Assessment of Groundwater Sustainability – A Case Study

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INTRODUCTION

Water resource systems, that are able to satisfy the changing demands placed on them, now and into the future, without system degradation can be called 'Sustainable' (McMohan, 1999). Sustainability includes the future economic, environmental, ecological physical and social impacts that will result from decisions and actions taken today. It is intimately related to various measures of risk and uncertainty about a future we can not know but which we can surely influence. As our guesses about the future may, with certainty, go wrong, they will need to be revised periodically.

The present lecture deals with some basic issues involved in assessment of sustainability of water resources, especially groundwater. Quantification of the accurate rate of natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management, although it is quite difficult to estimate. It cannot be measured directly and must be estimated from other measurements but indirect methods introduce various uncertainties (Rushton and Ward, 1979; Simmers, 1988).

Techniques based on groundwater level fluctuations are among the more widely applied methods for estimating recharge rates (Healy and Cook, 2002). In India, the methodology recommended by 'Groundwater Resource Estimation Committee- 1997' (GEC'97) is widely employed for groundwater assessment. This methodology involves use of the water table fluctuation (WTF) method (which is based on groundwater balance approach) and rainfall infiltration factor (RIF) method for making viable estimates of groundwater recharge (CGWB, 1998). Yet, these studies may involve certain degree of inaccuracy, if used indiscriminately. In the present study, groundwater recharge has been estimated for Suswa watershed for the year 2005-06 in accordance with a slightly modified GEC'97 methodology. Based on the findings of the computations, their sustainability has been assessed by considering other relevant parameters.

STUDY AREA

The Suswa watershed is located in the eastern part of Doon valley, Dehradun District, Uttarakhand, India (Figure 1). It includes the city of Dehradun to the west and hills of Mussoorie to the north whereas Siwalik range forms the southern boundary of the study area. The index map of Suswa watershed is shown in Figure 2.

The Suswa watershed is included in the larger watershed of the Song river which is a tributary of the Ganga river. The area, covering 291.6 km^2, lies approximately between 77°57' and 78°10' East longitudes and 30°08' and 30°27' North latitudes and is included in the Survey of India topographical sheets Nos. 53J/3, 53J/4, 53F/15 and 53F/16. Its altitude varies from 420 to 2000 m amsl. The average annual rainfall varies from 1600 to 2200 mm, most of which occurs in the monsoon months of June to August. Land cover/ land use is characterized by forest and agriculture besides the urban area of Dehradun city. Main crops grown in the area are paddy, wheat, maize and sugarcane.

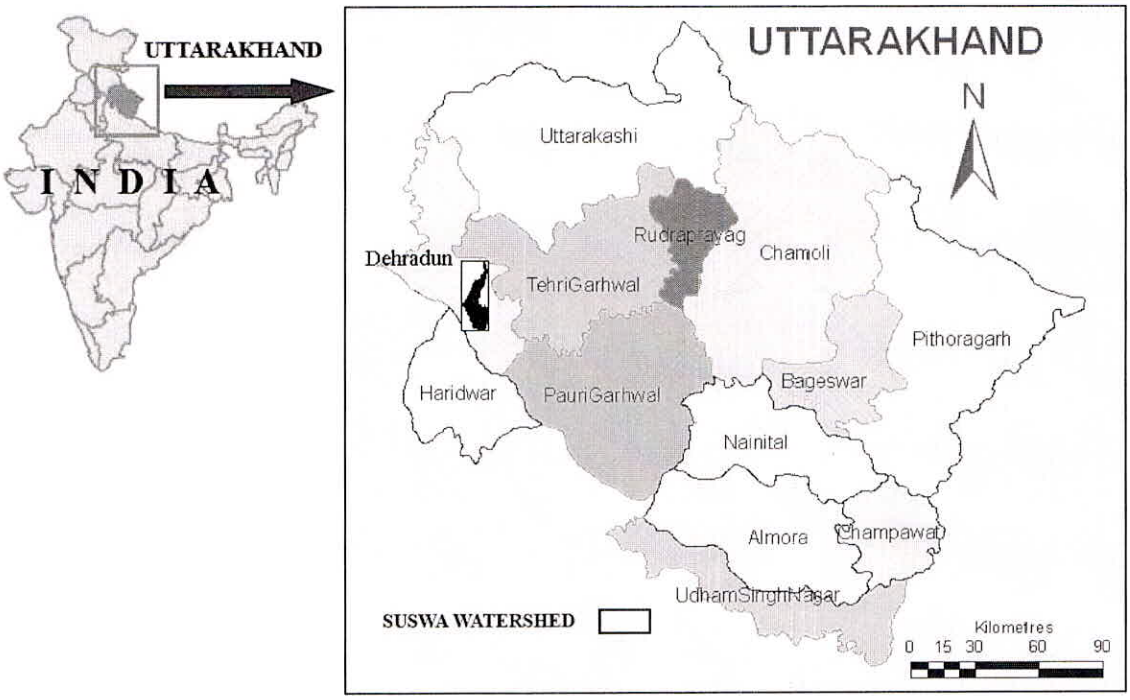

Fig. 1 Location map of Suswa watershed

The rechargeable area can be divided into command area and non-command area based on the existence of a canal irrigation system. Only the canals having a cultivable command area (CCA) of more than 100 hectares have been included in the command area.

SURFACE WATER RESOURCES

In order to assess the surface water resources in the present study area, an attempt has been made to estimate the annual runoff volume for recent 32 years (from 1973 to 2006) by employing the Natural Resources Conservation Services- Curve Number (NRCS-CN) method.

This computation involves daily rainfall as an input parameter which is available for 106 years (1901 to 2006) from India Meteorological Department (IMD). The summary of the rainfall data is given in Table 2.

