UNIVERSIDAD AUTÓNOMA DE BAJA CALIFORNIA

INSTITUTO DE INVESTIGACIONES OCEANOLÓGICAS

FACULTAD DE CIENCIAS MARINAS

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“El impacto de los cambios en las asignaciones de agua del río Colorado en los usuarios agrícolas y urbanos de Baja California”

TESIS

Presentada al Instituto de Investigaciones Oceanológicas como requisito parcial para obtener el grado de:

DOCTORA EN MEDIO AMBIENTE Y DESARROLLO

Presenta:

Astrid Hernández Cruz

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Tesis que para cubrir parcialmente los requisitos necesarios para obtener el grado de

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CONTENIDO

RESUMEN

El río Colorado es la principal fuente de agua de Baja California. Sin embargo, la alta dependencia de EUA y México por este río ha generado diversos planteamientos acerca de los problemas que pueden presentarse en función del cambio climático y a las reducciones en las asignaciones de agua. En este trabajo de investigación se utilizó una herramienta de planeación para evaluar el impacto de las reducciones en las asignaciones en los usuarios mexicanos de la cuenca del río Colorado. Se identificaron factores de estrés hídrico y estrategias de manejo para el abastecimiento de agua de los usuarios agrícolas, urbanos y ambientales. Las estrategias de manejo fueron simuladas bajo escenarios de reducciones del río Colorado y comparados con un escenario base. Uno de los principales resultados encontrados fue que el Distrito de Riego 014 (DR-014) será el usuario más afectado por las reducciones en las entregas del Río Colorado. En el escenario más desfavorable (reducción máxima y no tomar acciones adicionales), la sustentabilidad disminuyó de entre el 68% al 43% con respecto al escenario base Esta disminución se refleja en un déficit de agua de 643 Mm^3 para el año 2050, es decir, 30% de la demanda total del DR-014. El sistema actual tiene un mejor rendimiento a costa de la sobreexplotación de los acuíferos a largo plazo. Por otra parte, las transferencias de agua de uso agrícola a urbano, el aumento de eficiencia en la red urbana, el reuso de aguas residuales y la desalinización son las principales posibilidades para mejorar el actual suministro de agua en la zona costa (Tijuana, Rosarito, Ensenada). A través del uso de modelos de planeación y distribución de agua, la presente tesis muestra el espectro de posibles resultados que podrían esperarse desde los efectos de la inacción hasta la aplicación de una cartera de estrategias de manejo. Además de los impactos en el abastecimiento (cantidad) de agua ante las reducciones se estimó el aumento de salinidad en los recursos hídricos del río Colorado. El método desarrollado para la evaluación de las estrategias aplicadas para el uso sostenible del recurso hídrico puede ser aplicado a otras cuencas con problemas de desabasto.

Palabras clave: Río Colorado, modelo de asignación, escasez de agua, México

ABSTRACT

The Colorado river is the main source of water for Baja California. However, the high dependence of the U.S. and Mexico on this river has generated several questions about the problems that may arise due to climate change and possible reductions in water allocations. In this research work, a planning tool was used to evaluate the impact of allocation reductions on Mexican users of the Colorado river basin. Water stressors and water supply management strategies for agricultural, urban, and environmental users were identified. The management strategies were simulated under scenarios of Colorado River reductions and compared to a baseline scenario. One of the main results found was that irrigation district 014 (DR-014) will be the user most affected by reductions in Colorado River deliveries. In the most unfavorable scenario (maximum reduction and no additional actions taken), sustainability decreased from 68% (Base Scenario) to 43%. This decrease is reflected in a water deficit of 643 Mm^3 by 2050, 30% of the total demand of DR-014. The current system performs better at the cost of overexploitation of aquifers. Moreover, water transfers from agricultural to urban use, increased efficiency in the urban network, wastewater reuse, and desalination are the main possibilities to improve the current water supply in the coastal zone (Tijuana, Rosarito, Ensenada). This research shows the spectrum of possible outcomes that could be expected from the effects of inaction on implementing a portfolio of management strategies. In addition to impacts on water supply (quantity) in the face of reductions, the increase in salinity in the Colorado River resources was estimated. This research project demonstrates a method for strategy evaluation that can be replicated in other basins.

Keywords: Colorado River, water allocation model, water scarcity, Mexico

PUBLICACIONES Y MANUSCRITOS PRODUCTO DE LA TESIS

1. Hernández-Cruz, A., Sandoval-Solís, S., & Mendoza-Espinosa, L. G. (2022). An overview of modeling efforts of water resources in Mexico: Challenges and opportunities. Environmental Science & Policy, 136, 510-51 (Publicado)

2. Astrid Hernández-Cruz, Samuel Sandoval-Solís, Leopoldo G. Mendoza-Espinosa, Jorge Ramírez-Hernández, Josué Medellín-Azuara and Luis W. Daesslé. (2023) Assessing water management strategies under water scarcity in the Mexican portion of the Colorado River Basin. *Water Resources Planning and Management.* (Aceptado)

3. Astrid Hernández-Cruz, Leopoldo G. Mendoza-Espinosa & Samuel Sandoval-Solís (2023) Increased salinity in the Colorado River resources: Implications for Mexico. *Water Resources Planning and Management.* (Enviado)

ESTRUCTURA DE LA TESIS

La tesis está integrada por siete capítulos:

Capítulo 1. Correspondiente a la introducción, antecedentes, justificación, y objetivos. El objetivo de este capítulo es presentar el problema y los antecedentes referentes al manejo de los recursos del río Colorado.

Capítulo 2. Comprende el marco teórico sobre el uso de modelos cuantitativos para el manejo de recursos hídricos. El objetivo de este capítulo es identificar qué modelos y de qué forma se han utilizado en México para el manejo de agua. Se presenta en el formato del artículo aceptado.

Capítulo 3. Corresponde a la metodología y resultados del proyecto. El objetivo de este capítulo es presentar las estrategias de manejo de los recursos hídricos del río Colorado en México. Se presenta en el formato del artículo en revisión.

Capítulo 4. Comprende los resultados referentes a la salinidad de los recursos del río Colorado. El objetivo de este capítulo es presentar los posibles impactos de las reducciones de asignación de agua en la calidad de agua. Se presenta en el formato del artículo enviado a revisión.

Capítulo 5. Abarca la discusión general. El objetivo de este capítulo es discutir los resultados de los capítulos 2, 3 y 4 de forma integrada.

Capítulo 6. Se presentan las conclusiones de la tesis.

Capítulo 7. Comprende estrategias y recomendaciones finales para tomadores de decisiones.

CAPÍTULO I: INTRODUCCIÓN

La cuenca del río Colorado es una de las principales fuentes de agua para el oeste de Estados Unidos y noroeste de México, la cual abastece a más de 40 millones de personas en ambos países (Gerlak et al., 2021). En los últimos 20 años, la cuenca ha estado sometida a una gran presión por la demanda creciente de agua y sequías prolongadas (Berggren, 2018; Udall and Overpeck, 2017). La dependencia de ambos países por el agua del río Colorado ha generado diversos planteamientos acerca de los problemas que pueden presentarse en función del cambio climático y a posibles reducciones en las asignaciones de agua (Comisión Internacional de Límites y Aguas, 2012).

El reparto de agua entre los estados de E.U.A y México está fijado por el Tratado Internacional de Límites y Aguas firmado en 1944. En este tratado se estipula una dotación volumétrica anual de 1,850 Mm^3 a México (IBWC,1944). La cuenca baja del río Colorado representa la principal fuente de agua para el estado de Baja California. Cerca del 80% del agua disponible del estado proviene de los recursos hídricos de esta cuenca, los cuales corresponden a los 1,850 Mm^3 del agua superficial del tratado y 739 Mm^3 del agua subterránea de los acuíferos de Valle de Mexicali y San Luis Río Colorado en la Mesa Arenosa (IMTA, 2020).

El principal usuario de los recursos hídricos del río Colorado es el Distrito de Riego 014 (DR-014) conformado por los valles agrícolas de Mexicali y San Luis Río Colorado, que utilizan el 85% del agua, seguido por la industria (10%) y los usuarios urbanos (5%) (CEABC, 2018). La demanda urbana puede verse comprometida a medida que aumente la población. De acuerdo con la Comisión Estatal del Agua de Baja California (CEABC, 2018), se espera un aumento en la demanda urbana de 19.77 Mm^3 (2015) a 27 Mm^3 (2035), lo cual corresponde a las proyecciones de población, donde se espera un aumento de al menos un millón más de habitantes para el año 2035.

Además del Valle de Mexicali, la zona costa del estado de Baja California (Tijuana, Playas de Rosarito y Ensenada) y Tecate se abastecen del río Colorado a través del Acueducto Río Colorado-Tijuana (ARCT), esta zona presenta una condición de escasez de agua persistente que ha llevado al gobierno estatal optar por la instalación de plantas desaladoras de agua, a pesar de su alto costo de construcción y operación.

Otro de los usuarios de agua del río Colorado es el sector industrial, el cual ha incursionado en cambios de uso del agua en la región. El proyecto de instalación de una planta cervecera Constellation Brands en Mexicali fue motivo de protestas sociales por parte de la comunidad agrícola y pobladores de la región, que temían que la operación de la cervecera podría comprometer el agua utilizada por los agricultores y habitantes de Mexicali (Monroy, 2020). La cervecera no ha sido la única industria que ha representado incertidumbre para satisfacer las demandas urbanas y agrícolas en la región en un futuro, la mayoría de estas industrias (empresas trasnacionales) están orientadas principalmente a la exportación (ej. Taylor Farms) y consumen altos volúmenes de agua en sus procesos (Enciso, 2019).

Los recursos hídricos de la cuenca baja del río Colorado de la que dependen usuarios agrícolas, industriales y urbanos se ve comprometida ante el cambio climático. Milly y Dunne (2020) reportaron que el caudal del río Colorado ha disminuido en 9.3% por cada grado Celsius de aumento en la temperatura, por lo que se anticipa un futuro con alto riesgo de escasez de agua. La reducción del flujo del río se traduce a niveles bajos en los principales embalses (lago Mead y Powell), poniendo en riesgo la cobertura de las demandas de agua en los distintos usuarios. Este planteamiento llevó a E.U.A y México a tomar medidas de acción ante el panorama de escasez. Una medida plasmada en la Minuta 319 de la Comisión Internacional de Límites y Aguas (CILA) es la disminución de la asignación de agua del río Colorado (CILA, 2012). Las reducciones en las asignaciones de agua en México van de los 62 Mm^3, cuando la elevación del Lago Mead esté por debajo de los 1,075 pies sobre el nivel medio del mar, hasta los 154 Mm^3, cuando el nivel del lago se encuentre por debajo de 1025 pies (IBWC, 2017). Además, ambos países acordaron adoptar un plan de contingencia ante la escasez de agua, donde cada país se compromete al ahorro de volúmenes de agua dependiendo del nivel del lago Mead (IBWC, 2017). Con base en la elevación proyectada del Lago Mead para el 1 de enero de 2023, la asignación de agua de México se reduciría en 128 Mm^3 en 2023, con una reducción de agua de 86 Mm^3 y un ahorro de agua recuperable de 42 Mm^3 (CILA, 2022). La reducción de agua (123 Mm^3) representa el 6.65% de la asignación total de agua de México bajo el Tratado de 1944 (1,850 Mm^3).

Bajo este contexto, el manejo eficiente de los recursos hídricos en el estado de Baja California que depende de las asignaciones del río Colorado se vuelve esencial. Uno de los instrumentos de manejo identificados son los modelos de planeación y distribución de agua. Los modelos permiten plantear escenarios en el presente y futuro analizando los posibles impactos del cambio climático, el crecimiento de la población, cambios de uso en la tierra, prácticas de irrigación, entre otros (Yaykiran et al., 2019). El desarrollo de herramientas de planeación ha facilitado la evaluación de estrategias y resolución de conflictos en cuencas transfronterizas. Por ejemplo, la cuenca del río Tagus, compartida entre Portugal y España y considerada una de las cuencas con mayor estrés hídrico en la península Ibérica, ha sido estudiada utilizando un modelo de planeación para el manejo integral de sus recursos hídricos (Sondermann and de Oliveira, 2021). El modelo permitió visualizar que los esfuerzos existentes en ambos países para controlar y reducir la demanda de agua son insuficientes, y las condiciones de estrés operativo se complicarán si no se toman estrategias más drásticas. De igual forma, en África se han aplicado diferentes herramientas en las cuencas transfronterizas de los ríos Okavango, Orange-Senqu, Nilo, Zambezi, Mekong y Medjerda (Bukhari and Brown, 2021; Rajosoa et al., 2021). A pesar del potencial uso de modelos para la planificación de los recursos hídricos, y su presentación a los tomadores de decisiones, estos modelos no han sido aplicados en los procesos de toma de decisiones. (Klimes et al., 2019; Sandoval-Solis et al., 2011).

Los modelos son herramientas útiles para tomar decisiones informadas. Actualmente, el estado de Baja California no cuenta con el soporte de un modelo para la planificación de los recursos hídricos. Las asignaciones de agua del río Colorado son susceptibles al cambio climático y a cambios en la estructura actual, incluidos los tratados y derechos del agua. El objetivo principal del presente estudio es evaluar el impacto de estos cambios, así como reconocer estrategias de manejo de agua para mejorar la distribución y abastecimiento de los recursos hídricos de la cuenca baja del río Colorado en México.

1.1 Justificación

Los recursos hídricos del río Colorado son la principal fuente de agua del estado de Baja California. Sin embargo, la demanda creciente de agua y sequías prolongadas en la cuenca transfronteriza del río Colorado pone en riesgo el abastecimiento de agua de los usuarios agrícolas, urbanos y ambientales en ambos lados de la frontera. En la cuenca del río Colorado prevalece la sobreconcesión de derechos de agua, así como la alta vulnerabilidad ante el cambio climático, el cual ha alterado los patrones de lluvia y temperatura, afectando la disponibilidad del agua. Este panorama ha llevado a los países a tomar medidas de acción, incluida la disminución en la asignación de agua que recibe cada uno. En México, el principal usuario de los recursos hídricos es el DR-014, y, hasta hace poco, era el único a nivel nacional que tenía asegurado el suministro de agua sin importar las condiciones climáticas prevalecientes en la región. Además de los cambios en las asignaciones de agua, el DR-014 enfrenta problemas de salinidad en agua y suelo, así como la sobreexplotación de agua subterránea. Además del sector agrícola, los recursos hídricos del río Colorado abastecen al 88% de la población de Baja California. Los municipios enfrentan distintos desafíos en manejo de agua pero comparten la dependencia por los recursos del río Colorado y la sobreexplotación de acuíferos.

Dadas las condiciones de escasez de agua en la región, la sobreexplotación de agua subterránea y la reducción en la asignación del río Colorado, se hace necesario explorar estrategias que garanticen la sostenibilidad en el uso del agua garantizando el derecho al agua para la población y el desarrollo social y económico de la región. En este estudio se evalúan estrategias de manejo de los recursos hídricos del río Colorado en Baja California así como los impactos en el abastecimiento y calidad del agua ante reducciones en la asignación de agua. Se espera que las estrategias planteadas y el método para el estudio de confiabilidad de los recursos resulte útil para los tomadores de decisiones y pueda ser aplicado en otras cuencas con problemas de desabasto.

1.2 Hipótesis

1. El sector agrícola será el usuario de agua más afectado ante las disminuciones en las asignaciones de agua del río Colorado en México.

2. Existen estrategias de manejo en México capaces de contrarrestar los impactos negativos causados por las disminuciones en las asignaciones del río Colorado.

1.3 Objetivos

Objetivo General

Evaluación de las estrategias de manejo de los recursos hídricos del río Colorado en Baja California así como los impactos de la calidad del agua ante reducciones en la asignación.

Objetivos Específicos

I. Revisión de los modelos de planeación de los recursos hídricos para la evaluación de las estrategias de manejo en México (Capítulo II)

II. Analizar y describir las estrategias de manejo del agua en la parte mexicana de la cuenca del río Colorado considerando escenarios de reducción de agua (Capítulo III)

III. Cuantificar los impactos del aumento de la salinidad del agua considerando su evolución histórica y la potencial reducción de la asignación de agua del río Colorado a Baja California (Capítulo IV).

1.4 Antecedentes

1.4.1 Cuenca del Río Colorado

Desde su nacimiento en las montañas Rocallosas, el río Colorado fluye hacia el suroeste en dirección del golfo de California con una longitud aproximada de 2,334 km (Tillman et al., 2019). Los últimos 160 km los recorre entre los límites de los estados de Sonora y Baja California. La cuenca tiene un área de 637,137.08 km^2, de los cuales 97.58% corresponde a territorio norteamericano y sólo el 2.42% a territorio mexicano (IMTA, 2020). Existe una alta variación estacional en los caudales del río: 2,800 m^3/s durante el deshielo (mayo a julio) y 140 m^3/s durante el otoño e invierno (Adler, 2007). El volumen anual de agua que fluye por el río Colorado está estimado en 19,735 Mm^3 (2000-2018) (Kuhn y Fleck, 2019).

La repartición de agua se divide en: cuenca alta (Arizona, Colorado, Nuevo México, Utah y Wyoming) y cuenca baja (Arizona, California, Nevada y México). El río Colorado es fuente de abasto de agua para usos urbanos de grandes ciudades como Los Ángeles, California; Denver, Colorado; Phoenix, Arizona, así como valles agrícolas como el Valle Imperial (California, E.U.A) y el Valle de Mexicali (Baja California, México) (Samaniego, 2017) (Figura 1).

El río Colorado provee agua a cerca de 40 millones de personas en EU y México. El cauce principal del río es un sistema de alta ingeniería, con múltiples presas y capacidad de almacenamiento suficiente en los lagos Mead y Powell (E.U.A) para cumplir con las obligaciones de abastecimiento aguas abajo durante un período de cuatro años (Gerlak et al., 2021). La situación actual que prevalece en la cuenca del río Colorado puede ser resumida en tres aspectos: la sobreconcesión del agua, la vulnerabilidad ante el cambio climático, y la alteración antropogénica del ciclo del agua (Tillman et al., 2019; Udall and Overpeck, 2017; Margaret O. Wilder et al., 2020).

La cuenca del río Colorado es una de las cuencas más sobreconcesionadas del mundo. En 1925, Eugene Clyde La Rue, hidrólogo del cuerpo de geólogos norteamericano (United States Geological Service: USGS), alertó que la construcción de presas sobre este río fomentaría el uso de todas las concesiones existentes del agua, lo que resultaría en un régimen deficitario (IMTA, 2020). Castle y colaboradores (2014) reportaron que en el periodo de 2004 a 2013 la cuenca perdió un total de 64,800 Mm^3 de agua. Más de tres veces de su escurrimiento anual. Las pérdidas están dominadas por el agotamiento del agua subterránea. El total de los derechos de agua concesionada es de 21,586 Mm^3 mientras que el volumen anual registrado es de 19,734 Mm^3 (2005-2013)(Castle et al.,2014).

Figura 1. Cuenca hidrológica del río Colorado

Fuente: IMTA, 2020

Por otra parte, el impacto del cambio climático en la cuenca del río Colorado ha alterado los patrones de lluvia y temperatura, afectando la disponibilidad del agua (Christensen et al., 2010). Miller et al. realizaron proyecciones climáticas al 2099, encontrando menos días de congelación respecto al periodo base (1963 a 1992), lo que implica una disminución de la acumulación de nieve, mayores flujos de agua a través del sistema en el invierno, y menos durante la estación seca en los meses de junio, julio y agosto. También se espera una disminución en la acumulación de nieve en un 50% a final del siglo, lo cual anticipa un futuro con alto riesgo de escasez de agua (Miller et al. 2013).

La hidrología del río está regulada mediante una serie de presas y embalses, incluyendo 48 grandes presas. Esta infraestructura es capaz de almacenar entre cuatro y cinco veces el caudal anual del río (Hinojosa et al. 2010). Las principales presas son Hoover y Glen Canyon, almacenando el 95.45% respecto al almacenamiento total. En las últimas dos décadas, el río ha estado bajo intensa presión debido a las demandas crecientes y sequía prolongada (Berggren, 2018; Udall and Overpeck, 2017). Actualmente, las presas están a menos de la mitad de su capacidad (Bureau of Reclamation, 2022).

1.4.2 México y el río Colorado

La historia, la demografía y las condiciones climáticas han obligado a negociar bilateralmente la distribución de las aguas del río Colorado (Orozco-Ramos, 2007). Antes de 1944, el uso de las aguas del río Colorado únicamente estaban reglamentadas para fines de navegación de acuerdo con el Tratado de Paz, Amistad y Límites entre México y Estados Unidos firmado en 1848 (Orive Alba, 1945).

En 1892, agricultores del Valle Imperial de California buscaban aprovechar mejor el agua de los ríos Gila y Colorado por lo que proyectaron la construcción de un canal que tendría que atravesar por territorio mexicano haciéndose necesario el consentimiento del gobierno de México. Sin embargo, México consideró que mientras no existiera un acuerdo internacional que se sujetara a tratados, no podría otorgar concesión alguna, pues resultaría contrario a sus intereses (Franco Ruiz, 2012). Para facilitar el desarrollo del proyecto la empresa estadounidense California Development organizó como su filial en México, a la Sociedad de Irrigación y Terrenos de Baja California, S.A. en 1898 y en pocos años se convirtieron en terratenientes prácticamente de todo el Valle de Mexicali. Posteriormente, ignorando las protestas del gobierno mexicano, la empresa abrió una bocatoma en territorio mexicano que, por las fuentes crecientes en 1905 provocó inundaciones en grandes extensiones en ambos países (Franco Ruiz, 2012; Furnish and Landman, 1975). Ante estos conflictos en 1912 se formó una comisión con el fin de analizar e informar las bases para el reparto equitativo de las aguas del río Colorado, a fin de celebrar posteriormente una convención internacional (Orive Alba, 1945).

La empresa estadounidense llevó a cabo instalaciones para irrigación y rápidamente amplió la producción del monocultivo del valle: algodón. En 1913 se plantaron doce hectáreas de algodón, para 1929 había 64,000 ha. Antes de esta fecha, el valle había estado escasamente poblado (Furnish and Landman, 1975). Al no haber trabajadores nativos, se propició el flujo de trabajadores de China. La reforma Agraria posteriormente dio como resultado la mexicanización del Valle y para mediados de los cuarenta, la mayor parte se había distribuido entre ejidatarios. Esta distribución alentó a la migración del interior de México hacia el Valle de Mexicali y favoreció el ingreso proveniente del cultivo de algodón para muchas familias (Furnish and Landman, 1975).

De 1942 a 1944, los gobiernos de Estados Unidos y México acordaron compartir el agua superficial en el Valle Imperial y Valle de Mexicali. En un ambiente de cooperación entre ambos países, se firmó en 1944 el Tratado Internacional de Límites y Aguas. Con este tratado se garantizaba a México una cuota anual de 1,850 Mm^3 (CILA, 1944). La cuota mexicana, si se compara con la cantidad de agua que históricamente se usaba en el Valle de Mexicali, impulsó aún más la expansión de la agricultura. Sin embargo, el Tratado no cubría aspectos sobre el agua subterránea transfronteriza ni de la calidad de agua (Orive Alba, 1945). En la década de 1960, México reportó problemas de salinidad en las entregas de agua del río Colorado. El problema surgió como resultado de la puesta en operación de pozos profundos en el Valle de Wellton-Mohawk en Arizona, de los que extrajeron aguas fósiles salinas del subsuelo y las descargaron al río Gila justo en la intersección con el cauce del río Colorado, antes de los puntos de entrega a México (Secretaría de Relaciones Exteriores, 1975). La salinidad alcanzó a 2,700 mg L^{-1} a finales de 1961, comparado con los 800 mg L^{-1} del año anterior. El nivel de salinidad nunca volvió a los valores anteriores a 1961, pero se estabilizó el nivel a 1000-1250 mg L^{-1} gracias al Acta 242 titulada “Solución permanente y definitiva del problema internacional de la salinidad del Río Colorado”, en la cual se alcanzaron las metas de mejoramiento de la calidad del agua que México estableciendo que la diferencia de salinidad entre la presa Morelos (México) e Imperial

(USA) no debería ser superior a 121 ± 30 mg L^{-1} (CILA, 1973; Furnish and Landman, 1975). Sin embargo, aún existen conflictos derivados de la interpretación de la Acta 242 y frecuentemente se menciona que las medidas resultan desventajosas para México, ya que el cálculo del parámetro considera promedios anuales de salinidad en el agua del río Colorado entregada a México, y que ello al menos facilita las mezclas de agua menos salubre y agua más salubre en el lado estadounidense antes de la entrega a México (Cortez Lara, 2011).

Aunque el agua recibida en México cumple con los parámetros establecidos en el acuerdo internacional, los suelos del Valle de Mexicali continúan con problemas de salinidad y existe mucha variación en la salinidad en las entregas diarias (CEABC, 2015). La salinidad es un problema latente, y se esperan mayores niveles de salinidad en un futuro cercano debido a los bajos niveles de agua en las principales presas (Buró de Reclamación, 2021).

Los altos niveles de sales en cuencas transfronterizas han ocasionado tensiones entre países como Turquía, Irán, Iraq, Siria y Arabia Saudita, quienes comparten la cuenca de los ríos Tigris y Éufrates. Similar a la situación en el río Colorado, la construcción de presas aguas arriba, proyectos agrícolas, y el cambio climático ha impactado la calidad de agua de los ríos Tigris y Éufrates (Al-Ansari et al., 2019), siendo Irak el país más afectado. La falta de colaboración en torno al agua entre Siria e Iraq ha generado tensiones entre los países, incluso ha detonado guerras civiles (Lossow, 2020).

Otro conflicto entre México y Estados Unidos fue el revestimiento del Canal Todo Americano (CTA). El CTA conducía alrededor de 3453 Mm^3 a los valles Imperial y Coachella en California. En 1989, el Congreso Estadounidense autorizó el revestimiento del canal para recuperar pérdidas por infiltración. Estas pérdidas representaban 84 Mm^3 al año, 5% (4 Mm^3) aprovechadas por la vegetación natural, 10% (8 Mm^3) por el Valle Imperial, y 85% (72 Mm^3) por el Valle de Mexicali (Lesser et al., 2019). El gobierno de México manifestó en múltiples ocasiones, que el revestimiento del Canal Todo Americano perjudicaba a los agricultores del Valle de Mexicali y ponía en peligro de extinción a la flora y la fauna de los humedales de la Mesa de Andrade (protegidos por la Convención de Ramsar)(Oroz-Ramos, 2007). El proyecto de revestimiento es visto en México como una decisión unilateral de los Estados Unidos, ya que no fueron considerados los impactos que tendría en el Valle de

Mexicali (Cortez-Lara and García-Acevedo, 2000). En 2008 el proyecto finalizó. Los niveles de las aguas subterráneas en los piezómetros situados a una distancia de 1.5 km del CTA disminuyeron entre 1.43 y 1.93 m/año entre septiembre del 2008 a diciembre del 2010, lo que se ve reflejado en la pérdida de almacenamiento anual de 25 Mm^3 (2008-2011) (Lesser et al., 2019).

Durante la segunda mitad del siglo XX, la frontera México-EUA ha experimentado una acelerada expansión demográfica que se refleja en los patrones de consumo de agua para diferentes usos, especialmente el municipal y el industrial, lo que ha llevado a una competencia cada vez mayor entre los tradicionales usuarios agrícolas, las ciudades en constante crecimiento, y los ecosistemas naturales (Bustillos Duran, 2004). La disponibilidad de agua ha disminuido por la sobreasignación de agua, el crecimiento demográfico, y la disminución en la oferta por sequías prolongadas e impactos del cambio climático.

1.4.3 Las últimas actas

Desde el Tratado de 1944, el manejo de agua del río Colorado se ha llevado a cabo mediante mecanismos institucionales llamados Actas. Estas tienen como objetivo llegar a acuerdos y estrategias para encontrar soluciones técnicas a diversos problemas relacionados a la cuenca compartida. En 2012, los comisionados de la Comisión Internacional de Límites y Aguas (CILA-IBWC) firmaron el Acta 319. Un acta que, a diferencia de actas anteriores, abordó siete distintas problemáticas. El acta es una extensión del Acta 306, referida a asuntos ambientales y el Delta del Río Colorado; del Acta 317, sobre medidas para minimizar los impactos de la escasez de agua; y el Acta 318, que establecía medidas de cooperación para enfrentar la situación de emergencia por el terremoto del 2010 que afectó la infraestructura del Valle de Mexicali.

El Acta 319 se enfoca principalmente en dos aspectos: a nivel local, en las medidas a tomar con respecto a la actividad sísmica en la región de Mexicali; y a nivel binacional, expone la alta variabilidad climática en la Cuenca del Río Colorado y las medidas a tomar para evitar niveles bajos en las presas aguas arriba. En el acta se establecieron tres niveles de reducción en las entregas de agua a México. Las reducciones en las asignaciones de agua en México van de los 62 Mm^3, cuando la elevación del Lago Mead esté por debajo de los 1075 pies sobre el nivel del mar, hasta los 154 Mm^3, cuando el nivel del lago se encuentre por debajo de 1025 pies. El acta además introdujo alternativas de ahorro de agua mediante el uso de instalaciones estadounidense para retener el agua mexicana y diferir las entregas de acuerdo con sus propias necesidades, al mismo tiempo que se exploran fuentes alternativas de agua para aumentar la disponibilidad regional. En resumen, el acta introduce actividades de planificación y conservación a largo plazo, el mantenimiento de niveles altos de agua en el Lago Mead para proteger a los usuarios de la escasez, el desarrollo de posibles fuentes de agua adicionales resultantes de proyectos de inversión conjunta entre México y Estados Unidos y la inversión conjunta para la conservación del agua y la protección del medio ambiente (Sánchez y Cortez-Lara, 2015).

En 2017 se emite la más reciente acta con relación al río Colorado, el Acta 323 “Ampliación de las Medidas de Cooperación y Adopción de un Plan Binacional de Contingencia Ante la Escasez de Agua en la Cuenca del Río Colorado”. El Acta retoma la visión compartida en la “clara necesidad de realizar acciones adicionales y continuas, por los impactos en las elevaciones en el Lago Mead debido al cumplimiento de las demandas del sistema, las condiciones hidrológicas, el incremento en las temperaturas y otros factores”. En esta acta se introduce el Plan Binacional de Contingencia ante la Escasez de Agua, que especifica ahorros de agua que se aplicarán a México y Estados Unidos en ciertas elevaciones del lago Mead. A diferencia de las reducciones en las asignaciones planteadas en el Acta 319, los ahorros de agua de la 323 son recuperables cuando las condiciones del lago Mead mejoren (elevación en lago Mead >1100 pies). Los ahorros de México varían de los 51 a los 185 Mm^3. Además del plan de contingencia, en el acta 323 se retoman las reducciones en las asignaciones de agua, la creación de Reserva de Agua Mexicana, acciones para atender la salinidad y variaciones en los flujos que llegan a México, así como acciones relativas al medio ambiente e inversiones en proyectos de nuevas fuentes agua. La vigencia de esta acta es hasta el año 2026. En el 2019 se detonó el primer nivel ahorro de agua, y en 2020 México ahorró 51 Mm^3. En 2021 el Buró de Reclamación en EUA proyectó que la elevación del Lago Mead al 1 de enero de 2022 sería de 1065.85 pies, nivel al cual se detonan tanto reducciones como ahorros recuperables para ambos países. Es decir, en el 2022 la asignación de México fue reducida en 62 Mm^3 y, adicionalmente, México contribuyó con 37 Mm^3. Las probabilidades de que el lago Mead alcance niveles inferiores a 1025 psnm (máximo nivel de ahorros y reducciones) son muy altas para el 2025, por lo que se esperan más reducciones a corto y mediano plazo (Bureau of Reclamation, 2021).

