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Analysis of Watershed Characteristics of Nalagarh Watershed, Himachal Pradesh for Optimization of Recharge Structures and Management of Groundwater

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ABSTRACT

The study involves the study of Nalagarh watershed in Himachal as a topographically delineated hydrogeological entity which is allowing the entire surface runoff of its sub-watersheds to channelize through defined streams and drainage network to certain points in the watershed. Geomorphic analysis of Nalagarh watershed has enabled the study of qualitative and quantitative parameters of the watershed for efficient utilization and optimizing the management of its surface and groundwater resources. As Nalagarh valley has recently witnessed the highest industrial growth in the district and State of Himachal Pradesh, the study becomes all the more impertinent. The watershed has been delineated into 13 micro watersheds, based on the geomorphic analysis. To use the surplus monsoon runoff, a detailed study has been carried out for the computation of utilizable runoff and the number of structures that can be planned for its utilization. To effectively plan the rainwater harvesting structures, the morphometric analysis has been done.

INTRODUCTION

Nalagarh valley (243 km) represents some of the southernmost expanses of Solan district belonging to the fast-industrial belt of Baddi, Barotiwala, and Nalagarh (BBN). The valley has been rated as the fastest industrial growth in the last decade owing to the special packages of incentives granted by the Central government which act as a catalyst in uplifting industrial development in the state, particularly in the BBN area (Herojeet et al. 2013). Especially, the Baddi area is a fast-developing industrial hub with polluting and non-polluting industries, along with the development of domestic and commercial infrastructures to support the industry. In the industrial complex, there are more than 10,000 industrial units out of which 2500 are the pharmaceutical and food processing units and 5000 small and big units; some of them are textile units. The water supply to the industrial complex and other allied infrastructure depends entirely on the development of groundwater resources (HPEC 2011). The deep tube wells are being constructed by all the industrial units to meet their water demand. The utilization of groundwater is very high in the area due to the large number of industrial units and the resident population engaged as workforce in these units (Ahlawat & Kumar 2009, Bhatti 2013, Biswas 1991, Herojeet et al. 2013). The objectives of the study are:

1. Nalagarh watershed of Solan district is likely to encounter the multiplicity of water problems in the future. To study the total model of the recharge potential, the present study entails a detailed study of existing geology, subsurface lithology and the computation of non-committed monsoon runoff.
2. To use the surplus monsoon runoff available in the watershed a detailed study has been done for the computation of utilizable runoff and the number of structures that can be planned for its utilization.
3. To effectively plan the rainwater harvesting structures the present study involved morphometric analysis of the watershed by calculating linear parameters such as number and order of streams, bifurcation ratio, stream length ratio, basin length and areal parameters such as drainage density, frequency (km^2), form factor, circulatory ratio, elongation ratio. In the computation of the number of water conservation/recharge structures, various thematic maps have been prepared through visual interpretation of satellite data.

THE STUDY AREA

Location

The Nalagarh watershed area (243 sq.km) falls under the Solan District of Himachal Pradesh, between 76°43'12" E longitude and 31º3'00" N latitude and includes the industrial town of Baddi. Sirsa watercourse is the main watercourse that flows through the central part of the Nalagarh valley. Large-and small-scale industrial development along with urbanization has taken place randomly all over the Sirsa river catchment area in the last two decades. This results in the high industrial as well as domestic load in the Sirsa watershed. Hence, it is necessary to determine the Sirsa river quality for irrigation purposes. Nalagarh valley forms a south-eastern slim prolongation of a great outermost Himalayan intermountain valley space. It lies between northern latitudes of 30°52' to 31°04' and eastern longitudes of 76°40' to 76°55'. The valley has a common border with Haryana towards south-east, i.e. Kalka-Pinjor area and with Punjab towards the south-west, i.e. Ropar district. Sirsa river is a perennial river which flows south-westerly in the area and joins Sutlej 10 kilometres upstream of Ropar (Fig. 1). There are various perennial and impermanent streams rising from the NE flank passing through the industrial belt usually loaded with industrial and sewage discharges and transverse flow across the valley, to join the Sirsa River (CGWB 2009). The vital streams among them are Chikni River, Phula River, Ratta River, Balad River and Surajpur Choe. The discharge in the streams fluctuates depending on the climatic conditions. During the monsoon, the streams are flooded and carry an extensive amount of sediment and deposited it in the flood plain of the valley.

Regional Geology and Drainage

Nalagarh valley is mainly drained by the Sirsa River which enters the Himachal Pradesh in Solan district near Baddi and flows down to the Sutlej river in Punjab. The main tributaries of the Sirsa River in the study area are the Balad River and Ratta River along with minor tributaries. Sirsa River is a perennial river which flows north-westerly in the study area and joins Sutluj river, a few km upstream of Ropar. The study area is crisscrossed by many small to large khads, which join the Sirsa river at various places. The catchment area of the Balad River is 113.22 sq. km, Ratta River 30 sq. km and catchment area of Sirsa River 31.11 sq. km (Fig. 2) in the study area.

