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Estimation of Specific Yields of Individual Litho-units in a Terrain with Multiple Litho-units: A Water Balance Approach

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Abstract: In a terrain with more than one litho-unit, the traditional water balance approach provides a single spatially averaged specific yield. A methodology is proposed here, which can be applied to estimate specific yields of individual litho-units in such terrains. This approach is demonstrated here considering two watersheds, which are covered partly by limestone and partly by sandstone. Watershed wise specific yields were estimated using a traditional water balance method. The specific yields thus obtained are the volume-weighted averages of the specific yields of the individual litho-units in the watersheds. Based on the volumes of aquifers desaturated and the watershed wise specific yield values, a set of two linear equations in two variables was formulated. These linear equations were solved to get the specific yields of the individual litho-units. Specific yields of sandstone (Chandarpur Group) and limestone (Charmuria Formation) units in the study area were thus estimated to be 0.004 and 0.037 respectively.

Keywords: Specific yield; Dry season water balance, Chhattisgarh Basin.

INTRODUCTION

There are several field and laboratory methods for estimation of specific yield (Meinzer, 1923; Meinzer, 1932; Johnson, 1967; Moench, 1994; Boucher et al., 2009; Jie et al., 2011). Each method has its own advantages and limitations. In practice, water balance approach has been used extensively for estimation of specific yield (Saha a nd Agrawal, 2006) mostly because it is based on conventionally available data and provides good approximation of spatially and temporally averaged specific yields. In a watershed covered by a single geological unit, water balance study provides an average specific yield value of the concerned geological unit. However, in a watershed with more than one geological unit, the water balance approach provides only one specific yield value for the entire watershed irrespective of the different lithological units. The objective of this paper is to demonstrate an approach by which specific yields of individual litho-units can be estimated by applying water balance method. The proposed method in described here taking a case study from central India.

STUDY AREA DESCRIPTION

For application of traditional water balance approach, it is unlikely to get two separate watersheds with uniform geology so that specific yields of individual units could be estimated. On the other hand, it is more likely to get two watersheds where each of them is covered by both the geological units. Two watersheds (Fig.1) in Seonath sub-basin located in Durg district of Chhattisgarh state were identified to demonstrate the applicability of the proposed methodology. These watersheds namely Choraha nala watershed (CNW) and Devrani Jethani nala watershed (DJNW) occupy 95 and 122 km^2 area respectively.

The watersheds are covered partly by Chandarpur sandstone and partly by Charmuria limestone (Fig.1). These rocks belong to the Precambrian Chhattisgarh Supergroup of rocks (Das et al., 1992; Mukherjee et al., 2014). Chandarpur sandstone is the bottom most unit of the sequence (Precambrian Chhattisgarh Supergroup) and it unconformably overlies the granitoids. Thickness of Chandarpur sandstone varies from 20 to 90m. Charmuria limestone conformably overlies the Chandarpur sandstone. Thickness of Charmuria limestone varies from 200 to 250m. In terms of ground water potential, Charmuria limestone, owing to the presence of karsts is much more productive in comparison to Chandarpur sandstone, which for large parts is highly silicified.

Average annual rainfall in the area is 1142 mm (IMD: India Meteorological Department). Majority of the rainfall is caused by SW monsoon, which commences during mid