It is found that the annual runoff ranges from about 186 mm to 789 mm corresponding to the years of 2002 and 1973 against the annual rainfall of 1574 mm and 2915 mm respectively. The average surface runoff depth is about 421 mm resulting from the average annual rainfall of about 2161 mm. By assuming uniform depth of runoff over entire area of Suswa watershed, the minimum annual runoff volume is of the order of 54 million-m^3.

HYDROGEOLOGY AND AQUIFER GEOMETRY

The subsurface geological framework of Dehradun city is presented as a fence diagram (Figure 3) using the available lithological logs of 13 tube wells. These tube wells were drilled during different periods and have been selected out of the larger number of available lithologs of about 75 tube wells drilled in the recent past by Uttarakhand Jal Sansthan, Dehradun for supplying water for drinking purpose. All these tube wells show presence of admixture of boulder and clay in the upper portion and down to the depth of about 40 to 60 m bgl, which shows that the shallow unconfined aquifers may be interconnected to the deeper semi-confined/ confined aquifers in the study area.

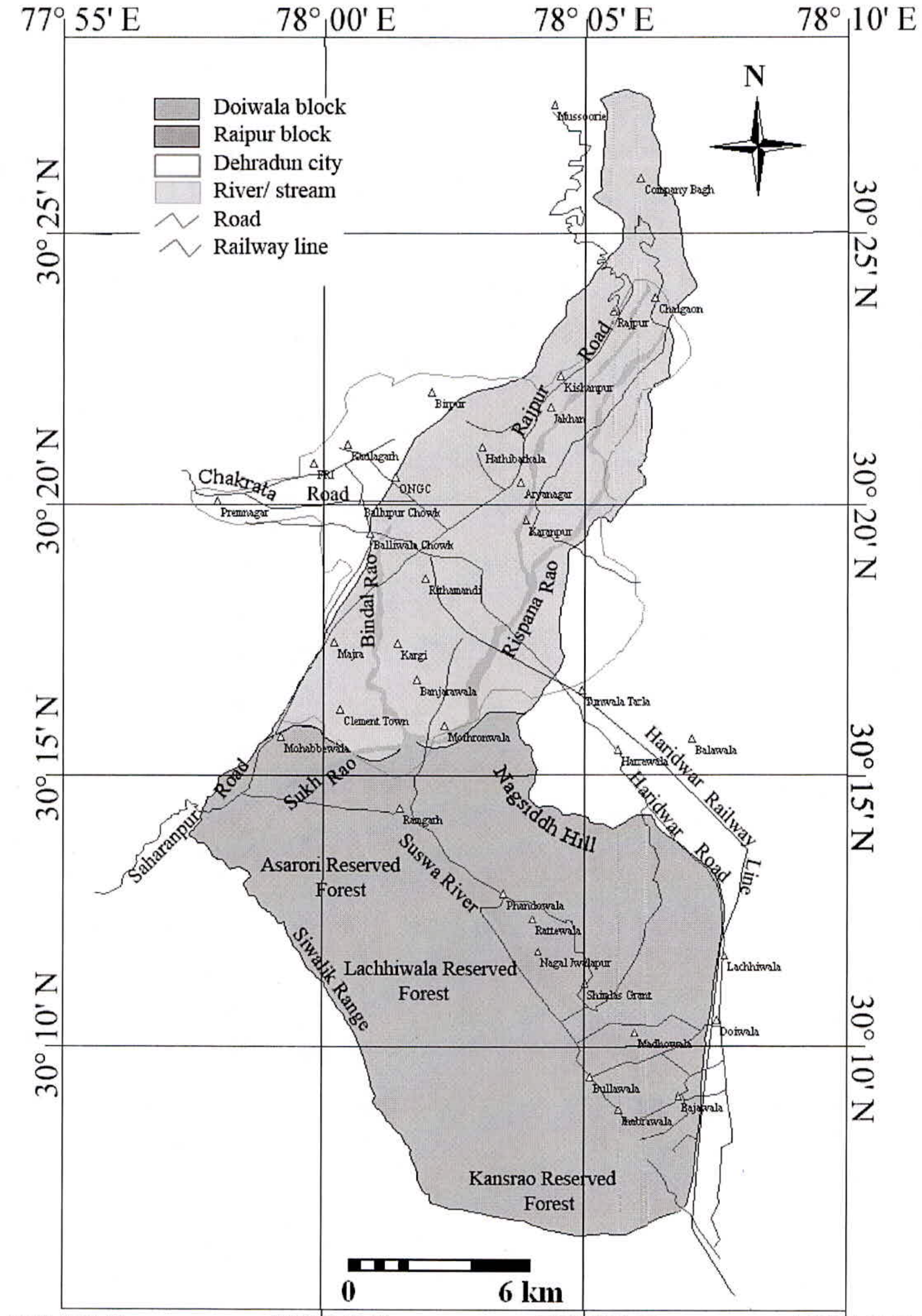

Fig. 2 Index map of Suswa watershed

In this context, it appears that the water level trend manifested in shallow wells (hand pumps) is in conformity with the trend shown by the deep tube wells in the study area. This justifies the combined use of groundwater level data of shallow wells and deep tube wells.

