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Potential and net recharge assessment in paddy dominated Hirakud irrigation command of eastern India using water balance and geospatial approaches

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Abstract

Spatially distributed potential and net recharge rates were assessed in the paddy dominated Hirakud command area (Eastern India) at 100 m grid resolution using surface water balance and Water Table Fluctuation (WTF) methods, respectively, for the period 2001–05. Net recharge estimated using the WTF method corresponding to observation well locations was further interpolated using kriging technique available in the ArcGIS software. Net recharge to potential recharge ratios (%) were also assessed spatially. Water balance components (i) runoff was estimated using the Natural Resources Conservation Service-Curve Number (NRCS-CN) method (ii) reference evapotranspiration by (Hargreaves and Samani, Applied Engineering Agriculture ASABE 1:96–99, 1985)), crop evapotranspiration by (Allen et al., Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage, Food and Agriculture Organization, Rome, Italy, 1998) and evaporation from uncultivated lands by Ritchie (1972) approaches, and (iii) canal seepage using simple canal flow model. Annual groundwater draft during *Kharif* and *Rabi* was found to be 144.41 and 112.49 ha-m, respectively. Nearly, 90% of the study area contributed runoff in the range of 200–400 mm during the years 2002–03, 2003–04, and 2004–05. The estimated seepage losses vary between 5 and 15% of irrigation depth for all distributaries. Potential groundwater recharge during wet, normal, and dry years ranges between 650 and 1033 mm, and equivalent to 67%, 78%, and 60% of annual rainfall, respectively. Net recharge ranges between 8 and 11% of the annual rainfall. Mean ratio between net recharge to potential recharge is nearly 30%, indicating that nearly 70% of potential recharge is accounted as outflow from the study area. Parmanpur distributary canal located at the centre of the study area that exhibited higher potential recharge can be scheduled at the end to avoid water logging problem. Further, extraction of groundwater during non-monsoon period for irrigation purpose not only helps in controlling waterlogging but also helps in maintaining stable groundwater level. Overall, spatio-temporal distribution of recharge in the command area indicated that the irrigation demands during non-monsoon season can be met through sustainable management of underexploited groundwater resources. Such an integrated management of surface and groundwater can help in improving water use efficiencies as well as agricultural productivity.

Extended author information available on the last page of the article

Keywords Potential recharge · Net recharge · Water table fluctuation · Paddy command area · Remote sensing · GIS

1 Introduction

Water demands for agricultural, industrial, and domestic sectors can be met through groundwater as it is a fresh resource and available throughout the year (Döll et al. 2012). Anthropogenic activities associated with the increase of the global population by four times in the past century led to overexploitation of freshwater nearly by eight times (Gleick 2006). Rockström et al. (2009) projected that nearly 59% of the global population will face water scarcity situation by the year 2050. In India, water requirements for 60% of the agricultural sector and 85% of the domestic sector are met through 432 BCM groundwater resources. Thus, nearly 230 km^3 of groundwater is being exploited annually for irrigating 39 Mha of agricultural land in India (Chinnasamy et al. 2018). World Bank (2010). Groundwater usage in India during the last four decades witnessed the dramatic rise, where the number of dug wells, shallow and public tube wells was increased from 3.86 to 10.5 million, 3000 to 6.74 million, and negligible number to 0.09 million, respectively (Mall et al. 2006; Chinnasamy et al. 2018). Although *Rabi* season crops are benefited from the groundwater pumping, its excessive usage poses a serious challenge on the long-term sustainability of groundwater resources. Thus, studies on groundwater recharge, surface and groundwater interactions and non-point source pollution are important for sustainable development of industrial, domestic and agricultural sectors (Dripps and Bradbury 2010; Scanlon et al. 2002). Therefore, groundwater assessment and management is necessary for ensuring groundwater security for present and future generations.

For sustainable groundwater management, groundwater recharge is a pre-requisite. However, out of water budget components such as recharge, precipitation, irrigation, withdrawals, evapotranspiration and surface runoff, the recharge is proven the difficult and complex hydrologic parameter to quantify (Dripps and Bradbury 2010). Vrie and Simmers (2002) mentioned that infiltration excess in any area can be considered as groundwater recharge. However, this may not be true, as the possibility of this water not reaching groundwater table exists due to base flow, unsaturated-zone processes and poor hydraulic conductivity. Thus, efforts should be made to quantify potential recharge and its conversion rate to actual recharge distinctly for optimal planning. Rushton, (1988) mentioned that potential recharge is that part of water infiltrated below the soil layer, while actual (net) recharge is the water that reached groundwater table.

Tracer and discrete numerical modeling approaches and lumped water balance approaches were widely used for quantification of groundwater recharge (Scanlon et al. 2002). Among these methods, Water Table Fluctuations (WTF) method classified under lumped water balance approach was considered to be simple and was extensively adopted by several researchers (e.g., Healy and Cook 2002; Sharda et al. 2006; Izady et al. 2017). Tracer technique was also employed in the past for recharge assessment (e.g., Gaye and Edmuds 1996; Herczeg and Leaney 2011; Koeniger et al. 2016). However, adoption of this technique is limited due to requirement of high technical skills for operation of special instruments coupled with expensive and tedious sampling procedure. Quantification of recharge through numerical models such as MODFLOW, MIKE-SHE, SWAT was carried out in the recent past (e.g., Sanford 2002; Keilholz et al. 2015; Ghouili et al. 2017). The major limitation in these models was that recharge was considered as an adjusted parameter during model calibration that leads to non-uniqueness solution of flow models (Anderson and Woessner 1992). This indicates that recharge estimation at a large scale through indirect methods is costly and laborious. Thus, spatio-temporal analysis of groundwater recharge using geospatial technologies offers a better solution for sustainable planning of groundwater resources for any identified region.

Several researchers across world have successfully employed Remote Sensing (RS) and Geographical Information Systems (GIS)-based techniques for estimation of groundwater recharge spatially (e.g., Chowdary et al. 2003; Meleswski et al. 2009; Wable et al. 2017). However, in India studies on the spatial and temporal assessment of groundwater recharge in irrigation command areas were limited (Jyrkama and Sykes 2007; Minor et al. 2007). Thus, this study is carried out in the case study area, Hirakud canal command of eastern India, Odisha with specific objectives namely (i) to assess the potential recharge spatially and temporally by accounting static parameters (soil texture and slope) and dynamic parameters (LU/LC, hydrometeorological factors), and (ii) to estimate net groundwater recharge using WTF method. Groundwater resources in the study command are primarily used for irrigation, followed by domestic and industrial use.

2 Methods and materials

2.1 Study area description

The study area, part of Hirakud canal command, Odisha state (one irrigation sector out of four irrigation sectors), eastern India is situated between 21°16′ N and 21°35′ N latitude, 83°52′ E and 84°9′ E longitude with a total geographical area of 382 km^2 (Fig. 1). Mahanadi river in the West, Hirakud dam in the North, Sason main canal in the East, and Humatail distributary in the South constitute boundaries of the study area. Canal distributaries: Humatail (HTD), Parmanpur (PD), Jamadarpali (JD), Talab (TD), Sason (SD), Kankhinda (KD), and Sambalpur (SMD) constitute the canal system. The study area experiences distinct seasons', namely extreme hot and dry summer, followed by the humid monsoon and severe winter. Study command area receives an average annual rainfall of nearly 1480 mm during southwestern monsoon season. Paddy occupies 95% of the total cropped area in the study area during *Kharif* (monsoon) and *Rabi* (non-monsoon) seasons (NRSA 2004). Other major crops cultivated in the study area are sugarcane, wheat, pulses, oilseeds, millets, vegetables, and condiments.