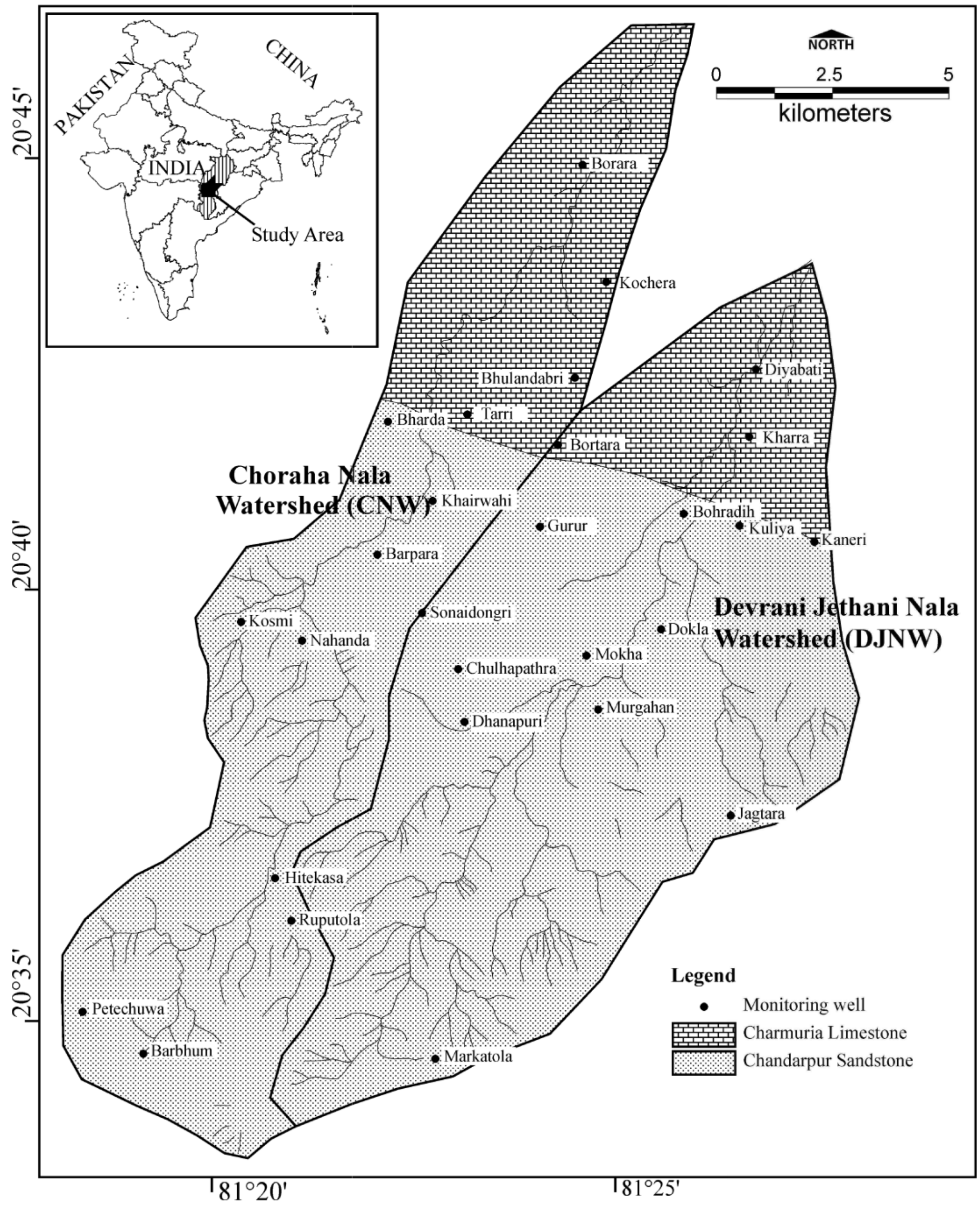

Fig.1. Drainage and geology of the study area with location of the monitoring wells. Inset: Map of India showing the state of Chhattisgarh (hatched) and the study area(black).

June and starts receding from October. There is a pronounced dry period (without any rainfall) of nearly eight months (October to May).

METHODOLOGY

In a water balance study (Walton, 1970), major recharge or input components are recharge from rainfall, return seepage from irrigation, seepage from canals, rivers, percolation tanks, village ponds, net inflow to the basin etc. Similarly, the output parameters include groundwater withdrawal for various purposes, evapotranspiration losses, effluent seepage to rivers, net outflow from the basin etc. During the dry period, several components of the water balance equation become negligible and the water balance equation becomes much simpler. The 'Dry season water balance approach' (CGWB, 1997) is especially suited for dry semi-arid conditions like that prevailing in central India, where there are well-defined rainy (four months) and dry periods (eight months). During dry period, recharge from rainfall is negligible and there is a net outflow from the aquifer. The following equation (Saha and Agrawal, 2006) can be applied in such a case to estimate the net volume of water discharged from the aquifer.

$$V_{out} = \mathrm{WP} - S_{pt} - \mathrm{RE} + \mathrm{ET} + E_{st} \quad (1)$$

where V_{out} = net volume of water discharged from the aquifer. WP = groundwater withdrawn for domestic and irrigation purposes. S_{pt} = seepage from percolation tanks. RE = return seepage from irrigation. ET = losses due to evapotranspiration. E_{st} = effluent seepage from the aquifers to the rivers

If the volume of aquifer desaturated can be calculated, specific yield (S_y) can be estimated using the following relation.

$$S_y = \frac{V_{out}}{V_{aq}} \quad (2)$$

where S_y is the specific yield, V_{out} is the net volume of water discharged from the aquifer and V_{aq} is the volume of aquifer desaturated.