COLLECTION AND GENERATION OF DATA

Groundwater Monitoring

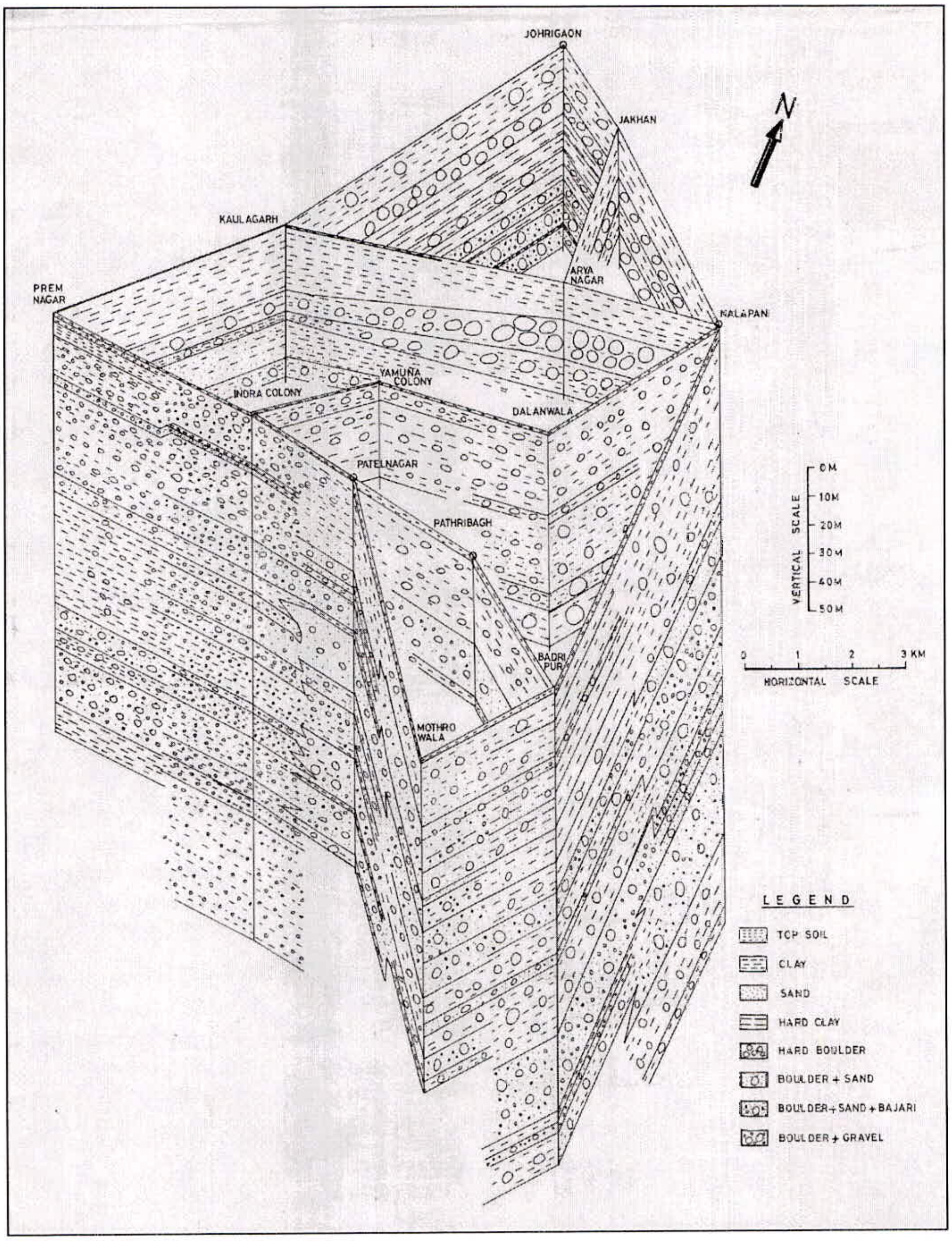

Fig. 3 Geological fence diagram of Dehradun city (modified after Sahu, 2009)

The groundwater levels in the four observation wells of the study area have been monitored two times in a year i.e. pre-monsoon (May-June) and post-monsoon (October-November) periods. A perusal of depth to water table data of the observation wells (Table 1) shows that the quantum of average seasonal (monsoon) rise in the groundwater levels (from 1998 to 2006) is steadily decreasing in the recent years in accordance with the reducing average annual rainfall (Figure 4).

Table 1: Water table fluctuation data of observation wells in Suswa watershed

Well No.	Location	Depth to water table for pre-monsoon 2005 (m bgl)	Depth to water table for post-monsoon 2005 (m bgl)	Seasonal water table fluctuation (rise) in 2005 (m)	Depth to water table for pre-monsoon 2006 (m bgl)	Decline during dry season (m)
(1)	(2)	(3)	(4)	(5) (=4−3)	(6)	(7)(=6−4)
W-1	Siwalik hills	9.50	8.78	0.72	9.57	0.79
W-2	Shewala Khurd	5.50	1.96	3.54	8.50	6.54
W-3	Kaonli	15.27	11.64	3.63	15.50	3.86
W-4	Kuanwala	15.64	3.68	11.96	17.34	13.66
			Average	= 4.96		= 6.21

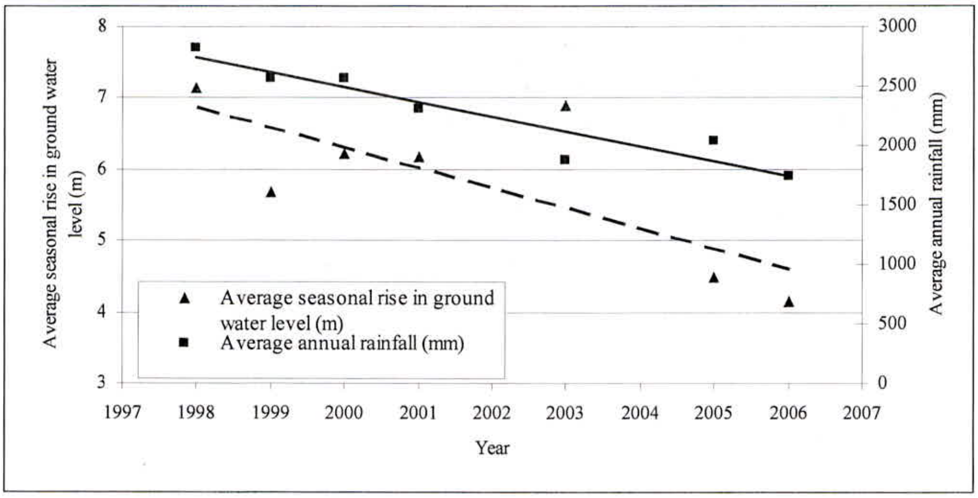

Fig. 4 Average seasonal rise in groundwater level (m bgl) and average annual rainfall (m)

