Water Conservation Science and Engineering (2024) 9:4
https://doi.org/10.1007/s41101-024-00236-0

CASE STUDY

Estimation of Groundwater Evapotranspiration and Extinction Depth Using Diurnal Water Table Fluctuation and Remote Sensing Observations: A Case Study in Agriculture-Dominated Watershed of Eastern India

Ankita Manekar[1] · Suraj Jena[1,2] · Rabindra Kumar Panda[1,3]

Received: 1 October 2023 / Revised: 21 December 2023 / Accepted: 7 January 2024 / Published online: 12 January 2024

Abstract

Groundwater models meticulously considering the water balance components have paramount importance in sustainable decision-making on groundwater. Plant uptakes and transpires water from the groundwater, called groundwater evapotranspiration (ET_G), ʽis one of the major contributions to the water balance. ET_G needs to be quantified for shallow groundwater areas as they account for major depletion in groundwater. This study evaluated the White and modified White methods to estimate ET_G for the agricultural-dominated Rana watershed with a tropical savanna climate in Eastern India. This modified method uses the sine function to capture the diurnal fluctuation of groundwater and estimates daily to seasonal ET_G. Additionally, a physical-based modeling strategy was adopted to estimate the ET_G over the study basin as a function of soil moisture change from the surface to the saturation depth and delineate the extinction depth of ET_G. Additionally, this study compared the efficacy of both the empirical methods with the physical-based model to estimate ET_G in agricultural land use. Results showed that ET_G was nearly 50–70% of crop evapotranspiration and was higher in magnitude in the dry periods of the year due to less availability of topsoil moisture. The range of extinction depth was observed to be from 1 to 3 m for the hard rock area, whereas the same was from 5 to 9 m for other regions. When the comparison is made on a seven-day window, the modified White method produced an R^2 of 0.88, whereas that of the White method was 0.40. Conclusively, the modified White method reliably estimates the ET_G and can be applied successfully in shallow groundwater level regions for reducing uncertainty in groundwater head prediction due to oversimplification of water balance components.

Keywords Groundwater evapotranspiration · Modified White · Extinction depth · Hydrus-1D · Tropical savanna

Introduction

Groundwater is the most reliable water source for most of the ecosystems in India, especially in tropical savanna regions [1]. India has two major groundwater systems, i.e., (i) deep aquifers and (ii) shallow aquifers. In shallow aquifers, the saturated zone below the water table gets penetrated by plant roots and the roots extract water from the groundwater system [2]. Moreover, in many parts of the country with a shallow aquifer system during monsoon, the groundwater table rises to intersect the root zone. When the hydrological processes of a watershed is considered, evapotranspiration (ET) is a vital component in the hydrologic cycle at various spatiotemporal scales and is about 70% of the global annual precipitation [3]. Approximately 40% of the rainfall in India returns to the atmosphere as ET [4, 5]. It is observed that in

✉ Suraj Jena
jenas@oregonstate.edu

Ankita Manekar
am54@iitbbs.ac.in

Rabindra Kumar Panda
rkpanda56@gmail.com

1 School of Infrastructure, Indian Institute of Technology Bhubaneswar, Odisha 752050, India

2 College of Agricultural Sciences, Oregon State University, 124 SW 26th Street, Corvallis, OR 97331, USA

3 Center for Climate Smart Agriculture, Siksha ʽO' Anusandhan University, Bhubaneswar, Odisha, 751030, India

the total ET, a reasonable portion of the groundwater also contributes which is termed groundwater evapotranspiration [ET_G; 51]. In some cases, ET_G exceeds 85% of potential ET for shallow groundwater regions [6]. Thus, the estimation of ET_G carries fundamental importance in water balance and management studies, sustainable water use in agriculture, as well as groundwater flow simulation studies at various spatiotemporal scales, and policy development for the sustainable use of groundwater resources. In the diverse ecosystem for sustainable water use and planning, considering the full range of ET losses becomes important [7–9]. In many reported groundwater balance studies, the ET_G parameter has been either taken constant or ignored, which leads to uncertainty in the model predictions [8, 10–12].

In drylands, the water table rises mainly due to deforestation resulting ET_G of 30–40% of the total recharge [13]. Further, as the water table depth increases the value of ET_G decreases [14], and ET_G becomes zero at a certain depth, demarketing the extinction depth [ED; 42]. ET_G and the ED have both varied spatially and temporally corresponding to changes in vegetation cover, physical properties of soil, and aquifer properties [15–17]. Estimating the ET_G and ED has great significance in groundwater resource management and precise water budgeting. However, very limited literature has been reported to investigate these two parameters in varying atmospheric settings and groundwater levels, also with heterogeneous land-use conditions at the basin scale [6, 18, 19].

It has always been challenging to quantify ET_G directly because it includes complex physical processes and spatiotemporal variability [1, 20]. Few researchers have studied ET_G from shallow water tables hypothetically, experimentally, and/or in situ. Isotopic tracers were used to determine the fraction of groundwater consumption by vegetation when water was isotopically differentiated from other sources [21, 22]. However, the method for estimating transpiration must be used in combination with the isotopic method. A water balance residual approach estimated groundwater evapotranspiration where the other components of water balance were calculated from monitored data [23]. However, there were uncertainties regarding inflows and outflows. Lubczynski [8] modeled the ET_G using the SEBAL model for semi-arid regions of Botswana and detected uncertainty in total recharge computation due to an error in ET_G estimation resulting in depleted actual recharge.

Another approach used mostly to quantify ET_G is introduced by the [24] which analyzes the groundwater fluctuations in a shallow aquifer. Researchers have recognized this method as it refers to evapotranspiration from the groundwater as the daily groundwater consumption by the vegetation. The White method considered that the plants transpire in the daytime, leading to an upward groundwater flow as the plants consume it during that period, this consumption is more than groundwater recharge; therefore, the decline in groundwater level is observed. Additionally, according to White, at night time the photosynthesis process ceases (midnight to 4 A.M.), and gradually the water level increases. Thus, the diurnal fluctuation pattern in the water table is the combination of groundwater recovery and plant water use. Due to groundwater consumption by phreatophytes, the loss in water is directly measured through the change in water level, which is stated as the major advantage of employing diurnal water table fluctuations to estimate ET [25–27]. Moreover, this method was found to be reliable, cost-effective, and involves simple calculations [16, 28, 29].

Various studies accounted water table fluctuation method to estimate ET_G for various land use types and arid regions like the recent study by [27], which investigated the forest ecosystem and they inferred that the water table fluctuation method was efficient and suitable for long-term ET_G estimates. They observed that the riparian forest uses groundwater during the late growing stages. Similarly, [15] used the water table fluctuation (White) method to estimate ET_G at different land uses for the semi-arid region. It was found that higher actual ET values were obtained where the water table was shallow suggesting it was due to groundwater consumption by grass vegetation. Considering the temperate region (Canada), [30] estimated ET_G, which shows that tree-dominated areas consumed more groundwater than grass, indicating that the ignorance of ET_G may lead to mismanagement of water resources in tree-dominated areas. Furthermore, many works of literature have presented the efficacy of the White method for wetlands [16, 18, 31], and areas with coarse soil [25, 26, 31], but studies on ET_G estimation for Indian tropical regions with distinct wet and dry periods in the agriculture dominated watershed is limited. Although, the White method is more straightforward and has advantages, but consists of uncertainties reported in different studies. This is mainly related to the specific yield calculation [26, 32, 33] and consideration of smaller recovery time intervals [34]. Thus, the White method was modified by using the time-series function for a 24-h window, which estimates ET_G on a monthly and weekly interval concomitant with water table fluctuations [34, 35].

In recent times, there has been an increase in the availability of spatiotemporal data with the help of satellites. The remote sensing approach provides long-term data (total terrestrial ET, soil moisture, precipitation, and energy fluxes), which can be further adapted to estimate ET_G. High spatiotemporal resolution data provided by the satellites can be used to quantify ET_G on a much finer scale and more accurately for a large area [8, 36, 37]. However, the direct measurement of ET_G using remote sensing is difficult and impractical except in arid regions [8, 38].

In this study, we applied the modified White method to estimate groundwater evapotranspiration (ET_G) and compared it with the original White [24] model for performance evaluation using diurnal water table fluctuation data in agriculture-dominated tropical savanna regions of Eastern India which is unexplored in the context of groundwater evapotranspiration estimates. Additionally, the use of remotely sensed soil moisture data with physical-based modeling was also adopted to determine the ET_G at various land use/land cover (LULC) classes over the study basin to investigate spatially varying extinction depths of ET_G for various LULC classes. In this process, we also compared the efficacy of the White [24] and modified White methods with the physical-based model for ET_G predictions for agricultural lands. To the best of the author's knowledge, this investigation is the first of its kind in an agriculture-dominated tropical savanna region with a shallow water table condition in the Indian subcontinent. The overarching objectives of the study were to (i) conduct a performance evaluation of White and modified White methods to estimate ET_G in agriculture-dominated shallow water table conditions; (ii) compare both empirical methods with physical-based model prediction for agriculture land use; and (iii) determine the spatial variability of extinction depths for ET_G for various LULC classes.

