Received: 3 July 2023 | Accepted: 12 April 2024

DOI: 10.1111/1752-1688.13206

RESEARCH ARTICLE

AMERICAN WATER RESOURCES ASSOCIATION
JAWRA Journal of the American Water Resources Association

Stream and aquifer water exchange in Mississippi Embayment under intensive pumping and extreme climate: A century-long assessment

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Abstract

The Mississippi Embayment (ME) is one of the fastest groundwater depletion zones in the world. This study investigated stream-aquifer water exchange in the ME over a 115-year period (1900 to 2014) under normal and extreme climates (i.e., precipitation increased and decreased by 20%) with and without agricultural pumping for crop irrigation. The average daily water flow from the aquifer to the streams was always greater than vice versa under all climate scenarios. Under normal climate, the average daily water flow from the aquifer to the streams was 2.52 times larger without pumping than with pumping. While the extreme climate had discernable impacts, the groundwater pumping, but not extreme climate, was the major factor for low flows and drying streams in the ME. These findings are essential to groundwater resource management in the region and provide a critical reference for other parts of the world with similar conditions.

KEYWORDS

century-long, extreme climate, Mississippi Embayment, stream-aquifer water exchange

1 | INTRODUCTION

An understanding of long-term water exchange between streams and aquifers is crucial to water resource supply planning, allocation, and management. Extensive studies have been made to assess this issue over the past several decades (Tripathi et al., 2021) using field methods such as seepage meters and tracer tests (Kalbus et al., 2006; Rosenberry & Morin, 2004) as well as computer models such as MODFLOW, HYDRUS-2D, GSFLOW, CATHY, and HGS (Delottier et al., 2022; Gatel et al., 2020; Ghysels et al., 2019; Larsen et al., 2022; Phogat et al., 2017). Among them, Rosenberry and Morin (2004) applied electromagnetic seepage meters to automatically measure water exchanges across the sediment/water interface between groundwater and surface water in New England. Kalbus et al. (2006) performed an overview of the methods for measuring interactions between groundwater and surface water and provided suggestions on how to choose appropriate field methods. Ghysels et al. (2019) developed a simple approach to simulate the river-aquifer interaction using the MODFLOW model and applied this approach to the Aa River in Belgium. Banks et al. (2011) investigated vegetation controls on variably saturated processes and effects on surface water and groundwater exchange. Phogat et al. (2017) quantified the stream and aquifer exchange in a variably saturated heterogeneous environment using the HYDRUS-2D model. In general, the use of field methods is limited to local scales, whereas the use of computer models

The author (Ying Ouyang) is the Associate Editor of this journal.

Paper No. JAWR-23-0051-P of the *Journal of the American Water Resources Association* (JAWR).

Discussions are open until six months from publication.

Research Impact Statement

We discovered that groundwater pumping, but not climate change, is a major factor in stream-aquifer water exchange in the Mississippi Embayment, which is essential to groundwater resource management.

can be extended from local to watershed or regional scales and are able to address the spatial variation of stream and aquifer exchanges and interactions.

With an increasing concern over global climate change, there has been a growing interest in potential impacts of abnormal climates on stream and aquifer water exchanges. Scibek et al. (2007) estimated groundwater and surface water exchanges under a changing climate in the unconfined Grand Forks aquifer of south-central British Columbia, Canada using the MODFLOW model. They found that future climate change shifts stream peak flow to an earlier date in a year although the overall hydrograph shape may remain the same. Saha et al. (2017) investigated temporal dynamics of groundwater and surface water interaction under a changing climate for the Kiskatinaw River watershed in British Columbia, Canada using the Gridded Surface Subsurface Hydrologic Analysis model. They showed that climate change influences significantly the temporal patterns of groundwater and surface water interaction by generating variable temporal mean contributions of groundwater to streamflow. Petpongpan et al. (2022) evaluated groundwater and surface water interactions due to changes in climate and groundwater extraction in the Yom and Nan River basins of northern Thailand using the SWAT-MODFLOW model. Their model predicted that from 2026 to 2045 with increased air temperature of 0.5–1.0°C and annual rainfall of 2%–16% would result in a decreased groundwater recharge of 7%–20% from surface water percolation, followed by a depleted groundwater flow of 11%–21% into the river, while the aquifer recharge from the river would be negligible. These and numerous other studies provide invaluable insights into water exchanges and interactions between streams and aquifers under various climate change scenarios in different parts of the world.

Groundwater depletion due to increasing water demand for agricultural, domestic, and industrial usages under a changing climate is a critical concern worldwide (Famiglietti, 2014; Gleeson et al., 2012; Ouyang et al., 2021). Many regions of the world are experiencing groundwater resource depletion (Dalin et al., 2017; Doll et al., 2014; Konikow, 2015; Ouyang et al., 2019, 2021). Lands in the Mississippi Embayment (ME), encompassing parts of Missouri, Illinois, Kentucky, Arkansas, Tennessee, Mississippi, Alabama, and Louisiana, are farmed extensively and intensively to produce row crops (Ouyang et al., 2021). To maximize crop yields, groundwater irrigation in this region has increased 92% since 1998 and resulted in a significant depletion of groundwater resources (Vories & Evett, 2014). The ME is believed to have one of the fastest groundwater resource depletion rates in the world (Aeschbach-Hertig & Gleeson, 2012). Clark and Hart (2009) developed the Mississippi Embayment Regional Aquifer Study (MERAS) model to quantify groundwater availability within the ME. These authors and others later enhanced the MERAS model to simulate groundwater availability for water resources planning in Arkansas (Clark et al., 2013). Ouyang et al. (2021) applied the MERAS model to address groundwater availability in crop and forest lands of Mississippi as affected by climate change. They reported that as compared to the base scenario, aquifer storage depletions were 1.76% more for the relatively dry scenario (i.e., corresponding to a 2% decrease in net groundwater recharge) and 1.8% less for the relatively wet scenario (i.e., corresponding to a 2% increase in net groundwater recharge). They estimated also that variations in groundwater levels in forest land would be smaller than in crop land under relatively dry and wet scenarios. A thorough literature search, however, reveals that very few efforts have been devoted to assessing long-term water exchanges between streams and aquifers in the ME as affected by intensive groundwater pumping for crop irrigation under extreme climates. Knowledge of this phenomenon is essential to water resource supply planning, allocation, and management and will provide a critical reference to other parts of the world with similar conditions. The goal of this study was to address this issue using the MERAS model.

