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Impacts of afforestation on groundwater resource: a case study for Upper Yazoo River watershed, Mississippi, USA

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ABSTRACT

Groundwater resource overdraft is a serious water resource concern worldwide. Although afforestation has been recognized as conserving water resources, improving water quality and mitigating river flood, the role it plays with groundwater resources is not fully investigated. Here we applied the US Geological Survey's Mississippi Embayment Regional Aquifer Study (MERAS) model to estimate impacts of afforestation in croplands on groundwater resource availability in the Upper Yazoo River Watershed (a humid subtropical climate), Mississippi, USA. Simulations showed that the average groundwater level had declined 1.2 m in the croplands over a 20-year period from 1987 to 2007, whereas the average groundwater level had declined only 0.13 m after afforestation for the same simulation period and occurred mainly due to no groundwater pumping and a slight increase in groundwater recharge. Our study implies that afforestation on low-productive croplands in a humid subtropical region could be an alternative to mitigate groundwater depletion.

1 Introduction

Groundwater overuse resulting from anthropogenic activities such as agricultural, domestic and industrial water usages is an issue of water resource concern. Many regions of the world are facing challenges in terms of the decline and/or shortage of groundwater resources (Giordano 2009, Famiglietti 2014). One such region is the humid subtropical Mississippi Delta (Konikow 2013, Ouyang *et al.* 2019), a key region for soybeans, corn and cotton production in the Southeast United States (MSU Extension Service 2020). To maximize crop yields, the land area for crop irrigation has increased by 92% since 1998, resulting in a significant depletion of groundwater resources (Powers 2007, Vories and Evett 2014, YMD (Yazoo Mississippi Delta Joint Water Management District) 2015, Ouyang *et al.* 2016). It is reported that the average loss of groundwater in the Mississippi Delta was about 493 000 000 m³/year from 1987 to 2014 (YMD (Yazoo Mississippi Delta Joint Water Management District) 2015). With a need to mitigate groundwater resource depletion in this humid subtropical region, several approaches are employed to reduce groundwater usage, including the construction of farm water storage ponds for crop irrigation (Ouyang *et al.* 2018), the improvement of irrigation efficiency (Kebede *et al.* 2014), and afforestation (Ouyang *et al.* 2013).

Cropland afforestation is a field process to grow trees in the croplands, especially in the marginally and low-productive croplands, to create forest plantations. Afforestation conserves rainwater, diffuses surface runoff and absorbs pollutants, which mitigates river flooding, reduces stream pollutant load and generates clean water (Ouyang *et al.* 2013). Despite the

above advantages, diverse results are obtained pertaining to the impacts of afforestation on groundwater recharge (Allison *et al.* 1990, Ilstedt *et al.* 2016, Owuor *et al.* 2016, Adane *et al.* 2018, Ouyang *et al.* 2019). Owuor *et al.* (2016) reported that forest lands reduce groundwater recharge in the semi-arid tropical and subtropical regions. Ilstedt *et al.* (2016), on the other hand, stated that groundwater recharge is maximized at an intermediate tree density. Using the Hydrological Simulation Program-FORTRAN (HSPF) model, Ouyang *et al.* (2019) recently demonstrated that forest land slightly increases groundwater recharge as compared to that of the cropland in a humid subtropical watershed of Mississippi. Although the above studies provided some useful insights on how forest lands affect groundwater recharge, a thorough review of the literature reveals that very little effort has been made to estimate the effect of afforestation on groundwater resource availability in the humid subtropical region.

Understanding the interaction of groundwater resources between the forest lands and the adjacent croplands is a prerequisite for afforestation in the regions affected by groundwater resource shortage and depletion. A quantitative estimate of groundwater resource availability from forest lands to the adjacent croplands is also crucial to groundwater withdrawal planning for crop irrigation in the regions. To date, very little attention has been paid to tackling these issues. Since the field measurement of groundwater resource availability (which varies with time and space) is time-consuming and challenging, a modeling approach is used in this study.

The goal of this study was to assess the roles of afforestation on groundwater resource availability in the humid subtropical region

using the MODFLOW model. As a case demonstration, the upper Yazoo River watershed (UYRW) in Mississippi, located in the humid subtropical region, was selected as the study site. More specifically, we have: (1) slightly modified the Mississippi Embayment Regional Aquifer Study (MERAS) model, which is a site-specific MODFLOW model developed by the United States Geological Survey (USGS), for the purpose of this study; (2) imported the modified MERAS model into the USGS ModelMuse modeling system for better pre- and post-processing of modeling inputs and outputs; (3) applied the model to assess the groundwater resources in the forest land and the adjacent cropland; and (4) employed the model in conjunction with the ZONEBUDGET model to ascertain the inflow and outflow of groundwater from the UYRW after afforestation.

2 Materials and methods

2.1 Description of models

MODFLOW is the USGS modular three-dimensional finite difference flow simulation model (McDonald and Harbaugh 1988). The governing equation describing a three-dimensional groundwater flow system is given as:

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

where S_s is the groundwater storage (L^{-1}); h is potentiometric head (L); t is the time (T); K_{xx}, K_{xx}, and K_{xx} are the saturated hydraulic conductivities (L T^{-1}) along x-, y-, and z-axes, respectively; and W is the sink or source term (T^{-1}). Since its first release in early 1980, several versions of MODFLOW have been developed. MODFLOW is well known and widely used internationally, and a detailed description of this groundwater model and its recent development can be found elsewhere (McDonald and Harbaugh 1988, Harbaugh 2005, USGS 2005, Hughes et al. 2017).