Methodology

Study Basin

The study basin, Rana basin, is located in Eastern India at the middle reach of the Mahanadi River basin extending from 85°23′E to 85°38′E and 20°07′N to 20°25′N with an area of 424.13 km^2 Fig. 1; [39, 40]. This basin underlies the watershed of the last tributary of the Mahanadi River, which is seasonal and flows from south to north. The selection of the basin was based on the climatic conditions, LULC pattern, and depth to the water table [groundwater level (GWL)] distribution. According to Koeppen's classification, this region falls under the tropical savanna type of climate with very hot temperatures in summer, ranging between 35 and 40 °C, and the minimum temperatures are

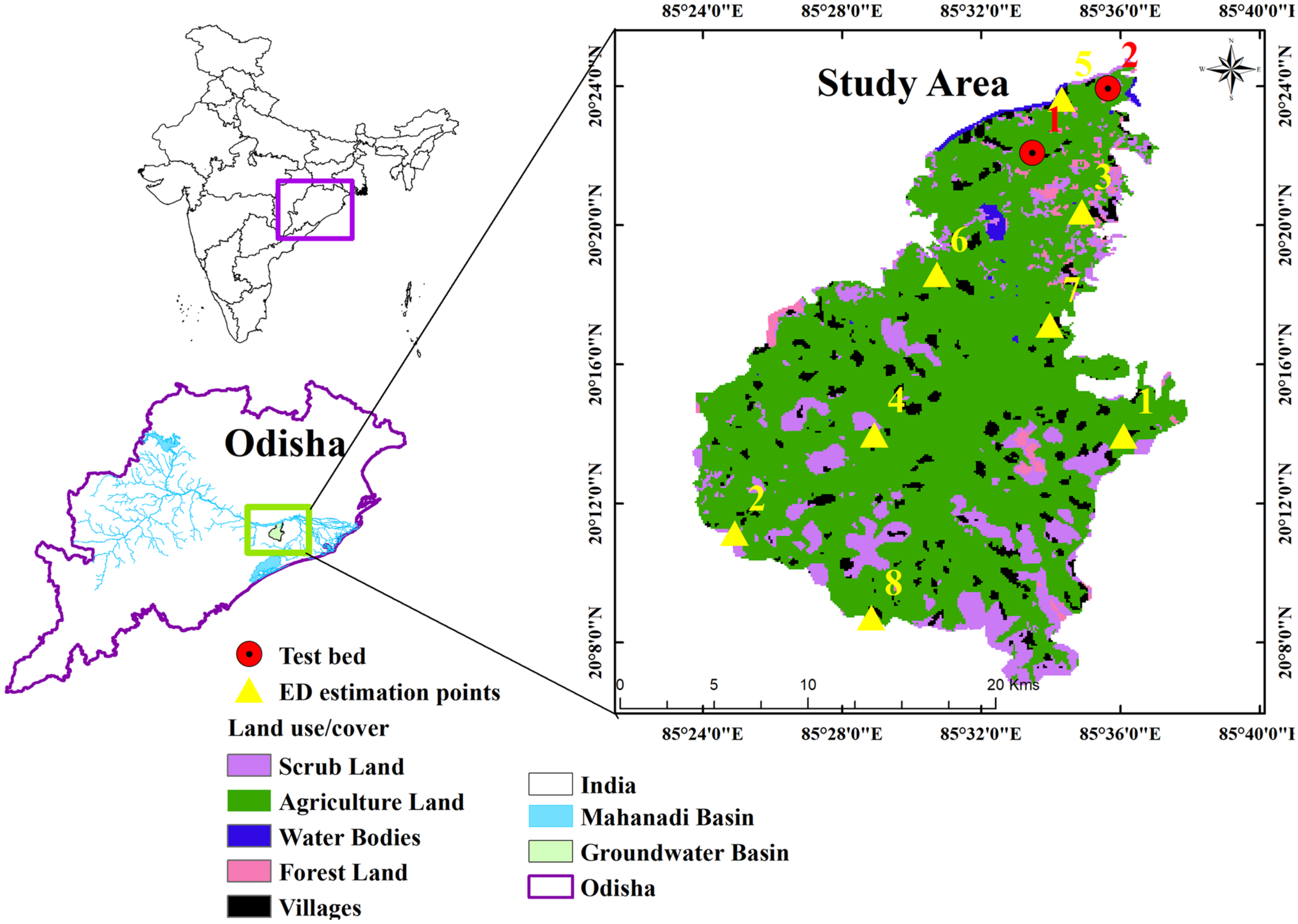


Fig. 1 Study groundwater basin with the LULC patterns, ED estimation locations, and observation stations (red circles): Observatory #1 and #2

usually between 12 and 14 °C. The rainfall varies from 100 to 200 cm/year [41] with distinct wet and dry periods. Around 70% of the average annual rainfall occurs in 3–4 months of the year [42]. Surface water availability is therefore limited to those 3–4 months of the monsoon season followed by the dry season during the remaining months of the year. Therefore, the only alternative left is to use groundwater for agriculture as well as domestic purposes. The observed data of GWL fluctuation in 46 observation wells showed that the GWL in the area fluctuates between 0 to 12 m in the monsoon and 4 to 21 m in the non-monsoon periods [42]; Fig. 2. This tropical savanna region gains water during wet periods (monsoon) and loses water during drier periods (winter, post, and pre-monsoon). Since there is a reasonable portion of the basin with shallow GWL in the wet and dry period of the year, estimation of ET_G for such conditions is imperative, which is limited due to the non-availability of suitable diurnal

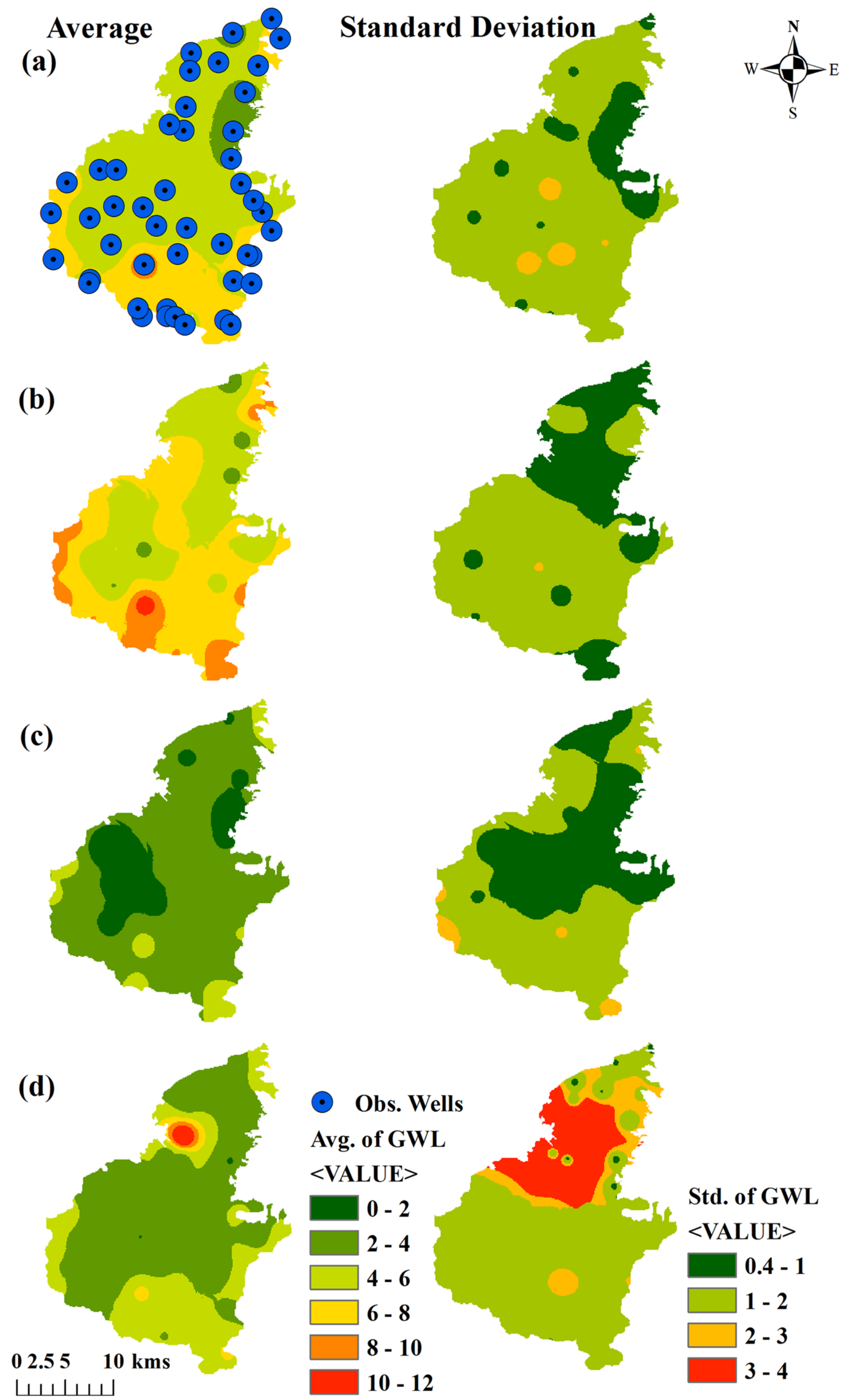


Fig. 2 The GWL seasonal variability in the Rana groundwater basin. The rows **a**–**d** represent the four different seasons, namely winter (Jan. to Mar.), pre-monsoon (Apr. to June), monsoon (July to Oct), and post-monsoon (Nov. to Dec.), respectively. The blue circles are the observation wells monitored on a fortnightly basis

GWL data. The agriculture area covers approximately 73% of the total basin area. The main crop grown in these areas is rice (paddy). The agriculture here is primarily rainfed.

