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Watershed Hydrology

Hydrology and Water Resources in the Salton Sea Watershed

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HIGHLIGHTS

- **The Salton Sea watershed in southern California and northern Mexico is one of the most productive agricultural regions in the United States.**
- **Salton Sea's water balance is controlled by complex interactions among agricultural water management practices, evaporation, and surface water-groundwater interactions.**
- **Survival of the Salton Sea is tied primarily to agricultural runoff and drainage from major agricultural regions in the basin— Imperial and Mexicali Valleys to the south and Coachella Valley to the north—and their associated water management decisions.**
- **No comprehensive assessment of lake-groundwater exchange has ever been performed. Consequently, efforts to make informed management decisions with an understanding of the consequences for lake water levels are severly limited.**

The Salton Sea watershed is a closed (endorheic) basin with an area of 8417.4 mi^2 (21,801 km^2), located in Southern California and the northern part of Mexicali Valley in Mexico (Figure 2.1). The watershed is one of the most productive agricultural regions in the United States and includes the Salton Sea, the largest inland terminal lake in California, with an area of 334 mi^2 (865 km^2) (Yao et al., 2019). The watershed is bounded by the Orocopia Mountain range in the northeast, the Santa Rosa Mountain range in the northwest, and the Chocolate Mountain range and the peninsular mountain ranges of southern and Baja California to the east and southwest, respectively (Tompson, 2016).

Nearly half of endorheic basins around the world, including the Salton Sea, are in water-stressed regions (Wada et al., 2011) where the lake storage is maintained

