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Rainfall Dependence of Springs in the Midwestern Himalayan Hills of Uttarakhand

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One of the most important parameters of the hydrological cycle, precipitation, is directly affected by global warming; as a result, natural spring flow that receives input from rainfall in the midwestern Himalayan hills is affected as well. Spring flow is of prime importance in this area: Springs are the backbone of all of the population's agricultural, social, and financial activities. The deterioration of spring flow results in outmigration and adversely affects the economy of the region. An 11-year study was undertaken of 2 watersheds in Uttarakhand, Chandrabhaga and Danda. These watersheds were observed using 9 automatic rain gauges and 2 river gauging sites. Spring flow measurements were made daily, covering almost all springs used by local inhabitants. A power regression relationship between precipitation and spring flow was developed, with high correlation. The time lag between precipitation and spring flow was investigated for different springs, based on 2 to 11 years of daily data. The springs in Chandrabhaga and Danda watersheds showed a daily measured lag of 1 to 30 days and a monthly measured lag of 0 to 2 months. It was observed that the discharge of springs in Chandrabhaga and Danda watersheds primarily responds to rainfall. Based on an analysis of average water availability, theoretical water demand, and actual water use in the 2 watersheds, we recommend planning for increasing the water retention power of each watershed, using drip irrigation in horticultural crops, and installing water conservation structures to capture rainwater during monsoon months for use during nonmonsoon months.

Keywords: *Spring flow; rainfall; correlation analysis; water availability; water demand; Western Himalaya.*

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Introduction

It is important to understand climatic trends in the Himalaya (Shrestha et al. 1999; Jianchu et al 2007) and their relationship to global trends. Unfortunately, the instrumental meteorological records from high elevations (greater than 4000 m above mean sea level) in the Himalaya are relatively short (Grabs and Pokherel 1992) and therefore provide only limited information on changes in high-elevation climate. Meteorological data from the Tibetan Plateau are also rare. Studies on climatic trends, therefore, have to rely on records from stations south of the Himalaya or outside the Tibetan Plateau.

Mean annual surface air temperatures in India have increased by 0.4°C over the past century (Hingane et al 1985; Dyurgerov 2003). A study of changes in air temperature in Qinghai-Xizang (on the Tibetan Plateau) showed a decreasing trend from 1950 to 1970 and an increase after 1970 (Li and Tang 1986). The direct effect of a global rise in temperature is the redistribution of surface water resources on the earth (Waggoner 1990). Climate change is expected to result not only in changes in temperature but also in a modification of the elements of the hydrologic cycle such as precipitation, evaporation, and runoff (Gleick 1987; Eheart and Tornil 1999; Loáiciga et al 2000).

Hao et al (2006, 2009) studied the response of karst springs to climate change and human activities for the Niangziguan Springs, China, and found that discharge has been declining since the 1950s. The response of springs to climatic change and anthropogenic influence were studied using a model-based discrimination between phases in the stream discharge record. The results show that the contribution of climate change to depletion of Niangziguan Springs is 2.30 m^3/s and the contribution of human activities ranges from 1.89 to 2.90 m^3/s. Karst aquifers at the Liulin springs respond remarkably to climate changes, in particular to changes in precipitation input.

Negi and Joshi (1996, 2004) found that the amount of spring flow during rainy and nonrainy seasons is affected by rainfall and recharge area characteristics. Seasonal springs receded much more rapidly than perennial springs. Valdiya and Bartarya (1991) explained that in the central Himalayas about 8 types of springs are recognized on the basis of the geology, nature of water-bearing formations, and conditions related to their formation.

The highest water-producing rate, about 405×10^3 L/d, was obtained from stream-originating springs, and the lowest, 7.2×10^3 L/d, from colluvium-originating springs (Negi and Joshi 2004). Mean annual spring water yield in the Himalayan region was found to range from 0.72×10^3 56.0×10^3 L/d (Rai et al 1998). Variations in discharge are marked; they follow rainfall and indicate rapid infiltration of rainwater and recharging of the colluvium-originating springs.

In the Himalayan region, mountain springs are the main source of water for drinking and other household purposes and for the habitat of the highlands and lowlands. The discharge from these sources has decreased drastically because of human activities (Negi and Joshi 2002; Valdiya and Bartarya 1991). Climatic change, such as increase in rainfall intensity and reduction in winter rain, could be reasons for the decrease in discharge (Tambe et al 2012). Natural springs emerge at the intersection of sloping ground and impermeable strata with the groundwater table. For the most part, unconfined aquifers are the sources for the springs, where the water emerges under gravitational pull. The behavior of a spring can only be measured and forecast by studying its temporal discharge variation, creating what is commonly known as a spring hydrograph (Vashishth and Sharma 2007).