Geologically, Hirakud command area is mainly underlain by granite and granite gneisses, which are hard, compact and lacks primary porosity. Groundwater in these areas occurred in weathered residuum under the unconfined condition and in fracture zones of semi-confined to unconfined conditions (Kumar and Sinha 2003). The thickness of weathered residuum in the areas above granite and granite gneisses ranges from 10 to 30 m with an average thickness of 15 m, where the scope for groundwater development is good. Generally, three to four water saturated fractures zones have been encountered within a depth of 100 m, beyond which fractures are not common. Important aquifer parameters such as hydraulic conductivity, specific yield for unconfined aquifer and specific storage for semi-confined layer ranges between 0.5 and 3 m/day, 0.03 and 0.05 and 0.0005 and 0.003 m^{-1}, respectively (CGWB 1998, Raul et al. 2011).

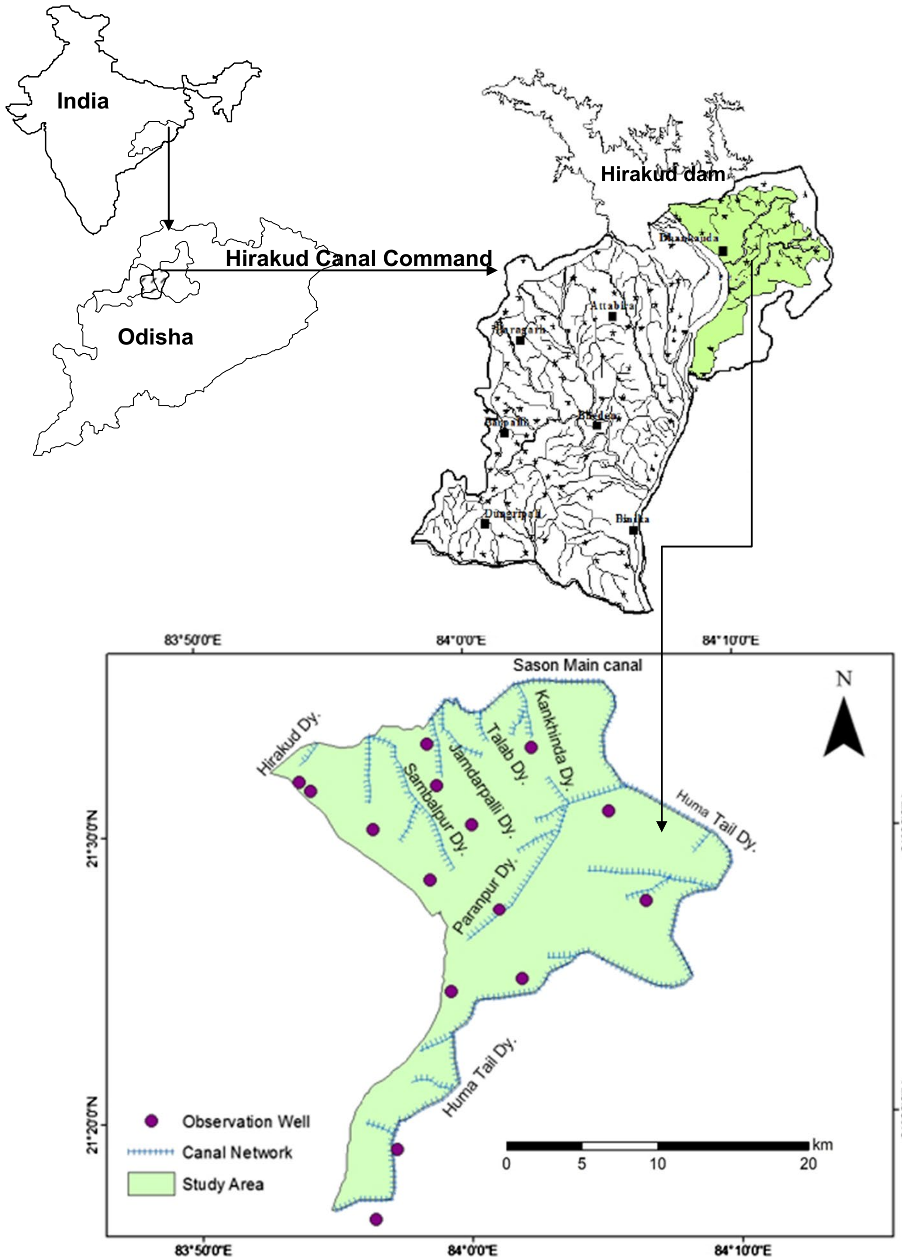

Fig. 1 Location map of the study area

2.2 Data used

Meteorological and canal release data, groundwater levels, soil, and LU/LC maps were acquired from multiple agencies. Daily rainfall, maximum and minimum air temperature data for the Dhankauda and Chiplima meteorological stations for the period 2001–05 were collected from India Meteorological Department (IMD), Pune. Census of tube and dug wells operating in the study area along with their abstraction pattern were obtained from Ground Water Survey and Investigation (GWS&I), Sambalpur, Odisha. Further, groundwater levels of the study area monitored using 14 observation wells during pre-monsoon (April) and post-monsoon (November) seasons were collected from GWS&I, Sambalpur for the period of 2001–05 (Fig. 1).

Salient features of the canal network (Fig. 1) along with canal releases during the period 2001–05 were collected from Hirakud Dam Circle, Burla, Odisha. Canal operation schedule almost remains constant for every year with 266 and 99 days of canal opening and closing, respectively. Soil map of the study area was acquired from National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Nagpur. Major soil textural classes, clay and clay loam constitute nearly 70% and 30% of the total study area, respectively (Fig. 2). Soil depth in the command varies between 130 and 150 cm. In this study, LU/LC map generated under National Land Use/Cover mapping project of National Remote Sensing Centre, Hyderabad at 1:50,000 scale was used (Fig. 3). Nearly, 85% and 50% of the study area was under paddy during *Kharif* and *Rabi* seasons, respectively (Table 1).

2.3 Estimation of potential recharge

Water balance approach for assessment of potential recharge at grid level and the equation is given as follows:

$$R_{\mathrm{p}} = P + I + D_{\mathrm{r}} + \mathrm{SL} - \mathrm{ET_c} - R_{\mathrm{off}} \tag{1}$$

