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PAPER

An innovative artificial recharge system to enhance groundwater storage in basaltic terrain: example from Maharashtra, India

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Abstract The management of groundwater poses challenges in basaltic terrain as its availability is not uniform due to the absence of primary porosity. Indiscriminate excessive withdrawal from shallow as well as deep aquifers for meeting increased demand can be higher than natural recharge, causing imbalance in demand and supply and leading to a scarcity condition. An innovative artificial recharge system has been conceived and implemented to augment the groundwater sources at the villages of Saoli and Sastabad in Wardha district of Maharashtra, India. The scheme involves resectioning of a stream bed to achieve a reverse gradient, building a subsurface dam to arrest subsurface flow, and installation of recharge shafts to recharge the deeper aquifers. The paper focuses on analysis of hydrogeological parameters like porosity, specific yield and transmissivity, and on temporal groundwater status. Results indicate that after the construction of the artificial recharge system, a rise of 0.8–2.8 m was recorded in the pre- and post-monsoon groundwater levels in 12 dug wells in the study area; an increase in the yield was also noticed which solved the drinking water and irrigation problems. Spatial analysis was performed using a geographic information system to demarcate the area of influence of the recharge system due to increase in yields of the wells. The study demonstrates efficacy, technical viability and applicability of an innovative artificial recharge system constructed in an area of basaltic terrain prone to water scarcity.

Keywords Groundwater recharge/water budget · Geographic information systems · Recharge shaft · Reverse gradient structure · India

Introduction

Groundwater supplies more than 85 % of rural India's domestic and agricultural water needs, which is depleting fast in many areas due to its large-scale withdrawal (Bhalerao and Kelkar 2013). The stress on groundwater in most of the rural areas of Maharashtra state can be ascribed to changes in the precipitation pattern and exploitation. Groundwater depletion has reached a critical state in certain areas within Maharashtra such that many watersheds have been reportedly declared overexploited (CGWB and GSDA 2005). The stress on groundwater affects the sustainability of sources as it creates imbalance in recharge and discharge under natural conditions (Kumar and Kumar 2011). The potential and availability of groundwater in basaltic terrain in Maharashtra not only depends on secondary porosity in the form of fractures, joints and the degree of weathering, but it also depends on geomorphological set up and hydrogeological conditions (GSDA and CGWB 2014; Katpatal et al. 2014; Obi Reddy et al. 2000; Katpatal and Dube 2010).

Recharge enhancement with subsurface storage is a known technology and has already successfully been implemented in many countries at different scales (Tuinhof et al. 2002). It represents a flexible and cost effective means to increase storage capacity. A significant change in approach to groundwater management was introduced by Dillon (2005)

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when he proposed the term 'managed aquifer recharge' (MAR) as a tool useful for replenishing falling groundwater levels. Managed aquifer recharge or artificial recharge is the purposeful recharge of water to aquifers for subsequent recovery for environmental benefit (Dillon et al. 2010).

Additional enhancements of natural recharge provide surplus water for various uses (Hollander et al. 2007). Artificial recharge of water to an aquifer is nowadays widely applied for emergency water storage (Van Ginkel 2015). Most of the studies relating to groundwater recharge explain the process as natural replenishment of an aquifer mainly through precipitation and replenishment through seepage from streams, lakes and return flow from irrigation canals and fields (Bhattacharya 2010). Groundwater storage can be replenished during the subsequent wet period through enhancement of the natural or artificial recharge. Groundwater storage is strongly related to the infiltration of water into the aquifers (Tuinhof et al. 2002). The streams are prime feeders to subsurface storage (Levick et al. 2008; Goodrich et al. 2004). Due to heavy silt accumulation, the infiltration rate is affected (BIS 2008). The compact soil has low infiltration rates which results in excessive runoff (Jagdale and Nimbalkar 2012). The impervious nature of the silt causes considerable increase in the runoff (Henry et al. 1992), thus affecting the sustainability of the groundwater abstraction structures. An earthen subsurface dam with either clay or plastic sheets is a common practice in Maharashtra but the method faces sustainability problems and has not been found effective in hard rock areas (GSDA and CGWB 2007). Gale (2005) has suggested methodologies for MAR and their application in semi-arid regions. These methods include channel modifications, well-shaft and bore-well recharge, and induced bank filtration. In India, to address the problem of sustainability of groundwater resources, several traditional artificial recharge structures have been proposed and are in use, including earthen dams, gully plugs, check dams, recharge shafts and bench terracing (CGWB 2000; BIS 2008; GSDA and CGWB 2007). The traditional system of subsurface recharge in Maharashtra state faces silting problems and reduced storage on the upstream of dams (VIIDP 2012). Hence, a recharge structure which can control the silting problem and enhance recharge in hard-rock terrain, like basalts with impervious soils due to clay content, is desired.

The village of Saoli in central India was facing acute water scarcity during summer. A detailed hydrogeological survey was carried out in 2010 and it was observed that out of 19 wells located in the village, 2 were drinking water supply wells and the remaining were irrigation wells. The depths of the wells range from 7.9 to 14.6 m. The post-monsoon water levels were in the range of 3.5–6.4 m depth and pre-monsoon water levels were in the range of 7.7–13.6 m depth. The post monsoon yield ranged from 36 to 60 m^3/day. Out of the 19 irrigation wells, only 2 wells were yielding (18–27 m^3/day) in the summer season, which was inadequate for the population of the villages (2,009 inhabitants) and for irrigation purposes. This had resulted in scarcity from the month of April onwards. The drinking-water-supply wells are located close to the stream. It was observed that the stream was heavily silted, and due to heavy silt, the recharge to the groundwater was affected.

This paper presents the conceptualization and design of an innovative artificial recharge system focused on increasing the groundwater yields by means of artificial recharge to increase the groundwater potential. The innovative artificial recharge system was constructed in hard rock basaltic terrain in the month of May 2011.

The conceptualized recharge system consists of three components, each to achieve a specific objective. The first component in the innovative artificial recharge system consists of a subsurface dam in the form of a reinforced concrete wall to arrest base flow. The foundation of the subsurface dam rests on impervious hard rock. Construction of subsurface dams is a known technology and has solved the drinking-water problem of the Holy City of Makkah in Saudi Arabia by creating subsurface storage (Khairy et al. 2010). In order to capture the base flow as well as subsurface flow, it is necessary to the seal the permeable strata to the impervious zone (Yadav et al. 2012). A subsurface dam arrests the groundwater in the pore spaces of rock for sustainable use; hence, the sites of subsurface dams should be located where the geological stratum has effective porosity, hydraulic conductivity and hard-rock basement (Ishida et al. 2011); Mutiso (2002), in his study in Kenya, showed that the water table behind the subsurface dam rose and extended laterally for distances up to 200 m on either side or 500 m in the upstream direction.