The study area of Baddi Industrial Complex lies between the Ratta River, Balad River and Sirsa River. Both the Ratta River and Balad River are tributaries of the Sirsa River. Sirsa River forms the western boundary of the study area and runs from south-east to northwest direction. Ratta River forms the northern boundary of the project area and runs from east to west direction. It meets Sirsa River in the northwestern part of the area. Balad River flows from northeast to southwest direction and forms the eastern boundary of the project. These Rivers were formed in the last phase of the upheaval of the Himalayas. All the tributaries khads of the Sirsa river flow from north-eastern directions and are almost parallel to each other. The tributaries show parallel to sub-parallel drainage pattern. The drainage developed in the area displays a dendritic pattern and conspicuously shows bad topography on the road section. A few southwest to northeast flowing seasonal nalas (small channels) of small magnitude from the outer Siwalik range of south-west flank also meets the main rivers in the valley areas. The valley-fill deposits have been deposited in sets of terraces by the Sirsa River. These deposits have been dissected to low lying plains and flood plains by various tributaries, nalas of the Sirsa river. The master slope of the study area is towards the northwest direction. However, the ground slope in the south-eastern part is from the flanks towards the Sirsa river. The Nalagarh valley has been carved

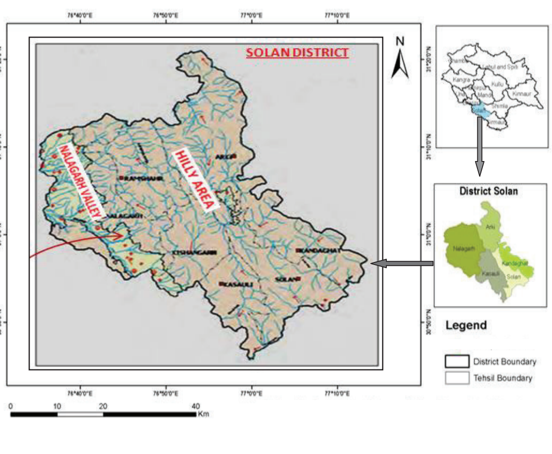

Fig. 1: Location map of the Nalagarh basin (arrow pointing towards Nalagarh watershed).

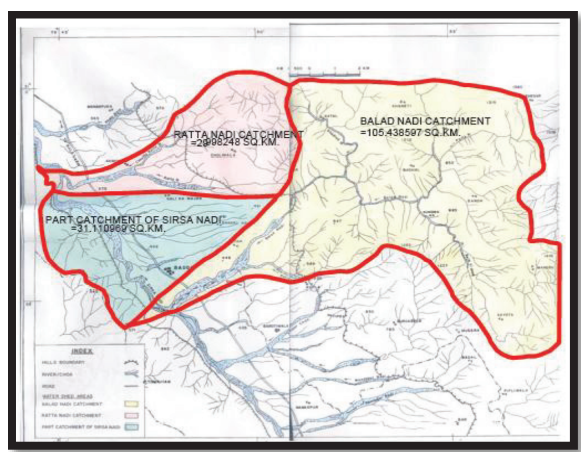

Fig. 2: Catchment area of Ratta River, Balad River and Sirsa River District Solan (H.P).

out in the Siwalik terrain of outer Himalayas and forms a part of the Sutlej Sub-Basin of Indus Basin. The valley is aligned in the northwest-southeast direction in conformity with the trend of main Himalayas in this part. The geology of the area is complex due to the neo-tectonic activity it has undergone. In terms of absolute relief, there is a sudden drop from the north-eastern to south-western into the dun. Relief of the dun ranges between 450 and 600 m, however, there are large variations between the different areas, related to local and regional tectonic conditions and unequal deposition and erosion. The regional variation in the absolute relief is correlated with the regional tectonic frame while in the local areas, variation in the deposition has been important. As a result of en echelon, faulting and tilting of the faulted block, the absolute relief within the dun is higher in the north-east and the south-east than in the north-west and south-west. In this dun, a large number of lower orders, geologically young tributaries fairly entrenched on the alluvial fans, have further broken the topography and produced a more complicated pattern of variations of local relief as the lithology of the area comprises valley-fill deposits of river terraces of immense thickness. These are horizontally bedded/stratified clay beds with lenses of fine sand and gravel. The geological sequence exposed in the area is given in Table 1. The geological map of Solan district is given in Fig. 3. The valley deposits are mainly fluvio-lacustrine in their characteristic. The deposits along the cutting of the nalas show thick clays with beds of boulders, gravels, sands and clay in the valley area. The sediments are more clayey and with lenses of fine sand along the Nalagarh section, which indicates that the sediments have been deposited under fluvio-lacustrine environment and more of the sediments are fine-grained and have been contributed by the River Satluj. The deposits again change to alternate beds of clay and boulders, cobbles, pebbles, gravels, sand and clayey towards the upstream sides of the nalas. The valley-fill deposits are coarser comprising of boulders, cobbles and pebbles, etc. towards the peripheral zone of the valley and from the recharge zone. The braided pattern of drainage in these zones also indicates recharge zones of the valley. The sediments continue to become finer until they blend into clay deposits. The horizontal layering of clay deposits also indicates that the deposits are lacustrine. The upper part of the Pinjore-Nalagarh dun along the foot of Himalaya is characterized by alluvial fans and colluvial deposits crisscrossed by a large number of small and large streams or choes. On the other hand, the south-western (lower) parts of dun are characterized by terraces that are open, wide and co-extensive with alluvial fans above. The growth of kankar was observed in the clay horizons due to the leaching of sub-surface water in the zone of aeration. The top of the terrace is covered with materials of cobble grade clays of fine grade.