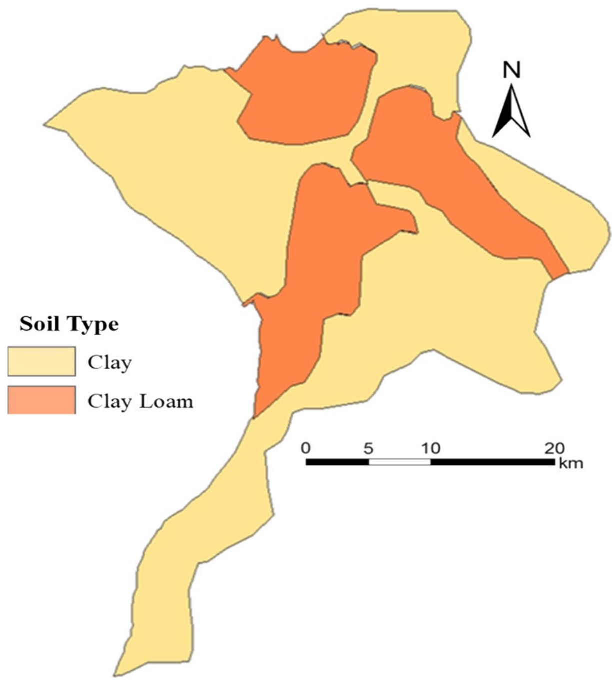

Fig. 2 Soil texture map of the study area

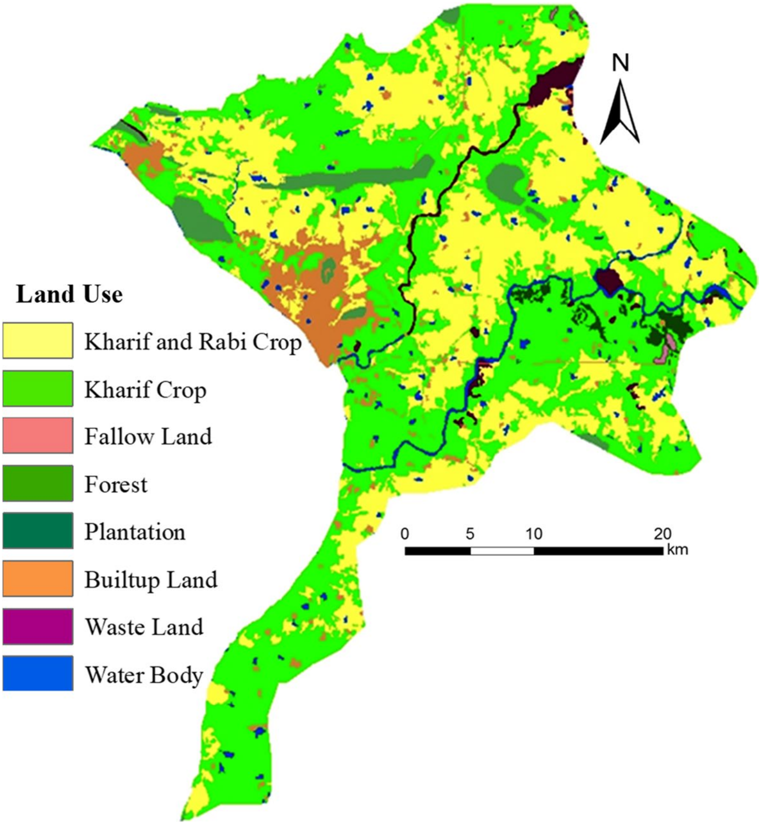

Fig. 3 Land use/land cover map of the study area

Table 1 Land use/land cover statistics in the study area

Land use/land cover class	Area (km^2)	Area (%)
Agriculture (*Kharif and Rabi*)	184	48
Agriculture (*Kharif*)	139	36
Fallow land	1	0
Forest	13	3
Plantation	4	1
Waste land	7	2
Built up land	23	6
Water body	12	3
Total	382	100

where R_p potential recharge (mm), P precipitation (mm), I irrigation (mm), D_r groundwater draft (mm), ETc evapotranspiration (mm), SL seepage loss from canal (mm), and R_{off} surface runoff (mm).

Water balance components ETc, I, D_r, SL and R_{off} were computed at daily scale. Soil, LU/LC, and canal command area maps were integrated into GIS environment to account spatial variability in water balance computations.

2.3.1 Assessment of surface runoff

Runoff is a general term to indicate the accumulation of excess rainfall and it occurs when rainfall intensity is greater than the infiltration rate of the soil. One of the most widely used technique, i.e., Natural Resources Conservation Service-Curve Number (NRCS-CN) method is adopted for assessment of surface runoff (USDA-SCS 1985). This approach assumes that for a given rainfall event, ratio of actual soil retention to potential maximum retention after the initiation of runoff process is equal to the ratio of direct runoff to potential runoff, i.e., available rainfall. Thus, abstraction from rainfall events was computed, where excess precipitation or direct runoff (R_{off}) depth was always less than or equal to precipitation depth (P). Additional water depth retained in the watershed after initiation of runoff is less than or equal to maximum potential retention (S). Further, initial abstraction (I_a) from the rainfall before ponding indicates no flow conditions. Algebraic manipulation and inclusion of simplified assumptions resulted in the following equations (USDA-SCS 1985) and mathematically, NRCS-CN method is represented as:

$$R_{off} = \frac{\left(P - I_a\right)^2}{\left(P - I_a\right) + S} \tag{2}$$

where R_{off} runoff volume uniformly distributed over a catchment (mm), P mean precipitation over catchment (mm), S maximum potential retention by catchment (mm), and I_a initial abstraction, which is equal to 0.2S, i.e., 20% of the potential maximum retention (S) before runoff initiation process. Therefore, Eq. (2) can be rewritten as:

$$R_{off} = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3}$$

where CN curve number value ranges 0–100. Thus, runoff is a function of CN, S, I_a and Antecedent Moisture Conditions (AMC). LU/LC and Hydrological Soil Group (HSG) maps were integrated using GIS, where each of these combinations was assigned curve numbers. Hydrological soil groups, namely A, B, C, and D were classified based on the soil properties such as texture, depth, and water transmission capacity. Further, wetness index, i.e., AMC condition computed based on the previous five day rainfall events indicate the effect on the moisture holding capacity of soil, which in turn influence runoff process. Initially, curve numbers were assigned to different combinations of LU/LC and hydrological soil groups for AMC II condition. Subsequently, curve numbers for AMC I (dry) and AMC III (wet) conditions were adjusted using the following equations:

$$CN(1) = \frac{4.2CN(2)}{10 - 0.058CN(2)} \tag{4}$$

$$CN(3) = \frac{23CN(2)}{10 + 0.13CN(2)} \tag{5}$$

Further, weighted curve numbers were computed at grid level, where sub-areas in each grid were assigned curve numbers based on the multiple combinations of LU/LC and HSG as given below:

$$CN_w = CN_1\left(\frac{A_1}{A_{total}}\right) + CN_2\left(\frac{A_2}{A_{total}}\right) + \ldots + CN_n\left(\frac{A_n}{A_{total}}\right) \tag{6}$$

where$n$ number of sub-areas in the watershed, A_1, $A_2 \ldots A_n$ area in 'm^{2}' of each sub-area having CN values CN_1, $CN_2 \ldots$ CN_n, A_{total} total watershed area in m^2 ($A_1 + A_2 + \ldots + A_n$). Higher curve numbers in any area indicate higher runoff values and thereby less recharge in that area and vice-versa.

2.3.2 Estimation of crop evapotranspiration

Hargreaves and Samani (1985) method was used for estimation of ET_o as this method requires minimum parameters such as extraterrestrial solar radiation (R_a) and mean monthly maximum and minimum temperature (T_{max} and T_{min} in °C) as inputs. Crop evapotranspiration (ETc) was computed by multiplying ET_o by corresponding crop coefficient (K_c) adopted from literature for different crop growth stages (Allen et al. 1998) and is given as follows:

$$ET_o = 0.0023R_a\left(T_{mean} + 17.8\right)\left(T_{\max} - T_{\min}\right)^{0.5} \tag{7}$$

whereT_{mean} mean value of T_{max} and T_{min} the maximum and minimum air temperatures in (°C). Cropping period for paddy and pulses was considered as 4 and 3 months, respectively, while remaining period was considered to be under bare conditions for ETc estimation.

Evaporation from fallow lands/uncultivated areas (E in 'mm') was computed using Ritchie's (1972) equation:

$$E = ET_o t^{-0.5} \tag{8}$$

where$t$ time after the last rain in days.

2.3.3 Assessment of recharge due to seepage losses

Seepage rate and wetted area in the canals are key parameters for estimation of seepage losses. The wetted area is a dynamic parameter that continuously varies with canal flow conditions. The seepage losses in a canal are computed as follows:

$$SL_r = SR \times P \times RL \tag{9}$$

whereSL_r seepage loss rate in the canal section (m^3/sec), P wetted perimeter of the canal section (m) ($P = b + 2.d\sqrt{(1 + z^2)}$), d canal flow depth (m), b channel section bed width (m), z channel side slope, RL section length (m), SR seepage losses per unit wetted surface area per unit time (m^3/m^2/sec). Actual seepage losses in the canal section length (RL) depend on the average depth of flow in the section (d in 'm'). Rao (1990) reported that the seepage rate is a function of surface (bed and side slope material) and subsurface canal conditions (water table depth, soil permeability, and aquifer drainage conditions). In this study, seepage factor of 2 m^3/s per 10^6 m^2 of the wetted area was considered as per the CGWB (1998).