The second component conceived in the system consists of three reverse-gradient deepened segments, each 100 m in length with varying depths of 1, 1.5 and 2 m respectively. These reverse-gradient segments increase surface-water storage for recharge. Gabion structures have also been provided at the end of the segment to capture silt. The third component provided in the system constitutes the five recharge shafts of 30 m depth, placed at an interval of 50 m within the reverse-gradient segments, from the subsurface dam to recharge the deeper aquifer. A recharge shaft is a structure commonly used for artificial recharge of aquifers which are separated by an impervious layer (Bhalerao and Kelkar 2013). The most important aspect is the efficiency of the recharge shaft, and at times acceptance rate of an aquifer may be up to 15 L/s at certain places (CGWB 2000). In this case study, the recharge shafts penetrate the impervious basaltic layer at 12 m depth and recharge the deeper vesicular basalt.

The objectives of the study include analysis of the groundwater balance in the affected area, the nature of the aquifer and the availability and potential of the groundwater resource. A further objective was to design a methodology for groundwater augmentation. Based on the analysis of hydrogeological parameters, the artificial recharge system was conceived, designed and constructed for groundwater recharge in 2011.

After completion of the construction in May 2011, continuous monitoring of the groundwater levels in pre- and post-monsoon periods during 2012 to 2015 recorded the impact of the recharge system. The study presents results on analysis of pre- and post-project groundwater levels and yields of the wells. A geographical information system (GIS) was used to spatially represent the area under the influence of the recharge system showing increase in groundwater availability. A Kriging interpolation method within GIS was used to identify the area of influence (AOI) of the artificial recharge system.

Study area

The study area is located in Saoli and Sastabad villages of district Wardha of Maharashtra state in India. The study area falls in micro-watershed No. 5/13 in elementary watershed No. WRW-2 of Wardha sub-basin of Godavari basin and has an area of 5.38 km^2 (Fig. 1). The area is bounded by latitude 20°38′45″N–20°40′N and longitude 78°46′E–78°48′E. The maximum and minimum temperatures are 47 and 8 °C, respectively, and the average precipitation during monsoon period is 890 mm.

The area is located on a slightly dissected plateau (Fig. 2) having a general slope of 1–3 % towards the SE direction. It is drained by first and second order streams which are influent in nature. The area is covered by clayey soil (Fig. 2), which has thickness between 1.3 and 1.5 m. The study area is covered by basalt of Lower Cretaceous to upper Eocene age (Patki et al. 2012). The geological profile of the study area (field survey by author) indicates that vesicular basalt is underlain by hard massive basalt (Fig. 3). The weathered and fractured vesicular basalt acts as an aquifer in this area.

Methods

The conceptualization and design of the innovative artificial recharge system focused on increasing the groundwater yield by means of artificial recharge to increase the groundwater potential. Analyses of parameters required for designing the recharge system are discussed in this section, including precipitation, runoff, soil properties and aquifer parameters.

Precipitation and runoff analysis and study of soil and aquifer properties

Precipitation and runoff analysis and studies of soil and aquifer properties in the study area are dealt with here. It has been observed that there is a relationship between hydraulic conductivity and hydraulic properties of the rocks, especially with respect to specific retention, specific yield, porosity etc. (Stanislaw 2011; Bear 1972). These properties are analyzed by conducting field and laboratory tests of the samples collected from the study area.

Precipitation analysis

The precipitation data (Agriculture Department, Government of Maharashtra) for the last 15 years (2001–2015, from the rain gauge station at Wardha) were analyzed to study the precipitation pattern. The precipitation analysis reveals that years 2004, 2006 and 2009 were low precipitation years and consequently water scarcity was observed in the following summers. Years 2007 and 2013 had above-average precipitation (Fig. 4a). The project was completed in May 2011. The daily precipitation data prior to the project were plotted for the year 2011 (Fig. 4b) to study storm events and the number of rainy days. In the year 2011, the number of rainy days observed was 35, and there were 5–6 storm events observed during the monsoon period. A correlation between precipitation and runoff was performed for the period 2001–2015 (Fig. 4c). The coefficient of correlation worked out as 0.977, which indicates a strong dependence of runoff on precipitation. The evaporation rate in Central India is reported to be 2–3 mm/day during the precipitation period (CWC 2006). Since the stream on which the project was constructed is a flowing stream and the study pertains to quantifying the groundwater recharge based on variation in groundwater levels, the evaporation aspect has not been considered.

Runoff calculation

Precipitation of the year 2011 was used to calculate the runoff in the study area in order to find out availability of water for conservation. The runoff was calculated by the Inglis method (Eq. (1); Karanth 1999), which is applicable in the study area where there is a slope of 1–3 %.

$$R = \frac{(P - 178)}{2540} \times P \tag{1}$$

In Eq. (1), P is the precipitation (mm) and R is the runoff (mm).

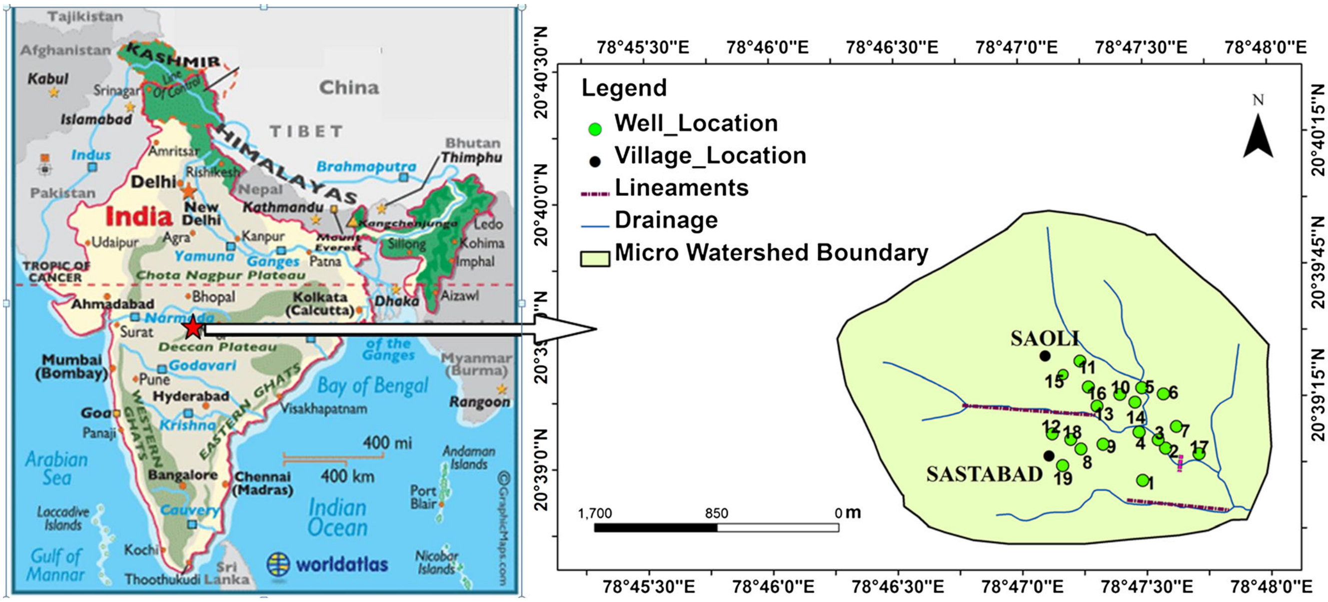


Fig. 1 Map of the study area showing micro watershed WRW-2-5/13 and Saoli and Sastabad villages (source of map of India-World Atlas)

Properties of soil

The properties of the soil were studied to assess soil type and hydraulic conductivity. These parameters were determined in the laboratory by collecting undisturbed soil samples from the study area. Liquid limit and plastic limit tests were conducted to determine the type of soil (Liu and Evett Jack 2008).

