centre for Development and Environment (CDE), University of Bern and the Global Diversity Foundation (GDF). 26 July - 15 August 2014.

2014 Fellowship, the 5th Workshop on the Ostrom Workshop (Indiana University - USA).

2014 Fellowship, National Socio-Environmental Synthesis Center (SESYNC - Maryland University - USA).

2014 Grant. Resilience Conference. Montpellier, France (CIRAC- France).

2013 Grant for Fieldwork. Rachel Carson Center for Environment and Society (Ludwig Maximilian University of Munich – Germany).

2013 Travel Grant, "Silent Spring: Chemical, Biological and Technological Visions of the Post-1945 Environment", International workshop (Birbeck College - United Kingdom.

2013 Grant. "Transformation Processes and their Meaning for the Sustainability Transition". International workshop (University of Westminster, Leibniz Institute of Ecological and Regional Development – United Kingdom).
2012 Research Scholarship. National Council of Science and Technology Mexico (Conacyt-Mexico).
2011 Grant. International Workshop on Governance for the Gulf of Mexico (UNIDO-USA).
2010 Scholarship. National Council of Science and Technology Mexico (Conacyt-Mexico).
2009 Research Scholarship National Council of Science and Technology Mexico (Conacyt-Mexico).
2004 Scholarship Ministry of Public Education Mexico (SEP-Mexico).

OTHER PROFESSIONAL ACTIVITIES

Delegate at the Permanent Forum on Indigenous Issues (UNPFII). United Nations Headquarters. New York.
Member of the Specialist Group of the IUCN World Commission on Protected Areas. Cultural and Spiritual Values of Protected Areas, IUCN. http://csvpa.org
Member of the Ramsar Culture Network. http://www.ramsar.org/activities/bio-cultural-diversity

ORGANIZATIONAL EXPERIENCE

The Resilience Conference. Sponsored by the Stockholm Resilience Center. Organization of panel session "Inequality and the Biosphere: Exploring the Interactions between the Biosphere and Human Well-Being through the Lens of Inequality". Stockholm Sweden. August 20-23, 2017.
World Conservation Congress 2016. Planet at the Crossroads. Sponsored by the International Union for Conservation of Nature. Actively collaboration with coordination of a group of participants, support of the assistant team. Hawaii, USA, 31 August – 7 September 2016.
Latin American Academy of Socio-Environmental Leadership (ALLSA) 2015. Transformative Environmental Learning: Our relationships with biocultural landscapes. Sponsored by the Global Diversity Foundation in collaboration with Instituto Nacional de Formación y Capacitación del Magisterio (INAFOCAM) of the Dominican Republic. Actively collaboration with the organization, coordination of participants, support of the assistant team, writing final reports, including scheduling, catering organization, and liaising with speakers, selection of students. Dominican Republic, 13 – 22 Nov 2015.
1st Gulf of Mexico Educator Alliance. Integrated Assessment and Management of the Gulf of Mexico Large Marine Ecosystem. Actively collaboration coordinating the assistant team, writing final reports and liaising with speakers. Sponsored by: United Nations Industrial Development Organization, Universidad Autónoma de Yucatán, Gulf of Mexico Large Marine Ecosystem, National Oceanic and Atmospheric Administration, Comisión Nacional de Áreas Naturales Protegidas, Secretaría de Medio Ambiente y Recursos Naturales, Harte Research Institute at Texas A&M University. Mérida, Yucatán. Ago 2012.

MENTORING – SUPERVISION WORK

- Supervisor of: Markus Dörflinger, Bachelorarbeit at Ludwig Maximilians Universität München, Fakultät Für Geowissenschaften, Human-Environment Research Group. Thesis Title: Stoffflussanalyse des Wasserverbrauchs in Haushalten in Yucatán, Mexiko (Material Flow Analysis of the Water Usage in Households in Yucatán, Mexico), Munich, Germany, 2014.
- Supervisor of: Lena Neidhardt and Alisa Utz. Human Geography And Sustainability – Monitoring, Modeling, Management. Simulation Modeling course. Title: Modeling Groundwater Pollution. The Case Of The Ring Of Cenotes In Yucatan, Mexico. Lecture: Simulation Modeling. Lecturer: Dr. Christian Neuwirth. Ludwig Maximilians Universität München, Fakultät Für Geowissenschaften, Human-Environment Research Group. Munich, Germany, 2016.

RESEARCH REPORTS IN SPANISH

Lopez, Y. 2015. Results from field experiments in the Geohydrological Reserve Zone of the Ring of Cenotes in Yucatan. Mexico. December 8 – 20, 2014.

Lopez, Y. 2015. Results from field experiments and workshop. Espacios de la Cultural del Agua "Liderazgo y Manejo de Grupos". Merida, Yucatan, Mexico. December 09, 2014.

Lopez, Y. 2015. Resultados del Taller de integración transdisciplinaria de datos para el estudio del Círculo de Cenotes de Yucatán (Results from field experiments and workshop of transdisciplinary data integration for the analysis of the Ring of Cenotes in Yucatan. Mexico. September 30, 2014.

EXPERIENCE OF COMMUNICATING RESULTS WITH STAKEHOLDERS/END USERS

Invited presentation for communitarian spaces of water culture in Yucatan. Co-organized by the National Council of Water in Mexico, Ministry of Health and Ministry of Environment in Yucatan Mexico (Lopez 2015).

Workshop with experts and members of the water sector for integration of knowledge towards system understanding and characterization of the Yucatan Peninsula Aquifer (Lopez 2015).

Dialogue with stakeholders and feedback of results in local communities in Yucatan during Master thesis project, Laboratory of Research and Community Participation (Lopez 2011).

OTHER PROFESSIONAL ACTIVITIES

Member of the Specialist Group on Cultural and Spiritual Values of Protected Areas of the IUCN World Commission on Protected Areas (WCPA). http://csvpa.org

Member of the Ramsar Convention's Culture Network. http://www.ramsar.org/activities/bio-cultural-diversity

MEMBERSHIPS

International Association for the Study of the Commons, 2015-onwards.

Regional Transition Association, 2014-onwards.

American Chemical Society, 2015-onwards.