

# Temporal and spatial variations in the engineering properties of the sediments in Ramganga River, Ganga Basin, India

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**Abstract** Development of infrastructure needs enormous natural Earth materials in the form of coarse and fine river aggregate materials. In India, flood plains of the Himalayan Rivers serve as an important source of river sand, leading to extensive sand mining. River Ramganga, the first major tributary of River Ganga, is one such river. In this study, 28 samples of river sediments across the stretch of the river were collected over two seasons: pre-monsoon and monsoon. The engineering properties of these sediments were studied with respect to the specifications of the Bureau of Indian Standards (BIS) and the American Society for Testing and Materials (ASTM) to understand the suitability of their use as fine aggregates in construction. An attempt has also been made in this study to correlate the variability of these properties with respect to the location and time of collection to the Ramganga River Dam at Kalagarh, the contribution of major tributaries, and the effect of monsoon. A pattern emerges from the variation of the physical properties that is explicable by these factors, whereas in general, the variation of the chemical properties does not follow a regular pattern.

**Keywords** River sand · Engineering properties · ASTM · Ramganga River · Ganga River

## Introduction

In the construction of buildings and roads, rock is an important material. Rocks used as construction materials can broadly be classified into three forms—dimension stone, broken stone, and crushed stone (Winkler 1994). Rocks of the size of gravel to sand are used as subgrade material in the construction of roads and are laid below the pitch. In railway lines, rock particles are used as ballast material (Anderson and Fair 2008). In construction of buildings, it is used as both coarse and fine aggregates depending on the particle size. In rock-filled dams, rocks are the primary construction materials as well as aggregates (Yoon et al. 2002). Rock masses are also used as aggregate materials in construction. Such aggregates are mixed in a specific ratio with cement to form concrete, mortar, and plaster. Ideally, fine aggregates used to create such mixtures must be strong and chemically inert. Aggregates are generally divided into coarse and fine aggregates. Clay-sized particles may be used to construct the clay core of a dam, in addition to kachcha houses in rural areas. However, a need for a set of standards arises due to the variability of rock properties (Brekke and Howard 1972).

The most common sources of fine aggregate are floodplains of rivers (Ilangovana et al. 2008), especially in developing countries. In Makurdi, the capital of Benue state of Nigeria, river sand obtained from the bed of river Benue is the only fine aggregate source for concrete production (Manasseh 2010; Alade and Olayinka 2012; Ashiquzzaman and Hossen 2013). Along the Brahmaputra river channel in Assam, river sand is procured for construction of rural roads under the Pradhan Mantri Gram Sadak Yojana (PMGSY) scheme. In addition to river sand, eolian sand has also been used as fine aggregate (Zhang et al. 2006; Al-Ansary et al. 2012; Wand and Feng 2006). In addition to that, fine sand is available from the blasted muck from slope and tunnel excavations. In recent years, artificial sources of fine

