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Comparison of groundwater distribution, exchange and storage between cropland and forestland over the past 115 years

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ABSTRACT

Using the US Geological Survey groundwater model, we compared spatial distribution, flow exchange, and storage of groundwater between cropland and forestland in the Upper Yazoo River Watershed, Mississippi, from 1900 to 2014. Under normal climate, average groundwater head declined 2.7 m in cropland but only 1 m in forestland over the 115 years. The average groundwater flow from forestland to cropland surpassed the reverse flow by a factor of 238, owing to a higher elevation in forestland and intensive groundwater pumping in cropland. Cropland was a net groundwater sink while forestland was a net groundwater source under all climates. Our findings underscore the discernible impacts of climate changes on groundwater storage and suggest that afforestation in the region would be an alternative for saving groundwater resources and supplying more waters to croplands. This study offers valuable insights into groundwater supply planning not only in Mississippi but also in comparable situations worldwide.

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1 Introduction

The decline in groundwater resources due to anthropogenic activities and climate change poses a significant concern worldwide. Various regions are now facing a certain degree of groundwater resource depletion, making it challenging to ensure sustainability amidst rising water demand and climate change (Konikow 2015, Maina *et al.* 2020, Ouyang *et al.* 2021a, 2021c, Ali *et al.* 2023, Scanlon *et al.* 2023, Sherif *et al.* 2023). Scanlon *et al.* (2023) reviewed global water resources affected by anthropogenic activities and climate variability. They reported that over the past century, groundwater has shown an increasing storage trend in northwest India, central Pakistan, and the northwest US but a decreasing storage trend in the High Plains of Texas and Central Valley of California. These authors further argued that climate variability may have some effects on groundwater storage, but groundwater pumping is a key impact factor. Konikow (2015) reported that groundwater storage in the US decreased by almost 1000 km^3 during 1900–2008. The three largest groundwater depletion regions are the High Plains, Mississippi Embayment (ME), and Central Valley aquifers, with an average depletion rate of 13.6 km^3/year during the last half of the century and about 24 km^3/year after 2000. The ME aquifer, encompassing parts of Missouri, Illinois, Kentucky, Arkansas, Tennessee, Mississippi, Alabama and Louisiana, is one of the largest alluvial groundwater aquifers in the US (Clark and Hart 2009). Farmlands in the ME have been extensively and intensively irrigated with groundwater to maximize crop yields since 1998 (Vories 2014, Ouyang *et al.* 2021a, 2021c). Ali *et al.* (2023) reported that the annual average groundwater depletion in the ME aquifer was 5.18 Gm^3 (giga cubic meters) in 1981–2000 and 8 Gm^3 in 2001–2008. They further stated that managed aquifer recharge is not a cost-effective practice and is unlikely to improve groundwater storage.

Climate change is an inherent natural occurrence, but human activities exacerbate this phenomenon, leading to abnormal climates. Climate extremes affect groundwater resources through their effects on surficial hydrological cycles and ecosystems (Doll 2009, Ferguson and Gleeson 2012, Crosbie *et al.* 2013, Russo and Lall 2017, Ouyang *et al.* 2021c). Zhang *et al.* (2014) investigated groundwater response to extreme climatic conditions in the northern China Plain using meteorological monitoring data. They stated that groundwater level response to precipitation is more obvious in the coastal plain than in the piedmont alluvial–pluvial and middle plains. Sperac and Zima (2022) assessed the impact of climate extremes (i.e. high air temperature and low rainfall) on groundwater resources in eastern Croatia and found that groundwater level is manifested by a maximum of 4–5 m in response to the extreme climatic conditions. Recently, Ouyang *et al.* (2024) estimated the stream and groundwater exchange in the ME under the intensive groundwater pumping and extreme climates (i.e. precipitation increased and decreased by 20%) over a 115-year period from 1900 to 2014. They reported that while the climate extreme had discernible impacts, the groundwater pumping, not the climate extreme, is the major driving force for stream and groundwater exchange in the ME.

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Forestlands play a crucial role in ecosystems as they conserve precipitation water, mitigate surface runoff, reduce river flooding, and purify contaminants. Despite this, there has been limited effort to compare groundwater resource variability between croplands and forestlands. Ouyang *et al.* (2021b) estimated the subsurface hydrologic processes, groundwater budgets, and spatial-temporal distribution of groundwater level in three National Forestlands in the ME using the Mississippi Embayment Regional Aquifer Study (MERAS) groundwater model. They reported that all three forestlands in the ME serve as groundwater sinks at times and sources at others.

While the above and many other studies have shed light on the impacts of anthropogenic activities and climate change on groundwater resources in forestlands, our thorough literature search reveals a lack of emphasis on comparing long-term groundwater resource variability between croplands and forestlands at the watershed scale. The goal of this study was to address this gap by utilizing the MERAS groundwater model and the Upper Yazoo River Watershed (UYRW) within the ME as a case demonstration. We investigated groundwater resource variations (i.e. head distribution, flow exchange, and storage) between a cropland and a forestland over the 115-year period from 1900 to 2014 under the normal, very wet, and very dry simulation scenarios.

2 Materials and methods

2.1 Description of models

Developed by the United States Geological Survey (USGS), MERAS is a site-specific MODFLOW model that is used to simulate groundwater flow and distribution in the ME (Clark and Hart 2009). The modeled area covers 202 019 km^2, which comprises parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri and Tennessee (Fig. 1) with a finite difference grid of 414 rows, 397 columns, and 13 layers. The modeled cell size is 2.59 km^2 (or 1 square mile) with varying thickness in layers, and the current version of MERAS-2.2 has 83 stress periods with a simulation period from 1870 to 2014 (Haugh *et al.* 2020). An elaborate description of MERAS modeling initial and boundary conditions as well as its calibrations and applications can be found elsewhere (Clark and Hart 2009, Clark *et al.* 2013, Haugh *et al.* 2020, Ouyang *et al.* 2021a, 2021b, 2021c).