This paper presents a long-term study of spring flow, its variability, and its relationship to rainfall in 2 watersheds in the Midwestern Himalayan Hills of Uttarakhand, one considered barely water sufficient and the other with distinct water scarcity in terms of the amount of water actually used by the local population and therefore readily available to them. It is the first such long-term study in the region. The lag between rainfall and spring flow was identified in terms of days and months and related to the variability of spring flow. The availability of water through springs was estimated and compared with the demand, in order to come up with recommendations.

Study area

The Himalaya has been longitudinally divided into 6 tectonic zones (Gansser 1974). From south to east these are the Outer (Sub) Himalaya, the Lesser (Lower) Himalaya, the Higher (Great) Himalaya, the Tethys (Tibetan) Himalaya, the Indus Suture Zone, and the Trans Himalaya. This same tectonic scheme is also applicable to the Western Himalaya, except that the Indus Suture Zone and the Trans Himalaya are grouped under one tectonic zone called the Trans Himalaya. Garhwal, in Uttarakhand, is drained almost entirely by the Ganga and its tributaries, which make up the Alaknanda, Ganga, Bhagirathi, and Yamuna drainage systems. Paradoxically, while water is the most abundant resource in the region, at the same time it is the least efficiently utilized and managed resource. Steep gradients with rapid runoff are the major obstacle to productive utilization of water. Subsurface flow from springs has been a traditional source of drinking water in the region. However, with the growing scarcity of groundwater recharge and drying up of the springs, people have to walk downslope significant distances to collect water.

The study area lies in the Western Himalaya in an agro-ecological region characterized by a subhumid ecosystem, with local variations from subhumid to per-humid, at elevations from 720 m to 2350 m (Figure 1). The climate of the study area is warm, with air temperatures of 3°C to 35°C, varying from subhumid to humid, with average annual rainfall of 900 to 1200 mm. There are medium, loamy, brown forest, and podzolic soils, shallow and with low or medium available water content, and deep loamy Terai soils with high available water content. Water deficit is generally low (300–500 mm), and the growing season lasts 180–210 days. Moist, subtropical, pine, and subalpine forest types are present.

The lithology of the study area is of the Chandpur formation (Lesser Himalaya), which Valdiya (1980) has described as "olive green and grey phyllite interbedded and finely inter-banded with meta-silt stone and a very fine grained wackes with local metavolcanics." The rocks are highly weathered and immensely fractured, which helps them to act as a filter that regulates the groundwater paths for springs as a conduit or diffused or a combination of both (Waltham 1972; Tambe et al 2012).

Chandrabhaga watershed is located between latitude 30°18′N and 30°19′N and longitude 78°35′E and 78°36′E. The altitude in this watershed ranges from 1150 to 2350 m above mean sea level. It is a subhumid region with an average annual rainfall of 1200 mm. The total area of the watershed is around 4 km^2. The area is in the Jakhnidhar block of the Tehri-Garhwal district in Uttarakhand and consists of 10 villages: Anjanisain, Badera, Bhainsoli Malli, Bhainsoli Talli, Bhutwara, Dapoli, Kaintholi, Kelan, Migwali, and Saima. Chandrabhaga watershed has many springs.

Danda watershed is located between latitude 30°14′N and 30°16′N and longitude 78°37′E and 78°39′E. The altitude in this watershed ranges from 780 to 1700 m above mean sea level. It is a subhumid region with an average annual rainfall of 900 mm. The total area of the watershed is around 3 km^2. The study area, locally known as Khas Patti, is located in the Hindolakhal Block (Devprayag Tehsil) of the Tehri-Garhwal district. Danda watershed consists of 11 villages: Danda, Centauli, Mayali, Rumdhar, Gajeli, Unnana, Limgad, Tayari, Burkot, Hingolia, and part of Dugyar. The area is known for scarcity of drinking water.

The springs in the area are gravitational fractured springs, which are mainly produced by fractures in the rock and overcropping of the water table at the surface during rain. The geological system allows a rapid to slow transit of water through the aquifer. In rapid flow systems, the aquifers are generally unable to store water for long