METHODOLOGY OF GROUNDWATER ESTIMATION

Normal & Seasonal Rainfall

The groundwater assessment has been carried out in the present study for the year 2005-06. According to the CGWB guidelines for groundwater estimation, the 'Normal Rainfall' obtained as the average rainfall over a sufficiently long years (106 years) has been considered for computing rainfall recharge. From Table 2, it is seen that out of average annual rainfall of 1668.2 mm, about 24.2 % is received during the non-monsoon season. The remaining 1264.5 mm (75.8 %) rainfall received in the monsoon season is the 'Normal Monsoon Season Rainfall' (NMR). The comparison between monthly rainfall for the year 2005-06 and the normal monthly rainfall for 106 years (from 1901 to 2006) shows that the total annual rainfall in 2005-06 (2044 mm) was in excess by 375.7 mm over the average annual rainfall (Table 2). The non-monsoon rainfall received in the year 2005-06 is 15.4 % (304.6 mm) of the annual total rainfall.

Annual Gross Groundwater Draft

The figures for unit groundwater draft per well for different types of wells have been estimated based on the values of unit draft calculated (instead of using norms of GEC'97) by using the pumping discharge rates of wells and the number of days the wells are in actual use during monsoon and non-monsoon seasons. These values of unit groundwater draft for monsoon and non-monsoon seasons (in ha-m) are given in Table-3.

Table 2: Rainfall data for Dehradun (Source: IMD, Dehradun)

Sr. No.	Month	Average monthly rainfall for 106 years (1901 to 2006) (mm)			Monthly rainfall for the year 2005-06 (mm)		
		Monsoon	Non-monsoon	Total annual (mm)	Monsoon	Non- monsoon	Total annual (mm)
2.1	January	-	42.8	42.8	-	62.74	62.74
2.2	February	-	47.2	47.2	-	88.66	88.66
2.3	March	-	39.2	39.2	-	29.21	29.21
2.4	April	-	23.4	23.4	-	5.33	5.33
2.5	May	-	41.1	41.1	-	21.84	21.84
2.6	June	-	183.2	183.2	-	96.27	96.27
2.7	July	490.3	-	490.3	747.54	-	747.54
2.8	August	500.5	-	500.5	606.56	-	606.56
2.9	September	235.3	-	235.3	382.76	-	382.76
2.10	October	38.4	-	38.4	2.54	-	2.54
2.11	November	-	8.1	8.1	-	0	0
2.12	December	-	18.7	18.7	-	0.51	0.51
2.13	Total	1264.5(**A**)	403.7(**B**)	1668.2(**C**)	1739.4(**D**)	304.6(**E**)	2044.0(**F**)
2.14	Percent (of total annual)	75.8	24.2	100.0	85.1	14.9	100.0

Table 3: Groundwater draft during monsoon and non-monsoon seasons

Area	Type of structure	Groundwater draft (ha-m)	
		Monsoon	Non-monsoon
Command area	State tube well	5.00	15.00
	Domestic private tube well	2.20	4.60
	Industrial private tube well	0.24	0.80
	Bore well with pump set	0.48	1.84
Non-command area	State tube well	8.00	24.00
	Domestic private tube well	3.30	6.90
	Industrial private tube well	0.24	0.80
	Bore well with pump set	0.48	1.84

Annual Recharge from 'Other Sources'

The sources of groundwater recharge other than rainfall are called 'other sources'. In Suswa watershed these are: canals and return flow from irrigation water applied by surface- and ground-water irrigation.

The recharge from these sources in command area has been computed separately during monsoon and non-monsoon seasons. Annual recharge from 'other sources' in command area have been arrived at by adding the values for monsoon and non-monsoon seasons. Likewise, annual recharge from 'other sources' in non-command area have been computed by adding the recharge from groundwater irrigation during monsoon and non-monsoon seasons (Table 4).

Table 4: Groundwater draft and recharge assessment in Suswa watershed

Sr. No.	Parameter	Value/ Description	
4.1	(a) Total area (ha)	29160.00	
	(b) Hilly area (ha) [slope > 20 %]	4480.00	
4.2	Groundwater recharge area (ha) [= 4.1(a)–4.1(b)]	24680.00	
4.3	Poor groundwater quality area (ha)	0.00	
4.4	Command area (ha)	1996.00	
4.5	Non-command area (ha)	22684.00	
Gross groundwater draft in command area in ha-m		Monsoon (A)	Non-monsoon (B)
4.6	State tube-wells (10 Nos)	50.00	150.00
4.7	Private tube-wells (3-domestic + 2-industrial) & dug wells (5 Nos)	16.80	34.80
4.8	Pump sets (21 Nos)	10.08	38.64
4.9	Gross groundwater draft, D_G	76.88	223.44
4.10	Current annual gross groundwater draft for all uses	300.32	
Gross groundwater draft in non-command area in ha-m		Monsoon (A)	Non-monsoon (B)
4.11	State tube-wells (90 Nos)	720.00	2160.00
4.12	Private tube-wells (27-domestic + 18-industrial) & dug wells (45 Nos)	180.90	375.30
4.13	Pump sets (189 Nos)	90.72	347.76
4.14	Gross groundwater draft, D_G	991.62	2883.06
4.15	Current annual gross groundwater draft for all uses	3874.68	
Recharge from 'other sources' in command area in ha-m		Monsoon (A)	Non-monsoon (B)
4.16	Recharge from canals	21.89	43.78
4.17	Recharge from surface water irrigation	228.87	419.60
4.18	Recharge from groundwater irrigation	12.50	37.50
4.19	Recharge from 'other sources' [4.16 + 4.17 + 4.18]	263.26	500.88
4.20	Annual Recharge from 'other sources' in command area	764.14	
Recharge from 'other sources' in non-command area in ha-m			
4.21	Recharge from groundwater irrigation	180.00	540.00
4.22	Annual Recharge from 'other sources' in non-command area	720.00	

