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Contributions to groundwater from National Forest lands in the Mississippi Embayment: a century-long simulation

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Abstract

Very little effort has been devoted to analyzing the contributions of National Forests to groundwater resources in the USA and around the world. In this study, the US Geological Survey's MERAS (Mississippi Embayment Regional Aquifer Study) model was used in the ModelMuse simulating system to estimate more than a century of subsurface hydrologic processes, groundwater budgets, and spatial-temporal groundwater level distributions in three forests in Mississippi, USA. The results showed that groundwater recharge and stream leakage are important for groundwater storage in this region. All three forests served as groundwater sinks at times and sources at others, but the volume changes were relatively small. Groundwater levels declined over the simulation period – 1900 to 2014 – beneath all three forests, especially around the DNF (Delta National Forest) where groundwater abstraction is relatively intense. Knowledge gained from long-term hydrologic simulations and water budgets is useful when managing forest land groundwater resources.

Key words: groundwater resource, long-term, MERAS model, Mississippi, National Forest

Highlights

- The century-long impacts of National Forests on groundwater were examined.
- Recharge and stream leakage are important for groundwater storage in the region.
- Groundwater levels declined for all National Forests over the past 100 years.
- National Forests serve as the sinks or sources of groundwater in some periods.
- Well pumping is a key driving force for groundwater level decline.

INTRODUCTION

Groundwater resource overdraft, resulting from agricultural, domestic and industrial water usage, is of increasing concern. Many regions in north Africa, the Middle East, south and central Asia, north

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China, North America and Australia, are experiencing a certain degree of groundwater resource depletion and/or shortage (Giordano 2009; Famiglietti 2014; Dalin *et al.* 2017; Ouyang *et al.* 2019; Scanlan 2019). This is also occurring in Mississippi, USA. It has been reported that the Mississippi Delta is a hot spot of groundwater depletion in the USA – the groundwater loss here was about 493 Mm^3/a from 1987 to 2014, resulting in about a 7 m decline in groundwater level (YMD 2015). The requirement to alleviate groundwater depletion has led to the implementation of several Best Management Practices including construction of farm water storage ponds for crop irrigation, improvement of irrigation efficiency, and afforestation of marginal croplands (Ouyang *et al.* 2013, 2018).

Forests provide a number of ecosystem benefits including rainwater conservation, diffuse surface runoff, and pollutant absorption, which mitigate flooding, reduce contamination, and improve water quality (Ouyang *et al.* 2013, 2019). Despite these benefits, mixed results have been reported regarding the impacts of forests on groundwater resources (Ilstedt *et al.* 2016; Owuor *et al.* 2016; Adane *et al.* 2018; Ouyang *et al.* 2019). Owuor *et al.* (2016) reviewed groundwater recharge rate and surface runoff, in response to land use and land cover changes in semi-arid environments. They reported that if forests are converted to rangeland, cropland and grassland, groundwater recharge increases by 7.8, 3.4, and 4.4%, respectively. In other words, forest land reduces groundwater recharge in semi-arid environments. Adane *et al.* (2018) modeled the effects of converting grassland to forest on groundwater recharge in the Nebraska National Forest of the Nebraska Sand Hills, a semi-arid region. Using the HYDRUS 1D model, they simulated two plots representing grassland and dense pine forest, and found that converting grassland to pine forest reduced the groundwater recharge rate by 9.65 cm/year, or 17%. On the other hand, Ilstedt *et al.* (2016) developed an optimum tree cover theory and applied it to a cultivated woodland in West Africa, and found that moderate tree cover increased groundwater recharge and improved groundwater resources. Recently, Ouyang *et al.* (2019) applied the HSPF (Hydrological Simulation Program – FORTRAN) model to estimate groundwater recharge and reported that forest land slightly increased rather than reducing groundwater recharge in a humid, subtropical watershed in Mississippi. These studies provide insight into forest land effects on groundwater recharge in different climatic regions and environments, and that the effect of forest stocking on groundwater recharge is complex.

Clark & Hart (2009) developed the Mississippi Embayment Regional Aquifer Study (MERAS) model to estimate the changes in groundwater flow in the Mississippi Embayment for a simulation period from 1870 to 2007. They found that groundwater abstraction comprises the largest outflow component, with a net rate of $68.88E^{+06}$ m^3/d for the entire Mississippi Embayment near the end of the simulation period in 2006. Recently, Haugh *et al.* (2020) updated the MERAS model (MERAS-2) and extended the simulation period from 2007 to 2014. MERAS-2 supplies the most recent datasets for water-use, precipitation and recharge, and streamflow and water-level observations (Haugh *et al.* 2020). They applied MERAS-2 to evaluate alternative water-supply scenarios in the Mississippi Delta, an intensive crop production area. Their alternative water-supply scenarios include irrigation efficiency, on-farm storage and tail-water recovery, in-stream weirs to increase surface-water availability, intra-basin surface water transfer, and groundwater transfer and injection. They observed that groundwater levels in the alternative water-supply scenarios are relatively higher than those in the base scenario, and their simulation results can be used to develop comprehensive water-management-optimization scenarios, as well as improve and enhance current and future groundwater monitoring activities in the Mississippi Delta.

One aspect of evaluating the influence of forest stocking on groundwater resources that has not been examined is the influence of national forest lands on subsurface hydrological processes and groundwater budgets. These forest lands, managed by the USDA-FS (United States Department of Agriculture, Forest Service), comprise about 781,000 km^2 and are managed for purposes including timber, recreation, grazing, wildlife, fish and water, with a mission to sustain their health, biodiversity, and productivity to meet the needs of present and future generations (USDA-FS 2015). A thorough literature search showed that little effort has gone into investigating national forest impacts on groundwater resources, and it is not clear whether those studied are sinks or sources of groundwater resources, although the outcomes could be site-specific. Understanding the contributions of national and other publicly-owned forest lands to groundwater resources will benefit US Forest Service managers responsible for resource stewardship.