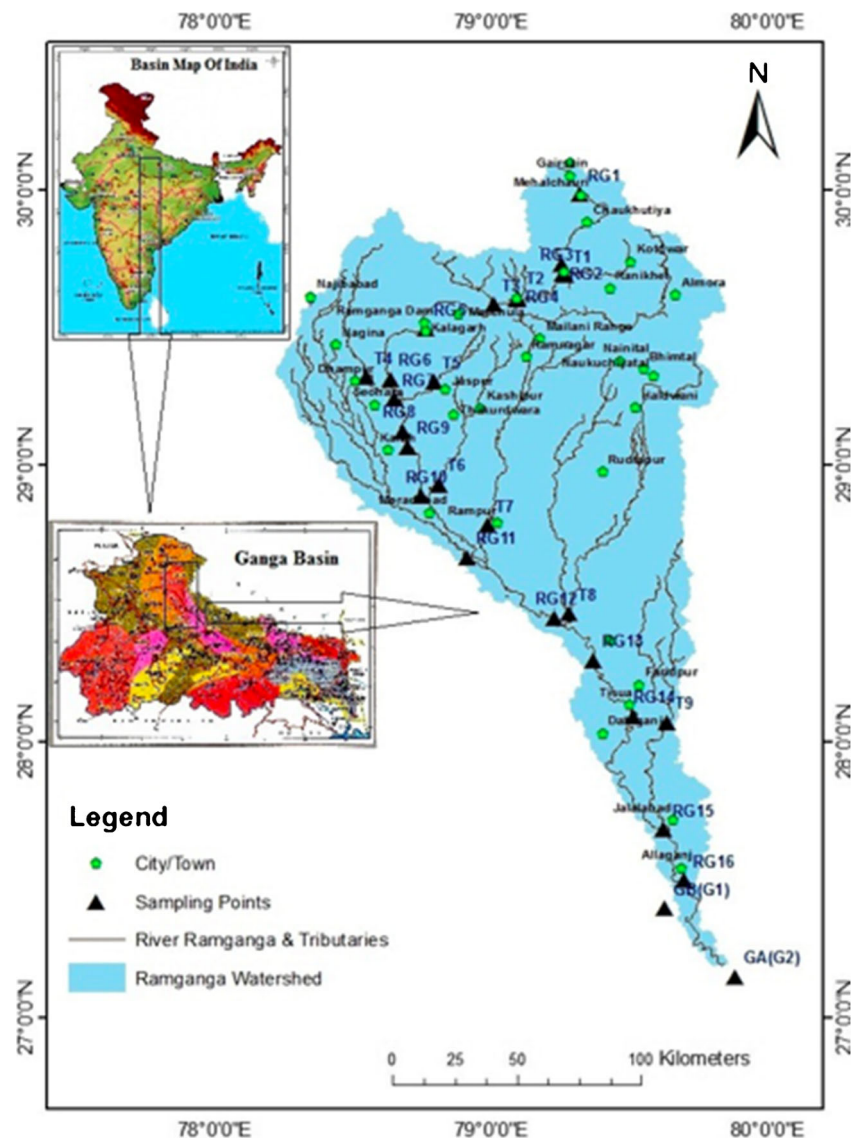
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**Fig. 1** Catchment area of Ramganga River (after Khan et al. 2016b)



aggregate have also been used such as sand-fiber mixture (Santoni et al. 2001), CRT glass (Hui and Sun 2011), and crushed granite (Manasseh 2010). However, properties of concrete made from river sand and crushed fine-recycled aggregates show only slight differences (Kou and Poon 2009).

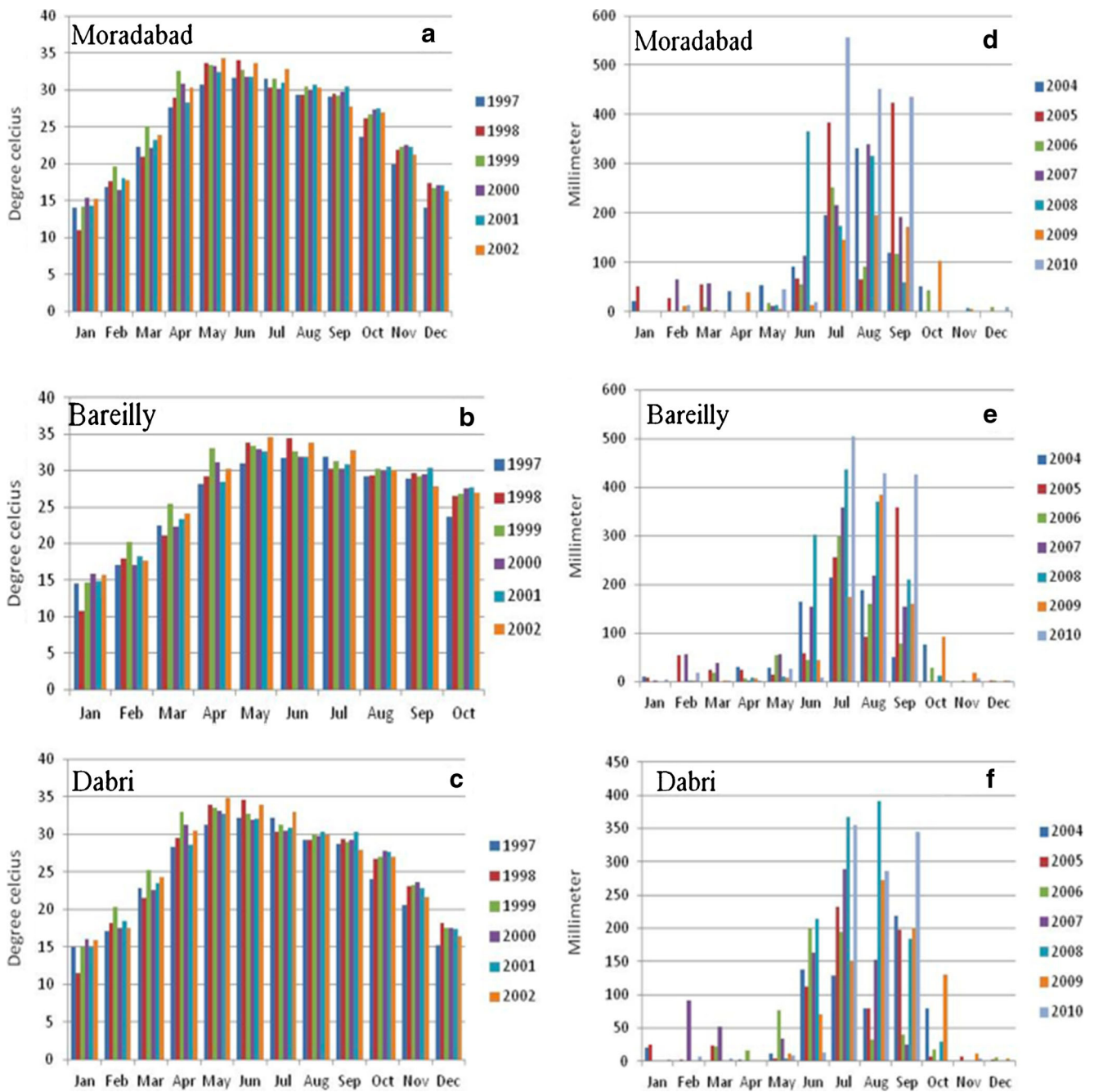
The sediments carried by Ramganga River are used in huge amounts for the construction of roads and buildings. These sands are mined after the monsoon season from various locations along the river channel. Materials used as fine aggregates for construction purposes should adhere to certain requirements prescribed by the Bureau of Indian Standards.