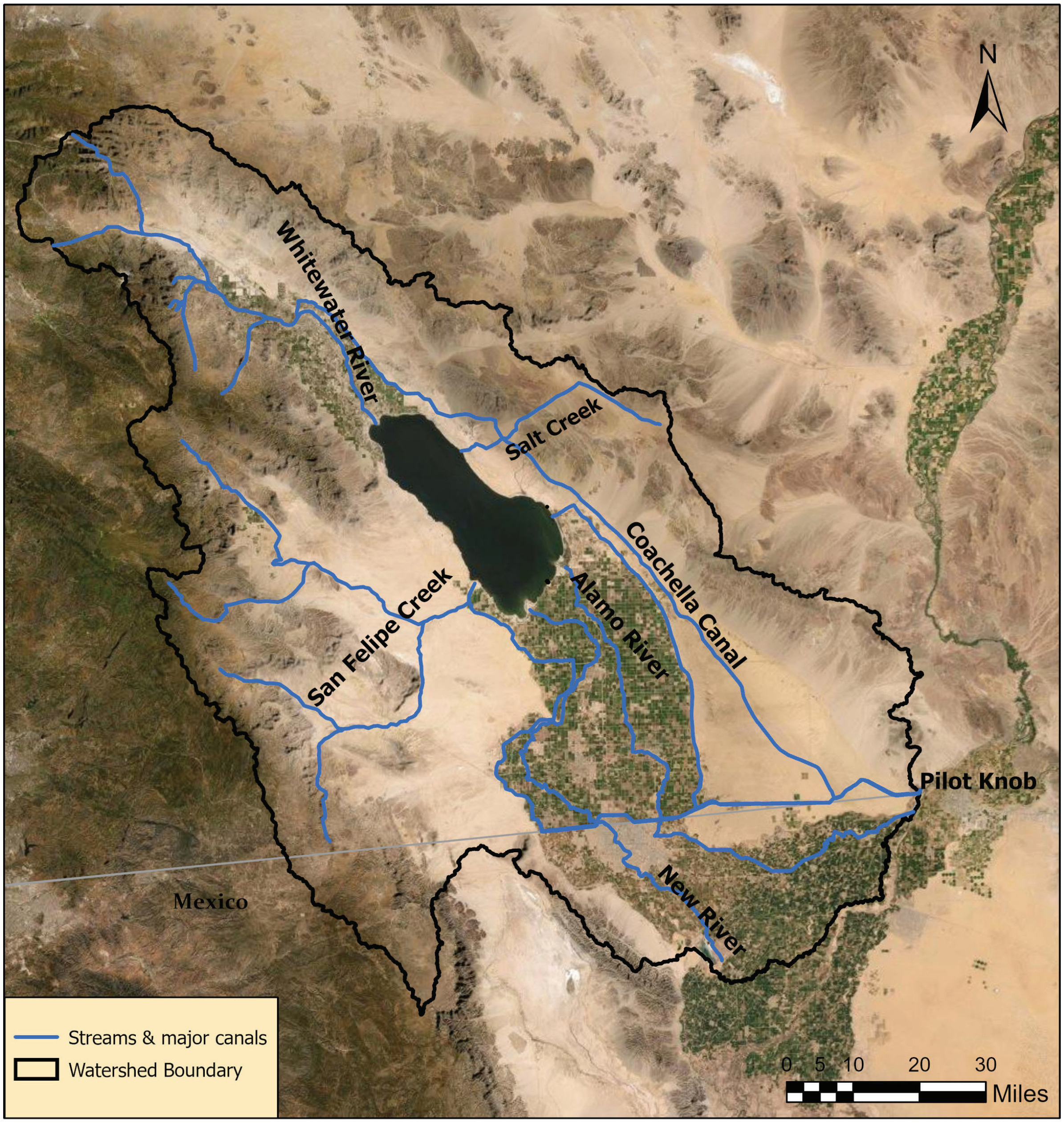

FIGURE 2.1 Location of the Salton Sea watershed and major streams and drainages. Credit: Hoori Ajami. Sources: USGS, ESRI.

by the balance between inflows (i.e., precipitation, surface runoff and groundwater inflow) and outflows (i.e., evaporation and discharge to groundwater). Recent analysis of remote sensing data and hydrologic modeling indicate a widespread water loss in endorheic basins globally during 2002–2016. The lakes' storage losses are attributed to losses in groundwater, surface water, and soil moisture caused by climate variability and water management (Wang et al., 2018). The climate of the Salton Sea watershed is hot and arid with mean annual precipitation of less than 6 inches per year (147.9 mm/yr), and high summer temperatures that can reach up to 115°F (49°C). Annual precipitation in the watershed during 1980–2018 indicates cycles of wet and dry periods relative to the long-term mean annual precipitation, which in recent decade since 2010 has been lower than the 39-year average (Figure 2.2).

Much of the concern about the Salton Sea in the 20th century was related to rising shorelines, but the lake trajectory is different today. During the period 1980–2018, average Colorado River inflows to the Salton Sea watershed at Pilot Knob Hydroelectric Plant were

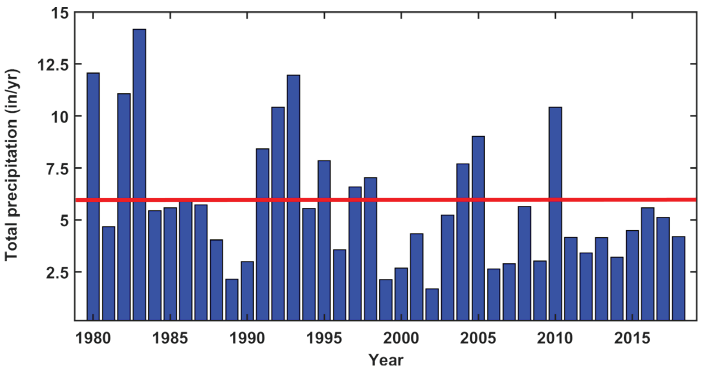

FIGURE 2.2 Annual precipitation in the Salton Sea watershed from a 4-kilometer resolution PRISM dataset. Annual precipitation in the most recent decade since 2010 has been lower than the 39-year average (red line). Credit: Hoori Ajami. Source: The Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group at Oregon State University.

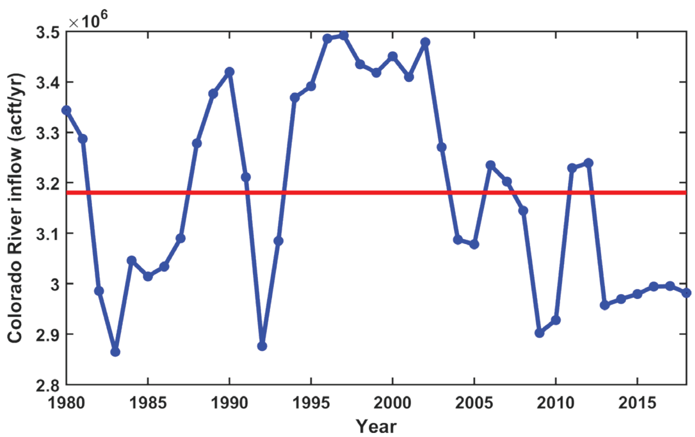

FIGURE 2.3 Annual Colorado River inflows at Pilot Knob (USGS 09527500). The red line shows a 39-year mean annual inflow. Credit: Hoori Ajami. Source: USGS.