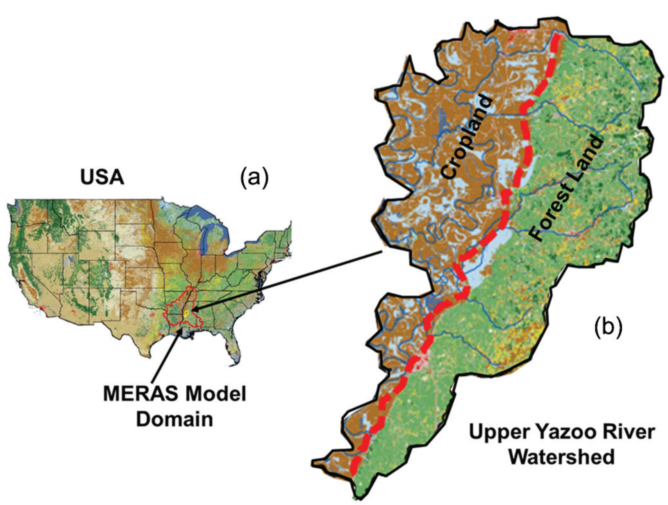

Figure 1. Locations of the Mississippi Embayment Regional Aquifer Study (MERAS) modeling area and the crop and forest lands in the Upper Yazoo River Watershed (UYRW).

MODFLOW, developed by the USGS, is a widely accepted modular three-dimensional groundwater flow model that has been in use since its initial release in the 1980s. The governing equation for MODFLOW is given as (McDonald and Harbaugh 1988):

$$S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) \pm W \tag{1}$$

where S_s is the groundwater storage (L^{-1}); h the groundwater head (L); t the time (T); K_{xx}, K_{yy}, and K_{zz} the saturated hydraulic conductivities (LT^{-1}) along x-, y-, and z-axes, respectively; and W the sink or source term (T^{-1}).

ModelMuse is a graphical user interface simulating system that incorporates MODFLOW, MODPATH, ZONEBUDGET, PHAST, SUTRA, MT3D-USGS, and WellFootprint models (Winston 2019). Besides being publicly available, ModelMuse offers significant advantages, including: (1) grid-independent spatial data and stress-period-independent temporal data, providing users with flexibility to redefine spatial and temporal discretization; and (2) the ability to visualize simulation results in two- or three-dimensional formats. In this study, the MERAS-2.2 model was imported into ModelMuse to enhance output displays, and the ZONEBUDGET model was employed for extracting groundwater budgets from the cropland and forestland of the UYRW. ZONEBUDGET is a computer model designed to extract sub-regional groundwater budgets using simulation results from the MODFLOW model (Harbaugh 1990).

2.2 Study site and simulation scenarios

The UYRW (Fig. 1) is situated within the MERAS modeled domain and about half of it is a crop production region in Mississippi, USA (MDEQ 2002). The west side of the UYRW is the alluvial valley of the Mississippi Delta, while its east side is bluff (Fig. 1(b)). The UYRW encompasses an area of 4025 km^2, with cropland accounting for 49% (1973 km^2), forestland 46% (1831 km^2), and other lands 5% (221 km^2). Predominant soil types are sand, loam, and clay, while major tree species include oak, gum, hickory, cypress, loblolly pine, and shortleaf pine (MDEQ 2002, Ouyang *et al.* 2021a). The average annual temperature is 18°C, with a mean minimum of 5.5°C in winter and a mean maximum of 32°C in summer. The long-term average precipitation is 1290 mm/year (Berkowitz *et al.* 2020). This watershed was selected for its nearly equal distribution of forestland and cropland, making it unique for the purpose of this study. In the past several decades, human-induced activities such as forest clear-cutting for croplands, hydrologic channel modifications for navigation and recreation, and groundwater withdrawals for crop irrigation, have resulted in river flooding, low flow, wetland loss, and groundwater level decline in the UYRW (Ouyang *et al.* 2019).

Given that the UYRW is part of the MERAS model domain, there is no need to define initial and boundary conditions for the watershed to execute the model. However, a moderate description of the UYRW hydrogeological settings is warranted for readers' convenience. The MERAS model employs 10 hydrogeologic units for the UYRW, namely the Mississippi River Valley alluvial aquifer, Vicksburg-Jackson confining unit, upper Claiborne aquifer, middle Claiborne confining unit, middle Claiborne aquifer, lower Claiborne confining unit, lower Claiborne aquifer, middle Wilcox aquifer, lower Wilcox aquifer, and Midway confining unit (Clark and Hart 2009). The UYRW is represented by 13 model layers: alluvial aquifer, Vicksburg-Jackson confining unit, upper Claiborne aquifer, middle Claiborne confining unit, middle Claiborne aquifer (Layers 5–7), lower Claiborne confining unit, the Winona-Tallahata, lower Claiborne aquifer, middle Wilcox aquifer, lower Wilcox aquifer, and lower Wilcox aquifer. There are 3126 pumping wells in the UYRW, with more than 90% located in the cropland. Detailed descriptions of the layers, streams and pumping wells can be found in Clark and Hart (2009).

Three simulation scenarios were created in this study: (1) a base case (BC) scenario characterizing normal farming practices, groundwater withdrawals, and climate conditions in the UYRW; (2) a very wet scenario (VW) mirroring the BC scenario except for a 20% increase in precipitation rate; and (3) a very dry scenario (VD) reflecting the BC scenario except for a 20% decrease in precipitation rate. These scenarios, with a 115-year simulation period, were formulated to determine how climate changes affect groundwater resources in the cropland and forestland of the ME.

