The impact of irrigation return flow on seasonal groundwater recharge in northwestern Bangladesh

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ARTICLE INFO

ABSTRACT

Irrigation is vital in Bangladesh in order to meet the growing food demand as a result of the increasing population. During the dry season, groundwater irrigation is the main source of water for agriculture. However, excessive abstraction of groundwater for irrigation causes groundwater level depletion. At the same time, the loss from excessive irrigation could end up contributing to aquifer recharge as return flow. Therefore, investigating the influence of irrigation on groundwater is important for the sustainable management of this resource. This study aims to assess the impact of irrigation on groundwater recharge in the northwest Rajshahi district in Bangladesh. A semi-physically based water balance model was used to simulate spatially distributed groundwater recharge with two scenarios (with and without irrigation). To evaluate the effect of irrigation, groundwater recharges from these two scenarios were compared. The result showed that the use of groundwater for irrigation increased over the study period whereas, there was a persistent trend of decrease in groundwater level during the study period. Groundwater provides 91% of overall irrigation in the study area. However, on average, about 33% of the total irrigation becomes return flow and contributes to groundwater recharge in the dry season. Irrigation return flow is around 98% of the total recharge during the dry season in this region. The spatially distributed seasonal return flow varies from 305 to 401 mm. In brief, irrigation has a significant role in groundwater recharge in the study area during the dry season. Hence, proper irrigation water measurement and management are necessary for sustainable groundwater resource management in this region.

1. Introduction

Groundwater has always been an important and reliable source of water, providing around 97% of freshwater around the world (Jakeman et al., 2016). In semi-arid regions, groundwater is often the only constant source of water throughout the year (Usman et al., 2015). Groundwater recharge is one of the governing factors of the regional groundwater system. Groundwater recharge variation in spatial and temporal aspects as well as difficulties in its direct measurement (Healy, 2010) makes it one of the least understood components of the hydrological system.

Groundwater is mainly recharged by rainfall and surface water sources like reservoirs and rivers (Liu and Yamanaka, 2012). Besides these, irrigation and irrigation return flow could be a significant source of aquifer recharge in agriculture-dominated areas (Jiménez-Martínez et al., 2009; Séraphin et al., 2016). Irrigation return flow is defined as "the excess of irrigation water that is not evapotranspirated or evacuated by direct surface drainage, and which finally returns to an aquifer" (Dewandel et al., 2008) and could contribute a substantial quantity to regional water resources (Cruz-Fuentes et al., 2014; Kendy et al., 2004; Scanlon et al., 2007).

Irrigation water is usually obtained from surface water or groundwater sources. A certain portion of irrigation water is evaporated from the soil surface or transpired by plants while a part of is discharged from agriculture fields as surface runoff to streams or drainage canals. The remaining water infiltrates into the soil and percolates to the groundwater. This excess water returning to the underlying aquifer is referred to as irrigation return flow (Rushton et al., 2020). In shallow aquifers, a large part of irrigation returns to groundwater (Neumann et al., 2009).
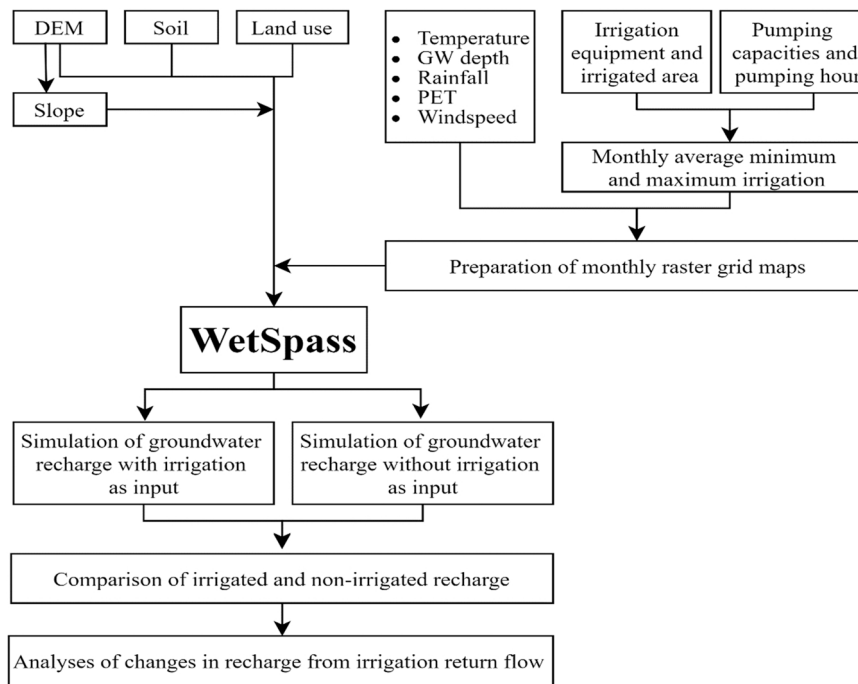
Fig. 1. Conceptual methodology of the study. GW: groundwater; PET: potential evapotranspiration (= reference evapotranspiration for the study); DEM: digital elevation model.

Irrigated agriculture in Bangladesh relies heavily on groundwater. As of 2019, groundwater is the source of irrigation water in 79% of irrigated areas in Bangladesh (Mainuddin et al., 2019). In the northwest region, groundwater which is extracted mainly by shallow and deep tube wells supplies about 95% of the total irrigation water (Mojid et al., 2019). The adoption of dry season Boro rice and other crops substantially increased the groundwater demand in this region (Peña-Arancibia et al., 2020).

The cultivation of Boro rice is important for national food security as it supplies over 55% of the total national production of rice (Mainuddin et al., 2019; Mainuddin and Kirby, 2015). On average, Boro rice covers 61% of the total cropped area of Bangladesh during the Rabi season (October-January) (BBS, 2012). In the Boro season, water loss can be up to 45% in rice fields (Mainuddin et al., 2020; Rashid et al., 2009). Dey et al. (2013) found that 21.3% of water abstracted for Boro rice irrigation is unnecessary in the northwest region. The excess water from irrigation could percolate from rice fields and reach the underlying aquifer as irrigated recharge during the dry season (Rushton et al., 2020). Moreover, this excessive irrigation may act as an important source of replenishing aquifer levels. However, this is not clear yet. Study on the contribution of this excess water to the water budget system is scarce worldwide. Therefore, a detailed investigation of irrigation and its influence on recharge is vital in policy-making to ensure groundwater sustainability globally as well as in the semi arid region like Bangladesh.

Researchers have taken various attempts to find out the influence and contribution of irrigation return flow to groundwater recharge. (Liu et al., 2004) showed that 21.2–23.4% of irrigation water contributes to recharging in terraced paddy fields. (Dewandel et al., 2008) found that return flow ranged from 43% to 59% for rice and 15–37% for vegetables from pumped irrigation water. (Ebrahimi et al., 2016) observed that 15.2% of the total irrigation water returns to aquifer as return flow in western Iran. (Vallet-Coulomb et al., 2017) quantified irrigation return flow and reported that annual return flow was 1190 ± 140 mm, constituting 51–86% of the total irrigation. Other studies around the world have also shown that the irrigation return flow coefficients vary from 2% to over 50% for different crops under various management practices (Bethune et al., 2001; Causapé et al., 2004; Jafari et al., 2019; Jalota and Arora, 2002; Kim et al., 2009; Meyer et al., 1987; Meyer and Mateos, 1990; Steiner et al., 1985; Willis et al., 1997). Most of the studies mentioned above measured only an annual value of irrigation return flow in the respective study area and spatial and temporal variation of the irrigation return flow has not been considered. However, understanding the Spatio-temporal variation of different hydrological components is important to ensure sustainable groundwater resources management (Taie Semiromi and Koch, 2019). Nevertheless, very limited studies have been conducted so far on Spatio-temporal variation of irrigation return flow and its impact on groundwater recharge. More research is needed to understand the Spatio-temporal variation of irrigation return flow and its impact on the groundwater system (Mair et al., 2013; Waibel et al., 2013).

Researchers in hydro(geo)logy have been using spatially distributed groundwater models to understand climatic and anthropogenic influences on groundwater systems to provide sufficient decision-making information (Barbosa et al., 2022; Mustafa et al., 2019). A spatially distributed return flow is an essential variable for a groundwater flow model parameterization in an overexploited aquifer (Mustafa et al., 2018; Nolte et al., 2021). However, there is very limited information available about that. Research with details on the Spatio-temporal variation of the return flow would also be very helpful for the hydrological modeler community to improve the reliability of the model prediction by reducing the uncertainty.

On the other hand, although researchers around the world have investigated the impact of irrigation on groundwater recharge, as far as the authors are aware, a very limited study has been conducted in Bangladesh. So, it is crucial to study on the estimation of spatially distributed irrigation return flow and their impact on groundwater recharge in that region.

Estimating recharge is a complicated process as it varies with different factors like soil, climate, land cover, and topography (Batelaan and De Smedt, 2007). Groundwater recharge estimation can be accomplished by the water table fluctuation (WTF) method, water budget method, Darcy's law, empirical relationships, groundwater models, and tracer techniques (Islam et al., 2016). The water table
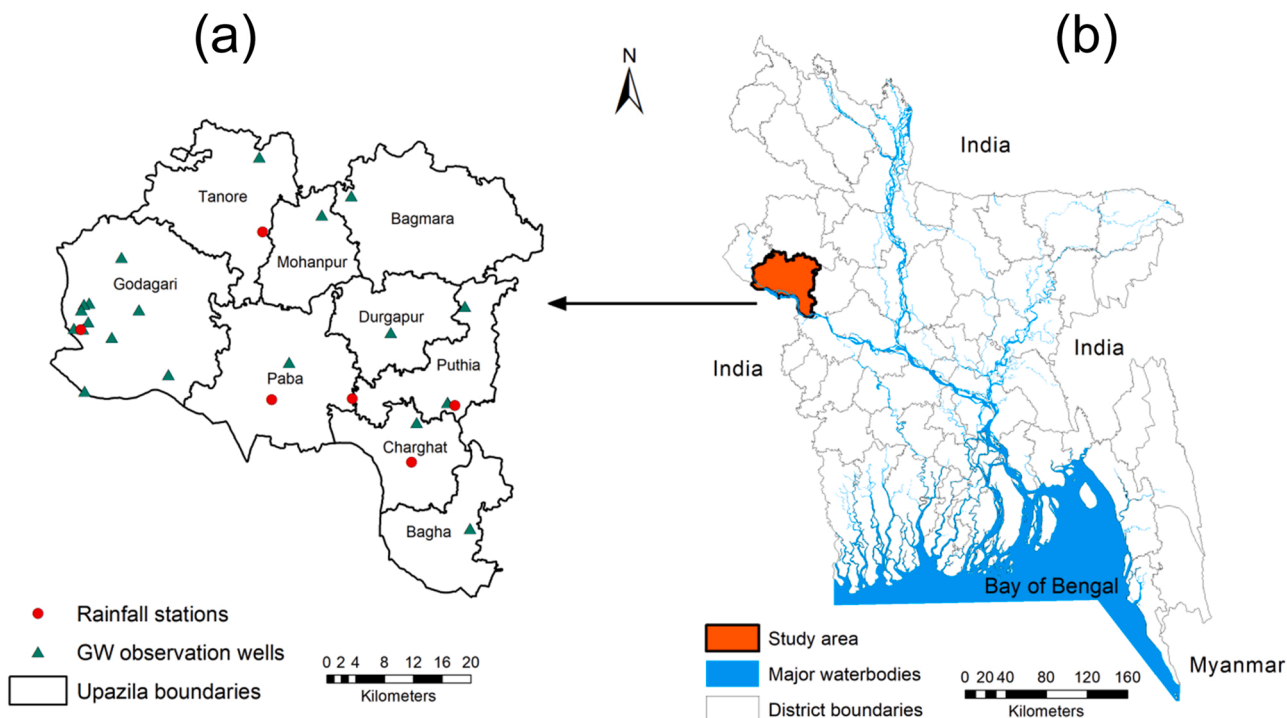
Fig. 2. Location of the study area: (a) Upazila (sub-district) boundary with rainfall stations (red circle) and groundwater observation wells (green triangle) and (b) location of Rajshahi district in Bangladesh.
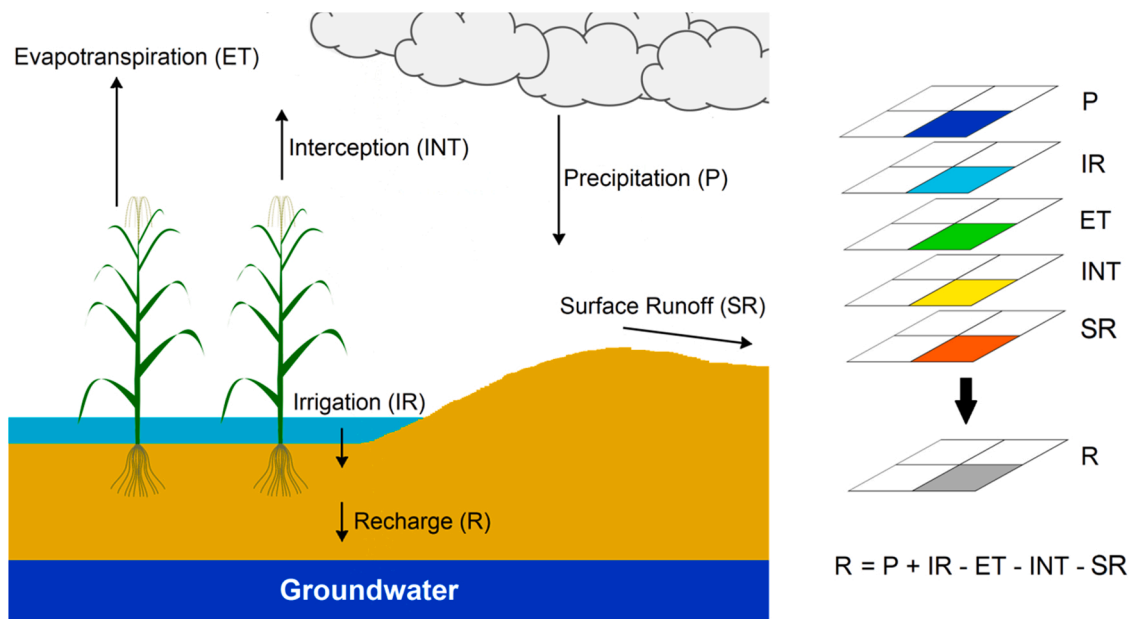

Fig. 3. Schematic representation of different water balance components used in simulating groundwater recharge in the WetSpass model.