The MERAS model, constructed by USGS with MODFLOW-2005, is used to assess groundwater availability within the Mississippi Embayment (Clark and Hart 2009, Clark et al. 2013). The modeled domain is approximately 202 019 km^2, encompassing eight states (Fig. 1a). The model includes 11 105 km of simulated streams, 70 000 well locations and 10 primary hydrogeologic units, and has a finite difference grid of 414 rows, 397 columns and 13 layers. Each model cell is 2.59 km^2 (or 1 square mile) with varying thickness by cell and by layer. The MERAS model has different hydrogeological and numerical boundary conditions, with 69 stress periods. A moderate description of these boundary conditions is given below for readers' convenience.

The hydrologic boundaries of the MERAS model mainly include areal recharge, groundwater pumpage, streams and no-flow. The areal recharge rates were estimated as a fraction of precipitation based on soil type, geomorphology, land use and surficial geology during model calibration. Groundwater
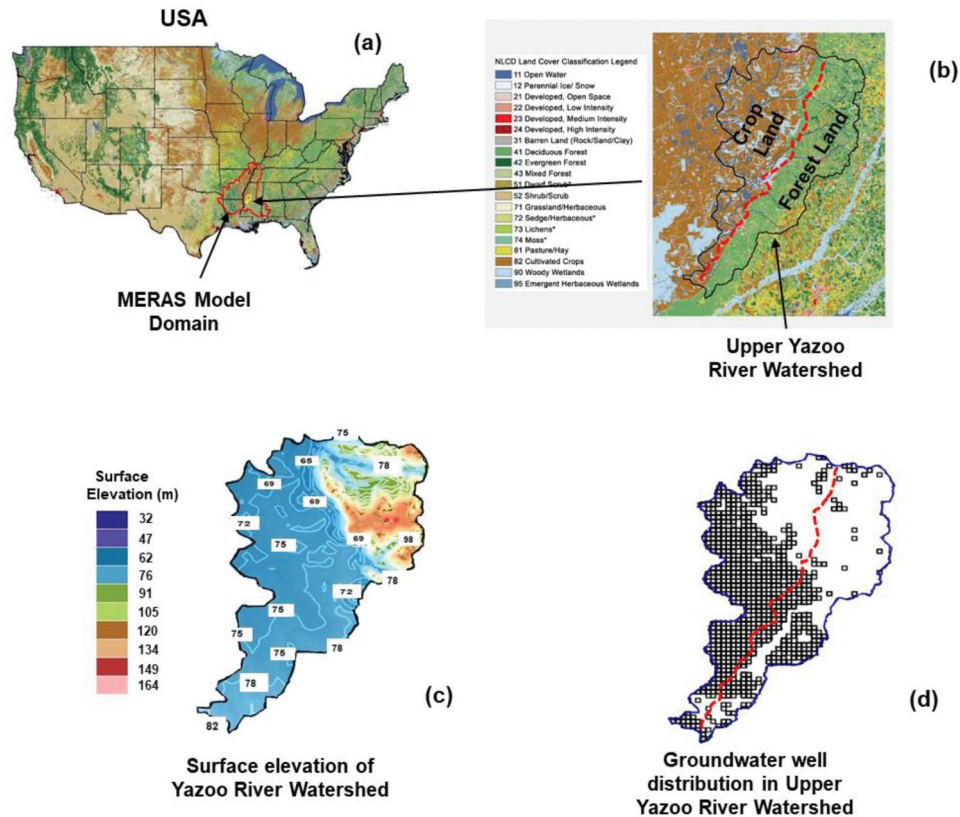

Figure 1. Locations of the Mississippi Embayment Regional Aquifer Study (MERAS) modeled: (a) domain, (b) land uses, (c) surface elevation, and (d) groundwater well distribution in the Upper Yazoo River watershed.

pumpage is modeled using the Multi-Node Well (MNW) Package in MODFLOW, which allows the simulation of flow in wells from the multiple aquifers or model layers. The number of wells increased during simulation time as the groundwater pumpage demand increased. A total of 43 streams was selected in the MERAS model using the Streamflow Routing (SFR) package. The SFR package allows input for surface run-off into streams. The perimeter of the model area and the base of the flow system are represented as no-flow boundaries. A no-flow boundary was used at the perimeter of the model area, which represents the area where flow into or out of the model area is assumed to be trivial. Initial conditions are obtained using a steady-state stress period representing conditions prior to 1 January 1870. In addition, the model was rigorously calibrated and validated prior to its applications. An elaborated description of the boundary and initial conditions used in the MERAS model can be found elsewhere (Clark and Hart 2009, Clark et al. 2013).

Developed and maintained by USGS, ModelMuse is a graphical user interface modeling system for running the MODFLOW, MODPATH, ZONEBUDGET, PHAST, SUTRA, MT3D, and WellFootprint models (USGS 2020). In addition to its public availability, the major advantages of ModelMuse are that the spatial data are grid independent and the temporal data are stress-period independent, advantages that provide flexibility for users to freely redefine the spatial and temporal discretizations. The MERAS model was imported into the ModelMuse in this study. Although it takes much longer to execute the MERAS model, ModelMuse provides a user friendly pre- and post-processing of model inputs and outputs.

ZONEBUDGET is a model that calculates sub-regional groundwater budgets using the simulation results from the MODFLOW model (Harbaugh 1990). Users delineate the sub-regions of interest and define them by zone numbers; the ZONEBUDGET model then calculates the groundwater budget for each zone by computing the hydrological components (e.g. recharge, aquifer storage, stream leakage, and well pumping or injection). The budget for a zone also includes a water component of inflow or outflow from the adjacent area. In this study, the ZONEBUDGET model was employed to calculate groundwater inflow and outflow from the UYRW.