3 Results and discussion

3.1 Model validation for the UYRW

To enhance confidence in the application of the MERAS model, we further validated the groundwater head in the UYRW, even though the entire MERAS model was calibrated by USGS prior to its applications. Our validation was performed by comparing the model-predicted groundwater head with the field measurement from 1943 to 2006 in the UYRW. The regression equation $Y_{predicted} = 0.98\ X_{measured}$, with $R^2 = 0.99$, $p < .001$, NSE (Nash-Sutcliffe efficiency) = 0.45, and nRMSE (normalized root mean square error) = 0.04 m (Fig. 2(a)), clearly demonstrated that the MERAS model predicted groundwater head very well in the UYRW, although forestland tended to have slightly higher simulated heads than observed ones and cropland had slightly lower simulated heads than observed ones. A time series comparison of groundwater heads between the model predictions and the field measurements is presented in Fig. 2(b), revealing a satisfactory visual match of the predicted peaks and valleys with the measured ones. This robust validation confirms the feasibility of the

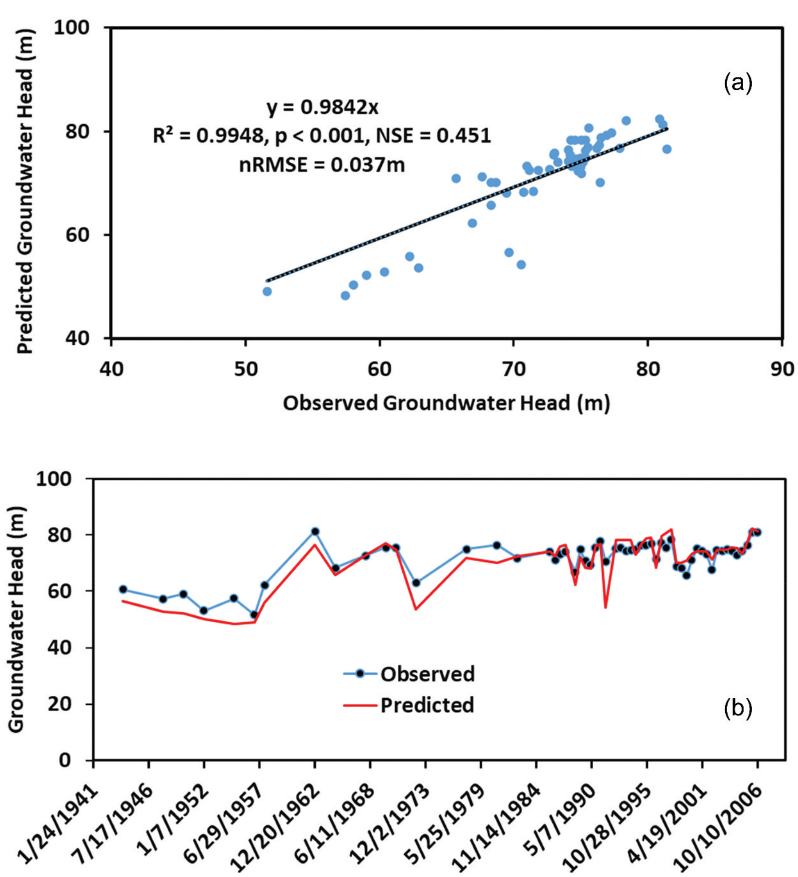

Figure 2. Validation of predicted groundwater heads with those measured through scatter plot (a) and time series plot (b) at the Upper Yazoo River Watershed.

MERAS model in predicting groundwater flow and head distribution in the UYRW.

3.2 Groundwater head distribution

The spatial distribution of groundwater heads in the cropland (left side of the dashed line) and the forestland (right side of the dashed line) of the UYRW in 1900, 1938, 1987, and 2014 over the 115-year simulation period is illustrated in Fig. 3(a). In general, groundwater head was higher in the forestland than in the cropland and was higher in the northeast than in the southwest of the UYRW.

A higher groundwater head in the forestland occurred primarily because forestland has a higher surface elevation and serves as the recharge zone while cropland is a discharge zone. These uneven distributions of groundwater head in the UYRW created a head gradient for groundwater flow from the forestland into the cropland in a direction from the northeast toward the southwest. Overall, the groundwater heads in both the cropland and forestland decreased during the 115 years from 1900 to 2014 (Fig. 3(b)). The average groundwater head in the cropland was 35.4 m in 1900, 35.2 m in 1938, 35.3 m in 1987, and 32.5 m in 2014, showing a decreasing trend of groundwater head in the cropland over the 115-year period with a difference of 2.7 m between 1900 and 2014. Analogous to the case of the cropland, there was a decreasing trend of groundwater head in the forestland with a difference of 1 m between 1900 and 2014. It is apparent that groundwater head declined much faster in the cropland than in the forestland. This finding reverses our traditional perception that forestlands lose more water than croplands because of higher evapotranspiration (ET) in forestlands (Verstraeten *et al.* 2005, Owuor *et al.* 2016) and thereby would decline groundwater head faster than that the croplands. For example, Verstraeten *et al.* (2005) compared the ET of Flemish forestlands and croplands using a soil water balance model. They reported that over a 30-year period, the average ET was 491 mm for 10 forest stands and 398 mm for 10 croplands. In other words,