1.4.4 Manejo de agua en Baja California

El estado de Baja California es el principal usuario de los recursos hídricos del río Colorado en México (Figura 2). El estado se caracteriza por tener clima árido y escasos recursos hídricos (CEABC, 2018; Malinowski, 2004). A la escasez natural de agua se añade el rápido crecimiento demográfico e industrial en las ciudades, la extensa agricultura por riego, y la creciente demanda de agua para el medio ambiente (CEABC, 2018). Ante estos desafíos, el manejo de agua se convierte en una tarea compleja que toma dimensiones ambientales, sociales, económicas y políticas. Entendiendo por manejo, al conjunto de acciones que van desde la planificación, asignaciones, distribución y uso/reúso de los recursos hídricos (tomando en cuenta la cantidad y calidad del agua) de acuerdo con las políticas de agua y regulaciones (FAO, 2017).

A pesar de la condición de escasez, Baja California es uno de los estados con mayor cobertura de agua potable en el país (97%) (CONAGUA, 2019). Sin embargo, a diferencia de otros estados de la república, Baja California depende en un 64% (oferta total: 3,449 Mm^3) de recursos externos. Gracias a los recursos superficiales y subterráneos del río Colorado, el 88% de la población es abastecida (2,728,236 habitantes), así como cerca de 200,000 hectáreas en el Distrito de Riego 014 (DR-014) (CEABC, 2016).

El DR-014 conformado por el Valle de Mexicali (Baja California) y Valle de San Luis Río Colorado (Sonora) es el principal usuario de agua en el estado, consumiendo el 85% de los recursos del río Colorado (IMTA, 2020). Dentro de los principales desafíos que presenta el distrito se encuentran la escasez de agua debida a la alta vulnerabilidad de los recursos del río Colorado, cambios en las asignaciones de agua, problemas de salinidad en agua y suelo, y sobreexplotación de agua subterránea (Acuífero Valle de Mexicali). Actualmente, existe preocupación de que los agricultores del Valle de Mexicali y tribus de la cuenca baja no han participado suficientemente en la gestión del agua de la cuenca (Rivera-Torres y Gerlak, 2021).

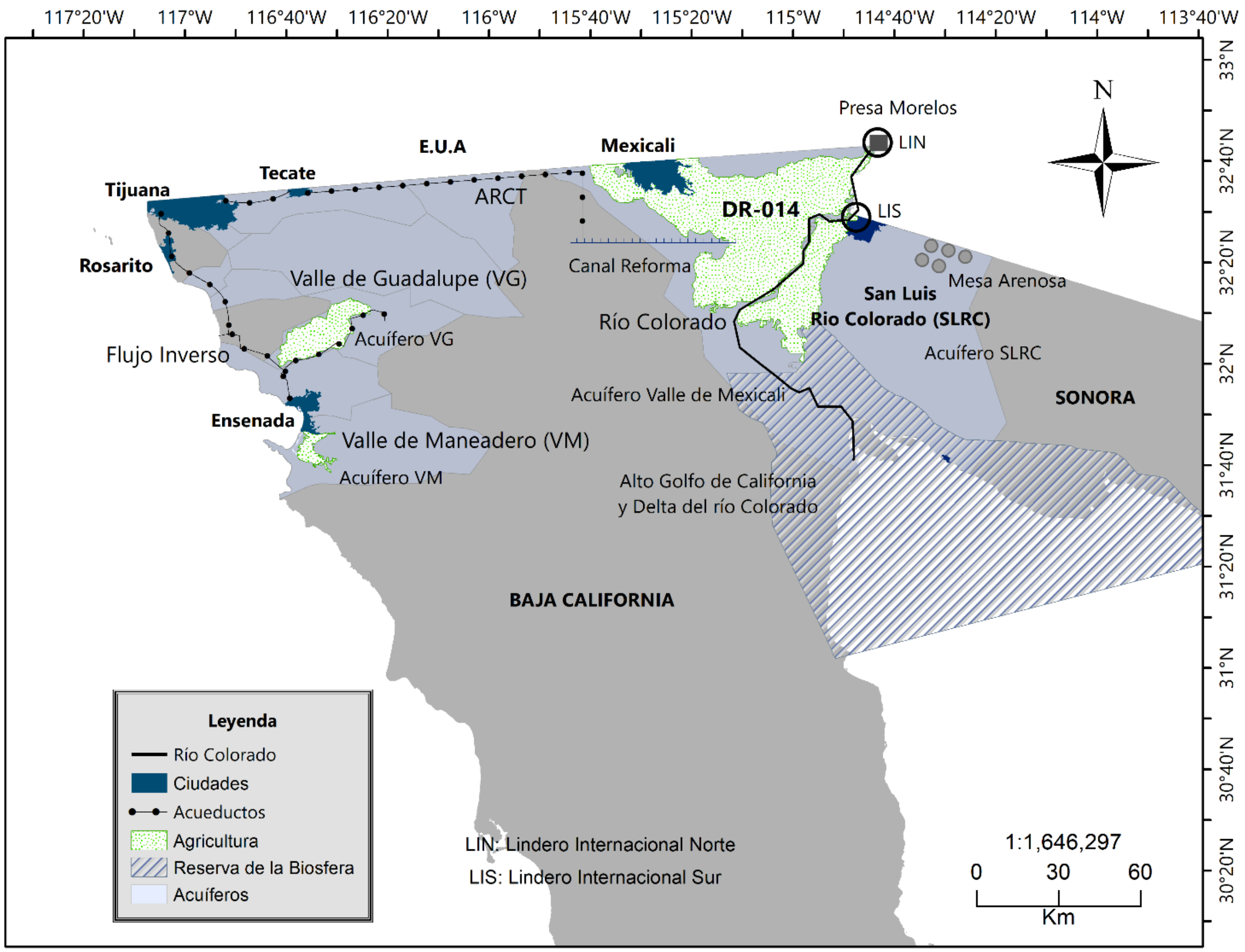

Figura 2. Usuarios urbanos, ambiental y agrícola (DR-014) dependientes del río Colorado en México

Por otra parte, Mexicali, la capital del Estado, es el segundo municipio más habitado del estado. Concentrando el 29.4% de la población total de Baja California (3,155,070 habitantes) (INEGI, 2015) tendencia que se espera prevalecerá estable hasta el 2035. Mexicali es también el segundo municipio con mayores niveles de urbanización, con 89.7% de su población residiendo en localidades urbanas y 10.3% en localidades rurales (CEABC, 2016). La dotación promedio de agua potable es de 287 l/hab/día, haciéndolo el municipio con mayor dotación de agua en Baja California, es importante resaltar que esta dotación suele mantenerse constante los 365 días del año, situación que no sucede en ninguna ciudad de México.

Al igual que Mexicali, el municipio de Tecate se abastece del río Colorado. Tecate sólo representa el 3.2% de la población total de Baja California (CEABC, 2015) y la dotación promedio es de 221 l/hab/día. A pesar de ser el municipio menos urbanizado del estado (80% de su población reside en localidades urbanas), Tecate se ha distinguido por su rápida urbanización, crecimiento poblacional, e industrialización. Lo cual ha comprometido la calidad de sus fuentes de agua locales. En los 2000s, el agua subterránea proveía el 30% del agua potable para el municipio, en 2017 solamente abasteció el 14% (CEABC, 2017). La contaminación debida a descargas industriales, efluentes con altas concentraciones de materia orgánica de una cervecera, baja calidad en los efluentes de la planta de tratamientos, entre otros, ha reducido la disponibilidad de agua, aumentando la dependencia de los habitantes por el agua importada del río Colorado a través de los 130 km del acueducto del río Colorado-Tijuana (ARCT) (Mahlknecht et al. 2018).

Tijuana es el municipio más poblado, con casi 50% de la población de Baja California. La dotación de agua potable es de 181 l/hab/día (CEABC, 2015). Tijuana y Playas de Rosarito son altamente dependientes del río Colorado, 99% de su agua disponible proviene del ARCT. De 1950 a 1980 Tijuana presentó escasez crítica de agua debido, entre otros factores, a movimientos migratorios y crecimiento industrial. La población aumentó ocho veces su tamaño (pasando de 65,364 a 514,583 habitantes). Para 1987, a tan sólo cinco años de la apertura del ARCT fue necesario ampliar su capacidad de 1,500 a 2,660 l/s, y para 1993 a 4000 l/s. Actualmente la capacidad es de 5,333 l/s, y se espera que la demanda de agua supere la capacidad de suministro en unos años (CEABC, 2017; Medellín-Azuara et al., 2009). Además, se ha identificado inequidad en la distribución espacial de los servicios hídricos en la ciudad, así como el casi nulo reúso de agua residual tratada. (Navarro-Chaparro et al., 2016a, 2016b).

Ensenada es uno de los municipios que enfrenta mayores desafíos en el manejo de agua. En el municipio habita el 17.4% de la población estatal y tiene la dotación de agua más baja, 147 l/hab/día (CEABC, 2015). En las últimas dos décadas, Ensenada ha experimentado un considerable aumento de su población y un proceso de degradación ambiental de los acuíferos, los cuales constituyen la principal fuente. Los principales problemas identificados con relación al agua reconocidos en Ensenada son la sobreexplotación de acuíferos, intrusión salina, falta de fiabilidad en el suministro urbano e ineficiencias institucionales (Medellín-Azuara et al., 2013). Ante esta problemática, se ha adoptado una perspectiva centrada en la oferta, lo que ha propiciado a adoptar estrategias de nuevos proyectos de infraestructura de abasto de agua potable como pozos, acueductos y desaladoras. Además de los acuíferos locales, Ensenada tiene una asignación de agua de 9 Mm^3 de los acuíferos de Mexicali y San Luis Río Colorado (desde 1996) (REPDA, 2020). Por mucho tiempo la ciudad no tuvo acceso a este volumen, fue hasta el 2015 que se puso en operación el acueducto de flujo inverso Tijuana-La Misión-Ensenada a través del cual se exportan actualmente en promedio 100 l/s (4 Mm^3 anuales) más la capacidad del acueducto es de 300 l/s (CESPE, 2020).

Además de asignar agua a los usuarios agrícolas y urbanos en Baja California, en los últimos años se ha reconocido la importancia de destinar agua para uso ambiental. Antes de la construcción del sistema de presas en la cuenca del río Colorado, el río desembocaba más de 15,000 Mm^3 por año (1900-1930) por año al Alto Golfo de California, creando una zona estuarina de cerca de 500,000 ha (Lavín y Sánchez, 1999; Rodríguez et al., 2001). La influencia del río se extendía 65 km mar adentro, formando una zona de gran importancia para la reproducción, desove y crianza de una gran variedad de organismos marinos. Por otra parte, en el delta del río Colorado, los flujos de agua dulce mantenían una zona de más de 400,000 ha de bosques riparios y humedales de agua dulce. La disminución de flujo al delta a partir del siglo XX causó la pérdida de más del 80% de las zonas de humedales y bosques riparios. A pesar de los impactos que han ocurrido, el delta del río Colorado sigue siendo uno de los sitios más importantes para la conservación de la biodiversidad. Los humedales del delta cubren cerca de 100,000 ha (Zamora-Arroyo et al., 2005). A pesar de no contar con una asignación de agua, estos humedales han logrado mantenerse gracias a desfogues esporádicos de las presas en Estados Unidos, flujos de drenes agrícolas y a escurrimientos de los canales de riego que no están revestidos (Glenn et al.,2001).

En el año 2000 se emitió la primera acta binacional con relación al delta, el Acta 306, que estableció el marco conceptual para el desarrollo de proyectos de cooperación en el uso del agua para fines ambientales. En 2012 se firma el Acta 319, y como parte de esta acta en 2014 ocurre el flujo pulso, liberando aproximadamente 130 Mm^3 al corredor ripario del delta (Kendy et al., 2017). Los esfuerzos de conservación continuaron y en el 2017 se extendieron medidas en el Acta 323. En el año 2021 de nueva cuenta se descargó agua para uso ambiental durante 164 días simulando los flujos de primavera y verano que se estima ocurrían en el cauce del Río Colorado bajo condiciones naturales (Ríos, 2021).

1.4.5 Modelos para el manejo de la Cuenca del Río Colorado

Uno de los primeros modelos reportados para la planeación de los recursos del río Colorado en México fue el presentado por Sanvicente-Sánchez (2009). El autor replicó el Sistema de Simulación del Río Colorado (CRSS, por sus siglas en inglés), herramienta utilizada por el Buró de Reclamación en Estados Unidos. El objetivo del estudio era que el modelo fuera compatible con el CRSS, y, de esta forma, México fuera considerado como usuario del río Colorado en el sistema de asignación. En el mismo año, Medellín y colaboradores (2009) presentaron un modelo de optimización hidro-económico (Baja CALVIN) el cual permitió la evaluación de estrategias como el reuso de aguas residuales, desalinización, expansión de infraestructura y mercados de agua. La herramienta permitió el análisis económico para seis escenarios de manejo. Encontrando que la combinación del reuso, ampliación de acueductos, y aumento en las capacidades de desalinización resultaba en un mejor costo de explotación y escasez baja.

Recientemente, Stella (2021) reportó el uso de la herramienta WEAP para representar el balance de agua en Baja California (a excepción de Ensenada). El autor reportó el balance histórico (1960-2016), encontrando que existe un desfase entre el agua total consumida por la región (agua consumida más pérdidas y flujo ambiental) y las entradas (entrega de agua reportada por las autoridades de EE. UU y recarga de agua subterránea), encontrando un déficit anual en el abastecimiento de 372 Mm^3.

Por otra parte, Cortés-Ruiz y Azuz-Adeath (2021) estimaron futuras demandas para Baja California (al 2030) considerando que el Estado alcance una condición de no escasez hídrica (≥ 1000 m^3/año per capita). Los autores discuten que la capacidad actual de las plantas de tratamiento y desalinizadoras no sería suficiente para satisfacer las futuras demandas en el estado. En el estudio se evaluaron estrategias como la reducción de cultivos en el Valle de Mexicali y la instalación de plantas para desalar agua del mar y de acuíferos salinizados. Los autores propusieron la reducción de 33,558 Ha (80% alfalfa, 20% algodón) de área irrigada en el Valle de Mexicali (cerca del 17% del área total irrigada) con un costo de 82 millones de dólares como la mejor opción para garantizar la demanda del resto de los usuarios.

En Estado Unidos, el Sistema de Modelado a Medio Plazo del Río Colorado (CRMMS, por sus siglas en inglés) y el CRSS son modelos que abarcan toda la cuenca del río Colorado, los cuáles fueron desarrollados en el software RiverWare™. Los modelos son actualizados y mantenidos continuamente por el Buró de Reclamación (en la cuenca alta y baja). Los dos modelos simulan la operación de las principales presas de la cuenca y proporcionan información sobre el estado futuro del sistema en un marco mensual. Dentro de las variables de salida se incluyen el volumen de agua almacenada, las elevaciones de las presas, la generación de energía, el caudal de los arroyos, y caudales de retorno de los usuarios del agua en todo el sistema. Estas simulaciones utilizan un balance de masa que tiene en cuenta toda el agua que entra, se almacena y sale del sistema. Ambos modelos simulan cómo se libera y suministra el agua bajo diversas condiciones hidrológicas con el objetivo de simular las operaciones reales. Así pues, los modelos son utilizados como herramientas auxiliares en la toma de decisiones en Estados Unidos. Si bien México es considerado en estos modelos, sólo es incluido como un bloque y no refleja el sistema de asignación ni desafíos en la parte mexicana de la cuenca del río Colorado.

CAPÍTULO II: USO DE MODELOS CUANTITATIVOS PARA EL MANEJO DE RECURSOS HÍDRICOS

Resumen

A medida que aumentan los retos del manejo de agua, los modelos de planeación del agua se convierten en una herramienta valiosa para la gestión de los recursos hídricos. El objetivo general de este capítulo fue la revisión bibliográfica del uso de modelos de planeación hídrica para evaluar estrategias de manejo en México. Se identificaron 36 estudios de modelación revisados por pares hasta julio de 2021 que tenían como objetivo apoyar los procesos de toma de decisiones. Principalmente, los modelos auxiliaron tres procesos: la planeación de los recursos hídricos (53%), el diagnóstico de la disponibilidad y la demanda de agua (36%) y la resolución de conflictos (11%). La mayoría de los estudios se han realizado en regiones áridas del país que enfrentan retos importantes en términos de escasez de agua. Dentro de las buenas prácticas se identificó que la comunicación hacia las partes involucradas, la modelación colaborativa, y el acceso a información confiable, actualizada y disponible, resulta en la verdadera aplicación de los modelos por los tomadores de decisiones. Sin embargo, la falta de participación de las partes interesadas, el limitado intercambio de conocimiento, las limitaciones en la obtención de datos obstaculizan la utilidad de los modelos. A medida que México va desarrollando, utilizando, y aceptando los modelos de recursos hídricos, es esencial la colaboración con los usuarios finales, los responsables de la toma de decisiones.

Palabras clave: manejo del agua, modelos de simulación, modelos de optimización, toma de decisiones

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An overview of modeling efforts of water resources in Mexico: challenges and opportunities

Abstract

As water management challenges grow, the use of water planning models become an essential part of water resources management. The overall goal of this research study was to assess the use of water planning models for evaluating water management strategies in Mexico. A total of 36 peer-reviewed modeling efforts were identified in Mexico until July 2021 that aimed to support decision-making processes. Primarily, three processes were supported: water resources planning (53%), water availability and demand diagnosis (36%), and conflict resolution (11%). Most of the case studies addressed are within arid regions facing the most significant water management challenges in the country. Successful modeling practices included stakeholder outreach, collaborative modeling, and reliable, timely and available information. However, the lack of stakeholders involvement, limited knowledge-sharing, data limitations and established stakeholders misconceptions are areas that hinder the usefulness of models. As Mexico is gradually developing, using, and accepting water resources models, it is essential to collaborate within the end-users, stakeholders, and decision-makers in the co-production of models.

Keywords: water management; simulation models; optimization models; decision-making

2.1 Introduction

Water management faces multiple challenges, especially under a changing climate and a rising global population (Cosgrove and Loucks, 2015). According to the World Water Assessment Programme (2015), water demand is predicted to increase by up to 55% by 2050 and, therefore, a rise in food and energy demand, economic-industrial activity, and water conflicts. Furthermore, many countries are currently impacted by political tensions, inadequate water management, and even armed violence. Water conflicts can arise because of several reasons, including competition over resources, territorial disputes, or political strategy (Klimes et al., 2019).

Improved water management requires incorporating policies that take into account water management at all levels and form agreements across society, public, private and academic actors towards a common approach (Stafford-Smith et al., 2017). Moreover, water management faces operational problems in performing the management instruments. A particular task to deal with these problems is to develop methods and systems that can support the information required for the decision making process in water management (McDonnell, 2008).

An important step in water resources decision support is the prediction of the consequences of different management alternatives and their social and environmental implications (Reichert et al., 2015). In order to support decision-making processes in water management, the use of models has been pursued, allowing for a better understanding of the system's behaviour.

Models usually integrate knowledge developed across a broad range of disciplines and are useful tools to analyse alternatives options with stakeholders and communicate results in a transparent way (Kelly (Letcher) et al., 2013).

Mexico faces several challenges, such as water scarcity, pollution, and inefficient water administration. These problems in Mexico have historical origins, including their socio-economic evolution, poor implementation of water regulations and abuses, aquifers overexploitation, pollution, and also the poor value that society confers to this resource (Arreguín-Cortéz et al., 2011). Even though integrated water resources management

(IWRM) principles are already established in Mexican laws and enforced by the National Water Commission (CONAGUA for its acronym in Spanish) (CONAGUA, 2012), it has not been reflected in problem-solving and often is omitted from decision-making processes. An important aspect is the participation of all stakeholders. Villada et al. (2019) identified critical challenges of public participation in water management in Mexico, such as the unification of technical and non-technical knowledge, decentralization, and the influence of non-governmental actors in decision-making. Although CONAGUA encourages public participation and the use of technical knowledge, alternative actions are usually restricted by politics and agreements without public participation (Godinez-Madrigal et al., 2019). The use of quantitative models could increase the transparency, acceptability, and efficiency of the decision-making process in the country. Thus, the overall goal of this research study is to assess the use of water planning models for evaluating water management strategies in Mexico. The main objectives of this study are to: (a) perform a thorough review of peer-reviewed water planning models in Mexico (b) identify their success and failures relative to the water management process they aimed to support and (c) discuss the challenges ahead and good practices as lessons learned. The review starts with the global status in water resources modeling to the give way to the presentation of examples of quantitative models in Mexico and recommendations for future work.

2.2 Models for water management

Effective water resources management requires an understanding of the interactions between environmental, economic, technical processes, policy choices and social complexity (Badham et al., 2019). Models can be a useful tool to represent these complex interactions. There is increasing adoption of models that integrate the hydrologic, ecologic, engineering, economic, social, and political aspects of large water resource systems (Loucks and van Beek, 2017).

These models have the potential to be used for management decisions supported by quantitative data provided by mathematical or computer-based models (Loucks and Jia, 2012). These quantitative mathematical models mostly fall into two main categories: simulation or optimization based. Usually, the simulation models answer the question of “what would happen if a strategy X is implemented” and optimization models estimate the opportunities that a system can reach given optimal conditions considering a set of constraints (Singh, 2014).

Despite the development of many models and their positive feedback from water management authorities, they are often not adopted by the intended end-users. McIntosh et al. (2011) identified that, in order to be successfully applied, models must improve their usefulness, establish trust and credibility, and offer an easy-to-use system. The success of a model, either simulation or optimization, is based on whether the tool adequately represents the real-world system and its processes, including model calibration and validation (Loucks and Van Beek, 2017). In recent years, the use of models as decision support tools during integrated water resources management and decision making are increasingly frequent (Global Water Partnerships, 2018). However, the implementation of these models and its need to focus on communicating its results among the different stakeholders is still a work in progress. The integration of modeling practice into the social and political components of the planning and water management enhancing those processes continues to be the main challenge for those who develop planning and management models (Loucks and Van Beek, 2017). Badham et al. (2019) identified important challenges in the implementation of models, such as knowledge sharing, overcoming data limitations, informed stakeholder involvement**,** social equity, and uncertainty management. In the present study, once the modeling efforts in Mexico are introduced, a section of *Challenges ahead* is discussed, including three main factors: (1) stakeholders' misconception of water resources models as the ultimate decision tool, (2) lack of stakeholder involvement, and (3) lack of knowledge sharing and overcoming data limitations.

2.3 Water management models in Mexico

Mexico faces significant water challenges like many other countries. The water availability per person has become progressively limited due to natural water scarcity in the center and north of the country, population growth, agricultural and industrial production. Moreover, the country has already been affected by climate change. Two-thirds of the national territory is arid or semi-arid, where water availability is limited to seasonal and regional factors that are linked to the rainy and hurricane season (Oswald-Spring and Sanchez-Cohen, 2011). Also, water pollution, poor water administration and governance, and deficiency of environmental planning are common (Arreguín-Cortéz et al., 2011). Given these complex challenges, researchers have explored ways to evaluate alternative strategies for water allocation with the use of analytical tools such as models for water management. Table 1 provides a list of modeling efforts in Mexico which are described in the next sections. It should be noted that different research objectives and modeling categories can be grouped (e.g., hydrological, management and water quality modeling are aggregated); their approaches and temporal-spatial scales are presented. Rather than comparing the studies, the success and failures of the modeling efforts were addressed. Figure 2 shows the location of the case studies (grouped by CONAGUA's hydrological regions) and the decision making processes intended to support. It must be noted that this is not a comprehensive list of water models in Mexico; it only includes peer-reviewed publications of water management models or modeling efforts that the authors are aware of up to July 2021. There may be other modeling efforts documented in grey literature (e.g., governmental reports, master thesis, PhD dissertations and proceedings) that have not been possible to locate. The literature was found in the following databases: ScienceDirect and Scopus from the Elsevier platform; Web of Science of Clarivate Analytics; Ebsco Host; Springer Link from Springer Nature, Google Scholar, and Scientific Electronic Library Online (SCIELO) and wateReview (DeVincentis et al., 2021). WateReview is a specialized platform for Latin America and the Caribbean that provides a literature review of more than 20,000 peer-reviewed water resources publications in English, Spanish, and Portuguese up to 2019. The search was performed using the keywords: optimization models, simulation models, water resources management, modelling, and decision-making process; Mexico (English and Spanish). Neither numerical models for water quality analysis nor surface water-groundwater flow models were considered for this study. The criteria for choosing the studies presented here was that the quantitative models provide information to embrace decision-making and planning processes in Mexico and the proposal of alternatives. Overall, 36 studies published between 1987 and 2021 focusing on optimization and simulation models for water management in Mexico were considered. The success of the modeling efforts (Success Evaluation) was assessed using the following four questions: (1) Did the study have a beneficial impact on the planning and decision-making process? (2) Did the results of the study make the debate over the proper choice of alternatives more informed? (3) Did it introduce competitive alternatives which otherwise could not have been considered? (Loucks and Van Beek, 2017) and (4) Did the outcomes of the modeling exercise informed the decision-makers for implementing a policy(ies). The scoring system is a modified version based on Loucks that consists of 4 questions: the first three questions were ranked with a scale from 0 to 2: 0 (none or rarely), 1 (to some extent) and 2 (often or mostly). The fourth question was evaluated as: (0) decision-makers were not informed or persuaded by the results of the modeling exercise during the decision-making process, (1) decision-makers were informed, and the results of the modeling exercise were considered during the decision-making process.

Table 1. Water models used in Mexico

Model type	Process	Objective	Case study	Software	Success (0-7)	Author
Simulation	Conflict resolution	Improve a water distribution agreement	Lerma-Chapala Basin	Stella	7	[23]
	Water resources planning	Evaluate water management scenarios	San Luis Potosí	UVQ	4	[32]
			Ensenada City	Stella	4	[38]
			Mexico City	Super D.	6	[57]
			Rio Conchos Basin	Powersim	4	[19]
			Rio Bravo Basin	WEAP	6	[53]
			Támbula-Picachos Basin	Aquatool	3	[22]
			Rio Sonora Basin	HEC-HMS	6	[34]
	Water availability and demand diagnosis	Evaluate climate change scenarios	Guayalejo-Tamesí River Basin	WEAP	3	[52]
			Guadalupe River Basin	SWAT	4	[40]
			Rio Bravo Basin	Ithink	5	[17]
			Durango State	Delphi	5	[51]
			Rio Conchos Basin	WEAP	4	[24]
			Valle de Juárez Aquifer	NA	6	[33]
		Characterize the hydrology of the basin	Colorado River Basin	WEAP	3	[54]
			Magdalena River Basin	SWAT	5	[25]
			San Juan Basin	WEAP	2	[65]
Optimization	Conflict resolution	Evaluate groundwater extraction scenarios	Alto Rio Lerma Irrigation District	NA	5	[49]
	Water resources planning	Evaluate water management scenarios	Morelia City	GAMS	4	[42]
			Northern Baja California	CALVIN	5	[37]
			Valley of Puebla Aquifer	MODFLOW	3	[50]
			Rio Yaqui Basin	MODFLOW	5	[41]
			Rio Yaqui Basin	NA	5	[39]
			Cuernavaca City	GAMS	5	[3]
			Mexico City	NA	6	[59]
			Río Mayo Irrigation District	GAMS	3	[7]
			Yaqui Valley	SNOPT	3	[56]
			Río Conchos Basin	NA	3	[16]
			Tierra Caliente Irrigation District	GAMS	3	[2]
			Querétaro City	NA	4	[44]
	Water availability and demand diagnosis	Estimate groundwater optimal extraction	Zamora Aquifer	MODFLOW Gambit	5	[29]
			Cuautitlán-Pachuca Aquifer	MODFLOW	5	[18]
			Valle de Querétaro Aquifer	FEFLOW	3	[6]
		Evaluate climate change scenarios	Santo Domingo Valley	MODFLOW	6	[66]

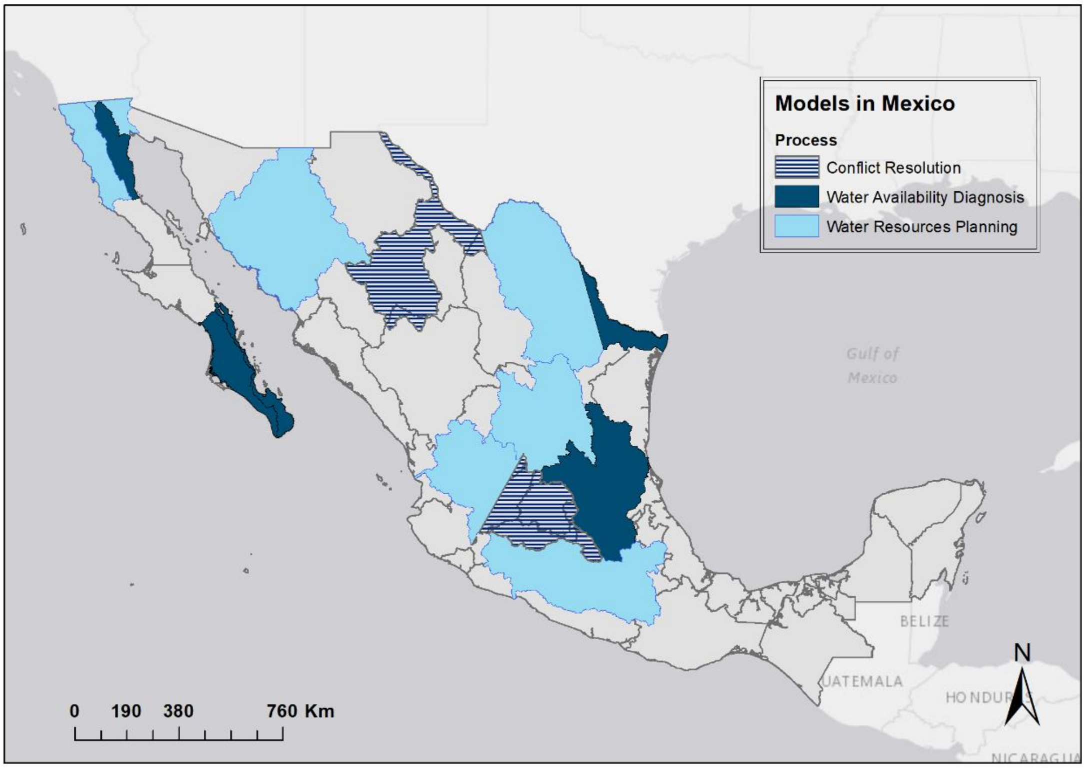

Fig.1. Location of case studies and water management process supported

2.3.1 Initial Water Management Modeling Efforts

One of the first peer-reviewed studies using models in Mexico was Chávez-Morales et al. (Chávez-Morales et al., 1992, 1987), who applied an optimization model for Irrigation District No. 38 in Sonora. The model described the water allocation system, cropping pattern requirements, and reservoir simulation. In Northern Mexico, Williams (1995) developed a planning model (WEAP platform) for the San Juan Watershed in Nuevo León. A water balance was carried out considering the physical and legal conditions to compare the water supply and demands under average and drought hydrological conditions until 2015.

Almost a decade later, Arreguín-Cortés and Alcocer-Yamanaka (2004) presented an optimization model (GAMS platform) applied for the city of Cuernavaca, in the state of Morelos. Their conceptual model considered the water quantity and quality for different conditions in wastewater treatment plants (WWTP) and water use efficiency strategies in

Cuernavaca City. The authors concluded that a reduction of extraction volumes without compromising water quality was feasible and found out that the installation and water reuse from two new WWTP for crop irrigation would reduce the extraction of the water resources.

Optimization and simulation models have also been used for irrigation studies. Salazar et al. (2007) evaluated specific groundwater management problems in the Alto Rio Lerma Irrigation District, located in the state of Guanajuato. The linear programming model estimated the optimal crop area for different groundwater extraction scenarios. The results identified the less profitable crops according to water availability.