Sand is considered a minor mineral under the Indian law, the extraction of which is governed by the state. However, river sand is often mined illegally. Even miners with permission to extract a certain limit of river sand often extract higher amounts. Overutilization of river sand can have environmental

problems. Since sand is a heavy commodity and requires considerable costs to transport, it is usually mined near the construction sites.

### The study area

River Ramganga is the first major tributary of Ganga. It originates from in the Dudhotali ranges of Kumaon Himalayas, located near Gairsain village of the Chamoli district in Uttarakhand. Ramganga flows through hills (Kumaon Himalayas), forests (Jim Corbett National Park), and highly industrialized areas of the Ganga plains in Uttar Pradesh. The elevation of its source is around 2926 m from the mean sea level (MSL). After emerging from the source, the river flows south and southwest to Bhikiasain, which is at an elevation of 761 m above MSL. Finally, the river emerges out of the mountains at Kalagarh, at an elevation of 262 m above the MSL.



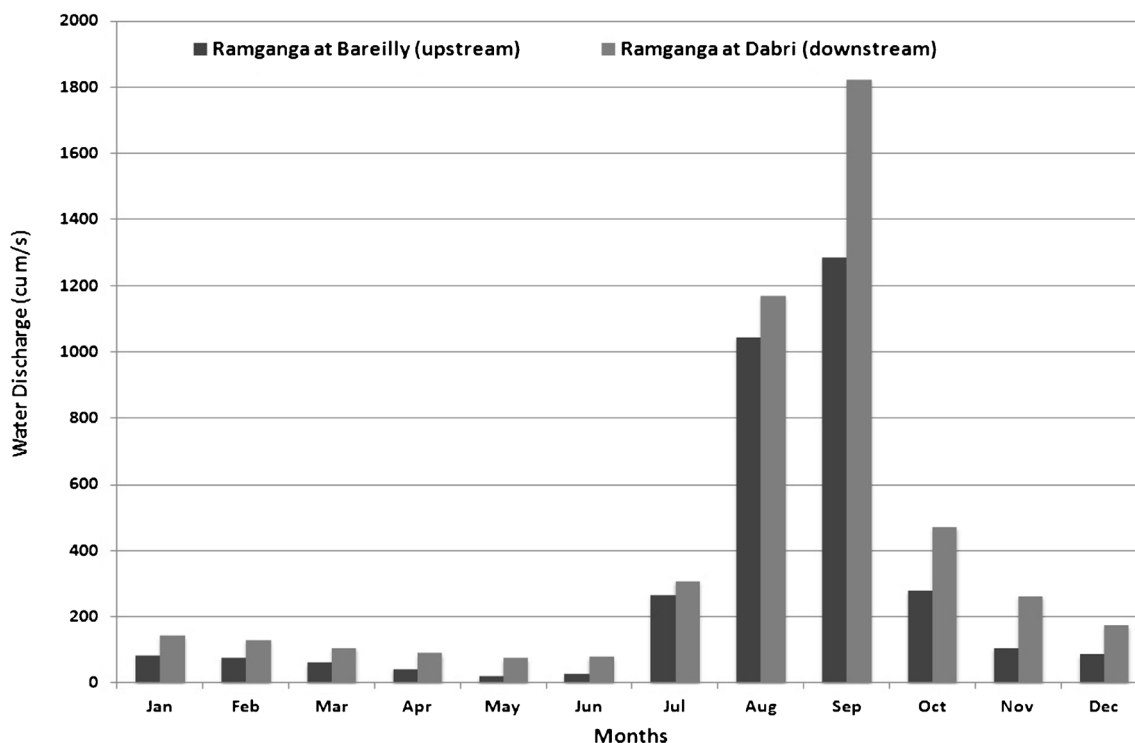
**Fig. 2** Average monthly temperature and rainfall patterns at three locations of Ramganga River—Moradabad, Bareilly, and Dabri (Khan et al. 2016a)