Canals

For computing the wetted area of canal segments, the required data of length of canal segments, design discharge of flow and base width pertaining to canals in the Suswa watershed have been collected from Irrigation Division, Dehradun. In this calculation, the values of design depth have been arrived at by assuming all canals to be lined and rectangular in cross section. Operating days of the canals has been considered as 30 days and 60 days during monsoon and non-monsoon seasons respectively (CGWB, 1995). As per GEC'97 norms, the canal seepage factor values assigned to main, branch and minor canal segments are 4.0, 3.5 and 3.0 ha-m per day per Mm^2 of wetted area respectively.

Irrigation water applied by surface water irrigation

Recharge from irrigation water applied by surface water irrigation is computed for the command area by using the design discharge data of canal segments collected from Irrigation Division, Dehradun. Quantity of irrigation water applied by surface water irrigation multiplied by the return flow factors (of 0.36 and 0.33 for monsoon and non-monsoon seasons respectively) gave the desired recharge values.

Irrigation water applied by groundwater irrigation

Recharge from irrigation water applied by groundwater irrigation is computed for both the command area and the non-command area during monsoon and non-monsoon seasons by using an approach similar to that applied for computing recharge from surface water irrigation. Quantity of irrigation water applied by the groundwater irrigation during a given season is considered to be the same as the gross groundwater draft during that season. Return flow factor for computing the recharge from irrigation water applied by groundwater irrigation of 0.25 have been adopted from GEC'97 for both command and non-command areas and also during the monsoon and non-monsoon seasons.

Specific Yield

An attempt was made to calculate specific yield (S_y) using groundwater balance equation for dry season in the watershed. However, this value was found to be too low (1.04 %) and could not be considered viable because it is abnormally low as compared to specific yield of 12 % computed from pumping tests carried out in Dehradun and adjoining areas (CGWB, 1995). Accordingly, specific yield of 12% has been used for calculating the rainfall recharge by using WTF method.

Rainfall Recharge for Monsoon Season

The water table fluctuation method has been employed for computing the recharge for the monsoon season in both the command and non-command areas. The product of water table fluctuation (rise) during monsoon season (h), the specific yield (S_y), and the corresponding command and non-command areas (A) give the change in the groundwater storage during monsoon season (ΔS). The rainfall recharge is then found out by adding the gross groundwater draft to ΔS and deducting the recharge from 'other sources' from the ΔS, for the command and non-command areas.

The rainfall recharge during monsoon and non-monsoon seasons of year 2005-06 has been estimated by employing the rainfall infiltration factor (RIF) method in both command and non-command areas. Rainfall recharge in the command and non-command areas by this method is the product of corresponding area, RIF and the normal rainfall in monsoon and non-monsoon seasons.

Annual Rainfall Recharge

The normal monsoon season rainfall (NMR) of 1264.5 mm and average annual monsoon season rainfall for the year 2005-06 of 1739.4 mm have been employed for computing the normalized rainfall recharge during monsoon season by WTF method (Table 5).

Table 5: Rainfall recharge assessment by WTF and RIF method

Sr. No.	Description	Command (A)	Non-command (B)
5.1	Average decline in groundwater level during dry season (m) [from Table 1]	6.21	
5.2	Average water table rise in monsoon season, h (m) [from Table 1)]	4.96	
5.3	Specific yield, S_y (as a fraction) [from pumping test data]	0.12	
5.4	Rainfall infiltration factor (as a fraction) [from GEC'97 norms]	0.22	
5.5	Change in groundwater storage during monsoon season (ha-m) ($\Delta S = h \times S_y \times A$) [= 5.2 × 5.3 × 4.4 or 4.5]	1188.02	13501.52
5.6	Rainfall recharge by WTF method during monsoon season (ha-m) [5.6 (A) = 5.5 (A) + 4.9 (A) – 4.19 (A)] [5.6 (B) = 5.5 (B) + 4.14 (A) – 4.21 (A)]	1001.64	14313.14
5.7	Normal rainfall recharge by WTF method during monsoon season (ha-m) [5.7(A) = 5.6 (A) × 2.13 (A)/2.13 (D)] [5.7(B) = 5.6 (B) × 2.13 (A)/2.13 (D)]	728.17	10405.29
5.8	Normal rainfall recharge by RIF method in monsoon season (ha-m) [5.8 (A) = 4.4 × 5.4 × 2.13 (A)/1000] [5.8 (B) = 4.5 × 5.4 × 2.13 (A)/1000]	555.27	6310.46
5.9	Normal rainfall recharge by RIF method in non-monsoon season (ha-m) [5.9 (A) = 4.4 × 5.4 × 2.13 (B)/1000] [5.9 (B) = 4.5 × 5.4 × 2.13 (B)/1000]	177.27	2014.66

The WTF method may yield rainfall recharge estimates which are either unreasonably high or low. This is taken care of by: (a) computing a term called the percentage difference (PD) which is the difference between the rainfall recharge by the WTF method and that by RIF method expressed as a percentage of the latter, and (b) finally assigning a value for the rainfall recharge during monsoon season in the command and non-command areas on the basis of a set of criteria which depends on the computed value of PD. The set of criteria adopted in above scheme is:

(a) if PD is from – 20 % to + 20 %, the rainfall recharge is taken as that obtained by the WTF method,

(b) if PD is less than – 20 %, then the rainfall recharge is taken as equal to 0.8 times the value obtained by the RIF method, and

(c) if PD is greater than + 20 %, the rainfall recharge is taken as equal to 1.2 times the value obtained by the RIF method (CGWB, 1998).