Data Used

Two observation wells were installed at Observatory #1 (20.367°N, 85.557°E) and Observatory #2 (20.439°N, 85.666°E) in the agricultural land use of the study basin (Jena et al., 2021). This study utilized the groundwater fluctuations observed for the year 2016 to estimate groundwater evapotranspiration (ET_G). GWL below ground level (m bgl) were logged in 30-min intervals using conductivity, temperature, and depth sensors (CTD-10 Sensor, Decagon Devices, 2365 NE Hopkins Ct/Pullman, WA 99163, USA) that were installed in two observatories developed in the aforementioned locations (Fig. 1). This data had a few missing values and needed to be pre-processed before using them for analysis. Filling missing data was performed using a Fourier transform approach which proved to have higher accuracy than multiple imputations and expectation means for estimating missing values [43]. In this study, MATLAB R2015a was used to perform the computational part of the Fourier transform method. Additionally, the distributed monitoring of GWL at 46 observation wells was also carried out on a fortnightly basis between 2015 and 2018 and was utilized in this study. Figure 2 shows the seasonality in GWL of the study basin. It can be very well felt that the GWL in the study basin was shallower, and during monsoon, it was within approximately 1 m bgl in the significant portion of the study basin.

This study utilized the specific yield (S_y) values that were determined through its own pumping test and collected data from Central Groundwater Board (CGWB) Bhubaneswar, Odisha, India, for the whole study basin (Fig. 3). Specific yield values for Observatory #1 and Observatory #2 were 0.31 and 0.35, respectively. Thus, in this study, the more reliable solution for the estimation of specific yield problems mentioned in previous studies has been taken care of. Topsoil moisture data were obtained from SMOS Level 2 soil moisture product with a spatial resolution of 15 km [44], which was used in Hydrus 1D-based modeling. The weather data required were obtained from the installed weather station in the two observatories, such as solar radiation, temperature, and precipitation.

Diurnal Water Table Fluctuation Method (White Method)

As proposed by a study in 1932 [24], diurnal trends of the water table from wells can be used to estimate the consumptive use of groundwater by phreatophytes. As plants transpire water during the day, causing an upward flow of groundwater due to consumption by the plants which is much more than groundwater recovery. This leads to the decline of groundwater level. According to this method

$$ET_G = S_y(24r \pm s) \quad (1)$$

where S_y is the specific yield, r is the rate of water table rise at night-time (00:00 to 04:00) (mm h^{-1}), and s is the net change in water table over 24 h (mm).

The influx rate of groundwater throughout the day was assumed as constant in this method. However, in real scenarios, groundwater recovery rates vary within 24 h [35], leading to uncertainties with this method. Majorly, the methodology was conducted only for coarse sediments such as sand and gravel [15, 26] and not for fine-grained soil types. Also, when the land-use type is considered, this method has been majorly implemented on wetlands [6, 18, 28, 31], grasslands [15], and forests [32] but not in agricultural-dominated areas. Initially, in the present study, the monthly average ET_G values were evaluated using the White method, and later in the study ET_G from different methods was compared. The observed water table fluctuation data for the study site was collected from the two observatory wells as discussed in the data section for the year 2016. The specific yield values used were 0.31 and 0.35 for two observatory wells respectively obtained from pumping test and CGWB.

Modified White Method

Recently, a modified White method has been proposed which expresses the groundwater with the periodic nature of diurnal fluctuations in shallow GWL [34]. Most of the previous literature is based on analyzing the GWL fluctuations for wetlands but limited studies have focused on the diurnal variation approach. Thus, the modified White method [34] was applied in an agriculture-dominated shallow water table with tropical savanna climatic conditions in this case study. The diurnal fluctuation offers a practical and simplified alternative method for estimating ET. White [24], initially established a relation between specific yield and groundwater recovery to estimate ET_G. White stated that the time rate of change in groundwater storage in the vicinity of the well is equal to the time rate of change in water table depth times the specific yield [35]. This storage is controlled by the net flow of groundwater to/from the vicinity of the well [$r(t)$] and the groundwater consumption rate ET_G. Some assumptions were considered in this study as recommended by [35] to ensure the validity of Eq. 2. Quantification of ET_G was done using the following governing equation suggested by White:

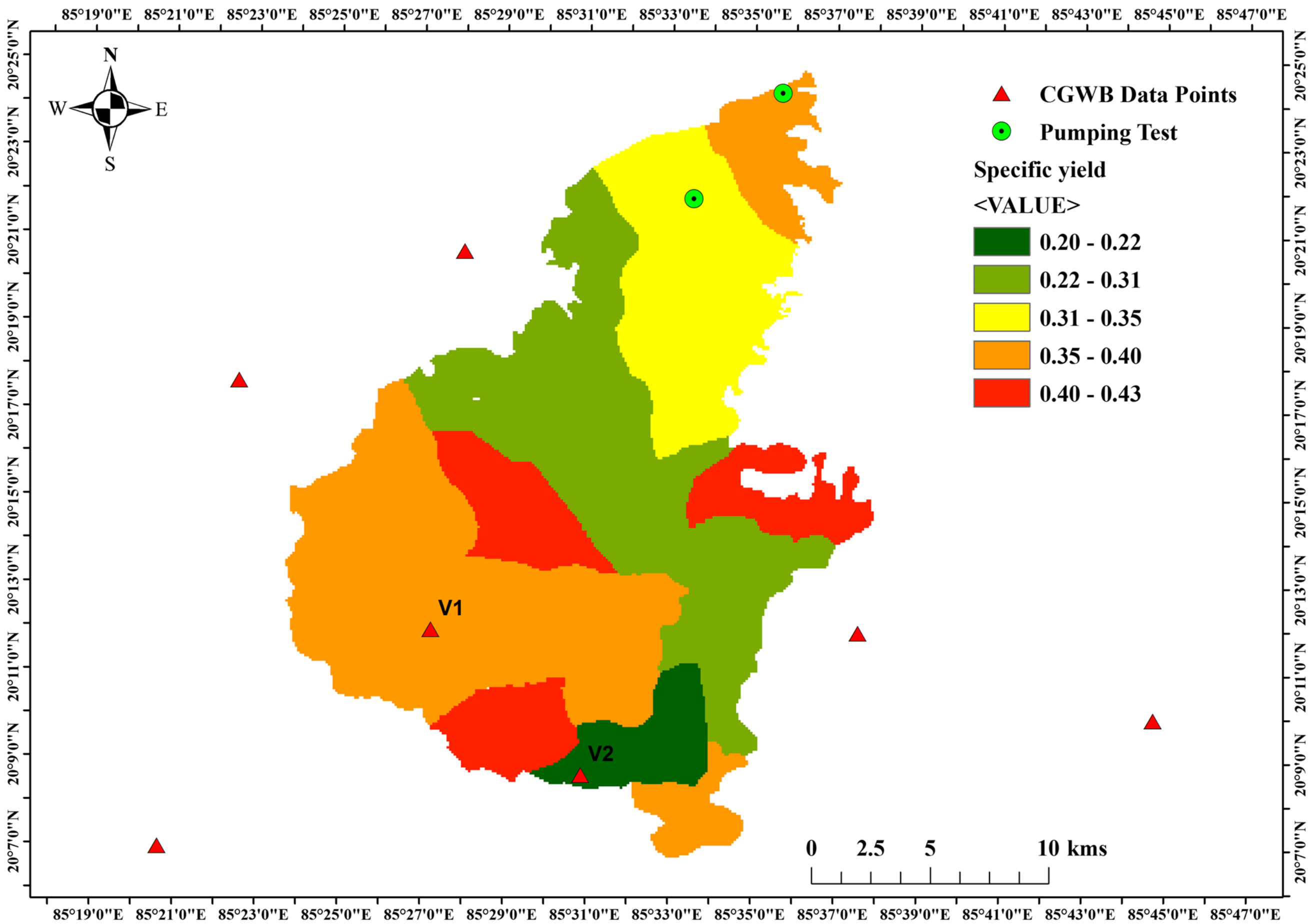


Fig. 3 The spatial distribution of aquifer S_y values obtained through inverse distance weighted based interpolation of S_y values obtained from CGWB and our own pumping tests. The red triangles are the locations of CGWB with S_y values, and green circles present our pumping test points (in the continuous monitoring observatories)

$$\frac{S_y dZ_{wt}}{dt} = r(t) - ET_G(t) \tag{2}$$

where S_y is the specific yield; r is the groundwater recovery; Z is the height of water table Eq. (1) is integrated over a time interval Δt to solve for total $\mathrm{ET_G}$:

$$ET_G = S_y\left(r_{gw} \pm s\right) \tag{3}$$

where ET_G was the daily total ET_G rate (mm/day), r_{gw} was estimated between midnight and 4:00 A.M. as the hourly rate of water table rise when transpiration was assumed to be negligible, and s was estimated as the net rise or fall of the GWL during the 24-h period (i.e., the daily change in storage). Positive or negative signs in Eq. 3 were used when the water table fell or rose, respectively.