2.2 Study site

In this study, we selected the UYRW, which is a watershed within the MERAS modeled domain (Fig. 1a). The UYRW is located in a humid-subtropical region of Mississippi. The west side of the watershed is within the alluvial valley of the Mississippi Delta, whereas the east side of the watershed is a bluff hill just adjacent to the Mississippi Delta (Fig. 1(b,c)). The watershed has an area of 4025 km^2, with 1973 km^2 of agricultural land (49%), 1831 km^2 of forest land (46%) and 221 km^2 of land devoted to other uses (5%). The major soil types are sand, loam and clay, and the major tree species are oak, gum, hickory, cypress, Loblolly pine and shortleaf pine (US-EPA 1998; MDEQ (Mississippi Department of Environmental Quality) 2008). This watershed was selected because it has both the forest and croplands necessary for the purpose of this study.

Since the UYRW is within the MERAS model domain, we do not need to define the boundary conditions of the UYRW in order to execute the MERAS model and obtain the simulation results for the UYRW. However, a general description of the hydrogeological and physical boundaries as well as the model layer information is given below for readers' convenience.

There are 10 hydrogeologic units covering part or all of the UYRW: 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 and Hart 2009). As shown in Fig. 1(b), there are some streams and surface water bodies in the UYRW in addition to the crop and forest lands.

Vertically, the UYRW was discretized into 13 model layers. Layer 1 is the alluvial aquifer, Layer 2 is the Vicksburg-Jackson confining unit, Layer 3 is the upper Claiborne aquifer, and Layer 4 is the middle Claiborne confining unit. The middle Claiborne aquifer occupies Layers 5 to 7. Layer 8 represents the lower Claiborne confining unit, Layer 9 represents the Winona-Tallahata, and Layer 10 represents the lower Claiborne aquifer. Layer 11 denotes the middle Wilcox aquifer, and Layers 12 and 13 denote the lower Wilcox aquifer. A detailed description of each layer can be found in Clark and Hart (2009).

2.3 Model evaluation and scenario

Although the entire MERAS model has been calibrated by Clark and Hart (2009), it is still necessary to evaluate the MERAS model performance for the UYRW. The evaluation was conducted by validating the groundwater head distributions over time through the comparison of model predictions and field observations using statistical measures such as coefficient of determination (R^2), normalized root mean square error (nRMSE), and Nash-Sutcliffe efficiency (NSE). The measured data for validation was obtained from Clark and Hart (2009). The nRMSE normalized by mean is calculated as (Otto et al. 2018):

$$nRMSE = \frac{1}{\overline{O}}\left(\sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)}{n}}\right) \qquad (2)$$

where O_i is the field observation, S_i the model prediction, $\overline{O}$ the average of field observation, and n the total number of field observations.

The NSE is given as (Nash and Sutcliffe 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \qquad (3)$$

The NSE ranges from $-\infty$ to 1 with a value of 1 for a perfect fit, > 0.75 for very good fit, 0.36–0.75 for a reasonable fit, and < 0.36 for an unsatisfactory fit of the model (Krause et al. 2005).

Two simulation scenarios were developed in this study. The first was a base scenario for the commonly used agricultural pumping conditions as well as for the natural forest conditions

that normally exist in the UYRW. A comparison of the simulated groundwater levels and heads from the forest land and cropland in this scenario would ascertain which land use conserves more groundwater resources under the natural conditions.

The second scenario was the same as the first except that the cropland was converted to the forest land as a result of afforestation. More specifically, all of the 3126 groundwater pumping wells at the UYRW (Fig. 1(d)) were removed (or turned off) from the cropland after it was converted to the forest land, because no groundwater pumping is needed for tree irrigation in this humid subtropical region. These wells have different pumping rates for different crop species during the growing season, which were obtained from local agencies and/or stakeholders by Clark and Hart (2009).

In addition, the groundwater recharge rate in the cropland was assumed to have increased by 1% after it was converted to the forest land. Recently, Ouyang *et al.* (2019) applied the HSPF model to estimate the groundwater recharge in the forest land of the Lower Yazoo River Watershed (LYRW), which is located just south of the UYRW. These authors found that the annual groundwater recharge rate is slightly (1%) higher in the forest land than in the cropland. Based on this research finding, the MERAS model was modified to increase the groundwater recharge by 1% after the cropland was afforested. The procedures used to modify MERAS for this purpose are described below.

The MERAS model cells for the croplands in the UYRW were identified using the recharge zone number, 108, which corresponds to the Legend 82 Cultivated Crops of National Land Cover Database. Groundwater withdrawals from these cells (or in the cropland areas) were turned off by modifying the Multi-Node Well (MNW1) package (filename "meras_mnw1b.mnw"), and a 1% increase in recharge was applied to these model cells by introducing an array multiplier in the Multiplier File Package (filename "meras_trSoils.mlt"). It should be noted that although the groundwater recharge rate in the afforested land varies with tree ages, we assumed that our simulation is for the average mature tree growth conditions. The second scenario would determine how the afforestation mitigates the groundwater resource depletion. The simulation started on 1 January 1870 and ended on 31 March 2007, for a total simulation period of 137 years, with a variable stress period.

3 Results and discussion

3.1 Head validation at the UYRW

It should be noted that the entire MERAS model has been calibrated and validated by USGS (Clark and Hart 2009, 2013), and the UYRW is within the MERAS modeled domain (Fig. 1). In the field of computer modeling, however, it is very common that a model at a large scale (or a low resolution) with very good calibration and validation may not be applicable at a small scale (or a high resolution). In this study, we further validated the groundwater head for the UYRW to develop confidence in the model application. The groundwater head validation was accomplished by comparing the model predictions with field observations. There were 106 observation sites

with 254 observed groundwater head data points at the UYRW from 1947 to 2006 over a 60-year period. The dataset was obtained by Clark and Hart (2009) and was used to test the model predictions in this study (Fig. 2(a)). With the linear regression equation $Y_{predicted} = 0.9885\ X_{measured}$, $R^2 = 0.791$, $p < .1$, NSE = 0.42, and nRMSE = 0.097 m, we demonstrated that the MERAS model predicted the groundwater head distribution reasonably well at the UYRW.