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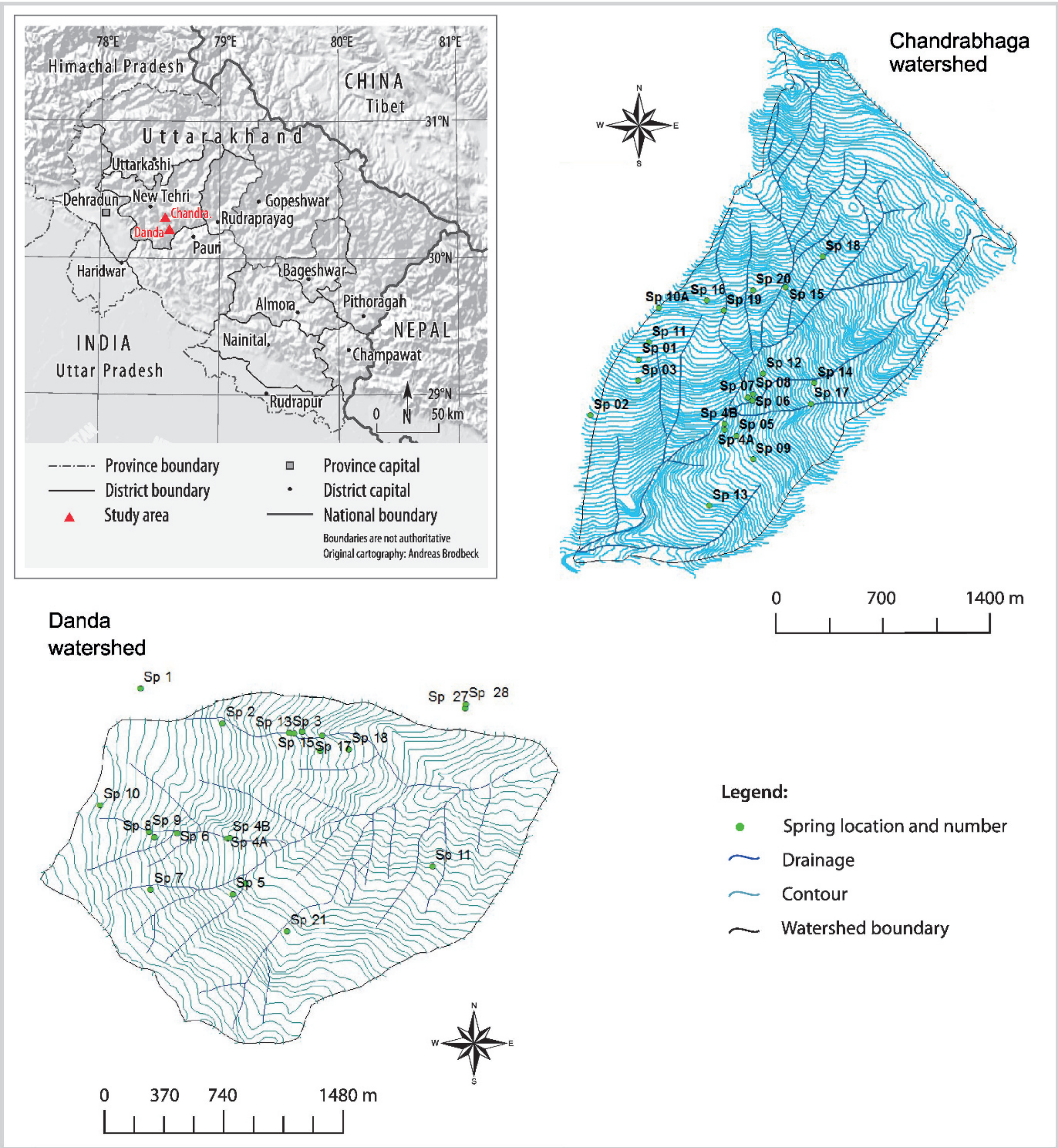
FIGURE 1 Maps of Chandrabhaga and Danda watersheds indicating location of springs. (Map of watersheds by Avinash Agarwal; overview map by *Mountain Research and Development*, based on a map by Andreas Brodbeck)



periods, and the spring hydrograph may have many peaks immediately after rainfall events. In slow flow systems, the aquifer retains water for much longer periods, with less fluctuation in the spring hydrograph (Fiorillo 2009).

The problem of water scarcity is acute in villages near the tops of ridges and in the upper parts of both watersheds. Villages situated near the streams normally get water from the streams or their tributaries. The main water source in the area is the springs. Springs dry up in early summer, as the water-retaining capacity of soils is being degraded by deforestation and thinning of forest cover and/or by a rainfall pattern of increasing high-intensity storms and longer dry spells. In the watersheds under study, some springs are perennial and some are seasonal. Within the area, there are places with sufficient water from springs. If properly managed, water-deficient areas can be supplied with surplus water from more water-rich areas. The location of the springs and their watersheds is shown in Figure 1.

Methodology

Springs in both watersheds were observed from July 1999 to June 2010, and daily spring flow discharge was recorded. As far as possible, all springs in the watersheds were considered for observation, except for 1 or 2 that are located in deep forest and are not easily accessible. In Chandrabhaga watershed, 21 springs were measured. In Danda watershed, 29 springs were initially considered, but because of a permanent interruption of flow in some springs, results were calculated only on the basis of 21 springs.

Measuring rainfall and spring flow

Hydrological variables were measured with automatic recording devices. The collection of data is the first step in planning for managing the natural resources of a watershed. Using an integrated approach based on hydrological instrumentation, investigation, remote sensing, and a geographic information system (GIS), a database containing spatial and nonspatial data for the two watersheds was prepared.