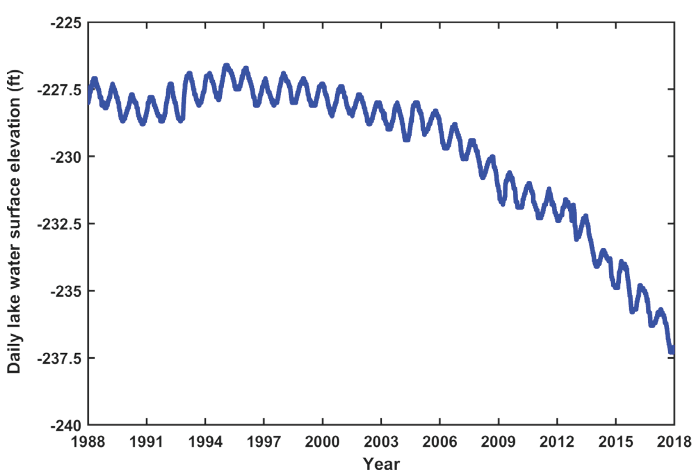

FIGURE 2.4 Daily lake water level observations at the Salton Sea near Westmorland (USGS 10254005) indicate a total lake water level decline of 8.7 ft (2.65 m) since 1988. Credit: Hoori Ajami. Sources: USGS; National Geodetic Vertical Datum of 1929.

3.2 x 10^6 ac-ft/yr (3.95 km^3/yr) (Figure 2.3); however, these deliveries have declined in recent years (Box 2A). Like other endorheic basins, Salton Sea has experienced a significant decline in lake water levels. Lake level observations near Westmorland indicate a total decline of 8.7 ft (2.65 m) since 1988 (Figure 2.4). Similarly, analysis of satellite imagery over the same period shows a decrease in lake area from 369.1 mi^2 to 339.5 mi^2 (Yao et al., 2019). Significant declines in lake water level and area between 1995 and 2018 coincide with declining trends in annual inflows to the Salton Sea, suggesting that lake-level declines may accelerate with future increases in air temperature and higher evaporation rates. Any further lake-level declines should be a top human health and environmental concern, as they will likely amplify crises already unfolding with lake water quality (Chapter 3), regional air quality due to lakebed exposure (Chapter 4), and ecological collapse of the unstable lake ecoystem (Chapter 5).

Surface Water

SURVIVAL OF THE SALTON SEA is tied primarily to irrigation runoff and drainage from major agricultural regions in the basin: Coachella Valley to the north and Imperial and Mexicali Valleys to the south. Agricultural lands cover 15% of the watershed area (1158 mi^2) based on the 2001 National Land Cover dataset. The abundant agricultural productivity in this arid watershed is dependent on the conveyed Colorado River inflows via the All American Canal to the US portion of the watershed. Morelos Dam, located on the Mexico-Arizona border, diverts Colorado River water to the Mexican portion of the Salton Sea Watershed with a mean annual flow of 1.86 x 10^6 ac-ft/yr (2.3 km^3/yr) (1980–2005). An extensive system of irrigation canals on the northern part of the All American Canal distributes water across the agricultural fields in the Imperial Valley and Coachella Valley irrigation districts. On average, 10 percent of the Colorado River inflow is transferred via the Coachella canal to the agricultural fields of the Coachella Valley, and the rest is transferred to the Imperial Valley.

Although most of the Colorado River inflows are used for irrigation, a small proportion is allocated for industrial and residential users. Irrigation water not used by crop evapotranspiration drains to the Salton Sea via the New and Alamo rivers in the south and

Salton Sea Origins and History

BOX 2A

1900s — The origin of the Salton Sea today is a result of uncontrolled Colorado River floods that occurred in 1905–07. During this period, continuous Colorado River inflows caused the lake water level to rise and reach a depth of 195 ft below sea level (-195 ft) (Figure 2.5). Starting in February 1907 with the closure of the break on the Colorado River's levee, lake water levels started to decline because evaporation exceeded inflows.