Complex models for simulation of the flow hydraulics in irrigation canals are available. However, these models do not account rotational irrigation management practices of India that involve rapid changes in the flow conditions. Thus, these models are data intensive and do not represent canal flow conditions adequately. Mandavia and Acharya (1995) suggested that simple models with minimum data requirements should be envisaged for simulation of flow hydraulics, as operational usage of complex models in India was not successful. Hence, a simple canal flow model based on Manning's equation proposed by Hajilal et al. (1998) was used in this study to compute seepage loss. This model requires discharge data at both the ends of the canal reach while assuming uniform flow conditions in the reach for computation of canal depth. Manning's equation to compute the depth of flow at either end of the reach is given below:

$$Q_c = \frac{A}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{10}$$

where Q_c measured discharge at the canal reach head (m^3/s), n Manning's roughness coefficient, S channel bed slope (dimensionless), R hydraulic radius (m), R A/P, A area of cross section of flow, m^2 ($A = b.\ d + z.d^2$).

2.3.4 Estimation of irrigation depth

Irrigation requirements in the study area are supplied from the Hirakud reservoir through well-distributed canal network. Conveyance losses play a major role in the canal irrigation systems; hence, seepage losses were accounted while computing available irrigation depth (I in 'mm') given as below:

$$I = \frac{1000\left(V_c - SL\right)}{CCA} \tag{11}$$

where V_c canal supply volume (m^3), SL seepage loss (m^3), CCA canal command area (m^2).

2.3.5 Groundwater draft computations

The annual draft from dug and tube wells were computed based on the CGWB (1998) guidelines. Administrative block wise distribution of tube and dug wells is given in Table 2. Groundwater draft is mostly used for Paddy cultivation during both *Kharif* (monsoon) and *Rabi* (post-monsoon) seasons and the draft is computed using the following equation:

$$TD = \frac{1000 \sum (Q_t \times ND_t \times H_t \times 3600) + (Q_d \times ND_d \times H_d \times 3600)}{A} \tag{12}$$

Table 2 Administrative block wise distribution of tube wells and dug wells in the study area. *Source*: GWS&I Sambalpur

Name of administrative block	Dug well	Tube well	Area (km^2)
Dhankauda	186	7	266.89
Maneshwar	126	20	299.10
Jujumura	148	17	652.80
Total	260	44	1218.79

where *TD* Total draft in the block (mm), *Q* unit draft (m^3/sec), ND number of pumping days during *Kharif* and *Rabi* seasons, *H* number of pumping hours, A cultivated area in the respective block (m^2). Subscripts *t* and *d* refer to the tube and dug wells, respectively.

3 Assessment of net recharge using WTF method

Assessment of net recharge during monsoon season is carried out by WTF method, where this method considers that groundwater level rise in an aquifer is proportional to the groundwater recharge. The groundwater balance equation for the monsoon season is expressed as (CGWB, 1997):

$$R_{\mathrm{gw}} - D_{\mathrm{w}} - B + I_{\mathrm{s}} \pm I_{\mathrm{g}} = R_{\mathrm{n}} \tag{13}$$

where R_{gw} gross recharge contributed by rainfall and other sources (m^3), D_w gross groundwater draft (converted ha-m into m^3), B base flow into streams from the area (m^3), I_s recharge from streams into groundwater body (m^3), I_g groundwater inflow/outflow across the boundary (m^3), and R_n is net groundwater recharge. Net recharge in the command area is computed as given below:

$$R_n = \left(A \times S_y \times h\right) + D_w \tag{14}$$

where S_y specific yield (adopted from CGWB (1998) report, which was estimated using pumping test); h the water table rise in monsoon season (m), i.e., increase in groundwater level between post and pre-monsoon seasons below ground level (bgl), A area contributing to recharge (m^2). Further, the Kriging interpolation technique was used in this study to predict values at unmeasured locations from the data of 14 observation wells. Interpolation of spatial data using the Kriging technique is widely used in geology, hydrology, and environmental monitoring applications (Stein 1999).

Rangarajan and Athavale (2000) proposed an empirical equation for estimation of net groundwater recharge (R_n) at annual scale based on the results of tracer test specifically conducted for Mahanadi basin, which is underlying with granite and gneiss rock formations. The empirical equation is given below:

$$R = 0.172 \times R_{avg} - 44.0 \tag{15}$$

where R_{avg} = average annual rainfall of the area (mm).

Subsequently, net recharge to potential recharge ratios were computed spatially for wet, normal, and dry year, respectively. Normal rainfall year is defined based on the long-term average annual rainfall, while wet and dry years indicate the increase and decrease in the annual rainfall by + 25% and −25% of normal rainfall, respectively (Subramanya 2008). Potential and net recharge along with water balance components were computed as per hydrological year (June of the current year to May of succeeding year).

4 Results and discussion

4.1 Assessment of water balance components for potential recharge estimation

4.1.1 Rainfall

Annual and monsoon rainfall variations for the period 1992–2005 are shown in Fig. 4. Average annual rainfall of the study area is 1480 mm and 95% of the rainfall is received during monsoon months (Fig. 4). Annual rainfall variations during the study period (2001–05) indicated that the years 2001–02 (2120 mm), 2003–04 (1540 mm), and 2004–05 (1200 mm) corresponds to wet, normal and dry years, respectively (Fig. 4).

4.1.2 Runoff

The maximum potential retention after runoff begins was calculated using the NRCS-CN method and daily runoff maps are generated and aggregated at monthly and annual scales using GIS. LU/LC and soil hydrologic conditions are important parameters for assessment of surface runoff using NRCS-CN method. Spatial variation of annual runoff for the years 2001–05 is represented in Fig. 5. Nearly, 90% of the study area contributed runoff in the range of 200–400 mm during the years 2002–03, 2003–04, and 2004–05, while 800–1000 mm for the year 2001–02. The runoff was found to be maximum during the year 2001–02 that can be attributed to the year being wet (Fig. 5). Runoff coefficients computed for wet, normal, and dry years were 0.45, 0.22, and 0.23, respectively. Further, report of the High-Level Technical Committee, Govt. Orissa (2007) indicated that surface runoff, an important surface water balance component from rainfall over the years in the Hirakud catchment varies between 17.95% (minimum in 2002 year) and 54.78% (maximum in 1961 year). Long-term average monsoon rainfall and runoff (inflow) for the period 1959–2006 at 75% dependence for Mahanadi catchment up to Hirakud is 934.33 mm and 298.51 mm, respectively. This indicated that the runoff-rainfall ratio (runoff coefficient) of

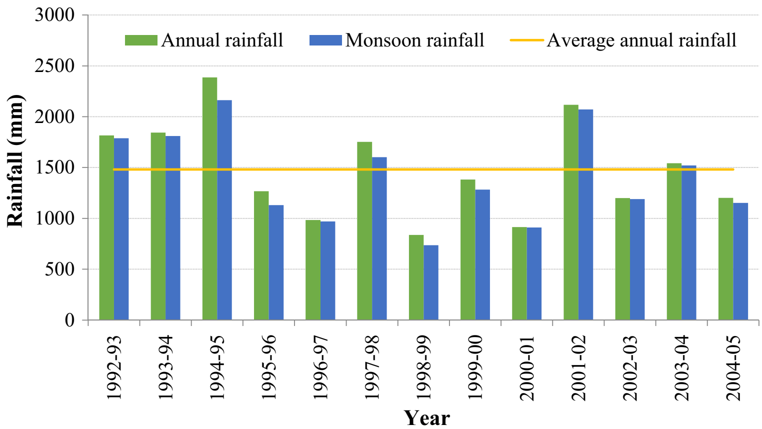

Fig. 4 Temporal distribution of annual and monsoon rainfall at Dhankauda rain gauge station during 1992–93 to 2004–05