Czikowsky and Fitzjarrald [45] studied diurnal streamflow signals and suggested that the Fourier methodology (a sine function) could further be used to describe diurnal variations as a modification in the conventional White method. Soylu et al. [34] suggested that the diurnal fluctuations often follow a periodic and sinusoidal nature in shallow groundwater levels, which can be represented in the sinusoidal wave function considering the overall rise and fall in the groundwater table. In the present study, the weekly and monthly $\mathrm{ET_G}$ were represented by the diurnal variations of groundwater. A sine function defining the streamflow was presented as a time series function (Eq. 4) by [45], and the various coefficients were calculated by empirically fitting the data.

$$Z(t) = At + D + B\sin\left[\frac{2\pi(t+E)}{24}\right] \tag{4}$$

where Z is the discharge or stage (L), t is time (in hours, T), A is the 3-day trend ($\mathrm{LT^{-1}}$), D is the mean bias (L), B is the diurnal amplitude (L), and E is the diurnal signal phase (T).

$$S_y \Delta Z_{wt}(t) = S_y\left[Z_{wt}(t) - Z_o\right] = \int_{\Delta t}\left(r - ET_G\right)dt = r\Delta t - \int_{\Delta t} ET_G dt \tag{5}$$

$$Z_{wt}(t) = Z_o + r_{gw}t - \frac{1}{S_y}\int_0^t ET_G dt = D + At + B\sin\left[\frac{2\pi(t+E)}{24}\right] \quad (6)$$

Using this approach, the estimation of ET_G was done by relating Eq. 5 to the governing equation for shallow GWL fluctuations, Eq. 3. In Eq. 6, D represents the initial GWL. The combined effects of both groundwater recovery and plant transpiration are accounted for under the observed water level At, whereas, the ET_G term $\int ET_G dt$ is represented by the sine function. The water level trend was majorly contributed by ET_G, depicting the whole trend as the result of ET_G. The detrending process was executed on the water level time series (removing D + At) in Eq. 6, which will remove a significant share of the ET_G signal. After the detrending, the term that remains on the right-hand side of Eq. 6 was the sine function with amplitude B (peak-to-trough = $2B$). Equating the daily total transpiration to $S_y(2B)$ might result in a significant underestimation of ET_G. So a correction factor was introduced, i.e., scaling factor (k) is a function of solar radiation. In this, the hourly solar radiation values were accrued over multiple days, and the scaling factor was evaluated [34]. The simplified ET_G model as a function of specific yield and the scaling factors were established.

$$ET_G = S_y k(2B) \quad (7)$$

Weekly and monthly average ET_G was estimated using Eq. 7 and utilizing groundwater fluctuation data for the year 2016 at Observatory #1 and Observatory #2 wells where the sensors were installed in the observation wells. The obtained ET_G results of Observatory #1 and Observatory #2 sites were compared with the crop evapotranspiration (ET_c) that was obtained using crop coefficient and potential evapotranspiration (ET_o). The Penman-Monteith equation was adopted for the calculation of daily ET_o that combines the energy balance equation with mass transfer [46] The crop coefficient (K_c) value used was 0.75 for the rice crop and sub-humid conditions [47]. Meteorological data (solar radiation, minimum temperature, maximum temperature, mean temperature, relative humidity, and wind velocity) were collected from the weather station installed in the observatory.

Estimation of ET_G and Extinction Depth Using Physical-based Modeling

The Hydrus-based ET_G was also estimated using soil moisture (SM) data obtained from SMOS Level 2 soil moisture products with a spatial resolution of 15 km. The study considered four soil layers at 0–10 cm, 10–30 cm, 30–60 cm, and 60–100 cm. The vegetation root depth in the upper 1 m of soil varies with land use type. Simulation using Hydrus-1D was performed to estimate moisture variations in the soil profile [15, 48, 49]. Richard's equation is used in Hydrus-1D model to simulate the variably saturated flow. The equation is given as follows:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\beta\right)\right] - S \quad (8)$$

where h is water pressure head, θ is volumetric water content, t is time, x is spatial coordinate, β is angle between the flow direction and the vertical axis, K is unsaturated hydraulic conductivity, and S represents the sink term. The Mualem-van Genuchten functions [15, 50, 51] were used to describe the relationship between θ, K, and h. The sink term "S" in Eq. 8 describes the volume of water removed from a unit volume of soil due to plant water uptake and was defined as follows [15]:

$$S_h = \alpha_h S_p \quad (9)$$

where $\alpha_{(h)}$ is the root water uptake function and S_p is the potential water uptake rate. The potential rate characterizes the water uptake rate when the plant is not experiencing any stress, i.e., $\alpha_{(h)}$ is equal to one.

Vegetation extracts water for ET both from the vadose zone and the saturated zone [52, 53]. It was assumed that the total ET loss in the area is equivalent to the crop ET loss determined using potential evapotranspiration. Thus, it can also be said that total ET loss is due to ET_G and vadose zone contribution (VZET), which need to be evaluated individually. Here, the VZET was estimated using soil moisture (SM) data (Eq. 10) for the entire column at different time steps and by subtracting two sequential values of modeled SM [50]. The groundwater consumption by vegetation is obtained as the difference between total evapotranspiration and VZET Eq. 11.

Evapotranspiration or vadose zone loss:

$$VZC \text{ or } ETL \mid t_i = \int_{\Delta s} \theta_{model}\, dz \mid t_i - 1 \quad - \int_{\Delta s} \theta_{model}\, dz \mid t_i \quad (10)$$

where θ_{model} is the simulated water content at depth z from the land surface at time t_i. Δs is the length of a soil column.

$$GWC = TETL - VZC \quad (11)$$

where $TETL$ is the total ET loss; GWC is the groundwater contribution.

Groundwater evapotranspiration for time interval Δt is calculated as follows:

$$ET_G = \frac{GWC}{\Delta t} \quad (12)$$

The ratio of groundwater contribution to evapotranspiration and crop evapotranspiration is calculated and the depth at which the ratio is less than 0.5% that level of the water table is said to be *extinction depth (ED)*.

Results and Discussion

Estimation of ET_G Using White and Modified White Method

The groundwater fluctuation data which was obtained using the CTD sensors installed in Observatory #1 and #2 for the year 2016 was used to estimate daily ET_G. From Fig. 4, it can be observed that there is an upward trend in the groundwater level before and after the growing season in the study region that starts in July and ends in September. During this period of July-September, the water table rose to 3.5–4.5 m and from 3.5 to 7 m for Observatory #1 and #2, respectively. In Oct-Nov, the transpiration demands are satisfied by the surface and unsaturated zone moisture as the GWL can be seen decreasing during this period. Whereas, it can also be observed that during the dry season of the year (February-April), great variation in the GWL depth was observed between the two observatories, with Observatory #1 having a GWL of 3–5.5 m whereas Observatory #2 with 7–8 m.

Initially, the ET_G for both stations was estimated using the *White* (1932) method. The results obtained can be seen in Fig. 5 with daily ET_G values for Observatory #1 varied from 0 to 8.84 mm/day during Jan-Dec 2016 (Fig. 4). Similarly, at Observatory #2, daily ET_G values vary from 0 to 5.12 mm/day using the *White* method for 2016 (Fig. 5). The mean daily ET_G value for Observatory #1 and Observatory #2 was found to be 3.08 mm/day and 0.95 mm/day, respectively. In the growing season of India (July-Oct), the ET_G values increased for both observatories. The ET_G values are less for the dry periods of the year, i.e., December and May-June for Observatory #1. This method gave reasonable estimation for this study, which is similar to the study by [31]. However, the model struggles with fine-grain materials and the associated specific yield [31].

Further, the modified *White* method was implemented in the study to estimate ET_G on a monthly time scale. The seasonal trend of ET_G values matches with the trend obtained by the White method with lesser values of ET_G during the April-June (mostly dry) months of the year. The average, maximum, and minimum ET_G values for Observatory #1 were 2.25 mm/day, 3.91 mm/day, and 0.84 mm/day, respectively (Fig. 6). Similarly, at Observatory #2, the average, maximum, and minimum monthly ET_G values were 2.03 mm/day, 2.37 mm/day, and 1.74 mm/day, respectively. Subsequently, similar to [28] the performance was compared among the White and modified White methods.

Estimation of ET_G Using Hydrus-1D

Using Hydrus-1D and remote sensing soil moisture turned out to be a useful and convenient method for spatial analysis of groundwater evapotranspiration (ET_G) in the Rana basin. The results showed that ET_G using Hydrus-1D follows the pattern observed using the modified *White* method. The average monthly ET_G value for the year 2016 was obtained to be 2.82, whereas the maximum was observed in the driest month of the year, i.e., April (5.03 mm/day), and the minimum monthly ET_G was in September observed to be 1.68 mm/day (Fig. 7). The monthly ET_G presented in Fig. 7 highly correlates with the wetting and drying cycle corresponding to the tropical savanna climate with monsoon as the major source. The study conducted by [35, 37] has also a similar conclusion on the periodicity of the estimation.