1920s — Irrigation development in the Imperial and Mexicali Valleys in the 1920s resulted in agricultural return inflows to become equal to the lake evaporation rates, subsequently stabilizing the lake water level to -250 ft until 1925 (Blaney, 1955). Due to safety concerns, the Federal Government issued an Executive order in 1928 to limit entry of public lands to regions below -220 ft elevation and designate any area below -220 ft as the Public Water Reserve.

1930s — After water shortages in 1931 and 1934 caused a temporary decline in the lake water level, Salton Sea's surface elevation began to increase once more, raising concerns regarding encroachment and damage to the neighboring lands.

1950s — In 1950, when the lake level was -238 ft, projections indicated lake level would rise and stabilize at -220 ft by 1980, and monitoring efforts were focused on accurate estimation of lake evaporation rate. By 1954, further expansion of irrigated agriculture and several severe storm events had caused lake water levels to reach -235.8 ft (Figure 2.5).

1980s–2010s — During the 1980–2018 period, the mean annual Colorado River inflows to the Salton Sea watershed at Pilot Knob Hydroelectric Plant were 3.2 x 10^6 ac-ft/yr (3.95 km^3/yr); however, these deliveries have declined in recent years. In 2003, the Imperial Irrigation District began transferring water from agricultural users in the Imperial Valley to municipal users in coastal southern California. To reduce the impact of the water transfer on the Salton Sea, "mitigation water" was temporarily directed to the Salton Sea; however, delivery of mitigation water ceased on December 31, 2017 (Barnum et al., 2017).

2020s — The future of Colorado River inflows to the Sea is highly uncertain. Survival of the Salton Sea today is tied primarily to irrigation runoff and drainage from major agricultural regions in the basin and their associated water management decisions.

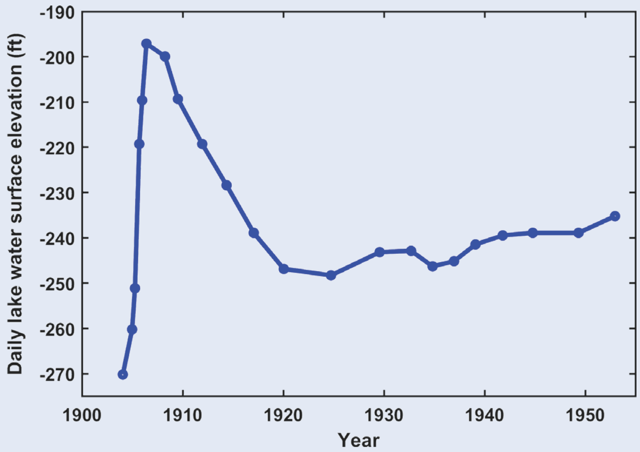

FIGURE 2.5 Historic water levels in the Salton Sea, from its formation due to uncontrolled Colorado River floods 1905–1907 through its recreational heyday in the 1950s.
Credit: Blaney, 1955.

the Whitewater River in the north as well as via many agricultural drains that discharge directly into the Sea. Continuous daily flow measurements at three US Geological Survey (USGS) gaging stations at the perimeter of the Salton Sea indicate total mean annual inflows of 1.1 x 10^6 ac-ft/yr (1.35 km^3/yr) to the Salton Sea during 1980–2018 period. About 95% of the total measured inflows to the Salton Sea originates from the Alamo and New rivers in the south with the rest from the Whitewater River in the north (Figure 2.6). The Alamo and New rivers originate from Mexico, and their flows at the international boundary are 2,100-3,620 ac-ft/yr and 108,400-145,000 ac-ft/yr, respectively (CA Water Boards, 2020). According to the Imperial Irrigation District, the agricultural drains inflows to the Salton Sea are estimated at 95,000 ac-ft/yr (CH2M Hill, 2018); however, no public dataset is available to determine the long-term variability of drain inflows. Other than direct precipitation and irrigation runoff, the only other sources of water to the Salton Sea are ephemeral flows from dry washes including Salt Creek in the east and San Felipe Creek in the west and groundwater.

Groundwater

THE EXACT CONTRIBUTION of groundwater inflow to the Salton Sea is uncertain. Estimates vary between 15,000-50,000 ac-ft/yr (Case III et al., 2013; Hely et al., 1966). Hely et al. (1966) estimates of groundwater inflows to the lake are: 30,000 ac-ft/yr from the Coachella Valley, 10,000 ac-ft/yr from the San Felipe Creek and less than 2,000 ac-ft/yr from the Imperial Valley. It is also possible that subsurface lake discharges into groundwater aquifers—representing an important loss of lake water that is not considered explicitly in the models informing current management plans.