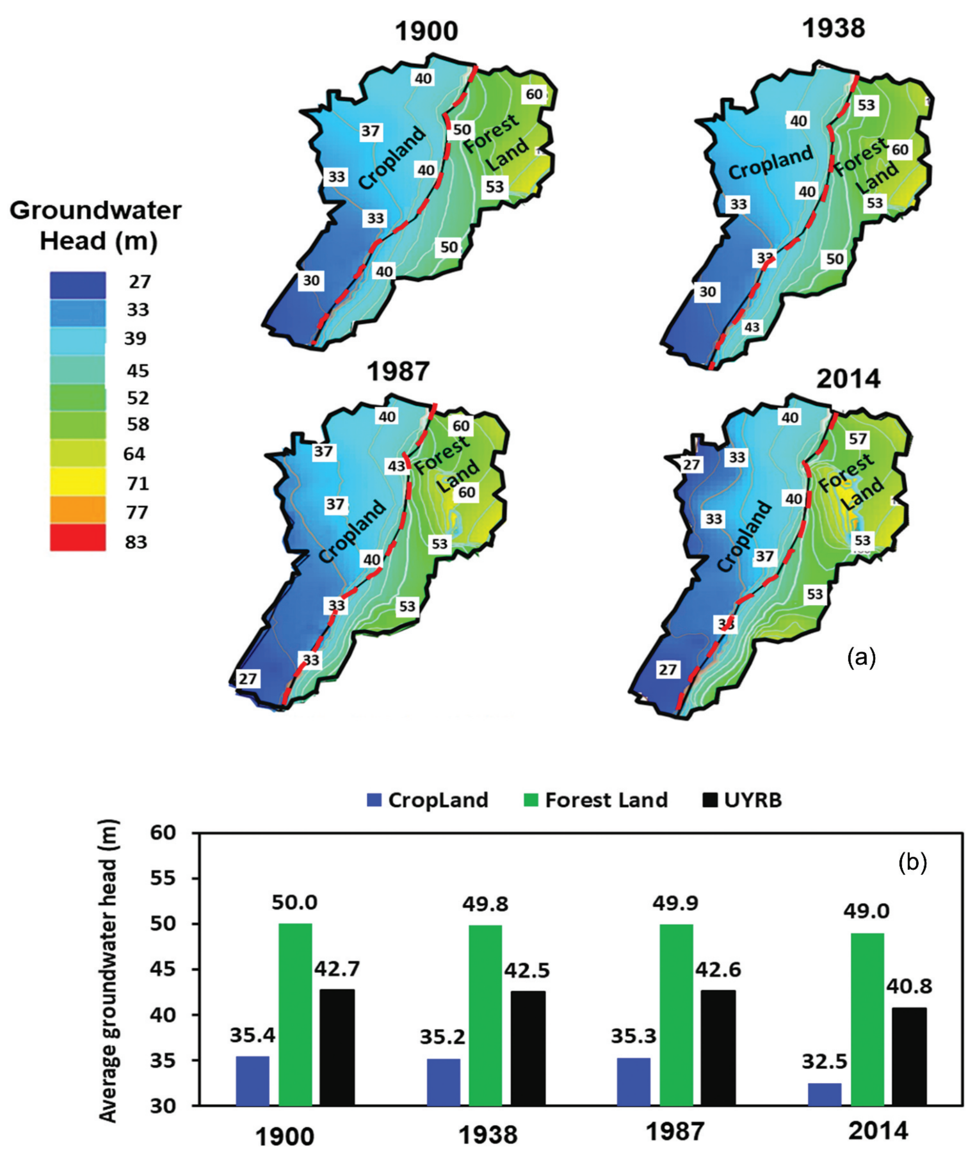

Figure 3. Spatial distributions of groundwater head in the UYRW (a) and average groundwater heads in the cropland, forestland, and UYRW (b) in 1900, 1938, 1987 and 2014.

the ET in the forestlands was about 23% higher than in the croplands, indicating groundwater head could decline faster in the forestlands than in the croplands. In contrast, the opposite result was obtained in our study. We attribute this distinct discrepancy between the Verstraeten *et al.* (2005) study and ours to groundwater pumping. There was intensive groundwater pumping for crop irrigation in the UYRW, especially from 1987 to 2014 (Fig. 4(a)). This intensive pumping activity not only increased cropland ET but also declined groundwater head. As a result, the groundwater head declined faster in the forestlands than in the croplands.

It should be noted that the groundwater recharge rate was higher in the cropland (Fig. 4(b)) than in the forestland (Fig. 4(c)) from 1987 to 2014. However, there was a much higher groundwater pumping rate in the cropland during this period (Fig. 4(a)) as compared to no pumping in the forestland. The higher groundwater pumping rate superseded the higher groundwater recharge rate in the cropland. As a result, the groundwater head decreased faster in the cropland than in the forestland from 1987 to 2014.

A close look at Fig. 3(a) further reveals that very small variations in spatial distribution of groundwater head in both the cropland and forestland were observed from 1900 to 1987. From 1900 to 1938, the average groundwater head was 35.4 m in 1900 and 35.2 m in 1938 with a decrement of 0.2 m in the cropland and were 50 m in 1900 and 49.8 m in 1938 with the same decrement (0.2 m) in the forestland (Fig. 3(b)). Such small variations occurred because of the small changes in groundwater recharge in the cropland (Fig. 4(b)) and forestland (Fig. 4(c)) as well as little groundwater pumping in the