The spatial distribution of ET_G for eight different points selected based on soil and land use type is presented in Fig. 8. The figure illustrates that the average ET_G is low

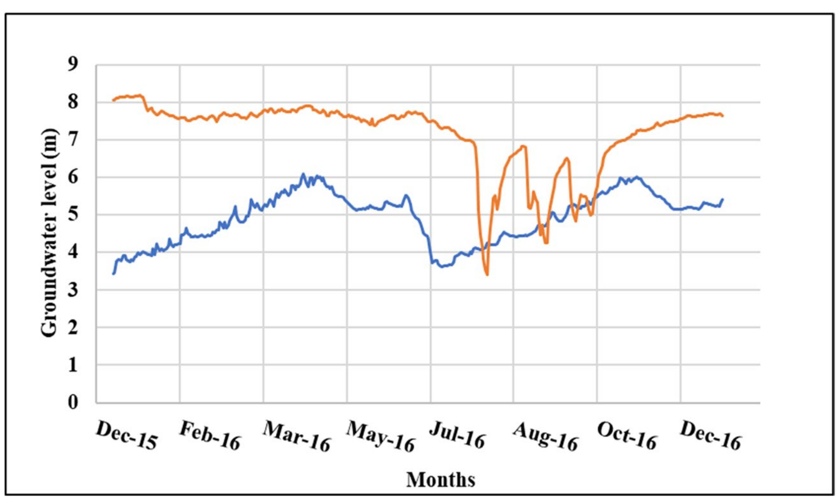


Fig. 4 Daily GWL (m bgl) for the year 2016 at Observatory #1 (blue) and Observatory #2 (orange)

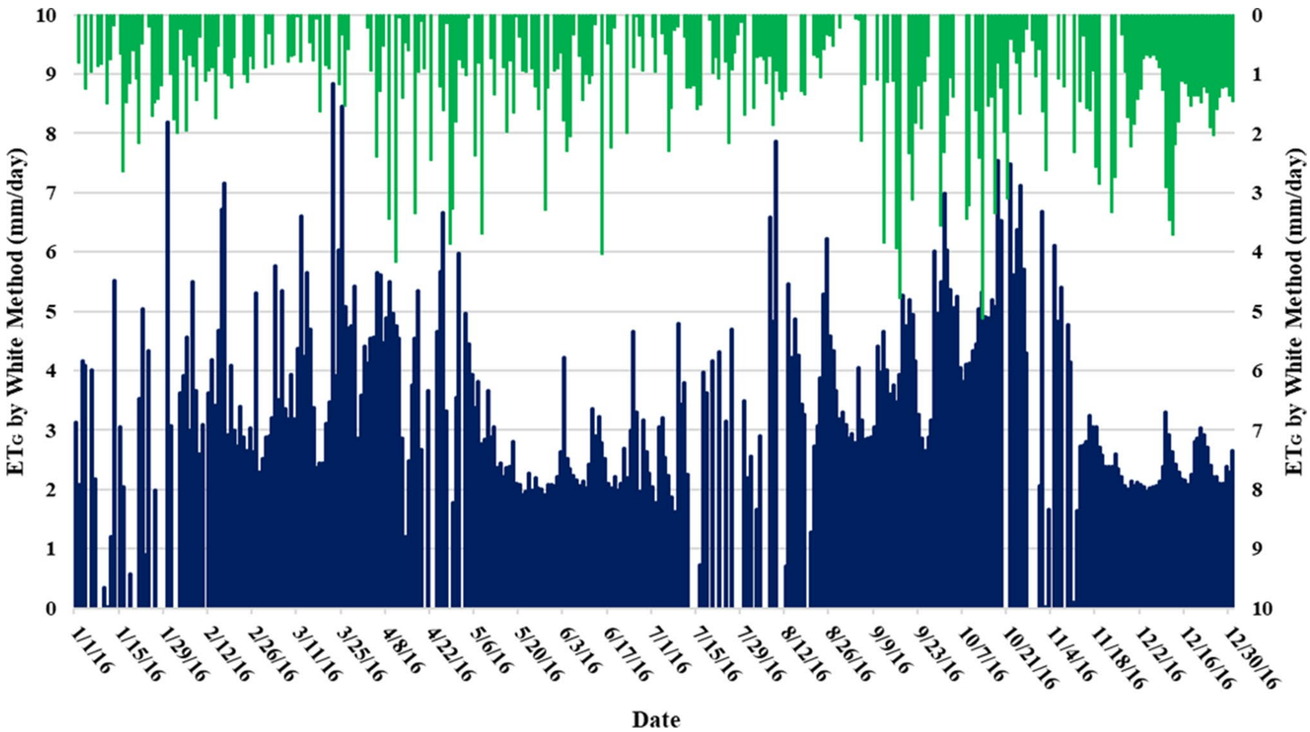
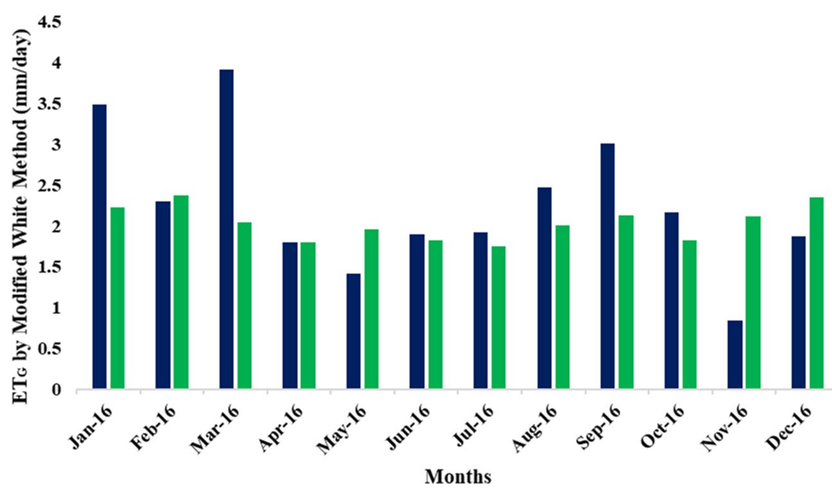


Fig. 5 Daily groundwater evapotranspiration (mm/day) for the year 2016 at Observatory #1 (blue) and Observatory #2 (green) stations

Fig. 6 Monthly groundwater evapotranspiration (mm/day) for the year 2016 at Observatory #1(blue bars) and Observatory #2 (green bars) station



(1.5–2 mm/day) for the month of June-Sept (wet period), which supports the fact that groundwater contribution will be less to total ET. This period of monsoon is the cultivation period of rice which has a maximum root depth of 60 cm which will lead to more vadose zone contribution to total ET. The values of ET_G vary with time and spatially due to the heterogeneity of the study area. Maximum ET_G is observed in the northern part of the basin which is near the riverbank, for all three periods. The southern region of the basin contributes very little to the ET. The major portion of the basin has a continuous contribution to ET_G owing to the agricultural activities and shallow GWL (Figs. 2 and 8). Comparing Figs. 2 and 8, it can be observed that there is a spatial correlation between the GWL and the amount of ET_G been contributed by the areas with shallow GWL regions. It can be observed from Fig. 8 that in the major portion of the year, the southern regions of the Rana basin with deeper GWL contribute the minimum to ET_G.

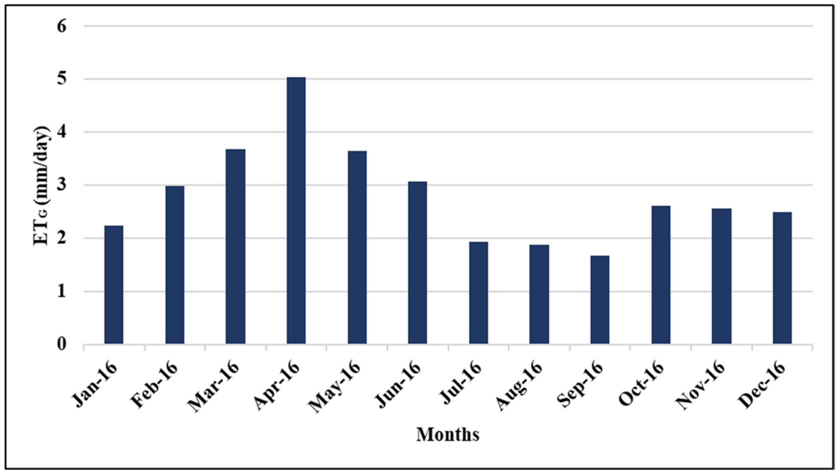


Fig. 7 Monthly groundwater evapotranspiration (mm/day) for the year 2016 at Observatory #1 station