Table 1
Pumping hours and days based on stakeholder discussion.

Month	Pumping hours (per day)	No. of pumping days (per month)
November	2–4	16
December	3–6	16
January	12–14	22
February	10–12	22
March	12–13	22
April	5–8	16

fluctuation method is only applicable for unconfined aquifers and tracer techniques are very time-consuming. For this reason, the water budget method was used in this study because of its application over a wide range of space and time variables (Scanlon et al., 2002). A semi physically based water balance model WetSpass (Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-steady State) (Abdollahi et al., 2017; Batelaan and De Smedt, 2007) is used in this study to measure spatial and temporal variability of monthly groundwater recharge which makes it suitable for the objectives of this study.

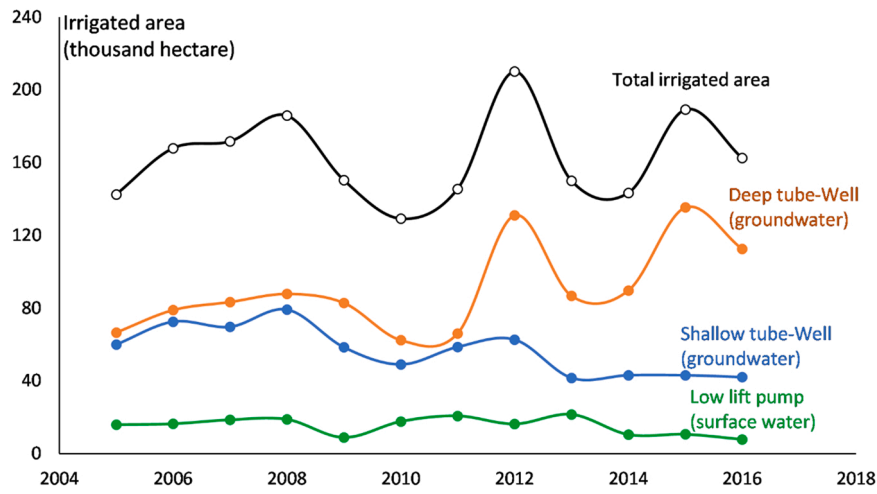Therefore, the general objective of this study is to evaluate the

Fig. 4. Trends in the annual irrigated area by shallow tubewells, deep tubewells, and low lift pump in Rajshahi district from 2006 to 2016.
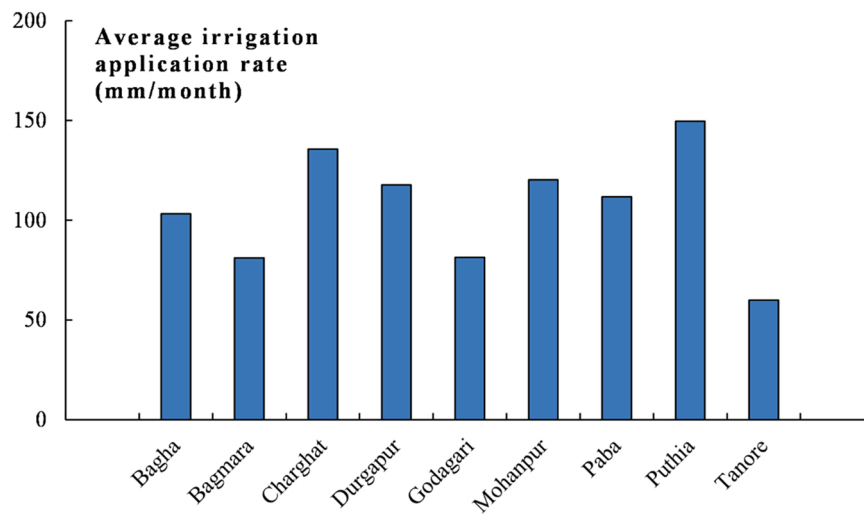
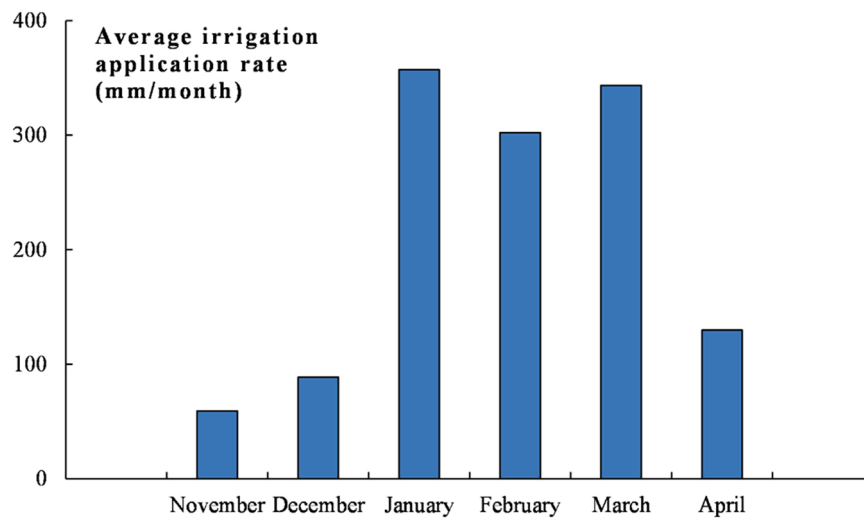**Fig. 5.** Upazila-wise (sub-district) average irrigation application rate.

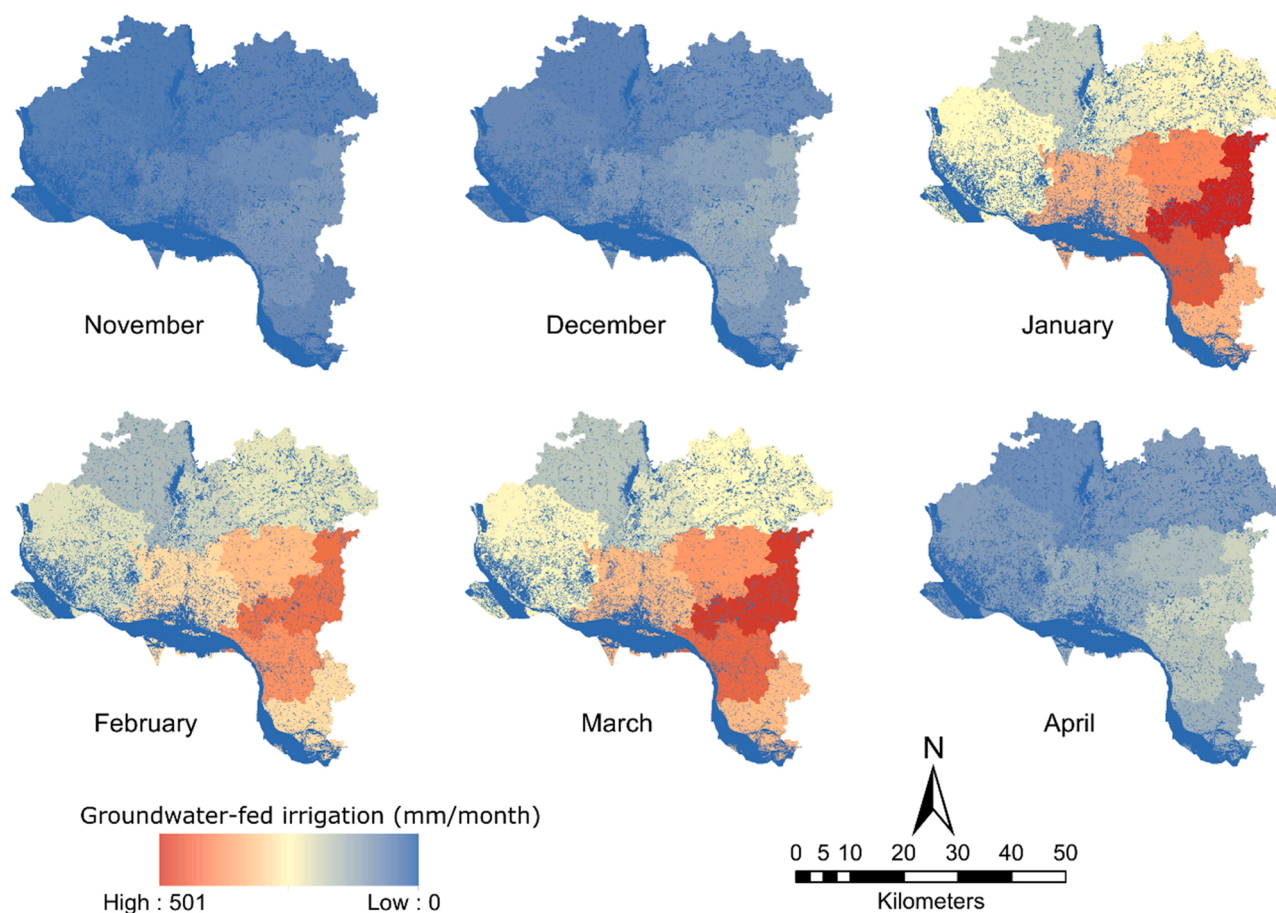**Fig. 6.** Monthly average irrigation application rate in the dry season.

Fig. 7. Spatial and temporal variation of monthly average groundwater irrigation.

impact of irrigation on groundwater recharge in the Rajshahi district of Bangladesh. Specific objectives of this study are to (i) evaluate the current status of irrigation and its impact on groundwater level, (ii) simulate recharge considering irrigation as input with other input variables and also without irrigation, (iii) simulate recharge without irrigation, (iv) assess simulated recharge relation with rainfall and soil-texture, (v) assess the contribution of irrigation in the total water balance, (vi) estimate the irrigation return flow and evaluate its impact on the groundwater recharge, (vii) quantify the spatial and temporal variation of the irrigation return flow and evaluate its impact on the groundwater system. Furthermore, maps of various resolutions are used as inputs to investigate the scaling effects of raster resolution. The results of the study will deliver information on the influences of irrigation on spatially distributed recharge and help with effective irrigation planning in northwest Bangladesh, especially in the Rajshahi district.

2. Methodology

A multi-step methodology was applied in this study to evaluate the impact of irrigation on groundwater recharge. At first, hydrometeorological, soil, elevation, land use, and irrigation data were collected from various sources. Secondly, these data were processed and grid maps were prepared to use as model inputs. Thirdly, the monthly groundwater recharge was simulated by WetSpass. Finally, the effects of irrigation return flow were analyzed from irrigated and non-irrigated recharge. Fig. 1 shows the conceptual methodology of this study.

2.1. Study area

The agriculture-dominated Rajshahi district in northwestern

Bangladesh was chosen for this study. The geographic location of the study area is between 24.12° and 24.72° northern latitude and 88.28° and 88.97° eastern longitude. The total area is 2407 km². Approximately 1588 km² of the total area is under cultivation whereas 1229 km² of agricultural land has a proper irrigation facility. The district is divided into 9 Upazila (sub-district), as depicted in Fig. 2.

The study area is situated in the sub-tropical climate region. The mean annual rainfall for the period of 1964–2009 is 1505 mm, which is lower than the national average of 2408 mm (Ghosh et al., 2015). The temperature rises above 40 °C during the summer but falls below 5 °C in winter. The mean relative humidity varies from 60% to 88% (Haque et al., 2012). The area is a part of the Ganges basin, consisting primarily of riverine alluvium. The soil textures include sand, silty loam, loam, clay loam, etc. The aquifer formation is of unconsolidated sedimentary type (Allison et al., 2003). According to several hydrogeological studies conducted in the region, the upper aquifers are unconfined or semi-confined, with thicknesses varying from 10 to 40 m (Asad-uz-Zaman and Rushton, 2006; Faisal et al., 2005; Jahani and Ahmed, 1997; Michael and Voss, 2009; Rahman and Shahid, 2004). The digital elevation model (DEM) shows that Rajshahi is 23 m above the mean sea level, although the elevation varies up to 62 m.