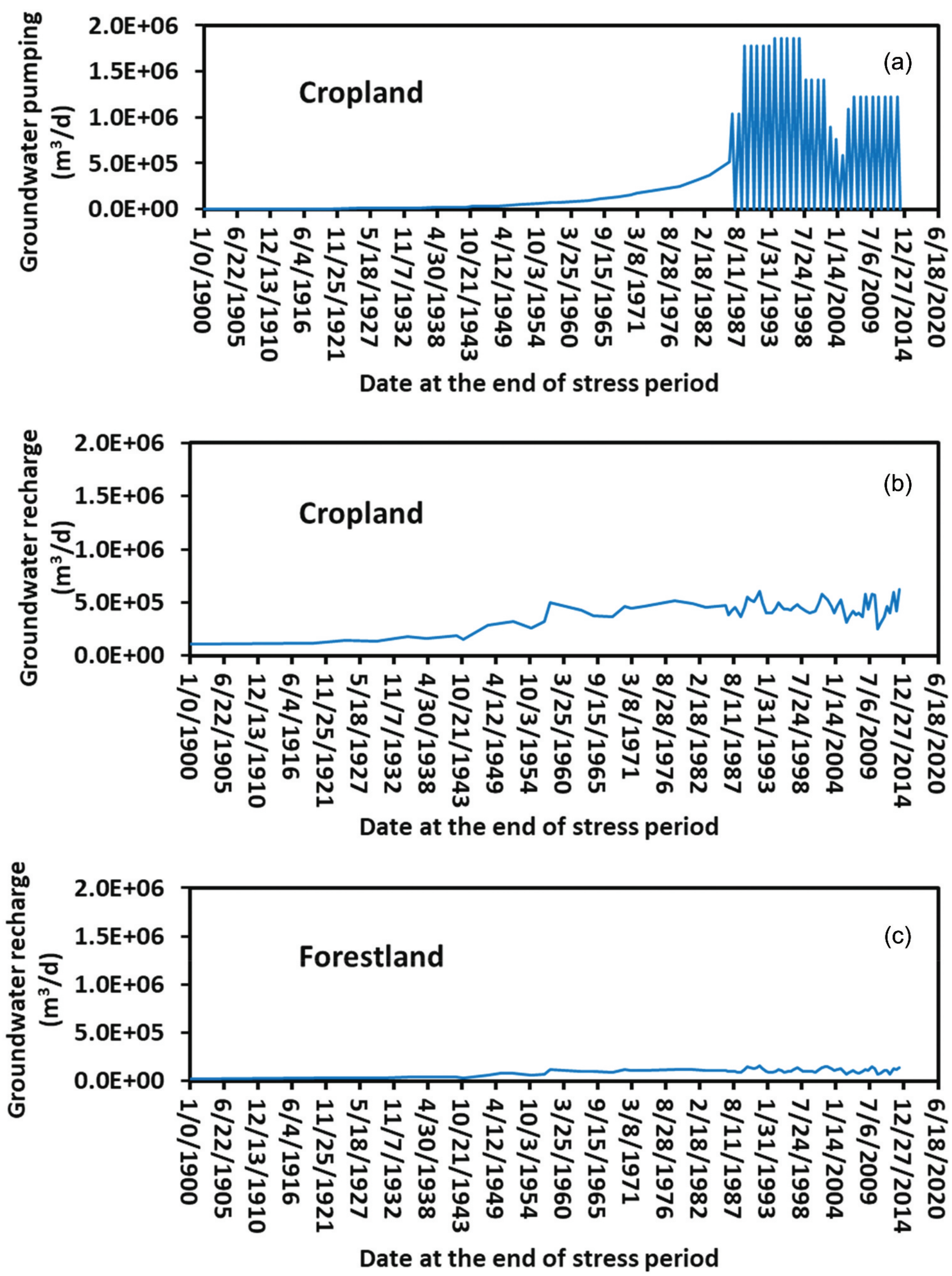

Figure 4. (a) Groundwater pumping in the cropland and groundwater recharge in the (b) cropland and (c) forestland for the dates at the end of the stress periods from 1900 to 2014.

cropland (Fig. 4(a)) and no groundwater pumping in the forestland. From 1938 to 1987, a slight increase in groundwater head was observed in both the cropland and forestland. The average groundwater head increment was 0.1 m in both lands between 1938 and 1987. We attributed the increment to the increase in groundwater recharge in both lands (Fig. 4(b,c)). There was widespread tree-cutting in the 1930s to 1940s, which would allow more precipitation water to infiltrate into the soil profile for groundwater recharge.

From 1987 to 2014, however, large variations in spatial distribution of groundwater head occurred in both the cropland and forestland. The average groundwater head in the cropland was 35.3 m in 1987 but 32.5 m in 2014 (Fig. 3(b)) with a decrement of 2.8 m. As compared to a tiny decrement of groundwater head (35.4 − 35.3 = 0.1 m) in the cropland over an 88-year period from 1900 to 1987, the large decrement of groundwater head (35.3 − 32.5 = 2.8 m) in the cropland that occurred more recently, in the 27 years from 1987 to 2014, indicates a dramatic depletion in groundwater resources. This occurred primarily because of the intensive groundwater withdrawal for crop irrigation during this period (Fig. 4(a)). Results suggest that groundwater pumping in this recent 27-year period led to a 2.7 m decline of groundwater head in the cropland. This new insight provides useful information to water resource managers, farmers and foresters in the region and around the world, in areas with comparable conditions, for developing better groundwater supply planning.

3.3 Groundwater exchange and storage

Groundwater flow exchanges between the cropland and the forestland over the 115-year simulation period are presented in Fig. 5. These flow exchanges were extracted using the ZONEBUDGET model. It is apparent that groundwater flow from the forestland into the cropland (Fig. 5(a)) was about five orders of magnitude larger than from the flow in the opposite direction (Fig. 5(b)). The minimum, average, and maximum groundwater flows from forestland into cropland over the 115-year simulation period were 12 285, 13 183, and 13 805 m^3/d, respectively, whereas the minimum, average, and maximum groundwater flows from cropland into forestland over the same simulation period were 0, 55, and 245 m^3/d, respectively. Overall, the average groundwater flow from the forestland into the cropland was 238 (i.e. 13 183/55 = 238) times larger than vice versa. This occurred because the groundwater head in the forestland was higher than that in the cropland, as discussed in