The goal of this study was to assess the century-long (1900–2014) impacts of all, or part, of three national forests in Mississippi on groundwater resources using MERAS-2, a site-specific MODFLOW model. The national forests, located in the humid subtropical climate zone, are the Bienville National Forest (BNF), the Delta National Forest (DNF), and the Yalobusha Unit of the Holly Springs National Forest (YUH). The objectives were to: (1) import the MERAS-2 model into the USGS (US Geological Survey) ModelMuse simulating system, to ease ZONEBUDGET simulation and improve pre- and post-processing of model inputs and outputs; (2) apply the model to assess long-term subsurface hydrologic processes including recharge, storage, stream leakage, well pumping, and flow exchange between the national forests and surrounding areas; and (3) determine whether the individual forests are sinks or sources of groundwater over the long term.

MATERIALS AND METHODS

The models

MODFLOW is a modular, three-dimensional, finite difference, groundwater flow simulation model, created by USGS (McDonald & Harbaugh 1988). MODFLOW is well known and widely used and, since its release in 1980, several versions have been developed. A complete description of the model and its most recent expansion can be found elsewhere (McDonald & Harbaugh 1988; Harbaugh 2005; Hughes *et al.* 2017; USGS 2020).

MERAS, constructed by USGS using MODFLOW-2005, is used to simulate groundwater flow and availability in the Mississippi Embayment (Clark & Hart 2009; Haugh *et al.* 2020). The modeled domain covers 202,019 km^2 and incorporates all or parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. The model has a finite difference grid of 414 rows, 397 columns, and 13 layers. Each model cell is 2.59 km^2 (one square mile) with varying thickness by both cell and layer. MERAS-2, the new version, has 83 stress periods for a simulation period from 1870 to 2014 (Haugh *et al.* 2020). In this study, Version 2.2 was used and the model domain was somewhat smaller (Figure 1). Detailed descriptions of the model, with boundary and initial conditions, are given in Clark & Hart (2009), Clark *et al.* (2013) and Haugh *et al.* (2020).

ModelMuse is a graphical user interface simulating system for running groundwater flow and solute transport models including MODFLOW and ZONEBUDGET (Winston 2020). The major advantages of ModelMuse are that the spatial data are grid independent and the temporal data stress-period independent, giving users flexibility to redefine the spatial and temporal discretizations. For this study the MERAS-2 model was imported into the ModelMuse system, enabling the ZONEBUDGET model, which is critical in this study, to be set up.

ZONEBUDGET calculates sub-regional groundwater budgets using the simulation results from MODFLOW (Harbaugh 1990). The sub-regions of interest are delineated and then defined with zone numbers. ZONEBUDGET then calculates the groundwater budget for each zone by computing the hydrologic components (e.g. recharge, aquifer storage, stream leakage, and well pumping or injection). A zone budget includes water inflow and outflow components from the adjacent areas.

The national forests

The BNF is located in Jasper, Newton, Scott, and Smith counties of central Mississippi (Figure 1) and covers 72,034 ha (USDA-FS 2015). The mean annual temperature is 18 °C and mean annual

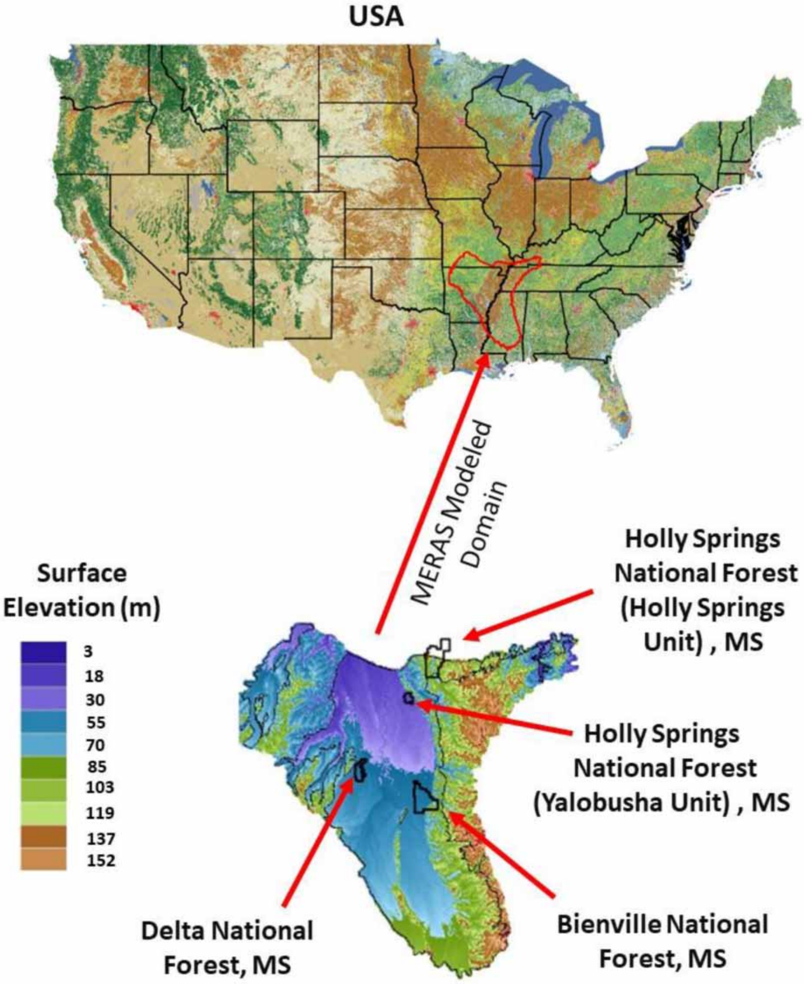

Figure 1 | Locations of the modelled domain and the three national forests.

precipitation is 1,525 mm (Nowak *et al.* 2015). The area is dominated by pine (*Pinus spp.*) and oak (*Quercus spp.*), and also contains species such as tulip poplar (*Liriodendron tulipifera L.*), sweetgum (*Liquidambar styraciflua L.*), tupelo (*Nyssa sylvatica* Marshall), hickory (*Carya spp.*), cherry (*Prunus spp.*), and magnolia (*Magnolia spp.*) (Nowak *et al.* 2015). Soils in the BNF are silty clay loam, silt loam, and sandy loam (Bergstrom & Page-Dumroese 2019).