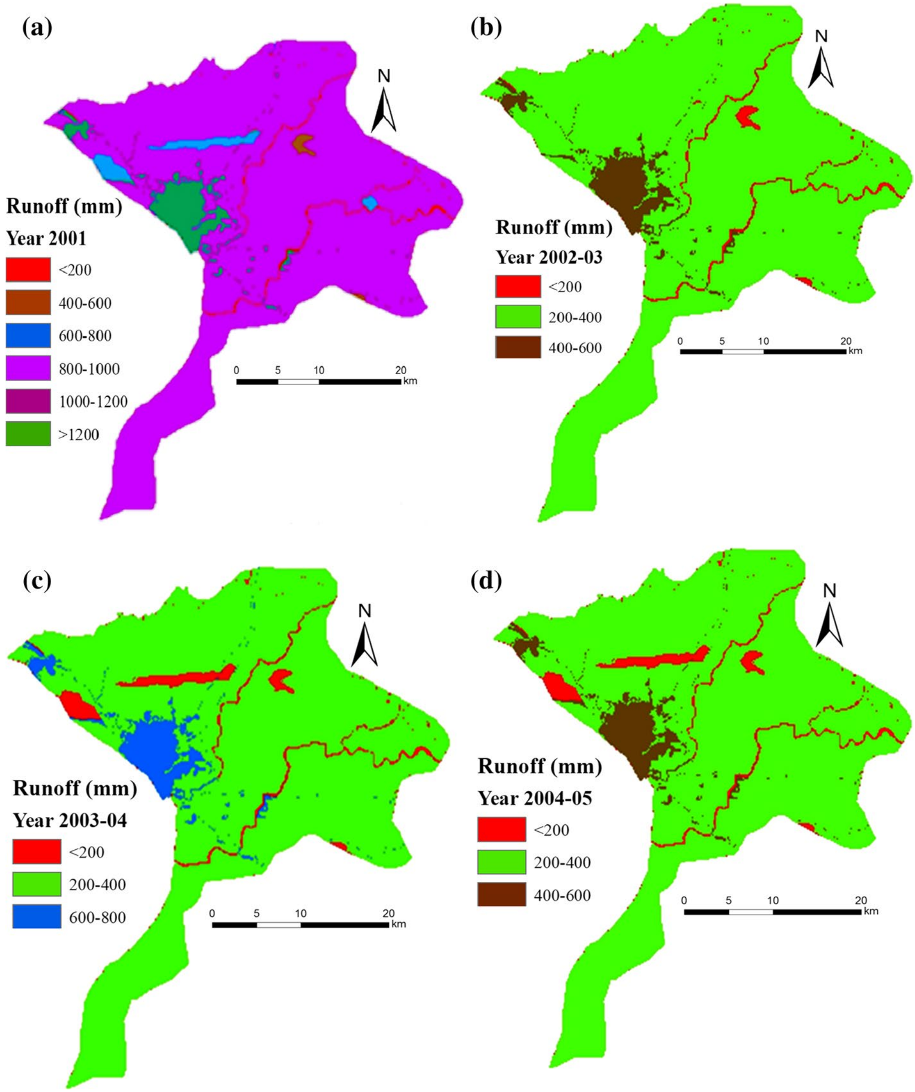

Fig. 5 Spatial distribution of runoff for different years **a** 2001–02, **b** 2002–03,**c** 2003–04, **d** 2004–05

31.95% is consistent with the results of this study where 90% of the study contributed to runoff in the range of 200–400 mm.

4.1.3 Evapotranspiration

Paddy occupies nearly 86% and 48% of the study area during both *Kharif* and *Rabi* seasons, respectively. Canal wise area under paddy cultivation during these crop seasons is shown in Table 3. K_c value for paddy and pulses, an important parameter for estimation of ETc was taken from Allen et al. (1998). Spatial distribution of ETc for the years 2001–05

Table 3 Canal wise paddy cultivation during *kharif* and *rabi* seasons

Canal name	Area under paddy crop (km^2)	
	Monsoon (*Kharif*)	Non-monsoon (*Rabi*)
Humatail distributary	123.41	37.98
Parmanpur distributary	92.58	51.39
Jamadarpali distributary	22.41	4.87
Talab distributary	16.96	7.91
Sason main	12.94	4.92
Kankhinda distributary	11.70	8.03
Sambalpur distributary	39.53	22.89

is shown in Fig. 6. During this period, much variation in the ETc is not observed, as temperature variations during this period are minimal. ANOVA test on the variability of mean temperatures among years shown that there is no difference, as F-calculated value (2.28) is less than F-critical value (2.61) at 5% level of significance. Evapotranspiration for nearly 85% of the study area ranges between 1000–1500 mm.

4.1.4 Groundwater draft

Annual groundwater draft from dug and tube wells was estimated as per CGWB (1998) guidelines (Table 4). Average annual draft for tube and dug wells is estimated to be 21.87 and 106.58 ha-m, respectively. Further, groundwater draft at 100 m × 100 m grid resolution was estimated based on the administrative block wise draft. Annual draft during *Kharif* and *Rabi* was found to be 144.41 and 112.49 ha-m, respectively (Table 4).

4.1.5 Seepage losses

The annual irrigation depth (mm) for each canal command area distributary and Sason main canal is shown in Table 5. The average irrigation depth was nearly 1500 mm, while maximum and minimum irrigation depths are observed for Sambalpur and Jamadarpali distributaries, respectively. It is assumed that canal irrigation was supplied to paddy crop during both the seasons. Spatial variation of annual irrigation depth in this command is shown in Fig. 7. Nearly 56% of the study area is supplied with irrigation depth of 600–900 mm (Fig. 7). Field-based seepage losses from the canal section are computed through inflow-outflow method, where the difference in the quantity of water entering and leaving a certain reach is measured. Simple canal hydraulic model was used in this study due to practical constraints in the field measurement of seepage losses from the canal network. This model is a function of canal flow depth that was computed using actual canal flow data collected from the canal authorities, while seepage rate for a unit-wetted area of canal section is adopted from Central Groundwater Board Reports, Govt. of India. However, hydraulic models assume steady flow condition in the Canal (Patel et al. 2016). The estimated seepage losses vary between 5 and 15% of irrigation depth for all distributaries (Fig. 8) are consistent with Chowdary et al. (2003) and Hajilal et al. (1998).