The regression model with a power form equation (spring flow = a * rainfall ^{b}) was used to simulate behavior of the springs (Brutsaert and Nieber 1977). The coefficient "b" is the decay parameter. Rainfall was measured with 4 to 5 automatic rain gauges installed in each watershed. The average amount of rainfall in the watershed was estimated as an arithmetical mean.

The spring flow measurements were manually recorded by measuring the time taken for a specific amount of water to come out of the spring. During the high-flow season in monsoon months, the quantity was 5 L, and in nonmonsoon months, the amount was reduced to 1 L; the flow rates were estimated accordingly. Since the springs are distributed throughout the watersheds, the measurements were taken every 2 or 3 days in both Chandrabhaga and Danda watersheds.

Measuring theoretical water demand and actual water use

A plan to provide water for household purposes can only be based on reliable sources of water. Springs are the only dependable water source in the two watersheds; all other sources are uncertain. Thus, availability of spring water determines the adequacy of water availability to the people of the watershed, especially for their domestic needs. Thus, a detailed survey of the watershed was carried out. The position of dependable springs was recorded using a global positioning system (GPS) device.

Theoretical domestic water requirements were estimated through a count of the human and animal population multiplied by standard norms of water use (45 L/d for adults, 25 L/d for minors, 10 L/d for large animals, and 5 L/d for small animals; BIS 1993). Actual domestic water use information was recorded based on answers by each family to a survey. Information regarding use of water for other purposes was also provided by each family and was added to actual domestic water use. Individual information on theoretical requirements and actual domestic water use per family was grouped first by spring and then by watershed.

Results and discussion

Springs in both watersheds are a major source of water when rainwater is unavailable. From 11 years of daily spring flow records, it can be seen that nearly all the springs monitored in the watershed flow throughout the year.

Spring flow analysis

The daily recorded discharges of the highest yielding springs in Chandrabhaga and Danda watersheds are shown in Figure 2, along with mean rainfall. The spring response to monsoon rainfall can easily be identified. This response slowly diminishes during the nonmonsoon period. The immediate response of a spring to rainfall suggests that the recharge area is in close vicinity to the spring and recharge is due only to rainfall.

Maximum, minimum, and average monthly flow information was extracted for each spring from the daily flow data to understand spring flow behavior (Tables 1 and 2). The maximum spring flow in Chandrabhaga springs varied from 0.167 to 2.703 L/s, indicating that springs had variable flow. The variation in minimum flow was from 0 to 0.022 L/s. A low variation in minimum flow suggests that all the springs of the area drain to a lowest level and the flow nearly reaches interruption or seizure. Even spring number 3, which had a high flow after rain, dropped to a minimum flow of 0.007 L/s, suggesting that it is a fast responding spring.

The maximum flow of Danda springs varied from 0.250 to 5.00 L/s and the minimum from 0.002 to 0.125 L/s. Thus, the maximum flow of Danda springs is higher than that of Chandrabhaga springs, while the minimum flow is almost the same. This suggests that the Danda springs are also fast responding springs with a higher average flow than Chandrabhaga springs.

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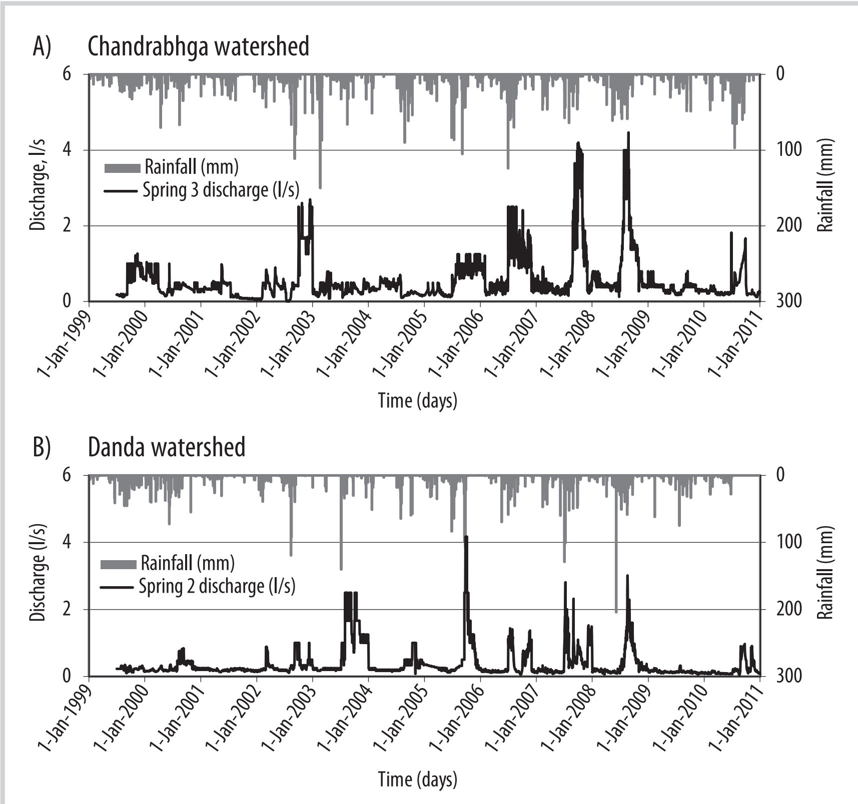
FIGURE 2 Daily discharge hydrograph for spring number 3 of Chandrabhaga and spring number 2 of Danda watershed.