Over the last two decades, the study area is facing a decreasing trend in groundwater level. The water table of most of the shallow tubewells in this area falls below the suction lift limit (6 m) (Mojid et al., 2019). Although some of them maintain a cycle of fluctuation, most of the tubewells fail to lift water in the dry season (Dey and Ali, 2010). Moreover, the introduction of high-yield rice varieties has expanded irrigation-fed agriculture in the study area (Adhikary et al., 2013) and increased crop intensity (Rahman and Mahbub, 2012).
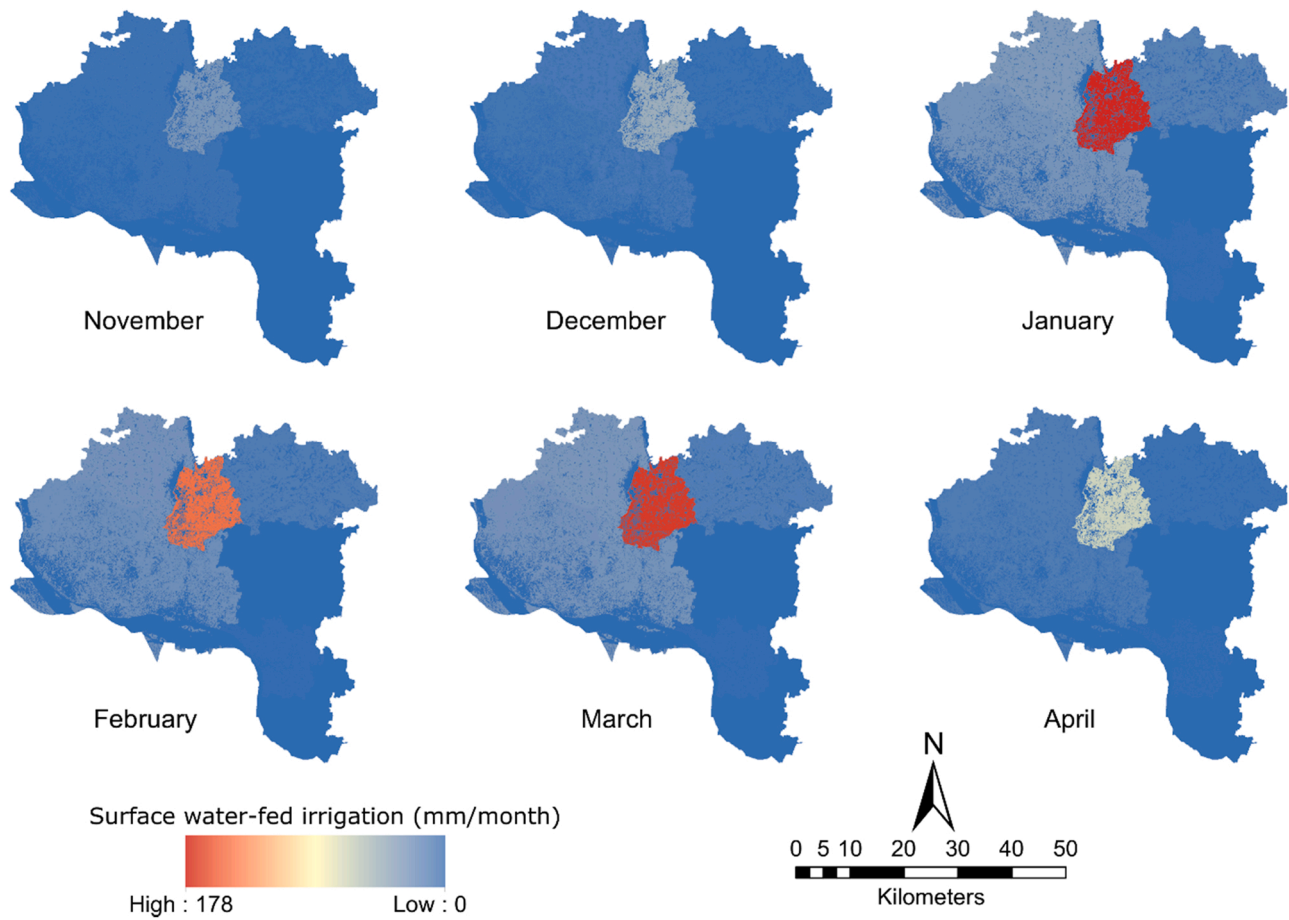
Fig. 8. Spatial and temporal variation of monthly average surface water irrigation.

Table 2
Model inputs, their sources, spatial and temporal resolution, and processing tools/method.

Inputs	Source (s)	Original temporal resolution	Temporal resolution (used)	Spatial resolution	Processing tools/method
Groundwater depth	BMDA, BWDB	Weekly	Monthly average	30 m	–
Rainfall	BMD, BWDB	Daily	Monthly sum	30 m	Interpolation using IDWa in ArcGIS
Temperature	BMD	Daily	Monthly average	30 m	
Potential evapotraspiration (PET)	Calculated using FAO Penman-Monteith equation from the observed climatic data	Daily	Monthly sum	30 m	Interpolation using IDWa in ArcGIS
Wind speed	BMD	Daily	Monthly average	30 m	–
No. of rainy days	Observed rainfall	Daily	Monthly sum	–	–
Digital Elevation Model (DEM)	SRTM	Static raster map	Static raster map	30 m	–
Land use	USGS	2016	2016	30 m	Explained in section "Model inputs"
Slope	Calculated from DEM	Static raster map	Static raster map	30 m	ArcGIS
Soil	SRDI	Static raster map	Static raster map	30 m	Lookup according to WetSpass-M model
Irrigation	BADC, BMDA, DAE	2006 to 2016	Monthly average	30 m	Interpolation using Spline (with barriers) in ArcGIS

[a] IDW inverse distance weighting

2.2. WetSpass model

Monthly groundwater recharge is simulated using a semiphysically based water balance model WetSpass (Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-steady State) (Abdollahi et al., 2017; Batelaan and De Smedt, 2007). The model uses climatic data, together with topography, land cover, and soil mapping to estimate average spatial patterns of surface run-off, actual evapotranspiration, and groundwater recharge (Batelaan and De Smedt, 2001). The model recognizes any region as a regular pattern of raster cells. Each raster cell is divided into four fractions (vegetated, bare-soil, open-water, and impervious). The water balance components are calculated individually for each cell from the inputs. The water balance equation for a cell can be expressed as,

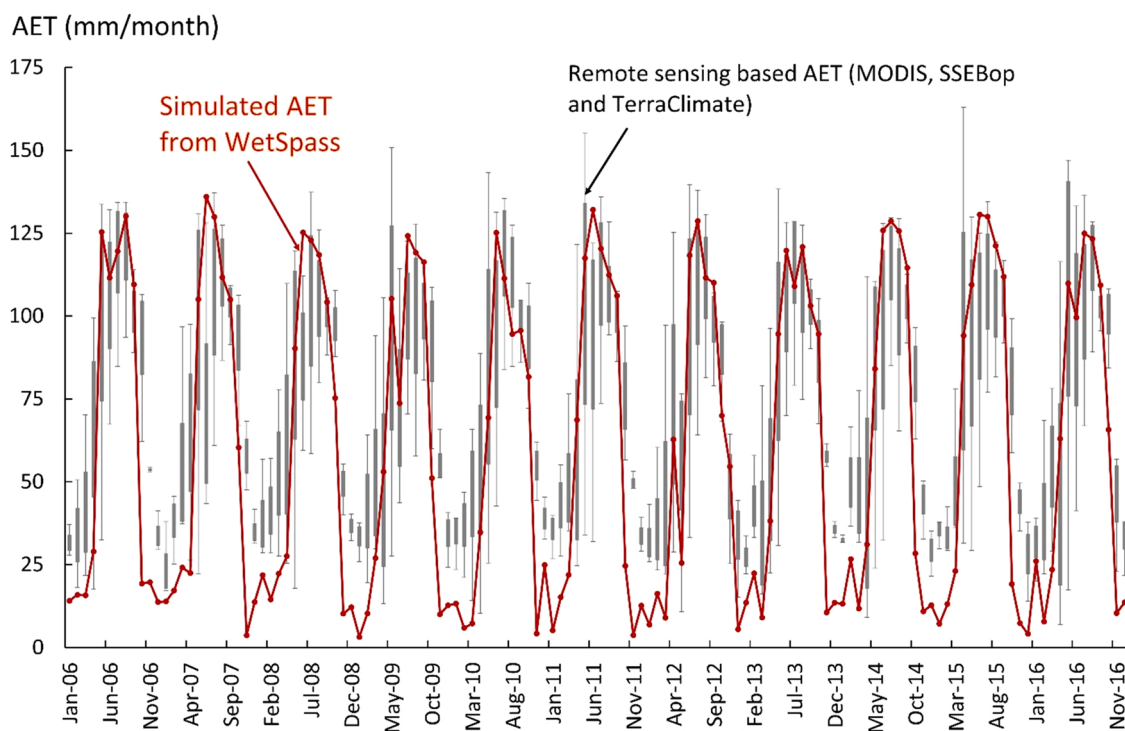$$P + IR = SR + ET + INT + R \qquad (1)$$

Fig. 9. Comparison of simulated AET (red line) and remote sensing AET (box plots) from 2006 to 2016; AET: actual evapotranspiration.

Where P is precipitation, IR is irrigation, SR is surface runoff, ET is evapotranspiration, INT is interception, and R is groundwater recharge. According to Eq. 1, precipitation and irrigation are considered the source of water in the model. Depending on the land use of the simulating cell, the model at first calculates interception as a percentage of water input (P + IR). After that, SR is calculated considering various factors such as land use, slope, soil moisture condition, soil texture etc. Then ET is estimated from the sum of actual evapotranspiration of the four land-use subdivisions (open water, vegetated, bare soil and impervious) for each cell. ET is the sum of evaporation from soil surface and transpiration from plants. In bare soil and open water land use, only evaporation is considered. The actual evapotranspiration of each land use subdivision is estimated from the PET of the cell. Finally, recharge is estimated from the residual part of the water balance equation. The grids are not horizontally connected and therefore, there is no horizontal movement of water like a process-based model. However, slope is a variable in water balance calculation so there is an indirect effect of horizontal movement of water (Abdollahi et al., 2017; Batelaan and De Smedt, 2007). Fig. 3 shows the water balance components. In this study, each raster cell resolution was taken 30 m × 30 m.

This model has been effectively used in different climatic conditions around the world (Abdollahi et al., 2017; Armanuos and Negm, 2016; Meresa and Taye, 2019; Mustafa et al., 2017, 2018, 2019; Salem et al., 2019). In order to use this kind of model, spatially distributed higher resolution raster data is required. Resolution plays a vital role in raster data analysis (Arnone et al., 2016). Coarser resolution often leads to lower accuracy in results (Cama et al., 2016). However, finer resolution might require higher computational performance (Arnone et al., 2016). On the other hand, time is valuable in policy planning especially when results are required within a short time. Therefore, researchers have to consider the computational performance as well as the required accuracy level of their analysis (Calder and Mayer, 2003; Maleika, 2015).

2.3. Irrigation

Irrigation data from dry season (November to April) agricultural

activities was collected and analyzed in the study to evaluate the effect of irrigation on groundwater recharge. Supplemental irrigation data from wet months (May to October) were excluded from the analysis of groundwater recharge estimation due to unpredictable pumping for rainfed agriculture.

Upazila (sub-district) wise number of irrigation pumps i.e. Deep tube wells (DTW), Shallow tube wells (STW) and Low lift pumps (LLPs) and their irrigated area for the period of 2006–2016 were collected from "Minor Irrigation Survey Report", recorded by Bangladesh Agricultural Development Corporation (BADC), Barind Multipurpose Development Authority (BMDA) and Department of Agricultural Extension (DAE) and published as a report by BADC. In general, pumping capacities for shallow tubewells (depth < 80 m below ground level), deep tubewells (depth > 80 m below ground level), and low lift pumps are assumed to be 0.5, 2, and 1 cusec, respectively (BADC, 2019; BBS, 2009; UNDP, 1982).

Irrigation map layers were produced assuming that only cultivated vegetated land types would need irrigation. Irrigation was considered zero for the remaining 3 land cover types (i.e., bare soil, open-water, and impervious). Based on stakeholder discussion (details in Section 2.3.1), the total pumping period per month was generated. Using pumping period per month and pumping capacity, average monthly pumped water was computed, which was considered as the monthly average irrigation in this study.

Monthly irrigation = monthly pumped water = pumping period per month × pumping capacity.