As described above, the watersheds considered here are covered partly by sandstone and partly by limestone. But the watershed wise specific yields obtained from the methodology described above are only the spatially averaged specific yield values of limestone and sandstone. For a particular watershed (say for Choraha Nala Watershed-CNW), this can be written as

$$V_{lst}^{CNW} \text{ x } S_y^{lst} + V_{sst}^{CNW} \text{ x } S_y^{sst} = S_y^{CNW} \text{ x } (V_{lst}^{CNW} + V_{sst}^{CNW}) \quad (3)$$

where V_{lst}^{CNW} = volume of limestone desaturated in Choraha nala watershed (CNW). S_y^{sst} = specific yield of limestone. V_{sst}^{CNW} = volume of sandstone desaturated in Choraha nala watershed (CNW). S_y^{sst} = specific yield of sandstone. S_y^{CNW} = average specific yield in Choraha nala watershed (CNW).

Similarly, for Devrani Jethani nala watershed (DJNW) the equation can be written as

$$V_{lst}^{DJNW} \text{ x } S_y^{lst} + V_{sst}^{DJNW} \text{ x } S_y^{sst} = S_y^{DJNW} \text{ x } (V_{lst}^{DJNW} + V_{sst}^{DJNW}) \quad (4)$$

where V_{lst}^{DJNW} = volume of limestone desaturated in Devrani Jethani nala watershed (DJNW). S_y^{lst} = specific yield of limestone. V_{sst}^{DJNW} = volume of sandstone desaturated in Devrani Jethani nala watershed (DJNW). S_y^{sst} = specific yield of sandstone. S_y^{DJNW} = average specific yield in Devrani Jethani nala watershed (DJNW).

Volume of aquifer desaturated terms in Eq.3 and 4 can be computed from water level fluctuations. Thus, eq. 3 and 4 constitute a pair of linear equations in two variables with a unique solution. Solving these equations, the specific yields can be estimated separately for sandstone and limestone units.

RESULTS AND DISCUSSIONS

For the dry season water balance study, a span of 99 days (From 23rd January to 1st May) in the year 2003 was chosen. This period almost coincides with the period of irrigation for paddy cultivation, which is practically the only crop grown during summer period here. All the streams in the region remain dry from December onwards. So effluent seepage from aquifer to river (E_{st}) was considered negligible. There are no percolation tanks built in the study area. The village tanks and ponds are few in number and the water available in these ponds during summer is also very poor. So the seepage from percolation tanks (S_{pt}) can also be considered negligible. With these considerations, eq. (1) now reduces to a simpler form (eq.5) with only three components, which remain to be estimated to compute the net volume of water discharged from the aquifer. These three components are briefly described in this section.

$$V_{out} = \mathrm{WP} - \mathrm{RE} + \mathrm{ET} \quad (5)$$

where V_{out} = net volume of water discharged from the aquifer. WP = groundwater withdrawn for all purposes. RE = return seepage from irrigation. ET = losses due to evapotranspiration.

Groundwater Withdrawal (WP)

Total groundwater withdrawal or draft is the sum of groundwater withdrawal for irrigation, industrial and domestic purposes. Frenzel (1985) presented three indirect methods to estimate irrigation pumpages: estimates based on power consumption, crop consumptive use and instantaneous discharge method. In the present study, groundwater draft for irrigation was estimated considering crop water requirements. Using remote sensing data, the cropped areas in DJNW and CNW were mapped to be 4.83 and 5.64 km^2 respectively (Mukherjee and Ray, 2009). Considering a crop water requirement of 1.2m (Pal et al., 2003) for the summer paddy, total groundwater drafts were estimated to be 5797440 m^3 for DJNW and 6771600 m^3 for CNW. There is no industry in the study area, so the groundwater draft for industrial use was not considered here. Groundwater draft for domestic use was estimated by multiplying 'population' with 'per capita per day water consumption' and 'number of days'. Village wise population figures (Census, 2001) were added to obtain watershed wise

Table 1 Values of parameters for estimation of watershed wise specific yields in the study area

Parameters (please see Eq.1 and 2)	Choraha Nala Waterhsed (CNW)	Devrani Jethani Nala Waterhsed (DJNW)
Total population	17543	29708
Groundwater withdrawal for domestic purposes in m^3	104205	176466
Groundwater withdrawal for irrigation purposes in m^3	6771600	5797440
Gross groundwater withdrawal (WP) for all purposes in m^3	6875805	5973906
Return seepage from irrigation (RE) in m^3	3047220	2608848
Losses due to evapotranspiration (ET) in m^3	30161	3408
Net volume of water discharged from the aquifer (V_{out}) in m^3 (WP + ET - RE) in m^3	3858746	3368466
Volume of aquifer desaturated (V_{aq}) in m^3	218741803	300240965
Watershed wise average specific yield (S_y)	0.0176	0.0112

populations for the two watersheds. As per these estimates population in DJNW and CNW are 29708 (156 persons/km^2) and 17543 (185 persons/Km^2) respectively. Per capita consumption of water for domestic purpose considered here is 60 liters per day (CGWB, 1997). Multiplying the population figure with per capita consumption of water, ground water withdrawals were estimated as 176466 m^3 for DJNW and 104205 m^3 for CNW (Table 1).

