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*Full Length Research Paper*

# Hydrology, geomorphology and Rosgen classification of Doodhganga stream in Kashmir Himalaya, India

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**Hydrology and geomorphology of streams determine their physical state which in turn regulates the chemical and biological setup of these ecosystems. In the present study the hydrology and geomorphology of Doodhganga stream, which is one of the principle tributaries to the River Jhelum in the Valley of Kashmir (northern India), was worked out. Applicability of Rosgen stream classification, an important morphological classification of rivers, was tested so that consistent, reproducible and quantitative descriptions can be made. The flow velocity and discharge, worked out for the time period of January 2005 to December 2006 during base flow/low flow conditions, decreased downstream and there was an abnormal decrease in both these parameters in the middle stretches because of diversion of water for agricultural purposes and also because of extraction for drinking water facilities. On a temporal scale the spring (March to May) and summer (June to August) months maintained higher flow and discharge values while the autumn (September to November) and winter (December to February) months maintained low values for these parameters. The stream belongs to order 5 and has steep channel (0.0443 m/m) and basin (0.0423 m/m) slopes and moderate stream channel sinuosity (1.35 m/m). The different study reaches fell into different Rosgen stream classes and in general the Rosgen stream classification applied very suitably. At stretches where the predictions of the Rosgen classification were not followed, the anthropogenic influences were seen to be the major contributors for causing the deviations from the natural structure of the stream.**

**Key words:** Base flow, flow velocity, sinuosity, discharge, Rosgen classification, Doodhganga stream.

## INTRODUCTION

Kashmir Himalaya, which is well known world over for its freshwater resources viz., streams, rivers, lakes, wetlands, springs etc. has seen of late deterioration in its precious water resources. The general paucity of scientific studies, particularly on the hydrological and geomorphological attributes of lotic systems, has made the prospect of understanding the behaviour of these ecosystems a very difficult proposition which in turn has made their scientific management an impossibility.

The present study has been conducted on “Doodhganga Stream” which is one of the principal tributaries to the River Jhelum in the Valley of Kashmir (northern India). An attempt has been made to understand the flow dynamics of the stream during base flow/low flow conditions and also the basic geomorphological parameters have been worked out. Researchers have for long used different features to classify streams. Davis (1899) first divided streams into three classes based on relative stage of adjustment: youthful, mature, and old age. Straight, meandering and braided patterns were described by Leopold and Wolman (1957). Many other workers have used different characteristics to classify streams (Khan, 1971; Schumm, 1977; Lotspeich, 1980; Lotspeich and Platts, 1982; Whiting and Bradley, 1993; Rosgen 1994, 1996; Montgomery and Buffington, 1997). The Rosgen stream classification (Rosgen, 1994) categorizes streams according to channel morphology so that consistent, reproducible and quantitative descriptions can be made. Through field measurements, variations in stream processes are grouped into distinct stream types. This classification has become the most widely applied stream

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classification system in the United States (Juracek and Fitzpatrick, 2003), having been adopted by hydrologists, engineers, geomorphologists, and biologists (Sullivan et al., 2004). This system is designed to predict a river's behaviour from its appearance, develop specific hydraulic and sediment relations for a given morphological channel type and state, provide a mechanism to extrapolate site-specific data collected on a given stream reach to those of similar character, and provide a consistent and reproducible frame of reference of communication. The measurements in Rosgen's system are based on bankfull discharge dimensions and the system places various physical, measurable geomorphic attributes into a hierarchal order. The classification hierarchy is: 1) Single or multiple threaded channels (three or more channels at bankfull), 2) Entrenchment ratio (defined as the flood-prone width divided by the bankfull width), 3) Width to depth ratio, 4) Sinuosity, 5) Slope ranges, and 6) Channel material. An attempt was made in this study to analyse the hydrological dynamics of Doodhganga stream in the Himalayan mountainous geomorphological settings. The applicability of Rosgen stream classification was tested so that reproducible and comparable results can be obtained for better understanding of the lotic systems in this part of the world.

## STUDY AREA

Kashmir valley lies between 33° 20' and 34° 54'N latitudes and 73° 55' and 75° 35'E longitudes and covers an area of 15,948 km$^2$. Topographically, it is a deep elliptical bowl-shaped valley bounded by the lofty mountains of the Pir-Panjal Range in the South and South-West and the Greater Himalayan Range in the North and East, with 64% of the total area being mountainous. The valley is an asymmetrical fertile basin, stretching from South-East to North-Westerly direction. Its diagonal length (from South-East to North-West corner) is 187 km, while the breadth varies considerably, being 115.6 km along the latitude of Srinagar. The altitude of the valley floor at Srinagar, the capital city, is 1,600 m a.s.l. and the highest peak among its surrounding mountains is that of the Kolahoi or 'Gwashibror' with a height of 5,420 m. Traversing the valley is the River Jhelum and its tributaries. The Jhelum (also called Vitasta/Vyeth) has been and continues to be the key element of the ecosystem of Kashmir (Raza et al., 1978). The shielded valley of Kashmir is characterized by distinct orographic features and snow clad peaks and resembles the mountainous and continental parts of the temperate latitudes. Thus, the Valley of Kashmir has a continental climate marked by well defined seasonality. The average rainfall at Srinagar during the two year study period of January 2005 to December 2006 was obtained to be 785.7 mm per annum with most of the precipitation occurring in the form of snow during December to March (Indian Meteorological Department, Srinagar).