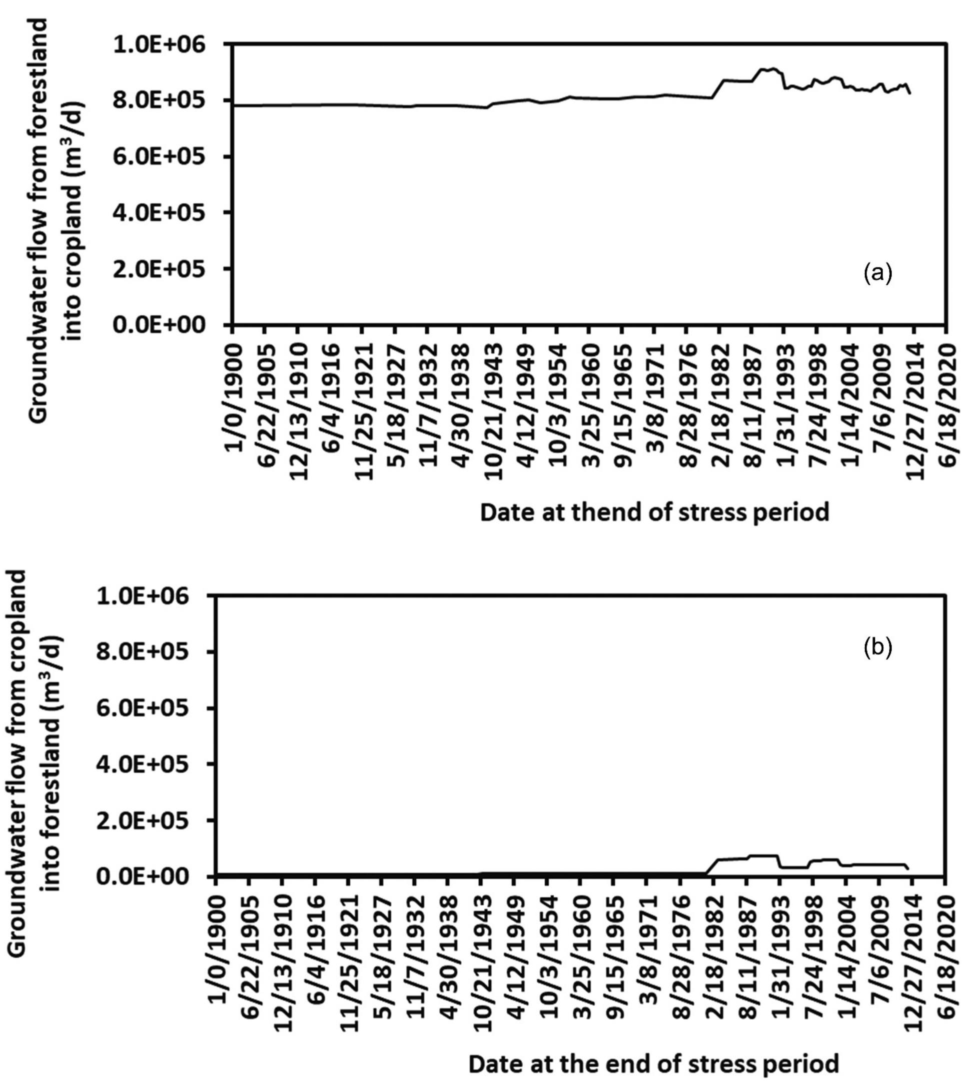

Figure 5. Groundwater flow (a) from forestland into cropland and (b) vice versa.

the previous section. Figure 5 further reveals that groundwater flow exchange between the forestland and the cropland was somewhat smooth from 1900 to 1982 but fluctuated from 1982 to 2014. While the actual reasons for this phenomenon remain to be investigated, one possible explanation would be the fluctuation in groundwater pumping from 1982 to 2014 in the cropland (Fig. 4(a)).

Little to no effort has been devoted to investigating the long-term groundwater flow exchange between forestlands and croplands in the literature. Our study is the first of its kind in estimating long-term groundwater flow exchange between these two land uses and provides a new paradigm for other researchers around the world. Our finding that the average groundwater flow from the forestland into the cropland was larger by a factor of 238 than the reverse groundwater flow from cropland to the forestland over the 115-year period provides a critical reference to stakeholders, engineers, scientists, and managers in the region and around the world in areas with comparable situations for better agricultural groundwater resources management.

Average groundwater-storage changes over the simulation periods from 1900 to 1987, 1987 to 2014, and 1900 to 2014 in both the cropland and forestland are shown in Fig. 6. The groundwater-storge change is the amount of groundwater entering an aquifer (recharge) minus the amount of groundwater leaving the aquifer (discharge). A positive value indicates that an aquifer receives groundwater and is termed as storage-in, whereas a negative value implies that an aquifer delivers groundwater and is denoted as storage-out. The average groundwater storage-in was lower during 1900–1987 (72 m^3/d) than during 1987 to 2014 (89 m^3/d) in the cropland (Fig. 6), indicating that the aquifer beneath the cropland received more groundwater during 1987–2014. We attributed this finding to the intensive groundwater pumping in the cropland during the same period (Fig. 4(a)). As more groundwater was pumped out from the aquifer in the cropland, more water from the aquifers in the surrounding lands flowed into the aquifer of the cropland, thereby increasing groundwater storage-in. Over the 115-year simulation period, the average storage was 83 m^3/d (Fig. 6), indicating the aquifer of the cropland was a net groundwater receiver. In contrast, the opposite was true in the forestland. That is, the aquifer in the forestland delivered groundwater to the cropland and other surrounding lands over the 115-year simulation period (Fig. 6). The average groundwater storage-out was −528 m^3/d from 1900 to 1987, −628 m^3/d from 1987 to 2014, and −593 m^3/d from 1900 to 2014 in the forestland. Results illustrated that the forestland delivered more groundwater (storage-out) during 1987 to 2014 than during 1900 to 1987. We attribute this finding to the groundwater head (or level) decline in the cropland (primarily due to the intensive groundwater pumping). The lower groundwater head in the cropland created a larger groundwater head gradient for more groundwater flow from the forestland into the cropland. Over the 115 years, the aquifer beneath the forestland was a net groundwater deliver (average storage-out = −593 m^3/d) or source, whereas the aquifer beneath the cropland was a net groundwater receiver (average storage-in = 87 m^3/d) or sink. Little work has been done to compare the groundwater storage between the cropland and the forestland in the literature. Our finding demonstrates that the forestland in this region supplies groundwater to the cropland. Therefore, afforestation in the region would be an alternative for supplying more groundwater resources to croplands and for saving water resources because of no pumping after afforestation.

3.4 Climate change impacts

The impact of climate change on groundwater storage in both the cropland and forestland over the 115-year simulation period is illustrated in Fig. 7. In comparison to the normal (BC scenario) climate, a 20% increase in precipitation (VW scenario) in the cropland led to a 25% rise in groundwater storage-in, while a 20% decrease in precipitation (VD scenario) resulted in a 33% reduction in groundwater storage-in. These findings underscore the substantial influence of climate changes on groundwater storage variations in the cropland. Similar trends were observed in the forestland, where a 20% increase in precipitation led to a 26% increase in groundwater storage-out, while a 20% decrease resulted in a 32% decline in groundwater storage-out compared to the BC scenario. The results indicate that during very wet conditions, the forestland had more groundwater available (storage-out) to the adjacent cropland, whereas under very dry conditions,