The permeability of the silt accumulated in the stream bed over the years was calculated by the variable/falling-head method (Eq. 2; Liu and Evett Jack 2008). The undisturbed samples of the deposited silt were collected using cylindrical cores (11.7 cm length and 10 cm diameter) at different depths in a progressive pit to a depth of 2 m. The undisturbed samples were analyzed in the laboratory for computation of the hydraulic conductivity using a variable-head method.

$$K = \frac{2.303 \times a \times L}{A \times t} \times \log\ 10\left(\frac{h_1}{h_2}\right) \quad (2)$$

In Eq. (2), K the hydraulic conductivity (cm/s), L is the length of sample (cm), A is the area of sample (cm^2), a is the cross sectional area of the stand pipe (cm^2), h_1 is the initial head (cm), h_2 is the final head (cm) and t is the time (s).

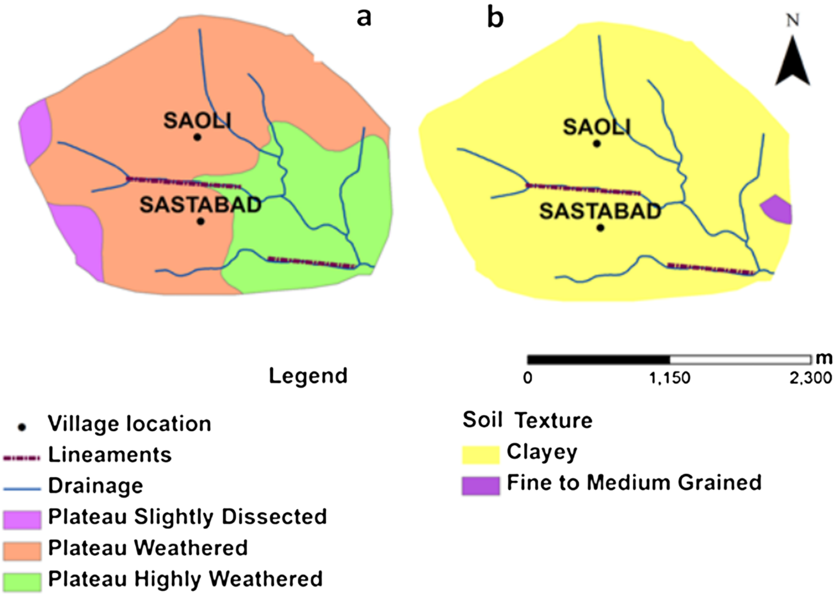


Fig. 2 **a** Geomorphology and **b** soil map of the study area

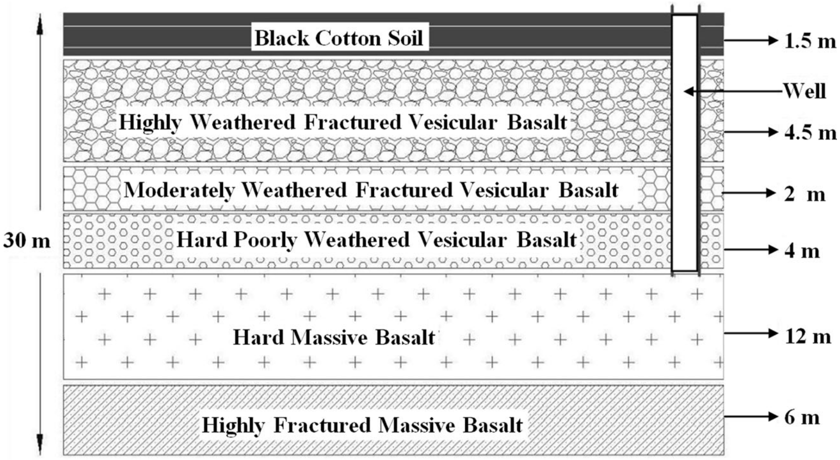


Fig. 3 Geological profile of the study area showing thickness of various formations and a well section of 14.6 m depth

Aquifer properties

The aquifer properties of rocks were studied by conducting laboratory tests in order to find out absorption capacity. The specific yield and transmissivity were calculated by the author by conducting an aquifer pumping test on a representative well in the study area (CGWB 1982, 1986). The specific capacity and the average discharge capacity of the representative well were calculated by conducting field tests. Specific retention of the rock (Karanth 1999) was calculated by conducting water absorption tests in the laboratory on the rock samples collected from the cut-off trench dug for the subsurface dam to a depth of 8 m.

The specific capacity and the discharge of the well were calculated using the Slichter formula (Eq. 3; Sammel 1974). The pumping test was conducted in the field on well No. 3, as a representative well since the aquifer conditions are the same across the area where the 19 observation wells are located. The drawdown and recovery were measured at specific intervals of time (Table 1). The discharge rate computed manually and that obtained from specific capacity were found to match. Since the discharge was known and constant (18 m^3/h), the specific capacity computed using the Slichter method matched the known discharge.

$$C = \frac{2303\pi \times r \times r}{t} \times \ \log10\left(\frac{s_1}{s_2}\right) \tag{3}$$

In Eq. (3), C is the specific capacity (L/min/unit of drawdown), r is the radius (m), t is the time (m), s_1 is the total drawdown (m) and s_2 is the residual drawdown (m).

Discharge of the well was calculated by Eq. (4).

$$Q = C \times D \times 1440 \times 10^{-3} \tag{4}$$

In Eq. (4), C is the specific capacity (L/min/unit of drawdown), D is the total drawdown (m), and Q is the discharge (m^3/day) of the well.

Transmissivity (T) is calculated by Eq. (5) (Papadopulos and Cooper 1967).

$$T = \frac{Q}{4\pi Sw} \times w \tag{5}$$

In Eq. (5), T is the transmissivity (m^2/day), Q is the discharge (m^3/day), Sw is the drawdown (m), W is the value (m) obtained from the y-axis after matching the time drawdown curve to Papadopulos and Cooper (1967) standard curves.