The DNF, lying in the lower part of the Mississippi Delta (Figure 1), covers 24,644 ha (USDA-FS 2015), and is occupied by bottomland hardwood forests such as American elm (*Ulmus americana* L.), and red maple (*Acer rubrum* L.), Nuttall's oak (*Quercus texana* Buckley), water hickory (*Carya aquatica* (Michx. F.) Nutt.), and sugar hackberry (*Celtis laevigata* Willd.) (Wehrle *et al.* 1995). Soils in the DNF originated from sediments and are primarily in the Sharkey, Alligator, and Dowling series. They are subjected to flooding, tend to remain wet much of the year, and composed of the highly plastic clays (MSU 2020). Average annual precipitation is about 1,320 mm and most of the rain falls in winter and spring, with highest rainfall in March and lowest in October. Mean annual temperature is 18 °C. A normal year includes 90 days when the temperature exceeds 32 °C and 30 days when the minimum is below 0 °C.

The Holly Springs National Forest covers 62,993 ha in north-central Mississippi (USDA-FS 2015; Figure 1), and comprises two units, Holly Springs in the north and Yalobusha in the south (USDA-FS 2020). The Holly Springs unit consists of hilly uplands characterized by dramatic relief (up to 140 m), a dendritic drainage pattern, and topographic levels up to about 215 m above mean sea level (Peacock & Fant 2002), whereas most of the Yalobusha unit is low alluvial land with a surface elevation ≤30 m (Figure 1). Located in a humid climatic environment, average annual precipitation in the Holly Springs National Forest is 1,397 mm. Winter and spring are wet, and summer and fall dry. The average annual temperature is 16.7 °C (Peacock & Fant 2002). The entire Holly Springs National Forest (two units) consists of stands of pine (61%), hardwood (29%), hardwood-pine (5%), and pine-hardwood (5%) (Aquilani 2006). In this study, only the Yalobusha Unit of Holly Springs (YUH) was selected because it is within the MERAS model domain, while about half of the Holly Springs Unit is not included (Figure 1). The YUH covers some 8,479 ha.

The DNF and most of YUH are in the Mississippi River Valley alluvial plain, while the BNF is on the East Gulf Coastal Plain. Ten hydrogeological units cover parts or all of the three forests – the Mississippi River Valley alluvial aquifer, the Vicksburg-Jackson confining unit, the upper Claiborne aquifer, the middle Claiborne confining unit, the middle Claiborne aquifer, the lower Claiborne confining unit, the lower Claiborne aquifer, the middle Wilcox aquifer, the lower Wilcox aquifer, and the Midway confining unit (Clark & Hart 2009).

Simulation scenario

The models were used in the ModelMuse system to assess the long-term spatial distribution of groundwater levels, as well as the subsurface hydrologic processes in the three forests. The groundwater flow exchange between each forest and the surrounding area was also examined, as well as the groundwater budget for each forest. The simulation period ran from January 1, 1870 to April 30, 2014, a total of 144 years. The subsurface hydrologic processes examined were recharge, storage, stream leakage, well pumping, and flow exchange. The combined effect of these hydrologic processes at any given time determines whether the forest concerned is a net sink or source of groundwater to the surrounding area.

RESULTS AND DISCUSSION

Subsurface hydrologic processes

Groundwater recharge variations over the 114-year simulation period – 1900 to 2014 – are shown in Figure 2. Groundwater recharge in the Mississippi Embayment is taken to include precipitation infiltration, stream leakage, and irrigation infiltration return flow to groundwater (Clark & Hart 2009). The net groundwater recharge is shown in the figure – that is, after evapotranspiration, surface runoff, and vadose zone soil storage. The dataset was obtained by Haugh *et al.* (2020) as the model input. Although all three forests had positive (received) groundwater recharge, two distinct variation patterns occurred. In the DNF and YUH (Figure 2(a)), groundwater recharge increased markedly and fluctuated slightly from 1927 to 1987, after which it fluctuated strongly with a slight decreasing trend. In the BNF, in contrast, groundwater recharge was almost constant from 1900 to 2014 (Figure 2(a)). The major reasons for the marked increase and then slight decrease in groundwater recharge for the DNF and YUH are thought to have been widespread harvesting in them after the 1920s. Harvesting reduces evapotranspiration and enhances groundwater recharge. This is in accord with reports by Ilstedt *et al.* (2016). Additionally, wet years increased groundwater recharge while dry years reduced it. Up to and after 1987, more trees may have been removed over time, increasing surface runoff to some extent and reducing groundwater recharge slightly. On the other hand, the low and almost constant groundwater recharge in the BNF indicated that it was not disturbed significantly by human activity. Soil type and topography also play an important role in groundwater recharge, of course.

The average groundwater recharges over the 114-year simulation period were 72,457 m^3/d in the DNF, 62,953 m^3/d in the YUH, and 4,127 m^3/d in the BNF. These average values cannot be used, however, to compare groundwater recharge in the forests because their areas are different. On that