Doodhganga stream takes its origin on the eastern slopes of the Pir Panjal mountain range of Himalaya below the Tatakuti peak which is at an altitude of more than 4500 m a.s.l. The source waters of the stream in the upper reaches are the snow fields, springs and a number of smaller lakes. The surface geology in the study area is dominated by sand/clay beds with lower floodplain reaches having accumulation of sand and silt mixed with clay. The Doodhganga drainage basin has extremely steep slopes of more than 70% restricted to the upper reaches which are generally snow covered. These slopes are followed by comparatively lesser steep slopes of 60 to 70% which reflect the different aspects of mainly the Karewa formations (plateau-like features developed in thick accumulations of the Pleistocene glacial moraines) in the middle parts of the study area. Downhill sides of these Karewa formations are characterized by moderate slopes which cover the major proportion of the middle reaches of the study area. The downstream catchment area and the flat table lands on the Karewa formations are under nearly level to level slopes (0-1%) (Hussain, 2011). A description of the study sites (Figure 1) is given:

**Site 1:** It was located just outside the Branwar forest area close to the Branwar village (33° 53' 18.6''N and 74° 40' 45.6''E) at an altitude of 2015 m a.s.l.

**Site 2:** The location of this site was in the area just before the entrance of the stream into the main Chadora town (33° 56' 34.2''N and 74° 47' 39.7''E) at an altitude of 1629 m a.s.l. Extraction of sand and boulders from the stream bed and banks was a constant activity in this area.

**Site 3:** It was located at Wathora village on Doodhganga stream before its confluence with the Shaliganga stream (33° 58' 17.9''N and 74° 48' 35.2''E) at an altitude of 1596 m a.s.l.

**Site 4:** It was located at Wathora village on Shaliganga stream (33° 58' 19.7''N and 74° 48' 34.1''E) which is the major contributor of water to the Doodhganga stream in the area. The altitude of the site was 1600 m a.s.l

**Site 5:** It was located in Kral Pora town (33° 59' 21.4''N and 74° 48' 44.9''E) before the place where from the Doodhganga drinking water treatment plant draws water from the stream. The altitude at the site was 1598 m a.s.l.

**Site 6:** It was located at a place called Natipora (34° 02' 43.4''N and 74° 48' 32.2''E) at an altitude of 1593 m a.s.l. The immediate catchment of the stream in this area is densely populated.

**Site 7:** It was located in Bemina city area (34° 04' 10.0''N and 74° 45' 51.5''E) at an altitude of 1595 m a.s.l. before the place where the stream empties itself in to the flood spill channel, which in turn feeds water to the Hokarsar wetland, a Ramsar site of international fame.

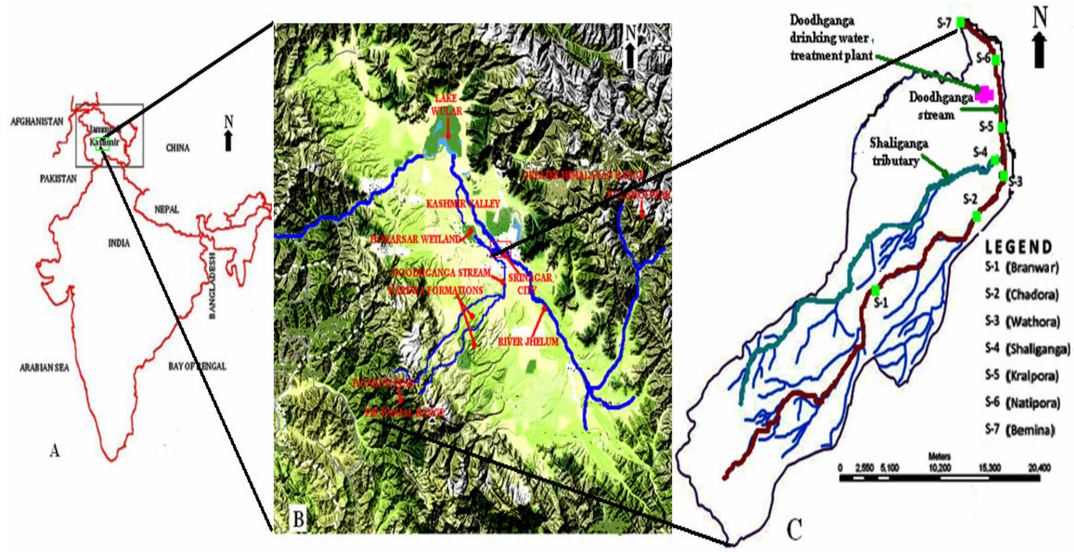


**Figure 1.** (A) Location map of Jammu and Kashmir (United Nations, 2005); (B) Terrain map of Kashmir region. (Google maps), and (C) Map of Doodhganga drainage basin showing location of study sites.