Groundwater in the Salton Sea watershed consists of shallow and deeper aquifer systems that extend to 2,000 ft and 20,000 ft in depth, respectively (Tompson et al., 2008). There are seven groundwater basins around the lake: Coachella Valley, Chocolate Valley, Clark-Ocotillo Valley, East Salton Sea Basin, West Salton Sea Basin, Orocopia Valley, and Imperial Valley (Case III et al., 2013). In the Imperial Valley, shallow groundwater aquifers in the perimeter of the valley are recharged by the mountain runoff and are more productive than the aquifers in the central region with low permeability sediments. The quality of groundwater is highly variable, and in certain aquifers salinity is high, resulting in poor water quality for irrigation.

Groundwater has been a major water source for agricultural, municipal and domestic users in the Coachella Valley since the 1920s. While importation of the Colorado River water to the Coachella Valley in 1949 reduced groundwater level declines until the 1970s, increased demand for water and subsequent groundwater pumping caused groundwater level declines of up to 98.4 ft (30 m) in some locations (Sneed et al., 2014). Interferometric Synthetic Aperture Radar (InSAR) measurements during 1995–2010 indicate a land subsidence rate of up to 0.15 ft/yr (45 mm/yr) (Sneed et al., 2014). Given any further land subsidence can significantly impact infrastructure in the region, the Coachella Valley Water District has been developing managed aquifer recharge projects to reduce groundwater level declines. Currently, the Coachella Valley groundwater basin is classified as one of the state's medium priority basins according to the recent groundwater basin classification under the Sustainable Groundwater Management Act by the California Department of Water Resources. A projected 82% increase in population by 2030 is expected to further impact groundwater resources of the Coachella Valley (DWR, 2020).

The natural groundwater recharge rate in this arid watershed is very low except at the mountain front re-

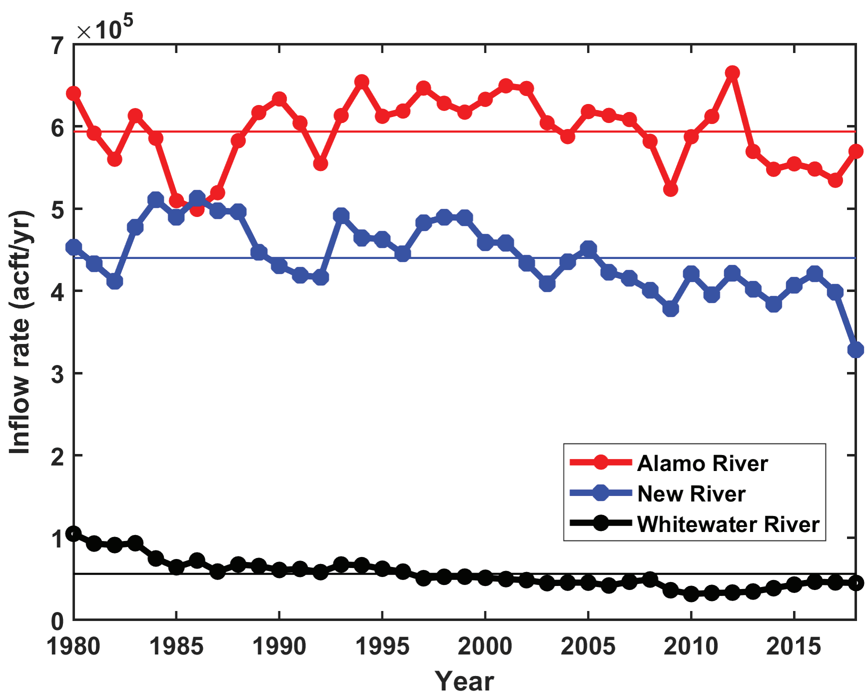

FIGURE 2.6 Annual river inflows to the Salton Sea as measured by the USGS gauges at the mouth of Alamo River (USGS 10254730), New River (USGS 10255550) and Whitewater River (USGS 10259540). Solid lines indicate 39-year mean annual inflows. Significant declines in lake water level and area between 1995 and 2018 coincide with significant declining trends in annual inflows to the Salton Sea, suggesting further declines in lake level with future increases in air temperature and higher evaporation rates. Credit: Hoori Ajami. Source: USGS.