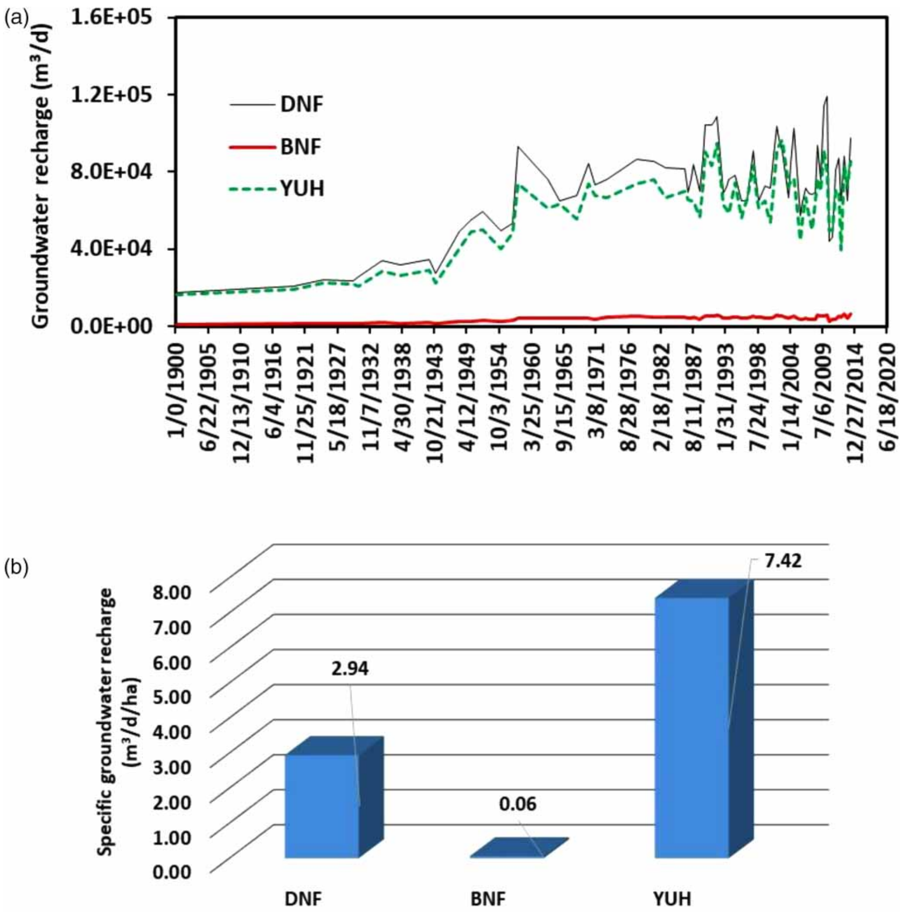

Figure 2 | Time-series plot of groundwater recharge (a) versus area-specific average groundwater recharge (b) over the simulation period (1900–2014).

basis, the concept of area-specific groundwater recharge was introduced. This is obtained by dividing the forest's average groundwater recharge by its area (Figure 2(b)). YUH had the highest area-specific groundwater recharge among the three forests, and the order was YUH (7.42 m^3/d/ha) $>$ DNF (2.94 m^3/d/ha) $>$ BNF (0.06 m^3/d/ha).

While the century-long average value provides an overall picture of groundwater recharge in the national forests, the short- or medium-term average value will present the dynamic variations of groundwater recharge in the areas. As shown in Figure 2(a), three distinct patterns were observed for groundwater recharge: (1) a relative constant from 1900 to 1927, (2) a marked increase from 1927 to 1987, and a slight decrease from 1987 to 2014. For the period from 1900 to 1927, the average groundwater recharges were 19,196 m^3/d in the DNF, 1,121 m^3/d in the BNF, and 17,310 m^3/d in the YUH. For the period from 1927 to 1987, the average groundwater recharges were 61,910 m^3/d in the DNF, 3,401 m^3/d in the BNF, and 52,884 m^3/d in the YUH. For the period from 1987 to 2014, the average groundwater recharges were 80,354 m^3/d in the DNF, 4,632 m^3/d in the BNF, and 70,172 m^3/d in the YUH. Results suggested that the largest average groundwater recharge occurred during the 27 years from 1987 to 2014.

Simulated stream leakage for the forests shows that no groundwater gains (+) or losses (−) occurred from the streams in the BNF or YUH, but a stream leakage fluctuation took place in the DNF (Figure 3). In the latter there was a net loss of groundwater to the streams from 1900 to 1938, as against net gains from the streams from 1938 to 1962 and, again, from 1971 to 2014. The loss to the streams indicated that the groundwater's topographic level was above stream stage, while the opposite was true when stream stage was above the groundwater level. In other words, the

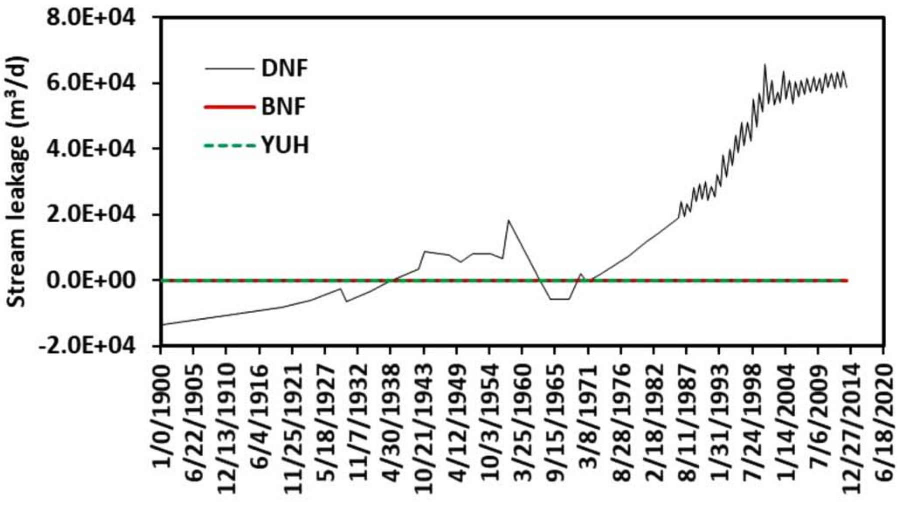

Figure 3 | Time-series plot of stream leakage from 1900 to 2014 in the DNF, BNF and YUH.

groundwater gain from the streams from 1971 to 2014 showed declining groundwater levels in the DNF during the past 43 years. In general, average stream leakage to groundwater over the 114 years was 32,157 m^3/d in the DNF, with an area-specific stream leakage of 1.31 m^3/ha/d.