2 | MATERIALS AND METHODS

2.1 | Description of MERAS model

MERAS is a site-specific MODFLOW model that was developed by U.S. Geological Survey (USGS) to quantify groundwater resource availability (Clark et al., 2013; Clark & Hart, 2009). The modeling domain is about 202,019 km^2 and encompasses eight states of the USA (Figure 1). The MERAS includes 43 streams with a total length of 11,105 km, about 70,000 wells, 10 primary hydrogeologic units, and 13 geological layers. Each grid cell is 2.59 km^2 (or one square mile) with varying thickness. The major boundary conditions used in the model include areal groundwater net recharge, well pumping, stream routing, and no-flow. The groundwater net recharge rate is calculated as a function of precipitation based on geology, soil type, and land use through model calibration. Groundwater pumping is simulated using the Multi-Node Well Package. No-flow boundary conditions are used for the perimeter of the modeled domain, where flow into or out of the model domain

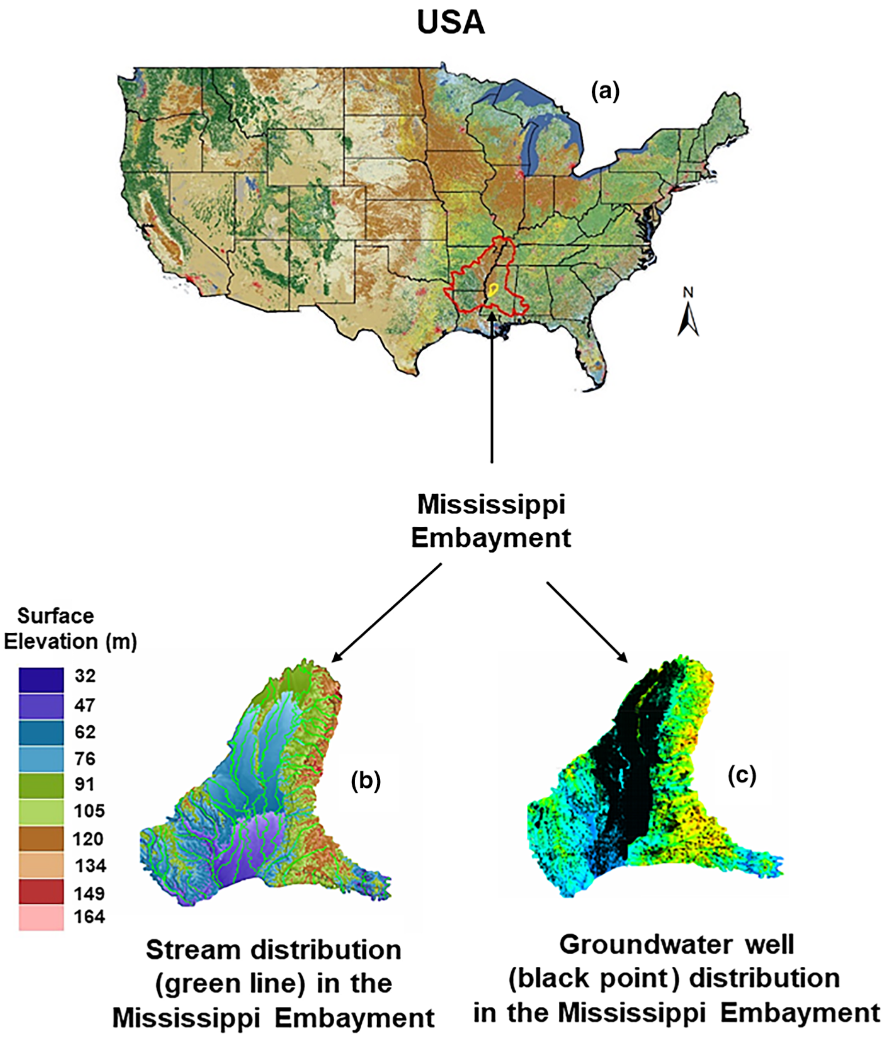

FIGURE 1 Location of Mississippi Embayment (a) along with stream (b) and groundwater well (c) distributions used in this study. Most wells are located in cropland areas.

is assumed to be trivial. Initial conditions are established using a steady-state stress period prior to January 1, 1870. The MERAS model was rigorously calibrated and validated by Clark and Hart (2009) and Clark et al. (2013).

MODFLOW is a groundwater model developed by USGS (McDonald et al., 1988) that is known and used around the world. The MERAS model was developed using a version of MODFLOW-2005. A detailed description of the MODFLOW versions is available at: https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs?qt-science_center_objects=0#qt-science_center_objects. Water exchanges and interactions between streams and aquifers in MERAS are simulated using the Stream Flow Routing Package (Prudic et al., 2004). This package includes five options for simulating stream depth and four options for diversions from a stream. The sources of water inflow (Q_{in}) to stream reaches in the package are calculated as (Prudic et al., 2004):

$$\sum Q_{in} = Q_{sri} + Q_{trb} + Q_{ro} + Q_{ppt} - Q_{Li}, \quad (1)$$

where Q_{sri} is the specified inflow at the beginning of the first reach of any segment, Q_{trb} is the sum of tributary flow from upstream segments into the first reach of a segment, Q_{ro} is the direct overland runoff to a reach, Q_{ppt} is the precipitation that falls directly on a reach, and Q_{Li} is the groundwater leakage to a reach. The term Q_{Li} is negative because groundwater flow to a stream reach is a negative value based on the MODFLOW convention.

The losses of water from stream reaches (Q_{out}) in the package are computed as:

$$\sum Q_{out} = Q_{sro} + Q_{div} + Q_{et} + Q_{Lo}, \quad (2)$$

where Q_{sro} is the streamflow out of a reach, Q_{div} is the specified diversions from the last reach in a segment, Q_{et} is the evapotranspiration from a reach, and Q_{Lo} is the leakage to the underlying aquifer. An elaborated description of the package can be found in Prudic et al. (2004).