The values of PD for monsoon season of year 2005-06 in command and non-command areas has been calculated as 31.14 % and 64.88 % respectively. Both PD values being more than 20 %, the rainfall recharge during monsoon season is taken as 1.2 times the normal rainfall recharge obtained by RIF method. Rainfall recharge during non-monsoon season is taken equal to the normal rainfall recharge obtained by using the RIF method. Finally, the annual groundwater recharge from rainfall is the sum of the recharge values obtained for monsoon and non-monsoon seasons (Table 6).

Stage of Groundwater Development

The stage of groundwater development in a given area is defined as a ratio of the current annual gross groundwater draft for all uses to the net annual groundwater availability in that area. Net annual groundwater availability has been arrived at by summing up the annual groundwater recharge from rainfall and the annual recharge from 'other sources'. The stage of groundwater development in the Suswa watershed has been computed as 18.68 % in command area and 37.59 % in non-command area, whereas overall stage for the whole Suswa watershed (for command- and non-command area) is of the order of 35.04 %, which categorizes Suswa watershed as SAFE (Yadav, 2010).

Table 6: Computations for stage of groundwater development

Sr. No.	Description	Command (A)	Non-command (B)
6.1	PD between rainfall recharge estimated for monsoon season by WTF method & RIF method (%) [6.1 (A) = {5.7 (A) – 5.8 (A)}/ 5.8 (A)] [6.1 (B) = {5.7 (B) – 5.8 (B)}/ 5.8 (B)]	31.14 (> 20 %)	64.88 (> 20 %)
6.2	Recharge from rainfall during monsoon season (ha-m) [Factor 1.2 × 5.8 (A)] [Factor 1.2 × 5.8 (B)]	666.32	7572.55
6.3	Recharge from rainfall during non-monsoon season (ha-m) [6.3 (A) = 5.9 (A)] [6.3 (B) = 5.9 (B)]	177.27	2014.66
6.4	Annual groundwater recharge from rainfall (ha-m) [6.4 (A) = 6.2 (A) + 6.3 (A)] [6.4 (B) = 6.2 (B) + 6.3 (B)]	843.59	9587.21
6.5	Net annual groundwater availability (ha-m) [6.5 (A) = 6.4 (A) + 4.20] [6.5 (B) = 6.4 (B) + 4.22]	1607.73	10307.21
6.6	Stage of groundwater development (%) [6.6 (A) = (4.10/6.5 (A)} × 100] [6.6 (B) = (4.15/6.5 (B)} × 100]	18.68	37.59
6.7	Categorization for future groundwater development	SAFE	SAFE

EVALUATION OF SYNOPTIC GROUNDWATER QUALITY

Melloul and Collin (1998) developed Index of Aquifer Water Quality (IAWQ) for assessing the synoptic groundwater quality of Israel's Sharon region by using the chloride and nitrate concentration. Based on the high values of IAWQ, they delineated areas where land use is affecting groundwater quality. In this approach, for relating groundwater quality data to global norms, each value of a parameter, P_i (field data value of parameter i), is related to its desired standard value P_{id} (Indian drinking water standards in the present study). Each relative value, X_i, can be estimated as:

$$X_i = P_i / P_{id} \quad (1)$$

To express X_i as a corresponding index rating value related to groundwater quality, Y_i has been assigned to each X_i value as follows:

- For good water quality, with X_i equal to 0.1, the corresponding index rating value would be around 1;
- For acceptable water quality, with X_i equal to 1 (the raw value of the parameter P_i equal to its standard desired value), the corresponding index rating value would be 5; and

- For unacceptable groundwater quality, with X_i equal to or higher than 3.5 (the initial value of the parameter P_i equal to or higher than 3.5 times its standard desired value), the corresponding index value would be 10.

Operational hydrological experience indicates that $Y_1 = 1$ for $X_1 = 0.1$; $Y_2 = 5$ for $X_2 = 1$ and $Y_3 = 10$ for $X_3 = 3.5$ (usually values of Y_i range between 1 and 10). For any parameter i, an adjusted parabolic function of rates $Y_i = f(X_i)$ can be determined from 2nd order polynomial as in equation (7.2) (Melloul and Collin, 1998):

$$Y_i = -0.712\, X_i^2 + 5.228\, X_i + 0.484 \qquad (2)$$

From this equation the corresponding rating Y_i can be estimated for any value of X_i. However, in order to avoid negative values of Y_i (which may result in negative indices), maximum values of X_i have to be restricted to 3.5. Thus, after this transformation of the field data, the IAWQ index formula (equation 3) involves only Y-values, representing input data for the development of IAWQ index formula to numerically assess any groundwater quality situation which is as under:

$$IAWQ = C/n\left[\sum_{i=1}^{n}(W_{ri}.Y_{ri})\right] \qquad (3)$$

where,

C = a constant, used to ensure desired range of numbers (taken as 10);
i, n = number of chemical parameters involved (i = 1, …, n), which is incorporated in the denominator to average the data;
W_{ri} = the relative value of W_i / W_{max};
W_i = a weight for any given parameter;
W_{max} = the maximum possible weight (taken as 5);
Y_{ri} = the value of Y_i / Y_{max};
Y_i = the rating value for the i^{th} chemical parameter [obtained from equation (2)];
Y_{max} = the maximum possible rating for any parameter (taken as 10).