## MATERIALS AND METHODS

### Hydrology

The two important hydrological parameters of the Doodhganga stream viz., flow velocity and discharge were determined on a monthly basis during January 2005 to December 2006 and readings were taken only during base flow/low flow conditions. In case of rains a gap of at least two days was kept between the cessation of rain and recordings. Flow velocity in the stream was determined by using the float method in which a correction factor of 0.8 was used for rough beds while a correction factor of 0.9 was used for smooth beds (Hynes, 1970; Hauer and Lamberti, 1996). Discharge was estimated by obtaining cross-section surfaces by multiplying the hydraulic depth at each site and the width at the water level and then the resulting values were multiplied by flow velocity values (Strahler, 1964; Hynes, 1970; Hauer and Lamberti, 1996; Wetzel and Likens, 2000).

### Basin and channel geomorphological characteristics

In order to evaluate some of the basin and channel geomorphological characteristics of the Doodhganga stream, field as well as geographical information system (GIS) techniques were employed. For GIS/remote sensing techniques a 15 m resolution Landsat Enhanced Thematic Mapper (+) imagery dated 24th October, 2004 and software packages namely ERDAS imagine 8.7, Arc GIS 9.0, ILWIS 3.2, Arc View 3.2 and ENVI 4.0 and Microsoft Excel were used for data processing and analysis. The morphometrical characteristics namely basin area, basin length, basin width, basin perimeter, basin shape, main channel length, main channel slope, basin land slop, sinuosity and stream order were evaluated. Basin area was delineated in the first place by following the watershed map (1983) of the Doodhganga watershed as prepared by the directorate of soil conservation of the government of Jammu and Kashmir. Then extensive ground truthing was carried out to ascertain the present course of the stream and accordingly the basin area was calculated. It is pertinent to mention that the course of the stream in the lower stretches has been changed by constructing a flood spill channel. Stream order was determined following the Horton-Strahler stream order classification system (Strahler, 1957).

### Rosgen stream classification

Rosgen stream classification system level II (Rosgen, 1994) was used to characterize individual study sites (reaches). The parameters namely single or braided channel determination, entrenchment ratio, width-to-depth ratio, sinuosity, water-surface slope and median size of the bed material were obtained using standard methodology (Wolman, 1954; Harrelson et al., 1994; Rosgen, 1994, 1996 and 1998).

## RESULTS

### Flow velocity

The flow velocity of the stream water was highly variable during the different months of the study period (January 2005 to December 2006) emphasizing the dynamic nature of the stream, and ranged between 0.05 m $S^{-1}$ recorded at Site 2 in January 2005 and 2.07 m $S^{-1}$ recorded at Site 1 in April 2005. April 2005 recorded the highest flow velocity at sites 1 and 2 while it was recorded in April 2006 at sites 4, 5 and 7. The maximum flow velocity at Site 6 was recorded in March 2005. Spring season recorded the highest average flow velocity at all the study stations except at Site 6 where it was recorded for summer and autumn seasons. Downstream the average flow velocity showed a gradual decrease with the Site 1 recording the highest monthly average flow velocity of 1.01 m $S^{-1}$ while Site 7 recorded the lowest monthly average flow velocity of 0.12 m $S^{-1}$. In

**Table 1.** Monthly averages with standard deviations in parentheses, ranges and seasonal averages of flow velocity (m $S^{-1}$) at different study sites during study period of January 2005 to December 2006.

| Statistic | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 |
|---|---|---|---|---|---|---|---|
| Average | 1.01 | 0.62 | 0.56 | 0.37 | 0.23 | 0.18 | 0.12 |
| (SD) | (0.78) | (0.39) | (0.14) | (0.10) | (0.04) | (0.05) | (0.01) |
| Range | 0.06-2.07 | 0.05-1.23 | 0.31-0.74 | 0.19-0.52 | 0.15-0.28 | 0.13-0.31 | 0.08-0.14 |
| Winter average | 0.20 | 0.16 | 0.42 | 0.39 | 0.21 | 0.16 | 0.11 |
| Spring average | 1.92 | 1.07 | 0.68 | 0.44 | 0.25 | 0.15 | 0.13 |
| Summer average | 1.49 | 0.85 | 0.68 | 0.29 | 0.25 | 0.21 | 0.12 |
| Autumn average | 0.41 | 0.40 | 0.45 | 0.36 | 0.21 | 0.21 | 0.11 |