Specific yield (S_y), which is the capacity of rock to drain water under force of gravity (Karanth 1999), is calculated by Eq. (6) (Papadopulos and Cooper 1967).

$$S_y = \frac{4 \times T \times t}{r \times r \times \theta} \tag{6}$$

In Eq. (6), S_y is the specific yield [percent], T is the transmissivity (m^2/day), t is the time (min), r is the radius (m), θ is the value obtained (min) from the x-axis after matching of time drawdown curve to Papadopulos and Cooper standard curves. By calculating S_r (the specific retention [percent]) and S_y (the specific yield [percent]), the percentage of voids (porosity) of the rock formation is determined (Raghunath 2006); these are based on the field observations and sample analysis in the laboratory. The results obtained are listed in Table 2.

The results pertaining to parameters related to precipitation, runoff, soil and aquifer properties are discussed in the following. It has been observed that:

1. A total runoff depth of 308 mm is available for water conservation structures in this area.
2. The stream was heavily silted before construction of the project. The value of plasticity index, PI, has been calculated as 21 %. If PI is more than 17 %, the soil is of clayey type in nature (Liu and Evett Jack 2008).

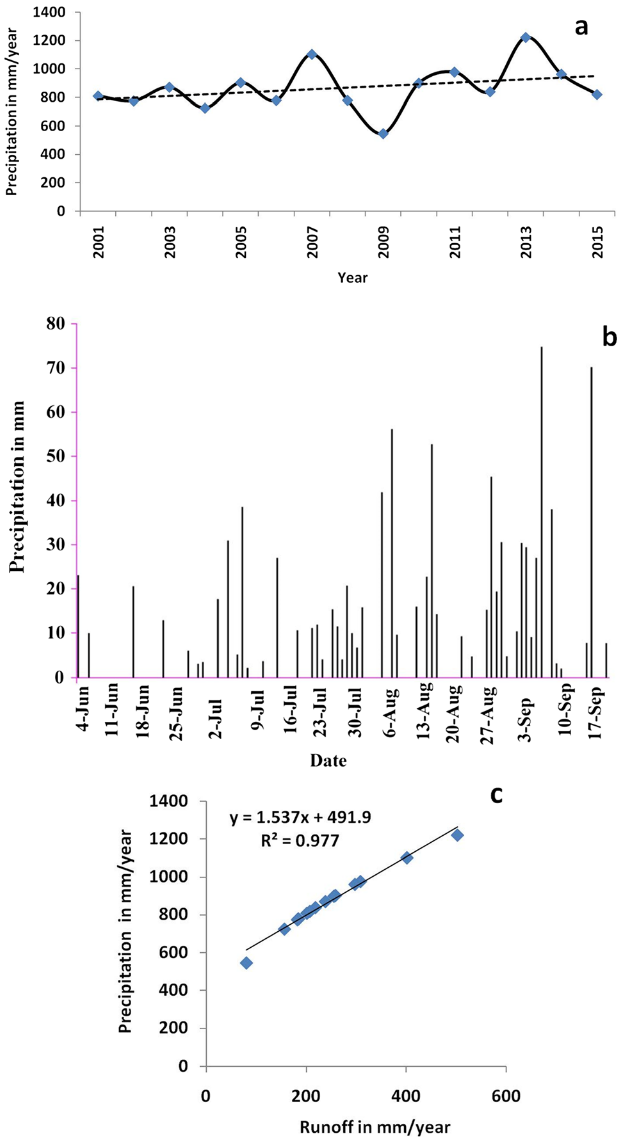


Fig. 4 **a** Yearly monsoon precipitation, **b** Daily monsoon precipitation in 2011, **c** Precipitation-runoff correlation for the period 2001–2015

3. The value of hydraulic conductivity, *K*, is 7.8×10^{-7}cm/s, which proves that soil is of clayey type.
4. The infiltration rate in this soil under natural conditions is very slow, i.e. 1.2 cm/h (Jagdale and Nimbalkar 2012).
5. The value of *K* of sand in the stream bed after removing clay and silt is found to be 2.08×10^{-3} cm/s, which indicates that the soil in the stream bed is of a pervious type (Jagdale and Nimbalkar 2012).

Thus, it is observed that stream deepening and reversal of the stream-bed gradient improves the infiltration rate considerably.

In the hard rock terrain, the streams are located on the lineaments which are weaker zones (Rajurkar et al. 1990; Bhuiyan 2015) and most of the groundwater abstraction structures are located on the banks of streams. The degree of weathering and intensity of fractures are greater in this area. It can be observed from Table 2 that the values of porosity (n), transmissivity (T) and specific yield (S_y) of weathered and fractured basalt are high but, due to overexploitation of groundwater, the water levels are declining. Hence, these sites are best suitable for artificial groundwater recharge through shafts and for capturing the subsurface flow by constructing subsurface dams.

Design of artificial recharge system and methodology of its construction

The design of the reverse gradient artificial recharge system consists of the following three components.

Deepening of stream bed to achieve reverse gradient

Silted streams were modified by resectioning and deepening to increase stream bed area in contact with water for storage and infiltration. This method may be adopted in areas where the streams are influent (Yadav et al. 2012). The 300-m-length segment of second-order stream was selected close to where drinking water supply wells are located. The cross section of stream after resectioning and deepening is a trapezoid with base width of 10 m and top width of 16 m. A variation in depth at 100-m horizontal intervals from the subsurface dam was created; the segment depths were 1, 1.5 and 2 m (segments III, II and I respectively as shown in Fig. 5). Due to the reverse-gradient trench, the surface-water velocity is reduced, the wetted perimeter is increased and storage volume is increased, thus increasing infiltration. Due to the reverse gradient, a sink of dimension 100 m × 10 m × 2 m is created in segment I for capture of silt and segments II and III enhance prolonged storage of water and facilitate infiltration (Fig. 5). The total water storage area in the trapezoidal section generated by the stream deepening in reverse gradient of the three different segments was calculated (Sahastrabudhe 2009) and is shown in Table 2.

After removal of clay and silt from the stream bed, the undisturbed samples were collected using a cylindrical core (5.7 cm length and 10 cm diameter) at three locations, one in each segment of reverse gradient. The hydraulic conductivity, *K*, was calculated by the constant head method using Eq. (7) (Liu and Evett Jack 2001).