2.3.2 Rio Bravo – Rio Grande Basin

A well-studied area in Mexico is the Rio Grande/Bravo (RGB) basin, a transboundary basin that marks the border between Mexico and the United States (US), and considered one of the most water-stressed basins in the world (Degefu et al., 2018). Sandoval-Solís et al. (2013) evaluated the hydrologic feasibility of current and alternative water management strategies. The model (WEAP platform) simulated the water allocation system of the RGB basin and represented critical institutional issues such as the division of water according to the Treaty of 1944 with the US. The modeling effort considered stakeholder's feedback for a better description of the basin and results were presented to stakeholders in both countries. The lack of support from governmental organizations prevented the use of this model in the decision making process. Furthermore, even when government institutions, NGOs, and most of the stakeholders were convinced of the usefulness of the model, CONAGUA was not convinced with the results from the model and decided to use another platform. In a parallel effort, the Texas Commission on Environmental Quality (TCEQ, 2006) commissioned Brandes (2004) to perform a water availability assessment for the RGB Basin. The company built a water resources model to determine the water availability in the basin for current and prospective water right holders following Rio Grande operating rules (TCEQ, 2006). There are limitations of this modeling effort, the operating rules for Mexico's reservoirs on tributaries were not accurately calculated. Brandes (2004) argued the difficulty of representing the water demands since Mexico at that time did not have an accessible and organized water rights database.

More recently, Duran et al. (2017) used a modeling approach to simulate the potential impacts of climate change on the availability and water quality in the US–Mexico border region of the RGB Basin. The authors used a system dynamics (SD) simulation model (ithink platform). The model simulated the effect of greenhouse gas (GHG) emissions in the water demand and supply of the system for the period 2010 to 2080. The results showed that water deficits appear in the year 2038 under the determined greenhouse gasses emission scenarios. In addition, several water management scenarios were evaluated, such as improvements of the current infrastructure, reduction of water consumption patterns, and virtual water scenarios. The tool simulated decisions under different scenarios and climate conditions and promising initiatives focusing on reducing GHG emissions that influence water demand and supply. Currently there are some efforts by CONAGUA and the Rio Bravo Basin Council to build, calibrate and validate a planning model to determine the water allocation rules for every user in the basin, that would include the feedback from water users; such model is currently under revision (Consejo de Cuenca del Río Bravo, 2021).

The Rio Conchos Basin, a main tributary of the Rio Bravo Basin in the state of Chihuahua, has also been well-studied. Gastélum et al. (2009) developed a simulation model (Powersim platform) to quantify the water resources management processes in the basin. The model evaluated long and short-term water allocation alternatives for irrigation districts and the water demands of the 1944 Treaty. This simulation model considered the annual water allocation policy established by CONAGUA in addition to reservoir operation rules and the water distribution efficiencies. Also, Domínguez et al. (2009) used a mathematical model for water distribution in the Rio Conchos Basin. The authors proposed two water management scenarios considering different upper limits of water extraction according to the concession titles. In both scenarios, favorable results were obtained, offering an increase in surface water volume available for water users. In addition, Ingol & McKinney (2011) evaluated a series of water management scenarios (WEAP platform) to adapt and mitigate the impacts of climate change in the Rio Conchos basin. The proposed scenarios identified some adaptation measures that could make the system less vulnerable, such as increased water use efficiencies in the irrigation districts through improvements in the irrigation infrastructure, the need for control structures, and technical support for farmers and decision-makers.

Mayer et al. (2021) modelled the Hueco Bolson/Valle de Juárez aquifer which is a shared aquifer between Mexico and the US. They developed a single compartment groundwater model and conducted a serious games workshop to explore collaborative solutions for groundwater depletion. A *serious game* is an exercise that helps participants understand a given situation by thinking of it as a game rather than a real-world challenge to learn new approaches (Mayer et al., 2021; Schmidt et al., 2015). Games can also prepare players (stakeholders) for the real situation to which the game refers, improving negotiation, agreement building, and changing participants' beliefs (Peters and Vissers, 2004). Stakeholders from both countries participated in setting targets for reducing depletion rates. Water supply and demand reduction strategies were discussed for the cities of Ciudad Juarez and El Paso. They highlighted that even though the serious game did not result in a single and clear resolution, it was a compelling dialogue about common concerns. A limitation found by the authors was the small number of participants and the irregularity of participation. Nevertheless, participants found the groundwater model reasonable and credible.

2.3.3 Tamaulipas

Sanchez et al. (2011) develop a water management model (WEAP platform) to quantify the vulnerability of water resources in the Guayalejo-Tamesí River Basin in the state of Tamaulipas, considering the effects of climate change. A rainfall-runoff model was included in the modeling effort to evaluate the basin’s vulnerability to climate change. Results showed water supply deficits for urban, rural, and agricultural sectors if there are no changes in water concessions and hydraulic infrastructure, even without considering climate change.

2.3.4 Colorado River Basin

In the Colorado River Basin, Sanvicente-Sánchez et al., (2009) built a water resource planning model (WEAP platform) to simulate the operational rules under water scarce conditions. This model is a replicate of the Colorado River Simulation System (CRSS)

(Bureau of Reclamation, 2007); except that the CRSS did not include the Mexican portion of the Colorado River. Unfortunately, this modeling exercise did not evaluate any water management scenarios since the study's main objective was to replicate the CRSS model and include the Mexican portion of the Colorado River. The model was compatible with the CRSS model and was validated by comparing the results against CRSS.

Medellín et al. (2009) built a hydro-economic optimization model (CALVIN platform) that evaluated water management strategies for the Mexican portion of the Colorado River, including wastewater reuse, seawater desalination, water markets, and infrastructure expansions. The model considered hydrologic, engineering, environmental and economic aspects of the region and examined a set of water allocations given a diverse set of economic values assigned to water uses. The authors reported the water deliveries, operation, and scarcity costs for six water management scenarios. The most promising scenario, with the lowest operation and scarcity costs, combined reuse, expanded aqueducts, and some seawater desalination capabilities.

2.3.5 Baja California Peninsula

In the city of Ensenada, Baja California, Mendoza-Espinosa et al. (2006) developed a systems model (Stella platform) to simulate different scenarios of greywater and recycled water use for new housing in Ensenada, which relies mostly on groundwater. The objective of this study was to estimate the water savings when comparing conventional and greywater reuse for municipal water supply. They argued that greywater reuse could save up to 37% of new water supplies and economic savings in reducing water supply and wastewater treatment volumes.

In the Guadalupe River Basin, Baja California, Molina-Navarro et al. (2016a) developed a water availability model (SWAT platform) to evaluate the impacts of climate change. Results showed a decrease of 45% on streamflows in the short term (2010–2039) and up to 60% in the long term (2070–2099) for the high emissions scenario. The model also projected a reduction of the aquifer recharge up to 74%, although the authors emphasized that the model may not entirely capture groundwater dynamics in the basin.

In the Santo Domingo aquifer, Baja California Sur, Wurl et al. (2018) built a groundwater model (MODFLOW platform) to estimate the seawater intrusion into the aquifer under future groundwater extraction scenarios and climate change conditions. Results from this study can be used as a reference for future groundwater management, with a particular focus on the coastal zone. The authors consulted with local stakeholders and discussed water management strategies, such as water saving technologies, and climate smart agriculture strategies, e.g., crop change according to predicted climate change conditions. The authors are worried about the effectiveness of governmental programs that introduce advanced irrigation technologies and crops adaption to local conditions. The Santo Domingo aquifer is the only aquifer in Mexico where a balance between groundwater extraction and recharge rates has been achieved, after a long period of overexploitation, although long-term water availability is still under threat.

2.3.6 Rio Yaqui and Rio Sonora Basin

In the Yaqui Valley of Sonora, Schoups et al. (2006) applied an optimization model (SNOPT platform) to identify an optimal conjunctive use of surface water and groundwater. The model demonstrated the trade-offs between agriculture water use and minimizing leaks and water losses. Later, Muñoz-Hernández et al. (2011) built an integrated hydrologic-economic model for the Rio Yaqui Basin to determine the economic impact in agricultural under different environmental flow scenarios and surface water allocation strategies using a rainfall-runoff and a groundwater model (MODFLOW) of the coastal aquifer. A cost benefit analysis estimated the net benefits of agriculture when evaluating three environmental flow scenarios. The agricultural net benefits decreased significantly as the environmental flows increased. To improve the environmental flow scenarios, the authors proposed more studies focusing on calculating the environmental flow requirements in the Rio Yaqui Delta and determining the farmers' willingness to sell their water for environmental purposes.

Minjares et al. (2010) built a hydrologic and agroeconomic model to identify sustainable water management strategies in the Irrigation District 041. Sustainability criteria like productivity, reliability, resilience, vulnerability, and equity were evaluated for the proposed strategies. A baseline and two alternative water management strategies were evaluated considering limited groundwater use and maximizing agricultural incomes by selecting the most profitable crops. The authors presented their recommendations to the irrigation district Hydraulic Committee, their decision-making organism.

In Hermosillo Sonora, Robles-Morua et al. (2014) organized a participatory modeling workshop to determine the value this technique for decision-makers; specifically, its capacity to change perceptions of water-related problems, causes and solutions. They built a hydrologic and water quality model (QUAL2K) for the Upper Sonora River Basin. Participants of the workshop considered the model as transparent, trustworthy, and valuable. At the end of the workshop, the decision-makers' perception changed in terms of water quality problems, a characteristic that is not frequently considered in the decision making process due to the lack of available water quality data. Most of the workshop participants were governmental personnel; therefore, the authors recommend expanding participation to a broader public.

In the Rio Sonora Basin, Mayer et al. (2017) also conducted a participatory modeling workshop to identify water supply and demand management strategies considering different climate conditions. A water resources systems model was built composed of a water balance and rainfall-runoff (HEC-HMS platform) models. The majority of the workshop participants were from the academic sector, but it was also attended by individuals from federal, state, local agencies, the private sector, and NGOs. Participants explored several strategies using the water supply reliability as the performance criterion for each strategy. The highest water supply reliability was estimated for a strategy that considered repairs in the distribution system and the reuse of reclaimed water for aquifers’ recharge. The authors emphasized the broad range of strategies chosen by the participants, reflecting the uncertainty in how decisions could be made in the future. They also argued that the low assistance of the government sector in all workshops could cause less influence on government policies and highlighted the importance of exploring more schemes for retaining a wider range of participants.

2.3.7 San Luis Potosí

In the city of San Luis Potosí, Martinez et al. (2010) evaluated water management strategies using a water quantity and quality model (UVQ platform). The model described water quantity and contaminant transport from source to sink in urban areas and included rainwater, wastewater, imported water and groundwater. Several strategies were evaluated, including aquifer recharge, increased water supply and the effect of water demand change. The authors proposed the reduction in leakages through pipe rehabilitation and replacement that can result in 20% reduction of pumping from the deep aquifer; however, a strategy like this can decrease groundwater recharge because leakages account for 74% of the total recharge of the aquifer. The authors proposed rainwater infiltration to reverse this effect. They also highlighted the importance of developing a groundwater model to assess the impact on groundwater levels for this strategy and any other strategy.

2.3.8 Durango

Sánchez-Cohen et al. (2015) developed a soil-water balance model to identify potential crops, likely areas where they can be grown, assess the risk of success or failure, and technologies to increase water productivity under current and climate change scenarios. The model was linked to a knowledge-based database, allowing the user to find available data to support cropping decisions. The model was written in Fortran and transferred to the Delphi platform to have a user-friendly interface. The target audience for this model were farmers, technicians, academics, and decision-makers in rainfed agricultural areas of Mexico. The model was calibrated for the state of Durango for maize crop, and it is expected to develop a knowledge-based database for the entire country.

2.3.9 Michoacan

In Michoacán, López-Corona et al. (2013) built a model for the Zamora Aquifer called the Natural Resources Optimal Management System (SMORN by its acronym in Spanish) to optimize the highest possible extraction of water while minimizing the extraction velocity. The model was integrated by a groundwater model (MODFLOW), with a genetic algorithm optimization tool (GA-toolbox) and a post-optimization analysis using game theory (Gambit platform). SMORN provided a set of four optimal solutions, the first favoured extraction, the second conservation, and the other two were intermediate performances where extraction and conservation were in equilibrium. All solutions showed that more groundwater could be extracted while avoiding aquifer overdraft. The set of solutions were used in a game theory analysis and demonstrated that success in cooperation depends mostly on the available information that the users have about the resource.

Nápoles et al. (2013) built an optimization model (GAMS platform) for the city of Morelia Michoacán, to find the optimal schedule that satisfies the water demands, maintains sustainable levels of the natural resources while maximizing the profits from sales of water and minimizing operational distribution and storage costs. The model evaluated alternative water sources, such as rainwater and reclaimed water, and found that these sources were economically viable and improved the sustainability of the system by reducing the water resources depletion. Moreover, results showed that even when an alternative water source is not available, an optimized water extraction policy from all sources can help maintain acceptable extraction levels from all sources. The authors argue that these reasons should outweigh the economic aspects in the decision-making process in the near future.

Arredondo-Ramírez et al. (2015) built an optimization model (GAMS platform) for Irrigation District 097 Tierra Caliente, Michoacán, to evaluate water management strategies, such as water capture, reuse, and distribution. The authors proposed strategies aimed to optimize economic and environmental objectives, balancing water savings for freshwater use and economical costs.

2.3.10 Puebla

In Puebla, Salcedo et al. (2013) built a groundwater (MODFLOW platform) and optimization model (MODRSP platform) for the Valley of Puebla Aquifer to estimate the optimal sustainable aquifer extraction volume considering different water allocation strategies. Results showed that the aquifer could recover up to 5 m in its groundwater levels through a gradual reduction in the extraction volume from the urban and industrial zone, preventing aquifer overdraft and the intrusion of poor-quality water. This extraction policy could encourage the conjunctive use of reclaimed and surface water as alternative water sources.

2.3.11 México City

In Mexico City, Galindo-Castillo et al. (2017) built a simplified-to-available-data groundwater simulation model (MODFLOW platform) of the Cuautitlán–Pachuca aquifer to evaluate water management strategies such as population growth rate, urban expansion, and climate change. The model allowed for the spatial and temporal analysis of the strategies. The authors highlighted the lack of data that researchers face in developing countries.

Jujnovxky et al. (2017) built a land use-rainfall-runoff model (SWAT platform) to estimate the ecosystem services (ES) that the Magdalena River provides of water provision to the society and economy of Mexico City. The authors estimated an annual provision of 18.4 Mm^3 of water, benefiting nearly 80,000 inhabitants. The authors used assumptions and their best professional criteria to overcome the large amount of environmental data required to build the model. They proposed to use the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and Artificial Intelligence for Ecosystem Services (ARIES) platforms for future evaluation, arguing that these tools are more accessible to non-experts and can facilitate the decision-making process.

Shelton et al. (2018) built a multi-criteria decision model (Super Decisions platform) called Dynamics of Multi-Scalar Adaptation in Megacities (MEGADAPT), to simulate stakeholders' decisions related to flood risk and water scarcity in Mexico City using a participatory framework. The study considered a role-play game involving two kinds of agents, the city's water managers, and vulnerable residents. The regions of Xochimilco, Magdalena Contreras, and Iztapalapa were selected as case studies that represent vulnerable areas suffering from scarcity and flooding events. The model included physical, environmental, social, and political drivers for the two hazards and the resulting strategies. The strategies included individual actions, like modifying houses' infrastructure, and collective actions, like o rganizing protests or cleaning drains. In general, participants expressed that protesting was the last option because of the time and effort it takes and the troublesome relations with their neighbours. Whereas preventive actions like investing in water storage containers, constructing barriers in front of their homes, and working together to keep drains clean gained more attention. This exercise could be used as a reference in further agent-based models for other case studies. The authors addressed how role-play games can validate quantitative models making them more accessible to stakeholders that are unfamiliar with algorithmic modeling.

Freeman et al. (2020) proposed a resilience planning framework to evaluate water management strategies of Mexico City. The approach integrated modeling tools and stakeholder preferences to evaluate alternative system configuration for improving water supply reliability under different climate scenarios. The authors used multi-objective evolutionary algorithms to test infrastructure capacity and operating rules, of which increasing storage capacity represented the highest-ranked strategy in terms of reliability. This study also showed that stakeholders shared common objectives and prioritized similar concerns, they recommended a shared vision about the future of the water resources in the region.

2.3.12 Guanajuato and Querétaro

In Támbula Picachos sub-basin, Guanajuato, Hernández et al. (2014) built a water allocation and groundwater model (Aquatool platform) to evaluate different water management strategies. The authors evaluated an increase in urban water demand by 2025 and 2050, different levels of aquifer recharge, increase in reservoir storage capacity, and a combination of strategies. The authors recognized some limitation for the modeling effort, the lack of data for the calibration process, specifically related to the aquifer's complexity and physical representation. However, the modeling effort identified groundwater depletion tendencies and strategies to decrease water demand.

Carrera-Hernández et al. (2016) built a groundwater model (FEFLOW platform) to estimate the groundwater flow patterns and the effect of reducing the extraction rate from public water supply wells for the Valle de Querétaro Aquifer. Two proposed scenarios reduced the groundwater extraction rate specified in the water management plans by the Mexican environmental protection agency (SEMARNAT). The authors recognized the models' limitations, and highlighted the uncertainties associated with groundwater extraction rates, the geometry of the aquifer, and potential aquifer recharge. Moreover, they highlighted that current administrative jurisdiction follows political boundaries and not hydrological limits, they proposed to include Guanajuato for an adequate representation of the groundwater flow dynamics.

Pérez-Uresti et al. (2019) built a multi-objective optimization model to assess the strategy of rainwater harvest as an alternative water sources and determine the optimal design for the water distribution network in Queretaro City. The authors estimated that at least 27% of the domestic demand could be supplied by rainwater harvesting. This strategy could benefit the recovery of deep wells since Queretaro city relies on an over drafted groundwater aquifer.

2.3.13 Lerma – Chapala Basin

The Lerma-Chapala basin is a basin shared by five states (Guanajuato, Jalisco, Mexico, Michoacán, and Querétaro), it is important because of the urban and agricultural water users that depend on it (Aparicio, 2001). Huerta (2004) built a system dynamics simulation model (Stella platform) to determine water allocation rules for surface water distribution agreement among the five states. The model represented the hydrological process, infrastructure and reservoirs, Chapala Lake storage, and agricultural production. Results showed that any sudden operational change (e.g., water transfers) could affect the future operation of the basin. Moreover, the application of any policy that benefits just one part of the basin could produce only a short-term advantage, but in the long term, could affect the entire basin. The model was collaboratively developed with the Lerma-Chapala basin council a multidisciplinary group integrated by stakeholders. However, the author emphasized that the lack of notion of the system dynamics' concept among the group affected the precise understanding of the model and the results it would produce.

2.4 Challenges ahead

The modeling efforts in Mexico have evaluated current and alternative water management strategies, identified optimal operation and infrastructure configurations, evaluated the impacts of climate change, highlighted uncertainties and data gaps, informed decision-making processes, and in general increased the understanding of water resources systems.

Most of the regions of study are located in the Northwest, North, and Central regions, which are the arid regions that face the most significant water management challenges.

Table 1 shows three primary water management processes supported by the models were identified: conflict resolution, water resources planning, and water availability and demand diagnosis. Conflict resolution is aimed to determine water allocations in highly competitive systems, such as the Lerma-Chapala basin (Huerta, 2004), the Alto-Rio Lerma District (Salazar et al., 2007) and Rio Bravo basin (Consejo de Cuenca del Río Bravo, 2021). Frequently, the approaches of game theory, systems dynamics (SD), and mass balance modeling are used for water resources conflict resolution. These models are useful tools to approximate complex nonlinear functions and to identify improved opportunities for water management given a set of constraints. However, they are not intuitive, and usually they lack an explanatory character that makes them difficult to comprehend and explain (Darbandsari et al., 2020; Kerachian and Karamouz, 2007). Moreover, social, and economic aspects are not easy to represent explicitly. For instance, the systems dynamics model of the Lerma-Chapala basin (Huerta 2004) was presented to an interdisciplinary group of stakeholders; however, the author emphasized that the lack of "systems dynamics among the group prevented the understanding the model's functioning and favoured unequal participation." Similarly, Duran-Encalada et al. (2017) also used system dynamics model for the Rio Bravo Basin. The authors recommended that, in addition to SD, another method or conceptual approach should be used to enhance the understanding of results, such as the Critical Realism method.

Water resources planning models were the most used tools. These studies were characterized by evaluating a portfolio of strategies (water demand, water supply, operation, and infrastructure) for different water sectors (e.g., agriculture, environment, domestic and urban users). Some of the models were referred as *decision support tools* that facilitated the data input, evaluation, and the display of output data (e.g., WEAP, Stella, and GAMS platforms). Several studies focused on increasing system's efficiency through improvements in infrastructure operation, irrigation systems, reservoir operation rules, and changes in water allocation policies (Gastélum et al., 2009; Sandoval-Solis et al., 2013). Models were also used for urban planning and encouraged the reuse of reclaimed water, such as in Cuernavaca, Morelia, and Ensenada (Arreguín-Cortés and Alcocer-Yamanaka, 2004;

Mendoza-Espinosa et al., 2006; Nápoles-Rivera et al., 2013). Other studies jointly considered the water availability and economic aspects (hydro-economic models) to improve the water supply for human users (Medellín-Azuara et al., 2009) and environmental users (Munoz-Hernandez et al., 2011). Some water resources planning models are more intuitive and interactive for stakeholders, allowing them to enter their data, operation rules and evaluating the impact of their own water management strategies. However, all modeling tools have limitations, they are an educated approximation of the real systems; they are not the instrument that will provide the solution for the water management problems at hand; they can provide useful information during the decision-making process, but the decisions are taken by the people involved.

Finally, the third process identified was water availability and demand diagnosis, which is the estimation of the natural water availability from different sources and compared it with the water demands by performing a water budget analysis. Two main categories were identified: (1) Evaluation of climate change scenarios and (2) Estimation of groundwater optimal extraction. The impact of climate change on future water availability was evaluated in the Guadalupe River basin (Molina-Navarro et al., 2016); Guayalejo-Tamesí river basin (Sanchez-Torres Esqueda et al., 2011); Rio Conchos Basin, (Ingol-Blanco and McKinney, 2011); and the Santo Domingo Valley (Wurl et al., 2018). Modeling efforts dedicated to estimate the optimal groundwater extraction while avoiding groundwater overdraft included the Zamora aquifer (López-Corona et al., 2013) and the Cuautitlán–Pachuca aquifer (Galindo-Castillo et al., 2017). Two limiting factors for water availability and demand diagnosis were identified. First, data availability and accuracy, especially in developing countries where researchers face the lack of reliable, available, and long-time measured data; thus, simplifications are used (Galindo-Castillo et al., 2017). Second, some of the modeling efforts were not presented to stakeholders, and therefore, they did not inform the decision-making process.

Moreover, the predominance of models for water resources between the United States and Mexico is notable (Duran-Encalada et al., 2017; Gastélum et al., 2009; Ingol-Blanco and McKinney, 2011; Mayer et al., 2021; Sandoval-Solis et al., 2013; Sanvicente-Sánchez et al., 2009). However, to our knowledge, there are no water planning models built for the shared resources between Guatemala, Belize, and Mexico in the southern border. This could be associated with the lack of political interest, water abundance, lack of research funding and scientific interest or willingness. Models in this region could be helpful for addressing flooding events in vulnerable communities, water availability and water allocation systems among users and countries.

In Mexico, some limitations identified in the transboundary case studies were the lack of governmental support for adopting tools already built (Sandoval-Solis et al., 2013); lack of information available for accurate representation of operating rules (R. J. Brandes Company, 2004), poor water demand representation due to the absence of organized water rights system in Mexico (R. J. Brandes Company, 2004). In the U.S., some limitations identified are the secrecy in private data for historical water use, water withdrawals for individual users cannot be tracked. For instance, water diversions for several users are grouped into a single diversion data point, that rarely can distinguish individual water use (Sandoval-Solis et al., 2013).

The lack of comprehensive hydrological data was another common limitation identified, especially when characterizing aquifers and groundwater data (Carrera-Hernández et al., 2016; Gastélum et al., 2009; Hernández et al., 2014; Medellín-Azuara et al., 2009; Wurl et al., 2018). Moreover, water quality data is very scarce (Robles-Morua et al., 2014) this highlights the lack of financial resources and monitoring culture in Mexico. Effectively monitoring groundwater extraction rates, water tables, aquifers recharges, seawater intrusion, and water quality is necessary for reliable water resources modeling.

2.5 Good practices and opportunities for improvement

According to the authors, stakeholder outreach was identified as a good practice, and in some cases, results were presented to decision-makers (17% of the total modeling efforts). Unfortunately, their results were not considered in the decision-making process. Paradoxically, stakeholders still have the false impression that the model application will provide the optimal policy and the results from models should be followed no matter what. However, the reality is that models are tools that can help to inform the decision making process, but the ultimate decision lies in the hands of the decision makers who are representatives of stakeholders. Also, frequent changes in government, technical and communication barriers hinder the adoption of these models and the incompatibility of interests of stakeholders is often embedded in a deeper political context (Klimes et al., 2019).

It must be recognized that the modeling efforts that used collaborative and participatory modeling, gained more support from decision-makers. Only eight studies (17%) mentioned the involvement of stakeholders from beginning to end, these studies have the highest score in the Success Evaluation (Table 1). To embrace the involvement of stakeholders, the authors propose the participation by non-governmental organizations, research centers and universities that have greater technical capacities through collaboration and join projects. Modelers should build models in conjunction with them to make more accessible tools for people unfamiliar with quantitative models, guided by the decision-making process objective and the stakeholder's goals.

The studies with higher score in the Success Evaluation conducted participatory workshops using approaches like collaborative modeling (Mayer et al., 2017; Robles-Morua et al., 2014; Sandoval-Solis et al., 2013; Shelton et al., 2018); resilience framework (St. George Freeman et al., 2020; Wurl et al., 2018) or serious game (Mayer et al., 2021) (Table 1). Shortcomings of the participatory process included low attendance of the government sector (Mayer et al., 2017) or overall (Shelton et al., 2018), and lack of model's familiarity from stakeholders (Huerta, 2004; Sandoval-Solis et al., 2013). Despite these limitations, most of the workshop's participants found the models trustworthy, highlighting the necessity to build models in conjunction with stakeholders to make them more accessible for people unfamiliar with quantitative tools. Nevertheless, stakeholders' trust in model results does not necessarily lead to model adoption. As Voinov and Bousquet (2010) explained, selecting the proper modeling tool is a critical phase of any participatory modeling exercise. Researchers should select a model platform and methodology guided by the decision making process objective, stakeholder's goals, data availability, funding, and time limitations.

Informed decisions require reliable, timely and available information. Models can represent complex water systems, the environmental, social, and economics interactions, and include relevant variables for supporting the decision making process (McDonnell, 2008). An example of effective model is the Australian Water Resources Assessment (AWRA) modelling system that provides data to inform water management and planning decision used by the Australian government (CSIRO, n.d.). As Mexico is gradually developing, using, and accepting water resources models, it is essential to collaborate within the end-users, stakeholders, and decision-makers.

2.6 Conclusions

As water management challenges grow, it becomes essential to describe the interaction of natural and social systems, and to evaluate water management strategies that can cope with challenges, such as population and water use growth, climate change, among others. The use of quantitative models could increase the transparency, acceptability, and efficiency of the decision-making process. In this study, we assessed the use of water planning models for evaluating water management strategies in Mexico. A total of 36 peer-reviewed modeling effort were identified in Mexico until July 2021. Most of the modeling efforts were located in the Northwest, North, and Central regions, which face the most significant water management challenges in the country in terms of water scarcity. Three water management processes supported by the models were identified, water resources planning (53%), water availability and demand diagnosis (36%), and conflict resolution (11%).

Common obstacles identified in this analysis related to using model results to inform decision making processes in Mexico are: (1) stakeholders misconception of water resources models as ultimate decision tool, (2) lack of stakeholder involvement, and (3) lack of knowledge sharing and overcoming data limitations. On the other hand, good practices that helped the effectiveness and implementation of the models with greater success included: (1) stakeholder outreach, (2) collaborative and participatory modeling, and (3) reliable, timely and available information.

Most of the studies introduce competitive alternatives and have beneficial impact on the planning and decision-making process, however, to our knowledge, only 1 out 36 of the peer-reviewed studies until 2021-was considered fully for implementing a new policy (Lerma-Chapala Basin case study). A successful modeling process not only requires the adequate representation of the water resources system, but also the active participation of academics, governments, and society for integrated management that embraces sustainable use of water resources. Moreover, if non-academics do not thrust, understand or are familiar with models, these tools are not likely to inform decision-makers to solve real water management problems. Only eight studies (17%) considered collaborative modeling and stakeholder engagement. The good practices discussed here stressed the importance of ensuring transparency, credibility, and shared understanding of stakeholders and decision-makers.

The modeling efforts in Mexico increased the understanding of water resources systems and supported water management processes. However, still are significant challenges for the modeling practice. The comprehensive hydrological data and effective monitoring of the water resources are essential for reliable models. Moreover, in addition to developing accurate models, it is also vital to communicate the complexity of management decisions to the end-users. All modeling tools have limitations, they approximate real systems and do not solve water management problems but can provide helpful information during the decision-making process.

2.7 Conclusiones

A medida que aumentan los retos de la gestión del agua, resulta esencial describir la interacción de los sistemas naturales y sociales, y evaluar las estrategias de gestión del agua que pueden hacer frente a retos como el crecimiento de la población y del uso del agua, el cambio climático, entre otros. El uso de modelos cuantitativos podría aumentar la transparencia, la aceptabilidad y la eficacia del proceso de toma de decisiones. En este estudio, evaluamos el uso de modelos de planificación hídrica para evaluar estrategias de gestión del agua en México. Se identificó un total de 36 esfuerzos de modelación revisados por pares en México hasta julio de 2021. La mayoría de los esfuerzos de modelación se localizaron en las regiones Noroeste, Norte y Centro, que enfrentan los retos más significativos de gestión del agua en el país en términos de escasez de agua. Se identificaron tres procesos de gestión del agua apoyados por los modelos, la planeación de los recursos hídricos (53%), el diagnóstico de disponibilidad y demanda de agua (36%) y la resolución de conflictos (11%).

Los obstáculos comunes identificados en este análisis en relación con el uso de los resultados de los modelos para informar los procesos de toma de decisiones en México son: (1) la idea errónea de los interesados de que los modelos de recursos hídricos son la herramienta de decisión definitiva, (2) la falta de participación de los interesados, y (3) la falta de intercambio de conocimientos y de superación de las limitaciones de los datos. Por otro lado, entre las buenas prácticas que ayudaron a la eficacia y a la aplicación de los modelos con mayor éxito se incluyen: (1) divulgación entre las partes interesadas, (2) modelización colaborativa y participativa, y (3) información fiable, oportuna y disponible.

La mayoría de los estudios introducen alternativas competitivas y tienen un impacto beneficioso en el proceso de planificación y toma de decisiones, sin embargo, hasta donde sabemos, sólo 1 de 36 de los estudios revisados por pares hasta 2021 fue considerado en su totalidad para implementar una nueva política (estudio de caso de la cuenca Lerma-Chapala). Un proceso de modelación exitoso no sólo requiere la representación adecuada del sistema de recursos hídricos, sino también la participación de académicos, gobiernos y sociedad para una gestión integrada que abarque el uso sostenible de los recursos hídricos. Además, si las personas ajenas al mundo académico no impulsan, entienden o están familiarizadas con los modelos, no es probable que estas herramientas informen a los responsables de la toma de decisiones para resolver problemas reales de gestión del agua. Sólo ocho estudios (17%) consideraron la modelización colaborativa y la participación de las partes interesadas. Las buenas prácticas aquí analizadas destacaron la importancia de garantizar la transparencia, la credibilidad y la comprensión compartida de las partes interesadas y los responsables de la toma de decisiones. Los esfuerzos de modelación en México aumentaron la comprensión de los sistemas de recursos hídricos y apoyaron los procesos de gestión del agua. Sin embargo, aún existen retos importantes para la práctica de la modelación. Los datos hidrológicos completos y el monitoreo efectivo de los recursos hídricos son esenciales para contar con modelos confiables. Por otra parte, además de desarrollar modelos precisos, también es vital comunicar la complejidad de las decisiones de gestión a los usuarios finales. Todas las herramientas de modelización tienen limitaciones, se aproximan a los sistemas reales y no resuelven los problemas de gestión del agua, pero pueden aportar información útil durante el proceso de toma de decisiones.