Return Seepage from Irrigation (RE)

In flood irrigation practice, water is allowed to stay in the paddy fields, as a result of which return flow from irrigation is substantial. As per GEC'97 (CGWB, 1997), 45% of the water used for irrigation of paddy crop is lost as return flow or return seepage. As described above, total groundwater draft for irrigation in DJNW is 5797440 m^3 and that in CNW is 6771600 m^3. Accordingly, the return flows from irrigation in DJNW and CNW were estimated as 2608848 m^3 and 3047220 m^3 respectively (Table 1).

Evapotranspiration (ET)

White (1932) based on experiments carried out with plants grown in tanks showed that evapotranspiration losses go on decreasing with increasing depth to water. Evapotranspiration losses in the study area (Fig.2) having deeper water levels (>3.5m) were considered nil as evapotranspiration becomes almost negligible when the water table is below 3.5m (White 1932). For the area having shallower water levels (<3.5m) evapotranspiration was estimated based on PET data of the nearest meteorological station (Raipur), which is maintained by India Meteorological Department (IMD). As suggested by White (1932) and Saha and Agrawal (2006), for an average water level of 3m bgl, actual ET can be considered as 3% of pan ET. Thus the evapotranspiration losses estimated for DJNW and CNW are 3408 and 30161 m^3 respectively (Table 1).

Volume of Aquifer Desaturated

Water levels were recorded from 28 monitoring wells (Fig.1) established in the study area covering both the watersheds. The wells were monitored once every month during the year 2003. The key wells (open dug wells and shallow borewells) ranged in depth from 12 to 40 m and represented the phreatic aquifer. The water level data (point data) were interpolated using kriging technique to generate grid maps. For each watershed two grid maps of water level data, one for the start period (23rd January) and another for the end period (1st May) were prepared. These grid files were then split using digitised geological map. Thus for each watershed, following four grid maps were generated: i) water level during 23rd January for sandstone covered area, ii) water level during 1st May for sandstone covered area, iii) water level during 23rd January for limestone covered area and iv) water level during 1st May for limestone covered area.

For calculation of volumes of aquifer desaturated, the grid for water level for the month of January was subtracted from that for the month of May. Volume of aquifer desaturated over the period of study was estimated by calculating the volume of the slice between these two water

Table 2. Values of the parameters for estimation of specific yields of individual litho-units

Parameters (please see eq. 3 and 4)	Estimated values
Volume of limestone desaturated in Choraha Nala Watershed (V_{lst}^{CNW}) in m^3	90494143
Volume of sandstone desaturated in Choraha Nala Watershed (V_{sst}^{CNW}) in m^3	128247650
Average specific yield in Choraha Nala Watershed (S_y^{CNW})	0.0176
Volume of limestone desaturated in Devrani Jethani Nala Watershed (V_{lst}^{DJNW}) in m^3	67769374
Volume of sandstone desaturated in Devrani Jethani Nala Watershed (V_{sst}^{DJNW}) in m^3	232471591
Average specific yield in Devrani Jethani Nala Watershed (S_y^{DJNW})	0.0112
Specific Yield of limestone (S_y^{lst})	0.037
Specific Yield of sandstone (S_y^{sst})	0.004