Table 1 Pumping test data for well No. 3, representing the village Saoli Taluka and District of Wardha

Time since pump started (min)	Water level depth (m)	Drawdown in the well, S_w (m)	Time since pump stopped (min)	Recovery (m)	Residual drawdown, s_1 (m)
0	9.10	0	0	0	0
15	8.92	0.18	15	0.08	1.49
30	8.76	0.34	30	0.18	1.39
45	8.66	0.44	45	0.3	1.27
60	8.56	0.54	60	0.41	1.16
75	8.46	0.64	75	0.5	1.07
90	8.36	0.74	90	0.57	1
105	8.27	0.83	105	0.65	0.92
120	8.19	0.91	120	0.74	0.83
135	8.10	1	135	0.81	0.76
150	8.02	1.08	150	0.86	0.71
165	7.96	1.14	165	0.92	0.65
180	7.88	1.22	180	0.98	0.59
195	7.83	1.27	195	1.03	0.54
210	7.78	1.32	210	1.06	0.51
225	7.73	1.37	225	1.1	0.47
240	7.68	1.42	240	1.16	0.41
255	7.63	1.47	255	1.23	0.34
270	7.59	1.51	270	1.29	0.28
285	7.55	1.55	285	1.32	0.25
300	7.53	1.57	300	1.35	0.22
315	7.53	1.57	-	-	-

Depth of the well: 14.20 m., radius of the well: 2.47 m, initial static water level depth: 7.53 m, pumped water level: 9.10 m

$$K = \frac{V \times L}{A \times t \times h} \tag{7}$$

In Eq. (7), K is the hydraulic conductivity (cm/s), V is the quantity of water collected (ml), L is the length of sample (cm), A is the cross sectional area of soil sample (cm^2), t is the time (s) and h is the head (cm). The estimated surface water storage of 5,850 m^3 created by stream deepening in reverse gradient is now available for various purposes. Due to this segment-wise deepening in the depth of 1–2 m, the storage in the segments is prolonged up to the month of March, which is the beginning of summer in India.

Subsurface dam

The yield of the wells starts reducing from the month of March onwards because of the downward movement of subsurface flow under hydraulic gradient in weathered and fractured rock. In order to capture the base flow, a subsurface concrete dam was constructed at about 10 m downstream of well No. 2. The cut-off trench for constructing the subsurface dam was excavated to 8 m below the stream bed level, to hard basalt. The subsurface dam, made of reinforced concrete, has dimensions of 0.20 m in thickness, 16 m length and 8 m depth. The thickness of the dam was fixed based on height of the dam (Khairy et al. 2010).

Storage created by the subsurface dam is calculated by two methods using Eqs. (8)–(9) (CGWB 2000; GSDA and CGWB 2007).

$$Sp = D \times A \times P \tag{8}$$

$$S_{SY} = D \times A \times S_y \tag{9}$$

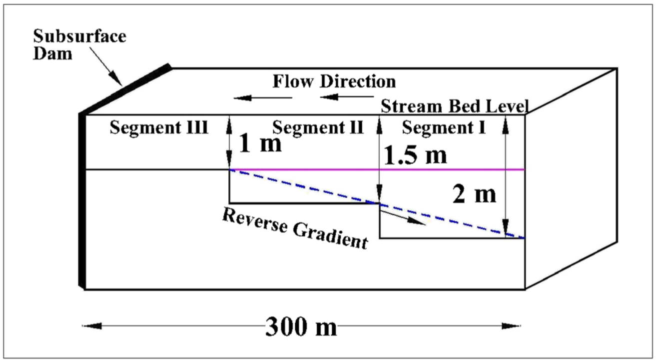
In Eqs. (8–9), S_P is the storage calculated by porosity (m^3), S_{SY} is the storage calculated by specific yield (m); D is the depth of subsurface dam (m); A is the effective area of influence (m), n is porosity (percent) and S_y is the specific yield (percent).

The groundwater available for exploitation through storage created by the subsurface dam considering the porosity

Table 2 Parameter values obtained from field and laboratory tests

Parameter	Input variables	Results
Runoff (*R*)	*P*: precipitation (960 mm)	308 mm
Hydraulic conductivity for clay (*K*)	*L*: length of sample (11.70 cm) *A* : area of sample (78.5 cm^2) *a*: cross sectional area of stand pipe (3.14 cm^2) h_1: initial head (112.5 cm) h_2: final head (97.5 cm) *t* : time (85,875 s)	7.8×10^{-7}cm/s
Hydraulic conductivity for sand (*K*)	*V*: volume of water collected (47 ml) *L*: length of sample (5.7 cm) *A*: cross sectional area of soil sample (78.5 cm^2) *t*: time (25 s) *h*: head (60 cm)	2.08×10^{-3} cm/s
Specific retention (S_r)	W_1: saturated weight of sample (0.645 kg) W_2: oven-dried weight of sample (0.61 kg)	5.78 %
Specific yield (S_y)	*T* : transmissivity (139.83 m^2/day) *t* : time (400 min) *r* : radius (2.47 m) θ (800,000): value obtained from x-axis after matching the time drawdown curve to Papadopulos and Cooper (1967) standard curves (min)	4.58 %
Porosity (*n*) of weathered basalt	S_r: specific retention (5.78) S_y: specific yield (4.58)	10.36 %
Transmissivity (*T*)	*Q*: discharge (344.70 m^3/day) S_w: drawdown (1.57 m) *W* (8): value (in m) obtained from y-axis after matching the time drawdown curve to Papadopulos and Cooper (1967)	139.83 m^2/day
Specific capacity of the well (*C*)	*r* : radius (2.47 m) *t* : time (300 min.) s_w: total drawdown (1.57 m) s_1: residual drawdown (0.22 m)	152.47 L/min/unit of drawdown
Discharge (*Q*)	*C* : specific capacity (152.47 L/ min/unit of drawdown) *D*: total drawdown (1.57 m)	344.70 m^3/day
Storage created by stream (*A*)	Trapezoidal section: Effective base width: 10 m Top width: 16 m Depth of deepened stream bed: h_1 (segment III): 1 m h_2 (segment II): 1.5 m h_3 (segment I): 2 m Length of stream segments: L_1, L_2, L_3: 100 m each	5,850 m^3
Storage created by subsurface dam (*S*)	*D*: depth of subsurface dam (8 m) *A*: effective area of influence (496 m^2) S_y: specific yield (4.58 %)	181,734 m^3
Total recharge by five recharge shafts	Q_m: volume of water not absorbed (0.02198 m^3) *r*: radius of bore well (0.5 m) *H*: head loss (2.80 m) Q_0: water absorbed (0.178 m^3) *V*: volume of water thrust (0.2 m^3) Desaturation period: 5 min	31,104 m^3/year

Fig. 5 Block model of the reverse-gradient structure



(n; 10.36 %) is 408,704 m^3, and considering the specific yield (4.58 %) is 181,734 m^3. The subsurface storage created due to the subsurface dam has no evaporation losses and also ensures availability of groundwater in the summer period. After the aquifer becomes oversaturated, sideways subsurface flow takes place, which was evident from observations in well No. 17, located about 80 m downstream of the subsurface dam; in well No. 17 there were no adverse effects and it does not show post project reduction in groundwater levels and yield (Tables 3 and 4). The post project monitoring during 2012–2015 indicates that no changes due to erosion were observed in the downstream of the dam as the height of the subsurface dam is just 0.20 m and it does not generate turbulent flow. The subsurface concrete dam is very stable and does not incur maintenance costs (Khairy et al. 2010).