CAPÍTULO III: PLANEACIÓN DE LOS RECURSOS DEL RÍO COLORADO EN MÉXICO

Resumen

El manejo de agua de los recursos del río Colorado se encuentra en un punto de inflexión. Este capítulo describe estrategias de manejo del agua en la parte mexicana de la cuenca del río Colorado considerando escenarios de escasez de agua. Se construyó un modelo de asignación de agua que representa la demanda y el abastecimiento actual y futuro. Se tomó como caso de estudio el sistema del Río Colorado en territorio mexicano, el cual se caracteriza en todas sus demandas de agua (DR-014, Mexicali, San Luis Río Colorado, Tecate, Tijuana-Rosarito y Ensenada). Se corrieron escenarios individuales por subsistema y posteriormente se analizó su impacto en todo el sistema para identificar los factores de estrés hídrico y las estrategias que favorecen el desempeño del sistema. El análisis de los resultados muestra que el DR-014 es el usuario más afectado en lo que respecta a los recortes de agua, ya que tiene la menor prioridad y, por lo tanto, cualquier reducción de las asignaciones del río Colorado les afecta directamente. El sistema actual tiene un mejor rendimiento a costa de la sobreexplotación de los acuíferos a largo plazo. La reducción de la superficie cultivada fue la estrategia que más aumentó el índice de sustentabilidad para el DR-014. Las transferencias de agua de uso agrícola a urbano, el aumento de eficiencia en la red urbana y el reuso de aguas residuales son las principales posibilidades para mejorar el actual suministro de agua en la zona costa (Tijuana, Rosarito, Ensenada). Esta investigación muestra el espectro de posibles resultados que podrían esperarse, que van desde los efectos de la inacción en todo el sistema hasta la aplicación de una cartera de estrategias de manejo.

Palabras clave: río Colorado, México, manejo de agua, modelo de asignación, escasez de agua

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Assessing water management strategies under water scarcity in the Mexican portion of the Colorado River Basin

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Abstract

The water management of the Colorado River is at a tipping point. This paper describes water management strategies in the Mexican portion of the Colorado River Basin considering water scarcity scenarios. A water allocation model was constructed representing current and future water demands and supply. The Colorado River system in Mexican territory is used as a case study and all its water demands are characterized [Irrigation District Rio Colorado (DR-014), Mexicali, San Luis Rio Colorado, Tecate, Tijuana-Rosarito, and Ensenada]. Individual strategies were run by subsystem and then their impact was analyzed systemwide. Performance criteria and a performance-based sustainability index were evaluated to identify water stressors and management strategies to improve water supply for agricultural, urban, and environmental users. Analysis of results shows that the irrigation district (DR-014) is the most affected user due to water cuts since it has the lowest priority and, thus, any reduction in Colorado River allocations affect them directly. A range of water management strategies was investigated, including a no-action scenario. The current system depends on the long-term aquifers overdraft to supply water demand. The reduction of the cultivated area was the strategy that increased the sustainability index the most for DR-014. Agricultural to urban transfers, water use efficiency, wastewater reuse, and desalination are prime possibilities to improve the current water supply in the coastal zone (Tijuana, Rosarito, Ensenada). This research shows the spectrum of possible outcomes that could be expected, ranging from systemwide effects of inaction to the implementation of a portfolio of water management strategies.

Keywords: Colorado River, Mexico, water management, allocation model, water scarcity

3.1 Introduction

There is a growing crisis of freshwater availability throughout the world (Padikkal et al. 2018). Accessible water resources are becoming more vulnerable due to increased pollution, uncontrolled groundwater depletion, and climate change impacts on water availability patterns (Khan et al. 2017). Water availability is under constant threat from increasing domestic, agricultural, and industrial demands. According to the World Water Assessment Programme (WWAP, 2015), water demand is predicted to increase worldwide by up to 55% by 2050. This prediction is based on the increment of the population from about 7.7 billion in 2019 to about 9.7 billion in 2050 and the subsequent increase in feed crops production to support animal-protein diets, energy demand, and economic-industrial activity. Moreover, intensified competition over water resources can increase water conflicts, which are predominant in transboundary waters (Padikkal et al. 2018).

Transboundary water resources are shared by over 70 % of the world's population and supply water for about 60 % of worldwide food production (Earle and Neal 2017). There are more than 280 shared river basins increasingly subject to water-related conflicts (United Nations 2018). Along the border region between the United States (US) and Mexico, there are significant challenges including overallocation, rapid urbanization and industrialization, surface and groundwater pollution, groundwater overdraft and climate uncertainties (Wilder et al. 2010). The 3218 km boundary between the two countries comprises four states in the U.S (California, Arizona, New Mexico, and Texas) and six in Mexico (Baja California, Sonora, Chihuahua, Coahuila, Nuevo León, and Tamaulipas) (Wilder et al. 2019). Transboundary river basins along the border include the Rio Grande - Bravo Basin (RGB), the Tijuana River Basin and the Colorado River Basin (CRB). The Colorado River (CR) provides water to almost 40 million people in seven US. states, 2.7 million people in two Mexican states (Baja California and Sonora), and 34 Native American Territories (Pulwarty and Maia 2015). The CR is a highly engineered system, with multiple reservoirs and enough storage capacity in Lakes Mead and Powell to supply water demands for a four-year period when of them were at full capacity (Gerlak et al., 2021). However, in the last two decades, the river has been under great pressure from increasing demands and prolonged droughts (Berggren 2018; Udall and Overpeck 2017). In July 2022, the reservoirs were less than half capacity at its lowest historical level (Bureau of Reclamation 2022). Climate change and sustained drought, population growth, management of the Colorado River Delta and stakeholder inclusion are some of the main challenges of the CR basin (Juricich 2022).

In recent years, increased awareness of overallocation and drought has catalyzed collaboration between the US and Mexico (Bussey 2019). The 1944 Water Treaty signed by both countries provided a water allocation to Mexico of 1,850 million cubic meters per year (Mm^3/y) from the CR. The 1944 Treaty is a living document and agreement, *Minutes* are the instrument by which the US and Mexico update the Treaty.

One of the latest amendments through Minute 323 (IBWC 2017) describes the Binational Water Scarcity Contingency Plan (BWSCP) "*to avoid reaching critical reservoir elevations at Lake Mead*", and specifies two main concepts for both countries: water savings and mandatory water reductions. Water savings is water that is stored and saved for later use for both countries to reduce Lake Mead releases under low elevations; these water savings are recoverable once reservoir elevation conditions improve. Mandatory water reduction is water that will be deducted from Mexico's water allocation without recovering it later. Based on the projected Lake Mead elevation by January 1, 2023, Mexico's water allocation will be reduced by 123 Mm^3 in 2023, with a mandatory water reduction of 86 Mm^3 and recoverable water savings of 42 Mm^3 (CILA 2022). Mexico will recover the water savings when the reservoir elevation in Lake Mead is projected to exceed 1,110 feet above sea level. The water reduction (123 Mm^3) represents 6.65% of Mexico's total water allocation (1,850 Mm^3).

Minute 323 is not the only water shortage and saving plan for drought conditions in the CR basin. The minute applies the principles of shared shortage and surplus by creating additions and reductions to Mexico in proportion to the reductions outlined in the 2007 Interim Guidelines for the states of Arizona, California, and Nevada (Bussey 2019; Secretary of the Interior 2007) and it is an ampliation of Minute 319 (CILA, 2012). Moreover, in 2019, the Upper Basin and Lower Basin Drought Contingency Plans (DCPs) were signed. The DCPs outline strategies to address the ongoing historic drought in the Colorado River Basin (Bureau of Reclamation, 2023). The 2007 Guidelines, Minute 323 and DCPs, all expire in 2026.

Moreover, Minute 323 also allows Mexico to temporarily store water in Lake Mead (Bussey 2019), and establishes measures to address Mexico's concerns over water salinity, which has been a longstanding problem since the enactment of Minute 242 in 1973. Moreover, both countries, in collaboration with a coalition of environmental non-governmental organizations (NGOs), committed to fund and allocate water to the riparian and estuarine system within the Colorado River Limitrophe and Delta. The US also agreed to provide Mexico with $31.5 million to develop conservation projects in Mexico, such as the modernization of irrigation districts, the creation of wetlands, wastewater reuse projects, among others (IBWC 2017). Minute 323 also establishes the Intentionally-Created Mexican Allocation (ICMA – Agua Mexicana Intencionalmente Creada) which is an instrument that allows Mexico to defer delivery of water volumes through adjustments to its annual delivery schedule, resulting from water conservation projects or new water sources projects. Minute 323 has been criticized for setting a policy instrument that allows the US to exchange money (funding for conservation, new water sources, and environmental projects) for water to fulfill Treaty obligations (Lewis 2019), considering the disproportionate difference in economic power between both nations.

In Mexico, Baja California is the main user of the Colorado River water. Surface water and groundwater of the Mexicali Valley aquifer and the San Luis Rio Colorado (SLRC) Valley aquifer serve 2.7 million people in Baja California representing 88% of the state's population, as well as more than 200,000 hectares in the Irrigation District 014 (DR-014) (CEABC 2018). Due to water demand pressures and the modification of Mexico's water allocation under Minute 323, there is a need to evaluate how the CRB in Mexico will respond to these stressors considering the current water allocation policies, infrastructure, and alternative water management strategies.

An important step towards decision support is the use of water planning models to estimate the consequences of different management alternatives and their social and environmental implications (Reichert et al. 2015). Recently, Hadjimichael et al. (2023) presented an intercomparison of models, highlighting the limitations of large-scale hydrologic models and water systems models that emphasize the environmental, infrastructural, and institutional characteristics. The study evaluates two such representative models to assess water scarcity vulnerabilities in the Upper Colorado River Basin (Hadjimichael et al. 2023).

The Water Evaluation and Planning System (WEAP) platform has been used for water resources management due to its integrated approach, user-friendly interface, and good compatibility (Kou et al. 2018; Shi et al. 2015). In Mexico, the WEAP platform has been widely used, to quantify the vulnerability of water resources in the Guayalejo-Tamesí River Basin (Sanchez et al. 2011) considering the effects of climate change; in the transboundary RGB(Ingol-Blanco and McKinney 2011; Sandoval-Solis et al. 2013b) to evaluate the current water allocation system and alternative water management scenarios; and in the CRB (Sanvicente-Sánchez et al. 2009) to simulate the operational rules under water scarce conditions. However, this last study did not evaluate any water management scenarios since the main objective of the study was to replicate the Colorado River Simulation System (CRSS) (Bureau of Reclamation 2007) model and include the Mexican portion of the CR. Therefore, there is a need to evaluate the recent water allocation and agreements (*e.g.,* Minute 232), as well as alternative water management strategies that consider the effects of climate change and preventing groundwater overdraft in the Mexican portion of the CR.

The overarching goal of the present research study is to evaluate the effect of current and future water management strategies in the Colorado River system that is located in the Mexican territory. The research question being: *In light of recent binational water agreements (e.g., Minute 323 and water allocation reductions), climate change, and other stressors, how will the water supply for the different users be affected when considering current and future water management strategies?* To address this question, the following objectives were defined: (1) construct a water resources planning model, (2) define and evaluate future availability and water management scenarios, and (3) identify key system stressors. The Mexican portion of the CRB is used as a case study. This research shows the impacts not only in this region but also some generalized water management strategies (e.g., reduction in water allocation or increased infrastructure capacity) that can affect the overall water supply in limited water resources systems.

3.2 Study Area

Northern Baja California and San Luis Río Colorado in Sonora are highly dependent on the Colorado River, mostly from Mexico's water allocation from the 1944 Water Treaty and supplemental groundwater out of the Mexicali Valley aquifer and the SLRC Valley aquifer (hereafter referred as Mexicali-SLRC groundwater system), within the Colorado River Delta. Both, surface river water and groundwater are conveyed south through 2,562 km of canals for Irrigation District 014 Rio Colorado (DR-014) that expands over Mexicali and SLRC valleys, and to the west coast through the Colorado River-Tijuana aqueduct (CRTA) (Fig. 1). The study region consists of two climate regions, separated by the peninsular mountain range. The western region, adjacent to the Pacific Ocean, is considered a semiarid zone with a Mediterranean climate and annual average precipitation range within 200-400 mm (CEABC, 2018). The eastern region , where Mexicali and SLRC are located, is considered an arid desert receiving less than 100 mm of annual precipitation.

The onset of climate change in the Colorado River basin has altered rainfall and temperature patterns, affecting water availability (Udall and Overpeck 2017). The total annual allocation of the Colorado River water resources (2,633 Mm^3) in the CRB corresponds to the sum of the surface water (1,850 Mm^3), which corresponds to the water allocation from the Treaty and is subject to reductions, and groundwater supply from the Mexicali Valley and San Luis Rio Colorado Mesa Arenosa (783.12 Mm^3) uses (IMTA 2020). The main water user in the system is DR-014 which receives 85% of the full water supply (surface and groundwater) (IMTA 2020). For groundwater extraction, the district has 489 federal wells (volume allocated by the federal government) and 220 privately owned wells. Although surface water is the focus topic in most of the Lower Colorado River basin conversations and is linked to groundwater, they are not managed conjunctively (Gerlak et al. 2021). The current cultivated area of DR-014 relies on groundwater overdraft from

Mexicali-SLRC groundwater system. Inefficiencies in irrigation infrastructure for agriculture constitute the primary source of aquifer recharge in the groundwater system (CEABC 2017; CONAGUA 2020b; Lesser et al. 2019). In addition, the recharge of the Mexicali Valley aquifer has been further reduced as result of the lining of the AAC (Leeser et al. 2019). Moreover, mineralization of the shallow aquifer layers and soil contamination process are identified in Mexicali Valley (Ramirez-Hernandez et al. 2008).

DR-014 is integrated by the Mexicali Valley in Baja California and San Luis Río Colorado Valley in Sonora, and is the fourth largest irrigation district in Mexico, producing 3,078 tons of crops mainly wheat, cotton, and alfalfa and worth $435 million US dollars per year (CONAGUA 2016). However, given the potential reductions of the water allocations related to Lake Mead elevation, salinity problems in water and soil, and overexploitation of groundwater, the water supply of Mexican users are at risk. Despite the relevance of DR-014 in the use of water from the Colorado River, its participation in binational water agreements has been minimal, such as voicing their concerns when the All-American Canal (ACC) was lined (Cortéz Lara 2011).

The city of Mexicali is the state's capital and the second most populated in Baja California (Table 1). Although Mexicali has a relatively secure water supply due to water rights transfers (the agricultural footprint that transform into urban uses transfer their irrigation permits to Mexicali), competition for water between the urban and agricultural sectors could compromise its near future water supply.. The city of Tecate is also supplied with water from the CR through the CRTA. Tecate has experienced rapid urbanization, population growth, and industrialization, which has compromised the quality of its local water resources. In the 2000s, groundwater provided 30% of the drinking water for Tecate, while in 2015, it supplied only 20% (CEABC 2015). Pollution due to low-quality industrial wastewater discharges into the Tecate River reduced such reliance on groundwater, increasing the Tecate region dependence on imported CR water through the CRTA (Mahlknecht et al. 2018).

Tijuana and Playas de Rosarito are highly dependent on the CR imports, since nearly 99% of their available water comes from the CRTA whose current conveyance capacity is 5,333 l/s, and water demand is expected to exceed supply capacity in a few years (CEABC

2018; Medellín-Azuara et al. 2009). Built as the final receiving reservoir of the CRTA, the El Carrizo dam is the primary supply reservoir for the cities of Tecate, Tijuana, and Playas de Rosarito (Malinowski 2004). El Carrizo provides 97% of Tijuana's water supply (CEABC 2015). The Abelardo L. Rodríguez (ALZ) reservoir is used for flood control and is generally considered an unreliable source (Malinowski 2004).

The city of Ensenada has experienced a considerable increase in population, groundwater overdraft, seawater intrusion in aquifers, unreliability of water supply and institutional inefficiencies (Medellín-Azuara et al. 2013). In addition to local groundwater supplies, Ensenada has a water allocation of 9 Mm^3 from the SLRC aquifer (Mesa Arenosa) since 1996 (REPDA, 2020) although, until recently, not all the allocated volume was being used due to the high urban demand of Tijuana and Rosarito that partially use the allocation to Ensenada. In 2015, the conversion of the Tijuana-La Misión-Ensenada (TLME) aqueduct (called inverse flux or *flujo inverso* in Spanish, as it used to carry water from La Misión aquifer to Rosarito) made it possible to import this water, at an average of 110 l/s (4 Mm^3 annually), which is lower than the aqueduct's capacity of 300 l/s (CEABC, 2017). Ensenada is also supplied with desalinated water at 132-190 l/s (CEABC, 2021), from a 250 l/s desalination plant privately owned by Aguas de Ensenada, which due to operational limitations does not operate at capacity. The Emilio Lopez Zamora (ELZ) reservoir is used primarily for surface water runoff collection.

In Ensenada, the nearby agricultural regions of the Guadalupe and Maneadero valleys, are economically important (Mendoza-Espinosa et al. 2019); the former being responsible for 90 % of Mexican wine production (Plata Caudillo 2010) with an annual gross income of $6 million (CEABC, 2018). All water used in Guadalupe Valley comes from the underlying aquifer, which is in an overdrafted condition (Campos-Gaytan et al. 2014; CONAGUA 2020a). In Maneadero Valley, the main crops are ornamental flowers, tomato, cucumber, asparagus, and brussels sprouts. The Maneadero Valley relies primarily on groundwater from Maneadero aquifer that is experiencing seawater intrusion due to longstanding overdraft (Gilabert-Alarcón et al. 2018); reclaimed water (80 l/s) is used for ornamental flower production of 100 ha since 2014 (Mendoza-Espinosa and Daesslé 2018).

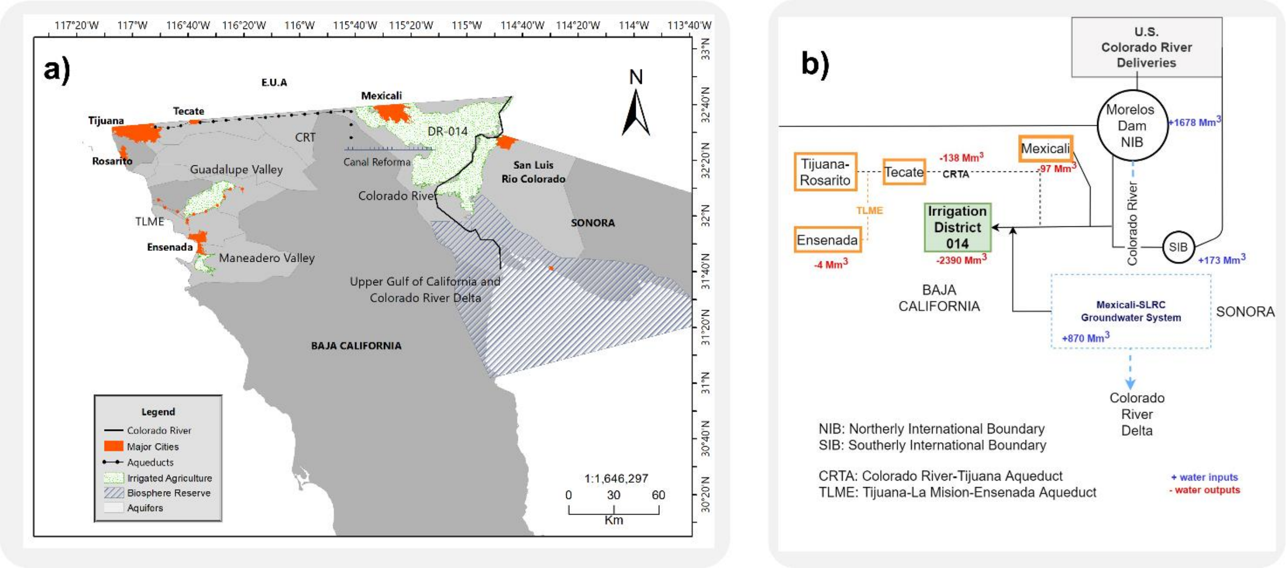

Fig. 1. a) Location map of the Colorado River system in Mexico. b) Simplified Distribution of the Colorado River System deliveries in Mexico

Table 1. Urban demands of Baja California

	Mexicali	Tecate	Tijuana-Rosarito	Ensenada
Population[a]	911,479 (28%)	102,406 (3%)	1,738,304 (54%)	486,639 (15%)
Water Use Per Capita[b] (l/inhab/d)	284	221	181	147
Water Supplies[b]	Colorado River diversion	CRTA aqueduct Tecate Aquifer	CRTA aqueduct Tijuana and La Mision Aquifers	Ensenada, La Mision, Maneadero Aquifers Desalinization Colorado River diversion

[a] Based on INEGI (2015)
[b] Based on CEABC (2017)

3.3 Data and Methods

3.3.1 Overall Method

The present study consisted of five major activities: (a) data compilation, (b) model development, calibration, and validation, (c) evaluation of individual water management strategies, (d) evaluation of meta-scenarios, which are combination of individual strategies, and (e) identification and evaluation of key system stressors, such as water allocation reduction, climate change, or reduction in irrigated area. A water resources planning model for the region was built in the WEAP platform (SEI 2020) to evaluate water management strategies and future strategies; it represents the water allocation system in northern Baja California and San Luis Rio Colorado, Sonora. Performance criteria were used to evaluate, compare, and synthesize results from water management strategies (Fig. 2).

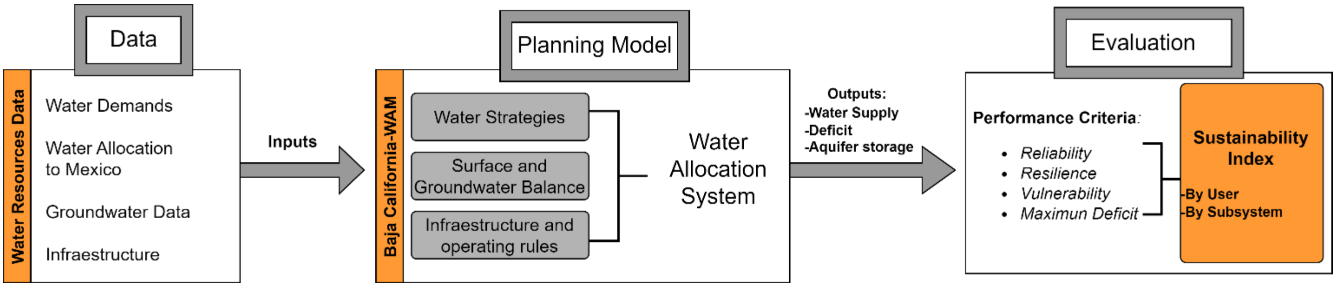

Fig. 2. Mexican portion of the Colorado River Basin Study Design

3.3.2 Baja California Water Allocation Model

The Baja California water allocation model (Baja California WAM) represents the water management of the CR water resources in Mexico. The WEAP system simulated the water supply-demand for the study area. A 35-year period of hydrologic analysis was considered, from January 2015 to December 2050, according to projections and action plans of the Baja California Water Plan (CEABC 2018). Years 2008-2013 were used as a reference for model calibration (*i.e.* historical scenario); these years consider the diminished recharge of the Mexicali Valley aquifer due to the 2008 lining of the All-American Canal (AAC) (Lesser et al. 2019), which according to García, López, and Navarro (2009), contributed to 14% of the total recharge to the Mexicali Valley aquifer (when unlined). Field evidence and modeling suggested continuous drawdown after the conclusion of the lining in 2008, with a drop in the groundwater table of 5.8 m after 4 years of monitoring (Lesser et al., 2019).

The input data consisted of water demands, surface water and groundwater hydrology, and water resources infrastructure (see Fig. S1). Model outputs were water inputs, water supply fulfilled, and aquifers recharge and storage. The present study does not consider modifying reservoir operation rules, it considers that water deliveries from the U.S. will follow the water demand requirements.

3.4.2.1 Urban demands

There are five urban service areas in Baja California WAM namely, Mexicali, SLRC, Tecate, Tijuana-Rosarito, and Ensenada. WEAP allocates water using a priority system, where 1 represents the first priority. For all urban areas the set priority was 1, consistent with the National Water Law (CONAGUA 2012). Urban demands were estimated from data reported by the local operating agencies through the National Transparency Portal (PNT) from 2008 to 2015, and the reports of management indicators (CEABC, 2015). Future water demands for the cities were projected for 2050 using current water use per capita (WUPC) for each city and populations projections by the National Population Council (CONAPO 2018). The local water agencies, Tijuana Water Commission (Comisión Estatal de Servicios Públicos de Tijuana - CESPT), Tecate Water Commission (Comisión Estatal de Servicios Públicos de Tecate - CESPTE), Ensenada Water Commission (Comisión Estatal de Servicios Públicos de Ensenada-CESPE) and Mexicali Water Commission (Comisión Estatal de Servicios Públicos de Mexicali-CESPM) reports provide current and projected water use for the residential, municipal, commercial, and industrial sectors.

3.4.2.2 Agricultural Demands

Twenty-four agricultural service areas were considered into the model: Guadalupe Valley, Maneadero Valley, and 22 demands for each module of the DR-014 (19 modules in Mexicali Valley, and 3 located in SLRC Valley). A water use priority of 2 was assigned consistent with the National Water Law (CONAGUA 2012). Agricultural demands were estimated from annual reports (2008-2015) of irrigated area and water use published by the Ministry of Agriculture (SIAP 2020) and the evapotranspiration estimates (2005-2008) of the principal crops published by the National Institute for Forestry, Animal Husbandry, and Agricultural Research of Mexico (INIFAP 2008). In DR-014, the three main crops are wheat, cotton, and alfalfa, which, in 2016 represented 83% of the total irrigated area (193,203 ha) (CONAGUA 2016). The breakdown of water supply by source between surface and groundwater by DR-014 module was derived from the Water Distribution Reports (CONAGUA 2005). In Guadalupe Valley, the main crops are grapes and olives, which represents 84% of the total area (2,528 ha). In Maneadero Valley, the main crops are ornamental flowers, tomato, cucumber, asparagus, and brussels sprouts, which represents 68% of the total area (2,855 ha). Guadalupe and Maneadero valleys are not water users of the CRB, however they are closely related to Ensenada's water supply and participate in interconnected water management strategies. Irrigation efficiencies (Sandoval-Solis et al. 2013a) and acreage factors (Lin et al. 2013) were considered in estimating the agricultural water demands.

3.4.2.3 Hydrology and calibration

Monthly surface water deliveries from the US to Mexico at the Northern International Boundary (NIB) (Morelos Dam) and Southern International Boundary (SIB) were obtained from the International Boundary and Water Commission (IBWC,). Additionally, Canal Reforma transports the water from the NIB to the CRTA. El Carrizo reservoir redistributes CRTA deliveries to Tecate and Tijuana-Rosarito, and then the water is diverted to Ensenada through the TLME aqueduct (Fig. 1a). In terms of groundwater sources, the Mexicali-SLRC groundwater system was considered as a single aquifer for modeling and planning purposes given its close hydrologic connection (Ramírez-Hernández 2020; Sanchez and Rodriguez 2021). Groundwater extractions and aquifer recharge from irrigation were estimated and compared with CEABC(2017) and CONAGUA(2020b) that determined groundwater overdraft.

A mass balance approach to back-calculate groundwater supply was applied to estimate the change in aquifer storage (AS) (Eq. 1):

$$AS_t = Recharge_t - GW\ Extraction_t \tag{1}$$

$$Recharge_t = Recharge_t^{AgSW} + Recharge_t^{AgGW} + Recharge_t^{Conv\ Losses}$$

Where the change in aquifer storage (AS_t) is calculated by estimating $Recharge_t^{AgSW}$ referring to the aquifer recharge due irrigation losses from surface water use, $Recharge_t^{AgGW}$ referring to the aquifer recharge due irrigation losses from groundwater use deep percolation, $Recharge_t^{Conv\ Losses}$referring to the aquifer recharge due to conveyance losses in canals and $GW\ Extraction_t$ refers to the groundwater extraction volume through pumping.

In addition, the Guadalupe and Maneadero aquifers are also overdrafted (CONAGUA 2020c; a). Groundwater extractions and the aquifers recharge were estimated considering the annual recharge reported by CONAGUA (CONAGUA 2020c; a) and the extractions reported by CESPE water agency (CEABC 2015). The model was calibrated for a groundwater balance that considered estimated aquifer recharge and historic water demand to determine groundwater overdraft and compared it to other studies (CEABC 2017; CONAGUA 2020b). Goodness-of-fit coefficients, such as the Nash-Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe 1970) and the Willmott index of agreement (Willmott et al. 1985) were calculated.

3.3.3 Water Management Scenarios

The study area was divided in three subsystems: Subsystem I (SS1) comprising the DR-014, the Colorado Delta and the cities of Mexicali and San Luis Rio Colorado; Subsystem II (SS2) comprising the cities of Tecate and Tijuana-Rosarito; and Subsystem III (SS3) comprising by the city of Ensenada, and the agricultural regions of Guadalupe Valley and Maneadero Valley. Table 2 summarizes the water management strategies by sub-region that included strategies outlined in Minute 323 (IBWC, 2017), the Baja California Water Plan (CEABC, 2018), and strategies discussed in regional forums of the Secretariat for the Management, Sanitation and Protection of the Water (SEPROA) and Baja California and SLRC Basin Council (2020-2021). Individual strategies were run by each subsystem and then their impact was analyzed systemwide. A baseline scenario was defined as the reference scenario representing the system without any alternative management strategy and considering that the water supply remains constant (2015-2050).

Table 2. Water management scenarios description

Subsystem	Scenario	Baseline Value[1]	Scenario Value	Source
SS1	Reduction in Colorado River deliveries	Water allocation: 1,850 Mm^3	-55 to -339 Mm^3	Minute 323 (IBWC 2017)
	Increase in crop evapotranspiration ET_C (m/year) due climate change	Wheat_{ETc}: 0.57	B1[1]:0.5898-0.5918 A2[2]:0.5872-0.5928	Based on García-Ávila (2012)
		Alfalfa_{ETc}: 1.93	B1: 2.0786-2.1034 A2: 2.0864-2.1067	
		Cotton_{ETc}: 1.14	B1:1.1675-1.1832 A2:1.1705-1.1840	
		Others_{ETc}: 1.19	B1:1.2501-1.2644 A2:1.2530-1.2661	
	All-American Canal (AAC) lining	Contribution of 0% in the aquifer recharge	Contribution of 14% in the aquifer recharge	Based on García-Saillé (2009)
	Application efficiency (E_a) increase	E_a: 65%	E_a: Increases from 2.5-10%	Percentages proposed by the authors in compliance with CEABC plan (2018) and the municipality of San Luis Río Colorado Sonora Basin Council (2020-2021) citizen consultation.
	Irrigated area reduction	Total irrigated area: 192,214 ha	Decreases from 2.5-10%	Percentages proposed by the authors in compliance with CEABC plan (2018)
	Reduction in alfalfa irrigated area	Alfalfa irrigated area:34,598 ha	Decreases from 2.5-10%	Percentages proposed by the authors in compliance with forage crops reduction CEABC plan (2018)
	Increase in water distribution network efficiency (E_n)	E_n: 83%	Increases from 2.5-10% in Mexicali	Percentages proposed by the authors
	Environmental water (Delta)	Environmental water allocation: 0 Mm^3	Environmental water allocation: 27.5 Mm^3	Minute 323 (IBWC 2017)
SS2	Increase CRTA capacity	Capacity: 5333l/s	Increases from 2.5-10%	Percentages proposed by the authors
	Rehabilitation of Tijuana aquifer wells	Use of 0 l/s	Use of 270 l/s	SEPROA (2021)
	Increase in water distribution network efficiency (E_n)	E_n: 80%	Increases from 2.5-10%	Percentages proposed by the authors in compliance with the Baja California and the municipality of San Luis Río Colorado Sonora Basin Council (2020-2021) citizen consultation.