2.2 | Development of simulation scenarios

Six simulation scenarios were developed in this study: (1) a base case (BC) scenario represents normal agricultural practices, groundwater pumping, and natural conditions existing in the ME; (2) an extremely wet scenario (EW) that is the same as the BC scenario except that precipitation rate increased by 20% and groundwater pumping rate decreased by 8%; (3) an extremely dry scenario (ED) that is the same as the BC scenario except that precipitation rate decreased by 20% and groundwater pumping rate increased by 8%; (4) a no-pumping scenario (BC-NP) that is the same as the BC except without groundwater pumping; (5) a no-pumping scenario with 20% increase in precipitation rate (EW-NP) that is the same as the EW scenario except without groundwater pumping; and (6) a no-pumping scenario with 20% decrease in precipitation rate (ED-NP) that is the same as the ED scenario except without groundwater pumping. These six scenarios were developed to assess water exchanges between the streams and aquifers in the ME as affected by extremely wet and dry climatic conditions associated with and without groundwater pumping. It should be noted that groundwater pumping rate and frequency are linked to climate extremes. Unfortunately, our thoroughly literature search and personal communications with growers revealed that no data are available in the ME on how to adjust groundwater pumping rate when precipitation increasing or decreasing by 20%. Apparently, this rate depends on many factors such as soil type, topography, crop species, and economic benefit. By a common irrigation practice, groundwater pumping rate will decrease when increasing precipitation or increase when decreasing precipitation. Ouyang et al. (2021) reported that there is an uneven monthly distribution of precipitation with 62% occurred during non-growing season from December to April and 38% occurred during crop-growing season (covered the groundwater pumping season) from May to November. In other words, while the average precipitation may increase (or decrease) by 20%, the actual precipitation during the pumping season would decrease (or increase) by about 8% (i.e., $20\% \times 38\% \approx 8\%$). This percentage is a "good" guest and was used in the EW and ED scenarios as stated above. However, further study is warranted to quantify the correlation between precipitation and pumping rate in the ME.

Clark et al. (2013) used the average daily rates of precipitation (2×10^9 m^3/day) and net groundwater recharge (1.49×10^7 m^3/day) in their MERAS model for the entire simulation period from 1869 to 2014. These rates indicate that about 1% [i.e., $(1.49 \times 10^7)/(2 \times 10^9) = 1\%$] of the precipitation water recharges into the groundwater aquifers of the ME. Recently, Ouyang et al. (2019) investigated the net groundwater recharge in the lower Yazoo River watershed within the ME using the HSPF model. They reported that about 1.2% of the precipitation water finally recharges into the groundwater of the watershed because of the thick clay layer. This finding is similar to the groundwater net recharge rate (i.e., 1% of the precipitation rate) used by Clark et al. (2013). In this study, the ±20% changes in precipitation rate represent extremely abnormal wet and dry climatic conditions in the ME. We also assume that the ±20% changes in precipitation rate produced equivalent changes in the ±20% changes in net groundwater recharge in the ME, according to the findings reported by Clark et al. (2013) and Ouyang et al. (2019).

The Multiplier File Package of MERAS was modified to account for ±20% changes in net groundwater recharge in this study. More specifically, two files were changed to account for the ±20% changes in net groundwater recharge. That is, a line "Open/Close RchRatio_d10.txt 1 (Free) -1" was added before the line "mltRhPt_1 FUNCTION" in the file "meras2.2.mlt". This addition means that the recharge ratio file "RchRatio_d10.txt" was modified based on percentage change. When the recharge rate was increased by 20%, all the values in the file "RchRatio_d10.txt" were changed to 1.2, while when the recharge rate was decreased by 20%, all the values in the file "RchRatio_d10.txt" were changed to 0.8. For no groundwater pumping scenarios, the pumping wells were turned off by adding the symbol "#" (or comment out) before the line "MNW1 22 meras_2.2wu.mnw" in the name file "meras_2.2.nam". The Multi-Node Well Package of MERAS was modified to account for reducing or increasing the pumping rate by 8%. Detailed description of the input files structures can be found in the MERAS documents (Clark et al., 2013; Clark & Hart, 2009).

Differences in daily water exchange among the six simulation scenarios were estimated using the Kolmogorov–Smirnov (K–S) test. The K–S test is based on the empirical cumulative distribution function (ECDF). Given N ordered data points $Y_1, Y_2, \ldots, Y_N$, the ECDF can be defined as (Chakravarti et al., 1967):

$$E_N = \frac{n(i)}{N}, \tag{3}$$

where E_N is the ECDF, $n(i)$ is the number of points less than Y_i and the Y_i are ordered from smallest to largest value. The K–S test statistic is given as (Chakravarti et al., 1967):

$$D = \max_{1<i<N}\left[F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i)\right], \tag{4}$$

where F is the theoretical cumulative distribution. The K–S test was performed using a web-based tool at https://www.aatbio.com/tools/kolmogorov-smirnov-k-s-test-calculator.

3 | RESULTS AND DISCUSSION

3.1 | Water exchange under normal conditions

Daily water exchanges between the streams and aquifers in the ME under normal agricultural practices and natural conditions (i.e., the BC scenario) over a 115-year simulation period (1900–2014) are presented in Figure 2a. In this study, water exchange refers to stream water flows into aquifers (positive value) and aquifer water leaks into streams (negative value). It should be noted that there were 43 streams, with a total length of 11,105 km, used in this study, and thus the stream flow to the aquifer was the sum of flow from all streams into the aquifers. Similarly, the aquifer leakage into the stream was the sum of flow from all aquifers to the streams.

In general, more water leaked from the aquifers to the streams (negative) than flowed from the streams to the aquifers (positive) over the past 115 years (Figure 2a). The average amount of daily aquifer water leaked to the streams was −3,477,767 m^3, whereas the average amount of daily stream waters that flowed to the aquifers was 2,838,890 m^3. In other words, the model predicted about 11.25% [i.e., (abs(−3,477,767) − 283,890)/283,890 = 11.25%] more water leaked from the aquifers to the streams than vice versa over the past 115 years. In specific, a relatively small amount of aquifer water contributed (negative value) to the streams from 1900 (predevelopment) to 1940. After this year, fluctuations in water exchange occurred with stream water flowing to the aquifers in some years and vice versa in the other years. The fluctuations took place more frequently after 1987 (Figure 2a). Similar results were also reported by Clark and Hart (2009).

