UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN CIENCIAS DE LA SOSTENIBILIDAD
INSTITUTO DE ECOLOGÍA

BARRERAS Y PUENTES PARA EL MANEJO COMUNITARIO DEL AGUA EN EL SOCIOECOSISTEMA RÍO GRANDE DE COMITÁN-LAGOS DE MONTEBELLO, CHIAPAS.

T E S I S
QUE PARA OPTAR POR EL GRADO DE
DOCTORA EN CIENCIAS DE LA SOSTENIBILIDAD

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Presente

Me permito informar a usted, que el Comité Académico del Programa de Posgrado en Ciencias de la Sostenibilidad, en su sesión 90 del 18 de abril del presente año, aprobó el jurado para la presentación del examen para obtener el grado de **DOCTORA EN CIENCIAS DE LA SOSTENIBILIDAD**, de la alumna **Alvarado Velázquez Jannice** con número de cuenta **409021662,** con la tesis titulada "Barreras y puentes para el manejo comunitario del agua en el socioecosistema Río Grande de Comitán-Lagos de Montebello, Chiapas", bajo la dirección de la Dra. Mazari Hiriart Marisa y del Dr. Jesús Mario Siqueiros García.

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Sin más por el momento me permito enviarle un cordial saludo.

ATENTAMENTE,

"POR MI RAZA HABLARA EL ESPIRITU"
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Los de después si entendimos

Cuenta la historia que, en un pueblo, se afanaban hombres y mujeres en trabajar para vivirse. Todos los días salían hombres y mujeres a sus respectivos trabajos: ellos a la milpa y al frijolar; ellas a la leña y al acarreo del agua. En veces había trabajos que los congregaban por igual. Por ejemplo, hombres y mujeres se juntaban para el corte del café, cuando era llegado su tiempo. Así pasaba.

Pero había un hombre que no eso hacía. Sí trabajaba pues, pero no haciendo milpa ni frijolar, ni se acercaba a los cafetales cuando el grano enrojecía en las ramas. No, este hombre trabajaba sembrando árboles en la montaña. Los árboles que este hombre plantaba no eran de rápido crecimiento, todos tardarían décadas enteras en crecer y hacerse de todas sus ramas y hojas. Los demás hombres mucho lo reían y criticaban a este hombre.

- "Para qué trabajas en cosas que no vas a ver nunca terminadas. Mejor trabaja la milpa, que a los meses ya te da los frutos, y no en sembrar árboles que serán grandes cuando tú ya hayas muerto".

- "Sos tonto o loco, porque trabajas inútilmente".

El hombre se defendía y decía: - "Sí, es cierto, yo no voy a ver estos árboles ya grandes, llenos de ramas, hojas y pájaros, ni verán mis ojos a los niños jugando bajo su sombra. Pero si todos trabajamos sólo para el presente y para apenas la mañana siguiente ¿Quién sembrará los árboles que nuestros descendientes habrán de necesitar para tener cobijo, consuelo y alegría?"

Nadie lo entendía. Siguió el hombre loco o tonto sembrando árboles que no vería, y siguieron hombres y mujeres cuerdos sembrando y trabajando para su presente.

Pasó el tiempo y todos ellos murieron, les siguieron sus hijos en el trabajo, y a éstos les siguieron los hijos de sus hijos. Una mañana, un grupo de niños y niñas salió a pasear y encontraron un lugar lleno de grandes árboles, mil pájaros los poblaban y sus grandes copas daban alivio en el calor y protección en la lluvia. Sí, toda una ladera encontraron llena de árboles. Regresaron los niños y niñas a su pueblo y contaron de este lugar maravilloso. Se juntaron los hombres y mujeres y muy asombrados se quedaron del lugar.

- "¿Quién sembró esto?", se preguntaban.

Nadie sabía. Fueron a hablar con sus mayores y tampoco sabían. Sólo un viejo, el más viejo de la comunidad, les supo dar razón y les contó la historia del hombre loco y tonto. Los hombres y mujeres se reunieron en asamblea y discutieron. Vieron y entendieron al hombre que sus antepasados trataron y mucho admiraron a ese hombre y lo quisieron. Sabedores de que la memoria puede viajar muy lejos y llegar donde nadie piensa o imagina, fueron los hombres y mujeres de ese hoy al lugar de los árboles grandes.

Rodearon uno que en el centro se estaba y, con letras de colores, le hicieron un letrero. Hicieron fiesta después, y ya estaba avanzada la madrugada cuando los últimos bailadores se fueron a dormir. Quedó el bosque grande solo y en silencio. Llovió y dejó de llover. Salió la Luna y la Vía Láctea acomodó de nuevo su retorcido cuerpo. De pronto un rayo de luna acabó por colarse por entre las grandes ramas y hojas del árbol del centro y, con su luz bajita, pudo leer el letrero de colores ahí dejado.

Así decía: "A los primeros: Los de después sí entendimos. Salud".

Los otros cuentos. Relatos del Subcomandante Marcos, 1999.

Contenido

Resumen

Garantizar el derecho humano al agua, a través de un manejo adecuado del recurso, es un desafío crucial para transitar hacia la sostenibilidad. A partir del año 2010 la Organización de las Naciones Unidas (ONU) reconoce el acceso al agua limpia y al saneamiento como un derecho humano, sin embargo, a pesar de las estrategias implementadas, aún tres de cada diez personas en el mundo carecen de acceso a este recurso. Uno de los principales retos que enfrentan actualmente las poblaciones para el acceso al agua es su manejo, el cual debería ser considerado desde un enfoque de sistema socio-ecológico. Debido a que el manejo del agua representa un acoplamiento del sector social con los sistemas hidrológicos, por lo tanto, no puede ser estudiado de manera separada. En este trabajo, se aborda de manera teórica el manejo del agua bajo un enfoque sistémico y su posibilidad de dirigirse a trayectorias sostenibles. Como caso de estudio este trabajo se enfocó en analizar el acceso al agua en comunidades rurales ubicadas en la cuenca del Río Grande de Comitán y los Lagos de Montebello, una zona perteneciente a la Región Hidrológica Grijalva-Usumacinta, una de las más importantes del país. En ella se localiza el Parque Nacional Lagunas de Montebello, un sitio reconocido por su importancia ecológica y económica para la población. Sin embargo, dentro de esta cuenca diversas presiones antropogénicas se han acentuado en los últimos 30 años, como la expansión agrícola, la deforestación, el crecimiento poblacional y la falta de tratamiento de aguas residuales. Dichas actividades, han impulsado la degradación acelerada de los cuerpos de agua que además de ser un atractivo turístico, son una fuente de abastecimiento para 194 mil personas dentro de la cuenca. Para analizar este proceso, se presenta un análisis de vulnerabilidad hídrica a través de sistemas de información geográfica y análisis multicriterio. Durante este análisis se identificaron las principales fuentes de contaminación puntuales y difusas, así como las subcuencas con mayor vulnerabilidad, lo cual coincide con zonas agrícolas y altamente pobladas. La mayor parte de la población en la cuenca accede al recurso hídrico sin una desinfección adecuada, ni un sistema de distribución formal. Por lo tanto, el manejo del agua ocurre de forma comunitaria con la finalidad de resolver el desabasto de agua, sin embargo, no siempre se garantiza un acceso en cantidad y calidad adecuados. El manejo se realiza a través de redes informales entre los usuarios y los gestores comunitarios y algunas veces instituciones gubernamentales, que, por lo general no cumplen en forma satisfactoria las demandas de abastecimiento de la población. En este trabajo, se describe el manejo comunitario, sus principales retos para acceder a vías más sostenibles de acceso al agua, así como sus oportunidades en términos de acción colectiva. A través de métodos mixtos se identificaron las principales barreras y puentes que determinan el manejo del agua en tres comunidades de la cuenca. Las principales barreras que se identificaron fueron la falta de infraestructura hídrica y la baja capacidad para distribuir el agua, asimismo, la colecta y acarreo del agua tienen un impacto mayor en las mujeres y los niños. En contraste, se pudieron identificar puentes que permiten mejorar el acceso al agua, a nivel comunidad se identificó la organización colectiva como una forma de organización para el manejo no solo del agua sino de los recursos como el suelo y el bosque.

Abstract

Guaranteeing the human right to water, through proper management, is a crucial challenge to move towards sustainability. As of 2010, the United Nations Organization (UN) recognizes access to clean water and sanitation as a human right, however, despite the strategies implemented, still three out of ten people in the world lack access to this resource. One of the main challenges that populations currently face for access to water is its management, which should be seen from a socio-ecological system approach. Water management represents a coupling of the social sector with hydrological systems; therefore, it cannot be studied separately. In this work, water management is theoretically addressed under a systemic approach and its possibility of leading to sustainable trajectories. As a case study, this work focused on analyzing access to water in rural communities located in the basin of the Río Grande de Comitán and the Montebello Lakes, an area that belongs to the Grijalva-Usumacinta Hydrological Region, one of the most important in the country. The Lagunas de Montebello National Park within this area, is a site recognized for its ecological and economic importance for the local population. However, within this basin, various anthropogenic pressures have increased in the last 30 years, such as agricultural expansion, deforestation, population growth, and the lack of wastewater treatment. These activities have promoted the accelerated degradation of the bodies of water that, in addition to being a tourist attraction, are a source of water supply for 194,000 people within the basin. To analyze this process, I present an analysis of water vulnerability through geographic information systems and multicriteria analysis. During this analysis, the main point and diffuse contaminant sources were identified, as well as the sub-basins with the greatest vulnerability, which coincides with agricultural and highly populated areas. Most of the population in the basin access water resources without adequate disinfection or a formal distribution system. Therefore, water management occurs on a community basis to solve the shortage of water, however, access in adequate quantity and quality is not always guaranteed. Management is carried out through informal networks between users and community managers, and sometimes government institutions, which generally do not satisfactorily meet the supply demands of the population. In this work, community management is described, its main challenges to access more sustainable ways of accessing water, as well as its opportunities in terms of collective action. Through mixed methods, the main barriers and bridges that determine access to water in three communities of the basin were identified. The main barriers that

were identified were the lack of water infrastructure and the low capacity to distribute water. Likewise, the collection and water fetching have a greater impact on women and children. In contrast, bridges could be identified that allow improving access to water; at the community level, collective organization was identified as a form of organization for the management not only of water but of resources such as soil and the forest.

Introducción

El acceso al agua en cantidad y calidad suficiente es fundamental para promover trayectorias hacia estados más sostenibles y fomentar el bienestar de los seres humanos y el soporte de los ecosistemas. En julio de 2010, la Asamblea General de las Naciones Unidas reconoció explícitamente el derecho humano al agua, con ello, se establece que el acceso al agua limpia y el saneamiento son indispensables para el desarrollo de una vida digna (ONU, 2010). De acuerdo con la Organización Mundial de la Salud (OMS), el acceso al agua debe ser de manera suficiente y continua para el uso personal y doméstico, esto incluye el agua para beber, el saneamiento personal, la preparación de alimentos y la limpieza del hogar. Por lo tanto, esta organización ha establecido que entre 50 y 100 litros de agua por persona al día son necesarios para satisfacer las necesidades básicas de desarrollo social y económico de un individuo (OMS, 2003). Actualmente, tres de cada diez personas en el mundo, no disponen de esta cantidad en sus hogares, lo cual podría ir en aumento debido a diversos factores, entre ellos un manejo inadecuado del recurso hídrico (UN-Water, 2015).

Acceder a fuentes seguras de abastecimiento de agua resulta cada vez más difícil. Las fuentes de agua, tanto superficiales como subterráneas, son vulnerables a la contaminación debido a la rápida expansión de las zonas agrícolas y urbanas (Giri y Singh, 2015). En este sentido, se pueden identificar dos tipos de fuentes de contaminación del agua, las fuentes difusas y las fuentes puntuales. Los contaminantes ingresan al ambiente de manera difusa, a través de la escorrentía o la infiltración; o de manera puntal, a través de tuberías o ductos que descargan directamente a los cuerpos de agua, lo cual puede ser más fácil de identificar o diferencia de las fuentes difusas (Brusseau, 2019). Ambos tipos de fuentes de contaminación representan las principales causas de la degradación de los sistemas acuáticos y, por lo tanto, la pérdida de fuentes de abastecimiento para el consumo humano. Por ello, la identificación y evaluación de las fuentes potenciales de contaminación resulta de importancia para las poblaciones (Alvarado et al., 2022a).

En poblaciones rurales de México y otros países con economías emergentes, el acceso al agua suele realizarse a través del manejo comunitario desde las fuentes de agua, donde se carece de sistemas de distribución y desinfección (COMDA, 2017), estas comunidades han desarrollado estrategias sociales y ambientales que les permite acceder al agua para cubrir sus necesidades (Barranco, 2020; Zamudio, 2020). Por lo regular, las comunidades acceden al recurso de forma manual o a través de sistemas de distribución que ellos mismos operan. De tal manera, que obtener agua segura en hogares rurales depende de diversos factores como las condiciones biofísicas del cuerpo de agua, la ubicación geográfica de la vivienda y la manera en cómo se toman decisiones en torno al manejo del agua (Elliott et al., 2019).

El proceso de toma de decisiones para el manejo de los recursos puede provenir tanto de instituciones formales como informales. Sin embargo, en ambientes rurales, las instituciones formales suelen estar menos involucradas en la provisión de servicios básicos como el agua y el saneamiento (COMDA, 2017; CONEVAL, 2020), dejando la responsabilidad del manejo del agua y otros servicios a las comunidades, o bien, las autoridades gubernamentales interfieren en las instancias y acuerdos comunitarios para disponer del agua a través de concesiones dejando a la población fuera de estas decisiones.

Un ejemplo de ello es la cuenca del Río Grande de Comitán-Lagos de Montebello (RGC-LM). Ubicada en el estado de Chiapas, dentro de la Región Hidrológica del Grijalva-Usumacinta, una de las mayores reservas de agua del país (Sánchez et al., 2015). En la cuenca se registran alrededor de 300 localidades, de las cuales el 50% presenta un grado alto de marginación (INEGI, 2020) y un acceso a los servicios de agua y salud deficientes. Aunado a ello, este sistema, presenta una vulnerabilidad hídrica que va de alta a muy alta en el 65% de su territorio (Alvarado et al., 2022a), lo cual, ha impactado de manera negativa a la población que depende de las fuentes de agua de forma directa. El acceso al agua en estas comunidades se realiza bajo manejo comunitario, siendo la asamblea ejidal el espacio de toma de decisiones en torno al manejo del agua y el suelo (DOF, 1992). Ante la falta de gestión municipal y de infraestructura adecuada, estas comunidades carecen de agua de forma continua, por lo cual, el almacenamiento prolongado y el acarreo del agua representan desafíos para acceder al agua de forma segura (Alvarado et al., 2022b).

Para hacer frente a estos desafíos, algunas comunidades visitadas han logrado organizarse para obtener agua. Sin embargo, aún existen algunos retos que resolver. Para hacer frente a diversas presiones ambientales es necesario que las personas se ajusten o adapten, no solo a presiones existentes, sino también a los nuevos retos de conocimiento y a los desafíos que se presentan para manejar los recursos (Eriksen et al., 2015). Los conceptos de adaptación y transformación como vías para alcanzar la sostenibilidad ofrecen un enfoque para abordar las interacciones socio-ecológicas y buscar nuevas trayectorias para el manejo de recursos (Beland-Lindahl et al., 2016). Las diferentes trayectorias que el manejo del agua pueda tomar, estarán definidas por cambios que se generen a partir de la toma de decisiones entre los usuarios y los gestores del agua. Se ha sugerido que la toma de decisiones debe plantearse de manera equitativa y solidaria, bajo el reconocimiento de la mayoría de los miembros comunitarios, con el fin de garantizar su cumplimiento a largo plazo, es decir, considerando en el proceso la participación de las mujeres y los grupos minoritarios.

Alrededor del proceso de toma de decisiones existen factores a nivel individual o comunitario que pueden moldear una trayectoria hacia estados sostenibles o insostenibles del manejo del agua. En este sentido el objetivo de este trabajo fue identificar estos factores y clasificarlos como barreras o puentes, los cuales pueden mejorar o inhibir el acceso al agua dentro del manejo comunitario, con el argumento de que las prácticas a escala local son críticas si se busca generar cambios a largo plazo en el manejo de los recursos (Hopkins, 2008).

Preguntas de investigación y objetivos

Partiendo de los desafíos que representa el acceso humano al agua en regiones rurales, se plantea la siguiente pregunta de investigación: *¿Qué componentes del manejo comunitario del agua, representan barreras o puentes para promover cambios hacia trayectorias sostenibles?* Para responder esta pregunta se plantea analizar tres casos de estudio en la cuenca Río Grande de Comitán-Lagos de Montebello (RGC-LM), en el estado de Chiapas, partiendo de las siguientes preguntas específicas:

1. ¿Cuáles son las condiciones hidrológicas actuales en la cuenca RGC-LM?
2. ¿Cuál es el contexto socio-ecológico en el que se desenvuelve el manejo comunitario del agua en la cuenca RGC-LM?
3. ¿Cuáles serían las principales barreras y puentes para el acceso al agua en comunidades rurales?

Para responder las preguntas de investigación se planta el siguiente objetivo general y objetivos particulares de investigación.

Objetivo de investigación:

Identificar componentes del manejo comunitario del agua, a nivel individual y colectivo, que propicien barreras o puentes hacia trayectorias sostenibles de acceso al agua.

Objetivos particulares:

1. Analizar las condiciones hidrológicas actuales de la cuenca RGC-LM y su vulnerabilidad ante fuentes de contaminación. Ver **Capítulo III**.

2. Conocer las prácticas actuales en torno al uso y manejo del agua, así como su relación con las fuentes de abastecimiento en tres comunidades de la cuenca RGC-LM. Ver **Capítulo IV**.
3. Identificar barreras y puentes para el acceso al agua a nivel individual y colectivo, dentro del manejo comunitario en tres comunidades de la cuenca RGC-LM. Ver **Capítulo IV**.

Como resultado del trabajo de investigación de esta tesis se generaron dos publicaciones científicas, las cuales se encuentran en los Capítulos III y IV del presente trabajo:

Alvarado, J., García-Meneses, P. M., Esse, C., Saavedra, P., Morales, R., Bonifáz, R., & Mazari-Hiriart, M. (2022). Spatially explicit vulnerability analysis of contaminant sources in a karstic watershed in southeastern Mexico. *Applied Geography*, 138(October 2021), 102606. https://doi.org/10.1016/j.apgeog.2021.102606

Alvarado, J., Siqueiros-García, J. M., Ramos-Fernández, G., García-Meneses, P. M., & Mazari-Hiriart, M. (2022). Barriers and bridges on water management in rural Mexico: from water-quality monitoring to water management at the community level. *Environmental Monitoring and Assessment*, 194(12). https://doi.org/10.1007/s10661-022-10616-5

Capítulo I. Marcos teóricos

I.I El manejo del agua como sistema socio-ecológico

Los procesos de manejo de recursos, como el manejo del agua en particular, están determinados por fenómenos no lineales acompañados de incertidumbre, por lo que se caracterizan como problemas complejos (Berkes et al., 2003). Junto con la teoría de la complejidad (Costanza et al., 1993; Holland, 1995; Levin, 1999) surge también la teoría de sistemas, en la que un sistema complejo puede estar compuesto de subsistemas que interactúan a través de relaciones de retroalimentación (Berkes et al., 2003). Muchos de los problemas del uso y manejo de los recursos están vinculados con la falta de reconocimiento de la estrecha relación y acoplamiento entre los ecosistemas y los sistemas sociales (Folke et al., 2010). En este sentido, el manejo del agua debe ser abordado de manera sistémica e integral, donde se considere la interacción entre las sociedades humanas y el componente biofísico, es decir, a través de los sistemas socio-ecológicos, que a su vez son sistemas complejos (Folke, 2006; Ostrom, 2009).

Recientemente, el manejo del agua ha sido abordado desde el enfoque de sistemas socio-ecológicos, considerando el desarrollo de las actividades humanas en torno a los sistemas hidrológicos con el objetivo principal de generar mejores aproximaciones a los problemas de acceso al agua (Sivapalan et al., 2014; Srinivasan et al., 2017; James y Shafiee-Jood, 2017). Debido a que el acceso y distribución del agua involucra retroalimentaciones en múltiples escalas con diferentes actores y fuentes de agua, no puede ser estudiado de manera separada (CEMDA, 2006; Sivapalan et al., 2014). Por lo tanto, de acuerdo con el Centro Mexicano de Derecho Ambiental (2006), un manejo adecuado del agua involucraría la interacción de instituciones gubernamentales, sector privado y sociedad civil, que permita estructurar reglas o normas para un acceso sostenible al agua, el cual sería ecológicamente apropiado, socialmente justo y económicamente viable.