SS3	Full allocation from the Colorado River	Ensenada receives 116 l/s	Ensenada receives 285 l/s	Strategy proposed in compliance with REPDA water rights (2020)
	Seawater desalination	Use of 100 l/s	Use of 250 l/s	Strategy proposed by the authors
	Increase in recycled water use in Maneadero Valley	Use of 80 l/s	Use of 200 l/s	SEPROA (2021)
	Use of recycled water in Guadalupe Valley	Use of 0 l/s from Tijuana WWTP	Use of 1000 l/s from Tijuana WWTP	Baja California state government plan as cited in Mendoza-Espinosa et al. (2019)
	Increase in water distribution network efficiency (E_n)	*En*: 83%	Increases from 2.5-10%	Percentages proposed by the authors in compliance with the Baja California and the municipality of San Luis Río Colorado Sonora Basin Council (2020-2021) citizen consultation.

[1]B1: Low emission scenario, [1]A2: high emission scenario

3.3.4 Analysis of Water Management Scenarios

Five performance criteria were considered for each water user to evaluate the impact of each water management strategy: 1) volumetric and 2) time-based reliability, 3) resiliency, 4) vulnerability, and 5) maximum deficit (Hashimoto et al. 1982; McMahon et al. 2006). These criteria relate water demand and water supplied for a given water user. Each performance criteria are expressed as a percentage between 0-100%; a non-failure state is considered 100% for reliability (volumetric and time-based) and resiliency, while for vulnerability and the maximum deficit criteria a non-failure state is 0% (Sandoval-Solis et al. 2011). Results for each water user were summarized into a single value from 0 to 100% using the water resources sustainability index (SI^{User}) which is the geometric mean of the (five) performance criteria. The sustainability index (*SI)* facilitates comparisons of performance among different water management strategies (Sandoval-Solis et al. 2011). The sustainability index by subsystem (SI^{SS}) was used to summarize the results of all users of a given subsystem into a single value, it is the weighted average of the *SI* values of individual users weighted by their water demand. The sustainability index by subsystem allows the comparison among different water management strategies and among subsystems. Definitions and procedures of performance criteria and SI are presented in Loucks (1997) and Sandoval-Solís et al. (2011).

3.4 Results

3.4.1 Model Performance

Model inputs are surface water allocation from the Colorado River, irrigated area by crop and module, crop coefficients, reference evapotranspiration and irrigation efficiencies. The estimated water supply from surface water and groundwater was compared against historical records to verify the model adequacy. Goodness-of-fit criteria were used to compare the observed (historical) and predicted values by the model over *n* time steps (Legates and McCabe Jr 1999). The Nash-Sutcliffe coefficient and the Willmott index of agreement were 0.64 and 0.90 respectively, which are considered an acceptable performance (Moriasi et al. 2007). Overall, the surface and groundwater use for DR-014 (2008-2013) estimated in this study was 2,376 Mm^3/year, compared to CONAGUA's estimate of 2,479 Mm^3, a difference of only 4%. In addition, the aquifer recharge for the Mexicali-SLRC groundwater system estimated in this study (836.44 Mm^3/year) was broadly consistent with the range reported by Lesser and associates for CONAGUA (2006) (902.6 Mm^3) and CEABC (2017) (766.29 Mm^3). Estimates of aquifer overdraft is 102.54 Mm^3/year (2008-2013), which is in between estimates from CEABC 2017 (132.27 Mm^3/year) (2006-2016) and CONAGUA 2020 (95.00 Mm^3/year).

3.4.2 Analysis of Scenarios

3.4.2.1 Baseline scenario

The baseline scenario was the system without the implementation of any alternative policies (e.g., Minute 323). The water deliveries from the Colorado River are maintained constant (1,850 Mm^3), and groundwater overdraft is allowed. Agricultural water demands were also maintained constant, whereas urban demands increase as the population grows (growth rate: 1%, CONAPO 2018). By 2025 a decline in the water supply is noticed, which can be associated with the reduction in groundwater storage due to overdraft decrease in the Mexicali-SLRC groundwater system. By 2050, a water deficit of 321 Mm^3 is experienced, suggesting only 89% of the total water demand is satisfied. Table 3 compares the performance of the baseline scenario for two aquifer conditions, with and without groundwater overdraft in the Mexicali-SLRC groundwater system. The water demand of DR-014 represents 85% of the total demand (2,778 Mm^3). In overdraft condition, the SS1 has higher performance (SI: 68%) during 2015-2050, yet (SI: 24%) when overdraft is not allowed. While apparently SS2 apparently it is not affected under non-overdraft condition, Tijuana and Tecate have a water right transfer from the Mesa Arenosa of SLRC Aquifer (Mesa Arenosa), which is interchanged with surface water from DR-014. As SS2 has priority in the supply, the water demand is guaranteed from surface water through CRTA.

Table 3. Average annual water demand and sustainability index for water users in the baseline scenario.

	Water User	Demand (Mm^3)	Sustainability Index (%)	
			Overdraft	Non-overdraft
SS1	DR-014	2362	66	18
	Mexicali	136	100	100
	SLRC	28	100	100
	Delta	27	100	100
	Subtotal	**2553**	**68**	**24**
SS2	Tecate	11	33	32
	Tijuana	150	32	32
	Subtotal	**161**	**33**	**33**
SS3	Ensenada	25	37	24
	Guadalupe V.	19	42	32
	Maneadero V.	20	43	33
	Subtotal	**64**	**49**	**30**

3.4.2.2 Individual water management scenarios

Table 4 shows the Sustainability Index, *SI* (i.e., composite of performance criteria) for individual water management scenarios for each subsystem with and without groundwater overdraft. Performance criteria of each scenario is shown in Appendix I (Table A1). For SS1, the reduction in the CR deliveries was the scenario with the lowest SI for both aquifers' conditions, while the reduction in the irrigated area (DR-014) had the highest score (94%) (as long as overexploitation is allowed). Volume reliability was the performance criteria with higher values, while resilience had the lowest (Table S1). Resilience criteria did not change compared to the baseline scenario, meaning that the deficit events (i.e., demand exceeds supply) and the probability of recovering are the same as the baseline scenario. The exception is the irrigated area reduction scenario, which increases resilience to 94% when groundwater overdraft is allowed. Increase in resilience does not happen without overdraft (resilience: 1%), indicating that SS1 never recovers when overdraft is not allowed. Furthermore, under no groundwater overdraft condition, the subsystem performance decreased from 68% (overdraft) to 24% in the baseline scenario; thus, SS1 is highly dependent on groundwater overdraft.

For SS2, the scenario that provided the most benefits was the increase in the water distribution network efficiency in Tijuana and Tecate (SI: 75%). For this study, the water distribution network efficiency is the percentage of the total water invoiced by the local water agencies divided by the total generated water in each city. Unlike the rest of the SS2 scenarios that increase water supplies, the increase in the water distribution network efficiency is directly related to the reduction of the amount required to meet the water demands, indicating that scenarios oriented to reduce the volume required to meet water demands improve the subsystem performance more than those oriented to water supply. Results for both aquifer conditions are similar because SS2 relies on 90% of surface water.

For SS3, the full allocation from the CR to Ensenada and the use of the total capacity of the desalination plant resulted in the highest subsystem performance. SS3 is highly dependent on groundwater (94% of the water supply); when overdraft is not allowed, the SI decreased from 49% (overdraft) to 30% in the baseline scenario.

Table 4. Evaluation of water management scenarios by subsystem

Scenario		Sustainability Index (%)	
		Overdraft	Non-overdraft
SS1	Baseline	68	24
	Reduction in Colorado River deliveries	43	19
	Increase in crop evapotranspiration (ET$_C$)	55	17
	Contribution of the AAC in the aquifer recharge	77	30
	Environmental water (Delta)	60	24
	Cultivated area reduction	94	62
	Reduction in alfalfa production	65	18
	Increase in application efficiency	63	17
	Increase in urban network efficiency	66	18
SS2	Baseline	33	33
	Increased CRTA capacity	47	47
	Rehabilitation of Tijuana aquifer wells	46	46
	Increase in urban network efficiency	75	75
SS3	Baseline	49	30
	Full allocation from the Colorado River	72	57
	Seawater desalination	72	54
	Increase in urban network efficiency	65	42
	Increase in recycled water use in Maneadero Valley	52	42
	Use of recycled water in Guadalupe Valley	61	42

3.4.3 Overall results

The SI by subsystem was calculated for all the permutations of individual water management scenarios to quantify the variability in performance when scenarios are combined and to compare them with respect to the baseline scenario (Fig. 3). All the permutations of alternative water management strategies for SS1 have a lower performance than the baseline scenario, i.e., the strategies oriented to improve the subsystem performance were not able to offset the drawbacks from: (a) the reduction in CR deliveries, (b) the increase in crop evapotranspiration due to climate change, and (c) no groundwater overdraft. In contrast, SS2 and SS3 can improve their SI performance in relation to their baselines if individual or a combination of strategies are implemented up to 90 and 80%, respectively. Notice that the SI performance of SS1 and SS3 are severely affected when there is no groundwater overdraft; in the worst-case scenario the SI decreased to 18% and 7%, respectively.

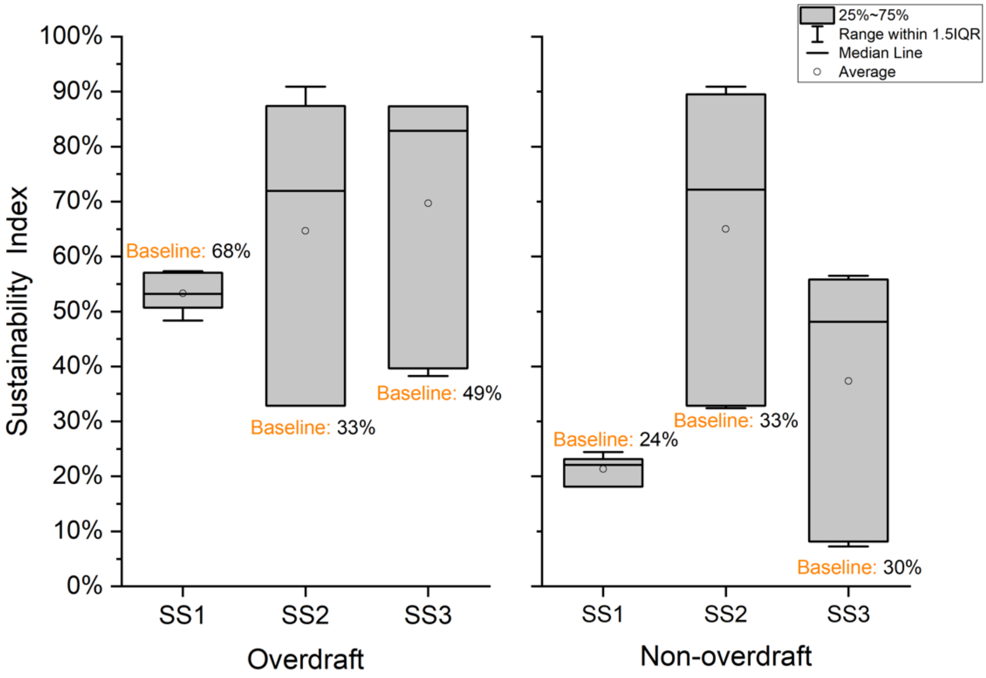

Fig. 3. Subsystems overall sustainability index. SI is the arithmetic average of five performance criteria namely: Volumetric Reliability (R_v), Time Reliability (R_t), Resilience (Re), Vulnerability (V), and Maximum Deficit (D_{max})

3.4.4 Subsystem 1: Mexicali Valley, San Luis Rio Colorado Valley and the Colorado Delta

The sensitivity analysis of scenarios for SS1 shows that the reduction in water allocation from the Colorado River was the strongest parameter. This variable has the largest standard deviation (SD) in SI results with respect to the baseline scenario (SD^{SS1}= 16%). The model was run for different reduction levels in the water deliveries from the US to Mexico according to Minute 323 considering all permutations of water management strategies (Fig. 4). In all cases, the performances of individual or combined strategies were lower than the baseline scenario. In general, the SI decreases as the water reductions from the CR increase. For instance, under overdraft conditions (Fig. 4), the subsystem performance decreases from 68% in the baseline scenario to 43% in the worst-case scenario when maximum reduction in the CR water allocation occurs (-339 Mm^3) and no additional actions implemented. In the scenario with no groundwater overdraft (Fig. 4), the subsystem performance plummeted, from 24% in the baseline scenario to 19% in the worst-case scenario, highlighting the high reliance on groundwater overdraft. In the case where there is a maximum reduction in water deliveries (-339 Mm^3) and no groundwater overdraft is allowed, a water demand deficit of 868 Mm^3 will be experienced by 2050, meaning that only 63% of the total demand can be satisfied.

Results of volumetric reliability are shown in Fig. 5, representing the overall volume of water supplied with respect to the sum of all water demands. For instance, a volumetric reliability of 70% means that over the period of hydrologic analysis (from 2015 to 2050), 70% of the total water demand volume was supplied, resulting in a criterion to understand the overall amount of water supplied in comparison with the baseline water demand. The minimum volumetric reliability for the maximum reduction with and without groundwater overdraft was 78% and 61%, respectively, meaning important reductions in the water supply under these conditions are expected. The median volumetric reliability declines linearly under overdraft and no overdraft conditions.

In terms of irrigated area, a reliability analysis was performed to estimate the cultivated area of DR-014 that could be fully supplied for each water allocation reduction, *i.e.*, volumetric reliability equal to 100% (Fig. 6). From an initial area of 192,214 ha in the baseline scenario to 153,771 ha for the best-case scenario (a reduction of 20%), up to 134,460 ha for the worst-case scenario (a reduction of 30%) (Fig. 6). Under non-overdraft condition, the reduction in the cultivated area would be more severe, guarantying the supply to only 105,718 ha for the best-case scenario (reduction of 45%) and to 76,886 ha in the worst case scenario (reduction of 60%) with the current crop production pattern (Fig. 6).

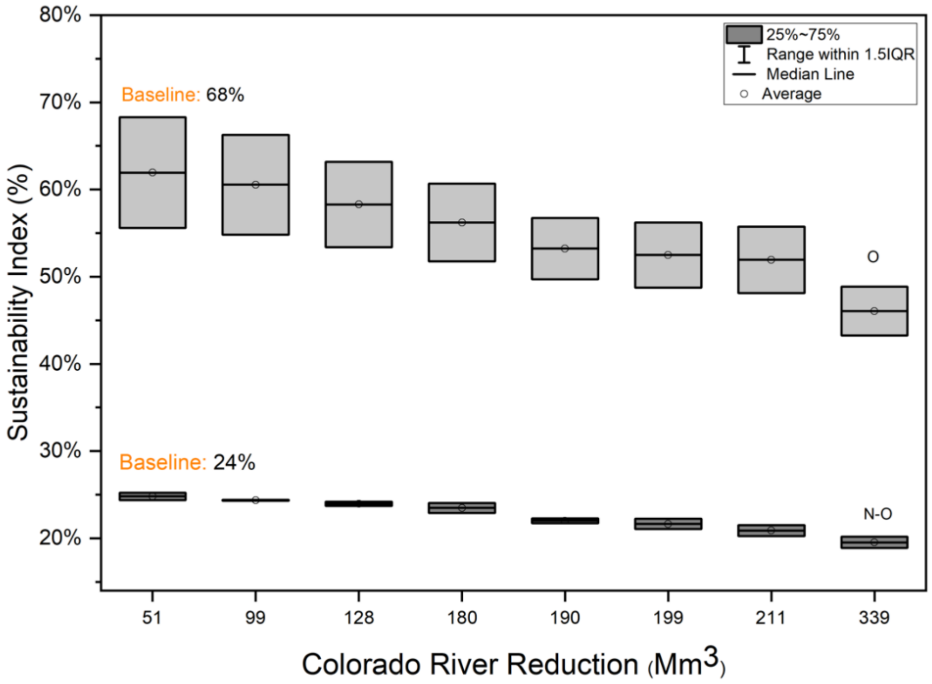

Fig. 4. Sustainability Index for SS1 associated with Colorado River water supply reductions to Mexico (O: Overdaft, N-O: Non-overdraft)

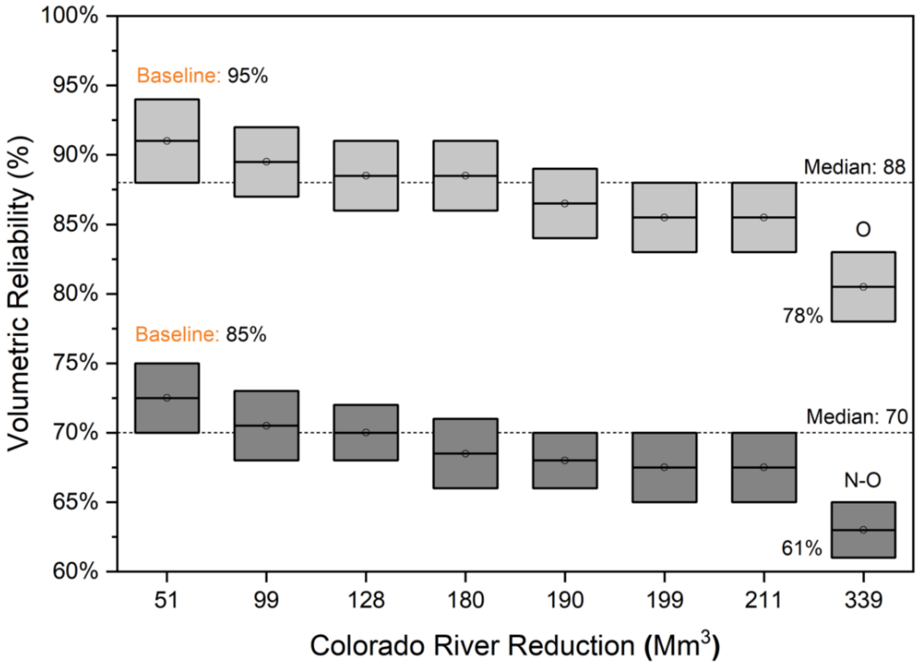

Fig. 5. Volumetric Reliability associated with Colorado River water supply reductions to Mexico (O: Overdaft, N-O: Non-overdraft)

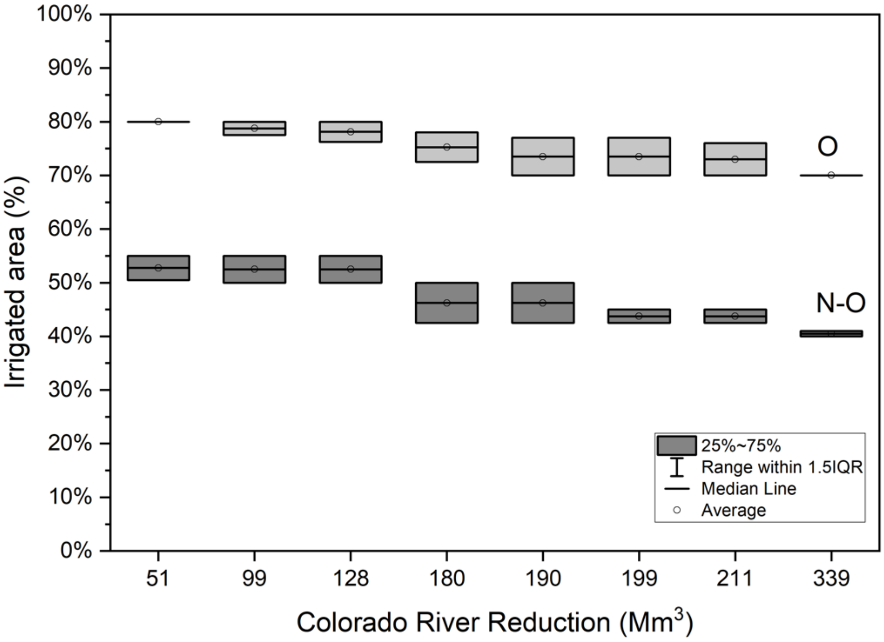

Fig. 6. Percentage of Irrigated area supplied with Colorado River water supply reductions to Mexico (O: Overdaft, N-O: Non-overdraft).

3.4.5 Subsystem 2: Tijuana and Tecate

Similarly, a sensitivity analysis of scenarios was performed for SS2, by using the water distribution network efficiency as the sensitive parameter, which has the largest standard deviation (SD) in SI results with respect to the baseline scenario (SD^{SS2} = 29%). The model quantified the SI for a set of increases in the network efficiency considering the individual implementation or combination of rehabilitation of wells in Tijuana and the increase in CRTA capacity (Fig. 7). The current water distribution network efficiencies of Tijuana and Tecate (January 2022) are 80% and 81% respectively (CEABC 2022). Increases in efficiency from 2.5% to 10% improved the SI performance. In the best-case scenario (maximum increase in efficiency and CRTA capacity expansion), the SS2 has a SI performance of 90%. The combination of strategies improves the SI performance to 90%, while the efficiency of individual scenarios was 75% (Table 4).

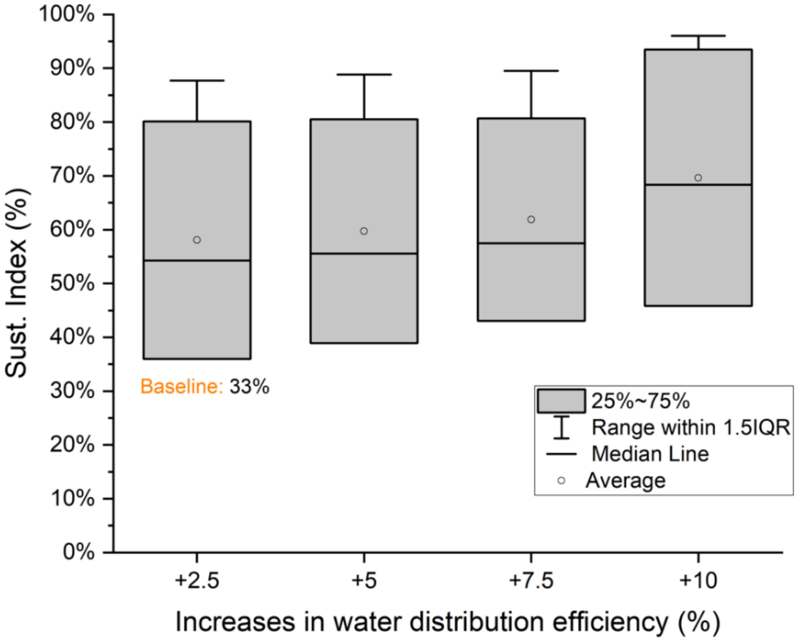

Fig. 7. Sustainability Index for SS2 associated with change in water distribution efficiency.

3.4.6 Subsystem 3: Ensenada, Guadalupe, Maneadero

For SS3, two sensitive variables were identified: the full allocation from the Colorado River (285 l/s or 9 Mm^3/yr) and the use of water from the desalination plant at full capacity (250 l/s or 7.9 Mm^3/yr), both variables with a SD of 30% with respect to the baseline scenario. These two variables were evaluated with individual or a combination of the remaining strategies, which are the use of recycled water and increase in the water distribution network efficiency (Fig. 8). Results show that the use of the full allocation of 9 Mm^3/year improved the SI performance for SS3. Moreover, the use of the desalination plant located at full capacity (250 l/s) also improves the sustainability index. When groundwater overdraft is not allowed (Fig. 8.b), the overall performance reduces significantly, showing SS3 dependence on groundwater overdraft. An aquifer recharge decrease will significantly reduce the SI performance for both aquifer conditions and sensitive variables. However, when all the water management strategies are applied, the performance of the system improves.

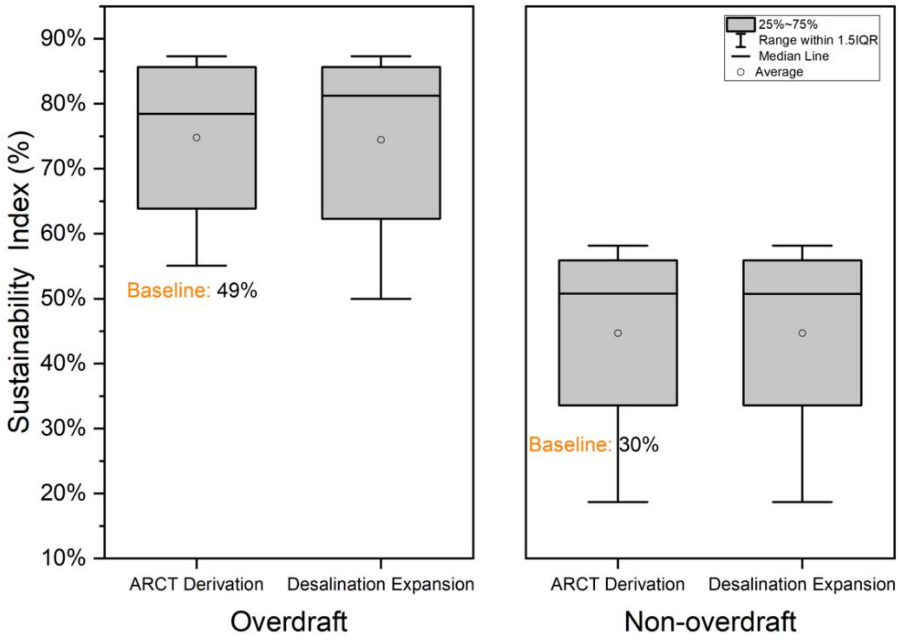

Fig. 8. Sustainability Index for SS3 associated with full allocation from the Colorado River and full capacity of seawater desalination.

3.5 Discussion

3.5.1 Colorado River Reductions

The agriculture sector will be the most affected water user for two reasons: (1) it has the lowest priority and thus any reduction in CR allocations affect them directly; and (2) the cultivated area (mainly forage crops with high water demand such as alfalfa) exceed future water availability in the region and heavily relies on groundwater overdraft. The reduction of the cultivated area was the strategy that increased the sustainability index the most for DR-014 (Table 4). This scenario reduces the total irrigated area evenly across the 22 modules considering the current crop production. A similar conclusion was reached by the Imperial Irrigation District, CA, which temporarily takes active farmland out of production (fallowing) and forecasted non-agricultural use in five-year increments from 2010 through 2050 (Imperial Irrigation District 2021). Moreover, Cortés-Ruiz and Azuz-Adeath (2021), estimated a reduction of 35,558 ha even without considering the water allocation reductions in the CR. The present study goes one step beyond and estimated the firm yield (Liu et al. 2018; US Army Corps of Engineers 2019) that guaranteed a 100% water supply reliability in DR-014 under current groundwater overdraft conditions, DR-014 should reduce between 38,443 to 57,664 ha; representing 20% to 30% of the cultivated area to cope with the lowest (51 Mm3) and highest (339 Mm3) water allocation reductions if the current crop production is maintained. This situation worsens when considering no groundwater overdraft, as DR-014 should reduce between 86,496 (45%) and 115,328 ha (60%) of cultivated area when producing the current types of crops. The reduction in the cultivated area of DR-014 will have significant social and environmental impacts that are out of the scope of the present study. However, the authors recommend future research to define policies that can improve prospects for environmental and social justice to the region.

Although urban demands are less likely to be affected by reductions in the CR water allocation reductions, this is only true if urban water demands remain a priority (CONAGUA 2012). If other water users decide not to obey the law, as it occurred in other Mexican states such as Chihuahua (López Obrador 2020), the increasing urban demands in SS2, particularly Tijuana-Rosarito metropolitan area, will be affected since the CR represents their main water source. Therefore, Tijuana and its metropolitan area are strongly linked to decisions and policy actions related to agricultural water management in Mexicali and San Luis Rio Colorado Valleys.

3.5.2 Groundwater Overdraft

Sustainable water management strategies should not allow for aquifer's overexploitation. The Mexicali-SLRC groundwater system is in overdraft condition and there is no question that at this rate of use groundwater will be exhausted, yet a question remains about the time horizon of such depletion. As presented in the results section for SS1, the system performance worsens when groundwater overdraft is not allowed; cultivated area reduction for DR-014 is the strategy that provides the most benefits in the long term. However, this strategy would have significant social and economic costs and it would be essential to involve farmers in a collaborative process.

The sustainability of water resources in SS1 also depends on the ability to monitor the aquifers, regulating groundwater extractions in each irrigation unit, law enforcement and the understanding of groundwater and surface water hydrologic connections. Ramírez-Hernández et al. (2013) conducted a hydrologic analysis of water releases from Morelos Dam (2009–2010), characterized the relationship between surface flows and its effect on the groundwater storage and infiltration rates. They determined a strong correlation between the volume of the water (up to 60.49 Mm^3 from November 2009 to April 2010) released from Morelos Dam and the increase of groundwater levels. Thus, further reductions in the CR allocation to Mexico could negatively impact the groundwater elevation and storage.

As shown in Fig. 8, the performance of SS3 decreases when overdraft is not allowed. This trend was also consistent with Medellín-Azuara et al. (2008) conclusions. The authors ran non-overdraft scenarios, finding that agriculture in Guadalupe and Maneadero were severely affected, as well as the increment of urban scarcity costs for Ensenada (Medellin-Azuara et al. 2008). In the present study, when no groundwater overdraft was allowed, the combination of water management strategies such as desalination, water reclamation and new infrastructure, improved the performance nearly to the baseline scenario of the overdraft condition. Users in the Guadalupe Valley have the highest potential to improve their water supply reliability by using reclaimed water (Mendoza-Espinosa et al. 2019). In addition, water exchanges between the Guadalupe Valley aquifer and the adjacent Mision aquifer need to be determined (Daesslé et al. 2020). Finally, the increase in reclaimed water use in Maneadero Valley (200 l/s) should be accompanied by a water right transfer to Ensenada to benefit the city's water supply.

3.5.3 Model Limitations

Like all quantitative models (Loucks and Van Beek, 2017), the results of Baja California WAM have limitations. The main uncertainties are associated with finer spatial resolution groundwater representation, long term data series, monitoring, a developing economic representation, and other system simplifications (i.e., social, political, and economic dimensions not addressed here).

The present study considered a comprehensive mass balance approach to determine aquifer storage, recharge and extractions; it provides an overall water budget for each of the aquifers analyzed in the main water use areas in the state. Future analysis should include the hydrodynamics of the surface and groundwater (Bushira et al. 2017). The lack of comprehensive hydrological data is a common limitation identified by modelers in Mexico, especially when characterizing aquifers and groundwater data due to the lack of financial resources and monitoring culture in the country (Carrera-Hernández et al. 2016; Medellín-Azuara et al. 2009; Molinos-Senante et al. 2014; Wurl et al. 2018). The present study considered the recharge of the Mexicali-SLRC groundwater system from irrigation runoff. It is recommended to include all the Cuenca Baja del Rio Colorado Transboundary Aquifer System (the Mexican and USA portions) to fully represent the dynamics of regional groundwater system. If there is a need to determine groundwater dynamics at a smaller scale resolution, a fine-detail aquifer characterization is needed to determine groundwater extraction rates and potential aquifer recharge necessary for all the aquifers included in the model. Groundwater quality should be added into further model runs, particularly salinity considerations in Mexicali Valley, in coastal aquifers, and RW quality for reuse in crops irrigation or aquifers' recharge.