The average annual volume of water in springs, estimated from the daily recorded values, is 21.29 mm for Chandrabhaga and 37.93 mm for Danda watersheds. The higher volume of the Danda springs suggests that the infiltration and transmissivity of the Danda aquifer is higher than that of the Chandrabhaga watershed. Overall the watershed has high infiltration with low storage capacity and high transmissivity. For a comparison, the average volume of water measured at the outlet of the V-notch installed for stream flow measurement was 189.39 mm, and average rainfall was 1067 mm for Chandrabhaga; for Danda, it was 278.4 and 742 mm, respectively.

Spring flow and rainfall regression analysis

Based on 2 to 11 years of daily data depending on the spring, monthly means were estimated. The relationships between rainfall and spring flow were analyzed for Chandrabhaga and Danda springs based on monsoon, nonmonsoon, and yearly periods. The correlation coefficient was rarely above 0.64 for monsoon, nonmonsoon, and annual rainfall–spring flow regression. In order to account for the delayed response and nonlinear behavior of the watershed between the 2 variables, the relationships were analyzed on a water year basis by considering cumulative mean monthly rainfall (mm) and respective cumulative stream flow values (L/s) from June to May. The correlations so obtained were too high. The correlation results are reported in Table 3. The values of r^2 were never below 0.90, which suggests a very high correlation between the variables.

Cumulative spring flow and cumulative rainfall for 5 springs in Chandrabhaga and Danda watersheds are presented in Figure 3. It can be seen that the cumulative spring flow indicated a linear response to cumulative rainfall for the period from June to September. A nonlinear response from September to January was evidenced, possibly because there was too little rainfall in the nonmonsoon period. From January to February, the spring again showed a linear response, as the watershed received winter rain during this period. The period from February to May was dry, and the spring response was again nonlinear. Similar behavior was observed with the springs of Danda.

From the study of spring flow behavior (see next section for details), a year could be divided into two distinct periods, June to September and September to May. Regression equations could be developed for these 2 periods separately and an improved understanding of the relationship between the cumulative rainfall and cumulative spring flow can thus be achieved.

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TABLE 1 Discharge characteristics and flow of springs in Chandrabhaga watershed.[a)]

Spring		Maximum flow (L/s)	Minimum flow (L/s)	Average flow (L/s)	Volume/year (m^3)
No.	Location				
1	Dapoli	0.900	0.006	0.091	3002
2	Badara	0.833	0.006	0.122	4120
3	Kailan	2.700	0.007	0.495	17,005
4A	Bainsoli	1.250	0.006	0.221	6541
4B	Bainsoli	1.250	0.012	0.182	5271
5	Bainsoli	0.900	0.002	0.068	2121
6	Bainsoli	1.000	0.004	0.136	3920
7	Bainsoli	1.690	0.002	0.187	4499
8	Bainsoli	0.386	0.003	0.050	883
9	Bainsoli	1.250	0.002	0.244	7240
10A	Hosp. Anj	0.833	0.003	0.131	3909
11	Bainsoli	0.556	0.001	0.054	1628
12	Bainsoli	0.167	0.004	0.027	531
13	Bainsoli	1.250	0.009	0.278	9316
14	Kaintholi	1.754	Nil	0.140	4734
15	Min Danda	2.959	0.006	0.268	7831
16	Bhatwara	0.900	0.004	0.090	2745
17	Kaintholi	1.667	0.012	0.190	4254
18	Min Danda	2.193	0.008	0.104	2846
19	Anjanisain	2.703	0.022	0.293	NA
20	Anjanisain	2.500	0.004	0.129	NA

[a)]No. = spring number.