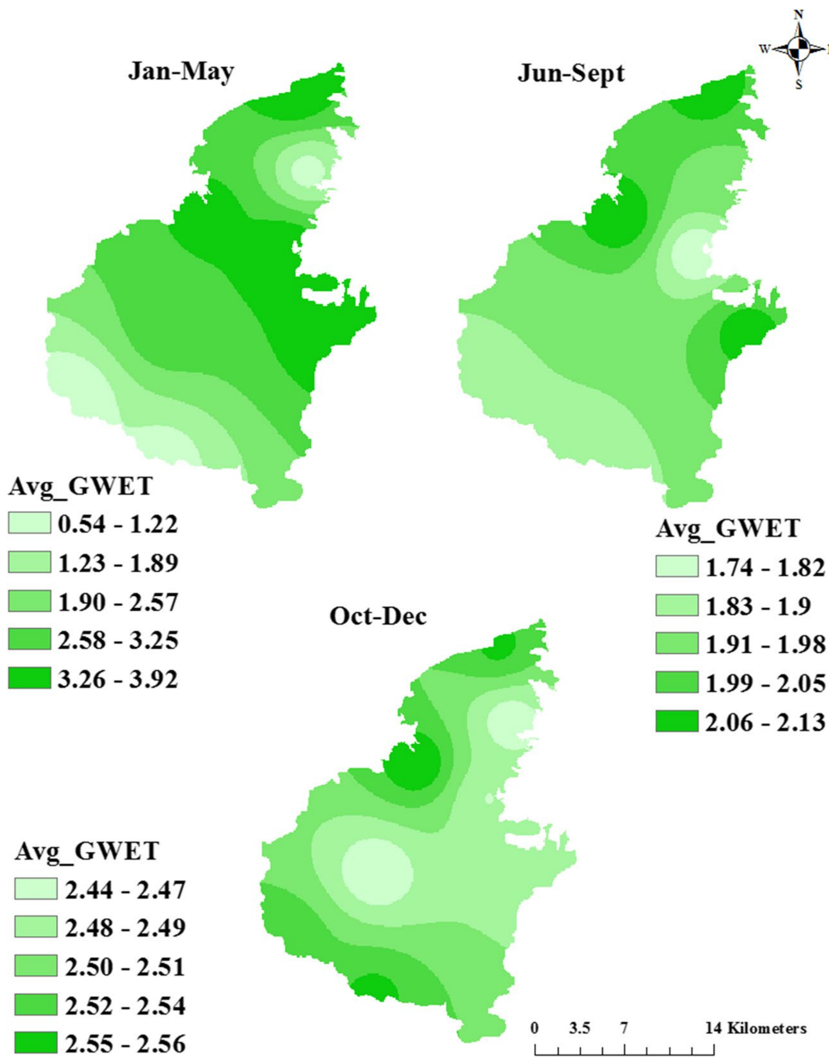


Fig. 8 Spatial distribution of average groundwater evapotranspiration (mm/day) for the year 2016 in the Rana groundwater basin

Comparison of ET_G Estimation Methods

A comparison of ET_G from *White*, Modified *White*, and Hydrus-1D is presented in Fig. 9. It was observed that the *White* method was over-estimating in some months with values higher than the Hydrus-1D ET_G. This can also be summarized by calculating the departure of *White* and modified *White* ET_G from the Hydrus-based ET_G for the year

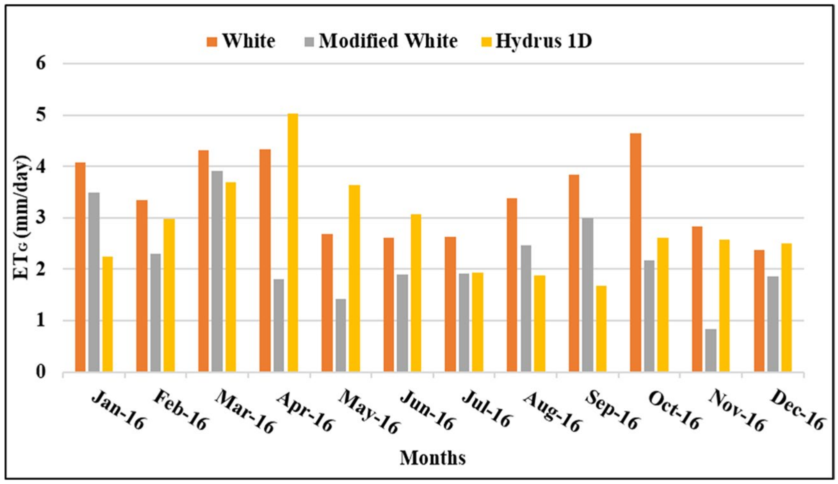


Fig. 9 Groundwater evapotranspiration (ET_G) for the duration of Jan-Dec 2016 at Observatory #1 (monthly average) using White, modified White, and Hydrus-1D

2016. The departure value obtained for the *White* method is −0.603, as it is over-estimating. On the other hand, the departure value is 0.56 for the modified *White* method. This suggests that the modified White method performed considerably better than the *White* method.

At Observatory #1, statistical comparisons of estimated ET_G and observed ET values were performed using the coefficient of determination (R^2) and RMSE values. The modified *White* method produced higher R^2 values (0.88) compared to the *White* method (0.40) for the weekly time scale. The modified *White* method also reduces ET_G RMSE from 0.64 in the *White* method to 0.27. Thus, the results indicate that the modified White method provides an improved alternative to the White [24] method in estimating groundwater evapotranspiration using GWL fluctuations in agriculture-dominated regions.

The relationship between monthly averages of potential evapotranspiration (ET_o) and ET_G is shown in Fig. 10 for Observatory #1. It can be concluded from Fig. 10 that the modified White method for Observatory #1 station gives considerably accurate results as ET_G obtained was nearly 50–70% of ET_o, which is also the case for Hydrus-1D ET_G and is reasonable for the actual condition. Whereas, in some cases the White method overestimated ET_G values, resulting in undesirable results. It is also evident that the pattern of estimated ET_G and the potential ET has a strong correlation. A similar relationship was also observed for Observatory #2 with ET_G obtaining nearly 40–70% of ET_o. The percentage contribution of ET_G to ET_o was observed to be significant and this may lead to prediction uncertainty if the ET_G is ignored in the groundwater water balance modeling.

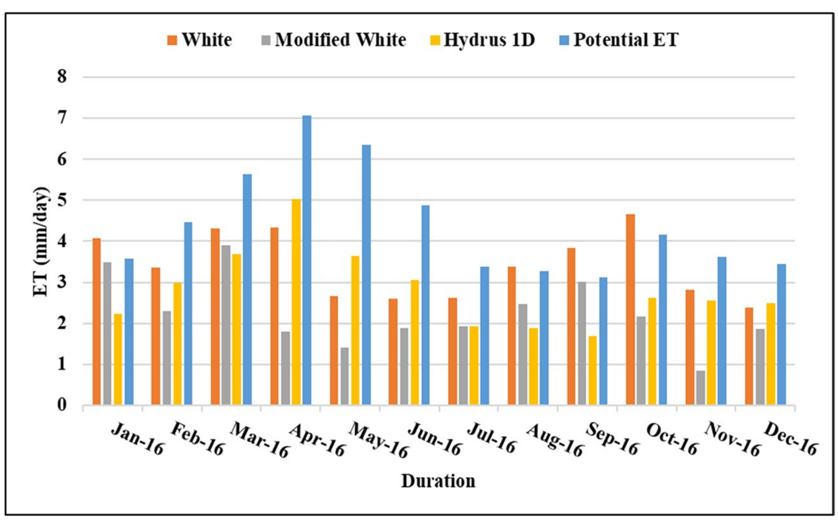


Fig. 10 Monthly average evapotranspiration and crop evapotranspiration at Observatory #1 for the year 2016

Estimation of Extinction Depth Using Soil Moisture Data

The spatial variation of extinction depth for groundwater evapotranspiration and GWL are presented in Fig. 11, and it can be observed that during the pre-monsoon period, i.e., January to May, the GWL was below the extinction depth in the southern part of the basin, which indicated that this area has negligible contribution to the ET_G. This finding was also in line with the findings presented in the "Estimation of ETG Using Hydrus-1D" section. A reverse scenario was witnessed in the upper region, where the GWL was shallower (1–3 m) than the extinction depth (5–9 m) indicating the region's contribution to the ET_G. A similar condition was observed in the middle region with a significant amount of ET_G contribution from this region, which can also be seen in Fig. 7. During the monsoon period, i.e., the months of June-September, it always contributes some amount to ET_G, but the value of ET_G was less as compared to another period of the year, as it was a cultivation period of rice with a maximum root depth of 60 cm and water-logging condition, which leads to more