The study area is of rectangular and runs parallel to the main strike direction of Siwalik formations. The area is carved between two semi-parallel hill ranges of Siwalik

Table 1: Geological sequence of the study area.

Formation	Lithology	Age
Holocene deposits	River alluvium and the sediments along the present course	Recent
Pre Holocene deposit (River terraces)	Boulders, cobbles, pebbles with layers/lenses of sand/clay	Upper Pleistocene
Upper Siwalik (Boulder conglomerate)	Boulders, pebbles with sandstone and clay	Lower Pleistocene

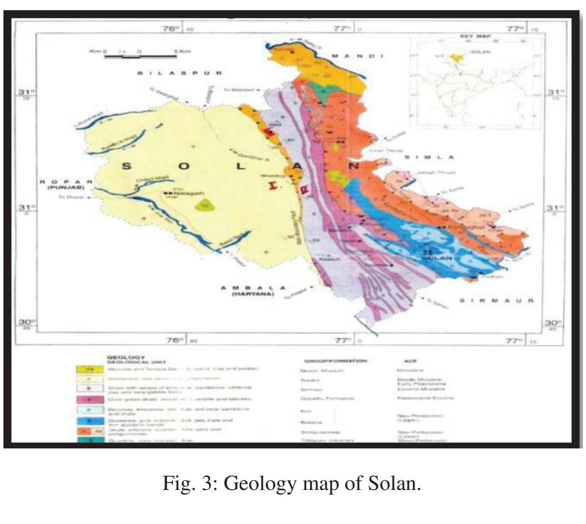

Fig. 3: Geology map of Solan.

formation in the southwestern side and the Kasauli formation on the north-eastern side. Most of the peaks of the ridge along the northeast flanks of the study area attain height more than 1000 m above mean sea level (MSL) and the Kasauli Dhar has the highest peak of 1926 m above mean sea level. The area under study has a higher elevation in the northwest and southeast direction. The topographic contour in the study area is given in Fig. 4. The slope of the area is from the northeast to southwest direction (CGWB 2007).

Climate

The area has a humid to the semi-arid type of climate and experiences three distinct seasons. The monsoon starts towards the end of June and continues till the middle of September. During October and November, the climate is generally pleasant with very scanty precipitation. The winter lasts from December to February. The minimum day temperature is usually around 5ºC. A moderate amount of winter rains are received during this period. The spring months of March and April are generally summer months which are quite hot days and oppressive. At Chandigarh (the observatory closest to Nalagarh) the temperature ranges between 30.4ºC and 16.5ºC. The maximum daily temperature of 38.6ºC is observed in June and the minimum of 6.1ºC in January.

Rainfall

The different parts of the area do not show any uniformity in the amount of rainfall throughout the year. The study area receives an annual average of 1100 mm rainfall which goes up to 1400 mm in the catchment of Balad River. The area thus receives about 1.32 million cu.m of rainfall which can be harnessed for recharging the aquifers. In order to have the increased sustainability of the aquifers to ensure the availability of groundwater to meet the demand for a longer period, the present project is of great significance. The five years (1999-2003) rainfall of the Nalagarh area under which the project area falls is given in Table 2. Due to high porosity and permeability, rainfall is generally absorbed in the soil as the soils are silty sand. Further, the study of data of the last twenty years has shown maximum rainfall recorded in 1988 as 1641 mm, and minimum rainfall recorded as 862 mm in 2006. While, the major share of precipitation, received in the district, i.e. around 70% is received from July to September.

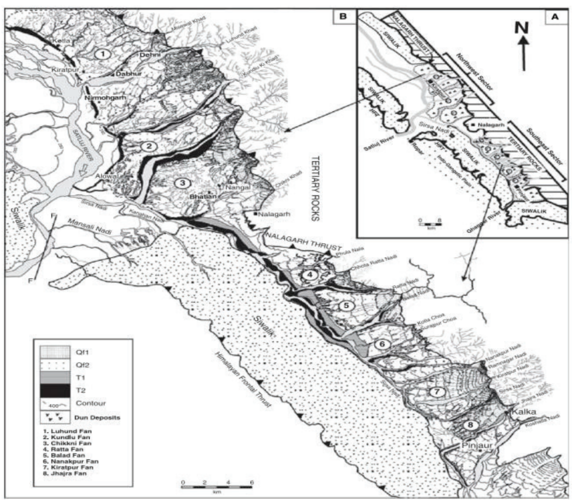

Fig. 4: Geological map of the study area, District Solan (Raivemann 2002).