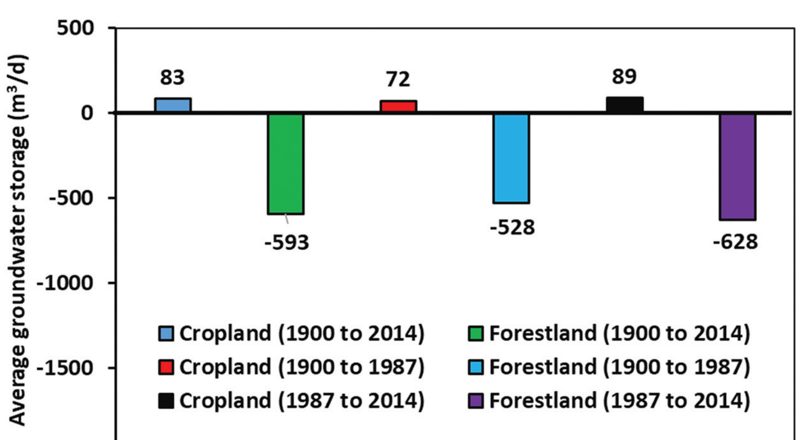

Figure 6. Average groundwater storage in the cropland and forestland over the 115-year simulation period.

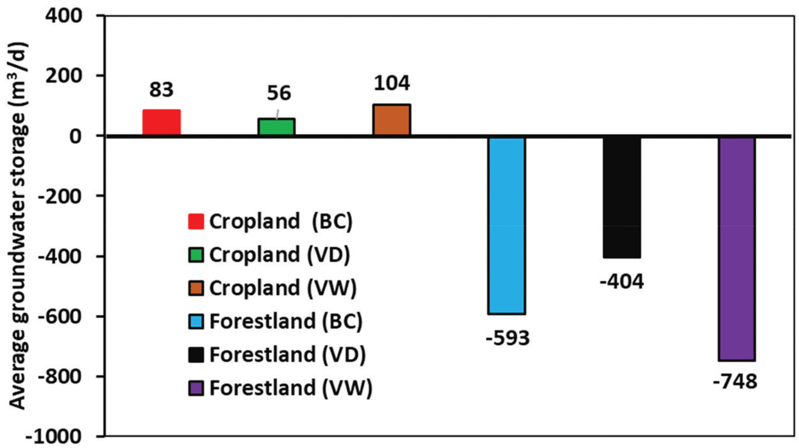

Figure 7. Average groundwater storage under the normal or base case (BC), very wet (VW) and very dry (VD) climatic scenarios over the 115-year simulation period from 1900 to 2014.

the forestland had less groundwater available (storage-out) to the adjacent cropland. Results further suggest that the forestland in the region is the source of groundwater to the cropland under all climate scenarios.

The above findings have practical implications for developing adaptive water resources management strategies for sustainable agriculture and food production under a changing climate (Crimmins 2023). The UYRW is located within the Lower Mississippi River Basin, which is one of the most agriculture-intensive regions in the world. Groundwater resource availability is projected to be a limiting factor, especially during episodic droughts (Yasarer *et al.* 2020). This problem will become common and intensified in the future as global temperatures continue to rise because of climate change (Veal 2021), leading to further decrease in baseflow and more frequent and extreme low flow conditions. Our results suggest that a viable forest resource in the region would help maintain groundwater recharge into the aquifer of forestland, which can deliver water to the adjacent aquifer of cropland and alleviate cropland groundwater shortage. However, warming temperatures may also alter the composition of trees in the forests, and more droughts would reduce forest productivity along with increased damage from insects and disease (EPA 2016). The interplay among climate change, forest health, and groundwater hydrology deserves further examination.

4 Conclusions

The MERAS (Mississippi Embayment Regional Aquifer Study) groundwater model developed by the USGS effectively predicted groundwater flow and distribution within the Upper Yazoo River Watershed (UYRW), as verified through our model validation.

In the UYRW, groundwater head exhibited higher levels in forestland compared to cropland, and the northeast displayed higher values than the southwest. This uneven distribution established a head gradient facilitating groundwater flow from the forestland toward the cropland in a northeast to southwest direction.

Under the normal climate and over the 115-year study period, the average groundwater head declined 2.7 m in cropland but only 1 m in forestland. The faster decline of groundwater head in the cropland was attributed primarily to intensive groundwater pumping for crop irrigation. Over the 115 years, cropland proved to be a net sink of groundwater with an average storage-in of 83 m^3/d, while forestland emerged as a net source with an average storage-out of −593 m^3/d. This finding reverses our traditional perception that forestlands lose more water than croplands because of higher evapotranspiration (ET) in forestlands and thereby would decline groundwater head faster than that in the croplands. We attributed the discrepancy between our study and others to the groundwater pumping. This intensive pumping activity for crop irrigation not only increased cropland ET but also declined groundwater head. Therefore, the groundwater head declined faster in the forestlands than in the croplands.

Average groundwater flow from forestland to cropland surpassed the reverse flow by a factor of 238, owing to a higher surface elevation in forestland and intensive groundwater pumping in cropland. Little to no effort has been devoted to investigating the long-term groundwater flow exchange between forestlands and croplands in the literature. Our study is the first of its kind in this regard and provides a critical reference to stakeholders, engineers, scientists, and managers in the region and in areas around the world with comparable situations for better agricultural water resources management.

Little work has been done to compare the groundwater storage between croplands and the forestlands in the literature. Our finding demonstrated that the forestland in this region supplies groundwater to the cropland. Therefore, afforestation in the region would be an alternative for supplying more groundwater resources to croplands and for saving groundwater resources because of no pumping after afforestation.

A comparative analysis revealed that, under a very wet climate scenario (i.e. a 20% increase in precipitation), cropland groundwater storage-in increased by 25%, while forestland storage-out surged by 30%. Conversely, in a very dry climate (i.e. a 20% decrease in precipitation), cropland storage-in decreased by 33%, and forestland storage-out diminished by 22%. These findings underscore the discernible impacts of climate changes on groundwater storage.

The implications of this study extend to water resource managers, farmers and foresters, offering valuable insights for groundwater supply and conservation planning in both agricultural and forest management contexts, not only within the studied region but also in comparable situations worldwide.

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Data availability statement

Data will be made available by the authors upon request.