El proceso de manejo de recursos, desde el enfoque de sistemas socio-ecológicos, puede ser mejorado haciéndolo más adaptable, a través de la capacidad de tratar con la incertidumbre y el cambio (Berkes et al., 2003). Varios estudios reconocen que la creación de relaciones colectivas entre diversos actores es crucial para desarrollar capacidades de respuesta ante disturbios ambientales (Bodin et al., 2006; Borgatti et al., 2009; Janssen et al., 2006). La interacción de actores de diversos sectores podrían potencialmente promover procesos de coordinación, flujos de información y actividades para generar conocimiento y prácticas de gestión de los recursos (Olsson et al., 2004), lo cual puede reforzar la capacidad de adaptación (Tompkins y Adger, 2004).

La capacidad de cambiar a estados más sostenibles de los sistemas socio-ecológicos, conlleva diversos desafíos dentro del proceso de toma de decisiones. Por ejemplo, el manejo del agua implica numerosos retos, desde la dimensión política en que se define y conceptualiza el acceso al agua, la forma en que se establecen los límites para su gestión, la forma en que se definen y relacionan otros temas en torno a los recursos hídricos, y la forma en que se diseñan y aplican normas o acuerdos para su uso. Todos estos procesos conllevan posibles conflictos entre los diversos actores. Por lo tanto, promover cambios hacia vías sostenibles de acceso al agua, implicaría cambios en la toma de decisiones y en las reglas colectivas, las cuales tendrían que ser promovidas desde la integración de diferentes actores cuyas decisiones se ejerzan a diferentes escalas (Barnes et al., 2017).

I.II El manejo comunitario del agua

A nivel global, existe una creciente preocupación por satisfacer las demandas de agua, principalmente para la agricultura, la industria y para el uso doméstico (Aguilar-Benítez et al., 2020). En México, como en muchos países con economías emergentes, el medio rural ha sido el más afectado para la gestión, distribución y el saneamiento del agua (Barranco, 2020). Por ello, diversas comunidades rurales han desarrollado estrategias sociales y ambientales que les permite acceder al agua para cubrir sus necesidades, aunque no siempre de forma segura (Barranco, 2020; Zamudio, 2020).

El manejo comunitario del agua es la forma en que las poblaciones en ambientes rurales y periurbanos asumen la labor de gestionar los sistemas de agua potable y saneamiento mediante la organización vecinal o comunal (Escobar, 2020), principalmente cuando carecen de servicios de agua potable administrados o regulados por los municipios o gobiernos estatales (Zamudio, 2020). Las comunidades se organizan en torno a de las fuentes de agua, asumen roles de trabajo y colaboración para la construcción y mantenimiento de los sistemas de abastecimiento y destinan parte de sus recursos económicos para su administración (Escobar, 2020; Zamudio, 2020). La gestión comunitaria del agua se sustenta por la participación de los usuarios mediante mecanismos de organización social como asambleas, comunitarias, creación de comités de vigilancia y las faenas (Barranco, 2020). Sin embargo, en México, los sistemas de manejo del agua comunitarios, por lo general, no reciben un reconocimiento jurídico que respalde su gestión.

Históricamente la distribución desigual del agua ha generado consecuencias sobre la salud y el desarrollo de las personas (CEMDA, 2006), por lo que el reconocimiento y la protección del derecho humano al agua resulta indispensable para alcanzar los Objetivos del Desarrollo Sostenible (UN-Water, 2015). Actualmente, se considera que una adecuada gestión del agua no solo es el resultado de reconocer legalmente el derecho humano al agua, sino de la interacción y cooperación entre instituciones gubernamentales, el sector privado y la sociedad civil (CEMDA, 2006). Sin embrago, las instituciones gubernamentales no ofrecen un reconocimiento formal a la gestión comunitaria, e incluso existe una disparidad en acciones en torno al acceso al agua entre las instituciones gubernamentales y las comunidades locales (Zamudio, 2020). Por ello, es importante reconocer el trabajo que las comunidades rurales e indígenas realizan para gestionar sus recursos, con el fin de involucrar sus estrategias de gestión en la planeación gubernamental del manejo de recursos (Bocco, 2019; Zamudio, 2020).

Si bien, diversas comunidades resuelven el reto de gestionar de manera colectiva sus recursos, no podemos dejar de reconocer los procesos de diferenciación y desigualdad social que se muestran en ejidos y comunidades rurales (Márquez y Legorreta, 2017). En particular, hay que reconocer que la mayor desventaja ante los problemas de agua y saneamiento en el mundo recae en mujeres, niñas y niños (Geere y Cortobius, 2017). Tradicionalmente, las mujeres son las responsables del cuidado e higiene del hogar, cultivar alimentos y prepararlos, así como de atender pequeños negocios. Estas actividades demandan tiempo y energía, incluso salud, para ir a buscar agua. Por ello, la escasez de agua afecta más a las mujeres que a los hombres (CEMDA, 2006; Geere et al., 2010; Geere y Cortobius, 2017). Sin embargo, a pesar de tener un papel crucial en el manejo domiciliario del agua, las mujeres tienen poca participación e incluso son excluidas dentro de los procesos de toma de decisiones del manejo de recursos.

Debido a que el manejo comunitario representa un proceso clave para el acceso al agua y el saneamiento en diversas comunidades rurales, este tipo de gestión no puede ser ignorada (Zamudio, 2020). Se ha sugerido que el manejo comunitario del agua depende en gran medida de la organización social, que se sustenta con los valores colectivos y los vínculos sociales, que promueven la participación de los usuarios, a través de asambleas, comités de agua y faenas (Barranco-Salazar, 2020). Por lo tanto, la participación plural y equitativa en el manejo de recursos es clave para alcanzar trayectorias más sostenibles de manejo del agua.

I.III Trayectorias: interacciones dinámicas de los sistemas socio-ecológicos

El concepto de trayectorias ofrece un enfoque para abordar los desafíos de sostenibilidad a través de la comprensión de las interacciones dinámicas de los sistemas socio-ecológicos, y que reconoce las opciones y los requisitos para buscar nuevas vías hacia la sostenibilidad (Beland Lindahl et al., 2016). Una trayectoria es definida como “la dirección particular en la que los sistemas sociales, tecnológicos y ambientales que interactúan co-evolucionan en el tiempo” (Leach et al., 2010, p. 13). Específicamente, las trayectorias sostenibles son “alternativas posibles de conocimiento, intervenciones y cambios que priorizan diferentes objetivos, valores y funciones. Estas vías, a su vez, prevén diferentes estrategias para tratar con la dinámica, para controlar o responder a choques o tensiones, y contemplan diferentes formas de enfrentar el conocimiento, destacando y respondiendo a los diferentes aspectos del riesgo, la incertidumbre, la ambigüedad y la ignorancia de maneras radicalmente diferentes” (Leach et al., 2010, p. 17).

En este trabajo se aborda el término de trayectoria, como un camino posible que un sistema socio-ecológico puede tomar a partir de la toma de decisiones de diferentes actores. Las diferentes trayectorias que el manejo del agua pueda tomar estarán guiadas por cambios, profundos o no, que se generan a partir de la toma de decisiones entre los usuarios y gestores del agua. Para abordar la dinámica de los sistemas socio-ecológicos y el conocimiento encaminado a explorar nuevas trayectorias, es necesario recurrir a métodos y prácticas que involucran flexibilidad, diversidad, adaptación y aprendizaje, y una política de sostenibilidad que apoye caminos alternativo (Leach et al., 2010).

I.IV Procesos de cambio en los sistemas socio-ecológicos

Para hacer frente a diversas presiones ambientales es necesario que las personas se ajusten o adapten, no solo a nuevos peligros, sino también a los nuevos retos de conocimiento y a los desafíos que se presentan para manejar los recursos (Eriksen et al., 2015). Eriksen y colaboradores (2015) argumentan que "la adaptación es un proceso sociopolítico que modula la forma en que individuos y sociedades se articulan con múltiples cambios sociales". Por lo tanto, promover cambios en el manejo del agua, requiere de cambios en la toma de decisiones dentro de una comunidad.

Por otro lado, dentro del campo de conocimiento de resiliencia surgen dos conceptos: (1) adaptabilidad y (2) transformabilidad, de los cuales se describe la capacidad de los sistemas socio-ecológicos para tolerar choques o impactos mediante (1) la aceptación del cambio o adaptación, y, por lo tanto, permitir el desarrollo a lo largo de la trayectoria actual; o (2) la capacidad de reorganizarse fundamentalmente o transformarse como respuesta a un estado insostenible, es decir, dirigirse a nuevas trayectoria de desarrollo (Folke et al., 2010; Walker et al., 2004). Otra postura sugiere que la adaptación no es simplemente implementar ajustes para mantener un sistema actual ante cambios biofísicos, sino que es parte de la dinámica de las sociedades dentro del procesos de toma de decisiones que se extiende entre los hogares a escala global (Eriksen et al., 2015).

Tomando en cuenta estos principios y conceptos, en esta investigación se considera que un cambio puede generarse a partir de la capacidad que tiene una sociedad de aprender, combinar experiencias y conocimientos, así como llevar a cabo nuevas acciones, con el fin de enfrentar el que ciertas perturbaciones alcancen escalas más grandes, físicas o institucionales (Barnes et al., 2017; Berkes et al., 2003). Un cambio profundo o transformativo sería impulsado por la capacidad de la comunidad para transformar o reorganizar un sistema totalmente nuevo hacia estados más sostenibles (Barnes et al., 2017; Eriksen et al., 2015; Walker et al., 2004). Un ejemplo de ello sería la filosofía del *Buen vivir*, la cual se incorporó en la constitución en Ecuador en 2008. Después de enfrentar un periodo extractivista y neoliberal, diversos movimientos de mujeres, campesinos, indígenas, y colectivos académicos lograron incluir en el marco político como alternativa de desarrollo el Buen vivir, el cual considera lo comunitario como espacio para promover los principios de reciprocidad, propiedad colectiva, relación y convivencia con la naturaleza, responsabilidad social y consenso (Arteaga-Cruz, 2017).

En este sentido, la toma de decisiones dentro del manejo de recursos, impulsadas por diversos actores, puede generar un gradiente de cambios más profundos o menos profundos, que promuevan diferentes trayectorias más sostenibles o menos sostenibles (Figura 1). Por lo tanto, entre más profundo sea un cambio dentro del proceso de toma de decisiones, es decir, cambios que modifiquen de raíz el problema o el paradigma de manejo, se promoverán trayectorias más sostenibles que puedan perdurar a largo plazo.

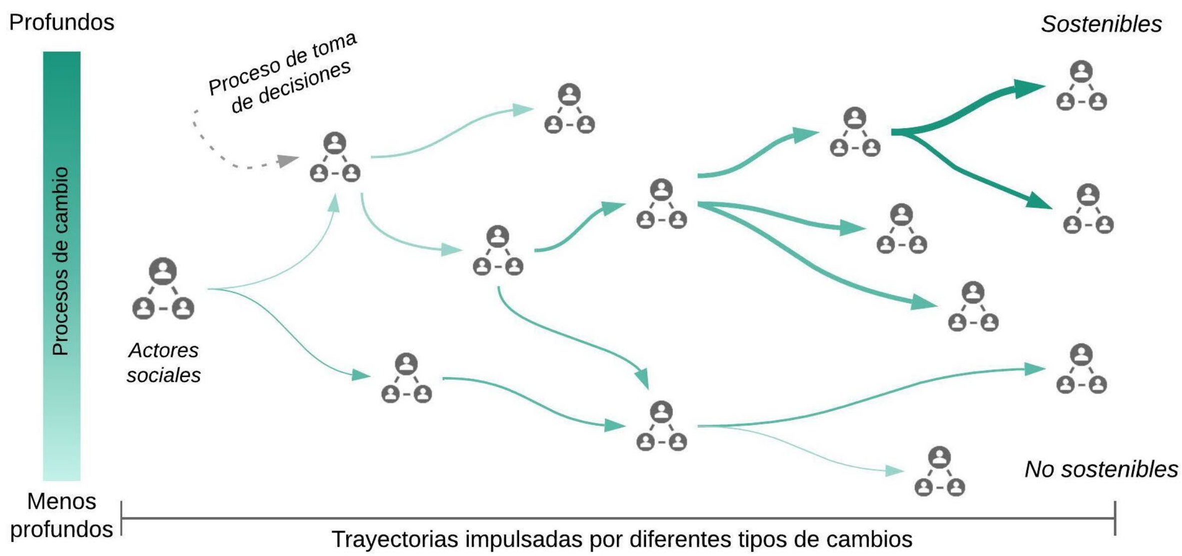

Figura 1. Gradiente de cambios adaptativos impulsados por la toma de decisiones de una red social que promueven diferentes trayectorias. La toma de decisiones está influenciada por la configuración de la red de actores. El color de las flechas indica la profundidad de un cambio adaptativo, el grosor de la flecha indica que tan sostenible es una trayectoria. Elaboración propia basado en Wise et al. (2014).

Para generar cambios más profundos y dirigirse a una trayectoria nueva, frecuentemente se requiere que los elementos del sistema socio-ecológico se reorganicen en formas novedosas, y algunas veces implica un cambio institucional (Moore et al., 2014). Asimismo, implicaría inducir cambios en el comportamiento humano promovidos bajo la aplicación de reglas o normas en los diferentes niveles de organización de una sociedad (Adger et al., 2005). Por otra parte, los cambios menos profundos implicarían que las personas ajusten su comportamiento en respuesta a una perturbación (Adger et al., 2005). Por ejemplo, la construcción o la adquisición de sistemas de almacenamiento de agua ante la escasez permite enfrentar el problema y resolver temporalmente las necesidades básicas familiares; sin embargo, esto no implica un cambio profundo o transformativo, ya que no resuelve de raíz el problema. Por lo tanto, un cambio ya sea profundo o no, requiere cambios en la toma de decisiones y en el comportamiento humano a diferentes escalas (Barnes et al., 2017). No obstante, los cambios en el manejo de recursos también están modulados por la capacidad adquisitiva que se tenga dentro de las diferentes escalas, a nivel familiar o comunidad, lo cual puede representar un puente o una barrera para el manejo sostenible del agua. En el caso de las zonas rurales y marginadas, los procesos de desigualdad representan barreras importantes para dirigirse a nuevas trayectorias de desarrollo.

Promover cambios dentro del manejo comunitario del agua requiere la interacción de los individuos, las comunidades, los gobiernos y otras organizaciones civiles, para conocer cuáles son sus opciones de respuesta, sus intereses y voces (Eriksen et al., 2015). Esto significa conocer las actividades cotidianas y las ambiciones de los individuos y grupos de la sociedad en múltiples escalas (O'Brien, 2012). En términos de manejo del agua, es importante conocer los procesos a través de los cuales los usuarios y gestores colaboran en el uso y distribución del agua dentro de las actividades cotidianas.

Es importante tomar en cuenta que cualquier proceso de toma de decisiones, ya sea fomentado por un individuo o gestor de los recursos, podría priorizar algunos intereses sobre otros, o privilegiar sectores, o escuchar algunas voces e ignorar otras (Eriksen et al., 2015). Por ello, la creación de relaciones sociales, entre una red diversa de actores, podría facilitar el intercambio de conocimientos e intereses y promover el cumplimiento de normas comunitarias (Bodin et al., 2006; Borgatti et al., 2009; Crona y Bodin, 2006; Janssen et al., 2006). Para ello, el papel de las mujeres como gestoras del agua debe ser reconocido e incorporado en el proceso de toma de decisiones (Geere y Cortobius, 2017) con la finalidad de fomentar la equidad y justicia en el manejo del agua (Panda, 2006).

I.V Barreras y puentes para el manejo sostenible del agua

Se ha argumentado que existen características intrínsecas de los sistemas socio-ecológicos que pueden funcionar como barreras o puentes para transitar de una trayectoria a otra. Por ejemplo, las condiciones biofísicas y climáticas, o los factores sociales como: la agencia humana (Charli-Joseph et al., 2018), el aprendizaje social, las estructuras de gobierno, las relaciones políticas y de poder, los grupos de actores, y las redes de instituciones formales e informales (Folke et al., 2005; Bodin et al., 2006; Crona y Bodin, 2006).

Algunos autores han reconocido que la creación de la colaboración colectiva entre individuos y organizaciones son cruciales para desarrollar estas características (Tompkins y Adger, 2004; Janssen et al., 2006). Sin embargo, los grupos sociales en desventaja se encuentran más expuestos a riesgos, por lo que sus capacidades de respuesta son limitadas, y los impactos de una perturbación pueden ser más duraderos (Bocco, 2019). En particular en zonas desfavorecidas, tales como el sur y sureste de México, las desigualdades y los riesgos que se manifiestan en el territorio tienen efectos diferenciados y por lo tanto pueden representar barreras para dirigirse a nuevas trayectorias (Saldaña-Zorrilla, 2008; Constantino y Dávila, 2011). Por lo tanto, es necesario proponer nuevas prácticas de gestión y manejo de los recursos y se debe partir del reconocimiento y entendimiento de la lógica de las prácticas tradicionales a diferentes escalas de las comunidades indígenas y campesinas (Márquez y Legorreta, 2017).

Conocer el proceso de toma de decisiones puede ser clave para identificar componentes que generen cambios en las reglas de uso y manejo del agua, las cuales promuevan el intercambio de recursos y conocimientos, fomentando el aprendizaje social, la construcción de confianza y la colaboración entre actores de diferentes niveles (Crona y Bodin, 2006). Por ello, en este trabajo se resaltan diversos componentes dentro del manejo comunitario del agua que podrían promover trayectorias más sostenibles del manejo del agua a partir de cómo se relacionan los actores, quiénes participan y como se relacionan con el componente biofísico:

I. Colaboración e intercambio de información. Con ello tanto los gestores como los usuarios del agua contarían con insumos para la toma de decisiones con base en experiencias previas y evitar afectaciones mayores ante alguna perturbación.

II. Establecimiento de reglas y prácticas comunes. El cumplimiento de normas y cuotas monetarias para el cuidado y manejo de las fuentes de agua, así como de los sistemas de abastecimiento es crucial para garantizar el acceso al agua a largo plazo.

III. Aprendizaje y generación de conocimientos. A través del intercambio de información podría llevarse a cabo un aprendizaje social en el cual las personas aprendan unas de otras para el beneficio colectivo.

IV. Resolución de conflictos. Se plantea que la capacidad de resolver conflictos en una red social es fundamental para garantizar la distribución equitativa del agua, además de promover la capacidad de respuesta ante eventos indeseados.

V. Prácticas en el uso de las fuentes de agua. La implementación de prácticas para preservar la integridad del ecosistema podría garantizar el suministro de agua a largo plazo. Esto incluye la preservación de bosques, el mantenimiento de la zona de ribera, la implementación de prácticas agroecológicas y riego de bajo consumo.

VI. Prácticas de uso del agua en la vivienda. La implementación de medidas que preserven la calidad del agua dentro de la vivienda garantizará un consumo saludable y podría prevenir enfermedades en el corto y mediano plazo. Esto incluye la adopción de métodos de desinfección y prácticas de higiene y saneamiento de las aguas residuales.

VII. Implementación y mantenimiento de infraestructura. La incorporación de infraestructura adecuada podría incrementar la disponibilidad de agua en forma más equitativa; con ello se contempla la instalación de bombas y ductos, la captación de agua de lluvia y otras formas de infraestructura contempladas colectivamente.

VIII. Monitoreo de la cantidad y la calidad del agua disponible. El conocimiento del estado actual de las fuentes de agua podría permitir la toma de decisiones asertiva para la distribución y el uso del agua dentro de una comunidad.

La efectividad de una comunidad para promover cambios y encaminarse a una trayectoria sostenible dependerá de las normas de uso y de los diversos conocimientos e intereses que guían la toma de decisiones dentro del manejo comuntario (Barnes et al., 2017; Elder-Vass, 2010). Se ha reconocido también que las condiciones para facilitar cambios en el manejo de recursos dependerá de la efectividad de los instrumentos de gobernanza, el grado de agencia humana y las actitudes e intenciones de los actores (Barnes et al., 2017). Las relaciones sociales pueden expresar procesos de desigualdad, diferenciación social y explotación, tanto como procesos de fortalecimiento, de reciprocidad y solidaridad entre sus miembros. Por lo tanto, las dinámicas socioeconómicas locales, la experiencia colectiva en la solución de conflictos, entre otros factores socioambientales, representan tanto barreras como puentes que influirán en la capacidad de dirigirse a nuevas trayectorias de desarrollo (Márquez y Legorreta, 2017).