Table 2: Rainfall (in mm) for the District Solan.

Year	Rainfall in (mm)
1999	1182.9
2000	937.4
2001	856.5
2002	908.9
2003	856.7

Table 3: Dynamic groundwater resources (Nalagarh valley) in MCM (CGWB 2007).

Annual Replenishable Groundwater Resources	77.07
Net Annual Groundwater Draft	10.25
Projected Demand for Domestic and industrial Uses up to 2025	6.84
Stage of Groundwater Development	15%

Hydrogeology

In the valley area of Nalagarh, the groundwater occurs in porous consolidated alluvial formation (valley fills) comprising, sand, silt, gravel, cobbles/pebbles, etc. Groundwater occurs each underneath phreatic and confined conditions. Wells and tube wells are the primary groundwater abstraction structures. Groundwater is being developed in the area by medium to deep tube wells, dug wells, dug cum bored wells. Depth of open dug wells and dug-cum-bored well in the area ranges from 4.00 to 60.00 m bgl (below ground level) wherein depth to water level varies from near ground surface to more than 35 m bgl. The yield of the shallow aquifer is moderate having well discharges up to 10 lps.

In the Nalagarh valley area, there are 12-hydrograph network stations where depth to water level is monitored four times a year and groundwater quality once during pre-monsoon period. The depth to the water table shows a wide variation. During the pre-monsoon period (May 2006), it ranged between 3.02 and 38.2 m bgl, while during the post-monsoon period (Nov 2006) depth to water level ranged from 3.3 to 36.86 m bgl. Deeper water levels are observed mainly in the northwestern part and along the foothills. In major parts of the valley, the depth to water level is less than 15.00 m bgl. The fast pace of groundwater development (Table 3) is observed in recent years in valley areas and this has resulted in declining water levels. In the major part of the valley water level falls ranging from 0.05 to 6.20 metres has been observed in the past decade. There is thus a need to initiate water conservation and artificial recharge measures in such areas. In alluvial areas of Nalagarh valley, though there is scope for groundwater development as the stage of groundwater development is only 15% (HPEC 2011), however, there is a need to adopt a cautious and phased manner groundwater development approach because of depleting water levels in some parts. This decline can be ascribed to the fast pace of development in recent years, both in the agriculture sector and industrial sector. Fig. 5 shows the location of the wells of the Baddi block.

The water supply to the industrial complex and other allied infrastructure depends entirely on the development of groundwater resources. The deep tube wells are being constructed by all the industrial units to meet their water demand without consideration of the sustainability of aquifers. The water table is declining fast and about 11 m decline has been observed in the last 10 years (Fig. 6).

Depth to Water Level

To study the variation in water levels, pre-monsoon water levels of the existing 56 groundwater structures were monitored. These include 27 tube wells, 26 dug wells, 2 artificial recharge wells and 1 hand pump. The depth to water level is deep in the vicinity of hills and it is shallow in the low-lying places and terraces. Based on the water levels recorded in the tube wells, the depth to water level map has been prepared (Fig. 6).

It is seen from the map that water levels in the area vary between 86 m (Well No. 8) to 2.5 m (Well No 44). Water levels are deep in the northeastern part and decrease towards the southwestern part of the area.

Water Table Configuration

Based on the water level data, the water table elevation map has been prepared. The direction of groundwater flow, in general, is from east to west direction (Fig. 7). However, it is observed that from the central part of Balad River near village Koti, the flow directions are towards the Ratta River in the north of the area and towards Sirsa River in the west direction. The water table elevation varies from 448 m above msl in the east and 360 m above msl in the northwest direction.

Allocation of Groundwater Resources for Future Utilization

The net annual groundwater availability is to be proportioned among domestic, industrial and irrigation uses. Among these, as per the National Water Policy 2002, the requirement for domestic water supply is to be accorded priority. The requirement for domestic and industrial water supply is to be kept based on the population as projected to the year 2025. The water available for irrigation use is obtained by deducting the allocation for domestic and industrial use, from the net annual groundwater availability.

Recharge from Monsoon Rainfall

Recharge from rainfall has been computed by using two methods, water level fluctuation method, and rainfall infiltration factor method. Recharge computation through the water level fluctuation method has been done using the following relation:

$$R^{wtf} = h \times Sy \times A + D_G - Rgw \qquad \ldots(1)$$

Where, R^{wtf} = possible recharge by water table fluctuation method, h = the rise in water level in monsoon season, A = area of computation of recharge, Sy = specific yield, D_G= gross groundwater draft, Rgw = recharge from groundwater irrigation during monsoon season. The specific yield value in the case of valley-fill deposits which includes boulders, cobbles, gravels, sand, etc. has been taken as 0.16.