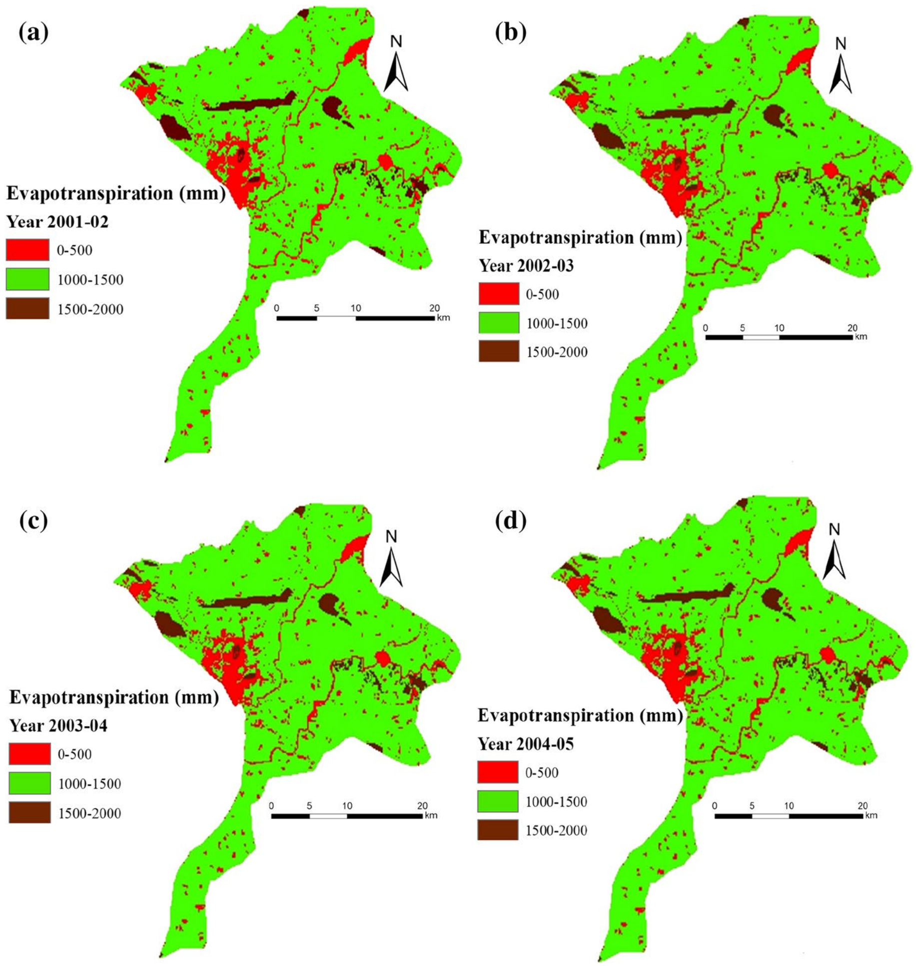

Fig. 6 Spatial distribution of annual crop evapotranspiration **a** 2001–02; **b** 2002–03 **c** 2003–04 **d** 2004–05

Table 4 Estimation of annual groundwater draft from dug and tube wells

Well type	Tube well		Dug well	
season	Kharif	Rabi	Kharif	Rabi
Average discharge (lps)	3	3	8	8
Hours of pumping per day	8	8	4	2
No. of days of pumping	152	210	76	105
Unit Draft (m^3)	13,132.8	18,144	8755.2	6048
No. of wells	14	14	144	144
Total Draft (ha-m)	18.34	25.40	126.07	87.09
Total Draft (mm)	0.48	0.66	3.30	2.28

Table 5 Annual irrigation depth for each canal

Canal name	Canal command area (km^2)	Irrigation depth (mm)
Humatail distributary	125.13	1460
Parmanpur distributary	51.86	1644
Jamadarpali distributary	4.95	1289
Talab distributary	2.63	1444
Sason main	9.11	1462
Kankhinda distributary	4.15	1436
Sambalpur distributary	40.3	1767

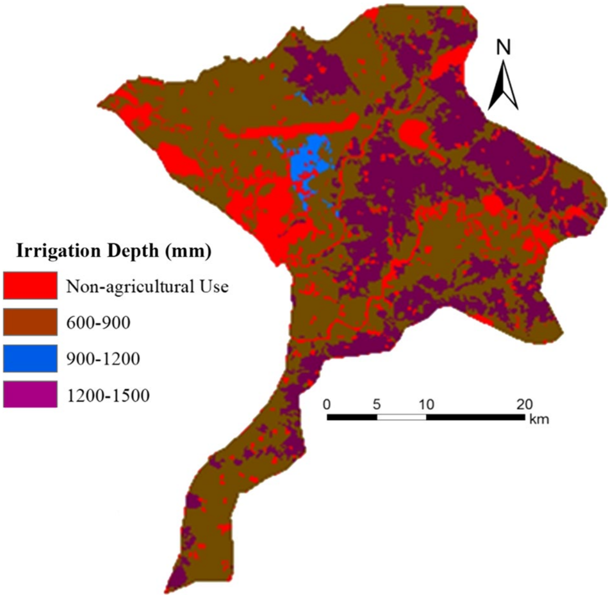

Fig. 7 Spatial variation of annual irrigation depth for paddy crop

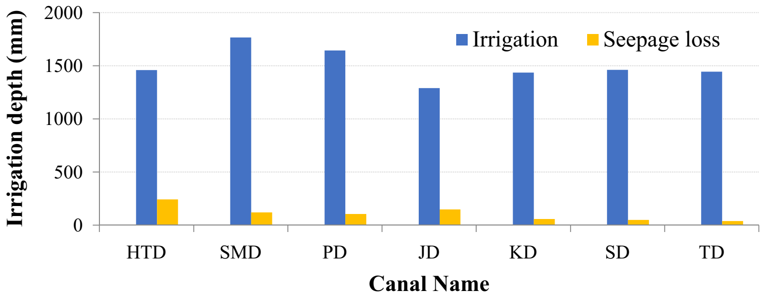

Fig. 8 Irrigation depth and seepage losses for different distributaries in the study area

4.2 Assessment of potential recharge using water balance approach

Water balance components at 100 m × 100 m grid cells in the study area were integrated using spatial analyst model of ArcGIS. Potential groundwater recharge was assessed spatially and temporally during three time periods that represent wet, normal and dry years using water balance approach (Fig. 9). The potential recharge was categorized as (i) < 300 mm, (ii) 300–600 mm, (iii) 600–900 mm, (iv) 900–1200 mm, (v) 1200–1500 mm, and (vi) > 1500 mm. Potential recharge of 600–900 mm was observed to be uniformly distributed in the nearly 35% (135 km^2) of the study area during the wet year (Fig. 9). Potential recharge in the Northeast (24%) and central part (15%) of the study area (15%) was computed as 900–1200 mm and 1200–1500 mm, respectively. Recharge less than 300 mm is observed in the northwestern part of the study area (20 km^2) while recharge greater than 1500 mm was observed in an area of 73 km^2 (19%). Similarly, for a normal year, maximum (40%; 152 km^2) and minimum (< 1%; 0.72 km^2) study area resulted with a potential recharge of 600–900 mm and 300–600 mm, respectively. Distribution of potential recharge