Capítulo II. Aspectos metodológicos generales

II.I Casos de estudio

Este trabajo se basó en tres casos de estudio en el sureste de México, dentro de la cuenca Río Grande de Comitán-Lagos de Montebello (RGC-LM). Este sisitema hidrológico se encuentra en el estado de Chiapas, el cual ocupa el segundo lugar de marginación en el país (CONAPO, 2020) y donde el 75.5% de la población vive en estado de pobreza (CONEVAL, 2020). Además de ser el estado con mayor rezago social en México (Carrillo-Sagástegui et al., 2022), paradojicamene también es uno de los estados con mayor riqueza cultural y diversidad biológica (Landa et al., 1997).

Particularmente, la cuenca RGC-LM se localiza dentro de la región hidrológica Grijalva-Usumacinta, la cual representa el sistema hídrológico superficial más importante de México ya que cuenta con el 30% de los recursos hidrícos del país (Sánchez et al., 2015). Dentro de la cuenca habitan 194,247 personas, de las cuales el 84% vive en la ciudad de Comitán (INEGI, 2020). Comitán de Domínguez es el principal centro urbano de la cuenca, y el único que cuenta con servicios de drenaje, el resto de las localidades carecen de alcantarillado y el servicio de agua en algunas localidades es intermintente y en otras se carece de infraestructura para contar con agua entubada. Las actividades económicas principales son las actividades agrícolas, el comercio y el turismo (CONAGUA, 2009). Siendo este último, la actividad que se realiza principalmente en el Área Natural Protegida "Parque Nacional Lagunas de Montebello". Esta región es considerada de importancia ecológica para la conservación y declarado como humedal de importancia internacional, sitio Ramsar, desde el año 2003.

Desafortunadamente, la cuenca RGC-LM, presenta una degradación ambiental promovida principalmente por la agricultura, la descarga de aguas residuales y el crecimiento urbano (Alcocer et al., 2018; Alvarado et al., 2022a; Mora et al., 2017) que se asocia a la dinámica transfronteriza entre México y Guatemala (CONAGUA, 2009). Estos factores han promovido el incremento de la vulnerabilidad hídrica en los últimos años, asociado a las fuentes difusas de contaminación principalmente (ver **Capítulo III**). Bajo este contexto, la población se ve expuesta a diversas presiones socioambientales, siendo el acceso al agua uno de los principales retos que enfrenten estas comunidades que ya se encuentran en desventaja (ver **Capítulo IV**).

Para contar con una visión de las condiciones y medio de vida de la población en la cuenca, se eligieron tres comunidades: Juznajab la Laguna, El Triunfo y Tziscao como casos de estudio. Los criterios utilizados para su elección fueron: i) ubicación geográfica dentro de la cuenca, ii) tipo de fuente de agua para abastecimiento de la comunidad, iiI) manejo del suelo y conservación, iv) diversidad de actividades económicas (Tabla 1).

Tabla 1. Características demográficas y condición de acceso al agua en tres comunidades de cuenca RGC-LM, Chiapas, México (INEGI 2020).

Comunidad	Ubicación en la cuenca	Población total	Viviendas habitadas	% viviendas sin servicio de agua	Fuente de agua	Manejo del suelo y conservación	Principal actividad económica
Juznajab	Cuenca alta	840	172	9.3	Lago	Acuerdo comunitario	Agricultura de temporal
El Triunfo	Cuenca media	5 660	1 290	1	Pozo	Ninguno	Agricultura de riego
Tziscao	Sistema lacustre	1 939	344	100	Lago y río	Decreto federal	Turismo y agricultura de temporal

II.II Métodos mixtos

Para responder las preguntas de investigación, este trabajo se realizó bajo un enfoque de métodos mixtos. Los métodos mixtos integran sistemáticamente aproximaciones cuantitativas y cualitativas, permitiendo evaluaciones más flexibles con la finalidad de combinar evidencia de diferentes fuentes, según lo dicte los propósitos de una investigación (Chatterji, 2010). Para los propósitos de esta tesis, los métodos mixtos permitieron integrar datos tanto de la cantidad y calidad del agua, como de las prácticas de manejo del agua domiciliario y comunitario. Lo cual, permitió contar con una aproximación más realista en los tres casos de estudio mencionados.

Las herramientas metodológicas utilizadas fueron: i) Análisis de la calidad del agua, el cual fue realizado tanto en las fuentes de abastecimiento comunitario como en los diversos tipos de almacenamiento intradomiciliario; los resultados de la calidad del agua fueron entregados individualmente en cada vivienda tres días depués de haber realizado el muestreo. ii) Entrevistas semiestructuradas individuales, fueron aplicadas a mujeres, quienes por lo general gestionan el manejo del agua en el hogar; las entrevistas fueron aplicadas voluntariamente bajo un consentimiento informado. iii) Grupo focal, a través de un mapeo participativo se facilitó una entrevista grupal de mujeres y hombres tanto usuarios como gestores del agua. Los detalles metodológicos se pueden consultar en el **Capítulo IV** (Alvarado et al., 2022b)**.**

Es importante resaltar que para este trabajo se consideran los siguientes indicadores como relevantes dentro del manejo comunitario del agua: i) el acceso al agua en cantidad suficiente, el cual considera 50 L por persona al día de acuerdo con la OMS; ii) el acceso al agua en calidad suficiente, considera que no contiene elementos dañinos para la salud; iii) el acceso al agua para el riego, considera agua suficiente para garantizar la irrigación adecuada de cultivos de traspatio; iv) el acceso a instalaciones de higiene y saneamiento, el cual considera el acceso a espacios con agua y jabón para realizar la higiene personal; v) las normas y acuerdos comunitarios consensuados de manera colectiva en torno al manejo del agua; vi) la variación climática, considera conocimientos y capacidades colectivas para enfrentar eventos climáticos que comprometan el acceso al agua.

Figura 2. A) Análisis de calidad del agua domiciliario en la comunidad de Juznajab la Laguna; B) entrevista semiestructurada a usuaria en la comunidad de Tziscao; C) mapeo participativo en la comunidad de El Triunfo; D) sistema de almacenamiento de agua comunitario en la comunidad de Tziscao. Fotografías tomadas por Gonzalo Sansón, Haydeé Vega Sánchez y Jannice Alvarado durante los años 2019 y 2020, Chiapas, México.

Capítulo III. Análisis de vulnerabilidad hídrica a fuentes de contaminación en una cuenca kárstica en el sureste de México

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En este trabajo se realizó un diagnóstico de vulnerabilidad hídrica en la cuenca del Río Grande-Lagos de Montebello, en la región sureste de Chiapas, México. En esta región predomina un ambiente kárstico que alberga una zona lacustre, cerca de la frontera con Guatemala. A través de un análisis multicriterio se identificaron áreas vulnerables a la contaminación del agua a escala de subcuenca utilizando un sistema de información geográfica y análisis espacial. Las fuentes potenciales de contaminación fueron georreferenciadas y analizadas junto con la precipitación y la pendiente del terreno para identificar áreas propensas al transporte e infiltración de contaminantes. Los resultados mostraron que tanto la agricultura de riego como la de temporal fueron las principales fuentes de contaminación, seguidas por las descargas de aguas residuales. Adicionalmente se realizó un análisis de cambio del uso del suelo y pérdida de cobertura forestal, donde las actividades agrícolas fueron los impulsores más importantes del cambio. Como resultado, se presenta un mapa de vulnerabilidad hídrica a escala de subcuencas, que permite clasificar el potencial de contaminación del agua en presencia de diferentes fuentes de contaminación utilizando los métodos de suma ponderada y normalización lineal. Se identificaron dos subcuencas dentro de las categorías más vulnerables, Comitán y El Triunfo. Dentro de esta región no se han realizado análisis previos de vulnerabilidad hídrica, por lo tanto, proponemos este mapa de vulnerabilidad como una herramienta para la toma de decisiones sobre la gestión sostenible del agua a una escala de subcuencas en zonas con escasa información y procesos de degradación de la calidad del agua.

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Spatially explicit vulnerability analysis of contaminant sources in a karstic watershed in southeastern Mexico

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ABSTRACT

A water vulnerability assessment was performed on the *Río Grande-Lagos de Montebello* watershed, in southeastern region of Chiapas, Mexico. This is a karstic environment highlighted by well-preserved lakes, close to Guatemala border. We used multicriteria analysis to identify areas vulnerable to water contamination at subbasin scale using geographic information system and spatial analysis. Potential contamination sources were georeferenced and overlapped with precipitation and slope layers to identify areas prone to contaminant transport and infiltration. The results showed that both irrigation and rainfed agriculture were the main contamination sources, followed by wastewater discharge. Supported by land use and forest change analysis, agricultural activities were the most important drivers of change. A water vulnerability map at subbasin scale is presented as an outcome, which enables the ranking of water contamination potential in presence of different contamination sources using the weighted sum and linear normalization methods. Two subbasins were identified within the most vulnerable categories, *Comitán* and *El Triunfo*. No previous water vulnerability analyses have been performed for this region. We propose this vulnerability map as a decision-making tool for sustainable water management at watershed scale in areas with scarce information and increasing water quality degradation processes.

1. Introduction

Contamination is one of the main threats to local, regional and global environmental health (Lu et al., 2015). In particular, surface water and groundwater are highly vulnerable to contamination, especially in agricultural, industrial or densely urbanized areas (Giri & Singh, 2015), and Mexican freshwater systems are not an exception. Mexico's land use change varies depending on the region, and the diversity of potential contaminant sources is closely related to those activities. The southeastern region of the country, which is one of the most biologically and ethnically diverse, is also one of the more extensively exploited and contaminated regions due to agricultural activities (Landa et al., 1997). As a case study, an important watershed of karst origin called the *Río Grande-Lagos de Montebello* (RG-LM), located in the southeastern part of Chiapas, has suffered from multiple socioeconomic pressures in the last three decades (Alcocer et al., 2018, 2021). Particularly, since 2003, some of the lakes have been altered with some evident repercussions, changing from clear waters to eutrophic conditions, fetid odors, and fish mortality (Alcocer et al., 2018). The *Río Grande* and *Montebello* lacustrine system, with 52 water bodies, has partially been impacted due to the expansion of urban and agricultural areas, promoting soil erosion and sediment transport. Additionally, the lack of adequate sewage systems and wastewater treatment plants in rural communities has caused degradation of water quality and loss of aquatic life. These current environmental conditions pose a risk to environmental health, human well-being and the local economy by affecting people's income reliant

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on tourism due to a potential reduction in visitors. This is the case for the whole state of Chiapas, where surface water resources represent 30% of the available resources in the country (INE, 2000), which makes it highly vulnerable to water contamination. In addition, Chiapas holds between 10% and 64% of the biodiversity of the country depending on the biological group (CONABIO, 2013), which also relies on the good health of the ecosystem. On the other hand, 50.7% of the population in this state is impoverished (CONEVAL, 2018). These pressures have enhanced the presence of point and diffuse contaminant sources with deleterious effects on the system.

Depending on how contaminants enter the aquatic environment, two types of potential contaminant sources (PCSs) can be identified: point or diffuse PCSs. Point sources are those that directly discharge substances from sewage systems to an aquatic system. In contrast, diffuse sources are not easy to identify because they are generally associated with land use changes, where natural vegetation has been removed to give way for agricultural or urban areas, promoting the input of contaminants through runoff or infiltration (Brusseau, 2019). Diffuse contamination sources represent a high risk of contamination in watersheds with karstic geological features, especially in regions with high precipitation, steep slopes and intensive agricultural systems (Ongley et al., 2010). Karstic systems facilitate the migration of water contaminants since highly heterogeneous secondary porosity can construct the flow networks of high permeability rocks (Alcocer et al., 2018; Doerfliger et al., 1999). The sum of these factors causes an accelerated eutrophication process in aquatic systems, significantly reducing their lifetime and affecting their ecological functions. Diffuse contamination has been recognized as the main cause of water quality degradation in surface and groundwater systems (FAO, 2017). However, there is no official information on the PCS of water systems, and the impacts of agricultural activities on water bodies that are evident have not been determined (Pérez- Espejo, 2012). Therefore, multicriteria analysis (MCA) through the analytic hierarchy process (AHP) could be a good tool to help prioritize factors based on expert criteria by comparing the contamination level (Saaty, 2008). The AHP provides a rational framework for multicriteria decision making by quantifying its alternatives using a matrix of pairwise comparisons. Hierarchization and spatial analysis information can provide information to obtain a good approach to carry out a water vulnerability assessment of contaminants that is highly relevant for the RG-LM karstic watershed.

Turner et al. (2003) defines vulnerability as the degree to which a system experiences harm due to exposure to stressors. More specifically, Doerfliger et al. (1999) defined water vulnerability as the intrinsic geological and hydrological characteristics that determine the sensitivity of aquatic systems to contamination by human activities. Water vulnerability assessment is critical for the implementation of watershed protection programs. In fact, watershed management has been globally recognized in recent decades as a fundamental strategy for surface and groundwater quality protection. Water vulnerability assessment methods allow for the splitting of geographic regions into subareas according to their vulnerability degree; this process facilitates the identification and implementation of effective water protection management plans that are focused on contamination-susceptible areas within a watershed (Neshat et al., 2014). However, in developing countries, the availability of geospatial information from official sources regarding PCS is insufficient or inaccurate, a condition that promotes the lack of effective water management plans. Therefore, a spatial representation of vulnerability would be extremely useful (van Westen et al., 2008). Contamination-vulnerability maps provide visual information for more vulnerable zones that help to protect water resources and to evaluate the potential for water quality improvement by changing agricultural practices and land use applications (Connell & Van Den Daele, 2003; Krishna et al., 2015).

This study aims to evaluate water vulnerability to potential contaminant sources using MCA and its spatial representation through GIS in the RG-LM watershed, Chiapas. Therefore, this work was focused on answering i) What is the water exposure to potential contamination sources? ii) Based on the exposure, what is the degree of water vulnerability caused by the movement of pollutants? and, iii) Which have been the land use and forest cover changes? There are different methodologies for assessing and mapping the water vulnerability. In this study, exposure is considered as the presence of potential contamination sources which were weighted through a multicriteria analysis. The vulnerability degree was considered as the sum of exposure and sensitivity, which was generated through the incorporation of precipitation and slope. Contamination sources are difficult to analyze, but as mentioned above they are closely related to land use change; therefore, we consider that they would be a good component to strengthen the discussion. These two variables are not incorporated in the vulnerability analysis, but they contribute to a better understanding of the changes in the basin.

2. Materials and methods

2.1. Study area

This study was carried out in a tropical karstic region of the State of Chiapas in southern Mexico in the *Río Grande-Lagos de Montebello* watershed. The watershed covers an area of 754 km^2, and it encompasses a natural protected area “*Lagunas de Montebello*” National Park, which has been declared Priority Land Area for Conservation (CONANP, 2007) and a Ramsar site since 2003. The main river is known as the *Río Grande de Comitán* (hereinafter *Río Grande*), whose drainage pattern flows in a northwest to southeast direction; along its route, the river crosses agricultural and rural areas prior to its final discharge into the Montebello lacustrine system, with approximately 52 lakes (CONANP, 2007) (Fig. 1). This lake system fulfills an ecological function as a climate regulator, regulatory vessel, and biological corridor and as a source of sustenance for a considerable number of communities that live off the income generated by agriculture and tourism (CONANP, 2007). However, higher humidity, warmer temperatures and an average rainfall ranging from 763 to 2366 mm in this karst region increase the fragility of the watershed exposed to human activities, favoring contaminant dispersion and diffusion in the whole hydrological system, including the river and the lakes (Alcocer et al., 2018).

This National Park receives approximately 300,000 visitors per year (CONANP, 2007). The basin had 194,247 inhabitants in 2020, and 84% of the population lives in the city of *Comitán de Domínguez* (INEGI, 2020). *Comitán* is the only urban area that has sewage services and a wastewater treatment plant, whose outflow is discharged to the *Río Grande*. The rest of the localities have only septic tanks and pipes that drain directly to the river.

2.2. Data collection

To obtain a hydrological representation of the RG-LM watershed, subbasins were delimited using the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) based on a hydrology map at a 1:50,000 scale (INEGI, 2010), which used points of confluence flow in the mainstream. In the lacustrine zone, the subbasins were delimited under geomorphological criteria (slope, slope breaks, slope profiles and presence or absence of karstic geoforms such as dolines of sink holes) (Mora et al., 2016) since the system lacks surface flow and watersheds cannot be adequately defined. Each subbasin was named based on the locality names.

Subsequently, an average annual precipitation map with 15 m resolution was generated using average monthly information from 2013 to 2016 via ten weather stations supported by the Mexican National Weather Service. The points were interpolated using an IDW (squared) algorithm due to the number of points and because of the homogeneous area. Afterward, the average precipitation per subbasin was calculated with zonal statistics using ArcGIS (10.2.2). A slope map was calculated

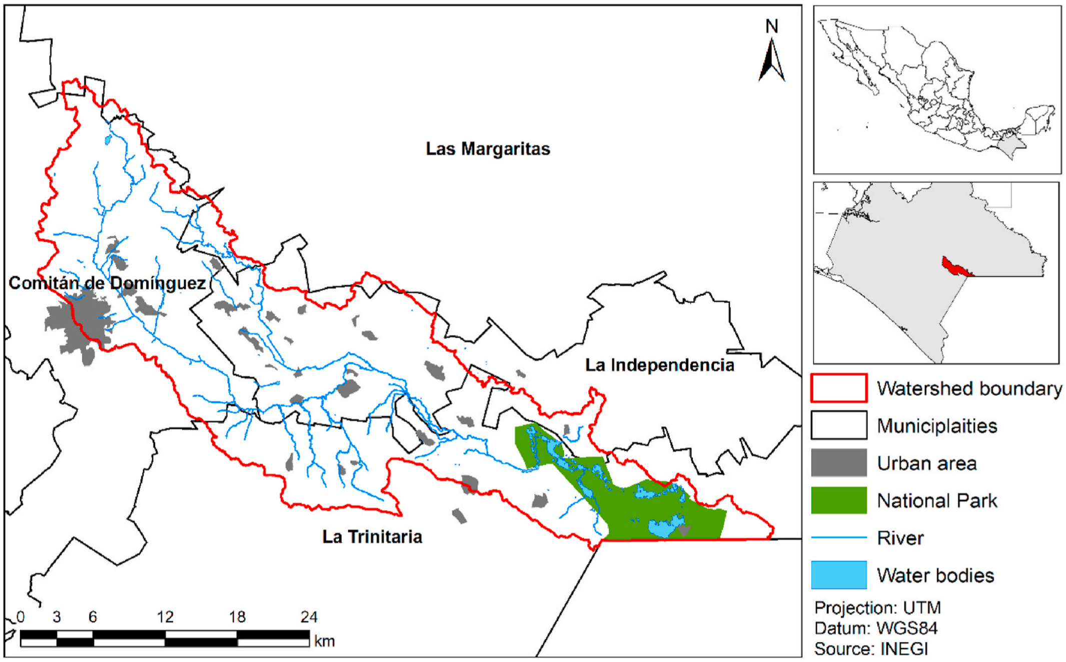

Fig. 1. Location of *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico.

with a 15 m resolution digital elevation model, and the average slope was calculated for each subbasin. Regarding the classification, we considered rainfed and irrigated agricultural lands, grasslands and urban areas as diffuse contamination sources. Rainfed agricultural land is considered a traditional temporal agriculture where crops such as corn, beans, and chilis are planted prior to the rainy season, and natural vegetation is removed with agrochemical products (Ávila, 2017). It must be considered that irrigated and technological agricultural land are more intensive and increase greenhouse gases and the wide use of agrochemical products (Ávila, 2017). Grasslands presented livestock activities. Urban areas were considered impermeable areas where runoff occurs. The information was taken from a land use and vegetation map with a scale of 1:250,000 in shapefile format (INEGI, 2013).

For point PCS, wastewater discharge sites, groundwater extraction wells, industries, hospitals, gas stations, livestock activities, construction sites, cemeteries and sand mines were considered. They were obtained through field observations across the watershed from 2013 to 2016 and topographic maps (INEGI, 2019). Each one was geographically referenced and imported as an individual shapefile.