Climate Change Impacts

BOX 2B

PROJECTED INCREASES in global average temperature and the resulting reduction in snowpack in the Rocky Mountains are expected to decrease Colorado River inflows in the future. Depending on the global climate model (GCM) projections and emission scenarios, Colorado River flows will decline by 35–55 percent at the end of century (Udall and Overpeck, 2017), making less water available to downstream users, including Californians. Although Colorado River water allocations are based on a complex set of agreements, some users may need to reduce water use if the Colorado River shortages continue.

The Colorado River Drought Contingency Plan is one of the most recent provisions introduced to address water shortages among the seven Western states, including California, with rights to Colorado River water. Projected mean annual precipitation for the Inland desert region of California that encompasses the Salton Sea indicates a drier mid-century (2035–2064) and a wetter late-century (2070–2090) relative to the historic period (1951–1980) (RCP 8.5) based on the 10 GCMs representative of California's climate (Hopkins et al., 2018). Although uncertainty of precipitation projections from GCMs is large, future climate change impact assessments should use results from multiple climate models and implement coupled surface water–groundwater models to simulate dynamic feedback processes between changes in land cover, land use, groundwater recharge, and surface runoff in response to changes in precipitation, temperature and human water use.

gions near the Coachella Valley and West Mesa, both of which are recharged by the mountain runoff. Other sources of recharge in the watershed emanate from irrigation recharge in agricultural areas (314,000 ac-ft/yr from the Coachella Valley and up to 250,000 ac-ft/yr from the Imperial Valley) and localized recharge from the All American Canal, Coachella Canal and other canals and reaches in the watershed (Tompson et al., 2008). Although leakage from the All American Canal and Coachella Canal was high in early years, subsequent lining of these canals in 2007 and 1980, respectively, reduced recharge to the watershed (Coes et al., 2015). No accurate long-term estimate of groundwater recharge is available, and future investigations should focus on estimating groundwater recharge from mountain runoff and irrigation. It is highly recommended to develop coupled surface water–groundwater models to better understand hydrologic processes and to design conjunctive surface water–groundwater management strategies to reduce the impacts of water transfers and agriculture on the Salton Sea.

Uncertain Future

FUTURE SALTON SEA LAKE LEVELS are highly uncertain. Colorado River deliveries are projected to decline, and there are serious drawbacks to the models currently in use to predict future lake water levels. The Imperial Irrigation District (IID) SALSA2 model, which is the basis for the Salton Sea Management Program's projected estimates for Salton Sea hydrology and salinity conditions, predicts that the Salton Sea inflow rates will stabilize around 700,000 ac-ft/yr by 2045 and will result in a lake water level of -260 ft (CH2M Hill, 2018). However, it is expected that the Colorado River flows will decline in the future due to population growth and reduced snowpack and prolonged droughts from climate change (Udall and Overpeck, 2017) (Box 2B). These shortages could result in potential water cutbacks to lower basins states as outlined in the Colorado River Drought Contingency Plan. Furthermore, competing demand among urban and agricultural users and natural ecosystems for water make future projections of lake water level highly uncertain.

The drawback of using statistically based models such as SALSA2 for these predictions is that they are trained based on historic data and do not consider non-stationary, hydrologic response due to changes in climate or land cover. Furthermore, detailed information about the SALSA2 model equations and parameters are not publicly available (CH2M Hill, 2018) and cannot be verified independently.

Alternative modeling approaches such as the Salton Sea Stochastic Simulation model consider a semi-distributed modeling approach to understand system

THE NEW RIVER, with abundant growth on its levees, near its terminus in the Salton Sea. Jonathan Nye

dynamics using empirical parameterization (Kjelland and Swannack, 2018). Although these types of models provide an overall understanding of the system behavior, they are not physically based and cannot be used as predictive tools for a wide range of scenarios (Kjelland et al., 2019). Furthermore, their parameterization does not allow assessing the impacts of changes in spatial distribution of crop types or canals.

In summary, it is extremely difficult to project future lake water levels and the area of exposed playa given models currently in use combined with the hydrologic and socio-economic complexities surrounding the Salton Sea. Lake-groundwater interactions are complex, and observational data are not available to quantify the exchange fluxes between groundwater aquifers and the lake. Furthermore, future streamflow and changes in water management practices and cropping patterns are uncertain. Any predictions about future lake levels require improving hydrologic models and climate change projections for the region and engaging stakeholders for scenario development.