A weight (W_i) is a numerical value given to a parameter to characterize its relative anticipated pollutant impact; lower numerical values define lower pollution potential, while higher values define heightened pollution potential. A W_i value would also be larger if a given parameter were toxic or hazardous to groundwater quality. The values of W_{max} and Y_{max} are incorporated into equation (3), to represent W and Y values as related to a reference level in order to assess the relative level of salinization and pollution, and also to ensure that the ultimate IAWQ value remains within a scale of 1–10. IAWQ values can thus be more readily compared from one site to the other, while providing a means of determining the relative influence of additional parameters upon groundwater quality.

GROUNDWATER QUALITY INDEX (GWQI)

Development of groundwater quality index (GWQI) in the Suswa Watershed has been explained in the following paragraphs:

- The range of water quality parameters considered in the original index was extended from two (chloride and nitrate in the original work of Melloul and Collin, 1998) to include major ions and heavy metals like TDS, total alkalinity (TA), Mg, SO_4, total hardness (TH), Cd, Cr and Ni. From the point of regional significance, only those parameters were included which reflected violation of the drinking water quality standards of BIS: 10500 (1991) and WHO (1998) in more than 10 % of the total samples collected in the study area (Fig. 5).

- Out of eight parameters shown in Fig. 5, total hardness (TH) is considered more significant than magnesium to include in the GWQI due to the fact that TH is a result of high concentrations of magnesium and calcium in the study area. Accordingly, the seven chemical parameters finally selected for estimating GWQI were Cd, Ni, Cr, TH, SO_4, TDS and total alkalinity (Table 7).

- Weights (W_i) were assigned to these seven parameters as per their analytical hierarchy in the human health (effecting) significance by using an Analytical Hierarchy Process (AHP).

The computational procedure employed for GWQI estimation in the Suswa Watershed is given in the following steps:

1. The relative ratios (X_i values) for selected seven parameters [viz. Cd, Ni, Cr, total hardness (TH), SO_4, TDS and total alkalinity (TA)] have been computed by using equation (1). As mentioned earlier, the values of X_i equal to or higher than 3.5 were replaced with 3.5 to avoid unreasonably extreme values of final index.

2. The Y_i and Y_{ri} values have been arrived at by using equation (2) with $Y_{max} = 10$.

Table 7: Percent of samples exceeding the drinking water quality standards

Sl. No.	Parameter	Percent of samples exceeding the BIS standards	BIS standards (mg/L)
1	Cadmium	42.9	0.01
2	Nickel	60.7	0.02*
3	Chromium	25.0	0.05
4	Total hardness (TH)	25.0	300
5	Sulfate	46.4	200
6	Total dissolved solids (TDS)	10.7	500
7	Total alkalinity (TA)	35.7	200

* drinking water quality standard of WHO (1998)

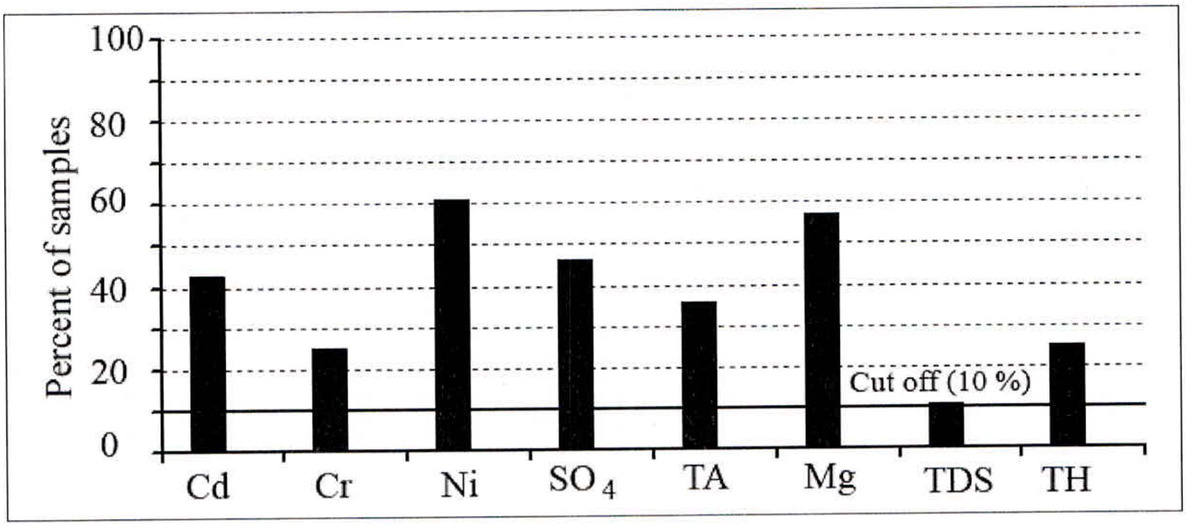

Fig. 5: Percent of samples exceeding drinking water quality standards

Sustainability Indicators

The application of the identified indicators of sustainability for overall calculation of sustainability is discussed below :

Forest Area as a Percent of Land Area

Deforestation rate (DR) is the compound annual rate of deforestation in the area of study in percent (between year P to year N):

$$DR(\%) = 100 \times \left(1 - \left(\frac{Forest\ area_{year\,N}}{Forest\ area_{year\,P}} \right)^{\frac{1}{N-P}} \right) \tag{4}$$

The annual deforestation rate (DR) in the Suswa Watershed is worked out for the periods from year 1972 to 1990 and from 1990 to 2000 by using equation 8.1 as 0.135 % and 0.888 % respectively. Although, the figures of deforestation rates are minimal, the one in the recent period of 10 years (from 1990 to 2000) is faster than that in the earlier period of 18 years (from 1972 to 1990).