Groundwater abstraction (pumping) from 1900 to 2014 in the DNF, BNF, and YUH is shown in Figure 4(a). During the period, there was little to no abstraction associated with the BNF and

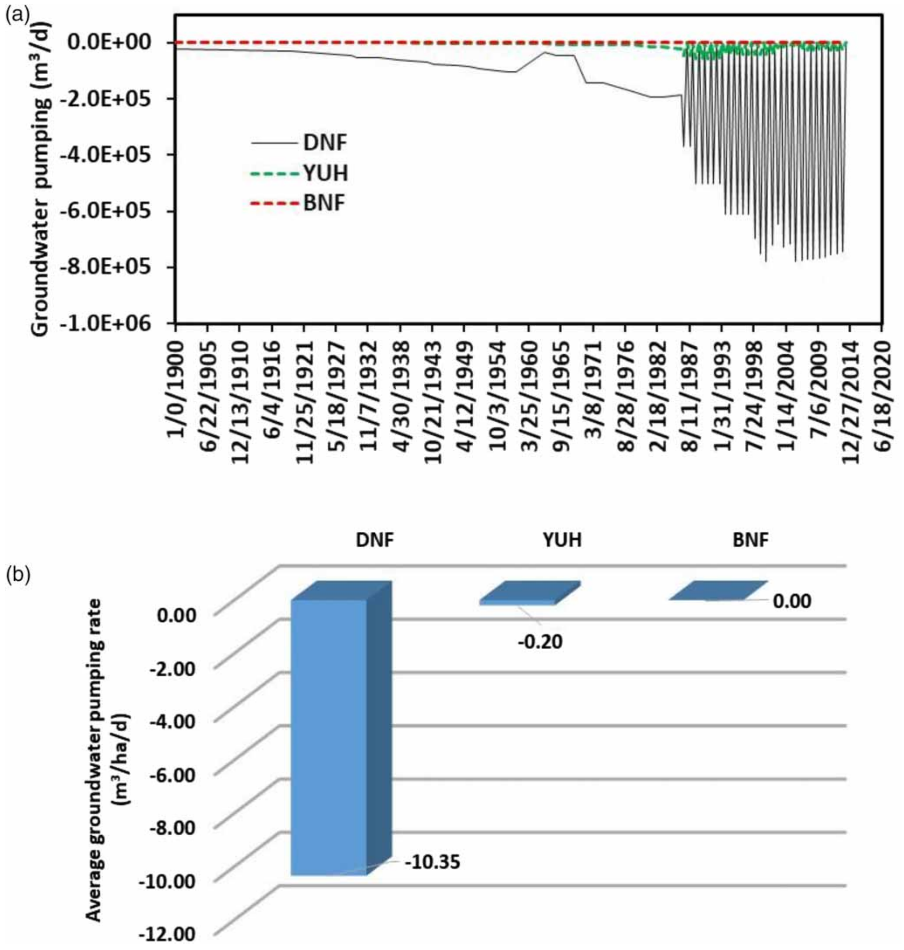

Figure 4 | Time-series plot of groundwater abstraction rate (a) and area-specific average groundwater abstraction rate (b) over the simulation period in the DNF, YUH, and BNF.

YUH, but that associated with the DNF was intense. The increase in abstraction associated with the DNF from 1987 to 2014 was likely due to extensive groundwater use for crop irrigation (Clark & Hart 2009). The area-specific groundwater abstraction rates during pumping were -10.35 m^3/ha/d in the DNF (Figure 4(b)).

Groundwater storage time-series plots for the period 1900–2014 for the forests show fluctuating patterns of storage (+) – that is, water stored in an aquifer – and loss (−) (Figure 5(a)). As with stream leakage, substantial fluctuations in groundwater storage occurred after 1987 for the DNF. The highest groundwater storage (positive value) for the DNF was 580,410 m^3/d in 2006 and the highest groundwater loss (negative) $-242{,}455$ m^3/d in 2009. The average groundwater storages were 31,831 m^3/d in the DNF, 550 m^3/d in the BNF, and 5,306 m^3/d in the YUH during the period from 1900 to 1987, whereas the average groundwater storages were 146,036 m^3/d in the DNF, 5,365 m^3/d in the BNF, and 54,587 m^3/d in the YUH during the period from 1987 to 2014. It is apparent that groundwater storage was much larger for the period from 1987 to 2014. On average over the 114 years, the area-specific groundwater storage was 4.25 m^3/ha/d in the DNF, 4.34 in the YUH, and 0.05 in the BNF (Figure 5(b)). The highest groundwater storage in the DNF was consistent with the highest groundwater recharge (Figure 2(b)) and more stream leakage (Figure 3) there.