Characteristics of rainfall to spring flow lags

The lags between rainfall and spring flow were identified based on daily and monthly data. Different springs in Chandrabhaga showed lags of 1 to 30 days, with an increase in correlation from 0.01 to 0.31, and in Danda from 0 to 2 months, with an increase in correlation from 0.01 to 0.64 (*Supplemental data*, Tables S1 and S2; http://dx.doi.org/10.1659/MRD-JOURNAL-D-12-00054.S1). A comparison between maximum spring flow and lags in days suggests no relation between the 2. A rapid increase of the rainfall–spring flow correlation with lag in days indicates that the springs are sensitive to rainfall and have low storage and retention capacity. No relationship between spring flow and a grouping formed on the basis of flow conditions could be established.

Increase in spring–rainfall correlation and lag for different springs were identified for both watersheds (Figure 4). It can be seen that, for both watersheds, the ratio of minimum to maximum correlation decreases with increase in time lag. The exponential decay function was applied between the variables with the following results:

$$y(\text{Chand}) = 0.8764e - 0.0232x \quad r^2 = 0.4985, \tag{1}$$

$$y(\text{Danda}) = 0.7314e - 0.0432x \quad r^2 = 0.5132, \tag{2}$$

where y is minimum/maximum spring–rainfall lag correlation and x is the lag in days. The correlation between the 2 parameters, however, does not confirm the relationship but certainly reflects the behavior of the variables. This behavior supports the idea that an increase in time lag decreases the minimum/maximum ratio, reflecting that the variability of spring flow decreases. This correlation ratio could be an indicator for identifying improvement and decay of springs in a watershed.

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TABLE 2 Discharge characteristics and flow of springs in Danda watershed.[a)]

Spring No.	Spring Place	Maximum flow (L/s)	Minimum flow (L/s)	Average flow (L/s)	Volume/year (m^3)
1	Danda	5.000	0.037	0.303	11,031
2	Gurali	5.000	0.055	0.409	13,542
3	Rumdhar	2.242	0.035	0.173	7016
4A	Tyari	5.000	0.015	0.319	13,194
4B	Tyari	0.250	Nil	0.061	2134
5	Burkot	2.500	0.039	0.429	14,794
6	Rupado	0.794	0.003	0.074	2936
7	Mayali	1.168	0.004	0.130	6241
8	Mayali	2.500	0.009	0.114	4151
9	Mayali	2.500	0.003	0.254	10,613
10	Kanpala khal	0.318	0.002	0.027	1328
11	Gajeli	1.667	0.025	0.161	6246
13	Rumdhar	Interrupted flow			4839
15	Rumdhar	0.597	0.011	0.102	3422
16	Rumdhar	0.986	0.007	0.128	3184
17	Rumdhar	0.500	0.008	0.093	3104
18	Rumdhar	Interrupted flow			2518
20	Burkat	1.667	0.019	0.293	10,777
21	Burkat	Interrupted flow			5301
27	Dugiyar	1.389	0.125	0.512	19,823
28	Dugiyar	2.500	0.100	0.612	21,474

[a)]No. = spring number.

The springs were classified on the basis of their flow into 3 groups:

(1) Springs with continuous flow
(2) Springs with interrupted flow
(3) Dead springs or springs that dried up very frequently.

The springs in the third category are those affected by construction, road widening, or other development in the vicinity; they did not dry up naturally. The springs with continuous flow and interrupted flow were approximately equal in number. The springs with interrupted flow indicated an initial higher correlation compared to the continuous flowing springs for Chandrabhaga, but not for Danda.

Domestic water availability and requirements

Theoretical domestic water requirements in Chandrabhaga watershed, which has a population of 364 men, 527 women, 671 children, and 409 animals, is 29,180 L/d. In comparison, actual domestic water use is 21,504 L/d. Thus, actual domestic water use is less than theoretical domestic water requirements (74%). Similar trends in water demand and use were observed for each spring.

The minimum monthly spring flow available for use was 27,932 L/d, which falls between theoretical domestic water requirements (29,180 L/d) and actual domestic water use (21,504 L/d). This suggests that on average the springs under minimum flow conditions are able to meet domestic water use but not theoretical water requirements. It is essential to carry out spring-by-spring analysis to identify the stress on springs. A similar trend was observed individually almost for all the springs. The average monthly spring flow availability was 266,782 L/d, around 9 times the minimum monthly spring water available and is higher than what is needed to meet requirements.