Research Needs

THE LIVELIHOOD OF THIS ARID WATERSHED is impacted by projected declines in the Colorado River flows, competing demands among urban and agricultural users and natural ecosystems for water, and increases in the exposed dry lakebed impacting human health. The key science need is to define the optimum lake water level to reduce lakebed dust and maintain wildlife habitat while recognizing the intersection between the Salton Sea and agricultural water use in the watershed.

Previous research efforts were focused on accurately estimating lake evaporation to determine the balance between inflows and outflows (Hely et al., 1966). Answering this question today requires understanding of the subsurface hydrologic processes and lake-groundwater interactions through implementation of several key tasks (Box 2C):

- Determine lake-groundwater connectivity by drilling monitoring wells perpendicular to the lake perimeter at several key locations.
- Characterize hydraulic parameters of the aquifers located inside the watershed.
- Quantify subsurface drainage rates to the lake from neighboring agricultural lands.
- Develop a distributed coupled surface water-groundwater model to understand and quantify lake water level dynamics in response to changes in Colorado River inflows, climate change

CURRENT RESEARCH: Lake-Groundwater Interactions

BOX 2C

UNDERSTANDING WATER FLOW both above ground and in the subsurface is crucial to determining optimal Salton Sea water levels and designing effective mitigation strategies. With an award from the National Science Foundation's Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) program, researchers at UC Riverside are setting up a coupled surface water–groundwater model for the Salton Sea watershed using the SWAT-MODFLOW package (Ajami et al., 2020). New estimates for water exchange between the lake and adjacent groundwater aquifers should be available soon and may help explain unexpected water level declines in recent years.

One of the major challenges of this ongoing hydrologic investigation is lack of access to datasets collected by various agencies in the Salton Sea watershed (Ajami et al., 2020). Future efforts should focus on setting up a public data repository for the watershed and implementing adaptive management programs. Success of such programs requires engaging various stakeholders in design and implementation of the management scenarios while considering climate change impacts on water resources.

and agriculture management practices, and groundwater use.

- Involve stakeholders in developing alternative management scenarios to inform decision making and mitigation strategies.
- Assess feasibility of pumping saline groundwater to maintain lake level.

These tasks will be crucial in answering science questions identified a decade ago in the Hydrology and Water Quality focused technical group formed to facilitate restoration efforts at the Salton Sea (Case III et al., 2013). As hydrologic processes are likely to be very different depending on which scenario plays out in the coming decade, perhaps the main question that we need to ask today is whether recent investments for the Salton Sea restoration will solve the problems associated with dust, the ecosystem and agricultural production. By focusing on advanced monitoring and hydrologic modeling efforts to save the Sea, it may be possible to maintain agricultural production and reduce land subsidence and toxic dust exposure, as well as to provide a healthy environment for the communities living in this region.

Failure to invest resources in these research efforts will increase the likelihood of scenario 1 (continued decline) leading to a crisis: The lake water levels will continue to decline as the current trend in lake water levels indicates. The decline could possibly worsen due to changes in subsurface water flows, higher evaporation rates, or lower Colorado River inflows owing to a lower snowpack and population growth or changes in water allocations due to droughts. Alternatively, we can intentionally direct water to the Sea (e.g., water purchases, wetland impoundments, or imported water from the Gulf of California) to stabilize lake levels (scenario 2) or possibly even raise water levels (scenario 3, recovery). These goals should be informed by developing coupled/integrated surface water-groundwater models and setting-up extensive monitoring network to assess effectiveness of our management decisions and adapt our approach based on the system response to reverse the current declining trends in the Sea. The main science question for water importation is how much water needs to be diverted from other sources or users to raise and maintain lake water level at an optimum level? Furthermore, what is the optimum level for the Salton Sea to maintain human health and wildlife?

We can be optimistic that Colorado River inflows will remain at their current rates or slightly lower in future and that lake water levels will eventually stabilize (scenario 2, stabilization). Defining the "optimal" lake level will depend on the costs of achieving that outcome, which means that the costs and benefits of various mitigation strategies will need to be explored and understood, including strategies such as water diversion, wetland construction, reduced pumping, increased fallowing and water importation. Above all, understanding the spatial dimension of the problem is crucial to determining optimal lakes levels and effective mitigation responses.

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