There were more clearcuttings of forests and modifications of hydrologic channels from 1940 to 1987 as well as an intensive groundwater pumping for crop irrigation since 1987 (Clark & Hart, 2009), which resulted in groundwater recharge variations (Figure 2b). These variations could explain the water exchange pattern between the streams and the aquifers in the ME over the past 115 years. Before 1940, a stable aquifer water leaked into the streams because of a somewhat stable groundwater recharge into the aquifers (Figure 2b). The somewhat stable groundwater recharge occurred because less forest harvests and fewer hydrologic channel modifications took place before this period. Forests absorb water and slow its movement across land thus allowing increased percolation into the soil that can lead to increased aquifer storage. Meanwhile, forests take up soil water and transpire from leaves into atmosphere, which offset aquifer water storage. Hydrologic channel modifications may increase or decrease the aquifer water storage depending on the purposes of the modifications and geological locations. After 1940, the stream water flowed into the aquifers in some years and the aquifer water leaked to the streams in the other years. This mutual water exchange occurred because of heavy forest cuttings and hydrologic channel modifications.

From 1987 to 2014, the frequent water exchange occurred primarily due to the intensive groundwater pumping for crop irrigation (Figure 2c). On average, the net surface-ground water exchange was $-9.79 \times 10^5\,m^3$/day over the 27-year period from 1987 to 2014. This negative average value indicated more stream water flowed into the aquifers than vice versa, resulting in groundwater level decline due to the intensive groundwater pumping for crop irrigation.

3.2 | Water exchange with and without pumping

A comparison between the BC-NP and BC scenarios showed a huge impact of agricultural pumping on the daily stream and aquifer water exchange over the 115 years (Figure 3). From 1900 to 1987, there was a slight to moderate difference in the stream and aquifer water exchange between pumping (BC) and no pumping (BC-NP). After 1987, a dramatic divergence in response lines began to develop and reached its maximum (−7,736,120 m^3/day) at the end of the simulation in 2014 (Figure 3a). Overall, the average daily stream and aquifer water exchange was −1,520,261 m^3/day with pumping but was −6,035,664 m^3/day without pumping. This difference was significant at $\alpha = 0.01$ based on the K–S test (Table 1). There was 2.52 [(−6,035,664)/(−1,520,261) = 2.52] times less aquifer water leaked to the streams with pumping than without pumping. The difference in stream-aquifer water exchange between the BC-NP and BC scenarios was −178,547 m^3/day in 1900 but was −7,771,083 m^3/day in 2014 (Figure 3b). The latter was about 44 times more than the former. In other words, there was 44 times more aquifer water leaked into the streams without pumping than with pumping. Before 1987, fewer groundwater wells were used for crop irrigation than in later years. Since then, many more wells were installed and are used for intensive crop irrigation (Figure 2c). As a result, less aquifer water leaked into the streams in the ME due to the depletion of the groundwater. Results indicated that groundwater pumping for crop irrigation played a vital role in the stream and aquifer water exchange.