Spatially distributed monthly irrigation maps were produced from this data using the spline interpolation method (with barriers). ASCII irrigation maps were produced from this data using the spline interpolation method (with barriers) for the model as inputs. This interpolation method was used because it has a higher tolerance to the effects of errors and needs fewer observations, resulting in improved results in practice (Zong et al., 2018). Irrigation data was obtained upazila-wise, which means the same set of data prevails within a particular upazila. So, an additional barrier technique was used with spline interpolation to distribute the same raster value within each upazila boundary.
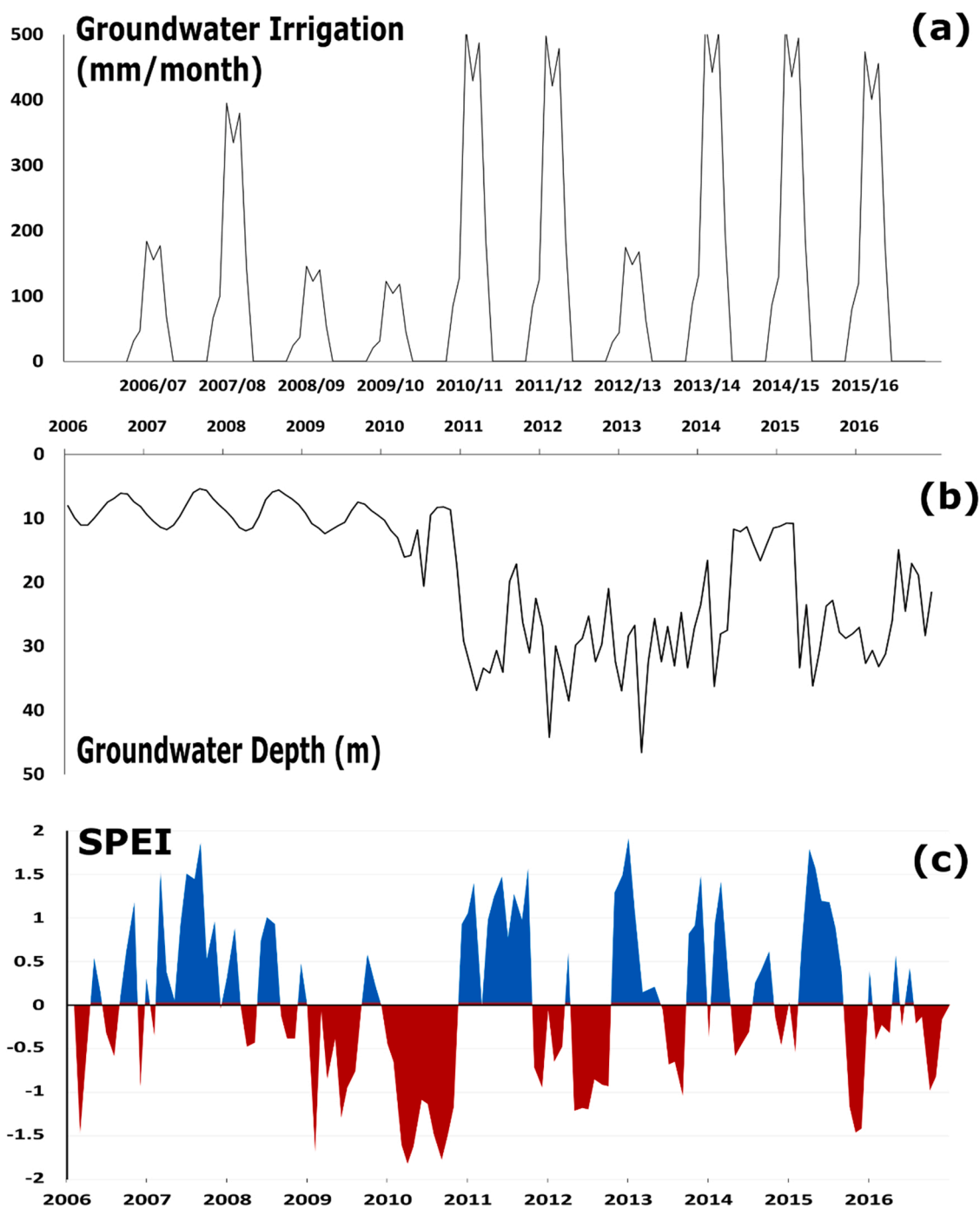
Fig. 10. Time series of the hydrological components: (a) seasonal average groundwater irrigation, (b) monthly average groundwater depth for Rajshahi district, (c) the average SPEI values at the timescale of 3-months.

2.3.1. Estimation of discharge

Upazila-wise monthly irrigation depth was computed from the total monthly discharge of a pump and irrigated area. Monthly discharge was calculated from pumping capacity, average daily pumping hour, and number of pumping days in each month. Actual pump capacity was estimated considering 80% pumping efficiency, because the pumping efficiency is decreasing day by day with respect to time. Pumping capacity, pumping efficiency and information on average daily pumping hours and number of pumping days (Table 1) were collected and verified through stakeholders' discussions. A face-to-face stakeholder's workshop was not possible because of the ongoing pandemic. So, several one-to-one discussions were performed with different stakeholders, including representatives of local farmers, Bangladesh government irrigation management authorities like Bangladesh Agricultural Development Corporation (BADC), Barind Multipurpose Development Authority (BMDA), Department of Agricultural Extension (DAE) and researchers from Bangladesh Agricultural University (BAU). The stakeholders shared their practical experiences and provided information about the number, performance, discharge, and existing conditions of irrigation equipment. Based on the per day pumping hours, the minimum range of pump operating time was used to calculate minimum irrigation maps and maximum range of pump operating time used to prepare maximum irrigation maps.
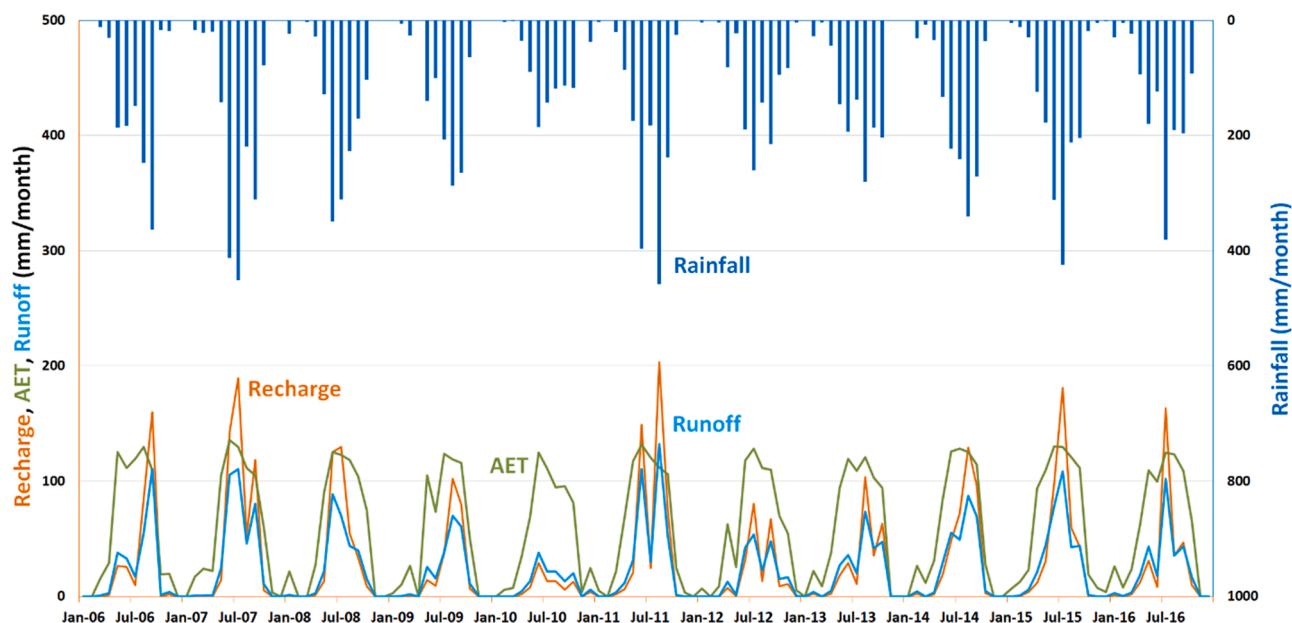
Fig. 11. Time series (from Jan-2006 to Dec-2016) of mean monthly groundwater recharge, Actual Evapotranspiration (AET) & Surface runoff (primary axis) and rainfall (secondary axis) without considering irrigation.
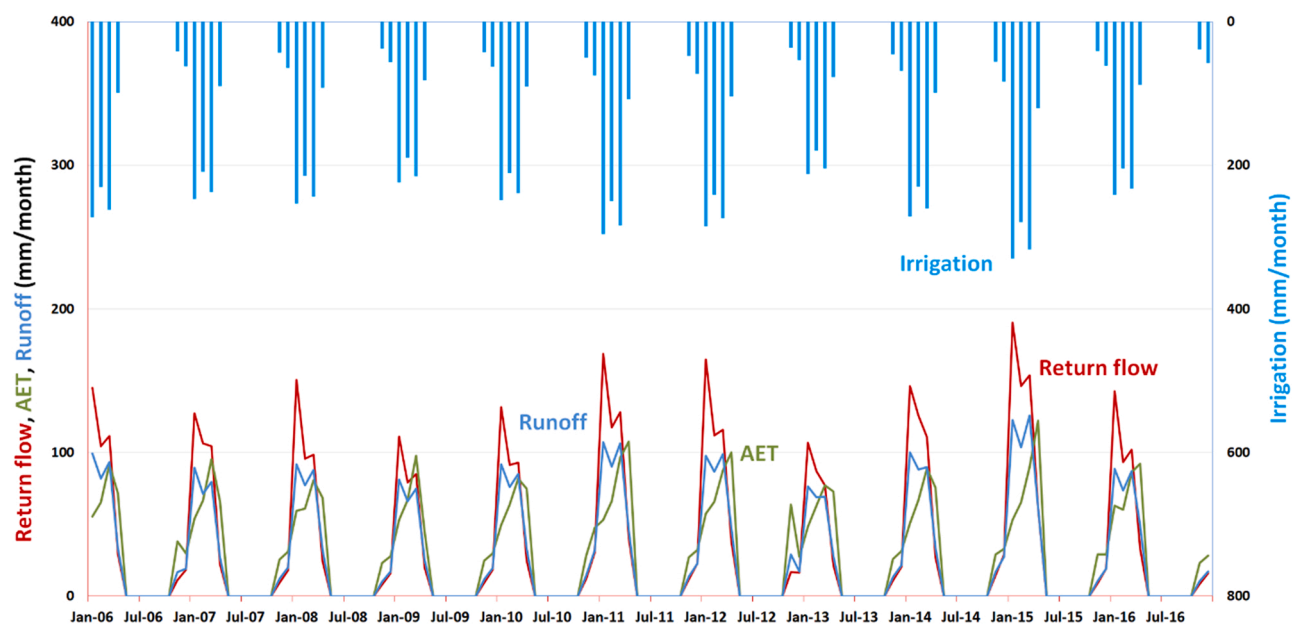

Fig. 12. Time series (from Jan-2006 to Dec-2016) of mean monthly irrigation (secondary axis) and irrigation return flow, actual evapotranspiration (AET) & surface runoff (primary axis) considering irrigation.

2.3.2. Current irrigation status

Fig. 4 illustrates the annual total irrigated area of Rajshahi district by different irrigation equipment from 2006 to 2016. The data showed the total irrigated area remained somewhat constant throughout the study period. An increase in area under deep tubewells (DTW) operated irrigation was observed (112,530 ha from 78,949 ha). In contrast, the total amount of irrigated area under shallow tubewells (STW) decreased over the 11 years, amounting to 42,114 ha from 72,567 ha. The irrigation supply from the low lift pump (LLP) showed a considerable decline (7869 ha from 16,414 ha) over the study period. In general, groundwater-fed irrigated area increased (154,644 ha from 151,516 ha) over the period even though the number of shallow tubewells declined. This might be caused by the widespread use of deep tubewell water for

agriculture. Also, BMDA, BADC, and DAE developed new Deep tube-wells in these 11 years. As a result, the use of DTWs increased drastically to get the necessary irrigation water. Mainuddin et al. (2019) reported similar findings in northwestern Bangladesh. Overall, the groundwater-fed irrigated area was greater than the surface water-fed irrigated area. However, the rate of change in total irrigated areas was inconsistent.

Fig. 5 illustrates the upazila-wise average irrigation application rate. The highest average irrigation rate was applied in Puthia upazilla (150 mm/month), closely followed by Charghat (136 mm/month). Conversely, the lowest average irrigation was in Tanore (60 mm/month). Fig. 5 shows the average irrigation application rate for the dry season in which January has the highest irrigation rate, which amounted
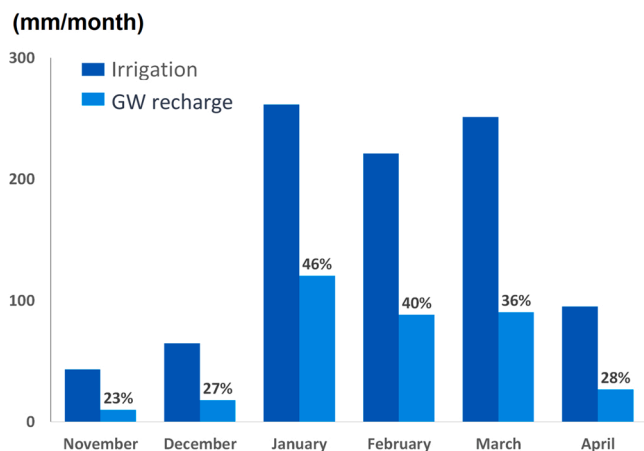
(mm/month)

Fig. 13. Monthly applied irrigation depth (dark blue) and contribution of irrigation to groundwater recharge in percentage (light blue).

to 357 mm/month. January was followed by March (344 mm/month), February (302 mm/month), April (130 mm/month), December (89 mm/month) and finally November (59 mm/month). Monthly variation in irrigation is closely connected with crop type. November and December months need low irrigation because various winter crops like; pulses, potato, mustard, winter vegetables, etc., which requires less water are cultivated in these two months. From January, farmers start rice cultivation in this area. Irrigation water requirement increases in January as rice requires great amount of water in that time due to puddling. However, irrigation requirement decreases again in April as crop water requirement decreases in the harvesting stage. Fig. 6.

The monthly average irrigation depths of the Rajshahi district are shown in Fig. 7 (groundwater-fed irrigation) and Fig. 8 (surface water-fed irrigation). The average minimum and maximum irrigation depths were 94 mm/month and 119 mm/month, respectively, and the mean irrigation depth was 107 mm/month. However, the depth of irrigation requirement was different in different locations and different months of the season. The rate of groundwater and surface water irrigation was vastly different. Figs. 7 and 8 show the monthly distribution of groundwater and surface water irrigation in different upazilas in the Rajshahi district. In January, the highest average groundwater irrigation was observed in the whole district to be 327 mm/month in contrast to only 30 mm/month from surface water. For groundwater irrigation, Puthia and Charghat had the highest average rates of 150 and 135 mm/month, respectively. In contrast, these two upazilas showed little to

almost no surface water irrigation (0 and 1 mm/month, respectively). The lowest average groundwater irrigation was found in Tanore (51 mm/month) and Mohanpur (67 mm/month). Tanore had moderately low surface water irrigation (9 mm/month). On the other hand, Mohanpur topped the surface water irrigation rate at 53 mm/month. This variability was mainly because of the number of the irrigation equipments, i.e., DTW, STW, LLP, etc. in different upazilas. Different sources of surface water irrigation are river, ponds, and reservoirs in this region. In general, groundwater irrigation out-quantified surface water irrigation over the Rajshahi district. Around 91% of the total irrigation was extracted from groundwater while the remaining 9% was from surface water sources. CSIRO (2014)) reported that nearly 100% of the total irrigation in the northwest zone was being supplied from a groundwater source.