The river covers around 158 km in the mountains (CWC 2012; Khan et al. 2016a). Ramganga flows through the cities of Bhikiasain, Marchula, Kalagarh, Moradabad, Bareilly, Rampur, and Dabri. It finally meets River Ganga in the Farrukhabad district of Uttar Pradesh. Ramganga covers a stretch of 642 km from its origin to its end, with a total catchment area of about 22,685 km<sup>2</sup>, at a mean elevation of 1530 m from the mean sea level (Khan et al. 2016b; Khan and Chakrapani 2016). Figure 1 shows the catchment area of Ramganga River.

**Hydrogeological parameters of Ramganga Basin**

The study area witnesses three distinct seasons—winter, summer, and rainy. The winter season starts in November after an autumn beginning in mid-October characterized by a significant temperature drop. Figure 2a–c shows the temporal temperature variations (<http://indiawaterportal.org/>).

From Fig. 2d–f, it is observed that the rainy season starts by the middle of June and continues up to late September or mid-October. In this study, May/June and October/November are



**Fig. 3** Average water discharge of Ramganga River at two locations Bareilly and Dabri for all months over the years 2009–2011

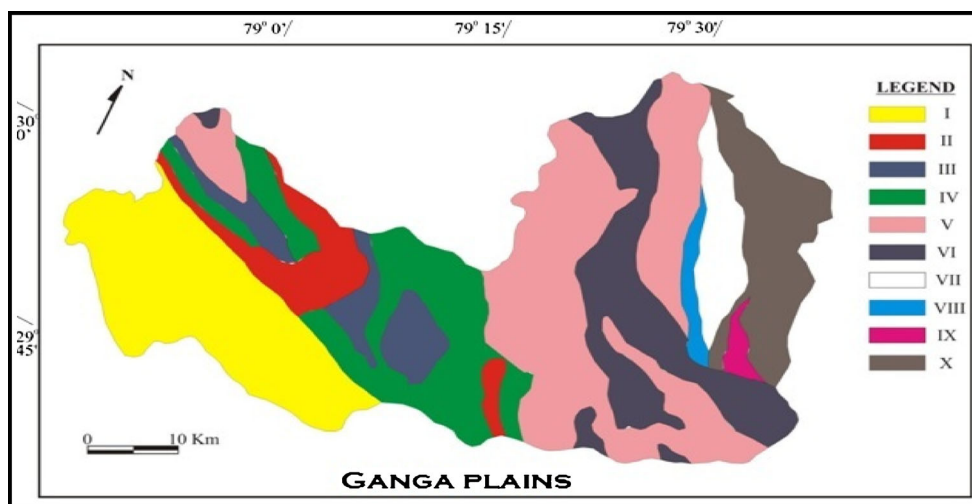
considered as pre-Monsoon and post-Monsoon periods, respectively. In addition to the rainfall during the monsoon months, there are occasional showers during the winter months too. Overall, the study area receives about 1000 mm of average rainfall annually (CWC 2012).

Figure 3 shows the variation of water discharge during different months averaged over the years 2009–2011 (CWC 2012). It is seen that the discharge varies over the months as well as the location of collection of data.

In general, the water discharge at Dabri is higher than that of Bareilly, as Dabri is located downstream of Bareilly. The

months from June to September constitute the Indian monsoon (Das et al. 1989). A significantly higher water discharge is seen during the monsoon months. With a higher water discharge, the river also carries a higher amount of sediments. In Ramganga River, over 80% of the annual sediment transport takes place during the monsoon months of June to September (CWC 2012), which indicates that a large amount of sediment is transported during the floods that happen in monsoon months across the whole stretch of Ramganga River. The deposited sediments are then mined and used as fine aggregates for construction purposes.