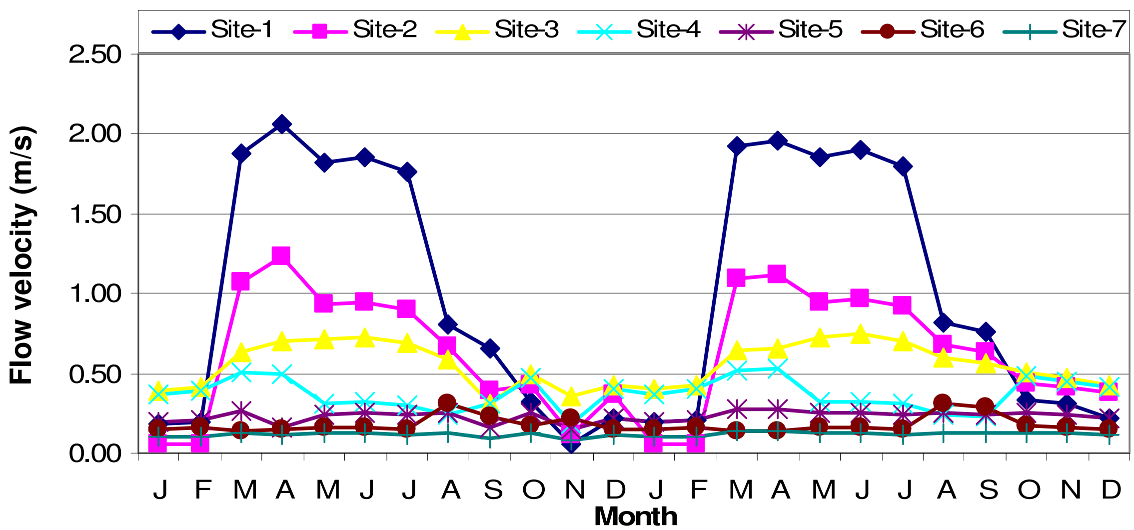


**Figure 2.** Temporal variations of flow velocity (m $S^{-1}$) at different study sites during study period of January 2005 to December 2006.

general the flow velocities peaked in spring and summer months and attained lows in the late autumn and winter months (Table 1 and Figure 2).

## Discharge

Discharge again was a highly variable hydrological parameter. It ranged from the lowest value of 0.06 $m^3 S^{-1}$ recorded at Site 2 in January and February of both 2005 and 2006 and the highest value of 8.61 $m^3 S^{-1}$ recorded at Site 1 in April 2005. The discharge in the stream peaked in spring and summer months while receded to lows in the late autumn and winter months. Seasonally spring recorded the highest average discharge at sites 1, 2, 3, 4 and 7 while it was recorded in summer for Site 5 and in autumn for Site 6. Spring and summer seasons recorded exceptionally high discharge at Site 1 as compared to other sites. Spatially in a downstream gradient Site 1 recorded conspicuously high average discharge which was appreciably decreased at Site 2. The average discharge at Site 3 in the Doodhganga stream improved a little and by the contribution of Shaliganga stream (Site 4) showed an enhancement at Site 5. The average discharge again declined at Site 6 and then showed an increase at Site 7 (Table 2 and Figure 3).

## Basin and stream geomorphological characteristics

The total basin area of Doodhganga stream was found to be 494.20 $km^2$. The basin length was found to be 46.41 km, the basin average width as 10.65 km, the main channel length as 62.62 km and the perimeter of the basin was obtained to be 135.65 km. The numerical value for the basin shape was obtained to be 4.36. The main stream channel slope was quite steep with a value of 0.0443 m/m as also was the case with basin land slope with a value of 0.0423 m/m. The stream depicted moderate sinuosity with a value of 1.35 m/m (Table 3).

**Table 2.** Monthly averages with standard deviations in parentheses, ranges and seasonal average of discharge ($m^3$ $S^{-1}$) at different study sites during study period of January 2005 to December 2006.

| Statistic | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 |
|---|---|---|---|---|---|---|---|
| Average | 4.19 | 0.67 | 1.29 | 0.75 | 1.64 | 0.82 | 1.48 |
| (SD) | (3.27) | (0.42) | (0.32) | (0.20) | (0.27) | (0.24) | (0.17) |
| Range | 0.26-8.61 | 0.06-1.32 | 0.72-1.73 | 0.38-1.07 | 1.06-2.00 | 0.61-1.42 | 1.06-1.71 |
| Winter average | 0.85 | 0.17 | 0.97 | 0.80 | 1.47 | 0.71 | 1.33 |
| Spring average | 7.99 | 1.15 | 1.58 | 0.91 | 1.77 | 0.66 | 1.60 |
| Summer average | 6.21 | 0.91 | 1.58 | 0.59 | 1.79 | 0.94 | 1.56 |
| Autumn average | 1.70 | 0.43 | 1.04 | 0.73 | 1.53 | 0.96 | 1.42 |