Data for DR014 represents a source of uncertainty since this study used the data reported by the water authorities, specifically the water distribution reports for the irrigation modules (CONAGUA 2005). Carrillo-Guerrero et al. (2013) argued that CONAGUA accurately measures the water delivered to DR014 from federal wells, but private wells, which contribute 10–20% of groundwater wells, are not as closely monitored. In addition, the application of water to individual fields is subject to uncertainty because water is measured at irrigation modules but not to individual fields. The present study used records of diverted water at individual modules.

Despite their limitations, models are useful tools for making informed decisions. Currently, there is no model for water resources planning for the state of Baja California. The current study provides insights on the impacts of the reductions in the Colorado River deliveries from the US to Mexico and promising water supply portfolios for Baja California considering the major water users. The capital cost of alternatives was not considered since institutional agencies already consider most strategies in their planning and budgeting efforts. However, a basic economic analysis could be beneficial to further screen tradeoffs involved in each strategy. Economic-engineering optimization models have been applied in Baja California to explore water supply options for environmental restoration of the Colorado River Delta (Medellín-Azuara et al. 2007) with a rather basic understanding of the water balance.

In addition, citizen participation can improve the quality of government decisions, incorporating different resources and capacities, and developing learning among stakeholders (Villada-Canela et al. 2019). Finally, making water planning tools available to stakeholders could embrace the region's planning and decision-making process related to water management.

3.6 Conclusions

The Mexican region of the Colorado River including the northern region of Baja California and San Luis Rio Colorado in Sonora is highly dependent on the Colorado River water supplies. The water management of the Colorado River is at a tipping point.

The present study highlights the effect of current and future water management strategies in the Mexican portion of the Colorado River. A water resources planning model that represents the system and facilitates its updating and the incorporation/removal of water management scenarios was developed. The study explored a range of strategies, from a no action scenario to a combination of all available water management strategies. The agriculture sector (DR014) has the biggest challenges ahead. In the most pessimistic scenario (maximum reduction and no additional actions), the sustainability index (SI) decreased from 68% in the baseline scenario to 43%, which represents a water deficit of 643 Mm^3/year by 2050 (30% of the total demand). The current system has a better performance (SI: 68%) at the expense of long-term aquifers overdraft, without overdraft the SI decrease to 24%. Agricultural to urban transfers, water use efficiency, wastewater reuse, and desalination are prime possibilities to improve the future water supply, especially for the coastal zone.

For Tecate and Tijuana-Rosarito area, increasing the efficiency of the water distribution network, rehabilitating wells, and expanding the capacity of the CRTA increased the sustainability of the subsystem from 33% (baseline) to 95% in the maximum efficiency scenario. Ensenada and its agricultural valleys increased their sustainability from 49% (baseline) to 88% by increasing water use efficiency, expanding reuse in the agricultural valleys, receiving the full allocation of the Colorado River resources, and the full use of the desalination plant capacity. This analysis revealed the importance of employing bundles of strategies across the interconnected subsystems.

3.7 Conclusiones

El estado de Baja California y San Luis Río Colorado, Sonora, depende en gran medida del suministro de agua del río Colorado. El manejo de agua del río Colorado se encuentra en un punto de inflexión. El presente estudio expone el efecto de las estrategias actuales y futuras de manejo del agua en la porción mexicana del río Colorado. Se desarrolló un modelo de planeación de recursos hídricos que representa el sistema y facilita su actualización y la incorporación/desincorporación de escenarios de gestión del agua. Se exploraron una serie de escenarios, desde un escenario de no acción hasta una combinación de todas las estrategias de gestión del agua disponibles. El sector agrícola (DR-014) es el que tiene mayores retos por delante. En el escenario más pesimista (reducción máxima y ninguna acción adicional), el índice de sostenibilidad (IS) disminuyó del 68% en el escenario base al 43%, lo que representa un déficit hídrico de 643 Mm^3/año para el año 2050 (30% de la demanda total). El sistema actual tiene un mejor rendimiento (IS: 68%) a expensas de la sobreexplotación de los acuíferos a largo plazo, de no considerarse la sobreexplotación, el IS disminuye al 24%. Los trasvases de agua del sector agrícola a la ciudad, la eficiencia en el uso del agua, la reutilización de las aguas residuales y la desalinización son posibilidades primordiales para mejorar el futuro abastecimiento de agua, especialmente en la zona costa. Para Tecate y la zona de Tijuana-Rosarito, el aumento de la eficiencia de la red de distribución de agua, la rehabilitación de pozos y la ampliación de la capacidad del ARCT aumentaron la sostenibilidad del subsistema del 33% (base) al 95% en el escenario de máxima eficiencia. Ensenada y sus valles agrícolas aumentaron su sostenibilidad del 49% (base) al 88% mediante el aumento de la eficiencia en el uso del agua, la extensión del reuso en los valles agrícolas, la asignación completa de los recursos del río Colorado y el uso completo de la capacidad de la planta desalinizadora. Este análisis reveló la importancia de la combinación de estrategias en los subsistemas interconectados.

CAPÍTULO IV: AUMENTO DE SALINIDAD EN LOS RECURSOS DEL RÍO COLORADO

Resumen

La salinización en la Cuenca del río Colorado es un reto a largo plazo agravado por la escasez de agua y las incertidumbres del cambio climático. El aumento de salinidad en el río Colorado se asocia a procesos de evaporación y flujos de retorno agrícola. En este capítulo se presentan los impactos del aumento de la salinidad (como Sólidos Disueltos Totales: SDT) en las aguas superficiales y subterráneas de la porción mexicana de la Cuenca del río Colorado desde una perspectiva histórica. La evolución histórica de SDT en agua superficial (1977-2020) y subterránea (1961-2020) es presentada. Considerando las potenciales reducciones en la asignación de agua en México, se simularon las concentraciones mensuales (2015-2050) de SDT (agua superficial y subterránea) asociadas a los diferentes niveles de reducción. El análisis de los resultados muestra que, desde la década de los 2000s, la diferencia de SDT entre las presas Morelos (México) e Imperial (Estados Unidos) ha superado el límite máximo establecido por la Comisión Internacional de Límites y Aguas (151 mg L^{-1}) el 40% de los meses. A diferencia de las aguas superficiales, la calidad del agua del acuífero del Valle de Mexicali no se monitorea continuamente. A medida que aumenta la salinidad, los agricultores del DR-014 se ven obligados a aumentar el uso de agua superficial para eliminar las sales de la superficie del suelo. La concentración base estimada de SDT (agua superficial y subterránea) es de 1,500 ± 109 mg L^{-1}. El aumento de la concentración de SDT en el agua superficial debido a las reducciones en las asignaciones del río Colorado podría comprometer los altos niveles de SDT en el agua subterránea y la subsecuente acumulación de sales en los suelos. La mayor concentración de SDT prevista para el nivel máximo de reducción (-358 Mm^3) fue de 2,154 mg L^{-1} (septiembre), 566 mg L^{-1} más que la concentración promedio de este mes. El aumento de la salinidad podría afectar a la producción de cultivos sensibles a la salinidad en el distrito de riego, incidir en la calidad del agua potable y en los costos de tratamiento, y poner en peligro ecosistemas sensibles del Delta del Río Colorado.

Palabras clave: salinidad, río Colorado, México, SDT, asignación de agua

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Increased salinity in the Colorado River resources: Implications for Mexico

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Abstract

Salinity concerns is a long-term challenge in the Colorado River Basin exacerbated by water scarcity and the uncertainties of climate change. Higher loads of salts are associated with evaporation and agricultural return flow processes. This study assesses the impacts of increased salinity (as Total Dissolved Solids: TDS) in surface and groundwater of the Mexican portion of the Colorado River Basin from an historical perspective. The evolution of TDS concentration in surface water (1977-2020) and groundwater (1961-2020) is presented. Given the potential reductions in the Mexican water allocation, monthly TDS concentrations (surface and groundwater) associated with different levels of reduction were simulated by simple linear mixing model. Results demonstrate that during 40% of the months between 1977 and 2020, the TDS concentration difference between the gaging stations at Imperial (US) and Morelos (MX) has exceeded the Water Treaty compliance threshold of 151 mg L^{-1}. Groundwater quality is not continuously monitored. As groundwater salinity increases, farmers in the irrigation district DR-014 are forced to increase the use of surface water to flush salts from the soil surface. The estimated baseline TDS concentration (surface and groundwater) was 1,500 ± 109 mg L^{-1}. The TDS concentration estimated for the maximum water allocation reduction (-358 Mm^3) was 2,154 mg L^{-1} (September), 566 mg L^{-1} higher than the average concentration for this month. Increased salinity could affect the production of salinity-sensitive crops, impact drinking water quality and treatment costs, and threaten sensitive ecosystems in the Colorado River Delta.

Keywords: salinity, Colorado River, Mexico, TDS, water allocation

4.1 Introduction

Water availability with adequate quality and quantity is essential for sustaining human societies and ecosystems. There is an increasing crisis of freshwater availability throughout the world (Padikkal et al., 2018). Accessible water resources are becoming more vulnerable due to increased pollution, uncontrolled groundwater depletion, and climate change impacts on water availability patterns (Khan et al., 2017).

Human activities are increasing the total concentration of dissolved inorganic salts (i.e., salinity) in freshwater (Cañedo-Argüelles et al., 2016). The salinization of rivers is occurring across the globe due the high loads of salts from anthropogenic activities such as agriculture and urbanization which accelerate weathering (Bolotin et al., 2022). Groundwater salinization is caused by overdraft (Bagheri et al., 2019), percolation from agriculture irrigation and return-flows (Foster et al., 2018), and saline intrusion in coastal areas (Chun et al., 2018; Werner and Simmons, 2009). Seawater intrusion in coastal aquifers has been an increasing phenomenon that has been intensified by the sea level rise caused by global climate change (Khanom, 2016).

Irrigation has been reported as one of the main causes for river salinization, especially in arid and semi-arid regions of the world where crop production consumes large volumes of water (Cañedo-Argüelles et al., 2013, Pitman and Läuchli, 2006). Paradoxically, salinity is one of the most severe factors limiting the agricultural productivity of crops. Yield reductions occur when the salts accumulate in the soil's root zone to such an extent that the crop is no longer able to extract enough water from the salty soil solution, resulting in water stress (Ayers 1985). Agricultural losses caused by salinity are difficult to assess, however, economic estimates are substantial and expected to increase with time (Pitman and Läuchli, 2006). High levels of salts have adverse effects on human health (Rahman et al., 2017) , increase the costs of drinking water treatment (Wilson, 2004), and can reduce freshwater biodiversity and alter ecological process (Dowse et al., 2017; Findlay and Kelly, 2011).

In the Colorado River, salinity increases as water it flows downstream (Bureau of Reclamation, 2020). The salts (mainly sodium, magnesium and calcium chlorides) in the Upper Colorado River Basin (UCRB) are naturally occurring due to the saline sediments deposited in prehistoric marine environments (Bureau of Reclamation, 2020; Lee and Howitt, 1996). Salts contained within the sedimentary rocks are easily eroded, dissolved, and transported into the river system (Lee and Howitt, 1996). Moreover, water development projects and irrigated agriculture have accelerated the rate at which these naturally occurring salts are leached from the soil (Lee and Howitt, 1996). Although the UCRB is the main contributor of salinity, most of the water users are located in the Lower Colorado River Basin (LCRB) (Keum and Kaluarachchi, 2015). Higher loads of salts in the LCRB are associated with evaporation and agricultural return flow processes (Bureau of Reclamation, 2017).

Salinity of the Colorado River has long been a major concern in Mexico. The 1944 Water Treaty (CILA, 1944) between the US and Mexico stipulates a water allocation of 1,850 million cubic meters per year (MCM/y) to Mexico. Adequate water quality was considered a given as part of the treaty (Orive Alba, 1945), but it was not stipulated in the treaty. The Colorado River salinity crisis (1961–1973) showed the devastating effects of high salinity levels in the agricultural production of the Mexicali Valley (Wilder et al., 2020). Minute 242 temporarily ended such dispute, however salinity is a long-term challenge (Deemer et al., 2020; Mumme, 2017). Mexico is most downstream user of the Colorado River and likely to be the most affected by salinity issues (Harding, 1995), it is expected to increase due to extended and severe droughts (Harding et al., 1995), increasing water demands and low reservoir level in the US (Bureau of Reclamation, 2020) and reduction in the water allocation to Mexico due to Minute 323 (IBWC, 2017).

Thus, there is a need to estimate how human and climatic stressors will change salinity concentrations in the Colorado River System in the Mexican territory and how Mexican water users will be affected. The goal of this study is to quantify the change in TDS concentrations due to reductions in the water allocation to Mexico from the Colorado River (2015-2050) and what are the implications for the agricultural, urban and environmental sectors in Mexico. The research question is if given the current and expected reductions in water allocations, what will be the impact on water quality and how will it affect Mexican water users?” The specific objectives are: (a) to present the historical evolution of TDS concentrations in surface (1977-2020) and groundwater (1961-2020) and (b) predict future TDS concentrations considering reductions in the water allocation.

4.1.1 Background

Ecosystems, communities, and economies rely on the Colorado River. The Colorado River Basin is located in the southwest of the United States (US) (Wyoming, Utah, New Mexico, Nevada, Colorado, Arizona and California) and northern Mexico (Baja California and Sonora). The Colorado River provides irrigation water to nearly 4.5 million acres of land, generates over 4,200 megawatts of hydroelectric power, and supplies water to over 35 million people in the United States and 3.3 million people in Mexico each year (U.S. Bureau of Reclamation, 2012, 2017).

The Colorado River salinity crisis (1961–1973) is considered a major turning point in the evolution of U.S.-Mexico hydrodiplomacy (Wilder et al., 2020). In 1961, the U.S. Bureau of Reclamation began operating groundwater wells to alleviate an accumulation of brackish water affecting the productivity of Arizona's Wellton-Mohawk Irrigation District (Mumme, 2017). The pumped water exceeded 4,500 mg L^{-1} of TDS and was dumped in the Gila Riverbed which joined the Colorado River, four miles upstream of Mexico’s Morelos Diversion Dam (Mumme, 2017). As a result, salt concentration increased in both natural watercourses and the irrigation network in the Mexicali Valley, registering levels of about 2,500 mg L^{-1} (Sanchez and Cortez-Lara, 2015). The crop production was soon affected, causing extensive protests in Mexicali, Baja California. Mexico's objection was rejected by the U.S., which points to Articles 10 and 11 of the Treaty, obligating Mexico to accept Colorado water from "any and all sources" and "whatever its origin" (Wilder et al., 2020). The Treaty specified the quantity of water the United States allocated Mexico but not the quality. The Mexican public and representatives questioned the fairness of the Treaty, demanding their water allocation be suitable for irrigation in terms of salinity (Gottlieb, 2012). The advocacy of farmers in the Mexicali Valley forced both the U.S. and Mexican governments to engage in solution negotiations (Cortez Lara, 2011; Gottlieb, 2012). The final resolution to the crisis in 1973 favored Mexican interests because of sustained farmers' activism for over a decade (Gottlieb, 2012). IBWC Minute 242, which ended the dispute, was signed in August 1973. Under Minute 242, the U.S. must keep water salinity (as TDS) at the international boundary (Morelos Dam) at a +/- level of 115 mg L^{-1}, difference with respect to the TDS levels at Imperial Dam (Wilder et al., 2020). Although the limit is rarely exceeded, since 1973 the difference is getting higher in the last years (Bureau of Reclamation, 2020). No studies on economic damages caused by increases in salinity have been reported in Mexico.

4.1.2 Salinity, an ongoing problem

Since the beginning of the salinity crisis in 1961 until now, high concentrations of sodium, magnesium and calcium chlorides in surface and groundwater have impacted crop lands in the Mexicali and San Luis Río Colorado Valleys (Judkins and Myint, 2012; Sánchez and Cortez-Lara, 2015; Seifert et al., 2011). The TDS concentration in water of the Colorado River delivered to Mexico increased from 660 mg L^{-1} in 1950 to an average concentration of 912 mg L^{-1} in the 2000s at the Northern International Boundary (NIB) located at Morelos Dam (CEABC, 2016; CILA, 2023). At the Southern International Boundary (SIB), the TDS concentrations are much higher, in 1973 the average concentration was 1,250 mg L^{-1} while the concentration in the 2000s was between 1300 and 2000 mg L^{-1} (CEABC, 2016).

Minute 323 emphasizes cooperation regarding salinity. The minute establishes that the "United States will fund, install, operate, and maintain electrical conductivity monitoring systems at key measuring points including Imperial Dam, Morelos Dam, and the SIB". In addition, Mexico should also operate and monitor electrical conductivity at NIB (Morelos Dam) and SIB (Canal Sanchez Mejorada) to validate the US measurements.

The distribution of water from the Colorado River in Mexican territory is the sum of the surface water (1,850 Mm^3/year) and groundwater (783.12 Mm^3/year) concessions, equal to 2,633.12 Mm^3/year. The main user is the irrigation district (DR-014), receiving 85% of the water resources (IMTA, 2020). Currently, the Mexicali Valley aquifer faces three major challenges: groundwater overexploitation, the presence of saline soils and brackish water (CONAGUA, 2018). Salinity and sodicity have been of particular concern in Mexicali Valley (Seifert, 2011). Leaching is a common practice for salinity control. High water salinity levels have caused substantial problems for its water users, mainly corrosion in infrastructure and reduced agricultural yields (Colorado River Basin Salinity Control Forum, 2013). Currently, the infiltrated water of farmlands and drains undergoes a very intense process of evaporation and, therefore, mineralization. Current groundwater extractions require pumping from the deep aquifer for agricultural use (Gómez-Puentes and Reyes-López, 2019) and excess water is applied in croplands to avoid the accumulation of salts in the soil root zone. Further reduction in flows will make it even more challenging to meet water quality standards since salinity is inversely related to streamflow.

4.2 Methodology

4.2.1 Overview

The present study consists of three major methodological aspects: (a) describe the historical evolution of TDS concentrations in surface and groundwater in the context of its compliance with the international treaties , (b) analyze the relationship between surface water discharge and groundwater extraction with TDS concentrations, and (c) model future TDS surface and groundwater concentrations, considering reductions in water allocation (Fig. 1). The water supply and simulation of TDS concentrations were calculated using the Baja California water allocation model (Baja California WAM) (Hernández-Cruz et al., 2023).

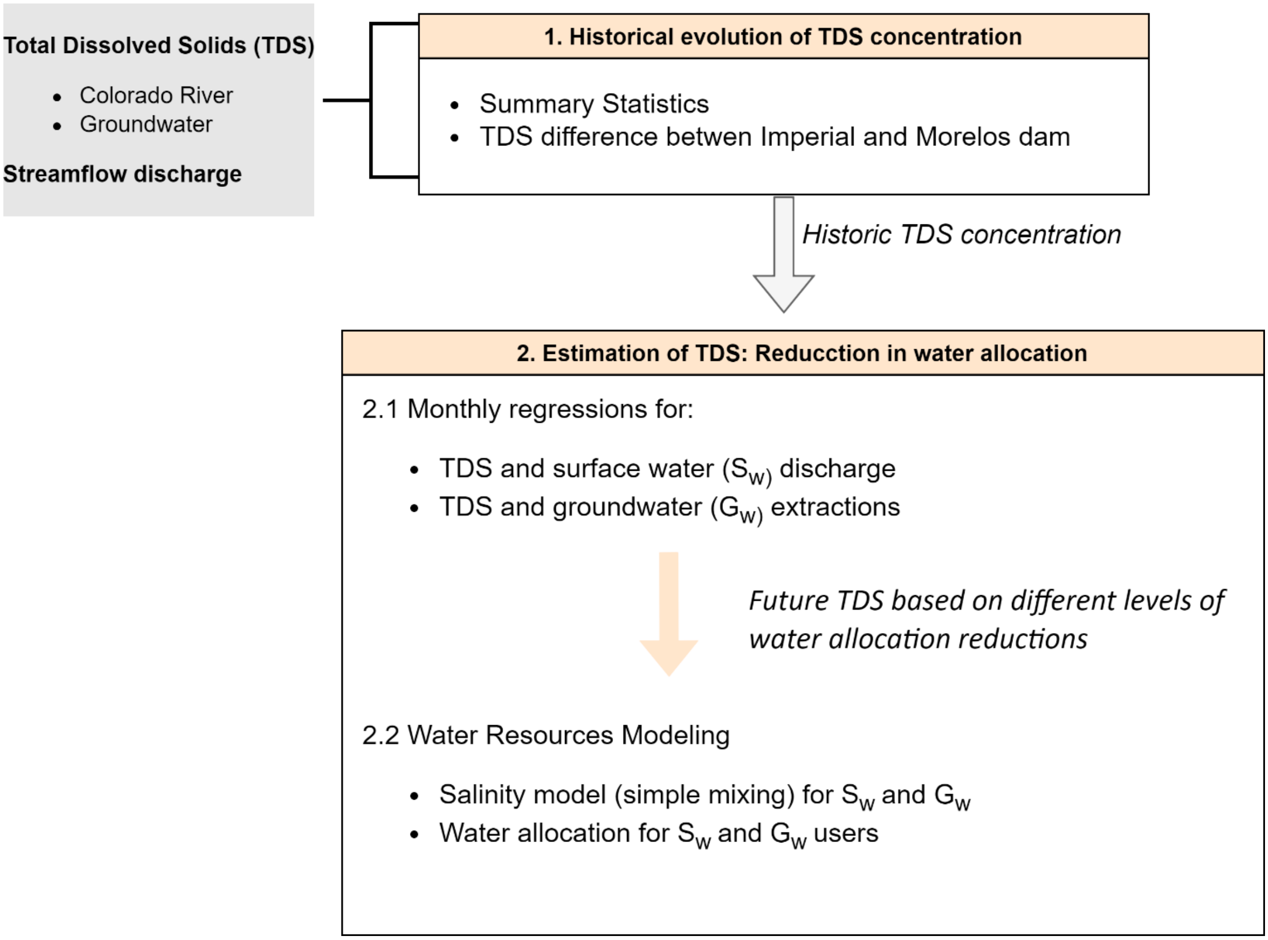

Fig. 1. Methodology for the historical evolution of TDS concentration (1977-2020) and future estimation (2015-2050) based on water allocation reductions

4.2.2 Historical evolution of TDS concentration in surface and groundwater

Data of monthly-mean TDS concentration in water is used (AWWA, 2018), for two USGS gauge stations along the Colorado River: above Imperial Dam, Arizona-California (USGS site 09429490) and at the northern international boundary (NIB) above Morelos Dam, Arizona (USGS site 09522000) (USGS, 2022) (Fig. 2). Summary statistics were performed (mean, minimum, maximum, and standard deviation). The TDS difference between the monitoring sites was calculated and compared with the Minute 242 (IBWC, 1973): “The U.S. shall adopt measures to assure [that the water quality] delivered to Mexico upstream of Morelos Dam, has an annual average TDS of no more than 115 mg L-1 ± 30 mg L^{-1} U.S. count (121 ± 30 mg L^{-1} Mexican count) over the annual average salinity of Colorado River waters which arrive at Imperial Dam”. Historical data of TDS of the Mexicali Valley (MV) aquifer was obtained from CONAGUA (CONAGUA, 2022), research papers, institutional informs, and thesis (Table A1). Summary statistics were also obtained for this dataset.

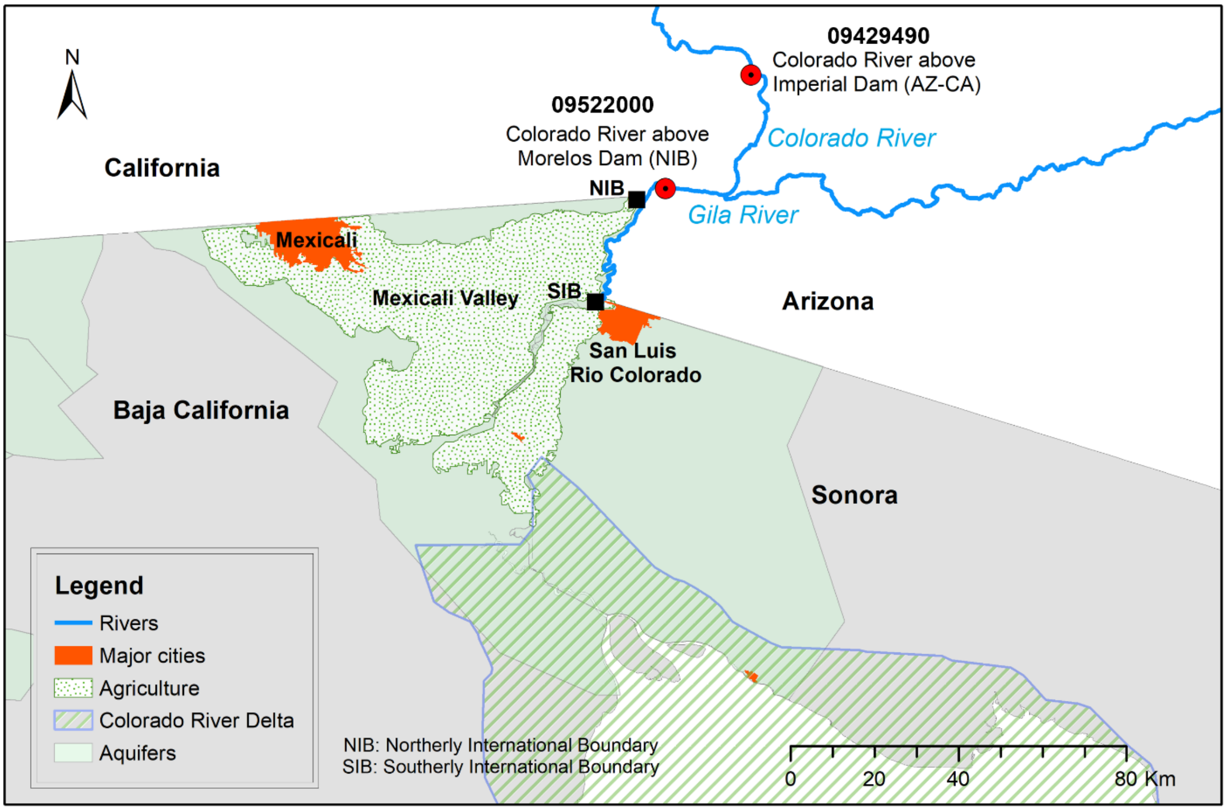

Fig. 2. Location map of USGS monitoring sites (09429490 and 09522000) and water users of the Colorado River resources in Mexico.

4.2.3 Estimation of TDS: Reduction in water allocation

Historical monthly TDS (mg L^{-1}) (2010-2020) at NIB at Morelos dam were obtained from CILA (2021b). These data were used to develop monthly linear regressions that relate TDS and monthly discharge volumes (see Table S1 in Supplementary Data). For March, April, May, and December, TDS concentrations were considered constant as historic salinity concentrations did not fluctuate during these months.

TDS concentrations for groundwater were obtained from a dataset provides by Ingeniería y Gestión Hídrica (consulting group contracted by the state water commission) (CEABC, 2017), comprised by 17 wells located throughout the Mexicali Valley (MV) area.

For the present study, the average TDS concentration (1,226 mg L^{-1}) was considered constant throughout the period of hydrologic analysis.

The water supply and TDS concentration were calculated using the Baja California water allocation model (Baja California WAM) (Hernández-Cruz et al., 2023) a water planning model built in WEAP (Water Evaluation and Planning) platform. The period of hydrologic analysis was 35 years, from January 2015 to December 2050, according to Baja California Water Program (CEABC, 2018). Hernández-Cruz et al. (2023) describes the construction, calibration, validation and use of the Baja California WAM. This study added the water quality component (TDS concentrations) into the model. Model outputs were water demands, supply delivered, aquifers recharge, and total TDS.

The monthly linear regressions were added to Baja California WAM. Future TDS levels were estimated using the aforementioned linear regressions. The total TDS S_t (surface and groundwater) was estimated by simple mixing using Equation 1.

$$S_t = \frac{(C_{SW} * V_{SW}) + (C_{GW} * V_{GW})}{V_{SW} + V_{GW}} \qquad \text{Eq. (1)}$$

Where t is a given month, C_{SW} is the TDS concentration of surface water; V_{SW} is the monthly surface water delivered to Mexico from the Colorado River at NIB; C_{GW} is the TDS concentration of groundwater; and V_{GW} is the groundwater extraction at that given month.

Moreover, to compare the estimated concentrations with the crop's tolerance level, expressed as electrical conductivity (EC: dS m^{-1}), a conversion from TDS (mg L^{-1}) to EC (dS m^{-1}) was performed when EC values ranged from 0.1 to 5 dS m^{-1} using Equation 2 (University of California, 2022).

$$EC\ (dS\ m^{-1}) = TDS(mg\ L^{-1})/640 \qquad \text{Eq. (2)}$$

4.3 Results

4.3.1 Historical evolution of TDS concentration in surface and groundwater

Monthly TDS values (mg L^{-1}) for Morelos and Imperial dams monitoring sites are presented in Fig. 3. The TDS difference between the dams was calculated and compared to the Minute 242 limit (121 ± 30 mg L^{-1}, Mexican count). From 1976 to 2022, the TDS exceeded the limit 28% of the monthly samples (n: 522 months). Since the 2000s, the TDS difference between Morelos and Imperial dams has been above the limit 40% of the months, on average 151 mg L^{-1}. Although the criteria have not been exceeded frequently on an annual basis, this limit is frequently exceeded on a monthly basis, especially in recent years (2010-2020). As a result, Minute 242 has been criticized because it considers the annual mean TDS for estimating the water quality standard, ignoring the high month-to-month variability (Cortez-Lara, 2011).

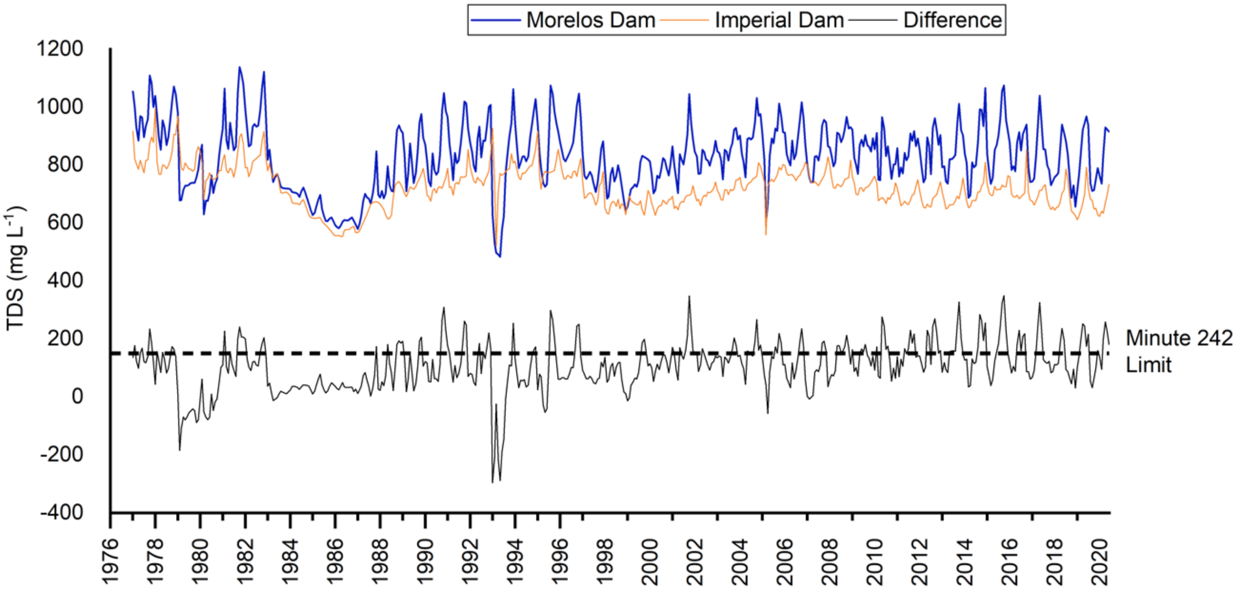

Fig. 3. TDS monthly average concentrations at Morelos and Imperial Dam (1976-2020) reported by USGS (2022)

In the last years (2010-2020), the average TDS in Morelos Dam was 849 mg L^{-1}, with a minimum and maximum value of 776 and 901 mg L^{-1} respectively. In comparison, the average TDS at Imperial Dam was 708 mg L^{-1}, with a minimum and maximum value of 666 and 774 mg L^{-1} respectively. Peak TDS (highest values) during the late summer and early fall are observed for both dams.