2.3. Spatial data analysis

Potential exposure to contamination was calculated for each subbasin. The PCS were weighted using Expert Choice V11 (Saaty, Forman, Expert Choice, Expert Choice, & Decision Support Software I, 1998), which is a support tool for multicriteria analysis based on AHP. The AHP helps prioritize factors based on expert criteria by comparing pairs of variables, where values from one to nine are assigned to each pair representing how much one element dominates the other. In this way, the analyst can focus on only two criteria at the same time. Then, in a judgment matrix, a priority vector is calculated and used to weight the elements of the matrix (Saaty, 2008).

The results of the AHP obtained from eight experts (who participated as researchers in the study area from the areas of geology, edaphology, aquatic pollution and sustainability science) were arithmetically averaged and incorporated as individual raster layers per PCS through the weighted sum tool in ArcGIS according to equation (1).

$$E = \sum_{i}^{n} w_i x_i \tag{1}$$

where E represents the exposure value, w_i is the weight assigned to each PCS with AHP and x_i is the value of the PCS present in each subbasin, which was calculated through linear normalization using values from one to five. This scale was used to make point sources comparable to diffuse sources and easy to replicate in this and other subbasins. The exposure values were classified into five categories by the natural breaks method through linear normalization; the categories included very high, high, medium, low and very low.

To develop a water vulnerability map, we also considered high precipitation values and steep slopes as the main factors that promote high runoff rates, therefore inducing erosion, sediment transport and contaminant dispersion (Ongley et al., 2010). The precipitation and slope layers were summed as individual layers on the exposure map according to equation (2).

$$V = \sum_{i}^{n} E_i y_i \tag{2}$$

where V represents the water vulnerability value; E is the exposure value; and y_i represents precipitation and slope present in each subbasin via the linear normalization method, where values were assigned from one to five. The final water vulnerability values to be represented on the map were classified into five categories by the natural breaks method through linear normalization, where the five categories include very high, high, medium, low and very low.

2.4. Land use and forest change analysis

To strengthen the discussion on potential diffuse sources of contamination, a land use and forest change analysis was carried out. For land use change analysis, INEGI cartographies corresponding to series IV (2009) and VI (2017) of land use and vegetation with a scale of 1:250,000 (INEGI, 2013) were used. The layers used were a generalization and simplification of the Dictionary of Vectorial Data of Soil Use and Vegetation (INEGI, 2014). The classes include the categories of i) natural vegetation: coniferous forest, pine forest, mesophilic mountain forest, evergreen forest, oak forest, hydrophilic vegetation; ii) induced grasslands: iii) cultivated grasslands; iv) rainfed agriculture; v) irrigated agriculture; vi) human settlements; and vii) water bodies. The land cover change matrix was made based on Pontius et al. (2004) and is a general cross tabulation matrix for comparing two maps from different points in time. The forest change analysis from 2001 to 2018 was based on a raster dataset from the University of Maryland and the Global Forest Watch Alliance (Hansen et al., 2013). First, the Hansen dataset was downloaded and processed and masked within the study area. Second, we extracted the forest coverage change values with an automated procedure with R and Python. Finally, we analyzed the annual forest coverage change in each subbasin.

3. Results

The RG-LM watershed was divided into ten subbasins: the upper basin, including *Juznajab, Comitán,* and *La Independencia*; the middle basin, including *Guadalupe Quistaj, La Patria*, *Venustiano Carranza*, *El Triunfo*, and *La Esperanza*; and the lacustrine system, including the Lacustrine Plain System (LPS) and Lacustrine Mountain System (LMS). The subbasin areas range from 43.9 km^2 to 120.9 km^2 (Table 1). The precipitation results showed an annual average ranging from 724.5 to 2243.5 mm, and the elevation ranges were from 1380.5 to 2441.3 masl (Table 1, Fig. 2).

3.1. Potential contamination sources

Four types of diffuse contamination sources for the entire watershed were obtained from land use and vegetation maps (Table 1), of which the most extensive land use was rainfed agricultural land with an area of 200 km^2 (26.5%), irrigation agricultural land with an area of 54.7 km^2 (7.3%), grasslands with an area of 122.7 km^2 (16.3%) and urban areas with an area of 33.2 km^2 (4.4%). The point contamination sources were mainly associated with the *Comitán* subbasin; however, throughout the entire watershed, activities that were considered point contamination sources were also identified (Table 2).

3.2. Multicriteria analysis

The weights derived from MCA through the AHP method range from 0.170 to 0.022 (Table 3). The main contamination sources detected within the RG-LM watershed, according to the specialists' judgment, were irrigated agriculture, rainfed agriculture and wastewater treatment plant discharge.

3.3. Potential exposure to contamination map

The exposure to contamination map (Fig. 3) shows the locations of the point contamination sources and the exposure level in each subbasin. Most point contamination sources were associated with the larger urban area within the Comitán basin.

3.4. Water vulnerability map

The water vulnerability map (Fig. 4) shows that *Comitán* and *El Triunfo* were the most water vulnerable subbasins, followed by *Guadalupe Quistaj*, *La Patria*, the *Lacustrine Plain System* and the *Lacustrine Mountain System.*

3.5. Land use and forest change

The 2009–2017 period presents an area of change of 11% (8368 ha) of the total area of the basin. The land cover transitions are shown in Fig. 5, while the magnitudes of the land cover change from 2009 to 2017 are presented in Table 4. The greatest gross losses were presented by the classes of induced grassland with 4509 ha, natural vegetation with 2228 ha and rainfed agriculture with 1265 ha. With respect to the gains, the greatest magnitudes were presented by the coverages of rainfed agriculture, natural vegetation and irrigated agriculture with 4840 ha, 1932 ha and 450 ha, respectively. The net change was configured with rainfed agriculture with 3575 ha and human settlements with 571 ha as the largest magnitudes of positive change, while the induced grassland and natural vegetation classes present the largest magnitudes of negative net change for the period, with net losses of 43,77 ha and 296 ha (Fig. 5).

The plot from the change forest analysis (Fig. 6) shows a particular area and period where deforestation occurred. There are four periods and two areas where deforestation hit the most. First, in 2006 and 2010, the Lacustrine Plain System presented the areas with the most deforestation, with values of 71.2 and 58.9 ha, respectively. Second, the Juznajab watershed presented two consecutive years, 2006 and 2007, with deforestation values over 40 ha.

4. Discussion

This study focused on the water quality protection perspective through a water vulnerability assessment at watershed scale. Currently, the water vulnerability status of the RG-LM watershed is heterogeneous, mainly due to different levels of exposure to contaminants. The RG-LM watershed landscape has been highly modified, particularly during the last 30 years, because of land use change by deforestation, increase in agricultural area and population growth, which have affected surface and groundwater water quality (Alcocer et al., 2018; Mora et al., 2017). Additionally, wastewater is discharged without adequate treatment and from different point contamination sources that are not monitored or controlled. This is an unfavorable condition because the basin drains into a lacustrine system, of which 194,247 people receive drinking water. Due to the karst origin, hydraulic conductivity is an important driver of contaminant dispersion, which could easily reach different water bodies. For this reason, attention must be paid to changes in land use and land cover and the increase in PCS within the basin, considering the fragility of the karst environment. In this study, GIS and multicriteria analysis represent the first step for the assessment of water vulnerability and the control of contaminants in this important region. The water

Table 1
Physical features and diffuse contamination sources in different subbasins in *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico.

Subbasin	Area (km^2)	Average annual precipitation (mm)	Average slope (°)	Rainfed agriculture %	Irrigated agriculture %	Grassland %	Urban area %
Juznajab	55.1	1016.0	11.6	27.2	0.0	1.1	0.0
Comitán	110.7	784.6	6.5	25.7	2.9	14.9	14.4
La Independencia	79.1	801.6	5.2	38.9	0.4	6.9	3.8
Guadalupe Quistaj	66.9	724.5	2.1	19.2	14.6	46.0	0.1
La Patria	76.6	874.5	3	46.4	15.7	14.5	4.5
Venustiano Carranza	89.2	904.5	4	19.1	13.0	36.1	3.9
El Triunfo	61.7	1187.6	4.9	20.8	15.8	8.2	3.0
La Esperanza	43.7	1038.3	1.7	47.0	10.0	11.1	2.9
Lacustrine Plain System	87.4	1666.9	6.9	23.4	3.9	17.1	4.0
Lacustrine Mountain System	83.4	2243.5	8.7	7.6	0.3	1.4	0.8

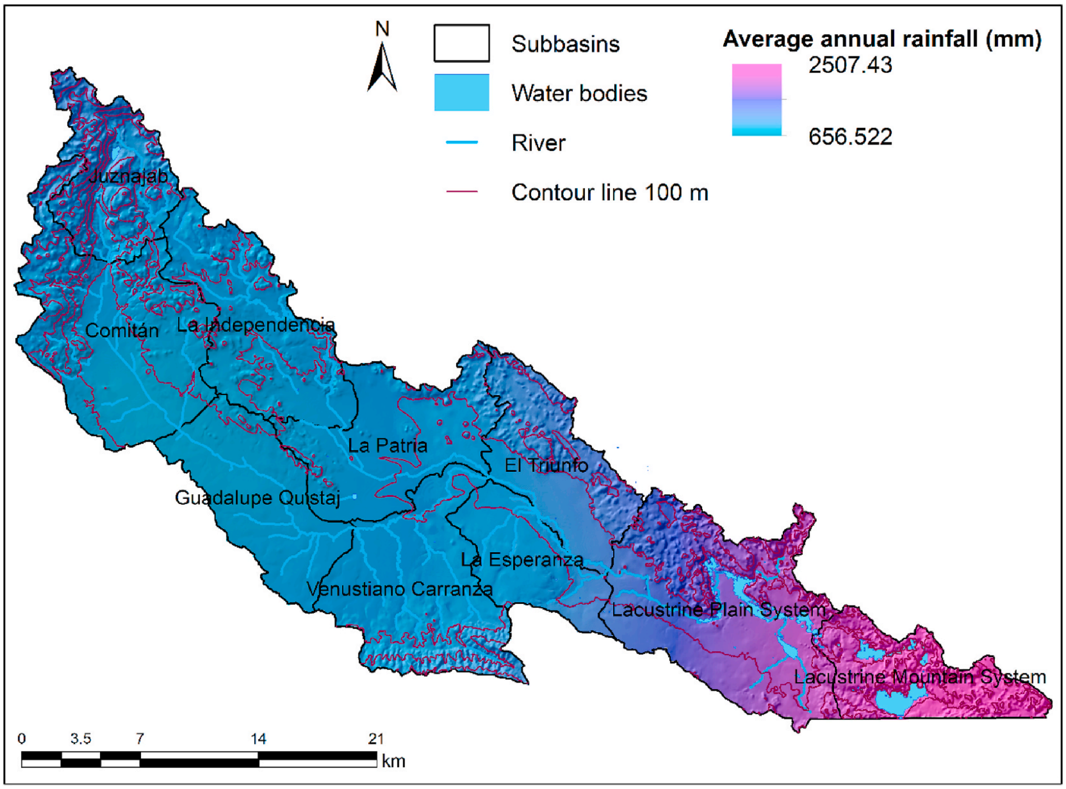

Fig. 2. Average annual rainfall and elevation terrain in the *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico.

Table 2
Point contamination sources in different subbasins in the *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico.

Subbasin	Wastewater discharge	Water wells	Livestock	Industry	Hospitals	Gas stations	Construction sites	Cemeteries	Material banks
Juznajab	0	0	1	0	0	0	0	1	1
Comitán	1	8	3	3	4	6	7	4	12
La Independencia	1	6	0	0	0	0	2	3	4
Guadalupe Quistaj	0	2	1	0	0	0	0	0	0
La Patria	0	6	0	0	0	0	0	6	0
Venustiano Carranza	0	6	1	0	0	0	0	1	0
El Triunfo	0	4	0	0	0	0	0	1	0
La Esperanza	0	2	0	0	0	0	0	2	0
Lacustrine Plain System	0	3	2	0	0	2	1	3	0
Lacustrine Mountain System	0	2	0	0	0	0	1	2	0

Table 3
Weights assigned to potential contamination sources in the *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico through multicriteria analysis.

Potential contamination sources	Weight
Irriagated agriculture	0.170
Rainfed agriculture	0.152
Wastewater discharge	0.103
Urban area	0.076
Livestock	0.073
Grassland	0.068
Water wells	0.050
Industry	0.046
Gas stations	0.035
Construction sites	0.026
Hospitals	0.025
Material banks	0.022
Cemetery	0.022

vulnerability assessment must include stakeholder participation and knowledge of governmental and institutional responsibilities in the future.

4.1. Potential exposure to contaminants

Land use and forest change are some of the main anthropogenic influences on ecosystems and affect water flow and quality (Dale et al., 2000). The main sources of water contamination are diffuse sources, which are driven by land use changes, such as urbanization and shifts in agricultural and livestock activities (FAO, 2017). In general, these activities are increasing and span large land areas, which makes controlling and monitoring difficult, inducing problems at regional scales, as their treatment frequently does not have a basin approach. Since the hydrologic processes in a basin are the primary transfer mechanisms between soil and water (Ongley et al., 2010), contaminant control from diffuse sources should focus on the transport of sediments, agrochemicals, nutrients, and microorganisms driven by runoff associated with high precipitation rates and steep slopes. Erosion and runoff control strategies should be implemented, especially in high areas with

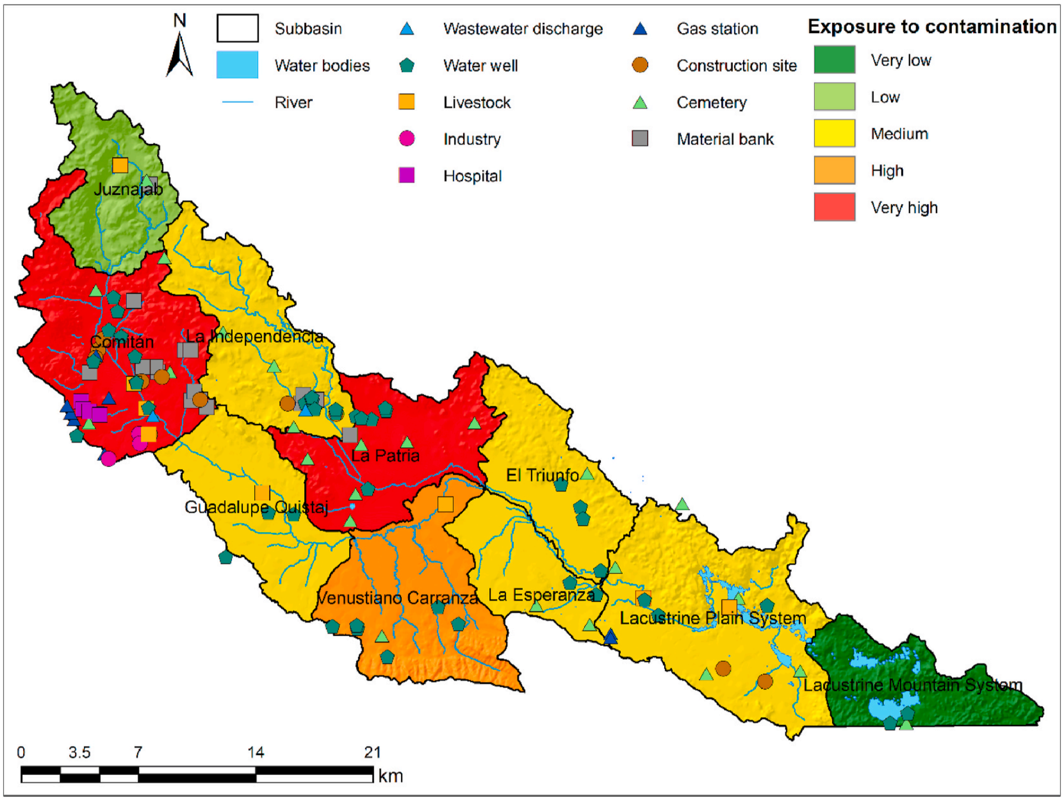

Fig. 3. Exposure to contamination per subbasin in the *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico.

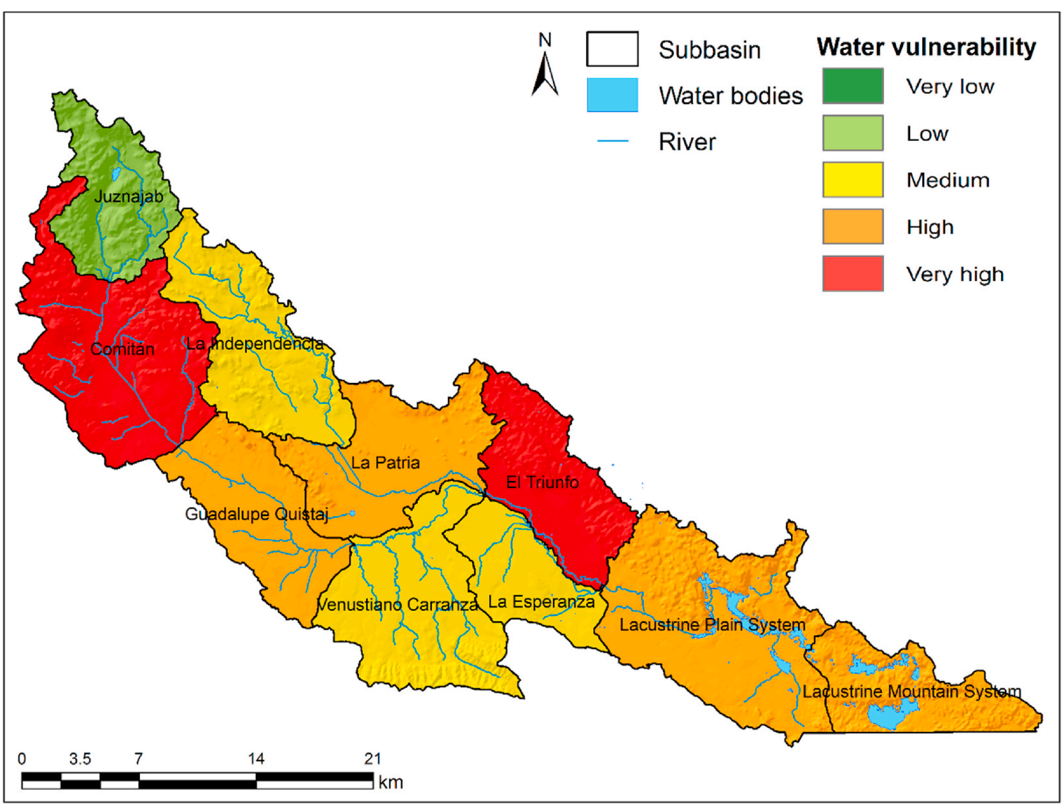

Fig. 4. Water vulnerability to contamination per subbasin in the *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico.