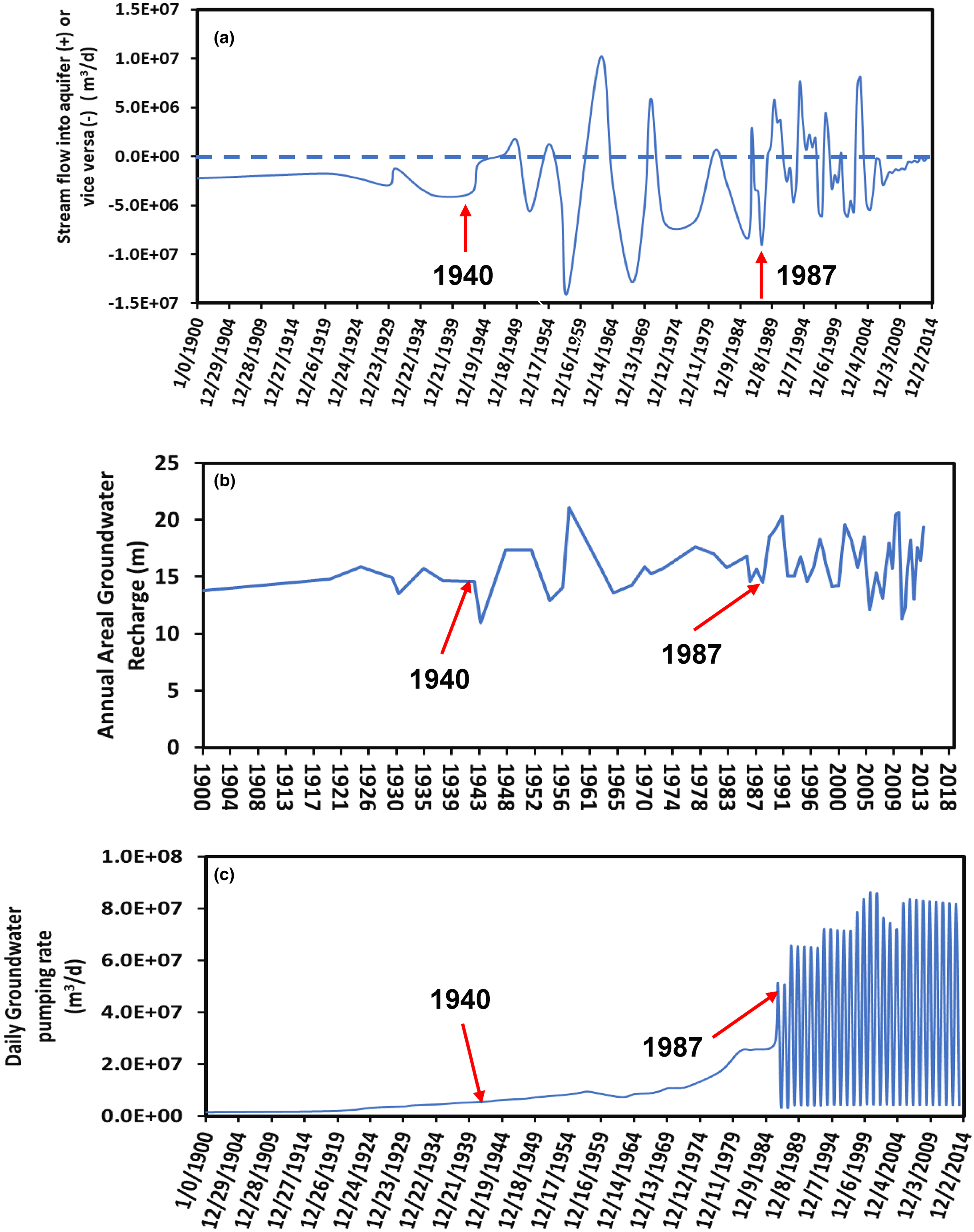

FIGURE 2 Daily water exchange between the streams and aquifers (a) and annual areal groundwater recharge (b), and daily groundwater pumping (c) over the 115-year simulation period from 1900 to 2014 for the BC scenario.

3.3 | Water exchange with pumping under extreme climate

Daily water exchanges between the streams and aquifers in the ME for normal, extremely wet, and extremely dry climates (i.e., the BC, EW, and ED scenarios) over a 115-year simulation period are given in Figure 4a. Three distinct patterns were observed among the scenarios: (1) water exchange varied with years; (2) water leakage (negative value) from the aquifers to the streams occurred more frequently than water

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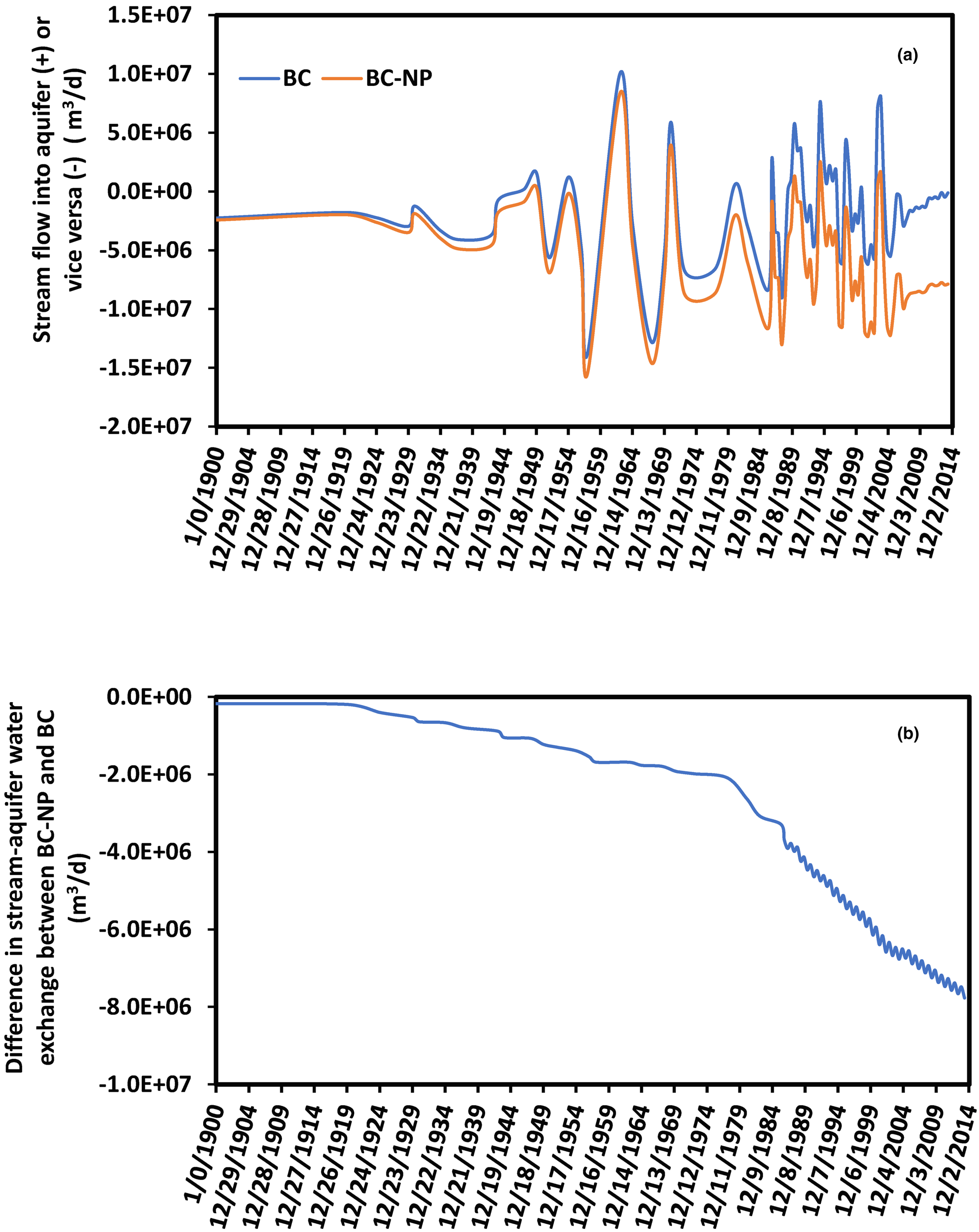

FIGURE 3 Water exchange between the streams and aquifers (a) and its difference between the BC-NP and BC scenarios (b) over the 115-year simulation period from 1900 to 2014.

flow (positive value) from the streams to the aquifers; and (3) water exchange took place more frequently after 1987. By scenario from greatest to least amount of water leakage from the aquifers to the streams (more negative) was EW > BC > ED, whereas water flow from the streams to the aquifers (more positive) was ED > BC > EW. Although these differences were difficult to visualize in Figure 4a due to the artifact of a wide range of y-axis (from 2.0E-07 to −3.0E-07 m^3/day), they were very significant ($\alpha = 0.01$) based on the K–S test (Table 1). Under the extreme wet conditions, more precipitation water recharged to the aquifers and thereby increased the aquifer water storage that leads to leaking into

TABLE 1 Differences between the BC scenario and the other five scenarios based on the Kolmogorov–Smirnov test.