2.4. Model inputs

The required input data of the WetSpass model (groundwater depth, rainfall, temperature, windspeed, soil, irrigation) were collected for a period of 11 years (2006–2016). Groundwater depth data were collected from the Barind Multipurpose Development Authority (BMDA) and Bangladesh Water Development Board (BWDB). Meteorological data (rainfall, temperature, and wind speed) recorded by Bangladesh Meteorological Department (BMD) and BWDB were collected from the Water Resources Planning Organization (WARPO) of Bangladesh. Reference evapotranspiration (ET$_0$) was calculated from maximum and minimum temperature using the "ET$_0$ Calculator" based on the FAO Penman-Monteith equation (Eq. 2) (FAO, 2009).

$$ET_0 = \frac{0.408 \quad \Delta \quad (R_n - G) + \quad \gamma \frac{900}{T+273} \quad u_2(e_s - e_a)}{\Delta + \quad \gamma(1 + 0.34 \quad u_2)} \tag{2}$$

ET$_0$ is the reference evapotranspiration [mm day^{-1}], R$_n$ is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [°C], u$_2$ is the wind speed at 2 m height [ms^{-1}], e$_s$ is the saturation vapor pressure [kPa], e$_a$ is the actual vapor pressure [kPa], e$_s$ – e$_a$ is the vapor pressure deficit [kPa], Δ is the slope vapor pressure curve [kPa °C^{-1}], γ is the psychrometric constant [kPa °C^{-1}].

This ET$_0$ is also considered as the potential evapotranspiration (PET) in this study. ET$_0$ was used to avoid crop related ambiguities derived from PET and ET0 is also far more widely used in agriculture and irrigation studies (Xiang et al., 2020). Table 2 summarizes the data used in this study along with their sources. All data were processed using GIS software ArcMap 10.5. For interpolation, in this case, Inverse Distance
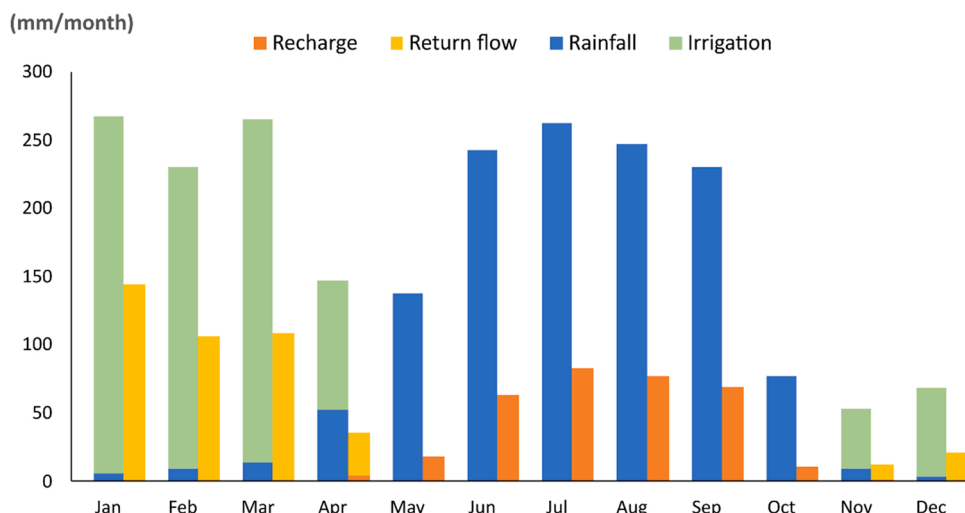

Fig. 14. Monthly average values of different parameters (rainfall, recharge from rainfall, irrigation and return flow from irrigation) ranging from 2006 to 2016.
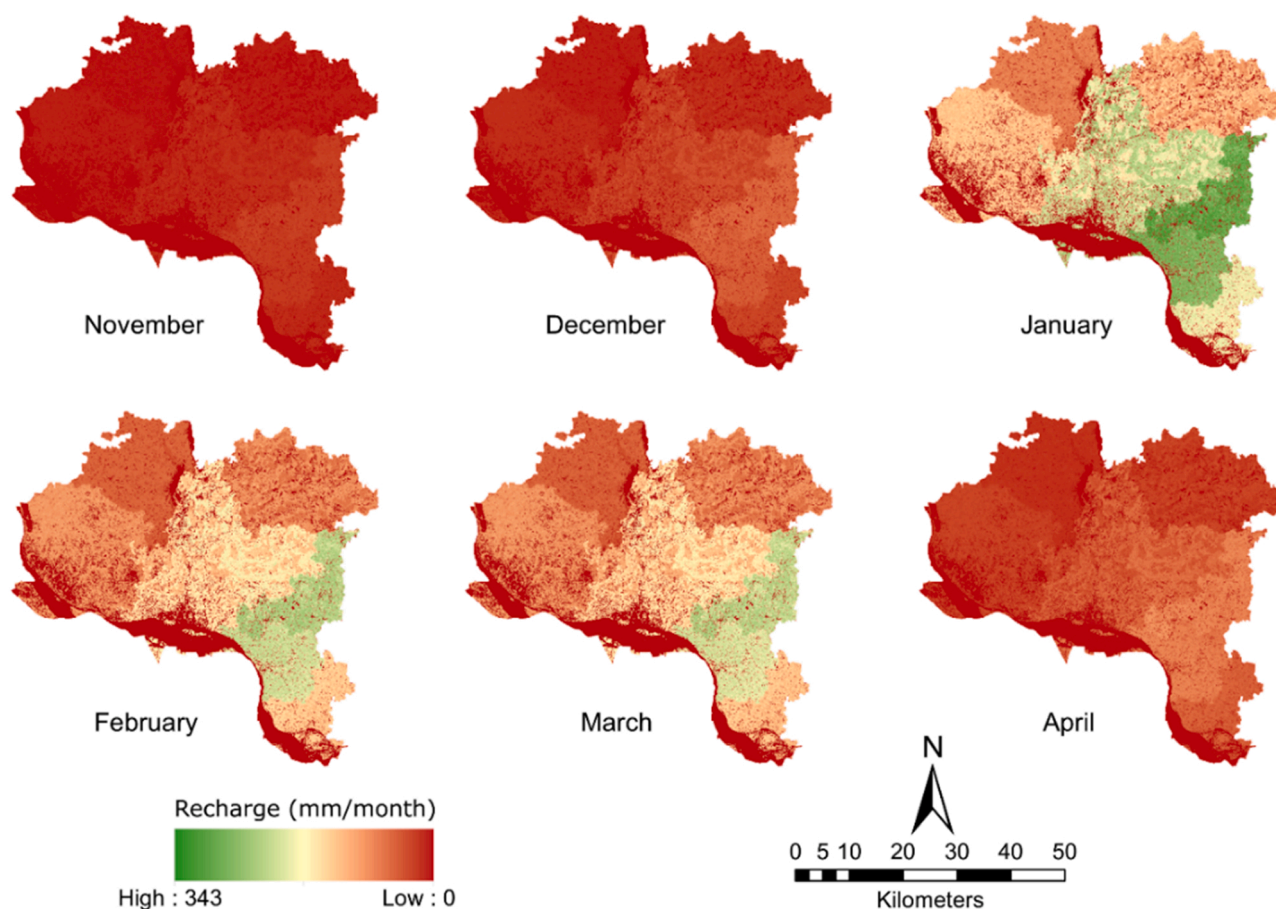
Fig. 15. Spatial and temporal distribution of long-term monthly average groundwater recharge over the entire simulation period using maximum irrigation.

Weighting (IDW) method was used for its simplicity and good performance compared to other methods (Hodam et al., 2017). A multi-step spatial data processing tool using ArcGIS Model Builder was developed to automate the creation process of raster maps.

The soil texture map of Soil Resource Development Institute (SRDI) was collected from WARPO and reclassified according to WetSpass soil classes. The Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of 30 m resolution was used as the elevation model. The slope map was prepared from the DEM. Dry seasonal land use map of 2016 processed by Siddik (2021) was used as land use input of the model. The model inputs are described in Table 2.

2.5. Calibration of the model

In-situ data of actual evapotranspiration (AET) and discharge in the study area are not present. The generated data sets were evaluated using (1) available groundwater recharge from other studies in the same study area and (2) available remote sensing (RS) AET products. At first, the simulated recharge was evaluated using the available groundwater recharge from other studies in the same area (details in Section 3.2). Additionally, the model performance has been evaluated using available remote sensing evapotranspiration products. Research shows that RS based AET can be a suitable alternative to actual data in areas where in situ measurements are not available (Weerasinghe et al., 2020). This study used three widely used RS AET products to assess the model performance. The products are the Moderate Resolution Imaging Spectroradiometer MOD16 algorithm (MODIS; Mu et al., 2007, 2011), Simplified Surface Energy Balance model (SSEBop; Senay et al., 2013) and TerraClimate (Abatzoglou et al., 2018). The result shows that RS AET and simulated AET are in good agreement (Fig. 9). It is observed

that the model is slightly underestimating the low values of the AET. However, temporal and seasonal variation of the AET is very well captured by the model, which confirms an acceptable simulation capacity of the WetSpass model.

2.6. 2.6 Irrigation impact analysis

A spatially distributed water balance model (WetSpass) was used to evaluate the impact of irrigation on groundwater recharge. Groundwater recharge was simulated with two scenarios. Irrigation was considered as an additional input along with other inputs in the first scenario, while in the second scenario groundwater recharge was simulated without considering irrigation as input. Finally, the impact of irrigation was evaluated by comparing the simulated groundwater recharge in the two scenarios (Fig. 1).

Net recharge to the aquifer from the irrigation has been calculated using the following equation to evaluate the overall impact of irrigation on the aquifer.

Net recharge to the aquifer from the irrigation = irrigation water returned (irrigation return flow) - irrigation water pumped from groundwater.

The positive value of the equation means the increase of groundwater level of the aquifer and negative value indicated depletion of groundwater level in the aquifer.

2.7. Effects of resolution

All the input grid maps having a resolution of 30 m × 30 m were resampled into 300 m × 300 m to examine the impact of resolution differences. The complete modeling methodology and analytical
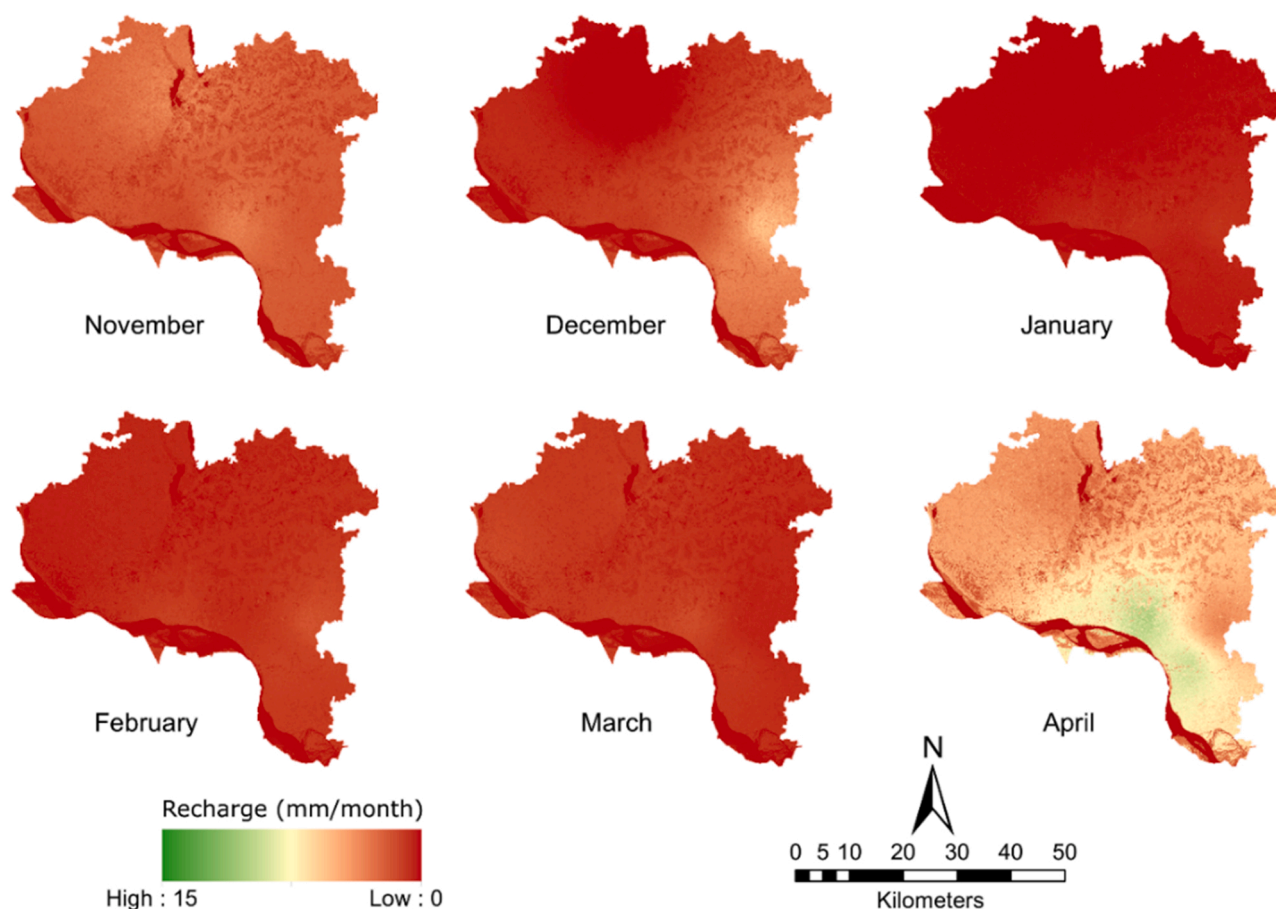
Fig. 16. Spatial and temporal distribution of long-term monthly average groundwater recharge over the entire simulation period without irrigation.

processes were repeated with the newly resampled maps. Time required for simulation process for both 30 m and 300 m resolution were recorded. Then the results and time requirement were compared with the results of 30 m resolution.