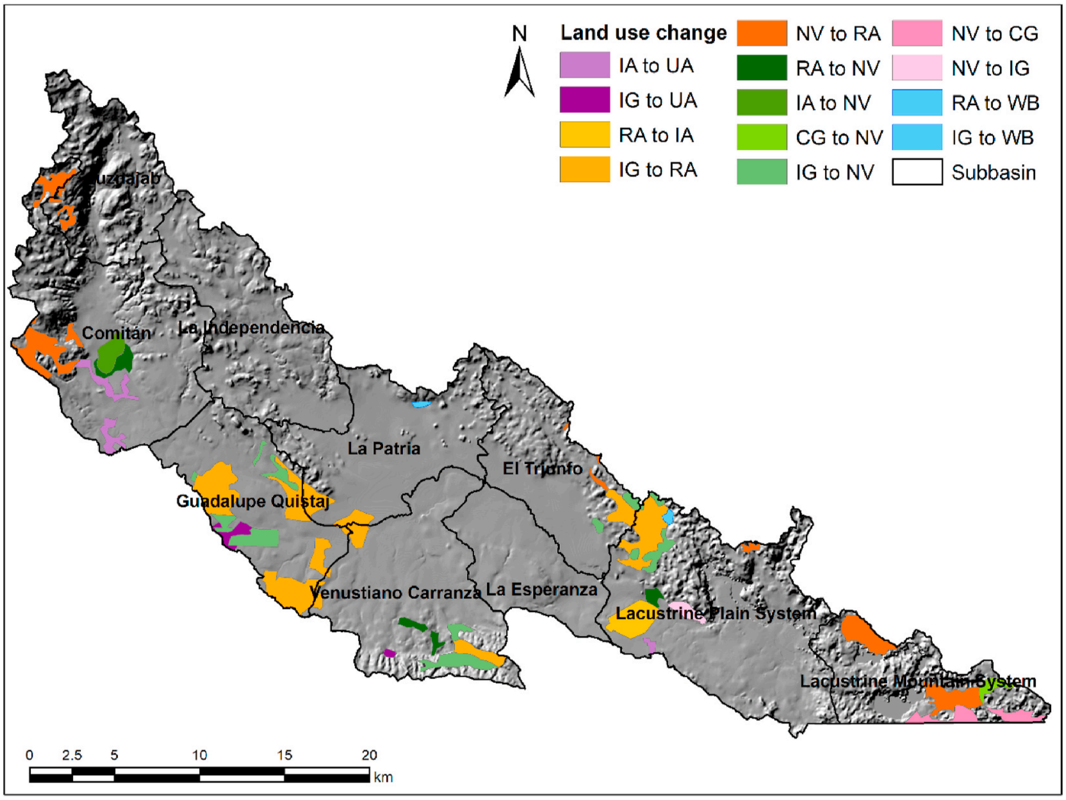

Fig. 5. Land cover transition map in the *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico. IA: Irrigated Agriculture, RA: Rainfed Agriculture, UA: Urban Area, NV: Natural Vegetation, CG: Cultivated Grassland, IG: Induced Grassland, WB: Water Body. For example, the IA coverage area in 2009 changed to a UA coverage area in 2017.

Table 4
Land cover change matrix in the *Río Grande-Lagos de Montebello* watershed. Each row corresponds to the coverage area (hectares) in 2009, and each column corresponds to the coverage area in 2017.

		2017								
		Irrigated agriculture	Rainfed agriculture	Urban area	Water body	Cultivated grassland	Induced grassland	Natural vegetation	Total 2009	Gross loss
2009	Irrigated agriculture	1657	0	0	0	0	0	245	1902	245
	Rainfed agriculture	450	30425	403	31	0	0	381	31690	1265
	Urban areas	0	0	2572	0	0	0	0	2572	0
	Water body	0	0	0	1070	0	0	0	1070	0
	Cultivated grassland	0	0	0	0	306	0	121	427	121
	Induced grassland	0	3117	168	39	0	5313	1185	9822	4509
	Natural vegetation	0	1723	0	0	373	132	26452	28680	2228
	Total 2017	2107	35265	3143	1140	679	5445	28384	**76163**	
	Gross gain	450	4840	571	70	373	132	1932		

agricultural or bare soils, such as *Juznajab*, *Comitán*, LPS and LMS.

In the RG-LM basin, agricultural activities cover 33.8% of the surface and represent an important diffuse water contamination source. The development of agricultural activities promotes the removal of natural vegetation and bare soil, which facilitates the degradation of water bodies through runoff and the transport of sediments and agrochemicals (Bouraoui & Grizzetti, 2014). The discharge of agrochemicals (e.g., nitrogen- and phosphorus-rich fertilizers) into aquatic ecosystems can cause turbidity increases, algae blooms, fish mortality and biodiversity loss (Carpenter et al., 1998). As a result of the MCA, different authors agree that irrigated agriculture is a more important diffuse source than rainfed agriculture since they are carried out in greenhouses throughout the year and the use of agrochemicals is greater. According to FAO (2017), irrigation is a major factor in agricultural intensification. Irrigation agriculture in the basin is carried out mainly in the middle basin, where the slopes are lower and the land facilitates the development of intensive agriculture, mainly in *El Triunfo* and *La Patria*. Greenhouse tomato cultivation has gained popularity among producers because it is a highly profitable product despite investment costs, with the feasibility of obtaining three to five crops per year (Ávila, 2017). In contrast, rainfed agriculture, which is mainly carried out in *La Esperanza* and *La Patria*, is an annual single-cycle activity whose main products are corn, beans, chili and squash, which are used for self-consumption. However, both agricultural activities represent important contamination sources

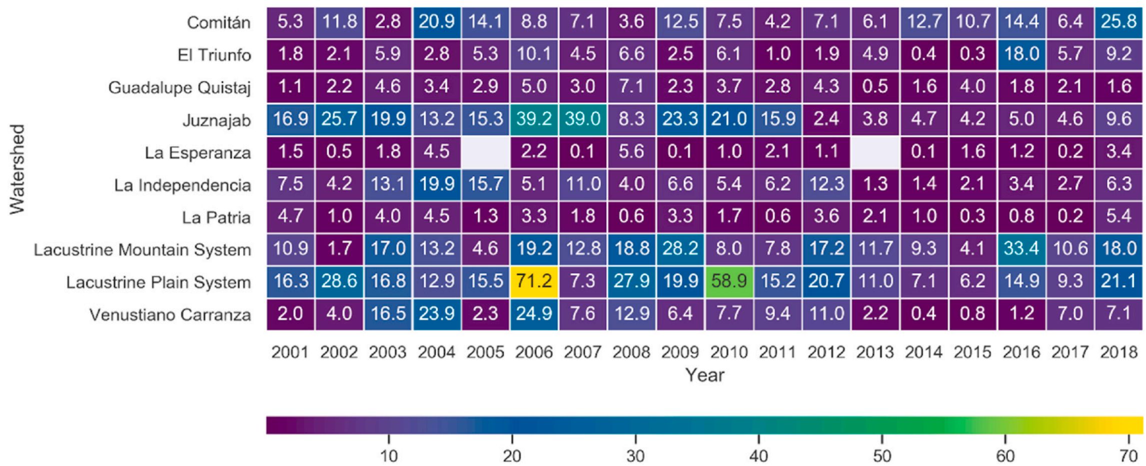

Fig. 6. Heat map chart of the total gross forest coverage change (ha) in ten subbasins between 2001 and 2018 in the *Río Grande-Lagos de Montebello* watershed, Chiapas, Mexico.

within the basin since the implementation of best management practices or agroecological production is considered to occur at a very low scale (Ávila, 2017).

In this study, grasslands were considered an area of deforested land for the development of livestock activity within the basin, where livestock are mainly used for self-consumption and on a small scale. Currently, the presence of livestock has resulted in surpluses of nitrogen and phosphorus, which are nutrients that contribute to water contamination, as well as the erosion of the land, mainly in grasslands (Svanbäck et al., 2019). In the last 20 years, new livestock contaminants have emerged, such as antibiotics, vaccines and hormones that are transported from farms to aquatic systems and drinking water sources, with a potential negative impact on human health (FAO, 2017). However, livestock represents an economic and cultural function in rural households, such as those in the RG-LM basin, as it contributes to improving the livelihoods of families, increasing income and even social status (Herrero et al., 2013). The subbasins that have a greater area of grasslands are *Guadalupe Quistaj* and *Venustiano Carranza*. FAO (2006) reported that the livestock sector is one of the three activities with the greatest environmental impact, including the degradation of water quality across all scales, ranging from local to global scales.

Urban growth has transformed soil into impermeable surfaces within built environments, such as roofs, roads, parking lots and sidewalks (Xian et al., 2007). Such areas prevent water infiltration from altering runoff rates within a basin and decreasing groundwater recharge, causing water quality degradation. The subbasin that showed the greatest coverage of urban areas was *Comitán*.

For the whole watershed, eight point contamination sources were found: wastewater discharge, where high levels of nutrients and pathogenic microorganisms (Hernández, 2015) generating blue-green algae blooms within the plant are discharged directly into the *Río Grande* and carried through the medium basin. Groundwater extraction could contribute to induction by depressurization and, therefore, different water qualities from the clay layer by consolidation (Soto-Galera et al., 2000). Industries and hospitals discharges could contain chemical substances and microbial agents in their wastewater, such as antibiotics, disinfectants and pharmaceuticals. Many of these compounds resist the conventional treatment of wastewater and end up in aquatic systems, disturbing the food chain, human beings and animals that are exposed by the consumption of water from surface sources (Pauwels & Verstraete, 2006; Verlicchi et al., 2010) now with COVID-19 exposure could be even more relevant. Additionally, gas stations were identified, and they could increase the risk of accidental leaks of gas to the subsoil in a karstic environment; therefore, discharge ends up in the aquifer, especially if these gas stations do not have ditches and pits to collect runoff in the case of leaks (Squillace & Moran, 2007). Cemeteries may contribute to groundwater contamination depending on the quality of cemetery infrastructure, and the time of human decomposition and its phases could last up to several months, or even years, related to the structure of the cadavers and the burial conditions (Żychowski & Bryndal, 2015). In addition, construction sites and sand mines are other contamination sources that add a variety of hazardous pollutants, such as asbestos-based, adhesive, corrosive flammable, and toxic materials (Ferronato & Torretta, 2019). Chiapas state, with 118 municipalities, is one of the states that is characterized as a final construction disposure site (Vera, 2010). Vera (op. cit.) recognizes that there is much to do in relation to construction disposure, and information on this is needed to create stronger normativity.

4.2. *Water vulnerability*

4.2.1. *Upper basin*

Juznajab is an area with springs where the Río Grande originates and where better water and forest management were observed because of local management performed by the population. However, the population is growing, and further sustainable management of the upper basin would be beneficial for the entire watershed. It is important to consider the presence of runoff due to high precipitation rates and steep slopes, which could rapidly impact the following subbasins. Therefore, contamination exposure and vulnerability are low (Figs. 3 and 4). Regarding the change in land use, in *Juznajab,* there was a loss of natural vegetation to rainfed agriculture between 2009 and 2017, and for forest change, 2006 and 2007 was where the greatest loss occurred (Figs. 5 and 6). The *Comitán* subbasin was classified with a very high level of water vulnerability and exposure because it has the largest urban area of the RG-LM watershed as well as all other point contamination sources (Figs. 3 and 4). The oxidation pond located within the subbasin is one of the most alarming contaminant sources. Within this subbasin, the land use change was focused on the increase in rainfed agriculture, urban areas and the growth in natural vegetation, which corresponds to floodplains where it is difficult to change land use (Fig. 5). *La Independencia* presented a moderate exposure level, with the second highest diversity of point source contamination sites. Furthermore, the water vulnerability map exhibited moderate values due to the biophysical features of the region, and the slope and precipitation were not important contributors to the transport of contaminants; thus, the vulnerability of the subbasin was moderate (Figs. 3 and 4). According to the analysis of land use and forest loss, this subbasin did not display significant changes.

4.2.2. Middle basin

Within the middle basin, there are five subbasins with the lowest slopes of the entire basin. *Guadalupe Quistaj* is a subbasin composed of 34% agricultural area. It is ranked first in grasslands, and the point contamination sources present are extraction wells and livestock. Despite low rainfall in the area, which limits the transport of contaminants, a high level of vulnerability was observed (Fig. 2). Furthermore, *La Patria* comprises 62% of the agricultural area, is ranked second in urban area, and is one of the two subbasins that presented a very high level of exposure to contamination; nevertheless, its characteristics do not facilitate the transport of sediments and contaminants due to low rainfall and flat slopes. *Venustiano Carranza* and *La Esperanza* presented a moderate level of water vulnerability. Although *Venustiano Carranza has* few point contamination sources, the temporary agricultural and irrigation areas are smaller than the same areas in the rest of the middle basin. *La Esperanza* is ranked first in rainfed agriculture and has the lowest average slope of the entire system. *El Triunfo* presented a very high vulnerability, mainly because it is the subbasin with the greatest agricultural irrigation area and several point contamination sources; additionally, it is the subbasin with the third-highest annual average rainfall and steep slopes. This area needs attention since agricultural dynamics tend to increase regarding tomato crops in greenhouses, increasing the use of agrochemicals, which are important sources of contamination.

4.2.3. Lacustrine system

The lacustrine system is composed of LPS with a high level of vulnerability and LMS with moderate vulnerability (Fig. 4). Since both systems belong to the discharge area and the region with the highest annual average rainfall, vulnerability increased concerning the exposure levels to contaminants (Fig. 3). LPS presented a higher vulnerability than LMS because it has larger agricultural, grassland and urban areas and more contamination sources (Table 1 and Fig. 3). According to Mora et al. (2017), the geologic composition suggests that LPS is more influenced by the *Río Grande de Comitán* than LMS, which seems to be related more to groundwater sources. The interconnectivity of LPS facilitates pollutant spread among lakes in flooding events during the rainy season (Alcocer et al., 2018), in contrast with LMS, which has an active hydraulic connection with groundwater and could easily contaminate aquifers. On the other hand, LPS suffered the greatest forest loss compared to other basins, highlighting losses of 71.2 and 58.9 ha in 2006 and 2010, respectively (Fig. 6). This study agrees with Pacheco et al. (2001), who argue that due to the nature of karstic origin, the lacustrine system is highly vulnerable to water contamination.

5. General discussion and conclusions

The results do not show homogeneous exposure and vulnerability in the RG-LM watershed. This is related to its land use and forest change history. An overall understanding of the impacts of diffuse and point contaminant exposure and the identification of vulnerable water bodies considering slope and precipitation, variables that contribute to the mobility and dispersal of contaminants, is extremely relevant for the management of the entire watershed for environmental and investment decisions.

The main drivers of change within the RG-LM watershed are the increase in agricultural activities and urbanized areas. This is a global trend, and this watershed is not the exception, but the karstic features of these systems accelerate superficial and underground dynamics. Diffuse sources of contamination from intensive agriculture provide a potential threat to groundwater quality in recharge areas (Goss et al., 1998). Moreover, it is well known that karst formations create very complex dynamics that are difficult to follow and monitor because of diffuse contamination. Diffuse contaminants have a great contribution from the medium basin and are probably one of the main reasons for the degradation of lacustrine systems. Karst systems are particularly vulnerable to overexploitation and contamination due to their high hydraulic conductivity and rapid infiltration processes that allow for the fast influx of runoff and contaminants into the aquifer (Kovarik et al., 2017).

Human activities such as agriculture produce a large amount of contaminants. High quantities of agrochemicals are discharged into the soil; they are not calculated correctly for the plantations and are commonly mixed among them without caution (pers. obs.). During the last three decades, this watershed has been increasing its agricultural activities, technification and an increase in tomato cultivation have put huge pressure on the area. Climate change is another driver that is pushing the use of agrochemicals due to the appearance of more plant diseases and infestations (Koli et al., 2019). Land use and forest change from 2006 to 2018 turned a great extension of the area into rainfed agriculture and irrigated agriculture for the studied watershed. Although it is difficult to monitor superficial and groundwater dynamics, the impact of agriculture and urban growth on water bodies and effluents is increasingly evident (Goss et al., 1998). The sustainability of noncontaminated groundwater in these systems is imperative for both humans and groundwater-dependent ecosystems (Kovarik et al., 2017). Generating an understanding of groundwater dynamics can refine vulnerability assessments, and it will contribute to real exposure assessments and therefore obtain a more realistic vulnerability vision of socioecosystems.

Community participation and perception are fundamental to finding solutions and sensitizing them regarding the problems that they generate. Social and economic variables are not considered factors that are of great importance. The socioecosystem is dynamic, and although a moment in time is measured, continuous monitoring of the measured and other variables is relevant in decision making (Esse et al., 2019). It spatially shows areas with relatively high vulnerability that should be considered a priority in the decision-making process.

Additionally, the use of GIS was useful to address PCSs since it provided a way to perform an analysis of the spatial distributions and statuses of all possible factors impacting watershed vulnerability; therefore, this method can be useful for long-term monitoring and control measurement of the outcomes expected after implementing partial or regional water management plans. It is worth noting that a similar instrument of historical records has never been implemented in this area.

Considering all of the above and under a low financial capability framework, which is what Chiapas has, water management plans should therefore focus on creation, modification and compliance with regulations on the most vulnerable regions through programs and initiatives to make efficient and impactful uses of the available limited budget, for example, a census of agrochemical use in regions where there is a significant presence of crop yield, exhaustive audits for industry stakeholders regarding waste and wastewater treatment and disposal plans, and public hydraulic infrastructure investment in the group of communities making major contributions to wastewater discharge directly into the *Río Grande* and the *Montebello* lacustrine systems.

On the other hand, the United Nations (UN-Water, 2018) has reported that more than 80% of wastewater resulting from human activities is discharged into rivers or the sea without any contaminant removal. These percentages are unknown for the *Río Grande* and *Montebello* lacustrine systems. To improve sanitation and access to drinking water (included in the Mexican Constitution as a human right), we identify the need for monitoring and increasing investment in the management of freshwater and sanitation facilities at a local level, as has been mentioned in the Sustainable Development Goal 6 (SDG6), where ensuring the available and sustainable management of water and sanitation is a right for all.

This study contributes to the identification of specific areas with potential exposure to contamination and could be a starting point for intervention and decision making by local actors. Even though more studies and further integration are needed, action must be taken in this watershed and other watersheds with the same problems. Vulnerability has already been identified, and the participation of all actors will increase access to clean water for human consumption in these marginalized communities, which are linked to goals 10 (reduce inequalities) and 13 (climate action) of the SDG.

CRediT authorship contribution statement

Jannice Alvarado Velázquez: Conceptualization, Methodology, Formal analysis, Software, Data curation, Writing- Original draft, Writing – review & editing. **Paola Massyel García-Meneses:** Conceptualization, Methodology, Visualization, Investigation, Writing – review & editing. **Carlos Esse:** Data curation, Methodology, Software. **Pablo Saavedra:** Data curation, Methodology, Software. **Ricardo Morales Trosino:** Data curation, Methodology, Software. **Roberto Bonifáz Alfonzo:** Methodology, Software, Funding acquisition. **Marisa Mazari-Hiriart:** Conceptualization, Reviewing and Editing, Project administration, Supervision, Funding acquisition.

Declaration of competing interest

None.

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Capítulo IV. Barreras y puentes en torno al manejo comunitario del agua: un enfoque de método mixto (*Artículo científico de requisito publicado*)

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El acceso suficiente al agua de calidad adecuada representa un desafío para lograr diversas dimensiones del desarrollo sostenible. Actualmente, el acceso al agua está restringido a tres de cada 10 personas en todo el mundo. En las zonas rurales de México y otros países de bajos ingresos, la cobertura podría ser aún menor debido a la ausencia de abastecimiento gubernamental; por lo tanto, las comunidades rurales suelen realizar el manejo del agua. En torno al manejo comunitario del agua surgen diversas interacciones socio-ecológicas que pueden determinar el acceso al agua. En este sentido, el acceso al agua dependerá de los obstáculos o capacidades que surjan dentro del sistema socio-ecológico en el que está inmersa la comunidad. En este trabajo se identifican barreras y puentes para el acceso al agua en un medio rural a través de métodos mixtos. Este artículo se basa en tres estudios de caso en el sureste de México mediante el análisis de 90 cuestionarios realizados a nivel hogar y tres grupos focales, en paralelo, se realizó un análisis de la calidad del agua y se evaluó su relación con las prácticas de gestión dentro de cada vivienda. Las barreras y puentes se clasificaron en seis desafíos de acceso al agua: i) acceso al agua en cantidad suficiente; ii) acceso a agua de calidad adecuada; iii) acceso al agua para el riego de cultivos de traspatio; iv) instalaciones de higiene y saneamiento; v) organización colectiva, y vi) variabilidad climática. Los principales resultados indican que la cantidad y calidad del agua en los hogares presenta deficiencias debido a la falta de infraestructura formal y representa un riesgo para la salud. El acarreo de agua tiene un mayor impacto sobre las mujeres y los niños en las zonas rurales pobres, y es una barrera importante para el desarrollo sostenible. En contraste, la organización colectiva demostró ser un puente esencial para el acceso al agua en estas comunidades.

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Barriers and bridges on water management in rural Mexico: from water-quality monitoring to water management at the community level

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Abstract Access to sufficient water of suitable quality represents a challenge for achieving several dimensions of sustainable development. Currently, water access is restricted to three of 10 persons globally. In rural areas of Mexico and other low-income countries, coverage could be even less due to the absence of formal supply; thus, rural communities usually perform water management. Surrounding community-based water management, various socio-ecological interactions emerge that determine access to water. Access to water will depend on the obstacles or capacities that arise within the socio-ecological system in which the community is immersed. This work identifies barriers and bridges to water access in a rural environment through mixed methods. The article draws on three case studies in southeastern Mexico by analyzing 90 questionnaires conducted at the household level and three focus groups in parallel with water quality analysis and its relationship with management practices. The barriers and bridges were classified into six water access challenges: (i) access to water in a sufficient quantity, (ii) access to water of adequate quality, (iii) access to water for household crop irrigation, (iv) hygiene and sanitation facilities,

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(v) collective organization, and (vi) climate variability. The main findings indicate that households' water quantity and quality show deficiencies due to the lack of formal infrastructure and represent a health risk. Water fetching has the highest impact on women and children in poor rural areas, and it is a significant barrier to sustainable development. In contrast, the collective organization proved to be an essential bridge for water access in these communities.