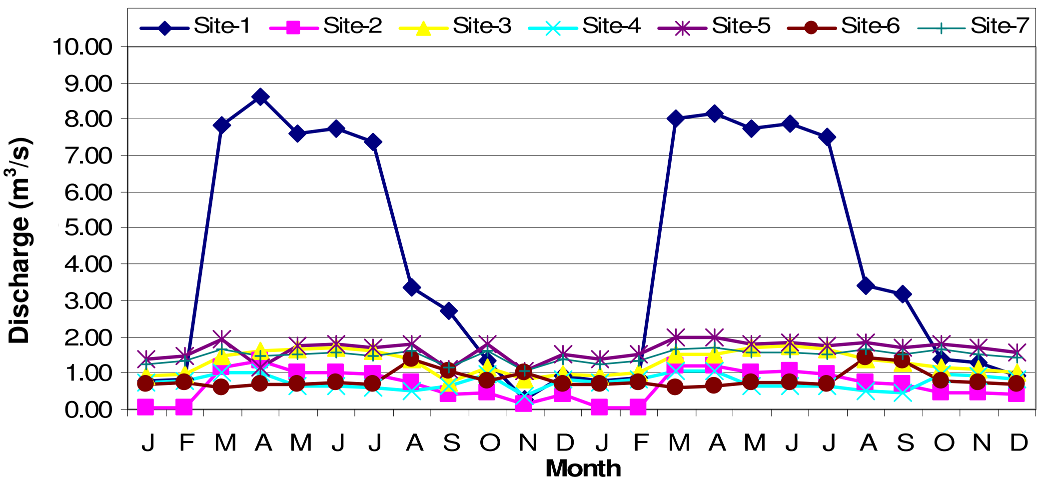


**Figure 3.** Temporal variations of discharge ($m^3$ $S^{-1}$) at different study sites during study period of January 2005 to December 2006.

**Table 3.** Doodhganga drainage basin and stream channel geomorphological characteristics.

| Basin/ Channel characteristic | Value |
|---|---|
| Basin area ($km^2$) | 494.20 |
| Basin length (km) | 46.41 |
| Basin width (km) | 10.65 |
| Basin perimeter (km) | 135.65 |
| Basin shape (dimensionless) | 4.36 |
| Main channel length (km) | 62.62 |
| Main channel slope (m/m) | 0.0443 |
| Basin land slope (m/m) | 0.0423 |
| Sinuosity (m/m) | 1.35 |

## Rosgen stream classification

Rosgen stream classification level II (morphological description) was used at the study site (reach) level and it was obtained that the different study sites (study reaches) belonged to different Rosgen stream classes (Tables 4 and 5). Study Site 1 was moderately entrenched showing an entrenchment ratio of 2.06 m/m and a high width to depth ratio of 63.9 m/m. The sinuosity at this site was moderate (1.236 m/m) and the channel material was dominated by cobble (D50 = 184 mm). The water surface slope was moderately steep (0.034 m/m). Study site 2 was again moderately entrenched (1.80 m/m) with a high width to depth ratio (39.8 m/m). The study reach depicted a low sinuosity value of 1.137 m/m and the channel material was dominated by gravel (D50=36 mm) at this site. The water surface slope was low (0.018 m/m). The entrenchment ratio at Site 3 was 2.75 m/m depicting it to be slightly entrenched and the width to depth ratio was very low (8.2 m/m). This study site showed very high sinuosity (1.885 m/m) and the channel material was dominated by sand (D50=0.08 mm) and the water surface slope was low (0.008 m/m). Site 4 located on the Shaliganga tributary stream maintained a high entrenchment ratio of 4.59 m/m showing it to be entrenched in character. The width to depth ratio at this site also was very low (8.5 m/m) with the stream depicting very high sinuosity (1.612 m/m) at this study

**Table 4.** Pebble count/sieve analysis data (in percentage with cumulative percentage in parentheses) for bottom substrate at different study sites using Wentworth scale for size classes.

| Size class (mm) | Pebble count data | | Sieve analysis data | | | | |
|---|---|---|---|---|---|---|---|
| | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 |
| <0.062 | 0.00(0.00) | 4.00(4.00) | 42.88(42.88) | 30.82(30.82) | 30.73(30.73) | 64.60(64.60) | 58.88(58.88) |
| 0.062-2 | 3.50(3.50) | 3.20(7.20) | 52.54(95.42) | 68.52(99.34) | 68.16(98.88) | 35.40(100.00) | 41.12(100.00) |
| 2-4 | 4.20(7.70) | 5.60(12.80) | 4.58(100.00) | 0.66(100.00) | 1.12(100.00) | | |
| 4-8 | 1.40(9.09) | 2.40(15.20) | | | | | |
| 8-16 | 4.90(13.99) | 4.80(20.00) | | | | | |
| 16-32 | 2.80(16.79) | 28.00(48.00) | | | | | |
| 32-64 | 8.39(25.18) | 17.60(65.60) | | | | | |
| 64-128 | 13.99(39.16) | 17.60(83.20) | | | | | |
| 128-256 | 20.98(60.14) | 11.20(94.40) | | | | | |
| 256-512 | 23.08(83.22) | 5.60(100.00) | | | | | |
| 512-1024 | 16.78(100.00) | | | | | | |