Rainfall recharge computed by this method has been normalized on the normal monsoon rainfall using the procedure recommended by GEC-97 (CGWB 2009) using the relation:

$$R_{rf}\,(\text{Normal wtfm}) = NMR \times R^{wtf}/AMR \qquad \ldots(2)$$

Where, R_{rf} (Normal wtfm) = Normalized rainfall recharge

NMR = Normal monsoon rainfall

R^{wtf} = Computed rainfall recharge

AMR = Actual monsoon rainfall in the year of assessment

As there is no draft data available for the last preceding years, hence recharge is normalized for the assessment year (2008-2009). Recharge computation by rainfall infiltration factor method during monsoon is given below:

Rainfall recharge during the monsoon period has been computed using normal monsoon rainfall (data obtained from Commissioner, Revenue Department, Govt. of H.P). The rainfall infiltration factor for valley fill has been taken as 0.22 as recommended by GEC 97 (CGWB 2009).

The equation used for computation of recharge is:

$$R_{rf}\,(\text{Normal rifm}) = NMR \times A \times RIF \qquad \ldots(3)$$

Where, R_{rf} (Normal rifm) = recharge from rainfall by rainfall infiltration factor method, NMR = normal monsoon rainfall, A = Area of the valley in hectare, RIF = rainfall infiltration factor

Per Cent Deviation: The results from the above two methods (water fluctuation and rainfall infiltration method) have been compared using per cent deviation using the following relation:

$$P.\,D = 100 \times \{R_{rf}\,(\text{Normal wtfm}) - R_{rf}\,(\text{Normal rifm})\}/R_{rf}\,(\text{Normal rifm}) \qquad \ldots(4)$$

Where, P. D. = Percent deviation, R_{rf} (Normal wtfm) = Recharge from (Normalized as computed water table fluctuation method), R_{rf} (Normal rifm) = Recharge from rainfall as computed by Rainfall infiltration factor method.

After computation of the per cent deviation, the following criteria as recommended by the methodology (GEC '97) has been to compare the recharge from rainfall:

i. if $-20 \le$ P. D. $\le +20$ then R_{rf} (Normal) = R_{rf} (Normal wtfm)

ii. if P. D. < -20 then R_{rf} (Normal) = $0.8 \times R_{rf}$ (Normal rifm)

iii. if P. D. > 20 then R_{rf} (Normal) = $1.2 \times R_{rf}$ (Normal rifm)

Total Annual Recharge

The total annual recharge resource was computed as the arithmetic sum of recharge from the monsoon, non-monsoon rainfall and recharge from other sources during monsoon and non-monsoon season. Provision for natural discharges has been kept as 10%, as per GEC '97 methodology.

Total Groundwater Resources of Nalagarh Valley

Net annual groundwater availability has been computed by deducting the unaccounted natural discharge taken as 10 % of the total annual recharge values calculated by rainfall infiltration factor method as per the criteria recommended by GEC-97 for recharge values calculated based on rainfall infiltration method. The stage of groundwater development has been computed using the relation:

Stage of groundwater Development =100 × Gross groundwater draft for all uses (D_G) …(5)

The stage of groundwater development of Nalagarh valley in Solan district is 50.85 % and falls under 'Safe' category.

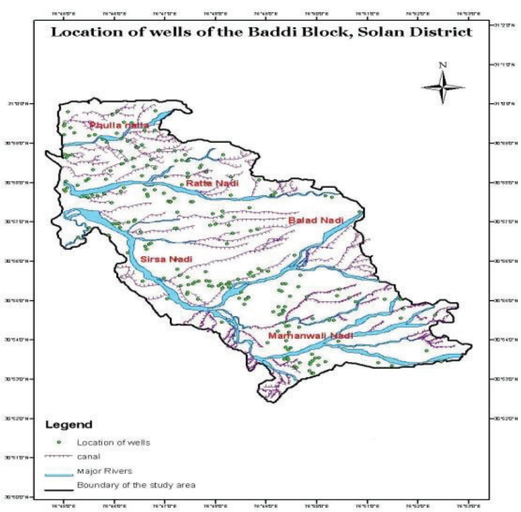

Fig. 5: Map of locations of wells of Baddi Block.