2.8. Methods and tools used for different analyses

The statistical significance of the results was checked by Mann-Whitney and Kruskal-Wallis tests using the Python SciPy module. For various data and result analysis and plotting, Python packages like NumPy, Pandas, and Matplotlib were used. For geospatial analysis and mapping, GIS applications (ArcGIS 10.5 and QGIS 3.6) and Python package Rasterio were used. The modeling simulations were performed using a computer having an intel core i5–4210 U @ 1.70 GHz processor and 4 GB RAM.

3. Results and discussion

3.1. Impact of abstraction for irrigation on groundwater depth

Fig. 10 represents the time series of different hydrological components including trend of groundwater irrigation and corresponding groundwater depth from 2006 to 2016 of Rajshahi district and also Standardized Precipitation-Evapotranspiration Index (SPEI) at the timescale of 3-months,. The figure shows that irrigation rate and groundwater depth increase over the years (Fig. 10a, b). The average groundwater depth was 8.4 m in 2006 and increased to 25.5 m in 2016. A noteworthy increase in groundwater depth was noticed in 2010/2011. This might be as a result of combined effect of overexploitation of groundwater for irrigation in 2010/11 season and multi-year

meteorological drought in 2009–2010 (Afrin et al., 2019).

There was an increase in groundwater irrigation in the 2007/08 season, even though the depth remained somewhat the same. This was likely due to the prolonged period of surplus water from rainfall during 2007–2008. The use of groundwater for irrigation increased significantly from 2010/11 with the exception of 2012/13. The decrease in groundwater use for irrigation in 2012/13 could be explained by the wet weather (positive SPEI) in the 2012/13 season, as shown in Fig. 10c.

This study used SPEI Calculator, developed by Vicente-Serrano et al. (2010), to estimate monthly SPEI. The software takes monthly total rainfall and mean temperature as inputs. Monthly potential evapotranspiration (PET) was computed from temperature by the Thornthwaite method (Sellinger, 1996; Thornthwaite, 1948) in the SPEI calculator. Finally, monthly SPEI was estimated from rainfall and PET series.

In general, the rate of groundwater irrigation was observed to have some effects on changes in groundwater depth. Therefore, groundwater abstraction for irrigation is one of the main factors but not the only factor influencing increase in groundwater depth or overall groundwater level depletion in this region.

3.2. Groundwater recharge without considering irrigation

Fig. 11 shows the monthly rainfall in secondary axis and monthly groundwater recharge, AET and surface runoff without consideration of irrigation. It indicates that recharge, AET and runoff had a similar trend to rainfall over the study period. Recharge was relatively higher in the wet season (May to October) than in the dry season (November to April). This was due to more significant rainfall in wet season and little to no rainfall in the dry season. (Rushton et al., 2020) also reported similar
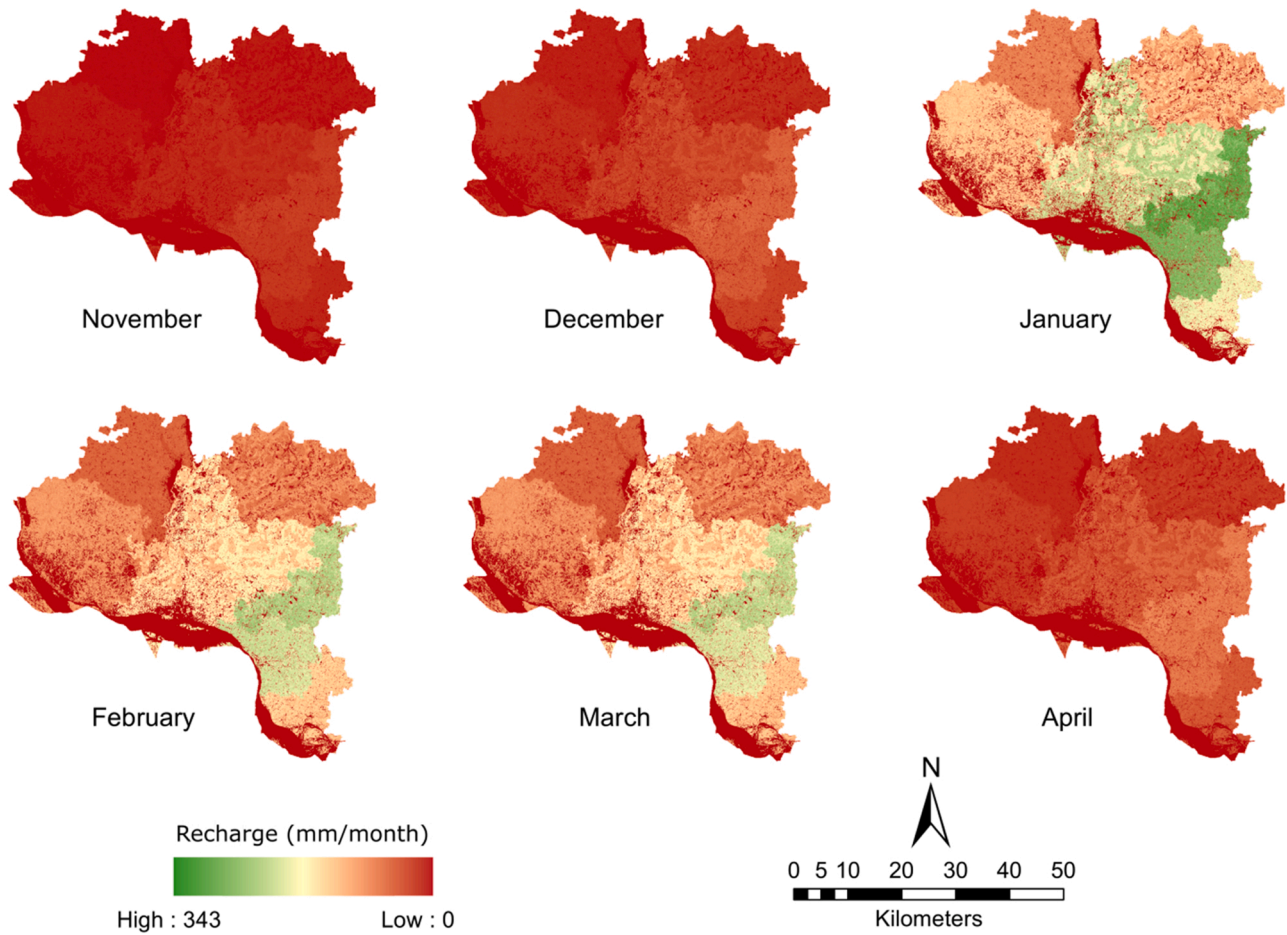
Fig. 17. Contribution of return flow considering maximum irrigation rate.
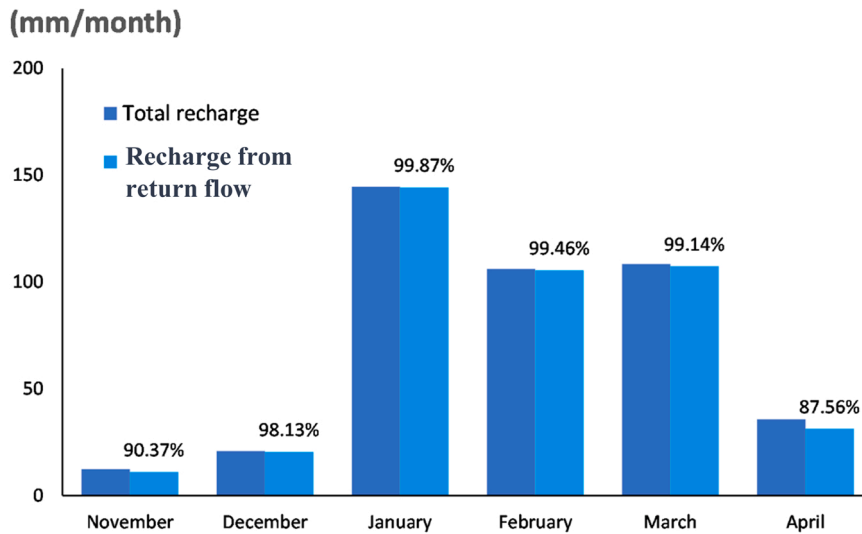
Fig. 18. Monthly average total recharge (dark blue) and contribution of recharge from irrigation return flow (light blue) to the groundwater recharge system in percentage.

results considering a similar pumping period. Average monthly recharge varied between 0.2 mm (January) and 83 mm (July), averaging at 28 mm/month. Average annual recharge ranged from 221 mm to 524 mm, the average being 330 mm. These findings are similar to Shamsudduha et al. (2011) in which they reported that the annual groundwater recharge varied from 250 mm to 600 mm. Mustafa et al. (2017) also observed annual recharge to be in between 230 mm and 660 mm in northwest Bangladesh. However, the recharge rate was not uniform over the study area.

Fig. 19. Time series of mean monthly net recharge to the aquifer from the irrigation during dry season (Nov to April) from 2006 to 2016.

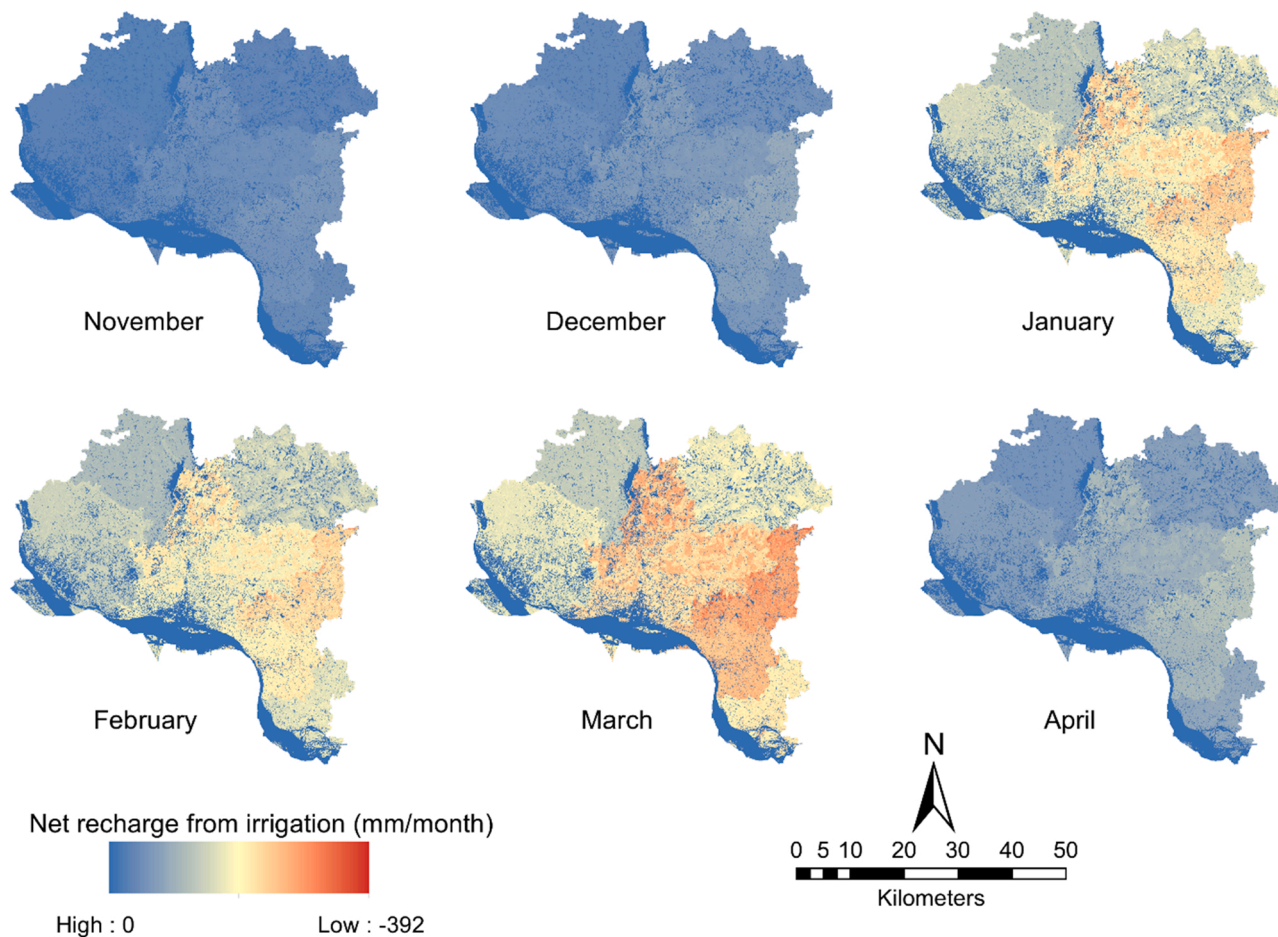**Fig. 20.** Spatial and temporal variation of monthly average net recharge to the aquifer from irrigation during dry season (Nov to April).
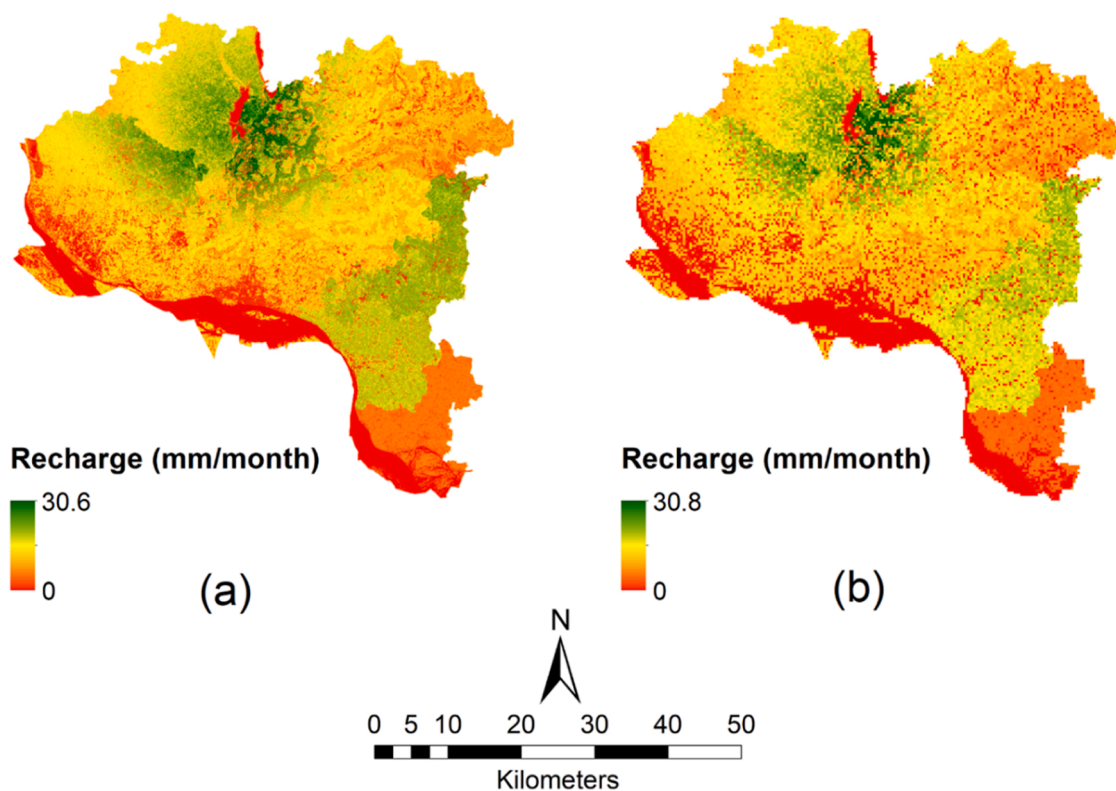
Fig. 21. Spatially distributed average groundwater recharge (January) maps with irrigation in (a) 30 m and (b) 300 m resolution.