A time series plot of groundwater heads between the model prediction and the field observation is given in Fig. 2(b). Results show that the model predictions of groundwater head visually matched the field observations of groundwater head satisfactorily, which further confirms that the MERAS model is feasible for predicting groundwater flow and head distribution in the UYRW.

3.2 Groundwater distribution in the crop and forest lands

Very few efforts have been devoted to comparing groundwater distributions between two connected forest lands and croplands in the literature. Figure 3 shows the spatial distributions of groundwater levels (depth-to-table) in the crop and forest lands at the UYRW in the springs of 1987 and 2007 from the base scenario. The cropland (left) and the forest land (right) of the UYRW are separated by a dash line in the figure. The groundwater level ranged from 23 to 57 m in 1987 with levels for the cropland of ≤ 34 m and for the forest land of ≥ 34 m. It is apparent that the groundwater level was lower (or shallower) in the cropland than in the forest land (Fig. 3(a)). This occurred because the cropland is located at the alluvial valley while the forest land is primarily situated at the bluff hill.

After 20 years, from 1987 to 2007, the groundwater level in the cropland had declined (or became deeper) in the UYRW (Fig. 3(b)). For example, the area with the groundwater level at 34 m in the cropland increased from about 80 km^2 in 1987 (Fig. 3(a)) to about 435 km^2 in 2007 (Fig. 3(b)). In other words, there were about 355 km^2 of the cropland in which the groundwater level had increased (or became deeper) from 29 m in 1987 to 34 m in 2007. A similar result was found for the forest land. That is, the area of groundwater level at 40 m was reduced as the area of groundwater level at 46 m was extended from 1987 to 2007. It is apparent that the groundwater level had declined (or became deeper) over a 20-year period at the UYRW. We attributed this decline to the pumpage of groundwater resource for crop irrigation. There were 3126 wells installed in the cropland of the UYRW, with various groundwater pumping rates and schedules during the growing season.

Spatial distributions of groundwater (hydraulic) head at Layer 1 for the UYRW in the springs of 1987 and 2007 from the base simulation scenario are shown in Fig. 4. The elevation of the top layer ranges from 65 to 149 m (Fig. 1(c)), and that of the bottom layer ranges from −120 to 215 m. There was no groundwater head in the forest land at Layer 1 because there was no groundwater in the forest land at this layer. The area of the cropland with groundwater head at 13 m decreased from 470 km^2 in 1987 (Fig. 4(a)) to 369 km^2 in 2007 (Fig. 4(b)). A 20-year time span reduced the area of the cropland groundwater head at 13 m by 101 km^2 or 22%. The area at 13 m was replaced by the area at 9 m. This change occurred due to the
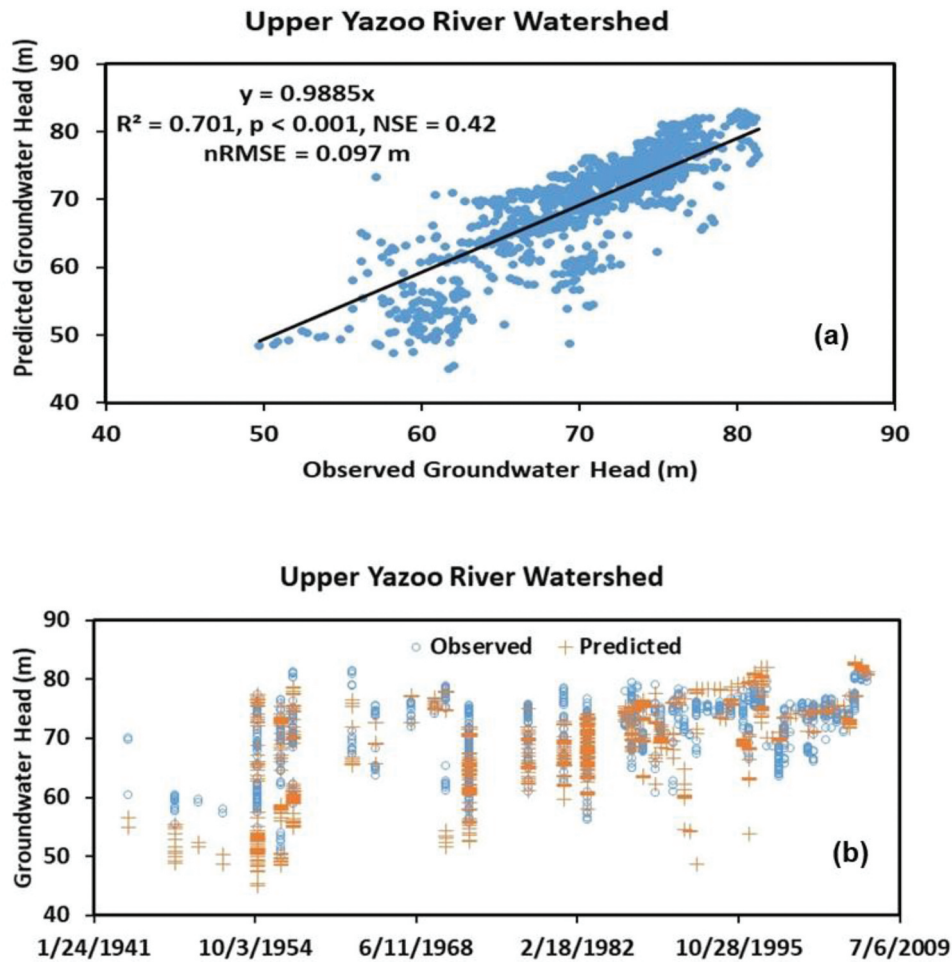
Figure 2. (a) Comparison of observed and predicted groundwater heads and (b) time series plots of the observed and predicted groundwater heads.
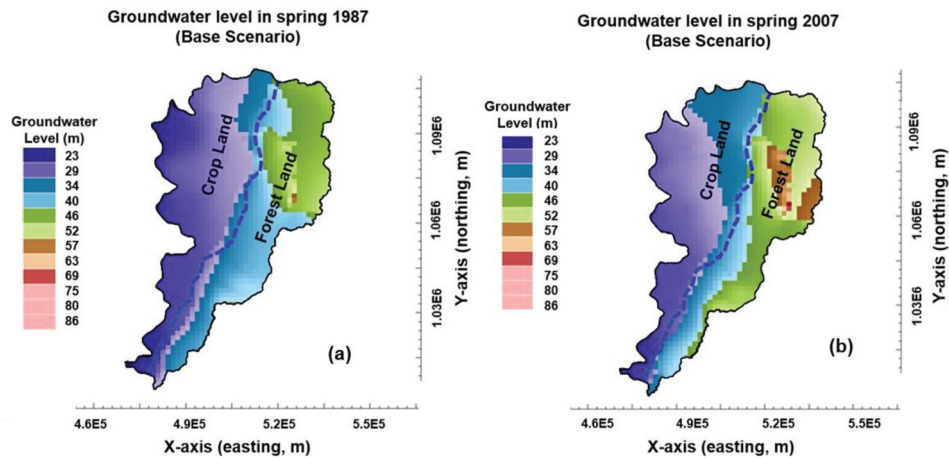