Parameter	Significance level (α)	*D* statistics	Inequality symbol	Critical value (*n*-scaled)	Result
BC vs. EW+20	0.01	0.139	<	0.508	Reject H_o
BC vs. ED-20	0.01	0.130	<	0.434	Reject H_o
BC vs. BC-NP	0.01	0.413	<	0.257	Reject H_o
BC vs. EW-NP	0.01	0.314	<	0.257	Reject H_o
BC vs. ED-NP	0.01	0.345	<	0.257	Reject H_o

Note: H_o represents the hypothesis of no difference.

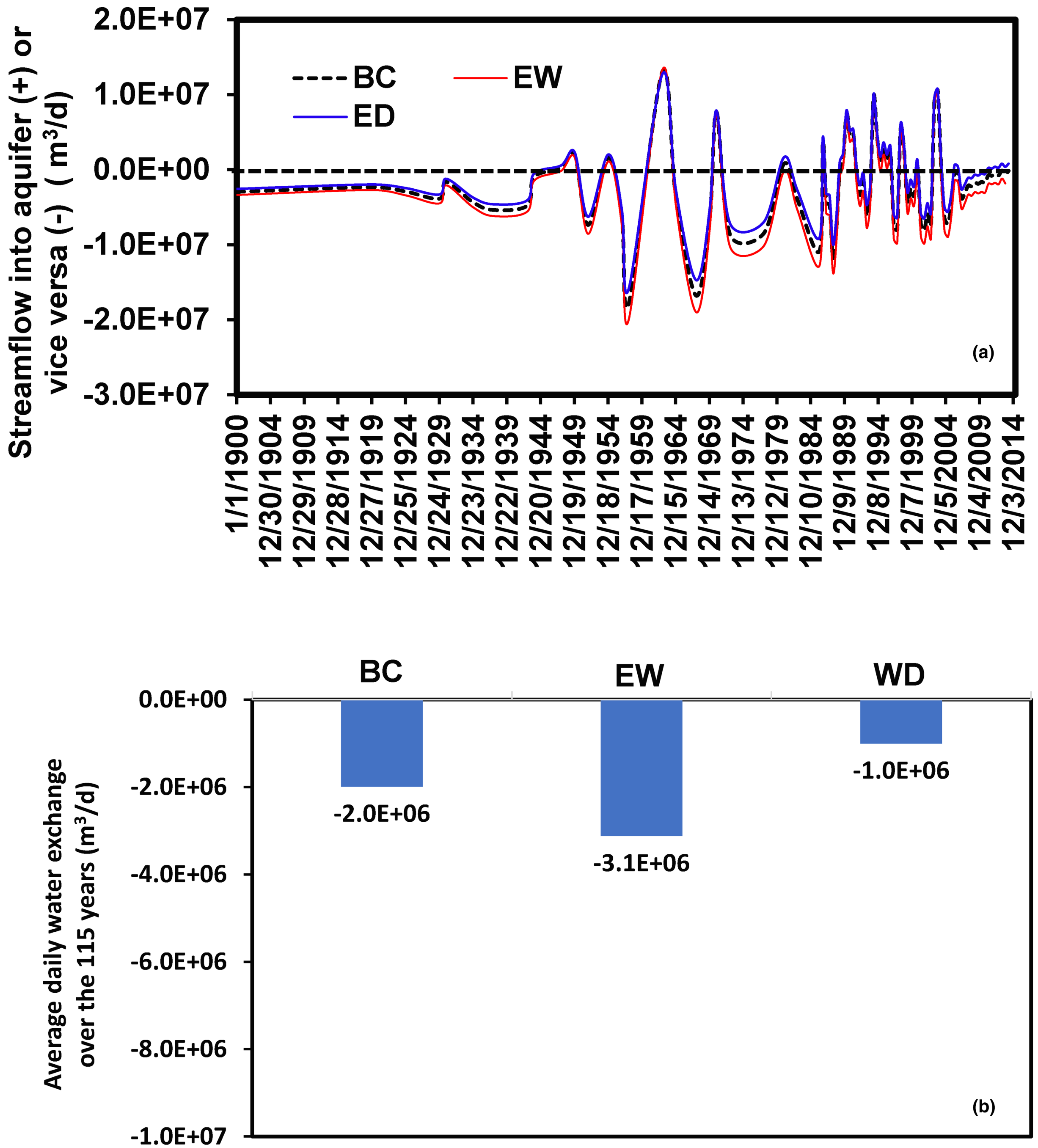

FIGURE 4 Water exchange between streams and aquifers over the 115-year simulation period from 1900 to 2014 for the BC, EW, and ED scenarios.

the streams. Under the extreme dry condition scenario, on the other hand, less precipitation water recharged into the aquifers, and when the aquifer water level was lower than the stream stage, water flowed from the streams to the aquifers. Overall, the average daily water exchanges over the past 115 years were −2.0E+06, −3.1E+06, and −1.0E+06 m^3, respectively, for the BC, EW, and ED scenarios (Figure 4b). These values were the averages of both the negative and positive values shown in Figure 4a. As compared to that of the BC scenario, there was a 36% increase in average daily water leakage from the aquifers to the streams under the extremely wet climate (EW) and a 49% decrease in average daily water leakage from the aquifers to the streams under the extremely dry climate (ED). Results suggested that more water leaked from the aquifers under the extremely wet climate than under the extremely dry climate over the past 115 years in the ME.