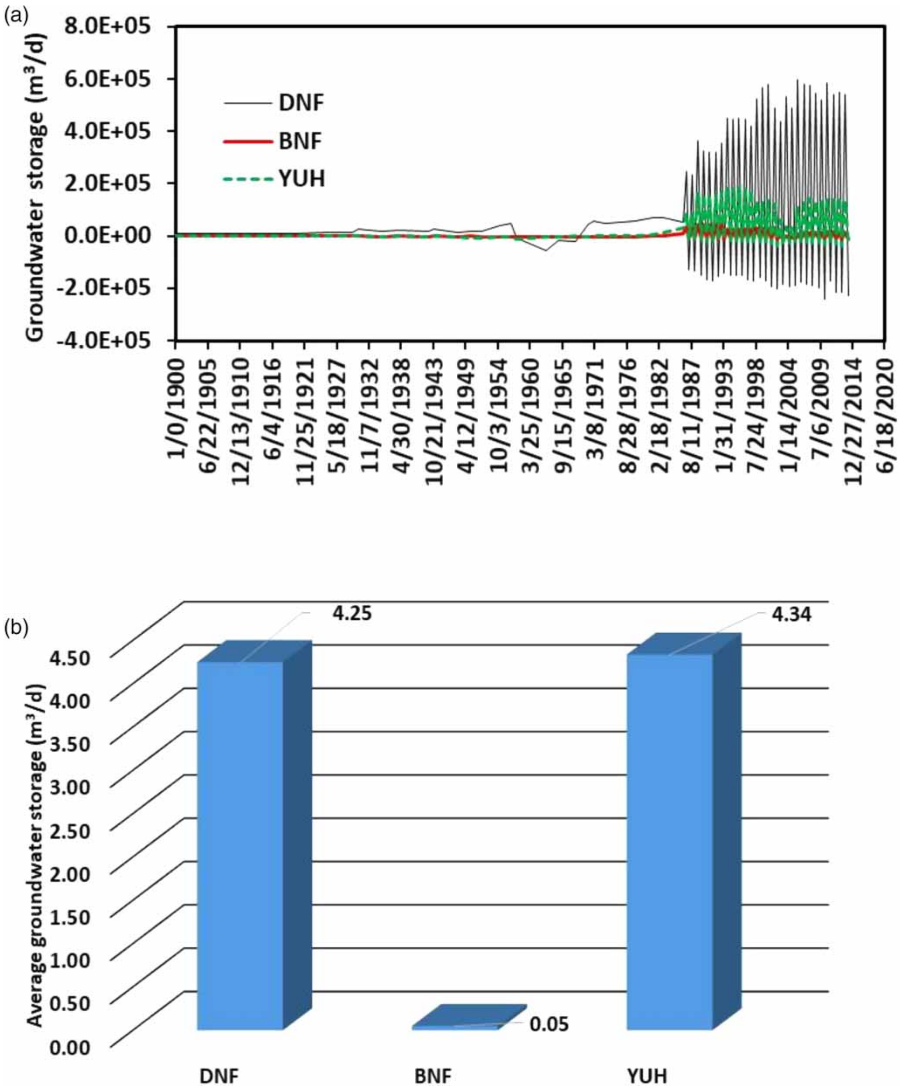

Figure 5 | Time-series plot of groundwater storage (a) and average groundwater storage (b) over the simulation period in the DNF, YUH, and BNF.

Groundwater budget

Figure 6(a) shows the groundwater budgets over the simulation period for all three forests. The groundwater budget is the difference between the aquifer's total gains and losses. A positive budget indicates that the aquifer receives groundwater and is a sink, whereas a negative budget indicates an aquifer delivering groundwater as a source. All three national forests were groundwater sinks during some periods and sources in others (Figure 6(a)). As an example, the maximum groundwater sink (positive) in the YUH was 12.1 m^3/d in 1990, while the maximum groundwater source (negative) at the same location was −18.4 m^3/d in 1998. From 1900 to 1970, fluctuations between groundwater sinks and sources might be due to the impact of wet and dry years. After 1980, frequent groundwater sink/source fluctuations occurred because of increasing agricultural and forest management activities, especially intensive groundwater abstraction in the adjacent croplands. As the groundwater level declined beneath the adjacent croplands due to abstraction, more groundwater flowed in from the forests. When groundwater abstraction stopped in winter, the forests received groundwater as sinks from recharge and stream leakage, and adjacent higher groundwater level locations.

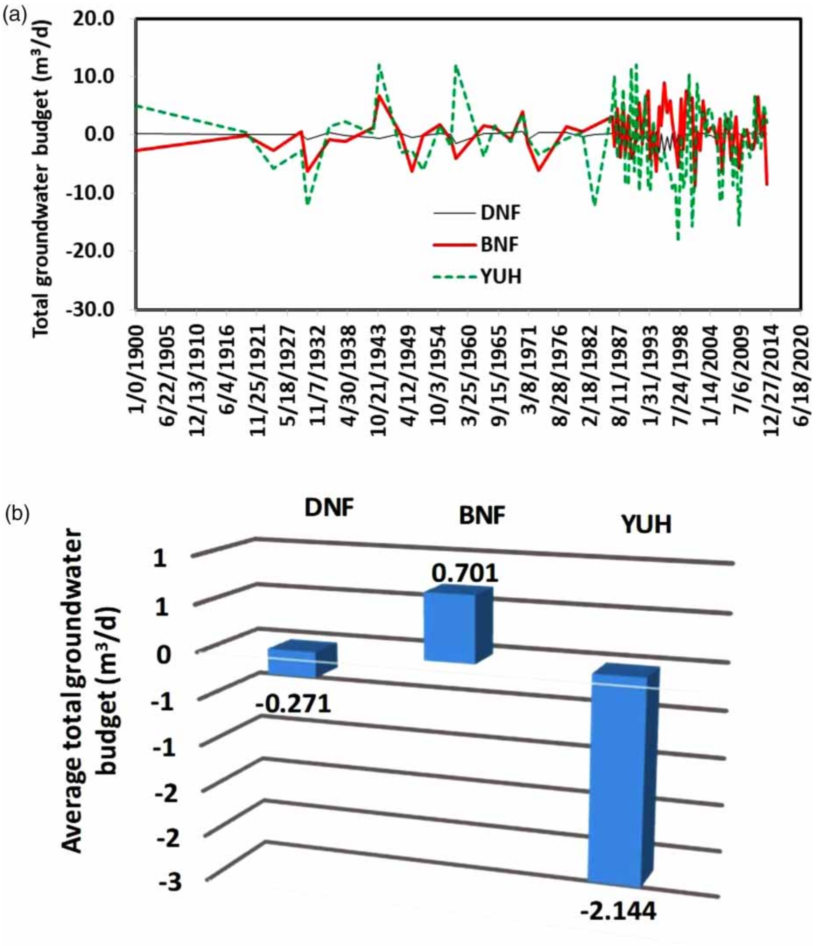

Figure 6 | Time-series plot of total groundwater budget (a) and average total groundwater budgets (b) over the simulation period in the DNF, YUH, and BNF.

The total groundwater budget is more interesting, however. The simulations showed that the average total groundwater budgets over the 114 years were −0.27, 0.70, and −2.14 m^3/d, respectively, for the DNF, BNF, and YUH (Figure 6(b)). In other words, the DNF and YUH delivered groundwater to their surrounding areas and were sources, while the BNF received groundwater from the surrounding areas and was a sink. Overall, the DNF and YUH were groundwater sources (negative budgets) because of the intensive groundwater abstraction in the surrounding croplands, which resulted in groundwater level decline in the croplands and caused groundwater flow from the DNF and YUH. In general, whether the forest was a sink or a source, the amounts of groundwater involved were very small.