Figure 3. Spatial distributions of groundwater levels from the base scenario in the springs of (a) 1987 and (b) 2007.

groundwater pumpage for crop irrigation. Groundwater generally flows from the high-head area to the low-head area. As the area with groundwater head decreased, less groundwater resource was available.

Variations in groundwater head at Layer 5 are shown in Fig. 5. The top elevation of this layer ranges from −544 to 215 m and the bottom elevation of the layer ranges from −616 to 212 m. In general, the groundwater heads at this layer were lower in the

cropland than in the forest land, indicating that the groundwater flows from forest land (high head) to cropland (low head) at this layer. Analogous to the case of Layer 1, the area with low groundwater head increased and that with high groundwater head decreased in the cropland as time elapsed from 1987 to 2007. For example, the area with groundwater head at 37 m in the cropland decreased by 27% over the 20-year period from 1987 to 2007 due to the use of groundwater resource for crop irrigation.
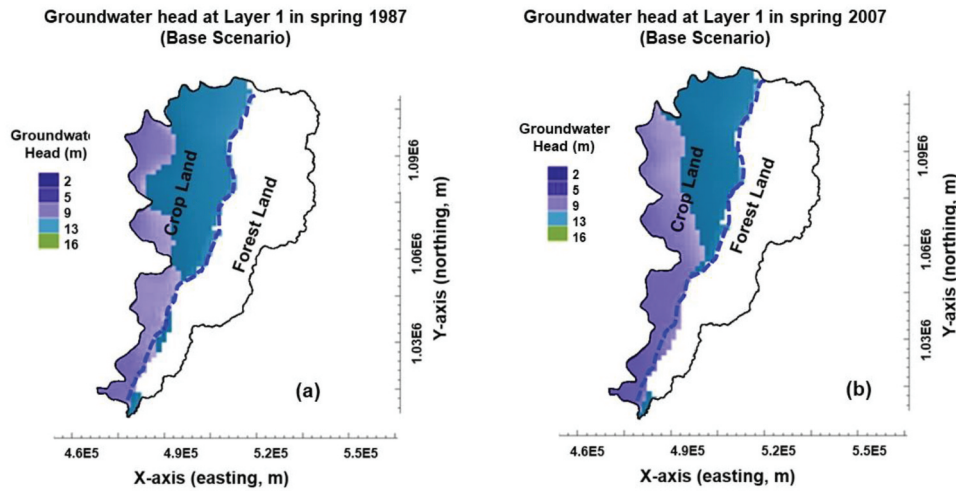
Figure 4. Spatial distributions of groundwater heads at Layer 1 from the base scenario in the springs of (a) 1987 and (b) 2007.
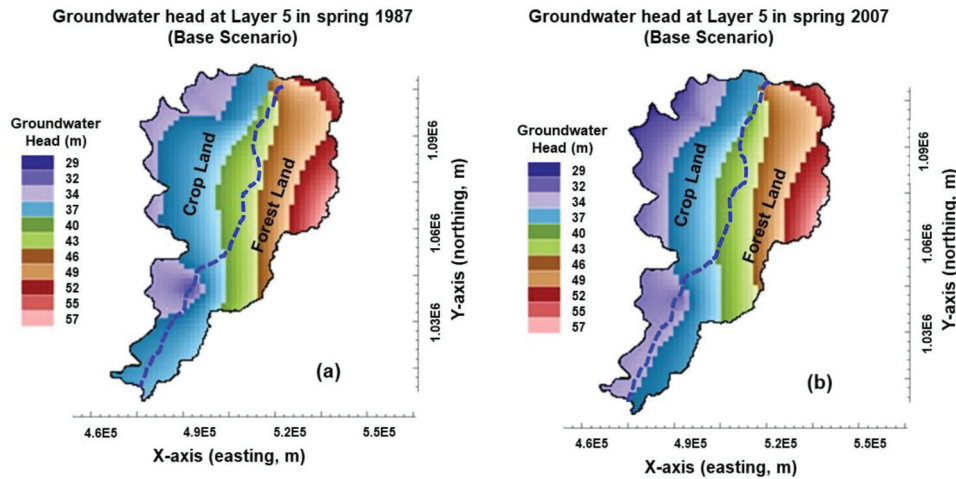

Figure 5. Spatial distributions of groundwater heads at Layer 5 from the base scenario in the springs of (a)1987 and (b) 2007.