Recharge shaft

It has been observed, through water absorption tests carried out in the field, that the hard massive basalt in the study area acts as an impervious layer between the shallow and deeper aquifers (Fig. 3). Hence, there is no direct recharge to the deeper aquifers. In order to recharge deeper aquifers, the recharge shafts were constructed in the resectioned nala bed on the upstream side of the subsurface dam. Five recharge shafts were constructed, separated by a distance of 50 m on the upstream side of the subsurface dam. These recharge shafts have borewells of 100 mm diameter and 30 m depth. Slotted casing pipes were used to case the borewells. Circular filtration chambers of 1 m diameter and 1 m depth, made of cemented bricks, were constructed around the borewells. Small holes were retained in the brick chamber at regular intervals to allow recharge of water. Graded filter media filled the chamber, with gravels up to 20 mm in size at the bottom and coarse sand at the top as shown in Fig. 6a,b. A slug test (Bouwer and Rice 1976) was carried out to determine the acceptance rate of the aquifer. A known quantity of water was thrust into the borewell and the desaturation time was noted.

The rate of acceptance of water through the slug test was calculated by Eqs. (10)–(11).

$$Q_{\mathrm{m}} = \pi \times r^2 \times H \tag{10}$$

$$Q_0 = (V - Q_{\mathrm{m}}) \tag{11}$$

In Eqs. (10)–(11), Q_{m} is the volume of water not absorbed (m^3), r is the radius of bore well (m), H is the head loss (m), Q_0 is the water absorbed (m^3), V is the volume of water thrust (m^3)and the desaturation period was 5 min.

The theoretical acceptance rate of water by one recharge shaft is 36 L/min, considering the availability of water for 120 days, total recharge by five recharge shafts will be 31, 104 m^3. The gabion structure, installed at the end of each segment of the reverse-gradient trench, stops deposition and ensures infiltration. The innovative artificial recharge system described in the present study (Fig. 7) has been implemented with positive changes to the groundwater levels and its availability.

Results

A comparative analysis of groundwater availability before and after the construction of the artificial recharge system is discussed in this section, whereby groundwater levels and yields of the wells before and after the construction have been compared. Spatial interpolation techniques in a geographic information system (GIS) were used to demarcate the increased area of influence (AOI) of the artificial recharge system.

Analysis of groundwater levels

The pre- and post-monsoon water levels for the pre-and post-project situations are shown in Table 3. It should be mentioned

Table 3 Pre-and post-monsoon water levels in m bgl (below ground level) in the study area showing post project enhanced groundwater recharge, by year

Well Nos.	Pre project, pre monsoon	Post project, pre monsoon				Pre project, post monsoon	Post project, post monsoon			
	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014
1	7.7	6.8	7.1	7.35	7.4	3.5	2.5	2.6	2.8	2.6
2	13.5	11.7	10.85	11.3	11.4	4.1	2.6	2.4	2.55	2.7
3	12.85	10.75	10	10.6	10.8	4.3	2.3	2.1	2.35	2.4
4	9.4	8.1	8.3	8.1	8	5.6	2.8	2.5	2.45	2.5
5	9.2	8.4	8.5	8.35	8.3	5.5	4.3	4.1	4.25	4.3
6	9	7.9	8.1	8.3	8.2	4.3	2.85	3.15	3.1	3
7	9	8.2	8	8.2	8	5.15	3	2.95	2.85	3
8	9.6	9.6	9.3	9.4	9.2	4.8	4.8	4.6	4.2	4
9	9.2	8.3	8.4	8.2	8.4	5.6	3.8	3.6	3.4	3.4
10	9.2	8.2	8.6	8.5	8.8	5.2	3.8	4.2	3.9	3.95
11	11	10.8	11.1	11	10.8	6.1	6.3	6.1	6.2	6.2
12	8.85	8.8	8.8	8.7	8.7	5.7	5.2	5.6	5.5	5.7
13	9	8.6	8.5	8.9	8.8	5.8	3.6	3.8	3.4	3.2
14	9	8	8.3	8.6	8.7	5.1	3.9	4.1	4	3.9
15	10.9	10.8	10.3	10.65	10.7	5.7	5.4	5.7	5.1	5
16	8.2	8.2	8	8.2	8	5.6	5.6	5.7	6.1	6
17	9.2	8.8	8.3	8.2	8.5	4.9	2.7	2.9	2.4	2.3
18	9	8.8	8.6	8.9	8.8	4.9	4.1	3.9	4.1	4
19	10.5	10.2	10.2	10.3	10	6.2	5.8	5.95	5.95	6

Table 4 Comparison of pre and post project and pre and post monsoon yields (m^3/day) of the wells in the study area

Well Nos.	Pre project, pre monsoon	Post project, pre monsoon				Pre project, post monsoon	Post project, post monsoon			
	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014
1	0	18	18	18	18	36	60	72	65	54
2	18	67	60	60	65	54	108	106	126	108
3	27	80	85	85	85	60	126	144	144	108
4	0	36	45	45	45	45	90	90	90	72
5	0	27	27	27	27	36	54	54	54	54
6	0	27	27	27	27	36	65	65	65	60
7	0	36	36	36	36	36	72	65	72	65
8	0	0	0	0	0	36	45	54	54	50
9	0	27	36	27	27	36	63	65	65	54
10	0	18	27	27	27	36	54	60	65	54
11	0	0	0	0	0	47	47	54	54	54
12	0	0	0	0	0	36	36	45	45	45
13	0	27	36	36	36	36	63	65	65	54
14	0	18	18	18	18	36	54	54	54	54
15	0	0	0	0	0	45	45	54	45	45
16	0	0	0	0	0	36	36	45	45	45
17	0	36	36	45	45	36	72	72	65	54
18	0	0	0	0	0	45	54	54	54	45
19	0	0	0	0	0	30	36	54	54	45