**Table 5.** Geomorphological characteristics of different study sites (reaches).

| Characteristic | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 |
|---|---|---|---|---|---|---|---|
| Rosgen type | B3 | B4c | E5 | E5b | C5c | C6c | C6 |
| Channel morphology | Single channel | Single channel | Single channel | Single channel | Single channel | Single channel | Single channel |
| Stream order | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Bankfull width (m) | 25.50 | 21.75 | 9.00 | 11.25 | 16.80 | 20.88 | 21.75 |
| Flood prone width (m) | 52.50 | 39.15 | 24.75 | 51.66 | 37.65 | 68.73 | 60.03 |
| Entrenchment ratio (m/m) | 2.06 | 1.80 | 2.75 | 4.59 | 2.24 | 3.29 | 2.76 |
| Bankfull mean depth (m) | 0.4 | 0.5 | 1.1 | 1.3 | 1.2 | 1.5 | 1.4 |
| Width to depth ratio (m/m) | 63.9 | 39.8 | 8.2 | 8.5 | 14.2 | 14.2 | 15.4 |
| Sinuosity (m/m) | 1.236 | 1.137 | 1.885 | 1.612 | 1.327 | 1.286 | 1.033 |
| Water surface slope (m/m) | 0.034 | 0.018 | 0.008 | 0.023 | 0.0006 | 0.0005 | 0.0028 |
| Dominant substrate (D50 mm) | Cobble (184) | Gravel (36) | Sand (0.08) | Sand (0.1) | Sand (0.095) | Silt/Clay (0.045) | Silt/Clay (0.05) |

site. The channel material was dominated by sand (D50 = 0.1 mm) with the water surface slope being on the steeper side (0.023 m/m). Study Site 5 was slightly entrenched (2.24 m/m) with a moderate width to depth ratio (14.2 m/m). The sinuosity of the stream in this study site area was high (1.327 m/m) and the channel material was dominated by sand (D50 = 0.095 mm). The water surface slope was very low (0.0006 m/m). Downstream study Site 6 maintained an entrenchment ratio of 3.29 m/m showing it to be slightly entrenched with a moderate width to depth ratio (14.2 m/m). The stream in this area depicted a high sinuosity (1.286 m/m) and the channel material was dominated by silt/clay (D50 = 0.045 mm). The water surface slope was again very low (0.0005 m/m). Site 7 was the most downstream study site in the present work on Doodhganga stream and it maintained a slightly entrenched character with an entrenchment ratio of 2.76 m/m and moderate to high width to depth ratio (15.4 m/m). The sinuosity at this site was low (1.033 m/m) and the channel material was again dominated by silt/clay (D50 = 0.05 mm) with the water surface slope being low (0.0028 m/m). On the basis of the criteria suggested by Rosgen (1994, 1996) the study sites (reaches) were characterised into different stream classes. Site 1 belonged to the stream class B3, Site 2 to B4c, Site 3 to E5, Site 4 to E5b, Site 5 to C5c, Site 6 to C6c, and Site 7 to C6.

## DISCUSSION AND CONCLUSIONS

### Hydrology

In the present study there was high variability in stream flow velocity (0.08 to 2.07 m $S^{-1}$) temporally as well as spatially which emphasizes the dynamic nature of the Doodhganga stream. Along the spatial gradient downstream there was a gradual decrease in the average flow velocity with Site 1 recording the highest average flow velocity of 1.01 m $S^{-1}$ and Site 7 recording the lowest average flow velocity of 0.12 m $S^{-1}$. The decrease in the flow velocity is related to the orographic features and in the present study area the drainage basin slope and the stream gradient decreased downstream and thus the flow velocity in the stream with flow velocity being significantly ($P = 0.05$) correlated with altitude ($r = 0.829$). It is pertinent to mention that, although, the Site 2 was situated at a higher altitude as compared to the other downstream Sites 3 to 7 the overall monthly lowest flow velocity was exceptionally recorded at this site in January 2005 which is attributable to the diversion of water at a number of places between Site 1 and 2 thus reducing the amount of water flowing at Site 2 and also to the flat terrain in this study site area.

Discharge was seen to fluctuate from month to month and recorded the lowest monthly value of 0.06 $m^3$ $S^{-1}$ at Site 2 in January and February of both 2005 and 2006 and the highest monthly value of 8.61 $m^3$ $S^{-1}$ was recorded at Site 1 in April 2005. The highest average discharge recorded at Site 1 is indicative of the intensive use of water in the downstream reaches and also the diversion of water from the stream. Spring season (March to May) maintained the highest discharges at majority of the study sites. The high discharges in spring season are because of the higher rainfall and also because of the spring thaw causing large snow melts in the upper areas which increase discharge in the stream. In a downstream gradient discharge values fluctuated with Site 1 maintaining higher discharges throughout the study period which was conspicuously decreased at the immediate downstream study site (Site 2) and then afterwards there was a gradual increase in the stream discharge and with the contribution of Shaliganga stream down Site 3 the discharge was conspicuously increased at Site 5 which again recorded a decline at Site 6. In downstream Site 6 there was an improvement in the discharge at Site 7. The conspicuous decrease in the stream discharge at Site 2 is primarily because of diversion of water between Site 1 and Site 2 for agricultural purposes as a number of irrigation channels are fed by the water from Doodhganga stream in this area. Then the second major decrease in discharge at Site 6 is attributable to the major extraction of water from the Doodhganga stream a few hundred metres below Site 5 by the Doodhganga drinking water treatment plant which supplies drinking water to a large population. The different behaviour of Site 6 in terms of the hydrological parameters is primarily attributable to the major contribution of water to the stream from the large urban population in the area in the form of sewage and sewerage waters.