In contrast, the changes in groundwater head were somewhat small in the forest land, especially at the heads of 49, 52, and 55 m in this layer. This likely occurred because most of the groundwater pumping wells were in the cropland and were placed in the top two layers, and therefore had few pumping effects on groundwater head in the deeper layer (or Layer 5) in the forest land.

A time series plot of averaged groundwater head for all 13 layers of the UYRW from the base scenario, over a 137-year simulation period from 1870 to 2007, is given in Fig. 6. Results show that the average groundwater head had declined since 1970. In particular, the average groundwater head was 33.1 m in 1987 but was 31.9 m in 2007. A 20-year elapsed time span resulted in a 1.2 m decline in the average groundwater head at the UYRW. With a total area of 4025 km^2 for the UYRW, the average loss of groundwater was estimated to be 4.83E + 09 m^3 over a 20-year period. In other words, the rate of groundwater decline was about 60 000 m^3/ha/year at the UYRW.

3.3 Effect of afforestation on groundwater

Spatial distributions of the groundwater level at the UYRW from the afforestation simulation scenario in 1987 and 2007 are given in Fig. 7. There was a very small change in groundwater-level distribution between 1987 and 2007 at the UYRW for this scenario, especially in the afforested area. Results indicated that afforestation had mitigated groundwater decline, primarily due to the removal (or shutoff) of groundwater pumping wells and, to a lesser extent, the increase of groundwater aquifer recharge by 1% after afforestation. A comparison of Fig. 3(b) and Fig. 7(b) reveals that the area with the groundwater level at 34 m was reduced by 19% but that at 29 m was increased by the same percentage after afforestation. Results show that afforestation increased groundwater level (i.e. it became shallower).

Spatial variations in groundwater head at Layer 1 in the springs of 1987 and 2007 from the afforestation simulation scenario are given in Fig. 8. After 20 years of afforestation, the area with groundwater head at 13 m in the afforested land increased by 30%. In other words, about 30% of the area with groundwater head at 9 m was replaced by area with groundwater head at 13 m. As the groundwater head increased, more water was stored in the aquifer. The results demonstrate that conversion of cropland into forest land increased groundwater resources in the top layer of the UYRW. This occurred
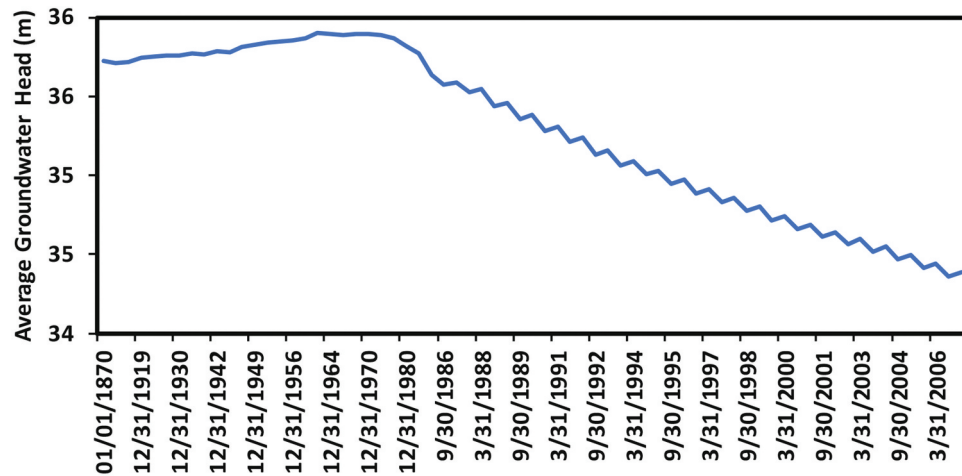
Figure 6. A time series plot of average groundwater head at the UYRW from 1870 to 2007.
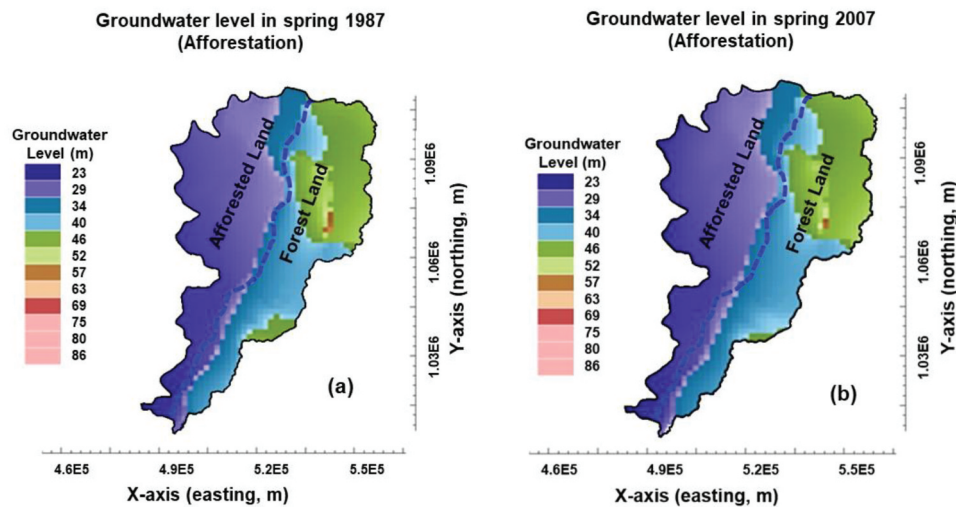