Water Barrier Index (WBI)

This indicator is based on annual per capita availability of renewable water (m^3 per capita per year) as given in Table 8. The water barrier concept is the most widely cited measure of water sufficiency for large regions and river basins. It has been used in a number of sustainability evaluation studies (Falkenmark and Widstrand, 1992; Gleick, 1993, 1997; Engleman and LeRoy, 1993). This approach has the advantage of providing a simple view for the basin, thereby stating the category to which it pertains. Notwithstanding the constraint of the size of the study area, this factor has been considered for the Suswa Watershed.

Table 8: Water barrier index demarcations (Source: Falkenmark and Widstrand, 1992)

Index (m^3 per capita per year)	Category/condition
> 1700	No stress
1000 - 1700	Stress
500 - 1000	Scarcity
< 500	Absolute scarcity

In the present study, the minimum and average annual surface water availability has been estimated as 63.19 million-m^3 and 122.68 million-m^3 respectively. Yet, the minimum figure of surface water availability (63.19 million-m^3) has been combined with the net quantity of groundwater available ($11{,}914.94 \times 10^4$ m^3) to arrive at the total minimum water availability in the Suswa Watershed. Thus, the minimum annual water availability is of the order of 18,23,39,400 m^3.

The population for 2005 in the Suswa Watershed (projected from the population of 2001 census) has been worked out as 7,10,938. Finally, the minimum WBI in 2005 is of the order of 256.48 m^3 per capita per year putting the Suswa Watershed in 'absolute scarcity' category.

Integrated Water Stress Score (IWSS)

This indicator, developed for analyzing the sustainability of water resources, is an outcome of the evaluation of eight parameters listed in the following Tables (9 & 10). The values for each of these parameters have been divided into three subgroups in conformity with the approach given by Narula et al. (2001) for Yamuna river basin: acceptable, average, and undesirable. Each sub-group has been assigned a score (referred as a point by Narula et al., 2001), e.g. acceptable is given a score of 1, average has a score of 2, and undesirable has a score of 3. As an example, a high rate of water table decline (more than 0.5 m/ year) falls in the 'undesirable' category and groundwater level decline rate of 0.1 m/ year or less and absence of waterlogging falls in the 'acceptable' category. Based on the summation of scores for each of the parameters, the scores are allotted in the form of integrated water stress and then converted into relative percentage by dividing the watershed score with 24 (8-parameters × 3-sub-groups).

Watersheds with a percentage stress score of more than 60 are classified as 'highly stressed'. In such areas further water development should be restricted or should only take place if it does not pose a further threat to water depletion and deterioration. 'Moderately stressed' watersheds are classified as having percentage stress scores ranging from 40 to 60. In these watersheds, development could be allowed to a certain extent. Watersheds with percentage scores less than 40 were classified as 'low stress' areas with scope for further water use and development. Tables 9 and 10 give the minimum and maximum possible integrated water stress scores for the present study area.

Table 9: Computations of minimum possible IWSS in the Suswa Watershed

Sl. No.	Eight parameters	Three sub-groups (scores allotted)		
		Acceptable (1)	Average (2)	Undesirable (3)
1	Population density	1	-	-
2	Irrigation intensity	1	-	-
3	No. of industrial facilities	1	-	-
4	Groundwater development	1	-	-
5	Water table decline/ rise	-	-	3
6	Groundwater quality	1	-	-
7	Surface water quality	1	-	-
8	Surface water flow	1	-	-
	Sum of scores	7	0	3
	Grand sum of scores	10 (7 + 0 + 3)		
	IWSS	41.67 [(10 × 100) / 24]		

Table 10: Computations of maximum possible IWSS in the Suswa Watershed

Sl. No.	Eight parameters	Three sub-groups (scores allotted)		
		Acceptable (1)	Average (2)	Undesirable (3)
1	Population density	-	-	3
2	Irrigation intensity	-	2	-
3	No. of industrial facilities	-	-	3
4	Groundwater development	1	-	-
5	Water table decline/ rise	-	-	3
6	Groundwater quality	1	-	-
7	Surface water quality	1	-	-
8	Surface water flow	1	-	-
	Sum of scores	4	2	9
	Grand sum of scores	15 (4 + 2 + 9)		
	IWSS	62.50 [(15 × 100) / 24]		

In this study, the lowest possible stress score (Table 9) has been of the order of 41.67 % when only one parameter (e.g. water table decline rate) is considered in 'undesirable' category and other seven parameters are considered as 'acceptable'. Based on the IWSS classification system, the Suswa Watershed can be classified as 'moderately stressed'. On the other hand, the Suswa Watershed can be classified as 'highly stressed' (with a stress score of 62.50 %) by considering only three parameters (e.g. water table decline rate, population density and number of industrial facilities) in 'undesirable' category; one parameter like irrigation intensity in 'average' category and the remaining four parameters in 'acceptable' category (Table 10). Thus, it is inferred that keeping in view the fast urbanization and increasing demands of population, the Suswa Watershed can either be classified as 'moderately stressed' to 'highly stressed', confirming the outcome inferred from the WBI approach.

CONCLUDING REMARKS

It has been observed that, the deforestation rate in the recent period of 10 years (from 1990 to 2000) is more rapid than that in the earlier period of 18 years (from 1972 to 1990), although it is not alarming in both the periods. The WBI computations have placed the Suswa Watershed in 'absolute scarcity' category whereas as per 'IWSS' approach, the watershed can be classified as 'moderately stressed' to 'highly stressed'. Thus, to improve the sustainability of water quantity in the Suswa Watershed, considerable efforts are needed which may call for significant policy changes vis-à-vis water resources development and management. Further, even maintaining the present level of sustainability also needs some efforts from users, stake holders and decision makers.

Based on the assessment of sustainability indicators related to water resources, this study explores an optimal approach to ensure the sustainability of water resources development. This study concludes that the regular assessment of sustainability indicators can play a valuable role in ensuring the sustainable development and management of water resources in the Suswa Watershed.