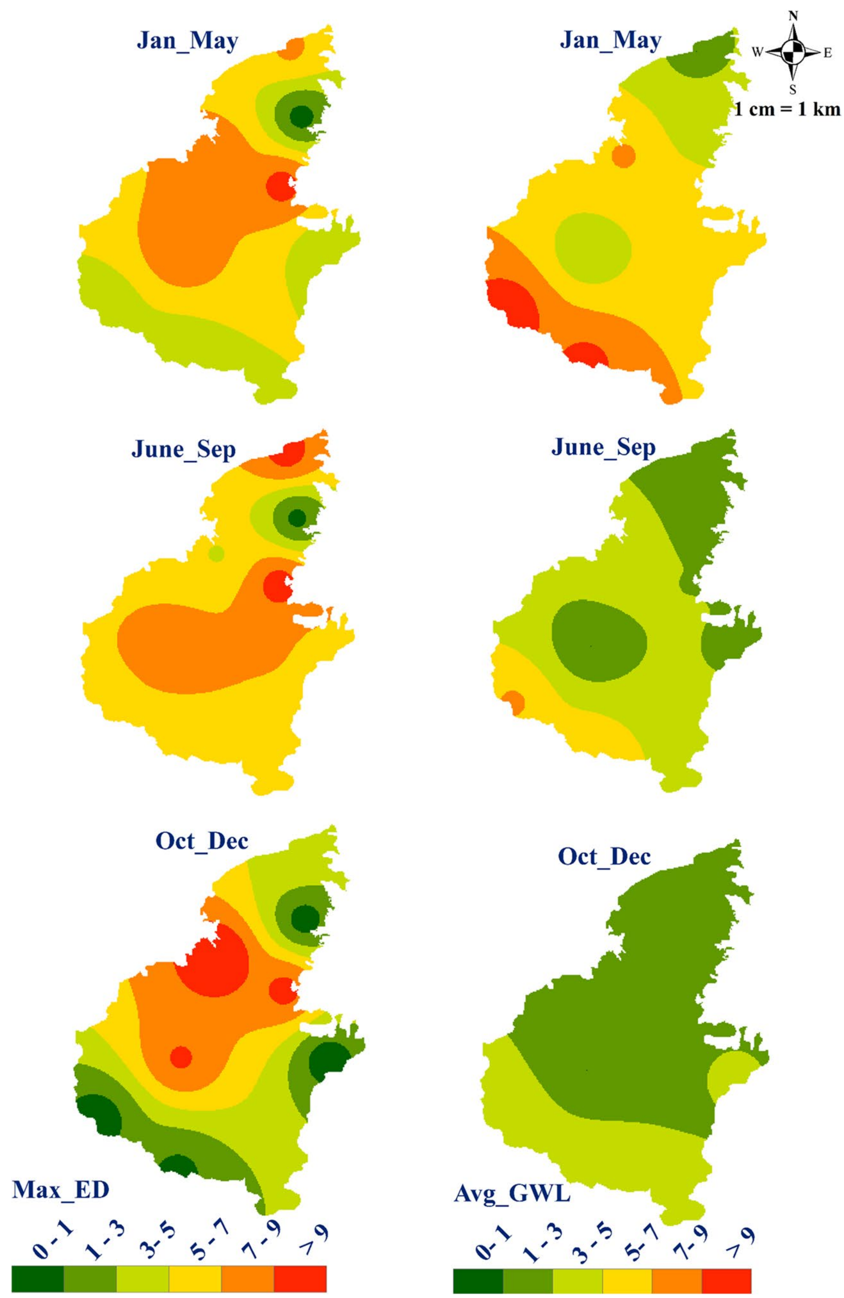


Fig. 11 Spatial distribution of maximum extinction depth (m) and average GWL (m) for the year 2016 in Rana basin

vadose zone contribution than groundwater. High variation in extinction depth was found in the post-monsoon period from October to December. It was also found that the lower portion of the region which is a hard rock area attained the extinction depth of 1–3 m, but the GWL is much lower than that; indicating, less ET_G values in this region. During the January to May period, the basin's southern region GWL was lower than extinction depth, indicating no contribution to ET_G. The prior studies with study regions having deeper GWL have also shown no intersection of GWL and extinction depth producing similar contributions [15, 50].

Conclusions

Groundwater evapotranspiration for varying soil-LULC types in tropical savanna with shallow water tables was analyzed using White, modified White, and physical-based (Hydrus-1D) approaches. Due to rainfall in the monsoon season, the GWL of the region rises, and during the non-monsoon period, the GWL declines. According to the White theory, the pattern of diurnal fluctuations in the GWL was caused majorly due to groundwater recovery and plant water use. This theory was applied to estimate ET_G, and it is observed that the White method sometimes overestimates the ET_G, which may induce uncertainty in groundwater flow models.

On the other hand, the modified White method gave reliable and accurate results. The ET_G obtained was nearly 50–70% of ET_o. In the dry period, as the topsoil moisture level was reduced, ET_G values obtained were higher than in the wet period of the year, showing lesser vadose zone contribution and an increase in the consumption of groundwater by the plants. In contrast, during the wet period, the surface and vadose zone satisfy the transpiration demands of plants. The modified White approach used in this study had a higher R^2 value (0.88) than the original White method (0.40) for a seven-day timeframe, improving the accuracy of ET_G estimation. The daily to monthly fluctuations in ET_G can also be calculated using this method.

Physical-based estimation of ET_G using remote sensing data produced reliable results for data-scarce and remote regions. Extinction depth values that identified areas contributing to ET_G showed large spatial variability. For the Rana basin, the extinction depth ranged from 1 to 3 m in certain areas with hard rock and from 5 to 9 m in other parts. Conclusively, the adopted methodology can be applied in similar hydroclimatic conditions, and the same can contribute to a basin to regional-scale water management. The modified White method can be a reliable, accurate, and cost-effective alternative to data-intensive physical-based approaches for the precise estimation of ET_G taking monitored water table fluctuation data in the tropical savanna regions with similar groundwater systems. Many vegetation types with deep root systems depend upon groundwater for their transpiration requirements, thus the investigation of the groundwater consumed by vegetation as evapotranspiration is necessary for the reliable management of groundwater and overall water resources at a regional scale. The effects of varying cropland over years where ET_G changes with crop growth and irrigation schemes could be explored in the future along with the inclusion of various soil properties. Additionally, The reliability of the modified White method for the deep-rooted forest covers of different categories will be an interesting future study. Using remote sensing data is reliable for data-scarce and inaccessible regions, which gave considerable estimates for ET_G. Additional studies should be performed to test these methods in different climatic conditions. The framework proposed through this study for shallow and agriculture-dominated regions is associated with ground observations at high temporal scales, which is often challenging for developing countries. However, the magnitude of contribution the ET_G is making for total ET_O demands sagacious attention to the parameter.

Acknowledgements The authors sincerely acknowledge the Central Ground Water Board (CGWB) for providing the required datasets for carrying out the present research. The authors also sincerely acknowledge the farmers for providing land to develop observatories and providing the necessary support during the field campaigns.

Author Contributions Ms. AM: conceptualization, methodology, formal analysis, investigation, validation, writing—original draft. Dr. SJ: conceptualization, methodology, validation, software, writing—original draft, writing—review and editing. Prof. RKP: resources, funding acquisition, supervision, project administration, writing—review and editing

Funding Financial support extended by the Information Technology Research Academy (ITRA) (Grant number: ITRA/15(67)/WATER/IGLQ/01), Ministry of Information Technology, Government of India for developing research infrastructure and carrying out the presented study is sincerely acknowledged.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Orellana F, Verma P, Loheide SP, Daly E (2012) Monitoring and modeling water-vegetation interactions in groundwater-dependent ecosystems. Rev Geophys 50(3):1–24. https://doi.org/10.1029/2011RG000383
2. Yeh PJF, Famiglietti JS (2009) Regional groundwater evapotranspiration in Illinois. J Hydrometeorol 10(2):464–478. https://doi.org/10.1175/2008JHM1018.1
3. Good SP, Noone D, Bowen G (2015) Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. Science.Sciencemag.Org (349) 175–177. https://doi.org/10.1002/2015GL064117