Figure 7. Spatial distributions of groundwater level from the afforestation scenario in the springs of (a)1987 and (b) 2007.
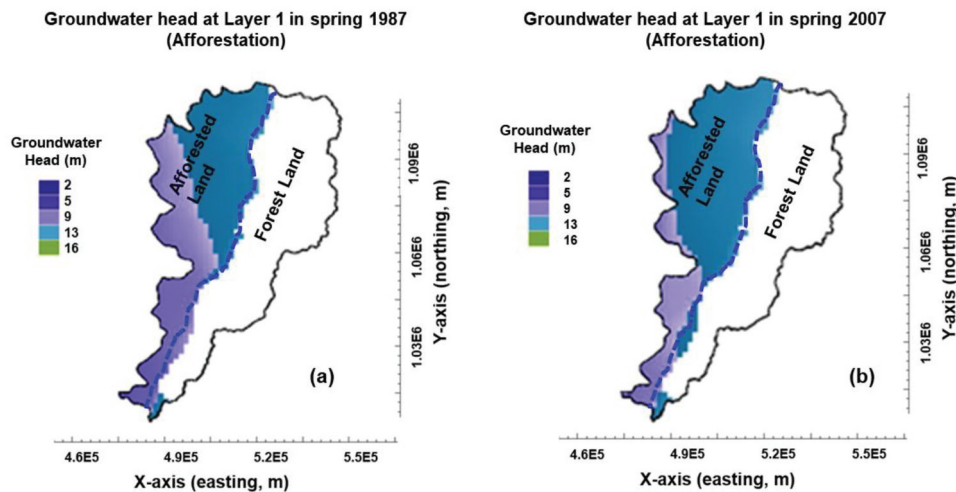

Figure 8. Spatial distributions of groundwater head at Layer 1 from the afforestation scenario in the springs of (a) 1987 and (b) 2007.

primarily due to the removal of deep aquifer pumping wells and the increase of groundwater aquifer recharge after afforestation.

Similar results were found in Layer 5 (Fig. 9). That is, the area with high groundwater head had increased in the afforested land. For instance, the area with groundwater head at
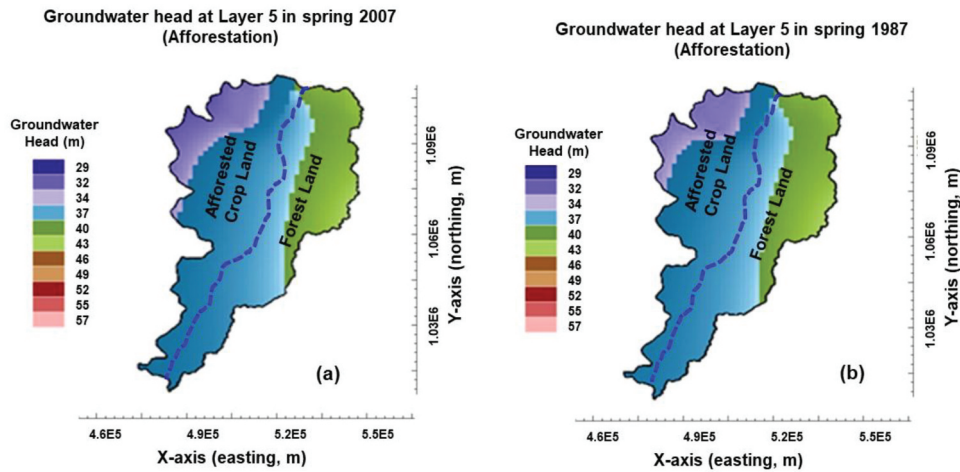
Figure 9. Spatial distributions of groundwater head at Layer 5 from the afforestation scenario in the springs of (a)1987 and (b) 2007.

37 m in the afforested land had increased by 5% at this layer over 20 years from 1987 to 2007, for the same reason as the increase that occurred in Layer 1. However, a comparison of Figs 8 and 9 shows that the increase in the area with the higher groundwater head was smaller in the deep layer (i.e. Layer 5 in this case) than in the shallow layer (i.e. Layer 1 in this case). This was expected, because most of the groundwater pumping wells are located in the top two layers.

A comparison of the average groundwater head changes for all 13 layers of the UYRW between the base scenario and the afforestation scenario from 1870 to 2007 is given in Fig. 10(a). Having begun in 1987, the difference in average groundwater head between the two simulation scenarios began to develop. More specifically, the average groundwater head had declined by 1.2 m over a 20-year period from 1987 to 2007 without afforestation, but had declined by only 0.13 m over the same period with afforestation. The 0.13 m decline is due to the regional pumping outside of the UYRW. Results further confirmed that afforestation in the cropland recovered the groundwater resource of this humid subtropical watershed.

We attribute this finding primarily to the "removal" or turnoff of the groundwater pumping wells. This attribution was validated by comparing the simulated average groundwater heads in the afforestation scenario with and without changing the groundwater recharge rate (Fig. 10(b)). As stated in Section 2.3, the groundwater wells were "removed" and the groundwater recharge rate had increased by 1% in the afforested land for the afforestation scenario. Simulation results show that the average groundwater heads over a 20-year period were slightly decreased for the conditions with and without a 1% increase in groundwater recharge rate (Fig. 10(b)). Therefore, the recovery of groundwater resources from the afforestation scenario was primarily due to the removal of groundwater pumping wells.

With a total area of 4025 km^2 for the UYRW and the average groundwater head loss of 0.13 m, the groundwater depletion after afforestation was about 5.23E + 08 m^3 (4.025E + 09 × 0.13 = 5.23E + 08) over the 20-year simulation period. In other words, the rate of groundwater decline was about 2616 m^3/ha/year after afforestation. As compared to the

rate of groundwater decline of 60 000 m^3/ha/year without afforestation, afforestation had saved groundwater by 57 383 m^3/ha/year (60 000–2616 = 57 383) over the 20-year simulation period at the UYRW.