## Geomorphology and Rosgen classification

The broader drainage basin geomorphological characteristics revealed that the Doodhganga stream belonged to Order 5 with steep channel and basin slopes and moderate stream channel sinuosity. In a downstream gradient the geomorphological characteristics of streams vary (Van Den, 1995; Knighton, 1999) and when individual study sites in the Doodhganga stream were considered, majority of the criteria for Rosgen classification were seen to vary from site to site. All the study sites (reaches) were characterized as single channel. An important element of the delineation is the interrelationship of the river to its valley and/or landform features. This interrelationship determines whether the river is deeply incised or entrenched in the valley floor or in the deposit feature (Rosgen, 1994). Entrenchment is defined as the vertical containment of river and the degree to which it is incised in the valley floor (Kellerhals et al., 1972). This makes an important distinction of whether the flat plain adjacent to the channel is a frequent floodplain, a terrace (abandoned floodplain) or is outside of a flood-prone area. A quantitative expression of this feature, "entrenchment ratio" depicted that there was a general increase in its value in the downstream gradient meaning that the flood plain available increased downstream. Sites 1 and 2 showed a moderate enrichment ratio while Sites 3 to 7 showed a slightly entrenched character depicting the increased flood plain available. The lowest entrenchment ratio of 1.80 m/m was shown by Site 2 which points to the degraded nature of its flood plain attributable to the extensive dredging of bottom and bank substrate material carried out at this site. The highest entrenchment ratio was maintained by Site 4 which points to the large flood plain available at this site.

The width/depth ratio describes the dimension and shape factor as the ratio of bankfull channel width to bankfull mean depth. The upper study sites (Sites 1 and 2) had a high width/depth ratio while the downstream Sites 5 to 7 showed moderate width/depth ratios with middle Sites 3 and 4 depicting low width/depth ratios. The higher width/depth ratios show that the stream sites are wide and such streams have been found to be quite resilient to moderate watershed changes (Rosgen, 1996).

In terms of sinuosity which is a measure of a stream's "crookedness", the upper and the lower study sites showed low to moderate sinuosity with the middle Site 3 and the Shaliganga Site 4 depicting high sinuosities. The sinuosity values in general are in agreement with the accepted theory of high slopes with low sinuosity and low slopes with high sinuosity. The exceptions to this were the decreased values of sinuosity for Sites 2 and 7 which seem to be because of the straightening of the stream in these areas by humans, being an alteration to the natural stream structure.

The bed and bank material of the river is not only critical for sediment transport and hydraulic influences but also modifies the form, plan and profile of the river. Interpretations of biological function and stability also require this information (Rosgen, 1994). The dominant particle size is identified in the cumulative percent curve as the median size of channel materials or size that 50% of the population is of the same size or finer (D50). Using this criterion it was seen that the study Site 1 was dominated by cobble, study Site 2 by gravel, study Sites 3, 4 and 5 by sand while the most downstream study Sites 6 and 7 were dominated by silt/clay. The changing particle size also reflects the changing hydrologic regime in the stream as the flow velocity was significantly ($P = 0.05$) correlated with the median particle size of the substrate ($r = 0.860$).

Water surface slope is of major importance to the morphological character of the channel and its sediment, hydraulic, and biological function (Rosgen, 1994). There was a gradual decrease in the slope characteristics in the downstream gradient with the upper sites showing moderate slopes which decreased to low slopes in the downstream sites. The water surface slope seems to follow the topographic profile of the area.

Using the criteria as discussed previously and following the Rosgen stream classification (Rosgen, 1994), study Sites 1 and 2 belonged to stream type 'B' which are wider than 'A' streams and have a broader valley but not a well developed flood plain. These single thread streams are moderately entrenched with moderate to steep slopes. Type 'B' streams are often rapid dominated streams with step/pool sequences. Bank heights are typically low. The high width/depth ratios and moderate entrenchment ratios make this stream type quite resilient to moderate watershed changes. Sites 3 and 4 belonged to stream type 'E'. For the single thread channels, the 'E' stream types are the evolutionary end point for stream morphology and equilibrium. The 'E' stream type is slightly entrenched with low width/depth ratios, and moderate to high sinuosities. 'E' stream types are generally found in wide alluvial valleys, ranging from mountain meadows to the coastal plain. Study Sites 5, 6 and 7 belonged to the stream type 'C'. Type 'C' streams are riffle/pool streams with a well developed floodplain, meanders, and point bars. These streams are wide with a width/depth ratio greater than 12. Type 'C' streams are moderately entrenched, and therefore, use their floodplain during large storms (Rosgen, 1994, 1996 and 1998).