Keywords Community-based · Water management · Collective organization · Rural communities · Water quality

Introduction

Access to water is essential to promote sustainable development and human well-being. In 2010, the United Nations General Assembly explicitly recognized access to water as a human right, establishing that access to drinking water and sanitation is crucial for developing a dignified life, which is established within the Sustainable Development Goal 6 (SDG 6) (UN-Water, 2015). According to the World Health Organization (WHO), water access must be sufficient and continuous for personal and domestic use, including water for drinking, personal sanitation, food preparation, and house cleaning. This organization has established that between 50 and 100 L of water *per person per day* are necessary to satisfy an individual's basic needs (WHO, 2003). Nowadays, three of 10 persons do not have this amount of water in their homes, and this could increase due to various factors, including inadequate resource management by the formal and informal institutions involved (UN-Water, 2015).

Water management remains a significant challenge worldwide, particularly in rural areas, exacerbated by a lack of formal network pipes or infrastructure. In Mexico, about 10% of the population does not have access to water, and of those who do, 30% do not receive water continuously or of acceptable quality (Perló, 2019). The municipalities oversee providing water and sanitation services to the population; however, they only partially complied with this. The government's absence and non-compliance with basic services drive communities to manage resources independently, promoting different strategies not considered within formal policies (COMDA, 2017). Water management tends to be community-based, whereby access to water in quantity and quality is not always guaranteed (Cavender-Bares et al., 2015; Elliott et al., 2019). Therefore, access to water will depend on the capacity of a community to face obstacles and unexpected changes (Gunderson et al., 1995; Pahl-Wostl et al., 2010).

In Mexican territory, renewable water, which can be used annually in a region, is naturally distributed in a heterogeneous manner since in the southeast of the country, renewable water is seven times greater than in the center and north, where the largest population is concentrated (CONAGUA, 2018). However, in Southeast Mexico, particularly in Chiapas, 56% of individuals do not have basic water services (CONEVAL, 2020), despite being the most important hydrological region in the country. Many families do not have continuous access to water, and toilets generally comprise latrines for shared use. One example is the Río Grande de Comitán-Lagos de Montebello (RGC-LM) watershed, in which water supply coverage is significantly lower and more limited than in urban areas. The RGC-LM watershed is located in the Grijalva-Usumacinta region, Mexico's most important hydrological region with the most significant amount of renewable water *per capita* (Sánchez et al., 2015).

From how water users relate with each other and with different components of the ecosystem, a variety of social and environmental interactions emerge, which can determine access to water through the decision-making process (Bodin & Crona, 2009; Bodin et al., 2006). In this study, water management actions were categorized as barriers and bridges, which change across scales. The barriers and bridges are the actions, individual or collective, that arise from the decision-making process around community-based water management, and they can improve or inhibit access to water in terms of quantity or quality. For instance, practices surrounding access to and storage of water, community agreements for the use of water, and activities around traditions or rituals, among others, can represent barriers and bridges to access to water of suitable quantity and quality. It is well known that poverty, inequality, and climate change, to mention a few examples, inherently condition the emergence of barriers and bridges and therefore individual and collective's access to water. These large-scale processes can influence the dynamics of socio-ecological systems (Folke, 2006; Ostrom, 2009) and can function as barriers to access to natural resources. However, practices on the local scale are critical if one seeks to generate longer-term changes.

Identifying local barriers and bridges could be the first step to achieving results that improve the conditions of access to water, in addition to aiding communication between users and decision-makers in the development of water management strategies oriented toward sustainability (Cavender-Bares et al., 2015). Challenges continue to be faced regarding access to water because the complex interactions of users with water sources are not considered. In addition, the capacity for change within water management, barriers, and bridges is unknown (Pahl-Wostl et al., 2010). In this regard, it is crucial to identify what determines water management dynamics, what the barriers are, and what the bridges are in a local context (Pahl-Wostl & Kranz, 2010).

This study aims to understand community-based water management by identifying barriers and bridges around access to water from the individual to the collective scale in a rural context. Therefore, we focused on answering the following: (i) What are the current practices surrounding water use and management at the household and community level? (ii) What is the relationship between water quantity and the quality of available water and management practices? (iii) What are the main barriers and bridges faced by the communities regarding access to water? The article draws on three case studies within the RGC-LM watershed, which were analyzed using mixed methods to have an inclusive perspective and integrate processes at different scales.

Case study

This study was conducted in Chiapas, specifically at the Río Grande de Comitán-Lagos de Montebello (RGC-LM) watershed, close to the Guatemala border. The watershed covers an area of 754 km^2 and is located within three municipalities: Comitán de Domínguez, La Trinitaria, and La Independencia. The RGC-LM watershed is within the Grijalva-Usumacinta Hydrological Region (INEGI, 2010), a region considered the main renewable water reserve (Sánchez et al., 2015). Located within this watershed is the Natural Protected Area "*Parque Nacional Lagunas de Montebello*," an area with 52 lakes of karst origin, which has been declared a Priority Land Area for Conservation (CONANP, 2007) and a Ramsar site since 2003 (Fig. 1). This hydrological system is considered a vulnerable water area (Alvarado et al., 2022) due to multiple socio-economic pressures over the last three decades (Alcocer et al., 2018, 2021). The lack of adequate sewage systems, wastewater treatment plants, and the expansion of urban and agricultural areas have caused the degradation of water resources (Alcocer et al., 2018; Alvarado et al., 2022). These impacts are unfavorable because, in the basin, 194,247 inhabitants receive water for human use and consumption (INEGI, 2020), and their livelihoods are tied to the lacustrine system.

For the development of this study, we selected three communities, including Juznajab, El Triunfo, and Tziscao, as case studies, which have inadequate or no water supply services, lack drainage, and water management is carried out by community members through committees. These communities were selected to include different water management practices and ecological conditions within the basin, applying the following criteria: (i) by the representativeness of the upper basin, middle basin, and lacustrine system; (ii) by water supply type; (iii) by soil conservation practices; and (iv) based on economic activities (Table 1).

Methods and analysis

Water management at the household level

For this work, we used a mixed-method approach, which was applied to three communities in the RGC-LM basin. The study of resource management and its governance requires quantitative information and qualitative analysis because different types of knowledge are involved that need to be integrated into an inclusive framework capable of incorporating processes at different temporal and spatial scales (Pahl-Wostl & Kranz, 2010).

We applied a questionnaire to 90 households in the three communities, 30 per community, between 2019 and 2020. We conducted convenience sampling (Patton, 1990), and saturation of responses was achieved in each community (Martínez-Salgado, 2012; Morse, 1995). The design of the questionnaire

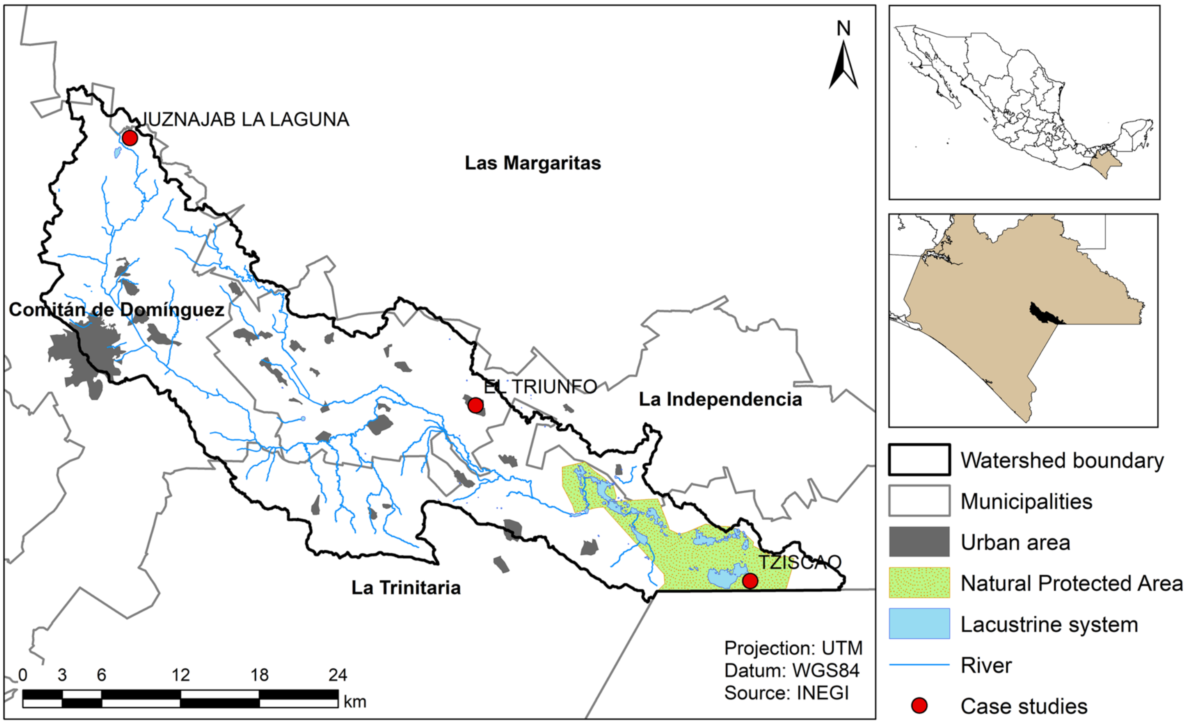

Fig. 1 This map shows, in red dots, the locations of the case studies within the Río Grande de Comitán-Lagos de Montebello watershed. Juznajab in the upper basin, El Triunfo in the middle basin, and Tziscao as the lacustrine system in the lower basin, located within the Natural Protected Area

was based on previous water access research (OMS & OPS, 2009; Bartram et al., 2014; UN-Water, 2015), which included the following five sections: (i) sociodemographic indicators, (ii) accessibility to water, (iii) water practices and uses, (iv) community agreements and rules, and (v) hygiene and sanitation practices. The instrument contained closed and open questions, allowing an analysis of the codification of management practices, water access conditions, water quality, and health issues. The data were captured in a database in excel and analyzed with descriptive statistics with the R version 4.0.3 statistical software program.

Water management at the community level

We conducted a focus group (Taylor & Bodgan, 1984) to obtain a collective perspective on community-based water management in each community, in which men and women of legal age (> 18 years) participated.

Table 1 Demographic characteristics and water access condition in three communities of RGC-LM watershed, Chiapas, Mexico (INEGI, 2020)

Community	Basin location	Total population	Inhabited houses	% Homes without water service	Water source	Land conservation	Main economic activity
Juznajab	Upper basin	840	172	9.3	Lake	Community agreement	Rainfed agriculture
El Triunfo	Middle basin	5660	1290	1	Well	None	Irrigated agriculture
Tziscao	Lacustrine system	1939	344	100	Lake and river	Federal decree	Tourist activities, rainfed agriculture

The conversation was guided through pre-established questions, while attendees were asked to draw on a flip chart. This method was performed through participatory mapping (Brouwer & Brouwers, 2016; Pathways Network, 2018), facilitating conversations on water management in the community. Different social actors attended each focus group, men and women, including water users at the household scale, water users at the parcel scale, water managers as members of the surveillance committees, and community authorities voluntarily. Participants made a map of the community as a group while describing the different water management practices, community agreements, and norms and identifying capacities and obstacles to access the resource individually and collectively. During the process, transcripts were made of the collective dialog that emerged around water management in the community.

Water-quality monitoring

In the three communities, we analyzed household water samples to link management practices with water quality from different water sources (lake, river, well, rainwater, and bottled water). The following physicochemical indicators were measured from the samples obtained: temperature (°C), pH, dissolved oxygen (DO) (mg/L), electrical conductivity (µS/cm), total dissolved solids (TDS) (mg/L), turbidity (NTU), ammonia nitrogen ($N\text{-}NH_4^+$), and nitrates (NO_3^-), using a YSI EX02 (Yellow Springs, OH) multiparameter water-quality probe. Residual chlorine in the water was measured using the Spectrophotometer model DR 2800 (Loveland CO). Additionally, we measured microbiological indicators in household samples with Petrifilm 3 M plates for total coliforms and *Escherichia coli*. The results were collected in a database for their statistical description and evaluated by Mexican Standard NOM-127-SSA-1994, which establishes permissible water limits for human use and consumption (DOF, 2000).

Subsequently, we performed a principal component analysis (PCA) to describe the relationship between water quality with community management practices. We used PCA to reduce the number of variables about water quality into a smaller number of variables, or components, which describe the results in a simpler way (conductivity, turbidity, *E. coli*, etc.). This allowed us to relate the components found with the management strategies (rainwater harvesting, water fetching, etc.). We used physicochemical and microbiological parameters as quantitative variables, and as qualitative variables, practices for access to water (water service inside the household, water service inside the property, rainwater harvesting, and water fetching). All analyses were performed with R version 4.0.3 statistical program software.

Identification of barriers and bridges

To reach the main objective of this work, we identify barriers and bridges through the coding and classification of questionnaires, water monitoring, and the results of the focus groups. As described previously, barriers and bridges in this study are defined as actions, individual or collective, that arise from the decision-making process around community-based water management. They can improve or inhibit access to water in terms of quantity or quality. The barriers and bridges were also categorized as individual and collective, based on the multilevel action situation proposed by Barnes et al. (2017). The individual level consists of obtaining water at home, where decisions regulate daily activities. The collective level is based on collective-choice rules, collaborative efforts, community agreements, or norms; at this level, decisions can affect or benefit several families and impose sanctions when they are not achieved. Barriers and bridges, both individual and collective, were grouped in turn in the following six water access challenges: (i) access to water in a sufficient quantity, (ii) access to water of adequate quality, (iii) access to water for household crop irrigation, (iv) hygiene and sanitation facilities, (v) collective organization (agreements and norms), and (vi) climate variability. The challenges (i), (ii), (iv), (v), and (vi) were chosen since those are considered objectives or indicators within the Sustainable Development Goals (SDGs) specifically on SDG 6 (UN-Water, 2015), as well as recommendations by the World Health Organization for access to water and sanitation (WHO, 2003). These frameworks make it possible to compare discussions that are taking place in other contexts or regions of the world. Challenge (iii) was incorporated after interviews with the local inhabitants since part of their livelihoods is self-consumption agriculture in the backyard. The SDGs address issues of marginalization, vulnerability, and inequity. However, it is important to consider that it is a global framework, which can leave aside local contexts (Fukuda-Parr, 2017).

Results

Community context

From the questionnaire applied, 100% of the respondents were women because they represented the leading water managers in their homes and were willing to respond to the interview. It is important to highlight that women manage water at the household level, however, in decision-making at the community level, women have little participation. The age of respondents ranged from 22 to 74 years; 43% had incomplete primary school studies, 22% had completed primary school, 20% had finished high school, 7% had no studies, and only 1% had a bachelor's degree. The main occupation was housewives with 89%, business or sales with 8%, farmers with 2%, and students with 1%. Monthly income ranges from USD 10 to USD 400 per month. Juznajab had the lowest average income with USD 75, Tziscao with USD 90, and El Triunfo with an average of USD 190 per month.

In these communities, land tenure is carried out through *ejidos*. An *ejido* is a portion of land for shared use, mainly destined for agriculture and forest and water use (DOF, 1992). Management is carried out under the agreements of an *Asamblea Ejidal* (assembly), in which the *Comisariado Ejidal* (commissary) and the *Comité de Vigilancia* (surveillance committee) participate. The Asamblea is where the decision-making process takes place, and it has the objective of the orderly management of community life and the productive and economic aspects. Water, forest, agriculture, and tourism regulation committees may arise from this Asamblea. Decision-making within the Asamblea is solely made by men.

Water access

Access to water for human use and consumption in these communities can differ regarding the available infrastructure and the primary supply source. For Juznajab, access to water is by water pumping, whose pipes were installed by the municipality in the 1990s and abandoned in the hands of the community. In Juznajab, 90% of families have water service inside the property, and 10% have water service inside the house (Fig. 2). Juznajab currently manages water, forest, and agricultural activities through community agreements. Water management is organized by a committee that collects fees (USD 0.25 per person per month) for pumping water, maintaining, and repairing pipes, and implementing actions to care for land and water. When these actions or agreements are not fulfilled, monetary fines are applied. In recent years, Juznajab received water only 3–5 h per day due to insufficient pumping and pipelines.

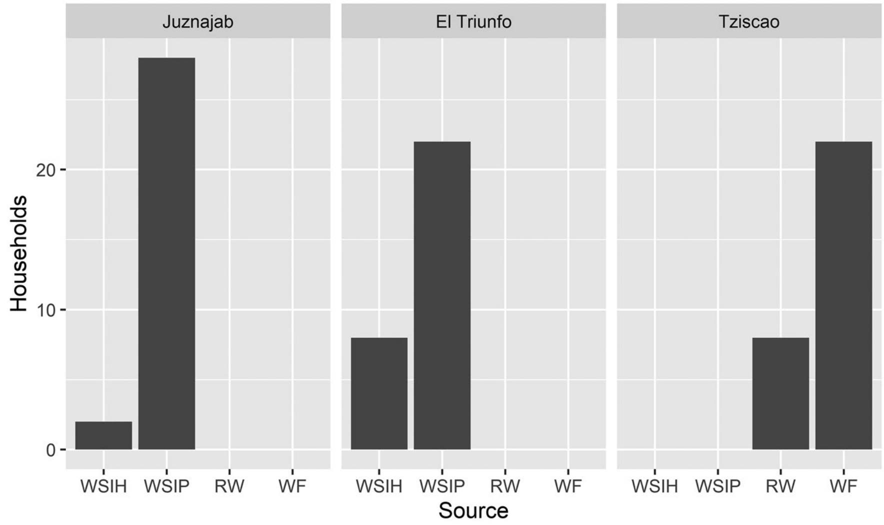

Fig. 2 Frequency of the primary water source for human use and consumption in three communities of the RGC-LM, Chiapas. Answers from a semi-structured interview (2019 and 2020). WSIH: water service inside the house; WSIP: water service inside the property; RW: rainwater harvesting; WF: water fetching

El Triunfo, located in the middle basin, has intensive agriculture activity. In this community, water is supplied through a well, in which 77% of the homes have water service inside the property, and 23% have water service inside the house (Fig. 2). The community handles pumping and water chlorination without any fee, and water scarcity is mainly due to the location of the household. Due to low pump pressure, homes on steep slopes do not receive sufficient water.

Despite being located within a Protected Natural Area and a lacustrine system, the community of Tziscao lacks a formal water service. Locals noted that they had made demands on the municipal government, but they still have received no response. Therefore, access to water is mainly via water fetching from the lake or the river and rainwater harvesting (Fig. 2). Another way to get water is to purchase water tanks (1000 L) from the river, the cost of these ranging between USD 5 and USD 7.5 each. In Tziscao, the interviewees mentioned that water scarcity in households is mainly due to low storage capacity and the scarcity of rain. On the other hand, we registered that bottled water represents the main water supply for drinking and cooking in 73% of households in the three communities.

Collective organization and community agreements

As already mentioned, the *Asamblea Ejidal* represents the decision-making process for water and land management in these communities. Proposals are put to the vote and are accepted if the majority agrees. Those attending the *Asamblea* are male farmers, and a woman can participate if she is a widow or sole heir to an *ejido*.