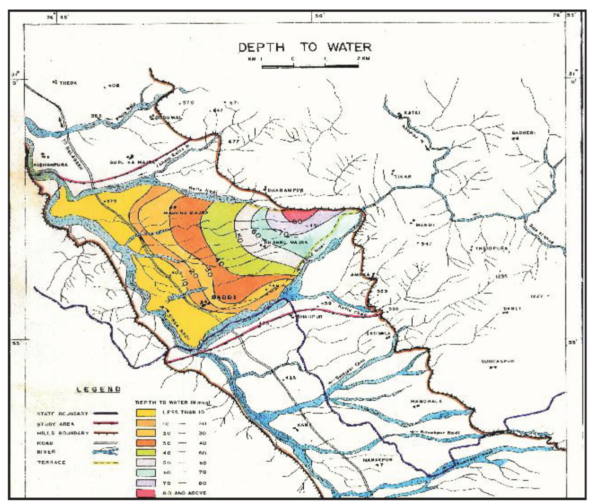

Fig. 6: Depth to water level map of the area.

Net groundwater availability for future use has been computed using the relation:

$$R = A-(B+C) \quad \ldots(6)$$

Where, R = Net annual groundwater available for future irrigation use

A = Net available groundwater resource
B = Gross groundwater draft for domestic and irrigation
C = Allocation for domestic and industrial water supply

IN-STORAGE GROUNDWATER RESOURCES

The Baddi industrial complex is part of Nalagarh, which covers the area of 23849 ha. Central and State govt. agencies have carried out drilling in Nalagarh valley down to a depth of about 160 meters.

From the lithological logs of various tube wells, it has been observed that the aquifer consisting of sand, pebbles, gravel, boulder constitute about 27% and clay bed constitute 73% of the total aquifer system. The thickness of various granular zones ranges from 2 m to 6 m, whereas for the clay beds range from 2 m to 20 m. The average depth to the water level in the valley is about 20 m. An average specific yield of 16% has been considered uniformly for the study area.

Methodology for Estimation of In-storage Groundwater Resource

The static groundwater resource of the area has been estimated based on the similar approach as adopted for the estimation of dynamic groundwater resources. The thickness of aquifer material below the zone of fluctuation and specific yield has been used to estimate the resources. The details of the methodology and formulae are given as under:

$$IR = A \times H \times SY \quad \ldots(7)$$

Where, IR = In-storage resources in ham

A = Area of the valley in ha

H = Thickness of aquifer sediments below the zone of fluctuation up to explored depth (explore depth - pre-monsoon water level in m)

SY = Specific yield of the aquifer in fraction

The salient features of the in-storage groundwater resource assessment are given in Table 4. The thickness of aquifer sediment has been estimated based on the study of the litholog of the area and only the aquifer part has been considered for estimation of resources. The total in-storage groundwater resources of Nalagarh valley are 158167 ham.

MORPHOMETRIC ANALYSIS

The analysis of drainage morphometry is normally essential for the assessment of hydrological qualities of the surface water basin. The Sirsa watershed has been analysed through detailed morphometric analysis (Chadha & Neupane 2011, Eesterbrooks 1969). In this region, a large number of drainage systems originate from the Sirsa River. Following geomorphologic procedures, the catchment area of Sirsa watershed and the surrounding basins was delineated by direct tracing of the drainage tributaries from topographic maps (scale 1:50000). Drainage system boundaries were identified. This was accompanied by a systematic digitizing of the traced tributaries and basin systems in the Geographic Information System (GIS) by using Arc-GIS 10 software. Along these lines, a drainage system map was produced including three significant catchment areas in the region. Topographic maps in combination with remotely sensed data and Landsat images were used to delineate the existing drainage system, thus identifying precisely water divides. This was achieved using Geographic Information System (GIS) to provide computerized data that can be manipulated for different calculations and hydrological measures.

The obtained morphometric analysis can help in determining: 1) stream behaviour, 2) morphometric setting of streams within the drainage system and 3) interrelation between connected streams. The study used an imperial approach of morphometric analysis that can be used in assessments of rainwater harvesting structures (Way 1978). The current study was accomplished using several approaches for drainage system analysis. The study aimed to analyse the major morphometric elements of Baddi watershed in Nalagarh district. It treated the characterization of streams' behaviour (e.g. meandering, frequency, etc), their setting with regard to the catchment and their relation to each other (e.g. patterns, junctions, etc). This provided valuable information that can be used in different water assessments and selecting sites for water harvesting. Additionally, the morphometric analysis can be applied to similar drainage systems in the larger watersheds of Himachal Pradesh.

MATERIALS AND METHODS

Morphometric analysis of a drainage system needs a delineation of all existing streams and reaches. Of the several methods of drainage system delineation, two procedures have been followed in the present study. These are the manual and automated system delineation. The manual sampling of the drainage network has been adopted from topographic maps, Survey of India open series map No. H43K13 of a scale of 1:50000 in combination with computerized tools, and Geographic Information System (GIS). The digital analysis has been carried out for Landsat Imagery using GIS software Arc GIS 10 and ERDAS Imagine Software and the Geo-informatics based multi-criteria evaluation has been done using

Weighted Overlays and AHP methods. For the unconnected drainage systems, satellite images were analysed using ERDAS Imagine software. These images can give information on the surface features, and able to detect buried stream networks. This can be achieved by applying thermal bands with 90m spatial resolution (i.e., capability to differentiate objects on the satellite image) in these images. The applied method in stream delineation was done digitally in GIS (Arc View software) system. Various digital applications were undertaken, including band combination, colour slicing, filtering and related measuring tools. Hence, all tributaries of different extents and patterns were digitized.