3.3. Irrigation return flow

Monthly average irrigation along with irrigation return flow, actual evapotranspiration (AET) & surface runoff are presented in Fig. 12. It shows a similar pattern between these entities. There was no return flow, AET and runoff in the wet months (May to October) as no irrigation was considered in the wet months. In these months, there was usually enough rainfall for crops. Thus, agriculture in the wet period was rainfed and no irrigation application was assumed which meant no return flow during the wet period. On the other hand, irrigation was the only source of water during the dry season because of insufficient rainfall. The average annual return flow was 353 mm. The average monthly return flow was highest in January (120 mm) and lowest in November (10 mm). Highest and lowest values of AET was found in January (88.65 mm) and November (30.86 mm). Similarly, highest and lowest values of runoff were also found in January (90.91 mm) and November (14.56 mm) respectively. This was likely because January has the highest rate of irrigation and November has the lowest.

The return flow was 20–50% of irrigation. On average, 33% of irrigation returned to groundwater as recharge. Dewandel et al. (2008) reported 44–52% and 20–28% return flow from total irrigation for rice and vegetables, respectively during the dry season in semi-arid India. Ebrahimi et al. (2016) and Jafari et al. (2019) reported that the rate of return flow is 15.2% and 15%, respectively in arid west and southeast Iran. The months with high irrigation had a higher return flow percentage compared to the months with lower irrigation supplies.

The monthly average rates of irrigation along with return flow are shown in Fig. 13. From the study, approximately one-third of the applied irrigation went back to the aquifer as return flow. This indicates excess amount of irrigation water loss. Rashid et al. (2009) found that water loss could be up to 45% in Boro season while Dey et al. (2013), found that 21.3% of irrigation water was unnecessary. This unwarranted lift of water decreased the overall irrigation efficiency.

Fig. 14 illustrates monthly average groundwater recharge and return flow from the rainfall and irrigation, respectively. The results show that aquifers are mainly recharged from rainfall during the monsoon, and return flow from irrigation is the main source of groundwater recharge during the dry season. In the dry seasons, irrigation is the main source of water for different crops. Groundwater recharge is also predominant from this irrigation in the dry season. The rainfall amount is very small during the dry season, and thus groundwater recharge from rainfall is also very insignificant.

On the other hand, in the wet season there are adequate amount of rainfall occurs in that region. That's why groundwater recharge is mainly from rainfall in the wet season. The amount of rainfall in the wet season is very similar to the amount of irrigation in the dry season. The average maximum rainfall was occurred in July, having 262 mm rainfall. The groundwater recharge was 83 mm, which was mainly from rainfall. The average maximum irrigation was found in January, having 261 mm. The irrigation return flow this month was 144 mm. Although having similar values for rainfall in July and irrigation in January, the recharge value is much higher for irrigation than rainfall. This happened because the value of surface runoff is insignificant for irrigation because this is applied only to agricultural fields. On the other hand, a large portion of rainfall is diverted as surface runoff which results in less recharge.

A report published by International Rice Research Institute stated that Bangladesh has the lowest irrigation efficiency in the region ($117.60/hectare) compared to India, Thailand, and Vietnam (The Daily Star, 2008). Hence, water-saving methods are necessary to reduce loss and increase efficiency. (Borrell et al., 1997) experimented with raised beds in Australia and reported 34% water saving over flooded rice. (Fahong et al., 2004) used furrow irrigation during winter in China and found 30% water saving over flood irrigation. (Cao et al., 2019) showed that irrigation scheduling could significantly reduce the amount of irrigation for rice cultivation compared to conventional irrigation.
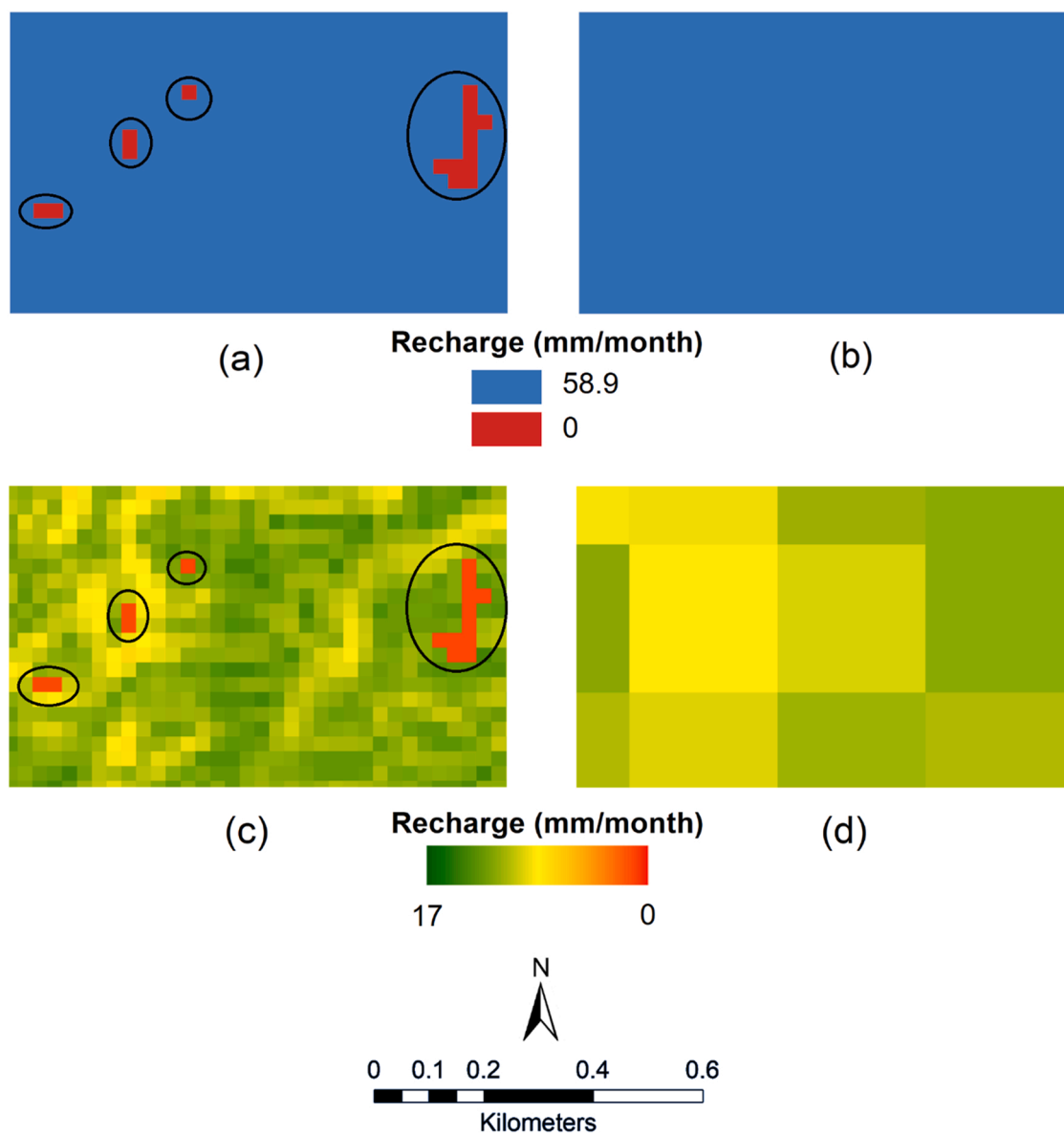
Fig. 22. Part of maps of (a) irrigation of 30 m, (b) irrigation of 300 m, (c) recharge (average January) of 30 m, and (d) recharge (average January) of 300 m resolution (black circles indicating the zones of interest).

Rainwater harvesting (Velasco-Muñoz et al., 2019), alternative cropping systems (Zhao et al., 2021) and deficit irrigation (Fereres and Soriano, 2006) can also be used as water savings methods for sustainable groundwater water management. Other measures like alternate wetting and drying (AWD), flush, sprinkler, drip irrigation could also be useful for water-saving (Bouman et al., 2007). However, Mojid and Mainuddin (2021) and Mainuddin et al. (2020) claimed that groundwater level is not depleted due to excessive groundwater abstraction for irrigation because excess irrigation water goes back to groundwater as return flow. They also highlighted the negative impact of the different water-saving technologies on groundwater dynamics. Indeed, excess irrigation water returns to groundwater as a return flow. However, in this study area, net

recharge to the aquifer from irrigation was negative as groundwater abstraction for irrigation is higher than the irrigation return flow, meaning the depletion of groundwater level in the dry season. Detailed investigation on the influence of different irrigation water-saving methods on groundwater systems has been done, including probable negative impacts.

3.4. Impact of irrigation on spatially distributed recharge

Recharge was simulated considering the minimum and maximum rate of irrigation for the six dry months (November-April). Without irrigation, the average recharge was 8 mm/ year in the dry season. With

irrigation, the average recharge was found to be 313 and 409 mm/year for minimum and maximum rates, respectively in the dry season. Spatially distributed monthly average groundwater recharge for maximum irrigation, minimum irrigation, and without irrigation are shown in Fig. 15, Fig. A1 (Appendix), and Fig. 16, respectively. The contribution of irrigation as irrigation return flow was 305 and 401 mm/year for minimum and maximum rates, respectively. The results revealed that there is a significant (p < 0.05; 95% confidence level) influence of irrigation return flow on groundwater recharge in the dry season over the whole study area.

Spatially varied irrigation return flow rates for both maximum and minimum irrigation are shown in Figs. 17 and A2 (Appendix), respectively. From both figures, the central east upazilas (Puthia and Durga-pur) had the most pronounced effects of return flow on recharge. The northern upazilas, such as Tanore and Bagha in contrast, has the lowest contribution of return flow. The difference was caused by the difference in irrigation rates in the upazilas. The upazilas with higher irrigation showed greater influence of irrigation return flow on recharge. Considering the months, January showed the highest return flow rates due to highest irrigation rate. On the other hand, November had a smaller contribution due to lower irrigation rate.

3.5. *3.5 Impact of irrigation return flow on the groundwater system*

Fig. 18 illustrates the monthly average total recharge and the contribution of the irrigation return flow to the groundwater recharge system. In the dry season (November – April), irrigation return flow was the main source of the groundwater recharge system. The month of November and April had a lower return flow percentage compared to other dry seasons because these two months had little rainfall that contributed to the groundwater recharge. The average total groundwater recharge in the dry season was 428 mm, where the contribution of return flow was 420 mm (98.20%). Jafari et al. (2019) have also reported that the contribution of return flow to groundwater recharge was 81.3% in the arid part of Iran.

3.6. *Net recharge to the aquifer from the irrigation*

Fig. 18 shows the mean monthly net recharge to the aquifer from irrigation from 2006 to 2016. The net recharge from irrigation is calculated from 'the groundwater recharge from irrigation' minus irrigation water pumped from groundwater. It is observed that net recharge to the aquifer from the irrigation is always negative, indicating the depletion of groundwater level in the aquifer. Although, on average, 33% of the irrigation water returned to the aquifer, the rest, 67% of the water, remains in the surface environment (discussed in 3.3 Irrigation return flow). This causes the groundwater level declining day by day in the dry season. As the water pumped from the groundwater is higher than the recharge from irrigation, the values of net recharge to the aquifer from the irrigation are negative. Here, the values from May to October are ignored as this study is done considering dry months (November to April) only.