**Fig. 4** Simplified lithological map: I sandstones and shales (Siwaliks); II limestone (Krol); III calcareous shales and siltstones (Blaini and Infrakrol); IV quartzites (Nagthat); V low-grade metamorphics; VI high-grade metamorphics; VII limestone (Deoband); VIII graywacke and siltstones (Damta); IX basic intrusives; X quartzites (Sandra) (simplified after Rupke 1974; Valdiya 1980)



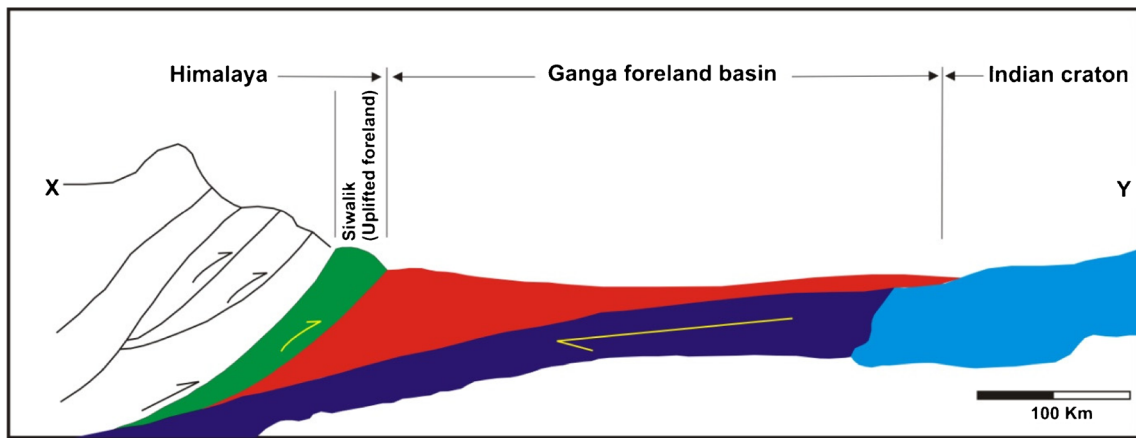


Fig. 5 Schematic cross section of the Ganga Foreland Basin (modified after Singh 1996a)

**Geology of the study area**

Rupke (1974) studied the geology of the Ramganga River Basin extensively, and minor modifications have been applied based on the work of Valdiya (1980).

The catchment area of the river falls under two major lithotectonic zones—the Sub-Himalayas and the Lesser Himalayas. Sandstone, siltstone, clays, and boulders, representing molasse sediments of Mid-Miocene to Pleistocene age, constitute the Sub-Himalayas. The Lesser Himalayas are composed of an unfossiliferous sequence of low- to high-grade meta-sediments of Paleozoic to Mesozoic age. To summarize, the major lithologies in the catchment are (1) quartzites (Nagthat and Sandra formations); (2) calcareous shales and siltstones (Blaini/Infrakrol formations); (3) limestones (Krol and Deoban

formations); (4) low-grade metamorphics (phyllites, slates, and schists); and (5) high-grade metamorphics (granite gneisses) (Fig. 4) (Gupta and Joshi 1990).

The Ganga Alluvial Plain is a foreland basin, which is closely linked to the orogenic activity in the Himalayan region (Fig. 5). The Quaternary lithostratigraphic sequence that has been established in the Ganga Alluvial Plain comprises (in ascending order) (1) Varanasi Older Alluvium with two facies, i.e., sandy facies and silt clay facies, (2) Ganga/Ramganga Terrace Alluvium, and (3) Ganga/Ramganga Recent Alluvium; the latter two constitute the Newer Alluvium.