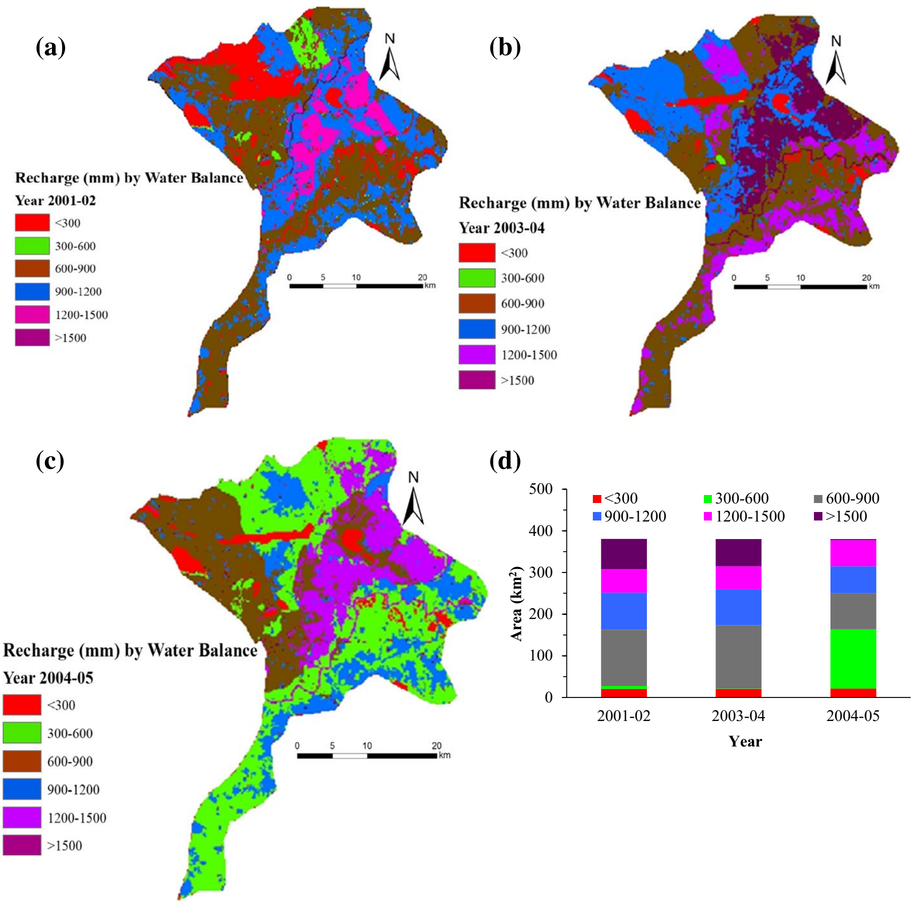

Fig. 9 Spatio-temporal distribution of potential recharge **a** 2001–02 (wet year) **b** 2003–04 (normal year), **c** 2004–05 (dry year), **d** Area statistics under different potential recharge categories for different years

categories, i.e. < 300 mm, 900–1200 mm, 1200–1500 mm, and > 1500 mm are observed to be nearly same during both normal and wet years, though the direction of spreading is different (Fig. 9). During 'dry year', potential recharge of 300–600 mm covers a maximum area of 142 km^2 (37%) that covered Northeast, Southeast and South directions of study area (Fig. 9). Similarly, potential recharge of 600–900 mm, 900–1200 mm, and 1200–1500 mm covers an area of 87 km^2 (23%) in the North–West, 64 km^2 (17%) all over, and 63 km^2 (16%) in the North–Eastern part of the study area. A small patch (< 6%) of study area spreads all over resulted a Potential recharge of < 300 mm and > 1500 mm. Mean potential recharge in the study area was computed as 650–1033 mm during the period 2001–05. Percentage of annual rainfall contributed to potential recharge during wet, normal and dry years are 67%, 78%, and 60%, respectively. Area under the potential recharge classes, i.e. < 300 mm and 300–600 mm during dry and normal years together increased to 37% indicates the need for groundwater management through artificial recharge.

4.3 Estimation of net recharge using WTF method

Kriging interpolation technique available in ArcGIS software was used to generate spatial maps of net recharge that was estimated for individual well using WTF method. Net recharge was also computed for three scenarios namely (i) wet (ii) normal, and (iii) dry years (Fig. 10). In a wet year, maximum net recharge of 100–125 mm is observed in 36% of the study area that mostly covered Northeast, Northwest and Southwest parts of the study area in strips. Net recharge of 75–100 mm is observed in 17% of study area situated in central portion. Northwest part of the study area (22%) is found to have the net recharge of 125–150 mm. The net recharge of 50–75 mm and 25–50 mm is observed in the Northeast part of the study area in patches. Contrasting results were observed in dry year where net recharge occurred in two classes, i.e., 100–125 mm in the Northeast and Southwest direction with an area of 136 km^2 (36%) followed by 125–150 mm in the remaining part of the study area (64%). On the other hand, east, northeast and northwest parts of the study area (218 km^2; 57%) normal year is observed to fall under the net recharge category of 175–200 mm during normal year. The maximum recharge category 200–225 mm (84 km^2; 22%) is observed in northwest part of the study area. In addition, 75–100 mm and 100–175 mm of net recharge are seen in spots with an area covering 36 km^2 (9%) and 42 km^2 (11%) of the study area, respectively. Rangarajan and Athavale (2000) reported that the net recharge estimates computed using the tracer test based empirical equation for Mahanadi basin for the average rainfall of 1480 mm is 14%.

4.4 Net recharge to potential recharge ratio

The ratio of net recharge to potential recharge was assessed for three climatic years that represent wet, normal, and dry conditions. The spatio-temporal distribution of net to potential recharge ratios for these years is shown in Fig. 11. Net recharge to Potential recharge ratios during both wet and normal years were distributed mainly in two classes: < 10% and 10–20%. During the wet year, net recharge of < 10% and 10–20% occupies an extent of 63% (239 km^2) in central and northeast part and 36% (136 km^2) in northwest, southwest and eastern parts of the study area, respectively. In contrast to wet year, net recharge of < 10% and 10–20%, respectively is observed in 39% and 57% of study area during the normal year. However, < 10% net recharge is observed in central and southern parts of the study area. Ratios between net to potential recharge during the years range between 10 to

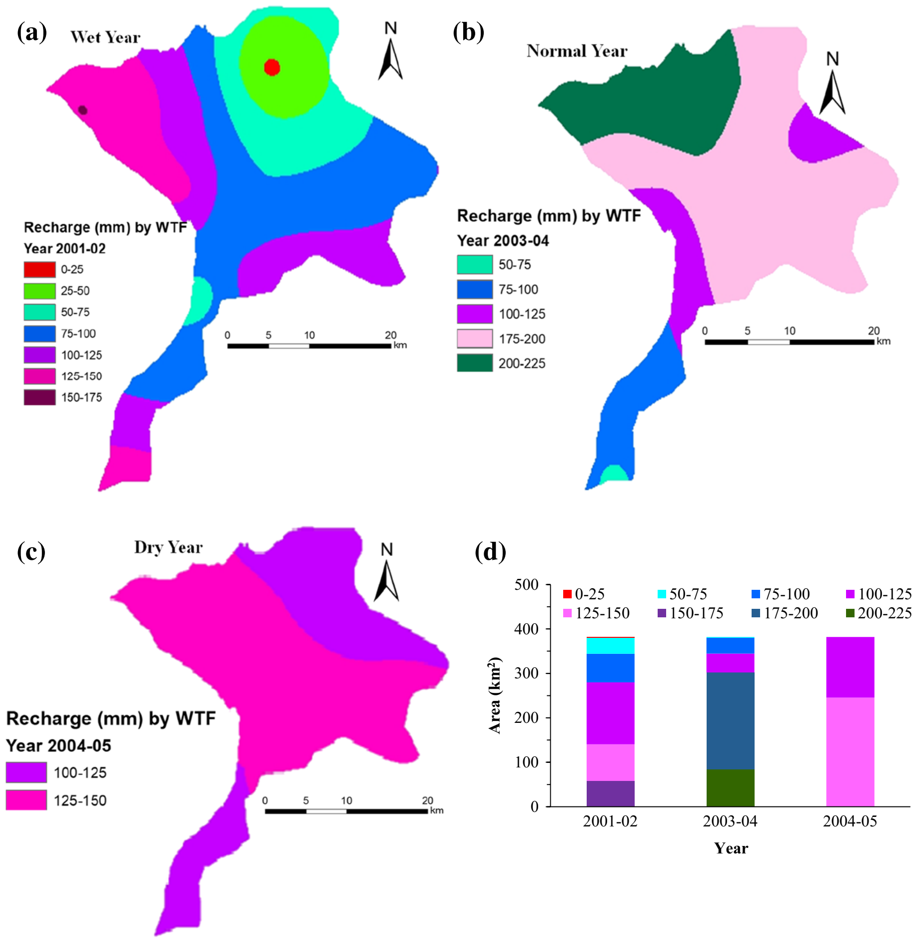

Fig. 10 Spatio-temporal distribution of net recharge **a** 2001–02 (wet year) **b** 2003–04 (normal year), **c** 2004–05 (dry year), **d** Area statistics under different net recharge categories for different years

40%. Overall, net recharge ranges between 8 to 11% of the annual rainfall of the study area. It is also observed that mean ratio between net recharge to potential recharge is nearly 30%. The unaccounted potential recharge can be considered as outflow from the basin. This can be attributed to the fact that the watertable level in the study command during the non-monsoon season is 0–5 m bgl while watertable surrounding the study area is 5–10 m bgl, indicates the greater possibility of groundwater outflow from the basin.