RESULTS, DATA ANALYSIS AND DISCUSSION

Drainage patterns: The arrangement of streams in a drainage system constitutes the drainage pattern, which in turn

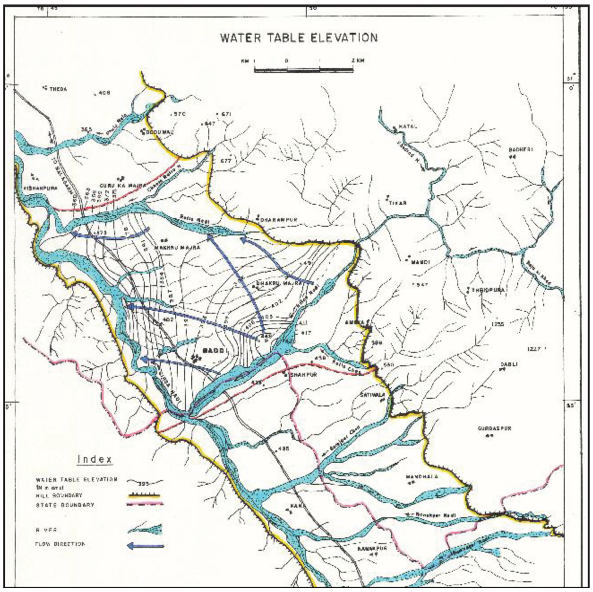

Fig. 7: Water table elevation map.

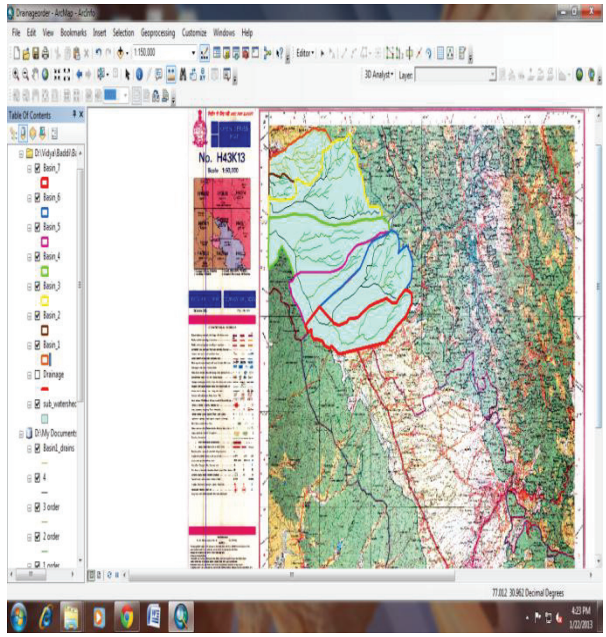

Fig. 8: Snapshot of the Arc view showing the division of the sub-watersheds of the Nalagarh watershed.

Table 4: Salient features of groundwater resource estimation for Nalagarh valley.

Recharge from rainfall during monsoon	6283.55 ham
Recharge from other sources during monsoon	168.43 ham
Recharge from rainfall during non-monsoon	1825.88 ham
Recharge from other sources during non-monsoon	336.85 ham
Annual groundwater recharge	861471 ham
Provision for natural discharge	861.47 ham
Net groundwater availability	7753.24 ham
Existing groundwater draft for irrigation	2021.11 ham
Existing groundwater draft for domestic and industrial water supply	1921.26 ham
Existing groundwater draft for all uses	3942.37 ham
Provision for domestic and industrial supply to 2025	1921.26 ham
Net groundwater availability for future irrigation development	3810.87 ham
Stage of groundwater development	50.85
Category	Safe
Total in-storage groundwater resources of Nalagarh valley	158167 ham.

Table 5: Linear and aerial parameters of Nalagarh watershed.

Micro Watershed No.	Area	No. of streams	Bifurcation Ratio (Avg) Nu/Nu+1)	Drainage Density	Frequency	Form Factor	Elongation Ratio	Basin Length in km
1	60	85	8	1.41666	2.666	0.32	0.032	15
2	124	628	6	5.6	1.625	0.04	0.1412	89
3	147	980	2.16	6.6	13.51	0.09	0.11	124
4	76	693	7.2	9.11	1.0524	0.04	0.03	42
5	77	452	3.12	7.5	5.8	0.04	0.22	42
6	80	147	2.83	5.03	1.83	0.03	1.01	50
7	110	397	3.21	2.6	3.6	0.014	0.13	87
8	41	571	3.15	1.8	14.2	14.2	1.65	19
9	42	450	2.95	3.2	10.14	0.0711	1.4	24
10	24	356	3.9	2.1666	14.1	0.074	1.3	18
11	23	294	5.3	4.325	2.78	0.0707	1.27	18
12	41	287	3.282	2.3	7.1	0.08	1.108	22
13	19	168	2.179	2.55	8.8	0.1319	1.1	12