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TABLE 3 Relationship between rainfall and spring flow in Chandrabhaga and Danda watersheds.[a)]

SN	Chandrabhaga springs			Danda springs		
	No.	$Sp = a * Ra^{b}$	Corr., r^2	No.	$Sp = a * Ra^{b}$	Corr., r^2
1	1	$Sp = 0.0213 * Ra^{1.0333}$	0.9087	1	$Sp = 0.0018 * Ra^{1.6823}$	0.9590
2	2	$Sp = 0.0243 * Ra^{1.0572}$	0.8860	2	$Sp = 0.0025 * Ra^{1.6572}$	0.9353
3	3	$Sp = 0.0035 * Ra^{1.2284}$	0.9268	3	$Sp = 0.0017 * Ra^{1.6193}$	0.9730
4	4A	$Sp = 0.0115 * Ra^{1.2584}$	0.9648	4A	$Sp = 0.0009 * Ra^{1.8242}$	0.9881
5	4B	$Sp = 0.0045 * Ra^{1.3842}$	0.9928	4B	$Sp = 0.0004 * Ra^{1.6743}$	0.9781
6	5	$Sp = 0.0024 * Ra^{1.3312}$	0.9840	5	$Sp = 0.0004 * Ra^{1.9455}$	0.9585
7	6	$Sp = 0.0177 * Ra^{1.0954}$	0.8806	6	$Sp = 0.0006 * Ra^{1.6764}$	0.9768
8	7	$Sp = 0.0003 * Ra^{1.7689}$	0.9758	7	$Sp = 0.0004 * Ra^{1.8666}$	0.9769
9	8	$Sp = 0.00009 * Ra^{1.6948}$	0.9936	8	$Sp = 0.00001 * Ra^{2.3208}$	0.9670
10	9	$Sp = 0.0163 * Ra^{1.2112}$	0.9380	9	$Sp = 0.0009 * Ra^{1.8092}$	0.9805
11	10A	$Sp = 0.0025 * Ra^{1.4069}$	0.9537	10	$Sp = 0.0004 * Ra^{1.5668}$	0.8668
12	11	$Sp = 0.0006 * Ra^{1.5041}$	0.9751	11	$Sp = 0.0053 * Ra^{1.4163}$	0.9578
13	12	$Sp = 0.0002 * Ra^{1.5057}$	0.9577	13	$Sp = 0.020 * Ra^{1.1539}$	0.9721
14	13	$Sp = 0.0073 * Ra^{1.3827}$	0.9796	15	$Sp = 0.0004 * Ra^{1.7150}$	0.9831
15	14	$Sp = 0.0043 * Ra^{1.3607}$	0.9814	16	$Sp = 0.0028 * Ra^{1.4048}$	0.9594
16	15	$Sp = 0.0077 * Ra^{1.3499}$	0.9750	17	$Sp = 0.00006 * Ra^{2.0071}$	0.9878
17	16	$Sp = 0.0098 * Ra^{1.1461}$	0.9457	18	$Sp = 0.0015 * Ra^{1.5036}$	0.9801
18	17	$Sp = 0.0119 * Ra^{1.2059}$	0.9967	20	$Sp = 0.0002 * Ra^{2.0129}$	0.9893
19	18	$Sp = 0.0019 * Ra^{1.4251}$	0.9926	21	$Sp = 0.00009 * Ra^{2.0400}$	0.9870
20	19	Equation not possible		27	$Sp = 0.0016 * Ra^{1.7821}$	0.9498
21	20	Equation not possible		28	$Sp = 0.0004 * Ra^{2.0337}$	0.9902

[a)]Ra = rainfall; SN = serial number; Sp = spring flow; No. = spring number in Table 1 or 2.

The theoretical domestic water requirement in Danda watershed, which has a population of 427 men, 377 women, 472 children, and 367 animals, is 47,460 L/d—compared to actual domestic water use of 14,725 L/d. This is only around one third of the theoretical domestic water requirement. This reflects the population's living conditions and difficulty in acquiring water.

A similar trend of water use was observed for each spring in Danda. The minimum monthly flow availability of all springs in use was 36,201 L/d, double the actual water use of 14,725 L/d but less than the theoretical domestic water requirement. This indicates that water availability, even under lowest condition of flow, is meeting the domestic water use. The average monthly spring flow availability is 262,056 L/d, around 7 times the minimum monthly spring water availability, and is higher than what is used in the current, very self-restricted water consumption.

Conclusions

Springs are the principal source of water for domestic use in Uttarakhand. There is a high variability between minimum and maximum spring flow in the study area, indicating that the springs respond quickly to rainfall. A power relationship exists between cumulative rainfall and cumulative spring flow. Daily data from Chandrabhaga and Danda indicate a lag between rainfall and spring flow of 1 to 30 days, with an increase in correlation up to a maximum of 0.31; based on a monthly analysis, the lag was from 0 to 2 months with an increase in correlation up to maximum of 0.64. It can be seen, for both watersheds, that the ratio of minimum to maximum correlation decreases with increase in time lag in days. Thus it appears that an increase in time lag decreases the correlation ratio, which could be an indicator for identifying improvement or decay of springs in a watershed.