Unlike surface water, the water quality of the Mexicali Valley (MV) aquifer is not continuously monitored, and studies are scarce (see Table A1). Four regions of interest were identified: (1) the entire MV, (2) the Northeast region, (3) Cerro Prieto region, and (4) the adjacent area of the riparian corridor. The average TDS concentration was 1380 mg L^{-1} for the entire MV from 1961 to 2020 (Table A1), with a minimum concentration of 220 mg L^{-1} in 2012 (CONAGUA, 2020a) and a maximum of 2978 mg L^{-1} in 2020 (CONAGUA, 2022). Moreover, water quality varies spatially throughout the valley, with the lowest concentrations in the northern area of the Mexicali Valley, especially adjacent to the All-American Canal (AAC).

4.3.2 Estimation of TDS: Reduction in water allocation

The reductions in the water allocation could negatively affect TDS concentrations in both surface and groundwater. Fig. 4 shows the monthly distribution of TDS concentrations associated with the different levels of water reductions. The dotted line corresponds to the baseline salinity without water allocation reductions. The lowest value for all reduction scenarios was 1300 mg L^{-1} (January), and the highest TDS concentration expected for the maximum level of reduction was 2154 mg L^{-1} (September), 566 mg L^{-1} more than the average concentration for this month (1588 mg L^{-1}).

Groundwater quality will be affected since irrigation in DR014 contribute additional salt concentration to groundwater through percolation of water from unlined irrigation canals and excess water applied for salt flushing and the subsequent dissolution of mineral salts. The average concentration of TDS in the aquifer was 1,226 mg L^{-1} in 2017, with a minimum level of 576 mg L^{-1} and a maximum level of 2008 mg L^{-1} (CEABC, 2017).

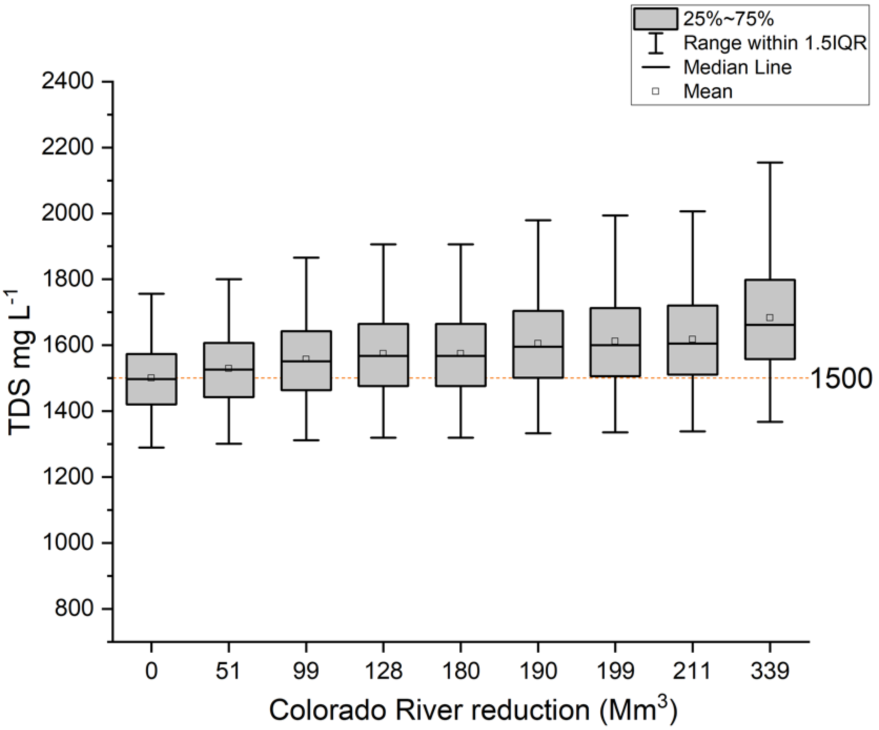

Fig. 4. Simulated salinity concentration versus water with annual water flow reductions (dotted line represents the baseline concentration)

4.4 Discussion

4.4.1 Water Treaty Compliance

Although the criteria have not been exceeded frequently on an annual basis, this limit is frequently exceeded on a monthly basis, especially in recent years (2010-2020). As a result, Minute 242 has been criticized because it considers the annual mean TDS for estimating the water quality standard, ignoring the high month-to-month variability (Cortez-Lara, 2011). Tillman et al. (2019) recognized a 10-to-15-year cyclical TDS oscillations in the lower Colorado River basin. The fluctuations complicate the U.S. Bureau of Reclamation's responsibility to meet the TDS criterion for the water deliveries to Mexico (Tillman et al., 2019).

The accumulation rates of TDS are moderately high for the Lower Colorado (Anning et al., 2006). In the Upper, Middle, and Lower Colorado River Basins, salinity-control projects have been enacted in many areas with elevated TDS, especially in areas upstream from Lees Ferry, Arizona. (Anning et al., 2006). In 1973, the Colorado Basin Salinity Control Act (IBWC, 1973) established TDS criteria to enhance and protect the Colorado River water quality. Three sites in the Lower Colorado River Basin were considered: Colorado River below Hoover Dam (723 mg L^{-1}), Colorado River below Parker Dam (747 mg L^{-1}), and Colorado River above Imperial Dam (879 mg L^{-1}). The criterion for Imperial Dam has never been exceeded because of the salinity-control projects, and the probability of exceeding the TDS criteria is low according to the projections through 2040 (Bureau of Reclamation, 2020). However, without salinity-control projects, the TDS criterion at Imperial Dam would have been exceeded by 2025 (Bureau of Reclamation, 2020).

According to the Colorado River Basin Salinity Control Forum (2020), the average annual TDS concentration at the Imperial dam will increase under different implementation scenarios, from 707 mg L^{-1} in 2020 up to 820 mg L^{-1} by 2040. It is expected that the total annual economic damages incurred in metropolitan and agricultural areas would increase from \$198.8 to \$318.9 million (Bureau of Reclamation, 2020).

Although salinity-control projects have decreased TDS in the lower and upper basins during the 20th century (Anning et al., 2006; Rumsey et al., 2021), the Colorado River system is subject to highly variable annual flow caused by climatic conditions (Deemer et al., 2020; Udall and Overpeck, 2017). TDS concentrations at Morelos dam in Mexico have fluctuated over the past 20 years, from 776 to 901 mg L^{-1}. While TDS at Imperial dam has a downward trend since 2006, there is no downward trend observed in Morelos Dam. The Morelos dam monitoring site is only 42 km downstream from Imperial dam. Still, additional diversions and irrigation return flows substantially increase variability in TDS over what is observed at Imperial Dam (Tillman et al., 2019). Establishing a numerical criterion could be helpful for Morelos Dam, rather than the lax criterion of "average annual TDS no greater than 115 ± 30 mg L^{-1}" which puts Mexico's water quality strongly dependable of upstream activities.

As part of Minute 342, in 1992 the Yuma desalination plant (YDP) was built to improve the quality of Colorado River water delivered to Mexico. The desalination plant was designed to reduce TDS from the Welton-Mohawk Irrigation and Drainage District. The YDP had not operated since 1993 except for: (a) a three-month demonstration run in 2007 at about 10% of total capacity, and (b) during an extended pilot test from May 2010 to March 2011 at about 30% of full capacity (Bureau of Reclamation, 2012; Eden et al., 2011). One of the main challenges during the YDP pilot test was the potential adverse effect of cutting off flow to the Ciénega de Santa Clara, a series of wetlands supported by the discharge from the bypass canal located in Mexico (Eden et al., 2011).

While surface water quality has been addressed in the international conversations, the quality of transboundary aquifers has not been addressed in any of the Minutes. MV aquifer is part of the Cuenca Baja del Rio Colorado Transboundary Aquifer System. Groundwater extraction from MV aquifer since 1950s, which subsequently resulted in a gradual decline in water levels. As extraction increased, zones of high TDS (> 2,200 mg L^{-1}) appeared close to the Colorado River, and increased in the northwestern part of the valley because this zones already had high TDS before the 1960s (Payne et al., 1979). As the Colorado River ceased to be the main source for aquifer recharge, direct vertical infiltration from the distribution channels and agricultural lands became the main source of deep percolation to the aquifer (Rodríguez-Burgueño, 2012). Moreover, according to García-Saillé et al. (2009), the lining of the AAC (which used to contribute 14% of the groundwater recharge) would impact the groundwater quality by increasing the concentration of TDS by 20.6 mg L^{-1} per year. However, there is still no evidence of higher concentrations, even 9 years after the completion of the canal lining (Fedemma, 2018). Therefore, an up-to-date quality analysis should be done to monitor the effect of the historical recharge from the AAC in the TDS level.

As seen in Table A1, CONAGUA's groundwater quality monitoring has been done consecutively only for three wells. Records from the public water registry in 2015 (CEABC, 2017) estimated a total of 1,408 wells in MV, 38% for domestic use, 36% for irrigation use, 5% for public-urban use, 3% for livestock use, and 18% (258 wells) are for industrial use, of which 253 are in the Cerro Prieto geothermal field. Groundwater quality has also been analyzed in areas surrounding the Cerro Prieto geothermal field (CPGF), located in western

MV which is the largest hot water system in the world generating 50% of electrical power (total capacity: 720 Mwe) required for the northwest region of Mexico (Moncada-Aguilar et al., 2010; Payne et al., 1979; Portugal et al., 2005; Ramírez-Hernández and García, 2004). The residual brine is disposed of in an evaporation pond whose seepage has contaminated groundwater that flows southwest from the evaporation pond (Moncada-Aguilar et al., 2010). The agricultural region to the south and southwest of CPGF has shown a soil productivity reduction due to the increase in TDS concentration caused by the effect of the geothermal fluids with TDS of 60,000 mg L^{-1} (Ramírez-Hernández and García, 2004). As salinity increases, farmers in DR-014 are forced to increase the use of surface water to flush salts from the soil surface.

4.4.2 Reduction in water allocation

The increase of TDS concentration in surface water due to the potential reductions in the Colorado River allocations could compromise the high levels of TDS in groundwater and the subsequent accumulation of salts in soils. Judkins and Lunt (2012) mapped the surface soil salinity in MV, finding low salinity (0.0–0.4 EC) in only 0.1 % of the total land study area, 29.6% with some minor salinity (0.5–0.9 EC9), and 68.3% showed elevated levels of salinity (1.0–1.4 EC).

According to Feddema (2018), the main driver controlling changes in groundwater quality in the MV aquifer is the salts imported from the Colorado River. Moreover, the lining of the All-American Canal could impact the groundwater quality by increasing the concentration of dissolved salts in adjacent areas of the aquifer (García-Saillé et al., 2009). Feddema (2018) mapped spatial and temporal patterns of groundwater quality in MV. The results showed that although the northern MV has not yet experienced a fast drop-off in water quality following the lining of the All-American Canal, it is likely that deterioration will be observed in future years as predicted by García-Saillé et al. (2009).

The main water user affected due to the increase of salinity will be DR-014 agriculture, which is the fourth largest irrigation district in Mexico, producing 3,078 ton/year of crops (mainly wheat, cotton, and alfalfa) that represents an income of $435 million US dollars per year (CONAGUA, 2016). Over a time period, salt removal by leaching must equal or exceed the salt additions from the applied water to prevent soil salt building to a damaging concentration (Seifert et al., 2011). It is estimated that 202 Mm^3/year of surface water is being used for flushing salts in DR-014 (CEABC, 2017). Based on the estimated increase of TDS due to the potential surface water delivery reductions to Mexico, it can be expected that more volume of water will be necessary for flushing salts. Based on the estimated increase of TDS due to the potential reductions in the water allocation for Mexico, the calculated EC using Eq. 2 varied from 1.28 to 2.03 dS m^{-1}. Wheat, alfalfa and cotton are the largest cultivated crops in MV, with annual irrigated crop areas of 43,815, 38,601 and 22,730 ha, respectively. Cotton and wheat are salt tolerant with a maximum irrigation water salinity (ECW) of 18 and 16 dS m^{-1}, respectively (Ayers and Westcot, 1985), thus crop yields are not expected to be affected. In contrast, alfalfa is moderately sensitive to salinity (maximum ECW: 10 dS m^{-1}) and its crop yield decrease by 10% with an ECW of 2.2 (Ayers and Westcot, 1985).

The increment of ECW will be more severe for specialty crops, such as green onions (maximum ECW: 5 dS m^{-1}) with an expected decrease of 25% in its crop yield at 1.8 EC (Ayers and Westcot, 1985). Green onions have a summer–fall crop season that matches the highest salinity concentrations, with an estimated maximum value of 2.03 dSm^{-1} (2,154 mg L^{-1}) in September that could further affect the crop yield beyond 25%. To put this result in perspective, in 2016 Baja California ranked first in green onions production accounting for 65.2% of Mexico's production, out of which MV produces 91.4%. This agricultural productions represents an economic value of $28 million US dollars (SEFOA, 2014). Moreover, challenges are not the same for all irrigation units in DR-014, as current distribution of water rights between farmers in the DR014 leads to a disparity in water quality.

The Colorado River supply water to 88% of Baja California's population, an estimated 2.7 million people (CEABC, 2016). Increased salinity can impact drinking water due to the leaching of contaminants in soils, sediments, and water infrastructure. Salinization also increases corrosion and leaching of sediments in aging water pipes, representing a severe health, economic, and engineering concern (Kaushal, 2016). The impacts of saline water supplies include damage to household water appliances and elevated costs for repair and maintenance, costs from the reduced lifespan of infrastructure, and operating costs (Wilson, 2004). Particular attention should receive to the water quality for the urban users of the

Colorado River since TDS levels in surface water are above 1,000 mg L^{-1}, which is the highest contaminant level for salinity allowed in Mexico (Diario Oficial de la Federación, 2022). Most water treatments plants in Baja California use direct filtration (CONAGUA, 2020b), which is not enough to lower TDS concentrations to desired levels. An increase in the levels of TDS could require more sophisticated technologies for salt removal (e.g., membrane filtration, reverse osmosis, and physical adsorption), which would lead to higher capital and operating costs.

Typically, legislation regulates maximum contaminant levels of salinity for drinking water and in irrigation, however, there is none for the environmental flows (Cañedo-Argüelles et al., 2016). Brackish agricultural return flows from Mexico and the US support the Cienega de Santa Clara (Lomeli et al., 2015). Baeza et al. (2012) determined the impact of salinity in the marsh vegetation, birds, mammals, and invertebrate species that live in the Cienega de Santa Clara located in the Colorado River delta in Mexico. The average TDS in the marsh is 2.8 g L^{-1}, with dominant vegetation of Typha domingensis. They found a linear reduction in relative growth rate based on biomass production with TDS, with a 50% reduction at 4.0 g L^{-1} and zero growth at 8.3 g L^{-1} TDS (Baeza et al., 2012). It can be expected that further increased TDS for surface water and groundwater could jeopardize the vegetation in the marsh.

Moreover, the impacts of reduced water volumes and high TDS levels due to a trial run of the YDP (2010) have been studied for the Cienega de Santa Clara, finding adverse effects on the vegetation due to the substitution of agricultural return flows from the US for the brine from the desalination operation.(García-Hernández et al., 2013; Glenn et al., 2013; Lomeli et al., 2015). Based on the impacts of the operation of the YDP at one-third capacity during the trial run, it can be expected that the permanent operation of the YDP would have a negative impact on the Cienega (Lomeli et al., 2015). Future efforts should be oriented to compensate the salinity increases in the Cienega if the YDP starts operating at the same time that improvements for water quality for the rest of the users (urban and agriculture) are achieved.

4.5 Conclusions

An increase in TDS concentration is expected due to reductions in the Colorado River water allocation to Mexico. Since 2000, the TDS difference between Imperial dam (US) and Morelos dam (Mexico) has been above the IBWC limit (151 mg L^{-1}, Mexican count) 40% of the months. The monthly variation should be considered rather than the annual mean for estimating the water quality standard. Establishing numerical criteria such as those implemented for Hoover, Parker, and Imperial dams could benefit Mexico. While TDS concentrations in the Colorado River are consistently measured and published, there is a lack of reliable data on TDS for groundwater in Mexicali and San Luis Rio Colorado aquifers. To implement high salinity mitigation efforts, it is necessary to understand trends and consistently monitor water resources on both sides of the border.

The present study estimates the relationship between TDS concentration in surface and groundwater due to the reductions in the water deliveries of the Colorado River to Mexico. The baseline concentration was 1500 ± 109 mg L^{-1} as TDS. As the reduction level increased, the TDS concentration also increased. The highest TDS concentration expected for the maximum level of reduction (-358 Mm^3) was 2154 mg L^{-1} (in September, the last month of the US water year), 566 mg L^{-1} more than the historical average (2010-2020) concentration for this month. This increment could affect the production of saline-sensitive major crops at DR-14 such as green onion and alfalfa. Moreover, more surface water will be needed to flush salts from soils, and it will impact the salinity of groundwater. Finally, urban users and environmental users will also be adversely affected by increasing levels of TDS due to higher treatment costs.

4.6 Conclusiones

Se espera un aumento de la concentración de SDT debido a las reducciones en la asignación de agua del río Colorado a México. Desde el año 2000, la diferencia de SDT entre la presa Imperial (EE. UU.) y la presa Morelos (México) ha estado por encima del límite de la IBWC (151 mg L^{-1}) el 40% de los meses. Para estimar el límite de calidad del agua debe tenerse en cuenta la variación mensual en lugar de la media anual. El establecimiento de valores fijos como los aplicados en las presas Hoover, Parker e Imperial podría beneficiar a México. Mientras que las concentraciones de SDT en el río Colorado se miden y publican consistentemente, se carece de datos confiables sobre las concentraciones de SDT en los acuíferos de Valle de Mexicali y Valle de San Luis Río Colorado. Para implementar esfuerzos de mitigación de altos niveles de salinidad, es necesario entender las tendencias y monitorear constantemente los recursos hídricos en ambos lados de la frontera.

El presente estudio estima la relación entre la concentración de SDT en aguas superficiales y subterráneas y los volúmenes de agua considerando las reducciones en las entregas de agua del río Colorado a México. La concentración de referencia fue de 1500 ± 109 mg L^{-1}. A medida que aumentó el nivel de reducción, también aumentó la concentración de SDT. La concentración más alta ¿ esperada para el nivel máximo de reducción (-358 Mm^3) fue de 2,154 mg L^{-1} (en septiembre), 566 mg L^{-1} más que la concentración media histórica (2010-2020) para este mes. Este incremento podría afectar a la producción de cultivos principales sensibles a la salinidad en el DR-14, como la cebolla verde y la alfalfa. Además, se necesitará más agua superficial para eliminar las sales del suelo, lo que repercutirá en la salinidad de las aguas subterráneas. Por último, los usuarios urbanos y medioambientales podrían verse perjudicados por el aumento de los niveles de SDT debido a los mayores costes de tratamiento.

CAPÍTULO V: DISCUSIÓN GENERAL

Los modelos cuantitativos son herramientas útiles para el manejo de agua. A pesar del potencial uso de estos instrumentos en la planeación de recursos hídricos, su aplicación en los procesos de toma de decisiones en México ha sido limitada (Capítulo II). La mayoría de los esfuerzos de modelación se han realizado en el norte y centro del país, regiones áridas que presentan problemas de escasez de agua. Los modelos han sido utilizados principalmente para auxiliar tres procesos: planificación de los recursos hídricos, diagnóstico de la disponibilidad de agua, y la resolución de conflictos. Destaca el uso de plataformas como WEAP, MODFLOW, Super Decisions, entre otros. La elección de la herramienta a utilizar es importante, y debiese ser guiada por el objetivo del proceso de toma de decisiones, los objetivos de las partes involucradas, la disponibilidad de datos, el financiamiento, y las limitaciones de tiempo. Sin embargo, no basta con la elección de una buena plataforma. Una de las principales conclusiones a las que se llegó en el Capítulo II es la importancia de involucrar a los tomadores de decisiones para garantizar la transparencia, la credibilidad, y la comprensión compartida de las partes interesadas y los responsables de la toma de decisiones. Además, para tener modelos fiables, el monitoreo y contar con datos confiables de los recursos hídricos es fundamental.

Los modelos introducen alternativas competitivas por que permiten el debate sobre la elección de estrategias y favorecen la transparencia en la toma decisiones. La mayoría de los estudios evaluados introdujeron alternativas competitivas y tienen un impacto benéfico en el proceso de planeación de recursos hídricos. Sin embargo, sólo 1 de los 36 estudios revisados por pares hasta 2021 fue considerado completamente para la implementación de una nueva política (caso de estudio Cuenca Lerma Chapala). Es importante resaltar que todos los modelos tienen limitaciones, que son aproximaciones a los sistemas reales y no resuelven los problemas de manejo del agua, pero pueden proporcionar información útil durante el proceso de toma de decisiones.

A pesar del potencial de los modelos como herramientas de planeación, la falta de datos confiables es uno de los desafíos en la modelación para la gestión integral del agua

(Badham et al. 2019). Como fue expuesto en el capítulo II, el acceso a datos confiables sigue siendo un reto en México. Los datos hidrológicos y meteorológicos básicos pueden ser incompletos y poco fiables no sólo en México, si no en diferentes países en desarrollo así como aquellos en donde los gobiernos dan poca prioridad a la inversión en redes de vigilancia (Badham et al. 2019, Oueslati et al. 2015, McDonnell, 2008). Por ejemplo, en Chile, la desaparición del lago Aculeo, ha sido asociado a factores antropogénicos, incluida la falta de estrategias sustentables de manejo de agua por parte del gobierno, así como la falta de planeación en uso de suelo (Valdés-Pineda et al. 2022). Valdés-Pineda et al. (2022) argumentan que la gestión se ha visto limitada por la falta de datos y estudios hidrológicos específicos que definan los volúmenes de almacenamiento necesarios para desarrollar una gestión sostenible del agua a largo plazo.

Las nuevas formas de observación, como los datos obtenidos por teledetección, ofrecen oportunidades en entornos con escasez de datos (Palmer, 2015). Por ejemplo, en Apulia, Italia, una región con datos limitados, D’Ambrossio et al (2019) llevaron a cabo un análisis espacial destinado a apoyar las aplicaciones de modelos hidrológicos y de calidad del agua. Los autores registraron el caudal y los parámetros de calidad del agua necesarios para calibrar y validar los modelos, creando una base de datos archivada en un entorno de Sistema de Información Geográfica (SIG).

Por otra parte, la adopción de modelos como herramientas de planeación para la toma de decisiones debe ir acompañado del involucramiento de los tomadores de decisiones. Merritt et al. (2017) identificaron como factores cruciales para la aplicación de estas herramientas la comunicación abierta y transparente, la confianza y el intercambio de conocimiento entre modeladores y usuarios. Actualmente los modelos de planeación son herramientas aplicadas en la toma de decisiones en manejo de agua en países como Australia (CSIRO, 2016), Estados Unidos (Buró de Reclamación, 2023) y Brazil (Cambrainha et al., 2018).

Bajo este contexto, en el capítulo III se propuso un modelo de planeación de los recursos del río Colorado en México. El modelo consideró las reducciones en las asignaciones de agua, cambio climático, entre otros estresores, para cuantificar el abastecimiento de agua de los diferentes usuarios mexicanos del río Colorado tomando en cuenta actuales y futuras estrategias de manejo. El modelo de asignación fue útil para identificar el impacto de las disminuciones en las asignaciones de agua en el abastecimiento de los diferentes usuarios de Baja California y Sonora así como las estrategias de manejo que favorecen (o desfavorecen) al sistema.

El modelo de Sanvicente-Sánchez (2009) fue el primer modelo en incluir a México como usuario de la cuenca del río Colorado, sin embargo el alcance de esta herramienta no permitió la evaluación y comparación de estrategias de manejo. Por otra parte, el modelo de optimización de Medellín y colaboradores (2009) demostró que la combinación del reuso, ampliación de acueductos, y aumento en las capacidades de desalinización resultaba en un mejor costo de explotación y escasez baja. De la misma manera, en el Capítulo III se determinó que la combinación de estrategias en los subsistemas II (Tecate, Tijuana-Rosarito) y III (Ensenada y sus valles agrícolas) favorece el desempeño sustentable para todos los usuarios. Para el caso del subsistema II, la combinación del aumento de eficiencia en la red urbana, el aprovechamiento de agua subterránea, y el aumento en la capacidad del acueducto río Colorado – Tijuana (ARCT) fue la combinación más benéfica para el subsistema. Mientas que para el subsistema III lo fue la expansión en el reuso de aguas residuales tratadas, el uso de su asignación completa del acuífero SLRC y el aprovechamiento de la capacidad actual de la desaladora de la ciudad de Ensenada.

A pesar de que las desaladoras se postulan como la mejor opción ante la escasez de agua, consumen una gran cantidad de energía, lo que también contribuye a la contaminación ambiental (Yoonus y Al-Ghamdi, 2020). Esto ha llevado a una búsqueda constante de opciones más viables para conservar los recursos de agua dulce sin comprometer la calidad medioambiental. En este sentido, el reuso de agua se postula como una de las mejores prácticas para enfrentar la escasez de agua, especialmente en el sector agrícola, el consumidor prioritario de agua en el mundo (Shoushtarian y Negahban-Azar, 2020). En zonas desarrolladas con intensa escasez de agua, la reutilización del agua se practica actualmente de forma eficiente. Entre esos lugares se encuentran el sur de Estados Unidos (principalmente, California, Florida, Texas y Arizona), Australia, Singapur, Israel y los países del Golfo Pérsico (Angelakis y Gikas, 2014).

Ensenada (Valle de Maneadero) ha incursionado en el reuso de aguas residuales para su aprovechamiento en la producción de flores ornamentales desde el 2014 (Mendoza-Espinosa y Daesslé, 2018), representando una alternativa a la extracción de agua del acuífero sobreexplotado Maneadero. El subsistema III se vio favorecido ante la expansión en el reuso de aguas residuales tratadas, sin embargo, el aumento del uso de agua residual tratada (ART) en el Valle de Maneadero (200 l/s) debería ir acompañado de una transferencia de derechos de agua al ayuntamiento de Ensenada, y, de esta forma, beneficiar el suministro de agua de la ciudad y para disminuir la sobreexplotación del acuífero.

Hay al menos más de 60 países en todo el mundo que practican diversos tipos de reuso del agua. En cuanto al volumen total anual, China, México y Estados Unidos son los países con las mayores cantidades de agua reutilizada. Sin embargo, en los dos primeros casos, el agua reutilizada corresponde a aguas residuales con tratamiento deficiente (Angelakis y Gikas, 2014).

En 2018, se aprobó un proyecto para transportar agua residual tratada (ART) desde la ciudad de Tijuana hasta el Valle de Guadalupe, cuya construcción sigue pendiente. El volumen de ART (aproximadamente 1,000 l/s) será suficiente para irrigar la superficie cultivada actual del Valle de Guadalupe e incluso ampliarla hasta 6,000 ha (Mendoza-Espinosa et al. 2019). Sin embargo, esta estrategia propuesta por el gobierno del estado de Baja California debe ser evaluada cuidadosamente, ya que podría afectar negativamente a los cultivos de riego, haciendo indispensable la verificación de la calidad de agua para ser aplicada a los cultivos. La calidad del agua del ART debe compararse con la del agua subterránea que actualmente se utiliza para riego (Daesslé et al. 2020; Weber et al. 2014). Además, es necesario determinar los intercambios de agua entre el acuífero del Valle de Guadalupe y el acuífero adyacente de la Misión (Daesslé et al. 2020).

De acuerdo con las proyecciones oficiales de la CEABC (2018), se espera un déficit de 292.9 Mm^3 en la región de Mexicali y SLRC al 2035, considerando agua superficial y subterránea, debido a los impactos del cambio climático. Como fue presentado en el Capítulo III, el déficit en el abastecimiento en Baja California podría alcanzar 643 Mm^3 para el año 2050 bajo el escenario más desfavorable (reducción máxima y no tomar acciones adicionales). El déficit anual en el abastecimiento del estado también ha sido estimado por Stella (2021) (372 Mm^3), sin embargo este estudio no contempla la evaluación de estrategias de manejo o escenarios futuros de disponibilidad de agua.

Por otra parte, en el Capítulo III se presentaron las reducciones de hectáreas necesarias para garantizar el abastecimiento de la demanda agrícola al 100% considerando las reducciones de asignaciones. Una de las limitantes del presente estudio es que se consideraron demandas fijas en los cultivos en función de la actual cédula de cultivo en el DR-014. En el mejor escenario (mínima reducción), el 20% (38,862 ha) del área total irrigada debe ser reducida (bajo el actual patrón de cultivos). A diferencia de Cortés-Ruiz y Azuz-Adeath (2021), que proponen la reducción del 80% de alfalfa (26,846 ha), en el presente estudio se consideró la reducción para todos los cultivos que conforman al Valle de Mexicali. Si bien el consumo de agua es superior para la alfalfa, es uno de los cultivos con mayor productividad económica en el valle, por lo que una reducción únicamente de este cultivo podría ser inconveniente económicamente. No hay duda de que la actual cédula de cultivo en el DR-014, ante sus superficies de riego, resulta insostenible en las condiciones actuales. Sin embargo, cultivos como la cebada, frijol, betabel, col rizada y avena, se postulan como una opción para sustituir gradualmente cultivos tradicionales (trigo, algodón, alfalfa) debido a que son cultivos menos demandantes de agua y con mayor rendimiento económico (Domínguez, 2022). De igual forma, en el Instituto de Ciencias Agrícolas de la UABC se ha desarrollado un paquete tecnológico para el cultivo del chile habanero como una alternativa para la reconversión del campo que puede fomentar un mejor aprovechamiento del suelo y mayores ingresos a los productores (UABC, 2022). Estas opciones de cultivos pueden ser introducidas de forma sencilla al modelo de asignación desarrollado en el presente estudio para poder representar el ahorro de agua que representa la inclusión de estos cultivos. Actualmente la reducción de hectáreas es una estrategia empleada por el distrito agrícola vecino (Valle Imperial, California) quienes aplican el descanso de tierras y contemplan la reducción de suelos agrícolas en incrementos de cinco años entre 2010 y 2050 (Imperial Irrigation District, 2021).

Considerando el orden de prelación en la Ley de Aguas Nacionales, el cual asigna prioridad a los usos doméstico y público-urbanos sobre la actividad agrícola, los mayores desafíos en el abastecimiento de agua en Baja California los tiene el DR-014. El distrito se verá afectado ante la disminución de la oferta de agua y al aumento de la temperatura incidiendo en la demanda de los cultivos (Capítulo III). Cortez-Lara y Castro-Ruiz (2019) llegan a la misma conclusión y exponen la manera en que la alta variabilidad climática afectará al sector agrícola del estado en el corto y mediano plazo toda vez que el orden de prelación se respete. Además, las modificaciones en los patrones de precipitación y ciclos de almacenamiento a nivel de cuenca cambiarán la disponibilidad estacional, anual e interanual de agua para los sistemas agrícolas (FAO, 2003).