To evaluate the collective organization in water management, we addressed aspects involving community agreements, community cooperation, and actions to improve access to water. Based on the interviews, most respondents, between 100 and 83%, mentioned community agreements for water management in the three communities (Fig. 3). The main actions carried out in Juznajab and El Triunfo are related to water quantity, specifically to avoiding the excessive use of water. Concerning water use for agricultural activities, in Juznajab, household

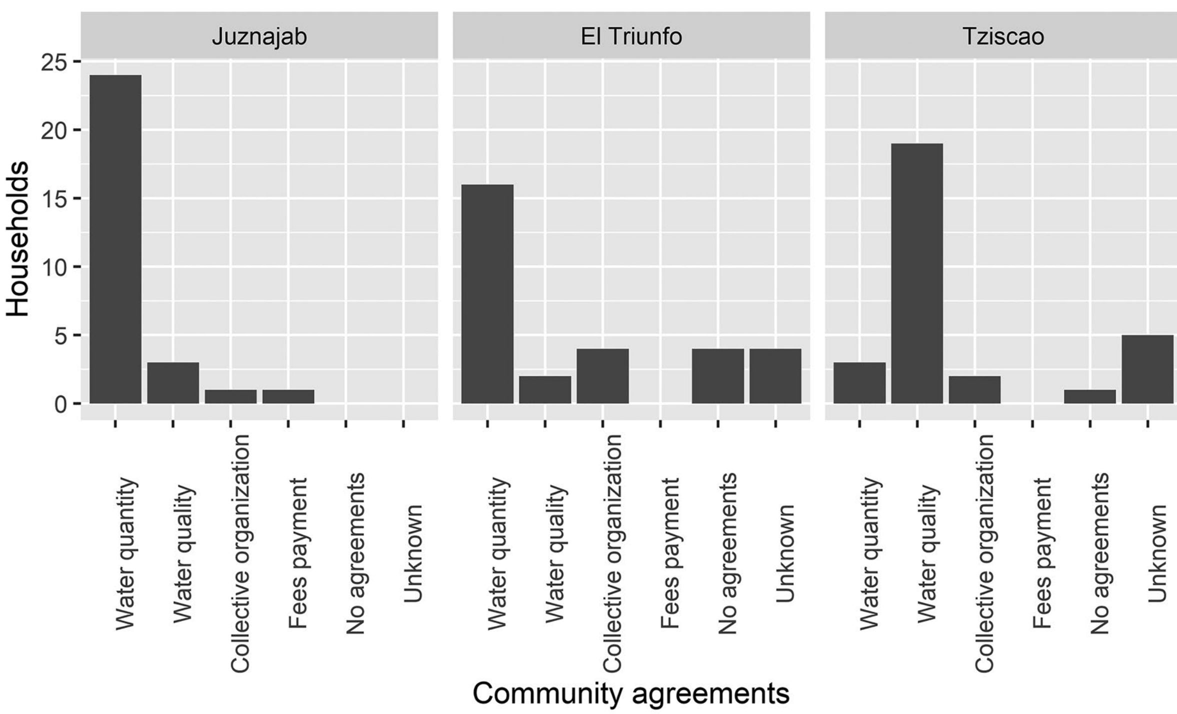

Fig. 3 Types of community agreements around water management in three communities of the RGC-LM, Chiapas. Answers were obtained through a semi-structured interview (2019 and 2020)

crop irrigation is restricted in the dry season, limiting vegetable cultivation and potentially affecting the family's diet. Water-quality care was mentioned most in Tziscao, referring to the need for chlorination and preventing the use of soaps and agrochemicals near water bodies. Some people mentioned the creation of water management committees within the collective organization agreements. The payment of community fees was another agreement, and other respondents mentioned that there were no agreements, or if there were, they did not know about it.

In terms of improving access to water, answers were focused on the need for a water supply system. In Tziscao, 63% of the respondents consider it necessary to have water inside the house through external support, either from the government or civil associations. In contrast, responders from Juznajab and Tziscao who have water services consider it necessary not to waste water or use less water. Under this heading, adaptive actions to improve water access at the household level in the three communities are related to the quantity of water: 55% refer to reducing their water use and storing more water.

Hygiene and sanitation habits

The lack of adequate water supply service in the three communities studied makes it essential to verify water disinfection practices for human use and consumption. Only 37% of the households disinfect water for drinking. Boiling water is the most widely used method in the three communities, a practice that can imply firewood harvest and consumption. On the other hand, fewer than 50% of households in Juznajab and Tziscao have a facility for washing their hands with water and soap, compared to 77% in El Triunfo. Regarding wastewater disposal, between 77 and 90% of the families use this for household crop irrigation in the three communities. Sewage disposal is performed through septic tanks in 80% of the homes due to the absence of a drainage system and a wastewater treatment plant facility.

Health and water sources

Health is a crucial factor affected by the absence of continuous and safe water. In the communities studied, 22% of those surveyed claimed to have had a gastrointestinal problem in the last year, but only 7% associated it with the drinking water, among which four inhabitants were in Juznajab and three in El Triunfo. The same interviewees perceive supply water sources as dirty or contaminated.

Regarding health services, 88% of those interviewed mentioned having a public-health service, 90% in Juznajab, 37% in El Triunfo, and 100% in Tziscao. Nevertheless, the service is considered deficient because physicians are rarely found in the clinics, and medicines are in short supply in the three communities. In this case, seeking care at private medical services is inaccessible for most persons, and only one person mentioned having access to a private medical service in El Triunfo.

Water quality and management practices

A total of 153 household water samples in Juznajab, El Triunfo, and Tziscao were obtained from different supply sources during 2019 and 2020. Table 2 shows the results of the three communities. The pH values were mainly homogeneous and around 8, all within the permissible limits of the Mexican Standard (6.5–8.5). The conductivity values are suitable according to WHO (2006) (<2500 μS/cm); we employed recommendations of this organization since the Mexican regulations do not consider this parameter. Turbidity values fell within the permissible limit of the Mexican Standard (5 NTU), although we found some atypical values above this limit in the different sources.

Free chlorine was measured to corroborate disinfection in supply sources. El Triunfo was the only community that complies with the recommended by Mexican regulations (0.2–1.50 mg/L). The remainder does not use chlorination as a disinfection method. Although the mean values of ammonia were found below the permissible limit (0.5 mg/L) by Mexican regulations, there are high values recorded in some samples in Tziscao, with high concentrations of ammonia in water indicating possible sewage or animal waste contamination. Likewise, the nitrate concentrations reported fell below the limit of 10 mg/L established by the Mexican standard. Nevertheless, some water samples in El Triunfo and Tziscao presented higher concentrations. Nitrate is used mainly in inorganic fertilizers, and its presence in

Table 2 Physicochemical and microbiological parameters of water quality in three rural communities in Chiapas, Mexico

Community	*n*	Metric	pH	Conductivity (µS/cm)	Turbidity (NTU)	Free chlorine (mg/L)	NH_4^+ (mg/L)	NO_3^- (mg/L)	Total coliforms (CFU/100 mL)	*E. coli* (CFU/100 mL)
Juznajab		Median	8.16	438.2	1.06	0.03	0.17	0.56	0	0
	30	SD	0.11	53.54	1.29	0.01	0.10	0.38	244.4	0
		Min/max	7.82/8.28	372.2/590.1	0/5.82	0/0.04	0.02/0.44	0.2/1.81	0/1 100	0/0
El Triunfo		Median	7.53	735	0.06	0.25	0.45	3	0	0
	60	SD	0.47	218.67	0.94	0.15	0.12	9.73	1397.5	0
		Min/max	6.62/8.46	72.7/981.2	0/6.4	0/0.65	0.01/0.35	0/31.91	0/8 200	0/0
Tziscao		Median	7.94	296.9	0.77	0.01	0.03	1	600	0
	63	SD	0.38	147.99	1.67	0.01	0.38	5.07	1882.32	185.79
		Min/max	5.84/8.96	8/777.8	0.02/7.81	0/0.03	0.01/2.34	0.12/31.58	0/10 000	0/1 000

groundwater and surface water is usually low. Nonetheless, it can reach high levels because of leaching or runoff from agricultural land or human or animal waste contamination.

Mexican regulations establish 2 CFU/100 mL as a permissible limit for total coliforms. Since this does not refer to the concentration of *E. coli*, it was evaluated by WHO (2006), which establishes 0 CFU/100 mL as a safe water goal, whose presence is considered evidence of recent fecal contamination. The presence of total coliforms was generally low in Juznajab and El Triunfo, and in Tziscao, it was higher, with a median of 600 CFU/100 mL. We registered an absence of *E. coli* in Juznajab and El Triunfo; otherwise, in Tziscao, there was 1000 CFU/100 mL.

The results of household water quality were calculated according to the supply source type (Table 3), which corresponds to bottled water, lake, rainwater, river, and well samples. We consider it relevant to show this because the water source can determine its quality and influence management practices. Therefore, we will discuss only those that stand out.

The conductivity values were heterogeneous for the different supply sources. Rainwater samples had the lowest mean value of 22.3 µS/cm, well water samples had the highest value of 735 µS/cm, and bottled water showed a more significant rank in the records. The means of the turbidity values fell within the permissible limit of the Mexican Standard (5 NTU), having some maximum values above this parameter in the different sources. Well water was the only source that complied with free chlorine concentrations by Mexican regulations (0.2–1.50 mg/L) and some bottled water samples. Bottled water samples showed the highest concentrations registered regarding ammonium and nitrate concentrations.

Total coliforms were mainly detected in rainwater and river water, with a median of 850 CFU/100 mL and 1600 CFU/100 mL, respectively. Although *E. coli* concentrations are significantly lower than total coliforms, they are still high for human consumption. The highest record was in rainwater and river water, with a 50 CFU/100 mL median, followed by the maximum value in bottled water. The presence of bacteria in bottled water is worrisome because it is usually consumed directly without any previous disinfection treatment.

The PCA results are described in two principal components, of which 53% of the variance is

Table 3 Physicochemical and microbiological parameters from different water supply sources, collected in households in Chiapas, Mexico

Water source	*n*	Metric	pH	Conductivity (µS/cm)	Turbidity (NTU)	Free chlorine (mg/L)	NH_4-N (mg/L)	NO_3^- (mg/L)	Total coliforms (CFU/100 mL)	*E. coli* (CFU/100 mL)
Bottled		Median	7.89	317.4	0.2	0.025	0.17	1.74	0	0
	58	SD	0.22	253.69	1.34	0.14	0.38	10.46	1521.04	31.96
		Min/max	7.52/8.46	72.7/981.2	0/6.97	0/0.54	0.01/2.34	0/31.91	0/8 200	0/200
Lake		Median	8.16	433.5	0.62	0.03	0.15	0.56	0	0
	30	SD	0.10	63.25	1.29	0.01	0.10	0.32	243.24	0
		Min/max	7.82/8.28	265/590	0/5.82	0/0.04	0.02/0.44	0.2/1.6	0/1 100	0/0
Rainwater harvest		Median	8.11	22.3	0.57	0.01	0.02	0.58	850	50
	17	SD	0.64	113.91	2.08	0.01	0.08	0.55	2645.72	112.36
		Min/max	5.84/8.96	8/472.6	0.09/7.81	0/0.03	0.01/0.28	0.12/2.25	0/10 000	0/300
River		Median	7.94	298	0.76	0.01	0.03	1	1600	50
	17	SD	0.24	126.19	1.23	0.01	0.06	3.58	1694.4	309.84
		Min/max	7.7/8.78	10.3/375.7	0.05/4.1	0/0.03	0.01/0.21	0.43/14.14	100/6 000	0/1 000
Well		Median	7.16	735.1	0.17	0.37	0.01	1.17	0	0
	31	SD	0.25	66.92	1.26	0.14	0.03	4.67	787.7	0
		Min/max	6.62/7.85	544.3/922.2	0/6.4	0.06/0.65	0.01/0.19	0/12.21	0/4 000	0/0

explained. We used a scree-plot criterion to select the principal components, of which three had an eigenvalue equal to 1. However, employing three principal components might not be the best way to visualize the data. The PCA analysis aimed to enhance the discussion concerning the relationship of water quality with management practices in the studied communities. We analyzed the results according to water access practices. Four different types were identified: rainwater harvesting, water fetching, water inside the house, and water inside the property (Fig. 4). The two water groups inside or outside the household did not show substantial differences in chlorine concentrations, conductivity, and pH, corresponding to groundwater characteristics in karstic environments and disinfection practices. Rainwater harvesting is related to nitrates and total coliforms. Water fetching presented a variation in water quality related to ammonia, microbiological indicators, and turbidity; this practice is related to the lowest water quality. Water fetching is present in Juznajab, where there is a lack of water infrastructure, which puts the water quality at risk when it is transported and stored.

Barriers and bridges around water access

The results of this analysis arise from the differences in water access and management among the three communities (Table 4). We present barriers and bridges, individual and collective, in the columns and six main challenges around water management in rows. This table summarizes the most outstanding results of the different methods that we applied. Based on water quality results (Tables 2 and 3), we infer the barriers and bridges as qualitative indicators. This interpretation is the base of Table 4. For example, the presence of coliform bacteria and *Escherichia coli* and low concentrations of free chlorine at a community level (Table 2) were related to the lack of a disinfection method mentioned in the interviews.

For access to water in sufficient quantity for human use and consumption, Tziscao is the community that faces the most significant barriers due to its need for water fetching, which implies a higher economic expense and investment of time. Lack of knowledge about disinfection methods represents a risk to health, which has been diminished by certain practices such as boiling water.

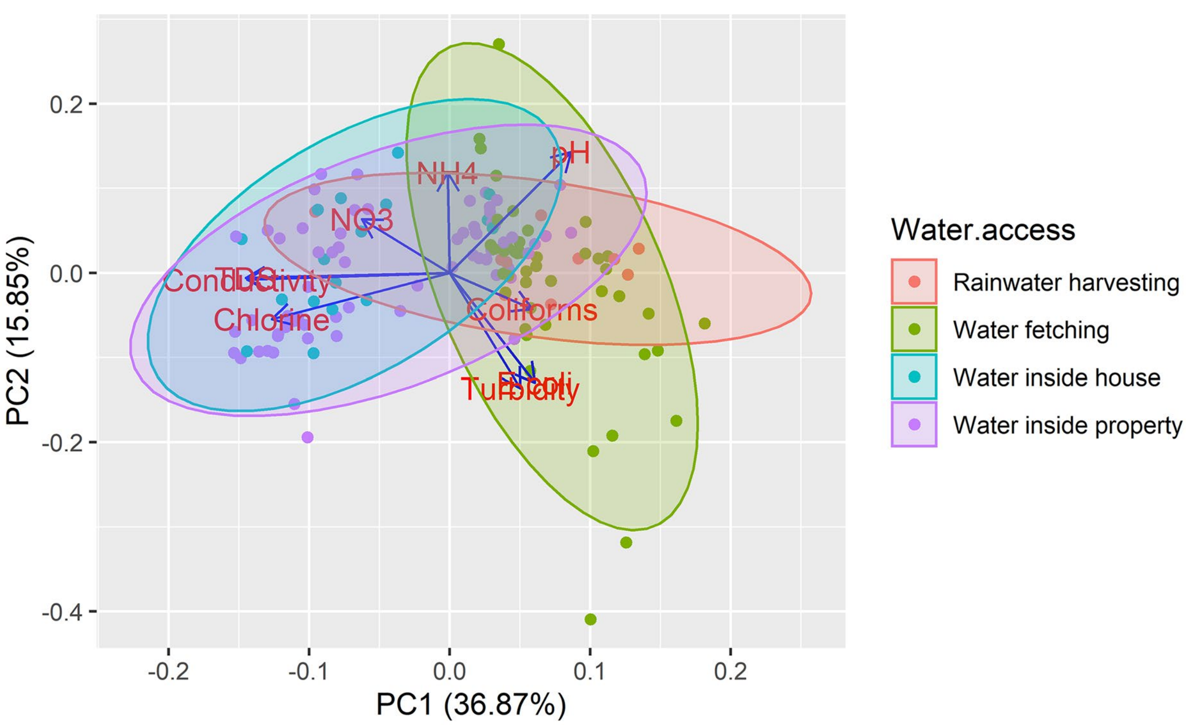

Fig. 4 Principal component analysis of water-quality parameters by type of water access in households

Table 4 Barriers and bridges around community-based water management in rural communities of the RGC-LM watershed, Chiapas

Community	Barriers		Bridges	
	Individual	Collective	Individual	Collective
I. Access to water in sufficient quantity				
Juznajab	Households on steep slopes or far from the supply source Low storage capacity	Deficient maintenance of water pumping	Installation of water storage tanks	Payment of community fees for maintenance and repairing
El Triunfo	Households on steep slopes or far from the supply source	Deficient maintenance of water pumping	Installation of water storage tanks	
Tziscao	Low storage capacity Low income for buying bottled water	Lack of a water supply service Sale of water tanks informally	Rainwater harvesting	Construction of community water tanks
II. Access to water of adequate quality				
Juznajab	Low use of disinfection methods	Lack of knowledge and monitoring of water quality	Boiling water as a disinfection method	Restricted activities near the lake
El Triunfo	Low use of disinfection methods	Lack of knowledge and monitoring of water quality	Boiling and chlorination as a disinfection method	Well disinfection practices
Tziscao	Water fetching and storage for a long period Lack of use of disinfection methods	Low maintenance of community water tanks	Boiling water as a disinfection method	
III. Access to water for household crop irrigation				
Juznajab	Inadequate quantity and quality of irrigation	Irrigation restriction in the dry season	Sowing rainfed crops	Agreements to plant rainfed crops
El Triunfo	Inadequate quantity and quality of irrigation	Lack of adoption of low-consumption irrigation systems	Sowing rainfed crops	
Tziscao	Inadequate quantity and quality of irrigation		Rainwater harvesting for irrigation Sowing rainfed crops	Rain most of the year
IV. Hygiene and sanitation facilities				
Juznajab	Lack of adequate facilities for personal and household hygiene	Lack of sewage and medical services	Recognition of the handwashing importance	Replacement of latrines with toilets
El Triunfo	Lack of adequate facilities for personal and household hygiene	Lack of sewage and medical services	Recognition of the handwashing importance	Replacement of latrines with toilets
Tziscao	Lack of adequate facilities for personal and household hygiene	Lack of sewage and medical services	Recognition of the handwashing importance	Replacement of latrines with toilets
V. Collective organization				
Juznajab	Disinterest or ignorance of community agreements	Restrict the participation of women	Be aware of community agreements about water quantity	Water management and vigilance committee Payment of community fees Community-based forest management

Table 4 (continued)

Community	Barriers		Bridges	
	Individual	Collective	Individual	Collective
El Triunfo	Disinterest or ignorance of community agreements	Restrict the participation of women	Be aware of community agreements about water quantity	Water management committee
Tziscao	Disinterest or ignorance of community agreements	Restrict the participation of women	Be aware of community agreements about water quality	Water management committee Tourism and conservation committees
VI. Climate variability				
Juznajab	Uncertainty about rain variability	Community agreements based on rain uncertainty	Postponement of rainfed planting	Agreements about water care in the dry season Reforestation plans
El Triunfo	Uncertainty about rain variability	Decisions based on the uncertainty of the rainy season	Postponement of rainfed planting	Access to groundwater
Tziscao	Uncertainty about rain variability	Decisions based on the uncertainty of the rainy season	Postponement of rainfed planting	Federal conservation agreements

Most families have a small crop inside their household, where vegetables and maize are irrigated with wastewater of inadequate quality because there is no drainage system, and irrigation is prohibited in the dry season. The lack of facilities for hygiene and sanitation represents individual and collective barriers. In recent years, the replacement of latrines with toilets has been promoted in these communities. However, sharing a facility to wash dishes, clothes, and hands represents a health risk, considering that clothing can contain agrochemicals and pathogens.

The main barriers to the collective organization are disinterest or ignorance about community agreements and the exclusion of some stakeholders from decision-making during the *Asamblea*, principally excluding women. However, most residents know about and carry out community agreements for water care and soil management, promoting bridges for safe access to water. Creating committees has also made it possible to monitor and maintain these agreements.

The last challenge for water access is climate variability, a complex phenomenon in which we only address the aspects of rainfall variation mentioned in interviews. Uncertainty concerning the rainy season represents a barrier that affects individual and collective decision-making, such as sowing and rainwater harvesting. On the other hand, individuals have acted in terms of water care, especially during the dry season, and they have implemented reforestation plans to promote the frequency of rain.

Discussion

Water management context

In rural areas of Mexico and other low-income countries, community-based rules or agreements are the usual way of managing water. However, access to water in quantity and quality is not always guaranteed (Cavender-Bares et al., 2015; COMDA, 2017; Zamudio, 2020). It has been suggested that community-based management may also positively affect the capacity for the development and empowerment of communities to manage their resources (Agarwal & Narain, 1999; Kearney et al., 2007; Zamudio, 2020). Community-based management arises from the interaction of stakeholders with the ecosystem through decision-making, which can limit or favor access to water on an individual or collective level (Alexander et al., 2016; Barranco, 2020). We identify this duality as barriers and bridges, which can hinder or impede access to water or create a window of opportunity to improve community-based management.