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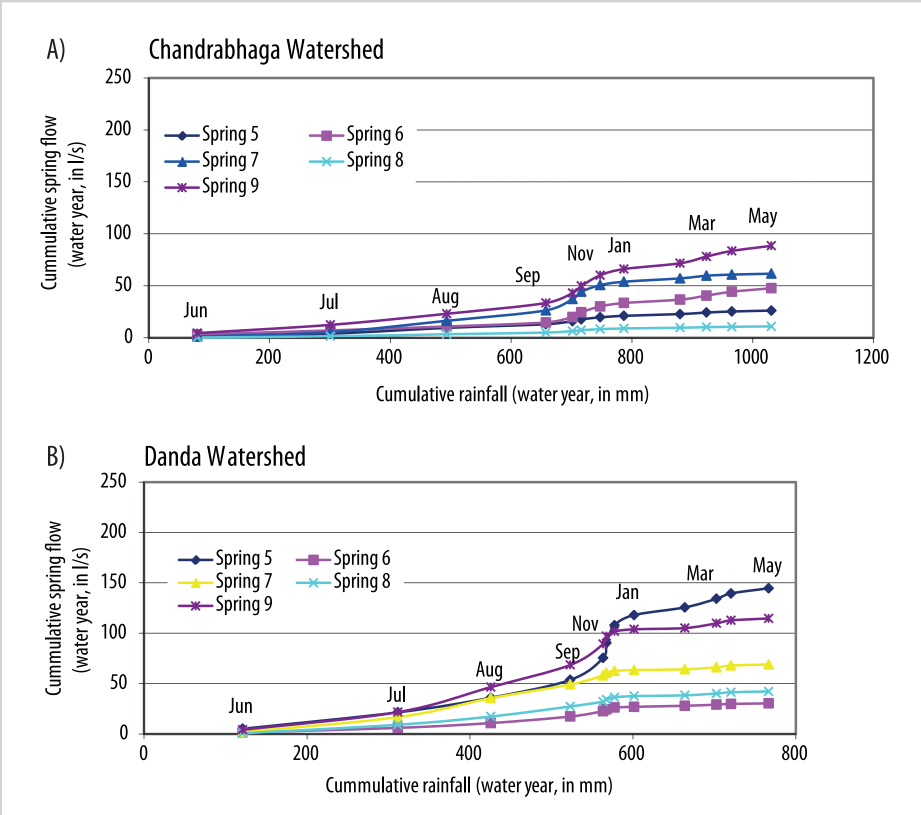
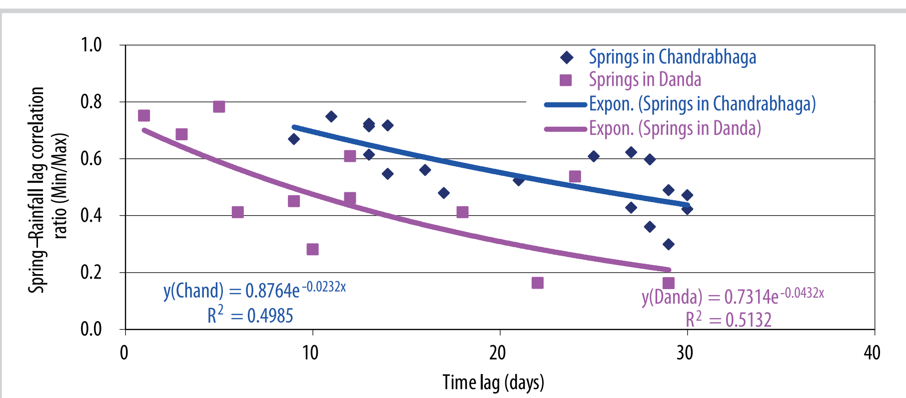
FIGURE 3 (A) Relationship between cumulative rainfall and cumulative spring flow for five springs in Chandrabhaga watershed. (B) Relationship between cumulative rainfall and cumulative spring flow for 5 springs in Danda watershed.



The theoretical domestic water requirement in Chandrabhaga watershed was slightly higher than actual water use, whereas the theoretical requirement for Danda watershed was three times higher than actual water use. Water storage structures could store excess spring flow after rainfall periods to make up for the water deficit during nonmonsoon months. Planning of proper storage and management of spring water is highly recommended, along with a system to transfer water based on existing social laws, from excess areas to shortage areas, through gravity flow or by pumping, whenever required by seasonal shortages. Water harvesting structures could be installed to store rainwater in monsoon months in order to increase the

FIGURE 4 Relationship between ration (spring-rainfall lag correlation, Min/Max) ratio and lag (days) for watersheds. This relationship defines the variability of spring flow; stable springs have low variability and high time lag.



flow in selected springs. Efficient drip irrigation is also strongly recommended with horticultural crops, in order to maximize the use of limited spring water.

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Supplemental data

TABLE S1 Duration of data collection, elevation, and time lags between rainfall and spring flow for the springs in Chandrabhaga watershed.

TABLE S2 Duration of data collection, elevation, and time lags between rainfall and spring flow for the springs in Danda watershed.

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