As for the cases of groundwater recharge and storage, the century-long average value gives an overall image of groundwater budget, but the short- or medium-term average value will reveal its dynamic variations. For the period from 1900 to 1927, the average groundwater budgets were 0.216 m^3/d in the DNF, -1.851 m^3/d in the BNF, and -0.123 m^3/d in the YUH. For the period from 1927 to 1987, the average groundwater budgets were -0.034 m^3/d in the DNF, -0.174 m^3/d in the BNF, and -0.148 m^3/d in the YUH. For the period from 1987 to 2014, the average groundwater budgets were -0.286 m^3/d in the DNF, 0.715 m^3/d in the BNF, and -2.145 m^3/d in the YUH. Results showed that all of the three national forests delivered groundwater (negative values) to the surrounding areas for the period from 1927 to 1987. More groundwater loss ($-$) or gain ($+$) occurred for the period from 1987 to 2014.

Groundwater distribution

Figure 7 shows the groundwater levels for all three national forests in 1900, 1987, and 2014. In this study, groundwater level is defined as the water table elevation above mean sea level (msl). In 1900,

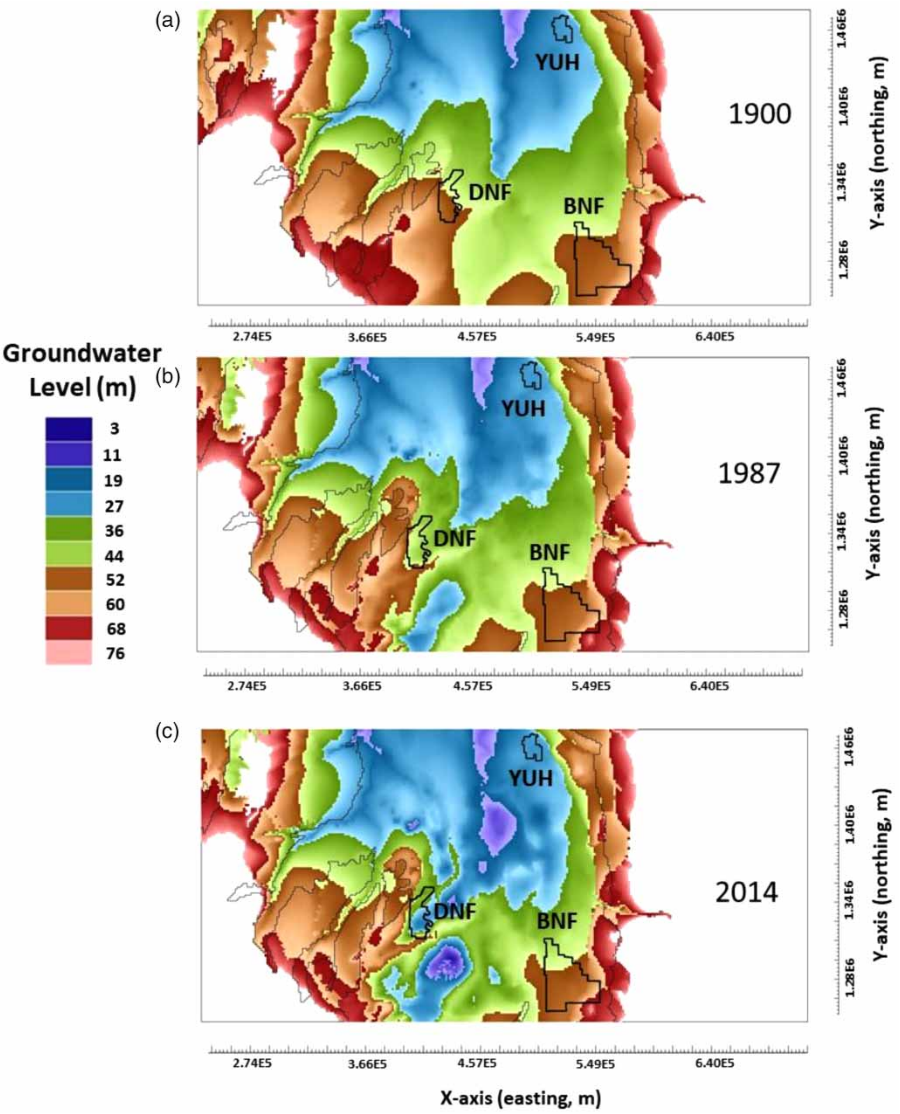

Figure 7 | Groundwater levels in 1900, 1987, and 2014 in the Mississippi Embayment that covers the three national forests.

the groundwater level ranges were 19–27 m msl in the YUH, and 44–52 m in the DNF and BNF (Figure 7(a)). By 1987, the range was about the same in the YUH, had declined to 44 m in most of the DNF area, and declined from 52 to 44 m in part of the BNF (Figure 7(b)). At the end of the simulation period in spring 2014, the groundwater level for about 45% of the DNF had declined to about 27 m, while more of the BNF showed a decline to about 44 m, compared to 1987 (Figure 7(c)). In the YUH, however, groundwater levels were in the same range in 2014 as in 1900 and 1987. The large decline in groundwater level in the DNF from 1987 to 2014 likely occurred primarily due to intensive groundwater abstraction (Figure 4). The area-specific average groundwater pumping rates were −10.35, −0.20, and 0 m^3/ha/d, respectively, in the DNF, YUH, and BNF (Figure 4(b)). The groundwater abstraction rate was more than 51 times higher in the DNF than the YUH. This led to a very substantial groundwater level decline in the DNF compared to the YUH. It is noted in this context