3.4 | Water exchange without pumping under extreme climate

Impacts of extreme precipitation due to climate change on water exchange between streams and aquifers without major human activities (e.g., no groundwater pumping) are given in Figure 5a. This diagram shows the daily water exchanges for the three non-pumping scenarios (i.e.,

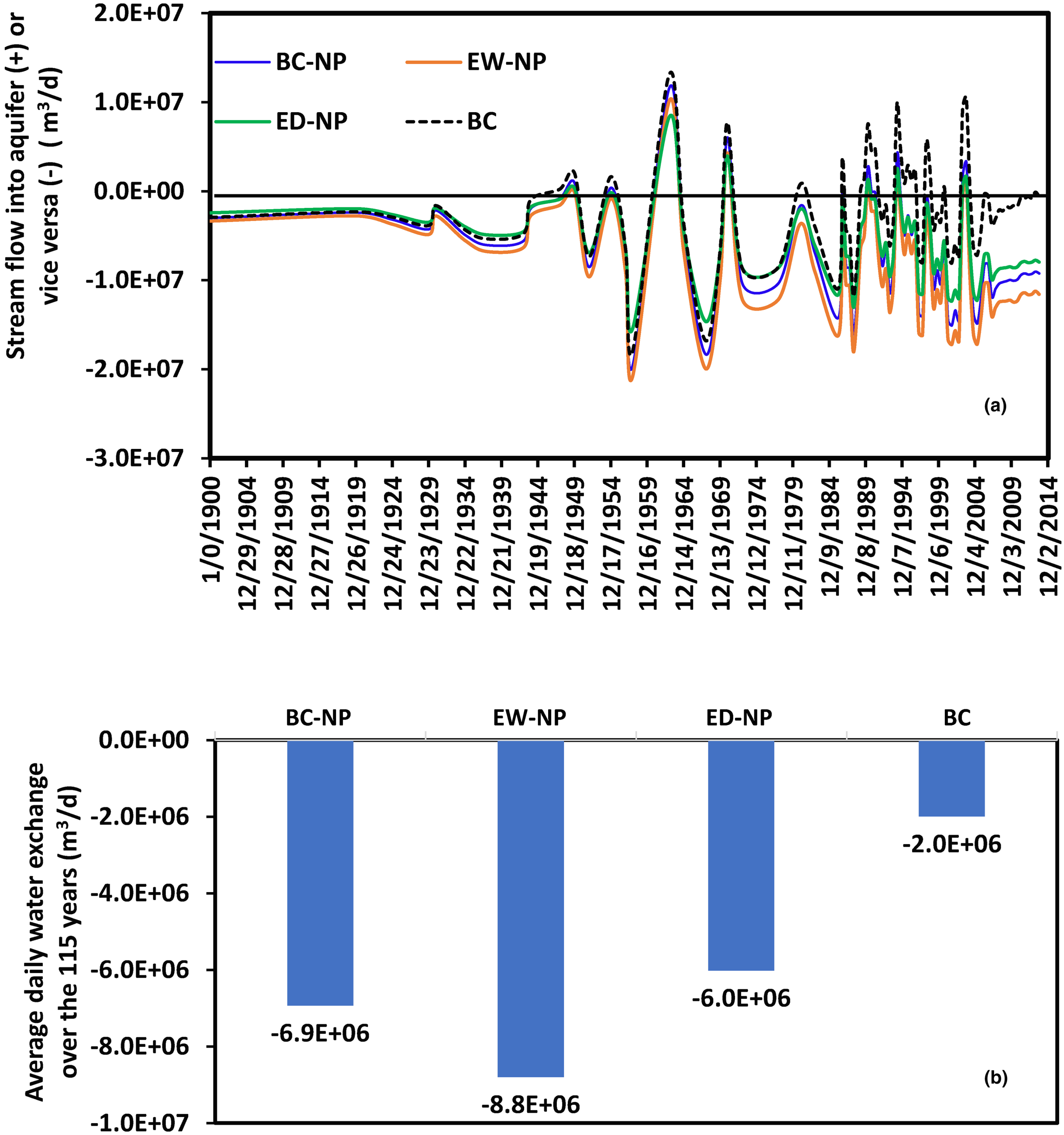

FIGURE 5 Water exchange between the streams and aquifers over the 115-year simulation period from 1900 to 2014 for the BC-NP, EW-NP, ED-NP, and BC scenarios.

BC-NP, EW-NP, and ED-NP) as compared to the BC scenario over the past 115 years. Like the pumping counterparts (i.e., BC, EW, and ED), the three non-pumping scenarios water exchange varied from time to time, water leakage (negative value) from the aquifers to the streams was much more than vice versa (positive value), and water exchange occurred more frequently after 1987. Overall, the amount of water leaked from the aquifers to streams (more negative) by scenario from greatest to least was EW-NP > BC-NP > ED-NP > BC. The differences were very significant ($\alpha = 0.01$) based on the K–S test (Table 1). Under extremely wet conditions without pumping (EW-NP), more aquifer water was available for leaking into the streams. Even under extremely dry conditions without pumping (ED-NP), there was still more water leakage from the aquifers to the streams as compared to that of the BC. Results of our simulations demonstrated that groundwater pumping reduced aquifer water leakage to the streams more than that of the climate-change modified scenarios and thus was the major factor for low flows and drying streams in the ME.

FIGURE 5b shows the average daily water exchanges between the streams and aquifers over the 115 years for the BC-NP, EW-NP, ED-NP, and BC scenarios. These values were obtained by averaging all the negative and positive values shown in Figure 5a. As compared to that of the BC scenario, the water leakage from the aquifers to the streams increased by 2.48, 3.42, and 2.02 folds, respectively, for the normal (BC-NP), extremely wet (EW-NP), and extremely dry (ED-NP) conditions without pumping.