The higher values of potential recharge are mainly by infiltration from the soil surface. Jannat et al. (2014) reported that the average infiltration resulting from rainfall in the agricultural dominant areas at annual scale was observed to be 60%. Recharge rates in the Hirakud command area are varied between 20 and 60% of the rainfall (Dhar et al., 2015). Further, surface runoff values in this study are consistent with the report of the High-Level Technical Committee, Govt. Orissa (2007), which indicated the runoff-rainfall ratio as 31.95%. Thus, potential recharge of 68% from rainfall at 75% of level of confidence is a standard adopted by Govt. of India as a success for water

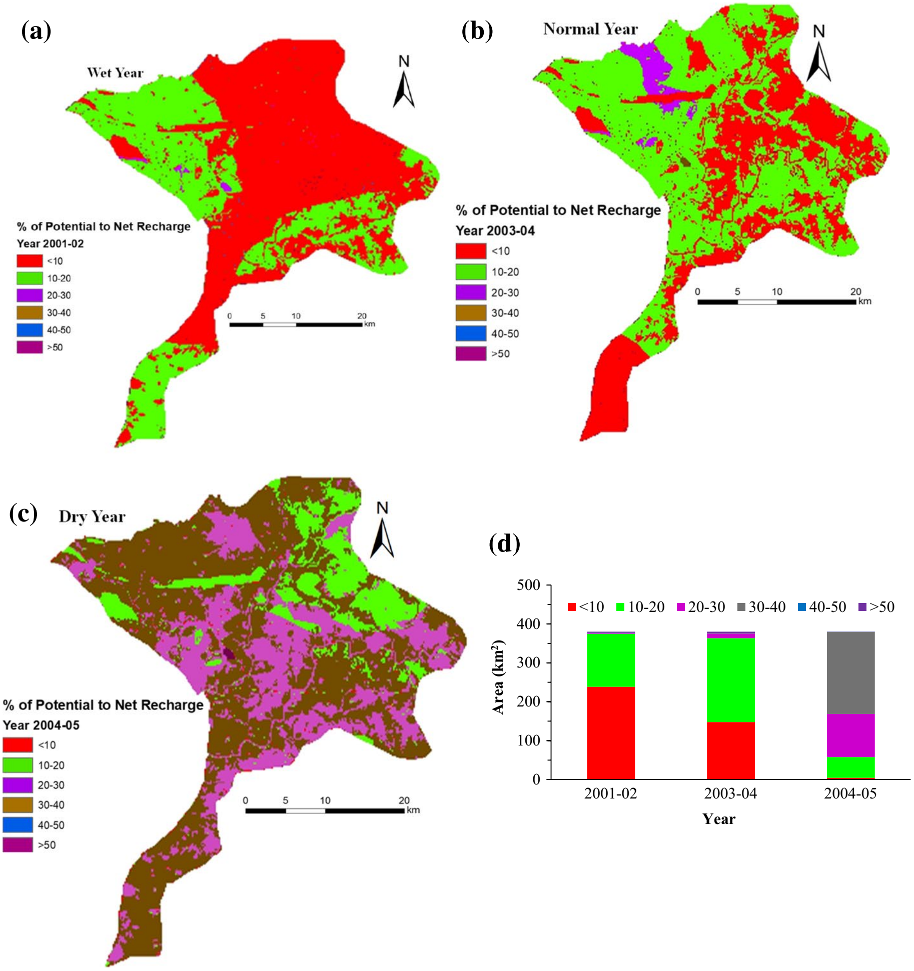

Fig. 11 Spatial–temporal distribution of potential to net recharge ratios (%) **a** 2001–02 (wet year), **b** 2003–04 (normal year), **c** 2004–05 (dry year) **d** Area statistics under different net to potential recharge ratios

resources projects for irrigation purposes. Thus, considering the contribution from irrigation, groundwater draft, seepage losses from canal, potential recharge of 60%–78% of annual rainfall in this study is considered to be consistent with earlier studies. Further, net recharge computed using net groundwater rise and specific yield in the study area ranges between 8 and 11% of the annual rainfall. Raul et al. (2011) reported that the net recharge in the Hirakud command area varies between 165 and 675 mm with an average being 317 mm. The other recharge studies carried out in the basins underlain by consolidated rocks, i.e., Granite and granite gneisses in semi-arid region of India having similar geological set up of the study area was found to be 1.2%–13% of the annual rainfall. Chand et al. (2004) observed that the tracer-based net recharge is 6–200 mm per annum for an average annual rainfall of 968 mm in Bairasagara watershed of Kolar district, Karnataka with similar geological conditions. Consolidated aquifers of India with basaltic and granite-gneissic complexes indicated a natural recharge rate of 3–15% (Sukhija et al., 1996). Thus, the average recharge, i.e., 10% of the annual rainfall observed in this study is consistent with the results found in the literature.

In general, water requirement for transplanted rice cultivation is invariably ranges between 1000 and 2000 mm depending on climate and soil type. Further, seepage and percolation losses in paddy greatly exceed the evapotranspiration demand due to unique water management practices followed in transplanted paddy cultivation (Panigrahi and Paul 2015). Random nature of irrigation supply and demand due to variations in reservoir inflows further create an imbalance in the irrigated agriculture system of the study area. Thus, information on potential and net recharge rates in the command area can be helpful in planning sustainable water management practices. Parmanpur distributary canal located at the centre of the study area that exhibited higher potential recharge can be scheduled at the end to avoid water logging problem. Such an integrated management of surface and groundwater can help in improving water use efficiencies as well as agricultural productivity. Further, this can also facilitate in maintaining rise in groundwater levels and in turn for controlling waterlogging problem in the command area. Extraction of groundwater during non-monsoon period for irrigation purpose not only helps in controlling waterlogging but also helps in maintaining stable groundwater level. Overall, spatio-temporal distribution of recharge in the command area indicated that the irrigation demands during non-monsoon season can be met through sustainable management of underexploited groundwater resources.

5 Conclusions

Potential and net groundwater recharges were assessed in the part of Hirakud canal command area, eastern India, where major cropping system is paddy-paddy. Potential and net groundwater recharges were assessed using a water balance model and water table fluctuation (WTF) method, respectively. Net to Potential recharge ratios were assessed spatially and temporally for three scenarios that correspond to wet, normal, and dry years. Potential recharge during the study period ranges between 650 and 1033 mm that constitutes nearly 63% of the annual rainfall. Area under potential recharge classes < 300 mm and 300–600 mm together constitutes 37% of study area during dry and normal years, indicates need for groundwater management. Parmanpur distributary canal located at centre of the study area can be scheduled at the last as its command area has higher potential recharge zones for better irrigation management. This information is useful not only for irrigation authorities but also for groundwater department for conjunctive use planning of both surface and ground water. It was observed that the net recharge classes do not follow the potential recharge classes in the same proportion during wet, normal and dry years, suggesting not all infiltrated water contributed to net recharge at the same location. Mean ratio between net recharge to potential recharge is nearly 30%, indicating that nearly 70% of potential recharge is accounted as outflow from the study area. The net recharge in the study area ranges between 8 and 11% of annual rainfall. Thus, spatio-temporal recharge maps corresponding to different rainfall conditions will help to formulate strategies for sustainable planning of both surface and groundwater resources in the study area. Particularly, these strategies help to manage paddy-based irrigated agriculture during non-monsoon season.

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