reflects mainly structural/or lithologic controls of the underlying rocks (Herojeet et al. 2013). The area of study holds within a miscellany of drainage patterns; however, dendritic drainage pattern is the most dominant type and occupies more than 95% of the area. Although having a difference in stream lengths and angle of connection, yet they are, in general, characterized by a treelike branching system, which is a dendritic drainage pattern that indicates homogenous and uniform soil and rocks (Way 1978, Saud 2009, Sharma et al. 2010). All the parameters calculated for the watershed are given in Table 5, Table 6, Table 7 and Table 8 and a snapshot of Arc view analysis is given in Fig. 8.

Drainage density (D): Drainage density is a measure of the length of the stream channel per unit area of the drainage basin. Mathematically, it is expressed as $D = \sum L$ (total length of all stream)/A (area of the basin). In this study, the drainage density map was obtained using the digital data from the obtained drainage map. This was accomplished using the GIS system (Arc View software), which is capable of measuring the actual stream lengths and numbers. Therefore, the drainage system was classified into frames of fixed area (5 km × 5 km). This classification relies on the visual density of streams in the area. Hence, the overall length of streams in each frame (25 km^2) was measured using Arc View software.

Drainage frequency (F): A similar mathematical relation to that applied in drainage density and stream frequency was also done by counting the number of streams in a specified area. Taking into consideration, this morphometric relation, several workers used stream frequency rather than drainage density (length density). Therefore, some hydrologic studies consider the density of drainage (Sharma et al. 2010), while others deal with drainage frequency. Stream frequency is expressed by the equation: F = N (number of streams)/A (area of the basin).

Meandering ratio (Mr): It is calculated to indicate the ratio between straight to curved lengths of the primary (major) stream within the drainage system. It shows how the real stream length is larger than the straight one, which is indicative of stage maturity (Chadha & Neupane 2011, Eesterbrooks 1969).

CONCLUSIONS

- This industrial area of Nalagarh is highly prone and vulnerable to surface and groundwater pollution, thus water quality monitoring in a close network is essential.
- Proper waste/effluent disposal measures are required to be adopted by all the industrial units established in the watershed and state authorities need to monitor it vigilantly.
- There is a need to protect, rejuvenate and rehabilitate traditional water harvesting structures like ponds and tanks to use these for rainwater harvesting and recharging shallow aquifers through the rainwater runoff collected through the drainage network in the watershed. It is estimated that it is possible to construct 22500 point recharge structures, 1500 storage/percolation tanks and about 10500 check dams, in order to effectively capture the runoff to be recharged.
- In hilly and mountainous terrain, traditional groundwater

Table 6: Water available for recharge in Baddi of Nalagarh watershed for all micro-watersheds.

S. No.	Name of the class	Area covered (in hectares)	Area covered in square meters	Runoff Coefficient	Average annual rainfall in mm	Intensity of rainfall in meters	Runoff potential (C*I*A) in m^3	MCM
1	Natural vegetation	16442.00	164420004.3	0.1	851	0.851	13992142	13.99214
2	Agriculture	36868.24	368682398.8	0.4	851	0.851	125499489	125.4995
3	Open area	18331.24	183312405.3	0.16	851	0.851	24959817	24.95982
4	Dry river bed	2291.41	22914050.66		851	0.851	0	0
5	Water body	5564.84	55648408.75		851	0.851	0	0
6	Settlement	6902.28	69022732.19	0.5	851	0.851	29369173	29.36917
						Water avai-able for recharge =	193820621	193.8206

Table 7: Different recharge structures for the Nalagarh watershed.

Utilizable runoff (MCM)	Sub-surface barriers	Percolation tanks	Check dam	Point recharge structure
193.8206	640	1500	10500	22500

Table 8: Unit recharge/structure/annum

Conservation structure	Unit recharge/structure/annum
Sub-surface	0.3
Percolation tank	0.2
Check dam	0.03
Point recharge structure	0.02

sources, viz. springs, bowries, etc. need to be developed and protected for better health and hygiene with proper scientific intervention.

- Springs need to be inventoried and studied for optimum utilization of their discharge either by fracturing, horizontal drilling, or by constructing galleries, etc.
- Rooftop rainwater harvesting practices can be adopted in hilly areas and urban areas since the district receives a fair amount of rainfall. Construction of rooftop rainwater harvesting structures should be made mandatory in all new infrastructural, construction projects and rainwater harvesting in rural areas should be promoted.
- Traditional water storage systems are required to be revived.
- People's participation is a must for any type of developmental activities. Proper awareness for utilization and conservation of water resources is needed.

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