It shows there is a very large depletion of groundwater levels during the dry season (Fig. 19). On the other hand, the aquifer is partially replenishing again in the rainy season (Fig. 14). As groundwater recharge in the rainy season is adding to the aquifer and the is only very limited abstraction of groundwater from supplemental irrigation. However, overall depletion of groundwater is higher than replenishment and that's why groundwater depth is continuously increasing in this area (Fig. 10).

Fig. 20 shows the spatial and temporal variation of monthly average net recharge to the aquifer from irrigation during dry season (Nov to April). Average monthly net recharge to the aquifer from irrigation is changing from − 392 mm/month to 0 mm/month. The negative value indicates depletion of groundwater level of an aquifer.

Although, excessive irrigation water can be returned back to the aquifer, however, net recharge to the aquifer is negative due to overexploitation of the aquifer for irrigation. So, groundwater abstraction for irrigation should be reduced by adopting different water saving methods (details on Section 3.3) in the agricultural fields to reduce the depletion of groundwater levels. Additionally, excessive abstraction of groundwater cause a steady increase in Sulphur and Calcium that worsen the water quality (Gejl et al., 2019). Excessive abstraction of groundwater can also have a negative impact on carbon footprint. Long term excessive abstraction of groundwater contributes to an increase CH_4 budget (Gooddy and Darling, 2005; Kulongoski and McMahon, 2019). Different irrigation improvement measures should be adopted and details study on the effect of irrigation return flow on overall groundwater effect should be done and simulated to obtain more accurate results. A detailed study should be conducted to know the actual amount of carbon and other materials mix-up with the groundwater due to excessive abstraction.

3.7. *Effect of spatial scaling*

Fig. 21 shows average groundwater recharge maps considering the irrigation of January of both 30 m and 300 m resolution. Overall, the results indicated that the difference in average recharge was 0.6 mm/year and 0.05 mm/month while the difference due to average irrigation was 0.3 mm/year when impact of irrigation was considered. The simulation time for one-year groundwater recharge using 300 m resolution inputs was 15.2 min which was 22 times faster than the time required for simulation using 30 m resolution inputs (339.4 min/year). Ovarall, the changes from different resolutions were relatively small eventhough simulation with 300 m resolution was much faster and less time-consuming.

However, the lower resolution irrigation maps had problems with accurate representation of irrigation rates. A raster cell had only one specific value within its area. So, a 300 m raster grid having an area of 90000 sq. m is homogeneous for specific input. On the other hand, for a raster of 30 m resolution, the area of homogeneity is 900 sq. m grid area. Areas with a smaller size than 90000 sq. m were not included and represented precisely in a raster of 300 m resolution. This results in smaller areas of a certain irrigation rate beign lumped into another irrigation rate value in a lower resolution raster map which in turn results in incorrect groundwater recharge calculations in those smaller areas. For example, Fig. 22 portrays some of the comparisons between maps of both resolutions. The black circles indicates the special interest zones. The small areas (black circle marked) in the raster map of 30 m having 0 mm/month irrigation (Fig. 22 (a)) and recharge (Fig. 22 (c)) were absent in the corresponding raster maps of 300 m (Fig. 22(b) and 21(d) respectively). This was a misrepresentation of spatially distributed irrigation and result of recharge. For example, in the airport area where there is no chance of irrigation and recharge, 300 m maps may misinterpret the built-up zone with the vegetative region. So, the heterogeneity of spatial irrigation value was lost to some degree in the lower resolution maps. Hence, studies requiring high precision on small areas will need raster maps of higher resolution.

4. Conclusions

The study focused on assessing the impact of irrigation on

groundwater recharge in the northwest Bangladeshi district of Rajshahi. Groundwater recharge was estimated using a water balance model WetSpass considering two different scenarios, (i) irrigation as an additional input and (ii) without irrigation as an input. Finally, the impact of irrigation on groundwater recharge and the contribution of irrigation return flow to the groundwater system was analyzed.

Deep tube wells fed irrigated area increased in the Rajshahi area from 2006–2016. However, the total irrigated area in Rajshahi remained constant. Surface water fed irrigated area decreased slightly. The highest irrigation rate was in Puthia upazila (sub-district) while the lowest was found in Tanore. Around 91% of overall irrigation came from groundwater, with the remaining 9% originating from surface water.

The trends of irrigation rate and groundwater depth revealed an increase in irrigation and groundwater depth. The parallel trend showed that groundwater abstraction for irrigation could be a reason for water table depletion.

The average return flow was 353 mm/year. It was highest in January and lowest in November. 20–50% of the total irrigation was observed to be return flow (33% on average). Around 98% of the groundwater recharge came from irrigation return flow during the dry season. The spatially distributed return flow ranged from 305 to 401 mm/year. It contributed significantly, during the dry season, to groundwater recharge in the study area. The highest return flow was in central right upazilas (Puthia and Charghat) and the lowest was in northern upazilas (Tanore and Bagha).

The scaling analysis showed a very small change in model simulation results for both 30 m and 300 m spatial resolutions. There was a substantial reduction in recharge simulation time with 300 m resolution inputs compared to 30 m raster maps. However, the raster maps of the lower resolution were not good for detailed analysis. Therefore, the use of lower resolution inputs can only be recommended when a quick investigation is required over precision analysis.

Finally, it could be concluded that irrigation has a significant impact on groundwater recharge during the dry season in Rajshahi district of Bangladesh And that irrigation return flow was the main source of groundwater recharge in the dry season. However, a huge quantity of groundwater still leaves the system due to excessive pumping. Therefore, effective irrigation management including efficient irrigation application methods and better irrigation scheduling is necessary to keep the groundwater sustainable in the study area.

Declaration of Competing Interest

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.

Data availability

Important data are summarized and presented in tables, figures, and references. Data are available from the authors upon request (syed. mustafa@abdn.ac.uk).
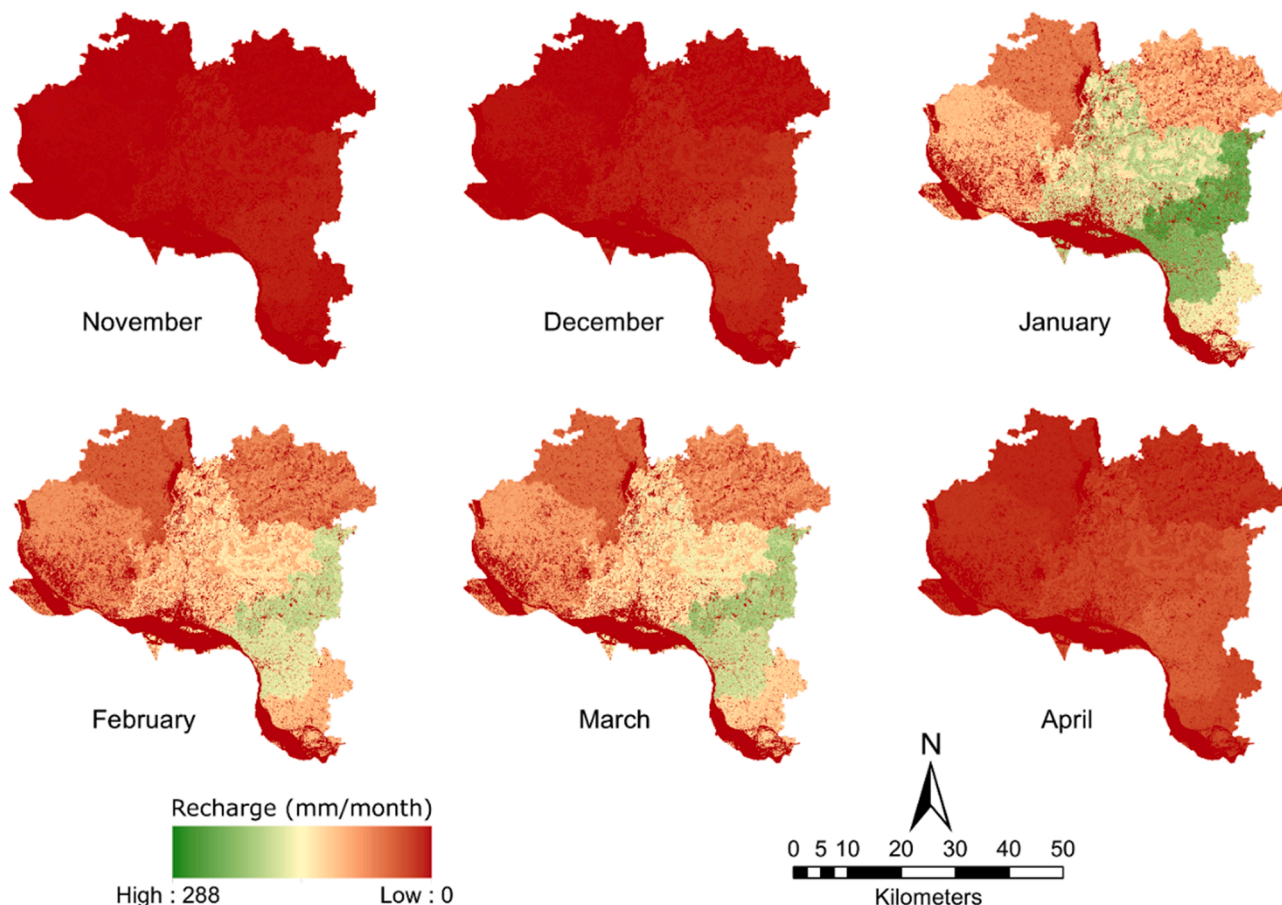
Appendix

see Fig. A1,A2.

Fig. A1. Spatial and temporal distribution of long-term monthly average groundwater recharge over the entire simulation period using minimum irrigation.
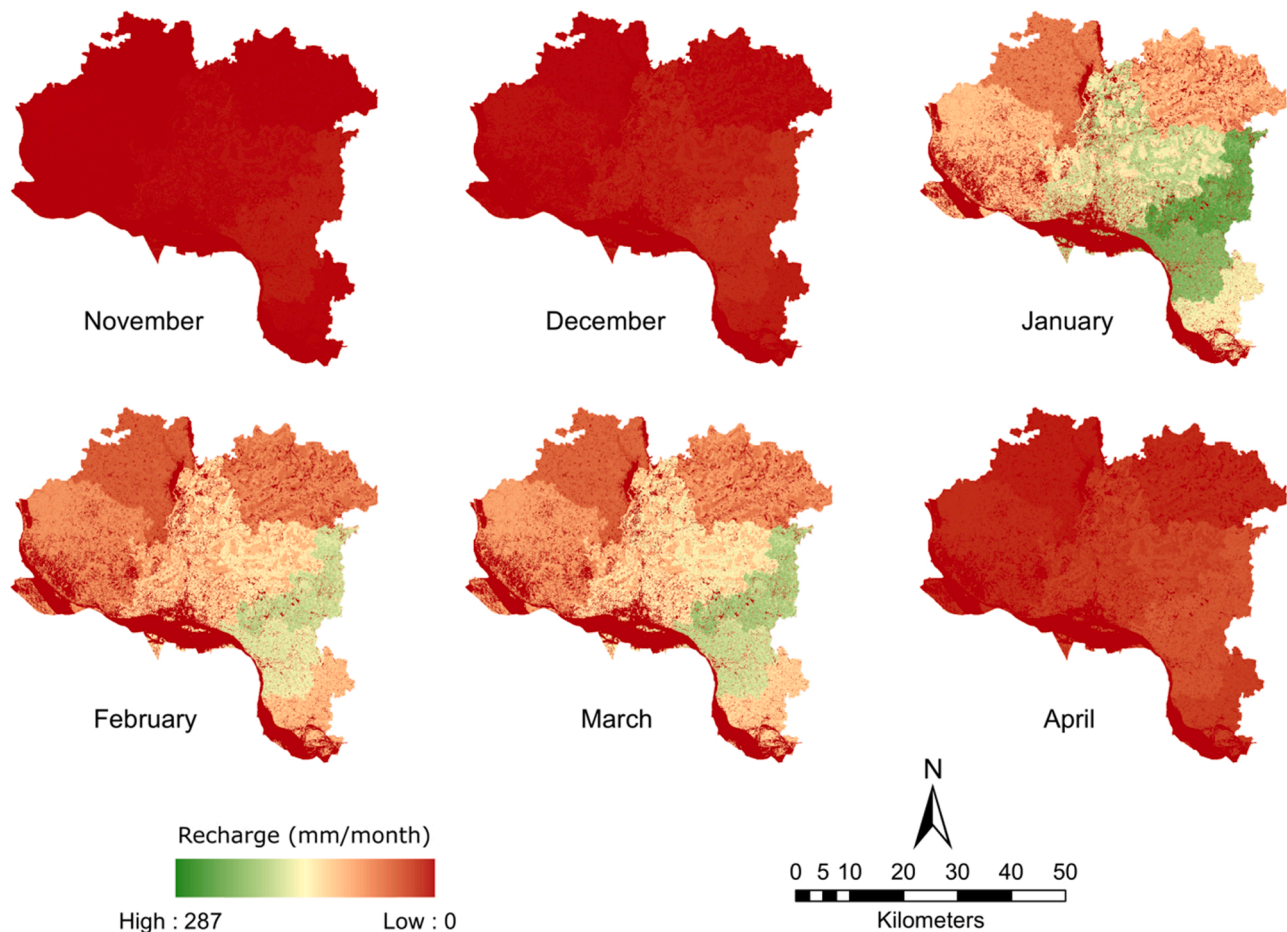
Fig. A2. Contribution of return flow considering minimum irrigation rate.

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