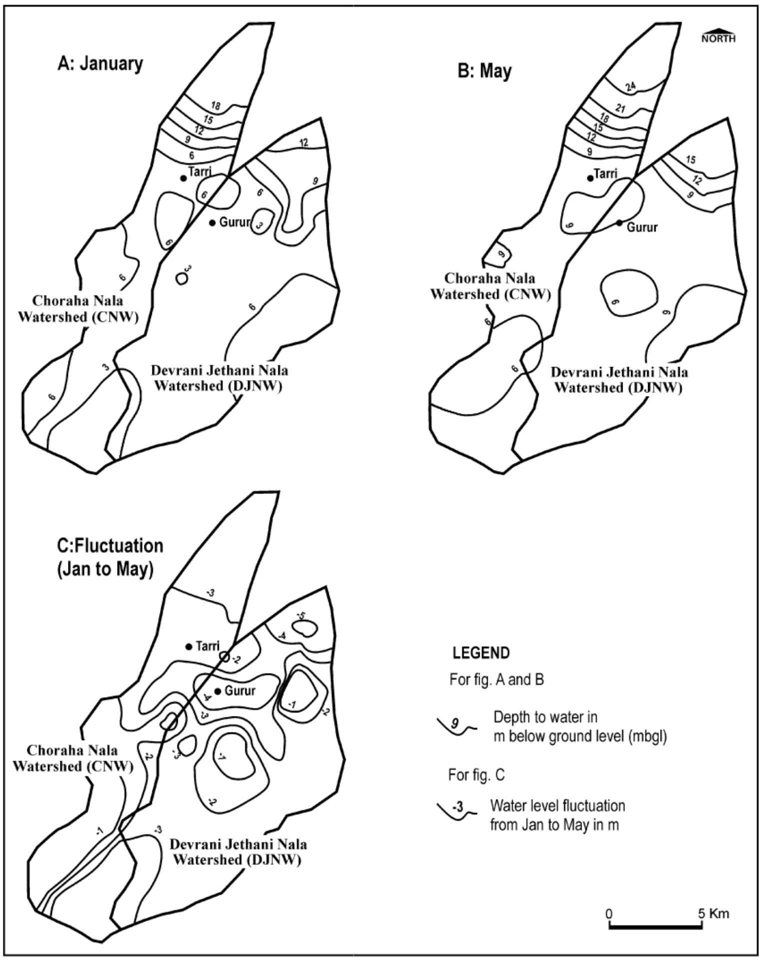

Fig.2. Change in depth to water table in the study area during the period of study-**A**: Depth to water table (in m below ground level) during January, 2003; **B**: Depth to water table (in m below ground level) during May, 2003 and **C**: Water table fluctuation from January to May 2003.

table surfaces. Volumes were calculated using trapezoidal rule. This procedure was repeated for both the geological units in both the watersheds. Interpolation of water level data, preparation of grid maps and other map based manipulations were carried out using Surfer 7.0 (1999). Using the above procedure the volumes of sandstone aquifers desaturated in DNJW and CNW were estimated as 232471591 and 128247650 m^3 respectively. Similarly the volumes of limestone aquifer desturated were estimated as 67769374 m^3 in DNJW and 90494143 m^3 in CNW (Table 1).

Specific Yield Values

The watershed wise specific yields were obtained from eq.(2) substituting the values of the components of the water balance equation as described above. The values of these components are summarised in Table 1. Substituting the estimated values of the components (Table 1), Eq.2 was customized to form two separate equations, one for DJNW and the other for CNW. These equations when solved provided watershed wise specific yield values as 0.0176 for CNW and 0.0112 for DJNW.

Substituting the values of aquifers desaturated and watershed wise specific yield values (Table 2) in equations (3) and (4) a set of linear equations was formulated. This pair of linear equations was solved using elimination method. Solution to a pair of linear equations is a simple procedure and can be done manually. In this paper all the calculations have been carried out using MS Excel® spread sheet application program. The final specific yield values for limestone and sandstone in the study area were thus obtained to be 0.037 and 0.004 respectively (Table 2).

CONCLUSIONS

The paper establishes a methodology for estimation of specific yields of individual litho-units in a terrain with multiple lithologies. The method was successfully applied to a set of two watersheds, Devrani Jethani nala watershed (DJNW) and Choraha nala watershed (CNW) in Durg district, Chhattisgarh. Both the watersheds are covered partly by Chandarpur sandstone and partly by Charmuria limestone. First the watershed wise specific yield values were estimated using a dry season water balance approach. The watershed wise estimated specific yields, so obtained are the volume weighted average specific yields of the sandstone and limestone units. Accordingly, a set of linear equations were formulated using the watershed wise specific yields and volumes of aquifers desaturated. This pair of equations was solved by elimination method and the specific yields of sandstone and limestone units were estimated. Average specific yield of Chandarpur sandstone was thus estimated to be 0.004 and that of Charmuria limestone was estimated to be 0.037.

The case study presented here is based on traditionally available data. Factors like return flow from irrigation and per capita water consumption were taken as per the *ad hoc* norms recommended by CGWB (1997). Similarly, the evapotranspiration losses were estimated based on PET data. These are some of the limitations of the present study and more site-specific data would improve the estimates. However, the use of linear equations to derive specific yields of individual litho-units discussed here can be used in similar cases where watersheds have multiple litho-units.

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