We analyzed three case studies in the RGC-LM watershed in the present study. Despite their being in the same basin, their inhabitants approach solution strategies for access to water differently. The main results showed that the studied communities do not have sufficient access to water in quantity and quality. In Juznajab and El Triunfo, the household water service could be considered *basic*, while in Tziscao, it is *limited* or *unimproved* according to WHO (2017), which criteria on accessibility, availability, and quality of drinking water services are included.

Water quantity and quality

To address the lack of water for human use and consumption, whether individually or collectively, storage capacity was the main bridge mentioned in the three case studies. However, water storage becomes a difficult task when it is necessary to go to the sources, as in the case of Tiszaco. The absence of infrastructure for water supply is the main barrier to accessing an adequate amount of water for the members of a family.

The water-quality monitoring provided evidence of fecal contamination in the three communities; Tziscao had the highest records of up to 10,000 CFU/100 mL of total coliforms and 1000 CFU/100 mL of *E. coli*. This situation could be related to management practices at the household level, such as water fetching and long storage time, which propitiate conditions for the proliferation of microorganisms (Falkenberg et al., 2018; Vázquez-Salvador et al., 2020). The remainder of the parameters is generally adequate conditions for human consumption according to Mexican Regulations (DOF, 2000), with some exceptions for nitrogenous nutrients. Bottled water presented the worst conditions compared to other water sources, which is of concern because bottled water is consumed without any disinfection treatment. Communities have implemented the boiling of water from natural sources to avoid purchasing bottled water, a significant economic expense for marginalized communities. On the other hand, the lack of adequate facilities for personal and household hygiene represents a barrier to sanitation, which is part of Goal 6 of Sustainable Development (UN-Water, 2015). Hand-washing and hygiene practices can mitigate waterborne diseases (Falkenberg et al., 2018), which is crucial, especially with exposure to COVID-19.

A common practice in these communities is household crop irrigation with wastewater. It has been argued that wastewater is an alternative source for agricultural irrigation and a sustainable solution for water scarcity (Asano, 2005). However, in low-income countries, wastewater quality for irrigation is not under control and can be a risk to human health (Vázquez-Salvador et al., 2020). Having a household crop allows communities to diversify their diet; therefore, we consider that restricting irrigation, which comprises a community agreement, represents a potential barrier to access to safe food.

Barriers and bridges around water management

We identified that the lack of water infrastructure and water fetching represents an important barrier on the individual and collective scale. Other studies suggest that water fetching is the highest impact on women and children in poorer rural areas and is likely to be a significant barrier to household water security and sustainable development (Geere & Cortobius, 2017) and a significant risk to health (Geere et al., 2010). Tziscao is the community that performs water fetching in the highest proportion; however, Juznajab and El Triunfo have access to water restricted to certain hours of the day since pump failure is frequent and forces them to seek water from other sources. As described in low- and middle-income countries, households often use more than one source to meet their daily water needs. These can represent an opportunity or bridge to bolster resilience (Elliott et al., 2019).

The collective organization has been one of the key aspects of community-based management (Kearney et al., 2007). The capacity of individuals to organize themselves effectively and together with leadership is often seen as crucial for the initiation of management at the community level (Bodin & Crona, 2008; Olsson et al., 2004). Therefore, a collective organization could be the main bridge for access to water on a collective level since recognition of a collective organization by most community members guarantees compliance. It has been studied that collective values strengthen social ties and promote community participation through norms and agreements established within assemblies or vigilance committees (Barranco, 2020). Establishing a relationship between individuals and their environment means empowering the community to manage its resources as a common good, promoting equity and, in the long term, the sustainability of water use (Agarwal & Narain, 1999).

To develop water management effectively, the role of women as water managers must be recognized and incorporated into the decision-making processes (Geere & Cortobius, 2017). It has been reported that women and girls are responsible for water collection in eight out of 10 households with water off properties (WHO, 2017). In this respect, reducing the time and distance of water fetching is vital because it could improve the amount of water available and foster gender equity in women's decision-making and participation in community-based water management (Panda, 2006).

"Global change, and in particular climate change, pose considerable challenges to water management and governance" (Pahl-Wostl & Kranz, 2010). Uncertainty about rainfall and temperature enhances existing challenges or creates new ones that communities confront concerning water management (Haro et al., 2021; Pahl-Wostl et al., 2010). In these communities, the uncertainty about the rainy season represents a barrier whose implications affect decision-making about the irrigation of domestic crops and the proper use of water sources. To compensate for the variability of the rains, community agreements have been reached on agricultural activities, reforestation plans, and water for irrigation, especially in the dry season, which are considered a collective agreement for adaptation bridge.

Since the study of resource management produces different types of knowledge, it must be integrated into an inclusive framework, which must be flexible and incorporate processes at different scales (Pahl-Wostl & Kranz, 2010). Therefore, this work integrated the analysis of different methods to present a comprehensive perspective of community-based water management. The institutional perspective was not included due to the fieldwork limitations during the pandemic and the government change in Chiapas. To enhance this work, it is necessary to analyze the external factors that shape community-based management. Although the vision of this article is on community water management, it would be enriching to know the current and future position of federal and municipal governmental institutions in the water sector in this region. We consider that understanding the practices around water management and determining barriers and bridges (Pahl-Wostl & Kranz, 2010) contribute to recognizing the importance of community-based water management in low-income countries and identifying opportunities for change.

Conclusions

We identify barriers and bridges that arise from decision-making processes, through mixed methods, as the first step to addressing community-based water management in marginalized communities in Southern Mexico. We collected evidence in three case studies, where access to water is differentiated by a diversity of practices at an individual and collective level. Our results reveal that these communities have basic-to-unimproved household drinking water services. The lack of water infrastructure and distribution capacity comprise the main barriers to access to water, promoting water fetching, whose implications mainly affect women and children. Through community agreements and norms, the collective organization became the main bridge for access to water on a collective scale. Their recognition by the majority of community members guarantees their compliance for the long term as a present and future strategy for access to water. Decision-making must be considered in an equitable and solidary way, that is, considering within this process the fundamental role that women play in water management since they invest time and effort in access to water for all family members. Finally, it is crucial to recognize the impacts that climate change has on the already established challenges of community-based water management.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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Discusión general

Se ha discutido ampliamente que el acceso al agua representa uno de los principales retos transversales para lograr el desarrollo sostenible (ONU, 2010; Panda, 2006; Rodríguez-Izquierdo et al., 2023; WHO, 2003). Sin embargo, poco se ha hablado sobre las brechas de acceso al agua bajo la gestión comunitaria (Zamudio, 2020). En esta tesis se aborda no solo el contexto sobre la vulnerabilidad hídrica bajo un enfoque biofísico, sino que, se analizan los factores socioecológicos que representan barreras o puentes para el acceso al agua bajo el esquema de manejo comunitario. El manejo del agua dentro de un sistema socioecológico considera las múltiples interacciones que ocurren entre las actividades humanas con los sistemas hidrológicos, las cuales ocurren a diferente escala simultáneamente (Sivapalan et al., 2014). El manejo comunitario ha sido la principal estrategia de las comunidades rurales para acceder a los recursos, tanto de agua como del suelo y la vegetación (Barranco-Salazar, 2020; Bocco, 2019; Zamudio, 2020). Por lo tanto, reconocer su importancia y evaluar tanto sus retos como oportunidades resulta fundamental para transitar hacia vías sostenibles de gestión, sobre todo en comunidades marginadas y en países con economías emergentes. A continuación, se abordarán las preguntas de investigación planteadas en este trabajo para desarrollar la discusión.

Para conocer **¿cuáles son las condiciones hidrológicas actuales en la cuenca RGC-LM?** se realizó un análisis de vulnerabilidad hídrica el cual arrojó como resultado una vulnerabilidad heterogénea debido a la presencia de fuentes potenciales de contaminación, principalmente las actividades agrícolas y la descarga de aguas residuales. Siendo la cuenca RGC-LM un sistema kárstico es particularmente vulnerable a la contaminación del agua subterránea debido a su alta conductividad hidráulica y sus rápidos procesos de infiltración que permiten la entrada rápida de escorrentía y contaminantes en el acuífero (Kovarik et al., 2017). Sin embargo, las fuentes de agua superficial también han sido afectadas por diversas fuentes de contaminación. En la cuenca habitan cerca de 190 mil personas (INEGI, 2020), por lo que mantener las fuentes de agua seguras, en este sistema kárstico, es indispensable tanto para los seres humanos como para los ecosistemas.

Para abordar **¿cuál es el contexto socio-ecológico en el que se desenvuelve el manejo comunitario del agua en la cuenca RGC-LM?** este trabajo se basó en tres casos de estudio, Juznajab la Laguna, El Triunfo y Tziscao, los cuales pertenecen al 85% de las localidades de categoría rural de la cuenca RGC-LM, mientras que solo el 15% son localidades de tipo urbano. Todas ellas localizadas en el estado de Chiapas, uno de los estados con mayor rezago social de México (Rodríguez-Izquierdo et al., 2023) y el segundo a nivel país en marginación (CONAPO, 2020), lo cual refleja un lento desarrollo y una calidad de vida muy baja para los pobladores de estas comunidades (De la Vega-Rivera y Rodríguez-Izquierdo, 2023). Estas condiciones socioeconómicas influyen de manera directa en el acceso al agua, lo cual está determinado por la capacidad que tenga la población de acceder a una fuente de agua, la capacidad de gestionar el recurso y la capacidad de generar acuerdos para su uso, entre otros. Por otro lado, en la cuenca RGC-LM las condiciones biofísicas también representan un reto debido a que diversas fuentes de agua se encuentran en un estado vulnerable de contaminación, principalmente por la pérdida de la cobertura vegetal impulsado por las actividades agrícolas y la descarga de aguas residuales (Alvarado, 2022a). Bajo estas condiciones socioecológicas en las que se desenvuelve el manejo comunitario del agua, al acceso al agua resulta un reto para satisfacer las necesidades de abastecimiento a la población. Sin embargo, existen también condiciones socioecológicas favorables que permiten el acceso al agua, como la organización social, que establece normas de uso y manejo del agua, así como la presencia de fuentes de abastecimiento aún de buena calidad y las tasas altas de precipitación que permiten la colecta de lluvia por varios meses, entre otros.

Para esta tesis se planteó como pregunta final **¿cuáles serían las principales barreras y puentes para el acceso al agua en comunidades rurales?** para ello, se identificaron dentro de la organización comunitaria factores que representan oportunidades o retos para acceder al agua. Como ya se ha mencionado en la sección de marco teórico, las comunidades rurales de México y de otros países similares enfrentan retos intrínsecos para el acceso al agua, como la marginación, la ubicación geográfica, la falta de voluntad política, etc. Sin embrago, el contexto local permite identificar estos factores a una escala individual y comunitaria que permitan evaluar las condiciones para promover cambios hacia trayectorias sostenibles. Se ha argumentado que la escala de comunidad tiene un importante potencial para influir en el cambio y representa una parte crucial para el desarrollo y la orientación de los sistemas sociales y económicos hacia la sostenibilidad, la justicia social y la equidad (Bodin, 2017; Bodin y Crona, 2008; Hopkins, 2008). En este trabajo es importante resaltar que el manejo comunitario de los recursos refuerza la idea de la autoorganización, ya que el objetivo no es la centralización de la toma de decisiones sino compartir experiencias, conocimientos, habilidades e ideas sobre las mejores prácticas (Hopkins y Lipman, 2009).

Sin embargo, no se pueden perder de vista los principales retos que enfrentan las comunidades para el acceso al agua, cuya causa principal es la infraestructura inadecuada para transportar y almacenar agua. Los gobiernos a menudo no priorizan la inversión en infraestructura en las comunidades rurales, lo que lleva a la falta de acceso a agua limpia en los hogares. Por lo tanto, el acarreo resulta la principal actividad para acceder al agua desde las fuentes de abastecimiento, como lagos, ríos o pozos, realizado principalmente por mujeres y niños (Geere et al., 2010; Geere y Cortobius, 2017; Panda, 2006). En el caso particular de Tziscao, donde la comunidad carece completamente de infraestructura hidráulica, el acarreo de agua en cántaros es una práctica común, lo cual implica una inversión significativa de tiempo y esfuerzo de mujeres y niños, restando oportunidad para realizar otras actividades de placer o recreación. Por su parte, las personas con mayor poder adquisitivo compran tinacos de agua de 1,100 L que son entregados en su vivienda. Sin embargo, ello implica un gasto de entre $400 o $500 pesos al mes, lo cual representa hasta 10 veces más en promedio de lo que paga un ciudadano de la Ciudad de México (Ortega-Font, 2018).

Otra de las causas de la crisis del agua en las comunidades rurales de México son los efectos del cambio o variabilidad climáticos. Esto ha provocado sequías más frecuentes o retrasos de la lluvia (Haro et al., 2021), lo que dificulta aún más el acceso al agua para las comunidades. Para enfrentar esto, algunas comunidades de la cuenca RGC-LM, como Juznajab la Laguna, han implementado acuerdos que restringen el uso del agua para riego, incluso en cultivos de traspatio, los cuales son parte fundamental de la dieta de las familias (Ávila, 2017). El incumplimiento de estos acuerdos implica por lo regular multas económicas, sin embargo, estos acuerdos son tomados solo por algunos miembros de la comunidad que cuenten con títulos ejidales dentro de las asambleas (DOF, 1992), en las que las mujeres no participan a menos que su esposo haya fallecido. Si bien se ha reconocido que la autoorganización es una capacidad fundamental para la transición a hacia la sostenibilidad (Bodin, 2017; Mostert et al., 2007), es importante reconocer que los acuerdos deben sumar a todos los usuarios para representar la mayor diversidad de intereses y no ponderar unos sobre otros (Barnes et al., 2017; Márquez y Legorreta, 2017).

Por lo tanto, ¿será posible promover cambios dentro del manejo comunitario para promover la transición del acceso al agua hacia estados más sostenibles? Esta tesis propone que la identificación de factores como barreras o puentes son el primer paso para ello. En este trabajo las barreras y puentes para el acceso al agua bajo un contexto de manejo comunitario se refieren a las prácticas individuales y colectivas que se realiza la población para obtener agua o a los factores externos, como el clima, que también influyen en el acceso al agua.

En la Figura 3 se ilustran los resultados de un análisis mixto de los tres casos de estudio en la cuenca RGC-LM con la finalidad de enriquecer esta discusión. En esta ilustración no se pondera la toma de decisiones comunitarias, únicamente se ejemplifican factores que promoverían o no una trayectoria más sostenible del manejo del agua. Por ejemplo, se ilustra que la toma de decisiones colectiva puede promover trayectorias sostenibles, sin embrago, es necesario la inclusión de la participación de las mujeres y otros grupos minoritarios (Panda, 2006). Por otro lado, el acarreo de agua resulta una barrera a superar (Geere y Cortobius, 2017), y por el contrario la captación de agua de lluvia podría generar nuevas posibilidades de acceso al agua (González-Padrón, et al., 2019). Consiguientemente, un cambio ya sea profundo o no, requiere cambios en la toma de decisiones y en el comportamiento humano a diferentes escalas ya sea comunitario, local, municipal, estatal o regional (Barnes et al., 2017).

Figura 3. Trayectorias del manejo comunitario del agua, representación gráfica de los resultados de Alvarado et al (2022b). Diseño digital por Viridiana Bamba.

Durante el trabajo de campo entre 2019 y 2020 se realizaron entrevistas domiciliarias y actividades colectivas como el mapeo participativo en las tres comunidades de estudio, de estos encuentros se compilaron diversos testimonios de los pobladores que considero valiosos plasmar para el cierre de esta tesis. A continuación, se muestran algunos de ellos.

"Algunas personas de la comunidad no tienen agua, porque su casa está en lo alto, nosotros les regalamos un tambito cuando ocupan agua" – Usuaria, Juznajab la Laguna.

"Antes el presidente (presidente municipal de Comitán) nos apoyaba con el asunto del bombeo, después nos dejó de apoyar y nosotros nos hacemos responsables" – Usuaria, Juznajab la Laguna.

"Eso si no, no tenemos suficiente agua para regar, si no llovió bien, se secan nuestras matitas, no tenemos agua para las hortalizas" – Usuaria, El Triunfo.

"Como no sirve la bomba, yo les doy agua a los vecinos, porque yo tengo un tanque, me da lástima los viejitos porque no pueden cargar el agua. Si nos ayudamos entre nosotros" – Usuaria, Tziscao.

"Yo no tengo seguro que el agua de la laguna y el río lleguen a los Lagos de Montebello, por eso no pienso hacer nada" – Usuaria, Juznajab la Laguna.

"El gran error que hemos cometido los seres humanos es no cuidar los bosques" – Miembro de comité de vigilancia, Juznajab la Laguna.

Conclusiones

Este trabajo ha sido enmarcado bajo el enfoque de sistemas socio-ecológicos como un concepto que permite explorar las interacciones entre los humanos y el agua, con el fin de acceder a ella para cubrir las necesidades de abastecimiento humano y de riego agrícola. El acceso al agua segura y suficiente es un derecho fundamental para los humanos y el funcionamiento de los ecosistemas. La cuenca RGC-LM al ser un sistema kárstico, presenta áreas con una alta vulnerabilidad hídrica, las cuales deberían ser consideradas como prioritarias en el manejo de la cuenca para garantizar la protección de las fuentes de agua que sirven para el abastecimiento humano. Es importante reconocer que las principales fuentes de contaminación dentro de la cuenca son las actividades agrícolas y la descarga de aguas residuales. Sin embargo, existen pocos esfuerzos para integrar a las comunidades para el planteamiento de soluciones ante esta problemática. Las comunidades de la cuenca RGC-LM, han enfrentado importantes desafíos para acceder al agua, pero también han encontrado oportunidades de gestión comunitaria.

Diversos estudios han descrito el rol de los sistemas sociales en el manejo de los recursos, sin embargo, pocos de ellos han profundizado en casos de estudio en contextos rurales en países en desarrollo. Este trabajo contribuye a la identificación de barreras y puentes para el acceso al agua dentro de un contexto comunitario en tres casos de estudio, lo cual, representa uno de los primeros pasos para guiar trayectorias hacia estados más sostenibles de acceso al agua. Esta contribución permite explorar las posibilidades socioecológicas de mejorar las condiciones de acceso al agua en comunidades rurales, marginadas y bajo la ausencia de instituciones gubernamentales.

Las principales barreras que se identificaron a nivel comunidad fueron la falta de infraestructura hídrica y la baja capacidad para distribuir el agua; en la escala individual la colecta y acarreo del agua tienen el mayor impacto en las mujeres y los niños, y representan una barrera importante para el desarrollo sostenible. En contraste, se pudieron identificar puentes que permiten mejorar el acceso al agua, a nivel comunidad se identificó la organización colectiva, que a través de la implementación de acuerdos y normas representa un factor esencial no solo para el acceso al agua sino para el manejo comunitario de los recursos como el suelo y el bosque; a una escala individual se observó que la recolección de agua de lluvia representaría una alternativa viable para satisfacer la demanda de agua familiar. Las barreras y puentes del manejo comunitario del agua surgen del proceso de toma de decisiones a escala comunitaria e individual o familiar, lo cual implica que la integración de la diversidad de actores es indispensable para representar todas las voces y evitar ponderar unas sobre otras. Por lo tanto, la toma de decisiones debe plantearse de manera equitativa y solidaria, es decir, considerando el papel fundamental que juegan las mujeres en la gestión del agua ya que ellas invierten tiempo y esfuerzo en el acceso al agua para todos los miembros de la familia.

Este trabajo demuestra que es indispensable invertir en el desarrollo de infraestructura hídrica, en campañas sobre higiene y saneamiento, y en sistemas de recolección de agua de lluvia, que incluyan la participación de hombres y mujeres, con ello, el manejo comunitario del agua podría dirigirse hacia soluciones reales que perduren con el tiempo y tal vez empezar a construir trayectorias sostenibles del manejo del agua. Por último, es importante resaltar que este trabajo enfrentó limitaciones en el trabajo de campo debido a la pandemia de COVID-19, lo cual impidió el acercamiento a las comunidades y dificultó la implementación de metodologías participativas que hubieran robustecido los objetivos de esta tesis. Asimismo, reconocemos que la profundización de la cosmovisión de las comunidades y el contexto etnográfico ha sido un elemento poco profundizado en este trabajo, y que sería recomendable ampliar para futuras investigaciones en esta zona de estudio o zonas similares.

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