Cuantificar los déficits de agua esperados puede ser útil para proponer estrategias de manejo en el distrito de riego. Las estrategias planteadas en el presente estudio mejoran el desempeño del distrito considerando la oferta actual de agua, sin embargo, no son suficientes para contrarrestar los impactos negativos de las disminuciones en las asignaciones, por lo que será indispensable evaluar nuevas acciones o extender el alcance de las actualmente contempladas. Sin embargo, no basta con tomar acciones en los valles agrícolas, ya que también existen áreas de oportunidad para los usuarios urbanos. A pesar de que el uso público-urbano está protegido por la Ley de Aguas Nacionales y tiene prioridad en la asignación de agua, los usuarios, especialmente los de la zona costa del estado, pueden verse favorecidos por la acción conjunta del aumento de la eficiencia de la red urbana, el uso de la capacidad total de la desaladora (Ensenada), por el reúso de ART, entre otras estrategias exploradas en el Capítulo II, de forma que la alta dependencia por los recursos del río Colorado sea menor. Por otra parte, el abastecimiento de agua para el usuario industrial podría verse comprometido debido a que es el uso de menor prioridad, por lo que podría esperarse un aumento en el déficit de agua (especialmente en Tecate y Tijuana).

Por otra parte, a pesar de que Mexicali cuenta con la demanda de agua cubierta, existe un desbalance entre la demanda (se factura 101.9 Mm^3) y su asignación proveniente de Mesa Arenosa (82 Mm^3) (CEABC, 2018). El resto de la demanda se solventa con la adquisición de derechos de riego de zonas de riego aledañas al área urbana (Cortéz Lara, 2021). Sin embargo, de acuerdo con el IMTA la disponibilidad de agua incrementará en 1 Mm^3/anual durante los próximos 30 años debido a las transferencias de derechos de agua del sector agrícola a la ciudad de Mexicali, lo que representa dejar fuera de producción 100 ha de riego por año (Salgado et al., 2018). El estudio del IMTA no consideró la disminución de agua por los escenarios de contingencia y reducción de asignaciones.9

Además del desarrollo del modelo de planeación (Capítulo III), el uso del índice de sustentabilidad facilitó la evaluación y comparación de las diferentes estrategias de forma objetiva. Este ejercicio podría ser adoptado por tomadores de decisiones a la hora de discernir entre una u otra estrategia guiados por el desempeño sustentable de cada una. Los indicadores de sustentabilidad han sido utilizados para la comparación de acuerdos de agua compartida en cuencas como la del río Colorado (porción estadounidense) y Murray Darling en Australia (Padikkal et al., 2018). En México, el índice de sustentabilidad ha sido aplicado para el manejo de la cuenca transfronteriza del río Bravo, el cual permitió la evaluación sistemática de estrategias para los usuarios de agua de forma individual, grupal, regional y para toda la cuenca (Sandoval-Solis et al., 2013). También se han utilizado criterios de desempeño para evaluar estrategias de manejo bajo condiciones de cambio climático en áreas áridas y semiáridas como la cuenca del lago Urmia en Irán (Ahmadaali et al., 2018), encontrando que la combinación de estrategias (cambio en los patrones de cultivo y aumento en la eficiencia de irrigación) resultaba en un mayor índice de sustentabilidad agrícola y ambiental.

El modelo de planeación propuesto en el Capítulo III es dinámico, lo que facilita su actualización, la incorporación/desincorporación y combinación de escenarios de manejo, adaptándose a las necesidades de los usuarios y a las condiciones cambiantes del sistema.

Además de las implicaciones en la cantidad de agua recibida por los usuarios de la cuenca del río Colorado, la calidad de agua puede verse comprometida ante la disminución de volúmenes de agua (asignaciones). En el Capítulo IV se presentó la evolución histórica de sólidos disueltos totales (SDT) en agua superficial y subterránea. En cuanto al agua superficial, la concentración de sales ha superado el límite máximo establecido por Estados Unidos y México. Desde el año 2000, la diferencia de las concentraciones de sólidos disueltos totales (SDT) entre las estaciones de la USGS 09429490 (por encima de la presa Imperial, Arizona) y la estación 09522000 (por encima de la presa Morelos Arizona) ha superado el límite máximo (151 mg L^{-1}) el 40% de los meses. El límite actualmente establecido en el Acta 242 considera la concentración de SDT promedio anual, pero no toma en cuenta la alta variabilidad mensual. Mientras que Estados Unidos ha definido niveles fijos en las concentraciones en tres presas de la cuenca baja del río Colorado (Hoover, Parker e Imperial), el límite en la presa Morelos se mantiene dinámico tomando en cuenta los niveles de salinidad en la presa Imperial. La concentración de sales en la presa Morelos ha fluctuado en los últimos años (900 mg L^{-1} en promedio) alcanzando concentraciones superiores a los 1000 mg L^{-1}(2010-2022), límite máximo permisible para el consumo humano de acuerdo con la normatividad mexicana (NOM-127-SSA1-1994), mientras que la presa Imperial ha experimentado una disminución gradual en su concentración por debajo de los 800 mg L^{-1}.

A diferencia de las aguas superficiales, la calidad del agua subterránea no se monitorea continuamente. La concentración promedio de SDT entre 1961 y 2020 fue de 1400 ± 223 mg L^{-1} considerando todo el Valle de Mexicali. A medida que aumenta la salinidad, los agricultores del DR-014 se verán obligados a aumentar el uso de agua superficial para eliminar las sales de la superficie del suelo. Para identificar el impacto en la disminución de asignación del río Colorado, se simularon concentraciones mensuales (superficial y subterránea) a partir de regresiones lineales de las concentraciones históricas. El valor más alto (2,154 mg L^{-1}) se obtuvo para el mes de septiembre bajo el escenario de máxima reducción en la asignación de agua (-339 Mm^3). El aumento de la salinidad podría afectar a la producción de cultivos sensibles a la salinidad en el DR-014 como el cebollín o la alfalfa. Los retos no son los mismos para todos los módulos de riego ya que la distribución actual de los derechos de agua entre los agricultores del DR-014 provoca una disparidad en la calidad del agua. Además de sus implicaciones en la agricultura, los altos niveles de salinidad pueden incidir en la calidad de agua para consumo humano y en los costos de tratamiento. Los costos derivados del aumento de salinidad en sistemas urbanos han sido estimados en países como Australia, India, Iraq, Estados Unidos, España, entre otros (Qadir et al. 2014). Destaca la inversión de Australia en soluciones a largo plazo para la mitigación de la salinidad en ciudades como Sídney, incluidas soluciones de ingeniería, revegetación y campañas de comunicación y educación para la sociedad civil y tomadores de decisiones (Parliament of Australia, 2023). Un ejemplo de aprovechamiento de aguas salinas procede de Hong Kong, donde el agua de mar se utiliza para las cisternas de los retretes. Aunque se trata de un campo de investigación incipiente, los estudios realizados hasta ahora revelan que el uso de agua de alta salinidad es prometedor como método para aumentar la seguridad hídrica con un impacto ambiental mínimo (Liu et al. 2019). Sin embargo, para muchos otros lugares del mundo requeriría mejorar las infraestructuras de distribución de agua para que no sean corroídas (Lassiter, 2021).

Especial atención deberá recibir la calidad de agua del río Colorado, así como las fuentes de agua subterránea. Es necesario cuantificar regularmente los niveles de sólidos disueltos totales de agua superficial y subterránea en ambos lados de la frontera, comparar valores, y compartir la información a todos los involucrados, incluidos agricultores y ciudadanía. Cortez-Lara (2014) establece que las afectaciones ocasionadas por la salinidad en la producción y productividad de los cultivos del Valle de Mexicali alcanzan niveles de hasta 20%, ya sea por reducción de superficies o por disminución de rendimientos en los cultivos. Los costos de las afectaciones en la producción y productividad se estiman en 1,230 millones de pesos anualmente, sin contar las necesidades de inversión de infraestructura para eliminar las sales acumuladas en los suelos y de gastos de operación para mezclar fuentes de agua que permitan tener agua en condiciones aceptables para uso agrícola (Cortez-Lara, 2014).

Como fue expuesto en el Capítulo IV, el algodón y el trigo, cultivos principales del Valle de Mexicali, son tolerantes a altos niveles de salinidad (Ayers y Westcot, 1985). Sin embargo, cultivos como la alfalfa (moderadamente sensible) y cebollín verde (altamente sensible) pueden verse comprometidos ante las altas concentraciones esperadas en el Valle. Judkins y Mynth (2012) aplicaron un método de variación espacial de la salinidad de suelo en el Valle de Mexicali, localizando distintas áreas con altos niveles de salinidad que comprometen la producción de cebolla y cultivos de la temporada de invierno en el distrito de riego.

Por otra parte, el riego con agua salobre puede ser viable para cultivos tolerantes como la cebada y la remolacha azucarera (betabel) (Pitman y Läuchli, 2002). Por ejemplo, en el Valle de San Joaquín, California, la eliminación de las aguas de drenaje salinas procedentes de tierras de regadío ha sido un tema controversial. Se han realizado estudios de viabilidad para la producción de algodón y betabel con agua salina de conductividad eléctrica de 9 dS m^{-1} (>5000 mg L^{-1}) con alto rendimiento de producción (Ayars, 2013).

Por otra parte, a pesar de que el trigo pertenece a la clasificación de cultivo altamente tolerante a la salinidad, el cultivo no mantiene esta tolerancia en todas las condiciones, como los periodos de tiempo caluroso y seco (Maas, 1990). Seifert et al. (2011) estimaron los efectos de la sodicidad y la salinidad en el rendimiento y la superficie de producción de trigo en el Valle de Mexicali. Los autores reportaron que la sodicidad es responsable de una pérdida media del 1.2% de la producción de trigo cada año (Seifert et al. 2011).

El marco completo para abordar los presentes y futuros desafíos referentes a la cantidad y calidad del río Colorado deberá incorporar una visión compartida por las partes interesadas de Estados Unidos y México que apueste al beneficio de la sociedad y el medio ambiente.

El modelo desarrollado en el presente estudio (Capítulo III) podría ser una herramienta útil para representar los usuarios de México y auxiliar los procesos de toma de decisiones. A diferencia de los modelos desarrollados por el Buró de Reclamación de los Estados Unidos, la demanda de agua de México es desagregada en todos sus usuarios, considera los recursos subterráneos compartidos y la calidad de agua. Los resultados de este trabajo fueron presentados a directivos de CONAGUA (2022) y CILA (2021). De igual forma se espera presentar al Consejo de Cuenca de Península de Baja California. La investigación sólo se abordó a nivel de planeación de recursos hídricos y desde una perspectiva de disponibilidad de agua. Sin embargo, la complejidad de la problemática expuesta en el Capítulo I exige tomar en cuenta los aspectos sociopolíticos y económicos para representar los intereses de todas las partes involucradas en el manejo de agua del río Colorado en México.

Por otra parte, la comunicación social de la vulnerabilidad del abastecimiento de agua en la región deberá ser tomada en cuenta para generar planes de mitigación. La aplicación de la ciencia ciudadana en temas relacionados con el al agua es relativamente nueva y está en crecimiento (Njue et al., 2019; Zheng et al., 2018). La incorporación de la sociedad en actividades de monitoreo y seguimiento científico tiene el potencial de traer consigo muchos beneficios locales a las comunidades que se involucran en estas actividades (Buytaert et al., 2014; Walker et al., 2020). Bajo este contexto, la herramienta de planeación de recursos hídricos desarrollada en este estudio puede favorecer la adopción de ciencia ciudadana, donde agencias gubernamentales y ciudadanos tengan acceso a la información y puedan observar el impacto de diferentes estrategias en la oferta y demanda de agua de la región utilizando un software libre y de interfaz amigable para el usuario.

CAPÍTULO VI: CONCLUSIONES

1. En México, los modelos cuantitativos se han utilizado para auxiliar tres procesos: la planeación de los recursos hídricos (53%), el diagnóstico de la disponibilidad y la demanda de agua (36%) y la resolución de conflictos (11%). Fueron identificados 36 estudios de modelación en el país (al 2021), la mayoría de los cuales se han realizado en el norte, noroeste y centro del país, en regiones áridas que presentan estrés hídrico.

2. A pesar de su utilidad, sólo 1 de los 36 modelos hídricos ha sido empleado por los tomadores de decisiones para la implementación de nuevas políticas públicas. Los principales desafíos en la modelación son la falta de datos actualizados y confiables, la poca participación de las partes involucradas en el manejo de agua, y el limitado intercambio de conocimiento. Por otra parte, la modelación colaborativa, el acceso a información, y la adopción de enfoques integrales resultó en una mejor aceptación de los modelos.

3. Un modelo de planeación de los recursos hídricos del río Colorado en México fue desarrollado y calibrado en la herramienta WEAP. El abastecimiento de agua calculado se comparó con los registros históricos para demostrar que el modelo representa adecuadamente el sistema. Se determinaron criterios de bondad de Nash-Sutcliffe (0.64) y el índice de concordancia de Willmott (0.90), los cuáles caen dentro del rango de rendimiento aceptable.

4. De acuerdo con la evaluación, el DR-014 es el usuario más afectado por las reducciones en las entregas del Río Colorado. En el escenario más desfavorable, la sustentabilidad disminuyó de 68% (Escenario Base) a 43%. Esta disminución se refleja en un déficit de agua de 643 Mm^3 para el año 2050, es decir, 30% de la demanda total del DR-014. El sistema actual tiene un mejor rendimiento a costa de la sobreexplotación de los acuíferos a largo plazo. La reducción de la superficie cultivada fue la estrategia con mayor beneficio para el DR-014.

5. Para la zona de Tecate y Tijuana-Rosarito, el aumento en la eficiencia de la red urbana, rehabilitación de pozos, y expansión de capacidad en el acueducto favoreció la sustentabilidad del subsistema de 33% (línea Base) hasta 95% en el escenario de máxima eficiencia. Por otra parte, Ensenada y sus valles agrícolas aumentaron su sustentabilidad de 49% (línea Base) a 88% al aumentar la eficiencia en la red urbana, expandir el reúso en los valles agrícolas, recibir la asignación completa de recursos del río Colorado, y el aprovechamiento total de la desaladora ya en operación.

6. En cuanto a la calidad de agua, desde el año 2000 la diferencia de sólidos SDT entre las presas Morelos e Imperial ha superado el límite máximo establecido por la CILA (151 mg L^{-1}) el 40% de los meses (1977-2020). Considerando las proyecciones de aumento de salinidad por disminuciones en los volúmenes de agua (asignaciones), el cumplimiento del nivel establecido será cada vez más difícil de alcanzar. A medida que aumenta la salinidad, los agricultores del DR-014 se verán obligados a aumentar el uso de agua superficial para eliminar las sales de la superficie del suelo.

CAPÍTULO VII: RECOMENDACIONES FINALES

El modelo de asignación de los recursos del río Colorado, así como la evaluación de estrategias de manejo, son un primer paso en la planeación de los recursos para garantizar el abastecimiento de los usuarios de México. El siguiente paso consiste en la comunicación social de la vulnerabilidad del abastecimiento de agua para los diferentes usuarios ante las disminuciones en las asignaciones y las áreas de oportunidad para un mejor manejo. A continuación, se plantean recomendaciones dirigidas a tomadores de decisiones:

- Coordinación con el DR-014. El usuario más afectado en las disminuciones de asignaciones es el distrito de riego. La vigencia del Acta 323, que define los volúmenes de recorte de agua, es hasta el año 2026, sin embargo, las probabilidades de el nivel del agua en el lago Mead sea inferior a 1025 psnm en un futuro cercano son muy altas. Es importante tener en cuenta esta posibilidad y coordinar esfuerzos siempre de la mano del sector agrícola.

- Proyectos de conservación de agua. De igual forma, en el Acta 323 se plantea la posibilidad de desarrollar proyectos de conservación como el revestimiento de canales, descanso de tierras, modernización y tecnificación de riego. Si bien son estrategias factibles será necesario detallar concisamente cada proyecto de forma transparente y participativa adaptándolos a las necesidades de cada módulo de riego que conforma al DR-014.

- La reducción de la demanda agrícola será inevitable. Como se plantea en los anteriores capítulos, la reducción de superficie de riego resulta la estrategia con mejor desempeño. Sin embargo, la reducción deberá ser gradual y coordinada. En este estudio se propuso una reducción máxima del 10% bajo el esquema actual de cultivos, pero no fue suficiente para contrarrestar los impactos de los estresores (reducciones y aumento de ETc) para el distrito de riego. Se recomienda analizar la posibilidad de aumentar este porcentaje y proponer esquemas de descanso de tierras. Otra de las estrategias planteadas fue la disminución de forrajes, específicamente de un 2.5 a 10% en la producción de alfalfa. Sin embargo la reducción de forrajes deberá considerar los posibles efectos negativos en el sector pecuario que depende de este tipo de cultivos (por ejemplo la reducción en la productividad y su implicación económica). El reemplazo gradual por cultivos menos demandantes de agua, tolerantes a la salinidad, y de mayor rendimiento económico, podría mejorar la disponibilidad de agua en el distrito.

- Oportunidades en la zona costa. No sólo se deberían realizar esfuerzos en el DR-014. Uno de los principales resultados del estudio es que existen áreas de oportunidad para los usuarios urbanos, incluidos los usuarios industriales y público-urbanos. Para el caso de Tijuana-Rosarito, aplicar acciones conjuntas como el aumento máximo del 10% en la eficiencia de la red urbana, y la rehabilitación de pozos beneficia a los usuarios urbanos y libera presión sobre los recursos del río Colorado. También es conveniente estudiar el reúso de agua en Tijuana con fines industriales y/o ambientales y no sólo contemplar la opción del reuso para el Valle de Guadalupe. Por otra parte, Ensenada puede favorecerse del aprovechamiento total de infraestructura ya existente (desaladora y acueducto Flujo Inverso) así como de la extensión del reúso en sus valles agrícolas y el intercambio de derechos de agua con el sector agrícola.

- Calidad del agua. Será necesario el monitoreo constante de la calidad de agua en el agua superficial y subterránea de los recursos del río Colorado en ambos lados de la frontera. Los niveles de salinidad se esperan aumentarán en los próximos años como consecuencia de menores niveles de agua en los reservorios por patrones de precipitación, evaporación, irrigación, entre otros factores. Además, por su relación directa, la salinidad en el suelo del DR-014 aumentará. A pesar de la disminución gradual en la concentración de SDT en la presa Imperial (US), en la presa Morelos (México) no se ha reflejado una disminución, evidenciado por la excedencia del límite superior el 40% de los meses (2010-2020).

- Incentivos. Finalmente, para alcanzar las metas anteriormente planteadas, un instrumento es el uso de incentivos específicos para los diferentes usuarios. Por ejemplo, certificaciones de compromiso ambiental para usuarios industriales (ejemplo ISO 14001), incentivos económicos para los agricultores de los diferentes módulos de riego, así como para organismos operadores (eficiencia red urbana) podría reflejarse en un ahorro de agua en la región

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APÉNDICE

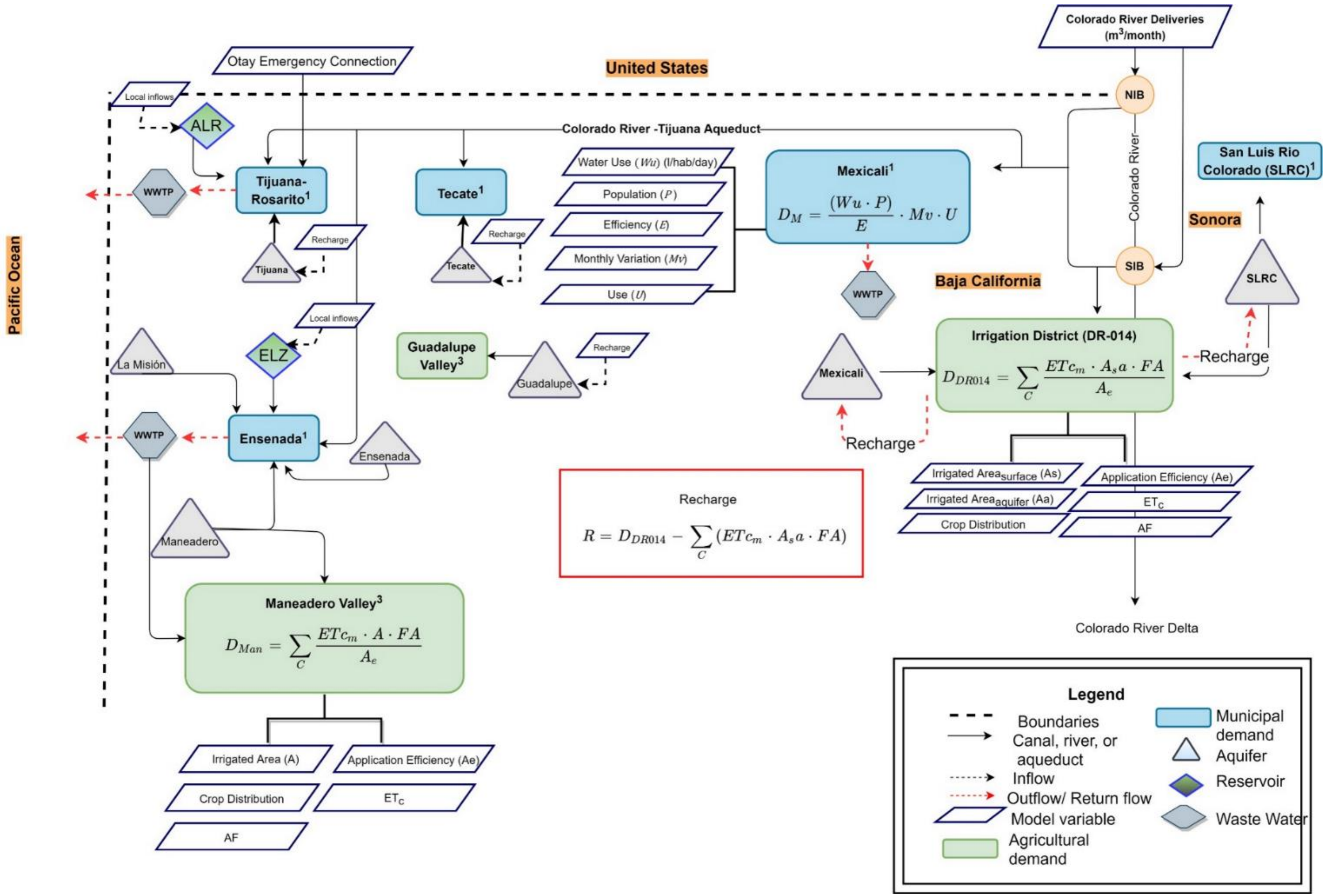
Capítulo III: Planeación de los recursos del río Colorado en México

Tabla A1. Criterios de desempeño para los escenarios individuales

	Escenario	Criterio de desempeño (%)					Índice Sustentabilidad (%)
		Confiabilidad		Resiliencia	Vulnerabilidad	Déficit Máximo	
		V	T				
	Sobreexplotación						
SS1	Base	95	39	6	11	31	**68**
	Reducción de asignación	83	18	6	23	47	**48**
	Aumento en la evapotranspiración de cultivo (ET_C)	92	27	6	13	33	**55**
	Uso Ambiental (Delta)	97	39	6	12	33	**60**
	Reducción en el área total de irrigación	100	94	94	1	1	**94**
	Reducción en la superficie de alfalfa	96	44	6	10	30	**65**
	Aumento en la eficiencia de aplicación	95	39	6	11	30	**63**
	Aumento en la eficiencia de red de distribución de agua	96	39	6	11	30	**66**
SS2	Base	87	27	4	10	29	**33**
	Aumento en la capacidad del ARCT	95	53	6	4	21	**47**
	Rehabilitación de pozos acuífero Tijuana	94	50	7	5	22	**46**
	Aumento en la eficiencia de red de distribución de agua	93	47	12	6	22	**75**
SS3	Base	85	41	15	12	31	**49**
	Asignación completa Mesa Arenosa	92	74	42	6	18	**72**
	Aprovechamiento total desaladora	92	73	41	6	12	**72**
	Aumento en la eficiencia de red de distribución de agua	91	41	15	6	13	**65**
	Expansión de reuso en Valle de Maneadero	87	73	41	10	18	**52**
	Reuso de agua residual en Valle de Guadalupe	87	55	38	10	27	**61**
	No-sobreexplotación						
SS1	Base	85	1	1	13	36	**24**
	Reducción de asignación	73	1	1	25	51	**15**
	Aumento en la evapotranspiración de cultivo (ET_C)	82	1	1	16	38	**17**
	Uso Ambiental (Delta)	92	7	1	10	28	**24**
	Reducción en el área total de irrigación	91	31	1	9	33	**62**
	Reducción en la superficie de alfalfa	86	1	1	12	36	**18**
	Aumento en la eficiencia de aplicación	83	1	1	14	39	**17**
	Aumento en la eficiencia de red de distribución de agua	86	1	1	11	33	**18**
SS2	Base	87	27	4	10	29	**33**
	Aumento en la capacidad del ARCT	95	53	6	4	21	**47**
	Rehabilitación de pozos acuífero Tijuana	94	50	7	5	22	**46**
	Aumento en la eficiencia de red de distribución de agua	93	47	12	6	22	**75**
SS3	Base	83	15	12	15	32	**30**
	Asignación completa Mesa Arenosa	84	51	21	13	24	**57**

Aprovechamiento total desaladora	84	48	18	17	27	**54**
Aumento en la eficiencia de red de distribución de agua	89	42	11	15	20	**42**
Expansión de reuso en Valle de Maneadero	84	25	11	12	30	**42**
Reuso de agua residual en Valle de Guadalupe	84	25	11	16	20	**42**

Fig. S1. Esquema del modelo de asignación de Baja California



Capítulo IV: Aumento de la salinidad en los recursos del río Colorado en México

Tabla A1. Sólidos disueltos totales (SDT) en el acuífero Valle de Mexicali (1961-2020)

		SDT (mg L^{-1})				
	# Pozos	Media	Min	Max	Subregión	Referencia
1961	451	1100	-	-	VM	CEA (2003)
1972	-	1350	700	2000	VM	Secretaría de Recursos Hidráulicos (1972)
1981	-	1217	218	2609	Noreste	CONAGUA/UABC (1981), citado en Feddema (2018)
1988	-	1685	-	-	VM	DR-014 (1988), citado en CEABC (2018)
1992	451	1700	-	-	VM	CEA (2003)
1996	-	1615	177	6232	Noreste	CONAGUA/UABC (1992), citado en Feddema (2018)
1997	22	1494	536	3484	Cerro Prieto	Portugal et al. (2005)
1999-2002	-	1307	-	-	VM	CNA (2002), citado en Ramírez-Hernández (2006)
2008	-	1426	609	3010	Noreste	CONAGUA/UABC (2008), citado en Feddema (2018)
2009	-	1800	-	-	VM	Saillé et al. (2009)
2012	10	1102	660	1730	Corridor Ripario	Orozco et al. (2015)
2012	7	-	220	1070	VM	CONAGUA (2020b)
2013	3	1246	719	1578	VM	CONAGUA (2022)
2014	3	1223	522	1720	VM	CONAGUA (2022)
2015	3	1443	644	2242	VM	CONAGUA (2022)
2016	3	1289	564	1798	VM	CONAGUA (2022)
2017	3	1218	578	1730	VM	CONAGUA (2022)
2017	6	1522	985	2197	Corridor Ripario	Gómez-Puentes et al. (2019)
2017	17	1226	576	2008	VM	Ingeniería y Gestión Hídrica (2017), citado en CEABC (2017)
2018	3	1338	526	1808	VM	CONAGUA (2022)
2018	32	961	410	2023	Noreste	Feddema (2018)
2020	3	1676	654	2978	VM	CONAGUA (2022)

Tabla S1. Regresiones lineares mensuales

Mes	Año	SDT (mg L^{-1})	Volumen (Mm^3)	Ecuación linear	R^2
Enero	2010	886	214.62	y = -0.3888x + 546.7	0.75
	2011	962	173.42		
	2012	939	161.45		
	2013	980	159.92		
	2014	932	179.68		
	2015	946	190.22		
	2016	1030	155.19		
	2017	994	153.96		
	2018	1029	149.80		
	2019	886	214.62		
Febrero	2010	964	173.02	y = -0.4348x + 583.81	0.70
	2011	855	213.17		
	2012	875	194.79		
	2013	882	198.67		
	2014	866	212.14		
	2015	873	221.92		
	2016	887	197.06		
	2017	897	178.92		
	2018	927	175.30		
	2019	964	173.02		
Marzo	2010	809	286.66	y = -0.2422x + 457.48	0.16
	2011	866	245.42		
	2012	841	233.51		
	2013	771	260.40		
	2014	838	269.14		
	2015	866	272.03		
	2016	845	249.88		
	2017	871	239.76		
	2018	851	230.26		
	2019	809	286.66		
Abril	2010	813	257.61	y = -0.0575x + 284.28	0.01
	2011	795	250.65		
	2012	807	225.23		
	2013	785	244.05		
	2014	836	258.21		
	2015	855	251.43		
	2016	797	223.02		
	2017	819	215.68		
	2018	853	209.49		
	2019	813	257.61		
Mayo	2010	886	214.62	y = -0.3888x + 546.7	0.75
	2011	962	173.42		
	2012	939	161.45		
	2013	980	159.92		
	2014	932	179.68		
	2015	946	190.22		
	2016	1030	155.19		
	2017	994	153.96		
	2018	1029	149.80		
	2019	886	214.62		

Mes	Año	SDT (mg L^{-1})	Volumen (Mm^3)	Ecuación linear	R^2
Junio	2010	964	173.02	y = -0.4348x + 583.81	0.70
	2011	855	213.17		
	2012	875	194.79		
	2013	882	198.67		
	2014	866	212.14		
	2015	873	221.92		
	2016	887	197.06		
	2017	897	178.92		
	2018	927	175.30		
	2019	964	173.02		
Julio	2010	809	286.66	y = -0.2422x + 457.48	0.16
	2011	866	245.42		
	2012	841	233.51		
	2013	771	260.40		
	2014	838	269.14		
	2015	866	272.03		
	2016	845	249.88		
	2017	871	239.76		
	2018	851	230.26		
	2019	809	286.66		
Agosto	2010	813	257.61	y = -0.0575x + 284.28	0.01
	2011	795	250.65		
	2012	807	225.23		
	2013	785	244.05		
	2014	836	258.21		
	2015	855	251.43		
	2016	797	223.02		
	2017	819	215.68		
	2018	853	209.49		
	2019	813	257.61		
Septiembre	2010	911	115.69	y = -0.0646x + 177.53	0.49
	2011	933	110.59		
	2012	1010	109.79		
	2013	1070	114.11		
	2014	1050	110.08		
	2015	949	112.62		
	2016	894	127.05		
	2017	935	115.30		
	2018	854	126.78		
	2019	911	115.69		
Octubre	2010	847	135.48	y = -0.1533x + 241.77	0.55
	2011	981	75.09		
	2012	978	84.17		
	2013	1130	80.35		
	2014	1150	72.14		
	2015	1010	73.92		
	2016	1094	80.10		
	2017	1021	83.08		
	2018	980	82.21		
	2019	847	135.48		
Noviembre	2010	878	140.52	y = -0.1912x + 302.63	0.42
	2011	942	113.00		
	2012	929	106.39		
	2013	1030	109.12		
	2014	1010	114.28		
	2015	981	118.94		
	2016	907	121.96		
	2017	938	119.25		
	2018	900	152.40		

	2019	878	140.52		
Diciembre	2010	128.91	928	y = -2.6376x + 1335	0.42
	2011	162.08	905		
	2012	120.70	1130		
	2013	128.71	1010		
	2014	138.03	965		
	2015	133.88	996		
	2016	128.28	964		
	2017	99.83	1038		
	2018	128.91	928		
	2019	162.08	905		