It is highly pertinent here to mention that the Rosgen stream classification system seems to be fairly applicable in case of Doodhganga stream and the only exceptions where the classification was not followed was in terms of lower sinuosities obtained for Site 2 (1.137 m/m) and Site 7 (1.033 m/m) as compared to what was predicted by the Rosgen classification (>1.2). The slightly lesser values for sinuosity at these two sites may be attributed to the anthropogenic influences. In the Site 2 area the extensive excavation of the bed and bank material may have led to the straightening of the stream channel while the Site 7 area is a diversion route for the Doodhganga stream, because the natural flow path of the stream in this area has been cut off due to the construction of Flood Spill Channel for River Jhelum. The diversion route is markedly channelized and straight leading to decrease in the sinuosity. Thus, the deviations from Rosgen stream classification at these study site areas seem to be prompted by the anthropogenic factor. The Rosgen stream classification has been suggested for natural streams and the deviations from the natural structure of streams is vividly shown by this classification as highlighted by the present work.

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## REFERENCES

Davis WM (1899). The geographical cycle. Geogr. J., 14: 481-504.

Directorate of Soil Conservation Jammu and Kashmir Government (1983). Codification of Watersheds in Jammu and Kashmir: Vol. 1. Jhelum Basin. Directorate of Soil Conservation Jammu and Kashmir Government Srinagar, Kashmir, India.

Google map of Jammu and Kashmir. Available at www.nationsonline.org/.../map/ google_map_jammu-and-kashmir/

Harrelson CC, Rawlins CL, Potyondy JP (1994). Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.

Hauer FR, Lamberti GA (eds.) (1996). Methods in Stream Ecology. Elsevier, Academic Press, New York. 674pp.

Hussain QA (2011). An Ecological Study of Doodhganga and its Drainage Basin—A Lotic System of Kashmir. Ph. D. Dissertation, P. G. Department of Environmental Science, University of Kashmir, Srinagar. 380pp.

Hynes HBN (1970). The Ecology of Running Waters. Liverpool Univ. Press, England, 555p.

Juracek KE and Fitzpatrick FA (2003). Limitations and implications of stream classification. J. Am. Water Resour. Assoc. 39: 659-670.

Kellerhals R, Neill CR, Bray DI (1972). Hydraulic and Geomorphic Characteristics of Rivers in Alberta. Research Council of Alberta, River Engineering and Surface Hydrology Report 72-1.

Khan HR (1971). Laboratory Studies of Alluvial River Channel Patterns. Ph. D. Dissertation, Dept. of Civil Engineering, Colorado State University, Fort Collins, CO.

Knighton DA (1999). Downstream variation in stream power. Geomorphol. 29: 293-306.

Leopold LB, Wolman MG (1957). River channel patterns: braided, meandering, and straight. US Geological Survey Prof. Paper 282-B.

Lotspeich FB (1980). Watersheds as the basic ecosystem: this conceptual framework provides a basis for a natural classification system. Water Resour. Bull., 16: 581-586.

Lotspeich FB, Platts WS (1982). An integrated land aquatic classification system. North Am. J. Fisheries Manag. 2: 138-149.

Montgomery DR, Buffington JM (1997). Channel-reach morphology in mountain drainage basins. Geogr. Soc. Am. Bull., 109: 596-611.

Raza M, Ahmad A, Mohammad A (1978). The Valley of Kashmir—A Geographical Interpretation, The Land. Vikas Publishing House Pvt. Ltd., New Delhi. Vol. I: 167p.

Rosgen DL (1994). A classification of natural rivers. Catena 22: 169-199.
Rosgen DL (1996). Applied River Morphology. Pagosa Springs, Colorado. 385p.
Rosgen DL (1998). Field Guide for Stream Classification.. Pagosa Springs, Colorado. 193pp.
Schumm SA (1977). The Fluvial System. Wiley, New York, 338p.
Strahler AN (1957). Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Union, 21: 913-920.
Strahler AN (1964). Quantitative geomorphology of basins and channel networks In: Chow, V.T. (ed.), Handbook of Applied Hydrology. McGraw Hill Book Company, New York, pp. 39-76
Sullivan SMP, Watzin MC, Hession WC (2004). Understanding stream geomorphic state in relation to ecological integrity: evidence using habitat assessments and macro-invertebrates. Environ. Manag., 34(5): 669-683.
United Nations (2005). Map of Jammu and Kashmir Area. UN, New York. Available at http://www.un.org/Depts/Cartographic/map/profile/kashmir.pdf.
Van Den Berg JH (1995). Prediction of alluvial channel pattern of perennial rivers. Geomorphol. 12: 259-279.
Wetzel RG, Likens GE (2000). Limnological Analyses. Springer-Verlag, New York. 429pp.
Whiting PJ, Bradley JB (1993). A process-based classification system for headwater streams. Earth Surface Processes Landforms 18: 603-612.
Wolman MG (1954). A method of sampling coarse river-bed material. Trans. Am. Geophys. Union 35: 951-956.