Impacts of afforestation on average net daily groundwater flow over the 136-year simulation period from 1870 to 2007 for the UYRW are shown in Fig. 10c. The simulation results in the figure were obtained with the ZONEBUDGET model. The net groundwater flow is the difference between the groundwater flow into and out of a watershed. A positive groundwater flow indicates the watershed receives groundwater as a sink from the surrounding area, whereas a negative groundwater flow indicates the watershed delivers groundwater as a source to the surrounding area. On average, the UYRW was a source (negative value) of groundwater over the 136-year simulation. Comparison of the average net daily groundwater flow between the base scenario and the afforestation scenario reveals that the UYRW supplied more groundwater as a source to the surrounding area after afforestation (Fig. 10 (c)). That is, the average net daily groundwater flow was −4.41E+07 m^3/d for the afforestation scenario and −4.39E + 07 m^3/d for the base scenario. After afforestation, the UYRW supplied 2.0E + 05 m^3/d groundwater to the surrounding area. Results confirmed the afforestation conserved the groundwater resource.

4 Conclusion

The groundwater level was shallower in the cropland than in the forest land at the UYRW, because the cropland is located at the alluvial valley while the forest land is situated at the bluff hill. Overall, the groundwater level had declined (or became deeper) over a 20-year period from 1987 to 2007 in this watershed, which occurred primarily due to the groundwater pumpage for crop irrigation and, to a lesser extent, because of the increase of groundwater recharge.

Over a 20-year simulation period, the area of high groundwater head was replaced with that of low groundwater head. This change was more significant in the top layer than in the deep layer, which occurred because most of the groundwater
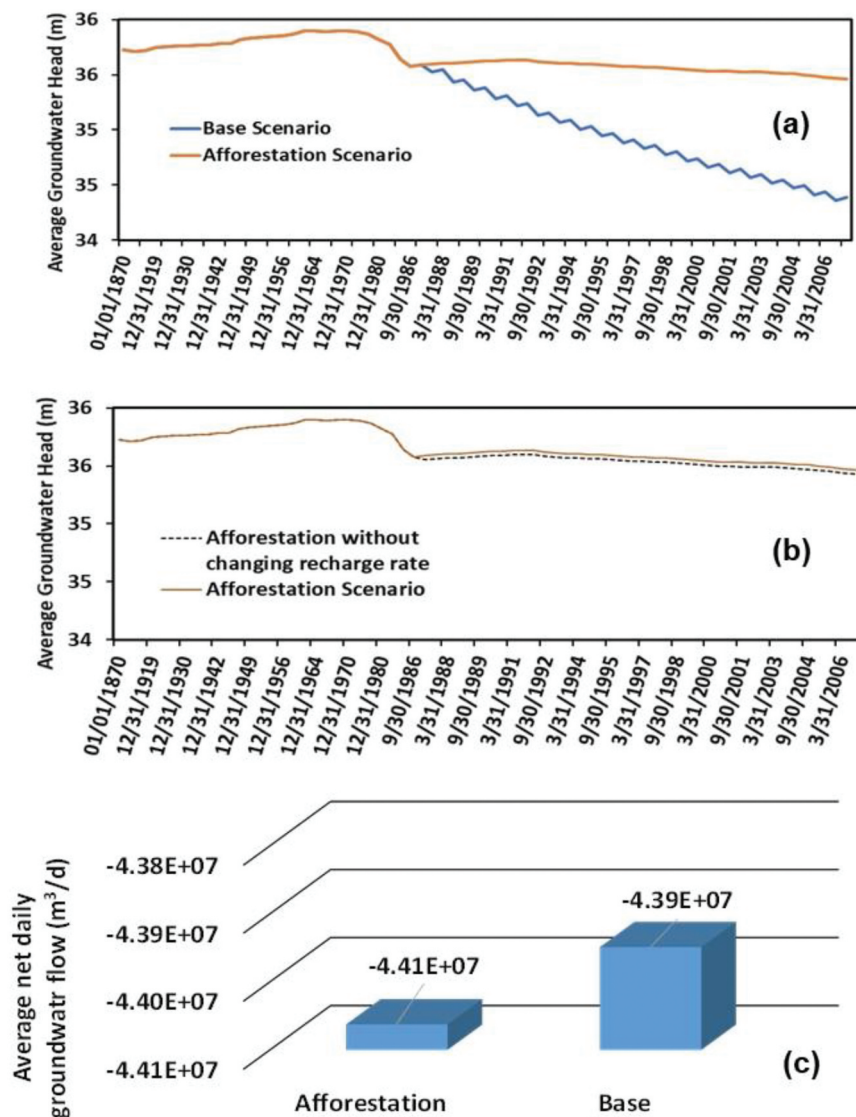
Figure 10. Comparisons of average groundwater heads between: (a) the base scenario and the afforestation scenario, (b) average groundwater heads with and without a 1% increase in groundwater recharge rate from the afforestation scenario, and (c) average net daily groundwater flow between the base scenario and the afforestation scenario over a 136-year simulation period.

pumping wells were placed in the top two layers, and therefore had few pumping effects on groundwater head in the deep layer. As the area with high groundwater head decreased, less groundwater resource was available. Our simulation further revealed that the average groundwater head had declined by 1.2 m, with a rate of reduction of 60 000 m^3/ha/y at the UYRW under the normal conditions without afforestation.

A very small change in groundwater head (with a decline of only 0.13 m over the 20-year period between 1987 and 2007) was observed at the UYRW after the cropland was afforested. Compared to the cropland, afforestation could save 57 383 m^3/ha/year over the 20-year simulation period. Afforestation therefore mitigated the groundwater resource depletion.

The average groundwater head difference over a 20-year period was very small for the conditions with and without a 1% increase in groundwater recharge rate for the afforestation simulation. Results indicated that the recovery of groundwater resources from afforestation was primarily due to the removal of groundwater pumping wells at the UYRW. This study

suggests that afforestation on marginally and low-productive croplands could be a feasible approach to mitigate groundwater depletion in the humid subtropical region.

Disclosure statement

There is no conflict of interests for this submission.

Data availability

Data are available from the authors upon request.

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