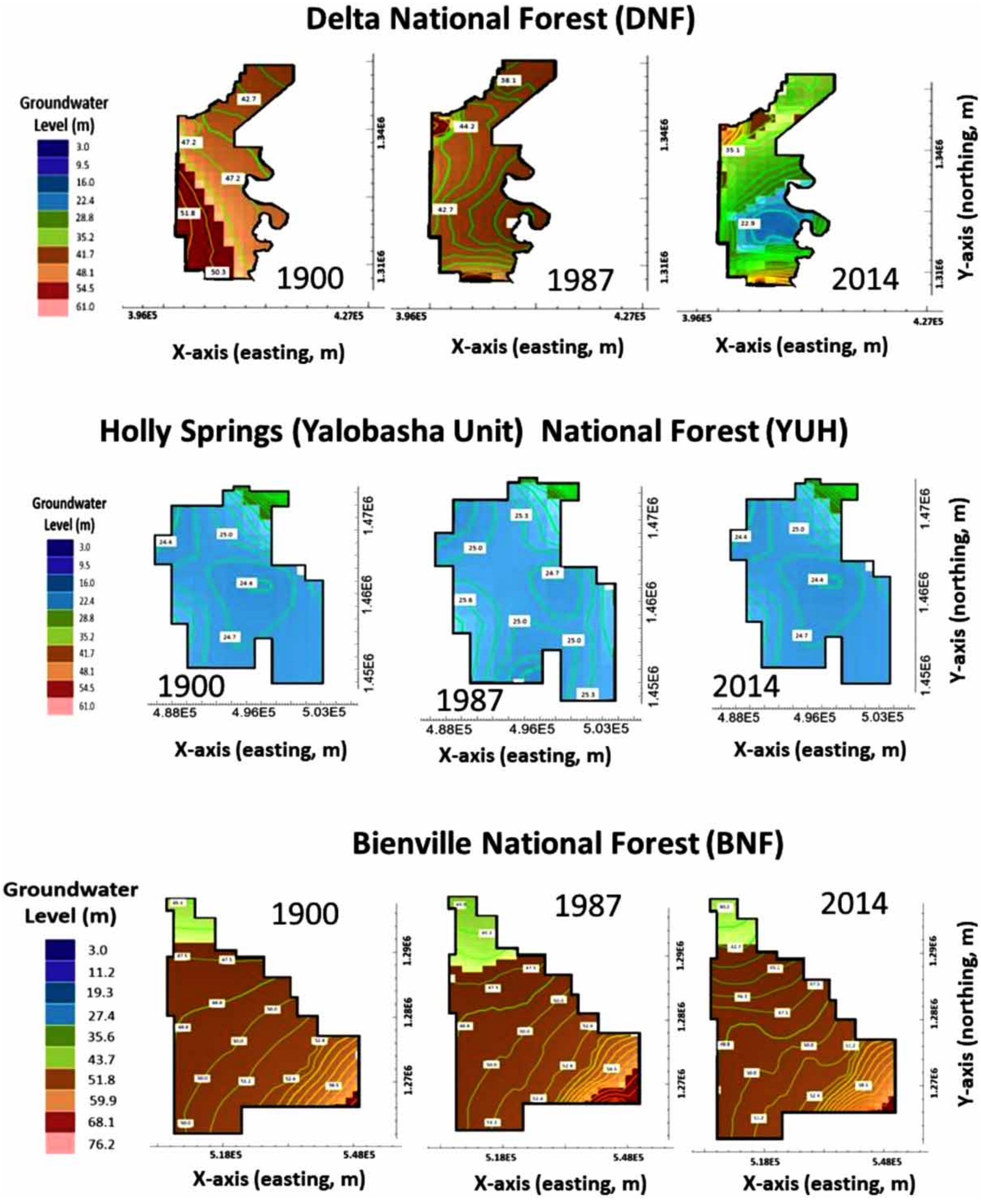

Figure 8 | Spatial distribution of groundwater levels in 1900, 1987, and 2014 in the DNF, YUH, and BNF.

that the intensive groundwater abstraction adjacent to the DNF – that is, in other parts of the Mississippi Delta (Clark & Hart 2009) – also contributed to the groundwater level decline in the DNF.

Spatial and temporal groundwater level variabilities in the DNF, YUH, and BNF are shown in Figure 8. In general, groundwater levels declined during the simulation period in all three forests. In particular, the level declined more in the DNF, than the YUH or BNF. The lowest groundwater levels were 40.2 in 1900 and 24.2 m in 2014 for the DNF; 23.6 and 21.5 m for the YUH (same years); and 45.1 and 39.5 m for the BNF (same years). The maximum groundwater level declines were 16 m (40.2–24.2) in the DNF, 2.1 (23.6–21.5) in the YUH, and 5.6 (45.1–39.5) in the BNF. The rapid decline in groundwater level in the DNF is thought to have arisen because of the intense groundwater abstraction (Figure 4(a)).

SUMMARY

Two distinct patterns of groundwater recharge were observed: (1) marked increases from 1927 to 1987 and strong fluctuations with a slight decreasing trend after that in the DNF and YUH; and (2) almost constant from 1900 to 2014 in the BNF. Groundwater recharge increased markedly in the DNF and YUH because of widespread forest harvesting in the 1920s, which reduced evapotranspiration. The subsequent strong fluctuations and slight decreasing groundwater recharge trend was due to more forest removal over time, which increased surface runoff and reduced groundwater recharge slightly. The constant groundwater recharge in the BNF indicates that there was no significant human or other disturbance.

All three forests served as groundwater sinks in some periods and sources in others over the simulation period. The average total groundwater budgets over the period were -0.27 (the DNF), -2.14 (YUH), and 0.70 (BNF) m^3/d. The net volumetric changes in groundwater storage from the three forest lands were, thus, very small. Groundwater recharge and stream leakage are important contributors to groundwater storage.

In general, groundwater levels declined over the simulation period for the DNF and YUH, that in the DNF more than that in the YUH. The greatest groundwater level decline observed was 16 m in the DNF over the 114-year simulation period and occurred because of intense groundwater abstraction in the vicinity.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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