Project construction was in May 2011

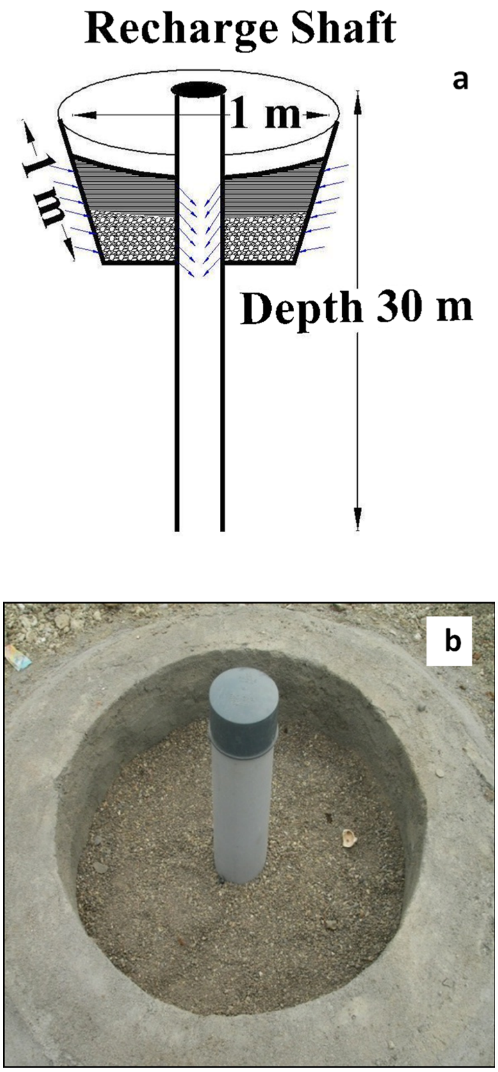


Fig. 6 **a** Design of the recharge shaft, **b** the recharge shaft after construction

that pre-monsoon observations means those taken before the precipitation period, and post monsoon observations are those taken after the precipitation period. The project was completed in May 2011 and so the pre-monsoon groundwater levels of 2011 are pre project. The post monsoon groundwaters levels of 2011 and later are the post project observations. It may be observed in Table 3 that there is significant rise in post-project groundwater levels. The rise in post-project groundwater levels may not be ascribed to increase in precipitation in 2013 as the groundwater levels show increased trends even in 2012 and 2014 when the precipitation was below normal and normal respectively. The comparisons of post and pre-monsoon water levels for the pre- and post-project scenarios have been graphically presented in Fig. 8a,b. It may be observed in Fig. 8a that the pre-monsoon groundwater levels of 2011 in the observation wells are deeper but show significant increase in pre-monsoon groundwater levels of years 2012, 2013 and 2014. A precipitation of 890 mm was recorded in the year 2011 and the pre-monsoon groundwater levels of year 2012 show significant rise. This increase in groundwater level may be only due to construction of the artificial recharge system, as post-monsoon groundwater levels (Fig. 8b) also show similar trends even with varying precipitation in the years 2012, 2013 and 2014.

Analysis of well yield

The yields of the wells in the pre- and post-project situations are given in Table 4 and are represented in the yield maps of the project area in Fig. 9. The well yields were estimated from the pumping rates and the number of pumping hours per day. It may be observed (Table 4) that the yields of the wells also improved significantly after the installation of the artificial recharge system. Significant improvement in well yield may be observed in the post project observations. It may be noticed that there is significant improvement in the yield of the wells in the years 2012 and 2014 when the precipitation was normal, and also when the precipitation was high in the

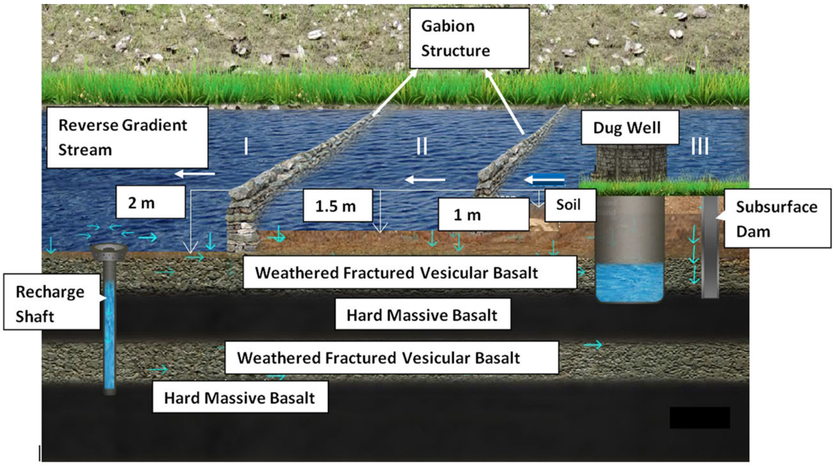


Fig. 7 The artificial recharge system showing various components

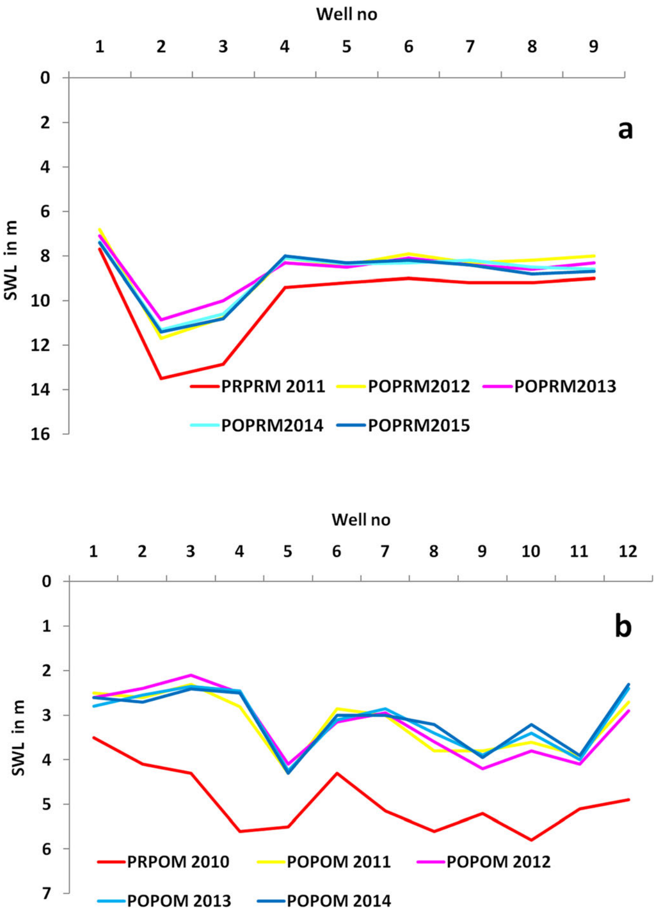


Fig. 8 Graphs showing **a** pre- and post-project comparison of pre-monsoon water levels (mbgl), and **b** pre-and post-project comparison of post monsoon water levels (m bgl)

year 2013. The changes in yield of the wells (Table 4) have been spatially interpolated in the GIS environment using a kriging method to show the increase of yields due to the artificial recharge system (Fig. 9). It may be noticed in Fig. 9 that significant increase in the yields is observed in the post project scenarios both in the pre- and post-monsoon periods.The area of influence (AOI) generated due to installation of the artificial recharge system is shown in Fig. 10. It may be observed (Fig. 10) that 12 wells have benefitted by the recharge system and show significant increase in groundwater levels and yields.