A comparison of water exchanges between the streams and aquifers among the six simulation scenarios showed that water leakage from the aquifers to the streams was much greater without pumping than with pumping in the ME (Figure 6). For example, the water leakage from the aquifers to the streams was −1,199,644 m^3/day under the extremely wet condition with pumping (EW-NP) but was −11,573,653 m^3/day under the extremely wet condition without pumping (ED-NP) at the end of the simulation in 2014. In other words, the water leakage from the aquifers to the streams without pumping was about 9.7 times greater (more negative) than without pumping. The average well pumping rate was 30,000,605 m^3/day over the past 115 years and was 1,052,815,405 m^3/day from 1987 to 2014 in the ME based on the input data provided

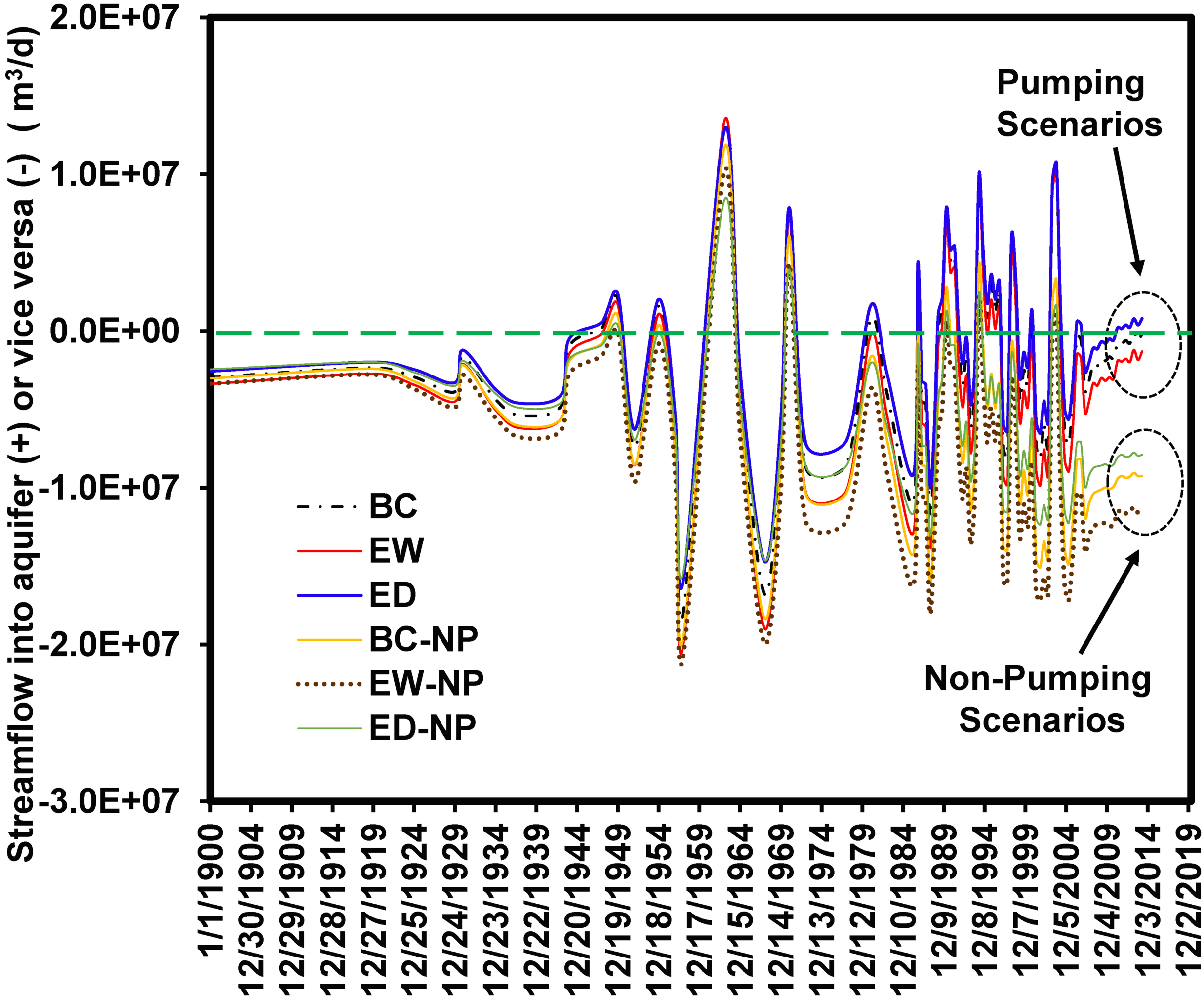

FIGURE 6 Water exchange between the streams and aquifers over the 115-year simulation period from 1900 to 2014 among the six scenarios.

from the MERAS model. Such a large groundwater pumping rate reduced the amount of aquifer water supplied to streams, which would result in low flows and drying streams in the ME.

4 | CONCLUSIONS

In general, three distinct patterns were observed among the six scenarios: (1) water exchange between streams and aquifers varied with years; (2) water leakage (negative value) from aquifers to streams occurred much more frequently than the water flow (positive value) from streams to aquifers; and (3) water exchange took place more frequently after 1987 due to intensive groundwater pumping for crop irrigation.

As compared to that of the normal climate (or the BC scenario), there were 36% increase and 49% decrease in average daily aquifer water supply to the streams, respectively, under the extremely wet and extremely dry climates over the past 115 years. Results demonstrated that the impact of climate extremes on stream and aquifer water exchanges was discernable.

There was about 9.7 times more aquifer water supplied to the streams without pumping than with pumping between the extremely wet (EW-NP) and the extremely dry (ED-NP) conditions. Even under the extremely dry condition without pumping (ED-NP), there was still more water leakage from aquifers to streams as compared to that of the normal conditions (BC).

The difference in stream-aquifer water exchange between the beginning of the simulation (1900) and the end of the simulation (2014) was 44 times larger without pumping than with pumping under the normal climate conditions. Groundwater pumping reduced the largest amount of aquifer water supplied to streams under all climate change scenarios. Therefore, groundwater pumping rather than climate change was a major factor for low flows and drying streams in the ME.

It should be noted that groundwater recharge rate in the MERAS model was estimated by USGS as a fraction of precipitation based on geology, soil type, and land use while excluding the effect of antecedent soil water content. A better approach is needed for estimating groundwater recharge in the ME.

AUTHOR CONTRIBUTIONS

Ying Ouyang: Conceptualization; data curation; formal analysis; investigation; methodology; resources; validation; visualization; writing – original draft; writing – review and editing. **Wei Jin:** Formal analysis; methodology; writing – review and editing. **Theodor D. Leininger:** Visualization; writing – review and editing.

ACKNOWLEDGMENTS

None.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Ouyang, Ying, Wei Jin and Theodor D. Leininger 2024. "Stream and Aquifer Water Exchange in Mississippi Embayment Under Intensive Pumping and Extreme Climate: A Century-long Assessment." *JAWRA Journal of the American Water Resources Association* 60 (4): 825–836. https://doi.org/10.1111/1752-1688.13206.