4. Irmak S (2008) Evapotranspiration. In: Encyclopedia of Ecology 2 1432–1438. Ecological Processes, Lincoln NE USA
5. Narasimhan TN (2008) A note on India's water budget and evapotranspiration. J Earth Syst Sci 117(3):237–240. https://doi.org/10.1007/s12040-008-0028-8
6. Sanderson JS, Cooper DJ (2008) Groundwater discharge by evapotranspiration in wetlands of an arid intermountain basin. J Hydrol 351(3–4) 344–359. https://doi.org/10.1016/j.jhydrol.2007.12.023
7. Condon LE, Atchley AL, Maxwell RM (2020) Evapotranspiration depletes groundwater under warming over the contiguous United States. Nat Comm 11(1). https://doi.org/10.1038/s41467-020-14688-0
8. Lubczynski MW (2000) Groundwater evapotranspiration: underes-timated component of the groundwater balance in a semi-aridenvironment—Serowe case, Botswana. Congress on Groundwater;Groundwater, Past Achievements and Future Challenges, CapeTown, South Africa, 26 November–1 December 2000, pp 199–204
9. Wang X, Huo Z, Shukla MK, Wang X, Guo P, Xu X, Huang G (2020) Energy fluxes and evapotranspiration over irrigated maize field in an arid area with shallow groundwater. Agric Water Manag 228(June). https://doi.org/10.1016/j.agwat.2019.105922
10. Beyazgul M, Kayam Y, Engelsman F (2000) Estimation methods for crop water requirements in the Gediz Basin of western Turkey. J Hydrol 229(1–2):19–26. https://doi.org/10.1016/S0022-1694(99)00196-1
11. Laczniak BJR, LaRue Smith J, Elliott PE, DeMeo GA, Chatigny MA, Geological Survey U, Roemer GJ (2001) Ground-water discharge determined from estimates of evapotranspiration, Death Valley regional flow system, Nevada and California Carson City Nevada. Water-Resources Investigations Report 01-4195, U.S. Department of the Interior, U.S. Geological Survey
12. Moreo MT, Andraski BJ, Garcia CA (2017). Groundwater discharge by evapotranspiration, flow of water in unsaturated soil, and stable isotope water sourcing in areas of sparse vegetation, Amargosa Desert, Nye County, Nevada. Scientific Investigations Report 2017-5079. Reston, VA: 68. https://doi.org/10.3133/sir20175079
13. Lubczynski MW (2011) Groundwater evapotranspiration – underestimated role of tree transpiration and bare soil evaporation in groundwater balances of dry lands. In: Climate Change and its Effects on Water Resources. Springer, Dordrecht, pp 183–190
14. Cooper DJ, Sanderson JS, Stannard DI, Groeneveld DP (2006) Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community. J Hydrol 325(1–4):21–34. https://doi.org/10.1016/j.jhydrol.2005.09.035
15. Diouf OC, Weihermüller L, Diedhiou M, Vereecken H, Faye SC, Faye S, Sylla SN (2020) Modelling groundwater evapotranspiration in a shallow aquifer in a semi-arid environment. J Hydrol 587(April):124967. https://doi.org/10.1016/j.jhydrol.2020.124967
16. Lautz LK (2008) Estimating groundwater evapotranspiration rates using diurnal water-table fluctuations in a semi-arid riparian zone. Hydrogeol J 16(3):483–497. https://doi.org/10.1007/s10040-007-0239-0
17. Zammouri M (2001) Case study of water table evaporation at Ichkeul Marshes (Tunisia). J Irrig Drain Eng 127(5):265–271. https://doi.org/10.1061/(ASCE)0733-9437(2001)127:5(265)
18. Carlson M, Martha L, Wiley MJ, Wilcox DA, Mazur C (2014) Estimating evapotranspiration and groundwater flow from water-table fluctuations for a general wetland scenario repository citation. Ecohydrology 7(2):378–390. https://doi.org/10.1002/eco.1356
19. Ridolfi L, D'Odorico P, Laio F (2006) Effect of vegetation-water table feedbacks on the stability and resilience of plant ecosystems. Water Resour Res 42(1):1–5. https://doi.org/10.1029/2005WR004444
20. Newman BD, Wilcox BP, Archer SR, Breshears DD, Dahm CN, Duffy CJ et al (2006) Ecohydrology of water-limited environments: a scientific vision. Water Resour Res 42(6):1–15. https://doi.org/10.1029/2005WR004141
21. Brunel JP, Walker GR, Kennett-Smith AK (1995) Field validation of isotopic procedures for determining sources of water used by plants in a semi-arid environment. J Hydrol 167(1–4):351–368. https://doi.org/10.1016/0022-1694(94)02575-V
22. Chimner RA, Cooper DJ (2004) Using stable oxygen isotopes to quantify the water source used for transpiration by native shrubs in the San Luis Valley Colorado USA. Plant Soil 260(1–2):225–236. https://doi.org/10.1023/B:PLSO.0000030190.70085.e9
23. Weeks EP, Sorey ML (1973) Use of finite-difference arrays of observation wells to estimate evapotranspiration from ground water in the Arkansas River Valley Colorado 2029. Library of Congress catalog-card No. 73-600187, U.S. Department of the Interior, U.S. Geological Survey
24. White WN (1932) A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: results of investigations in Escalante Valley Utah. US Government Printing Office, Washington
25. Jiang X, Sun Z, Zhao K, Shi F, Wan L, Wang X, Shi Z (2017) A method for simultaneous estimation of groundwater evapotranspiration and inflow rates in the discharge area using seasonal water table fluctuations. J Hydrol 548:498–507. https://doi.org/10.1016/j.jhydrol.2017.03.026
26. Loheide SP, Butler JJ, Gorelick SM (2005) Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: a saturated-unsaturated flow assessment. Water Resour Res 41(7):1–14. https://doi.org/10.1029/2005WR003942
27. Yonghong S, Qi F, Gaofeng Z, Qi Z (2022) Evaluating the different methods for estimating groundwater evapotranspiration using diurnal water table fluctuations. J Hydrol 607(January):127508. https://doi.org/10.1016/j.jhydrol.2022.127508
28. Fahle M, Dietrich O (2014) Estimation of evapotranspiration using diurnal groundwater level fluctuations : comparison of different approaches with groundwater lysimeter data. Water Resour Res 50:273–286. https://doi.org/10.1002/2013WR014472
29. Jia W, Yin L, Zhang M, Zhang J, Zhang X, Gu X, Dong J (2021) Modified method for the estimation of groundwater evapotranspiration under very shallow water table conditions based on diurnal water table fluctuations. J Hydrol 597(March). https://doi.org/10.1016/j.jhydrol.2021.126193
30. Satchithanantham S, Wilson HF, Glenn AJ (2017) Contrasting patterns of groundwater evapotranspiration in grass and tree dominated riparian zones of a temperate agricultural catchment. J Hydrol 549:654–666. https://doi.org/10.1016/j.jhydrol.2017.04.016
31. Butler JJ, Kluitenberg GJ, Whittemore DO, Loheide SP, Jin W, Billinger MA, Zhan X (2007) A field investigation of phreatophyte-induced fluctuations in the water table. Water Resour Res 43(2):1–12. https://doi.org/10.1029/2005WR004627
32. Gribovszki Z, Kalicz P, Szilagyi J, Kucsara M (2008) Riparian zone evapotranspiration estimation from diurnal groundwater level fluctuations. J Hydrol 6–17. https://doi.org/10.1016/j.jhydrol.2007.10.049
33. Hou X, Yang H, Cao J, Feng W, Zhang Y (2023) A review of advances in groundwater evapotranspiration research. Water (Switzerland) 15(5):1–19. https://doi.org/10.3390/w15050969
34. Soylu ME, Lenters JD, Istanbulluoglu E, Loheide SP (2012) On evapotranspiration and shallow groundwater fluctuations: a Fourier-based improvement to the White method. Water Resour Res 48(6):1–17. https://doi.org/10.1029/2011WR010964

35. Loheide SP (2008) A method for estimating sub daily evapotranspiration of shallow groundwater using diurnal water table fluctuations. Ecohydrology 1:59–66
36. Beamer JP, Huntington JL, Morton CG, Pohll GM (2013) Estimating annual groundwater evapotranspiration from phreatophytes in the Great Basin using landsat and flux tower measurements. J Am Water Resour Assoc 49(3):518–533. https://doi.org/10.1111/jawr.12058
37. Groeneveld DP (2008) Remotely-sensed groundwater evapotranspiration from alkali scrub affected by declining water table. J Hydrol 358(3–4):294–303. https://doi.org/10.1016/j.jhydrol.2008.06.011
38. Meijerink AMJ, Bannert D, Batelaan O, Lubczynski MW, Pointet T (2007) Remote sensing applications to groundwater. United Nations Educational, Scientific and Cultural Organisation. IHP-VI, Series on Groundwater No.16. https://unesdoc.unesco.org/ark:/48223/pf0000156300
39. Jena S, Panda RK, Ramadas M, Mohanty BP, Pattanaik SK (2020) Delineation of groundwater storage and recharge potential zones using RS-GIS-AHP : application in arable land expansion. Remote Sens Appl: Soc Environ 19(April):100354. https://doi.org/10.1016/j.rsase.2020.100354
40. Jena S, Mohanty BP, Panda RK, Ramadas M (2021) Toward developing a generalizable pedotransfer function for saturated hydraulic conductivity using transfer learning and predictor selector algorithm. Water Resour Res 57(7). https://doi.org/10.1029/2020WR028862
41. Jena S, Panda RK, Ramadas M, Mohanty BP, Samantaray AK, Pattanaik SK (2021) Characterization of groundwater variability using hydrological geological, and climatic factors in data-scarce tropical savanna region of India. J Hydrol: Reg Stud 37(May):100887. https://doi.org/10.1016/j.ejrh.2021.100887
42. Thakur I, Jena S, Panda RK, Behera M, Pattanaik SK (2021) Groundwater vulnerability assessment from a drinking water perspective: case study in a tropical groundwater basin in Eastern India. J Hazard Toxic Radioact Waste 25(3):05021004. https://doi.org/10.1061/(asce)hz.2153-5515.0000610
43. Rahman SA, Huang Y, Claassen J, Heintzman N, Kleinberg S (2015) Combining Fourier and lagged k-nearest neighbor imputation for biomedical time series data. J Biomed Inform 58:198–207. https://doi.org/10.1016/j.jbi.2015.10.004
44. Kerr YH, Member S, Waldteufel P, Richaume P, Wigneron JP, Member S et al (2012) The SMOS soil moisture retrieval algorithm. IEEE Trans Geosci Remote Sens 50(5):1384–1403
45. Czikowsky MJ, Fitzjarrald DR (2004) Evidence of seasonal changes in evapotranspiration in eastern US hydrological records. J Hydrometeorol 5(5):974–988. https://doi.org/10.1175/1525-7541(2004)005<0974:EOSCIE>2.0.CO;2
46. Cai J, Liu Y, Lei T, Pereira LS (2007) Estimating reference evapotranspiration with the FAO Penman-Monteith equation using daily weather forecast messages. Agric For Meteorol 145(1–2):22–35. https://doi.org/10.1016/j.agrformet.2007.04.012
47. Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration - guidelines for computing crop water requirements - FAO irrigation and drainage, vol 300. FAO - Food and Agriculture Organization of the United Nations, Rome
48. Jha RK, Sahoo B, Panda RK (2017) Modeling the water and nitrogen transports in a soil–paddy–atmosphere system using HYDRUS-1D and lysimeter experiment. Paddy Water Environ 15(4):831–846. https://doi.org/10.1007/s10333-017-0596-9
49. Singh A, Panda SN, Uzokwe VNE, Krause P (2019) An assessment of groundwater recharge estimation techniques for sustainable resource management. Groundw Sustain Dev 9:100218. https://doi.org/10.1016/j.gsd.2019.100218
50. Shah N, Nachabe M, Ross M (2007) Extinction depth and evapotranspiration from groundwater under selected land covers. Ground Water 45(3):329–338. https://doi.org/10.1111/j.1745-6584.2007.00302.x
51. van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44(5):892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x
52. Yawson DO, Adu MO, Mulholland B, Ball T, Frimpong KA, Mohan S, White PJ (2019) Regional variations in potential groundwater recharge from spring barley crop fields in the UK under projected climate change. Groundw Sustain Dev 8(October):332–345. https://doi.org/10.1016/j.gsd.2018.12.005
53. Ghose D, Das U, Roy P (2018) Modeling response of runoff and evapotranspiration for predicting water table depth in arid region using dynamic recurrent neural network. Groundw Sustain Dev 6:263–269. https://doi.org/10.1016/j.gsd.2018.01.007