Technical suitability of the artificial recharge system

The stream modification is an old practice, but modification to achieve reverse gradient, as proposed in the present study creates different segments of varying depths to arrest silt deposition in segment I (Fig. 5) and enhance more infiltration in segments II and III (Fig. 5). Segment I is provided with a gabion structure to arrest silt and also reduces the velocity of steady stream flow. The three segments also create prolonged storage for infiltration and groundwater recharge through recharge shafts. In some parts of India, the streams usually dry up after the monsoon period. The base flow captured in the reverse gradient structure is further recharged to lower aquifers through the recharge shafts within the sinks created through the reverse gradient structure (Fig. 5). This artificial recharge system is best suited to the basaltic terrain that has a weathered and fractured zone to 8 m depth. The artificial recharge system proposed is not applicable where thickness of soil and local alluvium is more than 3 m. The deepening of streams should be limited to 2–3 m or to the depth of the lowermost layer of soil or alluvium. The reverse gradient structures, as well as the filter chambers of the recharge shafts should be manually desilted after the monsoon period but the silt must be removed after the streams dry up.

Conclusions

The present study was conducted to augment the water availability scenario by implementation of an innovative artificial recharge system in basaltic terrain and post project impacts have been observed to be encouraging. From the results derived and post project observations, the following conclusions may be drawn.

After the construction of the recharge system, a maximum rise of 2.8 m was observed in the post-monsoon groundwater level and a maximum rise in the yield was observed to be 66 m^3/day. The minimum rise in the post-monsoon groundwater level was observed to be 1 m, while minimum rise in the yield was 18 m^3/day. Before the construction of the artificial recharge system, 17 out of 19 existing wells went almost dry in the summer (pre monsoon) period with only 2 wells yielding water (with yield of 18–27 m^3/day). However, after the construction of the recharge system, there was a significant rise in the groundwater levels and yields in 12 wells within the AOI of the recharge system in the summer period. The maximum rise in summer in groundwater level was 2.1 m and minimum rise was 1 m. The maximum increase in yield in summer was 63 m^3/day, while the minimum increase in yield was 18 m^3/day. After implementation of the artificial recharge system, the area of influence of storage was generated through spatial interpolation in a GIS environment and was observed to be 0.49360 km^2

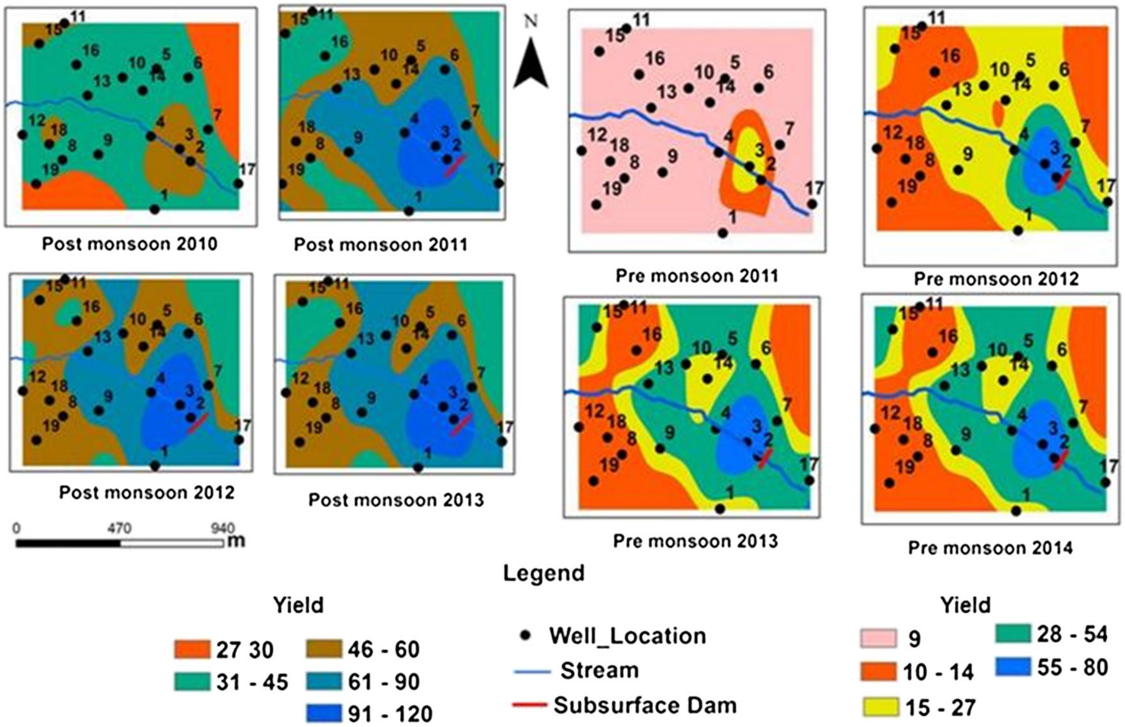


Fig. 9 Comparison of pre- and post-project yields (m^3/day) of the wells in the pre- and post-monsoon periods. The year of construction was May 2011 (pre monsoon)

(Fig. 10). The artificial recharge system proposed in the present study is best suited to basaltic terrain that has a weathered and fractured zone to 8 m depth, followed by an impervious massive basalt zone. After observing the success and efficacy of the artificial recharge system in the study area, the system is being extensively used in scarcity-affected areas of basaltic terrain in the other parts of state of Maharashtra, India.

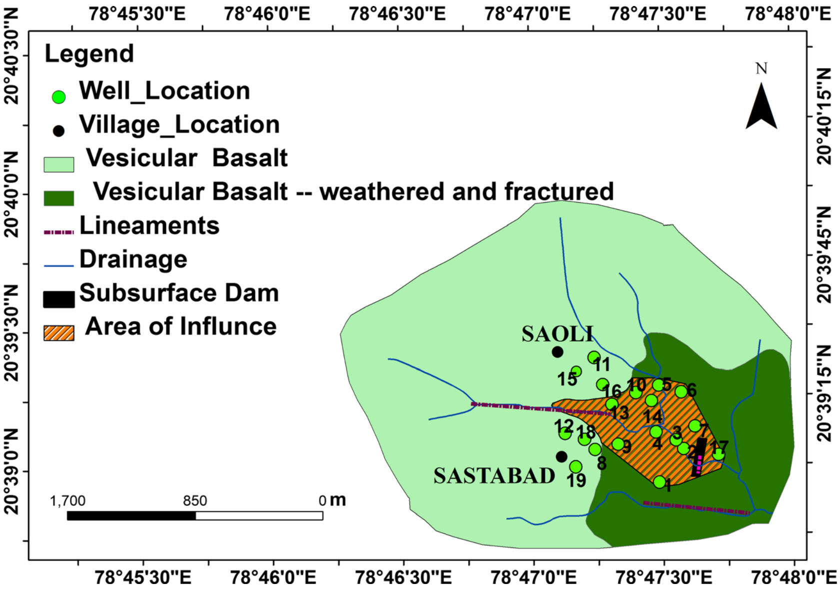


Fig. 10 Map showing the storage area under influence of the artificial recharge system

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