References

Ali, A.A., *et al.*, 2023. Hydro-economic modeling of managed aquifer recharge in the lower Mississippi. *Jawra Journal of the American Water Resources Association*, 59 (6), 1413–1434. doi:10.1111/1752-1688.13141.

Berkowitz, J.F., Johnson, D.R., and Price, J.J., 2020. Forested Wetland hydrology in a large Mississippi river tributary system. *Wetlands*, 40 (5), 1133–1148. doi:10.1007/s13157-019-01249-5.

Clark, B.R. and Hart, R.M., 2009. The Mississippi Embayment Regional Aquifer Study(MERAS): documentation of a groundwater-flow model constructed to assess water availability in the Mississippi embayment. U. S. Geological Survey.

Clark, B.R., Westerman, D.A., and Fugitt, D.T., 2013. Enhancements to the Mississippi Embayment Regional Aquifer Study (MERAS) groundwater-flow model and simulations of sustainable water-level scenarios. *US Geological Survey Scientific Investigations Report*, 5161 (29), 2013.

Crimmins, A.R., 2023. Fifth national climate assessment: overview: understanding risks, impacts, and responses.

Crosbie, R.S., *et al.*, 2013. Potential climate change effects on groundwater recharge in the high plains aquifer, USA. *Water Resources Research*, 49 (7), 3936–3951. doi:10.1002/wrcr.20292.

Doll, P., 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environmental Research Letters*, 4 (3), 035006. doi:10.1088/1748-9326/4/3/035006.

EPA, 2016. *What climate change means for Mississippi. EPA 430-F-16-026.* Washington DC: United States Environmental Protection Agency.

Ferguson, G. and Gleeson, T., 2012. Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change*, 2 (5), 342–345. doi:10.1038/nclimate1413.

Harbaugh, A.W., 1990. *A computer program for calculating subregional water budgets using results from the U.S. geological survey modular three-dimensional finite- difference ground-water flow model.* Reston, VA. Denver, Co: U.S. Geological Survey; Books and Open-File Reports Section [distributor].

Haugh, C., Killian, C., and Barlow, J., 2020. *MODFLOW-2005 model used to evaluate water-management scenarios for the Mississippi Delta*. US Geological Survey Data Release. doi:10.5066/P9906VM5.

Konikow, L.F., 2015. Long-term groundwater depletion in the United States. *Groundwater*, 53 (1), 2–9. doi:10.1111/gwat.12306 .

Maina, F.Z., *et al.*, 2020. Determining the impact of a severe dry to wet transition on watershed hydrodynamics in California, USA with an integrated hydrologic model. *Journal of Hydrology*, 580, 124358. doi:10.1016/j.jhydrol.2019.124358.

McDonald, M.G. and Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model. US Geological Survey.

MDEQ, 2002. State of Mississippi water quality criteria for intrastate, interstate, and coastal waters. MDEQ (Mississippi Department of Environmental Quality), Jackson.

Ouyang, Y., *et al.*, 2019. Estimating impact of forest land on groundwater recharge in a humid subtropical watershed of the Lower Mississippi River Alluvial Valley. *Journal of Hydrology: Regional Studies*, 26, 100631.

Ouyang, Y., *et al.*, 2021a. Impacts of afforestation on groundwater resource: a case study for Upper Yazoo River watershed, Mississippi, USA. *Hydrological Sciences Journal*, 66 (3), 464–473. doi:10.1080/02626667.2021.1876235.

Ouyang, Y., *et al.*, 2021b. Contributions to groundwater from National Forest lands in the Mississippi Embayment: a century-long simulation. *Water Practice and Technology*, 16 (1), 83–95. doi:10.2166/wpt.2020.098.

Ouyang, Y., *et al.*, 2021c. Impact of climate change on groundwater resource in a region with a fast depletion rate: the Mississippi Embayment. *Journal of Water and Climate Change*, 12 (6), 2245–2255. doi:10.2166/wcc.2021.326.

Ouyang, Y., *et al.*, 2024. Evidence of higher evapotranspiration in croplands than in forestlands in four Mississippi watersheds over the past decade. *Agricultural Water Management*, 302, 108992.

Owuor, S.O., *et al.*, 2016. Groundwater recharge rates and surface runoff response to land use and land cover changes in semi-arid environments. *Ecological Processes*, 5 (1), 1–21. doi:10.1186/s13717-016-0060-6.

Russo, T.A. and Lall, U., 2017. Depletion and response of deep groundwater to climate-induced pumping variability. *Nature Geoscience*, 10 (2), 105–+.

Scanlon, B.R., *et al.*, 2023. Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, 4 (2), 87–101. doi:10.1038/s43017-022-00378-6.

Sherif, M., *et al.*, 2023. A review of managed aquifer recharge potential in the Middle East and North Africa Region with examples from the Kingdom of Saudi Arabia and the United Arab Emirates. *Water*, 15, 742.

Sperac, M. and Zima, J., 2022. Assessment of the impact of climate extremes on the groundwater of Eastern Croatia. *Water*, 14, 254.

Veal, A.J., 2021. Climate change 2021: the physical science basis, 6th report. *World Leisure Journal*, 63 (4), 443–444. doi:10.1080/16078055.2021.2008646.

Verstraeten, W., *et al.*, 2005. Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE. *Hydrology and Earth System Sciences*, 9 (3), 225–241. doi:10.5194/hess-9-225-2005.

Vories, E.D. and Evett, S. R., 2014. Irrigation challenges in the sub-humid US Mid-South. *International Journal of Water*, 8, 259–274. doi:10.1504/IJW.2014.064220.

Winston, R.B., 2019. ModelMuse version 4: a graphical user interface for MODFLOW 6. Scientific Investigations Report-US Geological Survey (2019-5036).

Yasarer, L.M.W., *et al.*, 2020. Trends in land use, irrigation, and streamflow alteration in the Mississippi River Alluvial Plain. *Frontiers in Environmental Science*, 8, 66.

Zhang, Y., *et al.*, 2014. Response of groundwater to climate change under extreme climate conditions in North China Plain. *Journal of Earth Science*, 25 (3), 612–618. doi:10.1007/s12583-014-0443-5.