The Varanasi Older Alluvium, which is the oldest among the Quaternary formations, is extensively developed in the doab of Ganga and Ramganga Rivers. It rests unconformably over the Siwalik Supergroup. The thickness of the Varanasi Older Alluvium varies from 300 to 517 m. The Siwalik sediments, further, rest over the Vindhyan Supergroup basement, development during the

**Table 1** Locations of different sampling points of Ramganga River

S. no.	Code	Location	River
1	RG1	Mehalchauri	Ramganga
2	RG2	Jainal	Ramganga
3	RG3	Bhikiyasain	Ramganga
4	RG4	Marchula	Ramganga
5	RG5	Kalagarh	Ramganga
6	RG6	Mubarakpur	Ramganga
7	RG7	Surjannagar	Ramganga
8	RG8	Malakpur Shamli	Ramganga
9	RG9	Karanpur	Ramganga
10	RG10	Moradabad	Ramganga
11	RG11	Saifni	Ramganga
12	RG12	Thiria Buzurg	Ramganga
13	RG13	Bareilly	Ramganga
14	RG14	Nagria Kalan	Ramganga
15	RG15	Zarinpur	Ramganga
16	RG16	Dabri	Ramganga

**Table 2** Locations of different sampling points of the major tributaries of Ramganga River and Ganga River near its point of confluence

S. no.	Code	Location	River
1	T0	Chachroti	Binau
2	T1	Bhikiyasain	Gagas
3	T2	Marchula	Deota
4	T3	Diyor	Mandal
5	T4	Sherkot	Kho
6	T5	Kishanpur	Phika
7	T6	Pipalsana	Dhela
8	T7	Mansurpur	Kosi
9	T8	Thiria Khetal	Bhakra
10	T9	Bilpur	Baigul
11	GB	Farrukhabad	Ganga
12	GA	Kusum Khor	Ganga



**Fig. 6** Variation of fineness modulus across both seasons



Pre-Cambrian. The thickness ranges from about 300 to 517 m, forming a polycyclic sequence of silt, clay, and sand. Sporadic Kankar concretions are also present in the silty clay at depth. The sandy facies of this unit are exposed and comprise fine- to medium-grained micaceous sands. These have been oxidized at the top, therefore showing a deep brown color, which turns snowy gray with depth. Sedimentary structures are also present in these sands at depth, like parallel laminations and cross beddings. These sedimentary structures indicate that these sands are of fluvial origin. The silt clay facies is deep khaki brown, and Kankar concretions may be present (Khan and Rawat 1992).

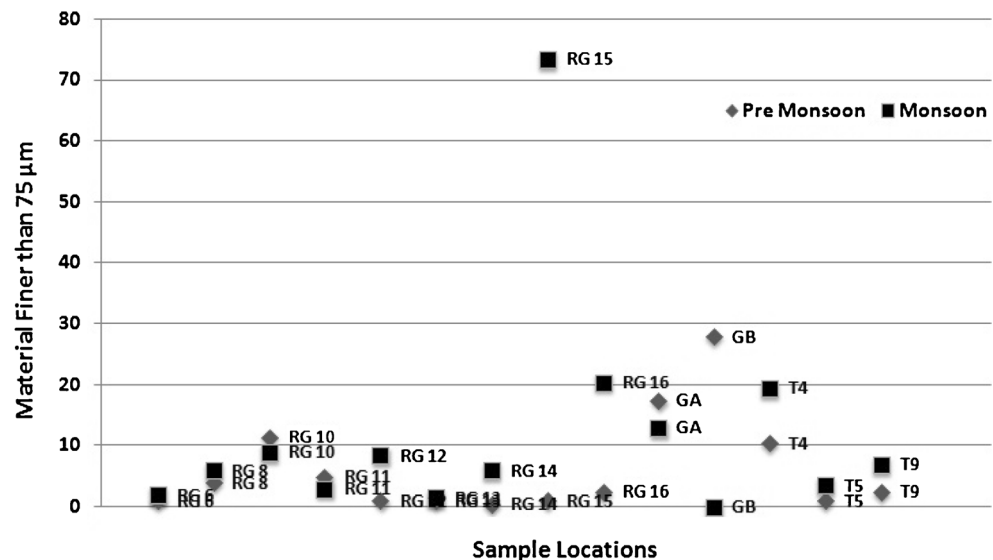
Ganga Terrace Alluvium, which is present in between the paleobanks of Ganga or Ramganga, is composed of alternate

beds of unoxidized silty clay (gray in color) and fine to medium sand. These sands show an abundance of sedimentary structures like cross bedding and parallel laminations (Khan and Rawat 1992).

The sands of Ramganga Terrace Alluvium are found to be slightly coarser in size than the sands of Ganga Terrace Alluvium. Sedimentary structures are also well preserved in these sands. In Ganga River, the Terrace Alluvium has been developed at two levels, T1 and T1a, with T1a sediments being more arenaceous than T1 sediments (Khan and Rawat 1992).

The Ganga and Ramganga Recent alluviums are contained within the present-day bank limits. These sands are represented by fine to medium gray color sands. Thin drapes of silt are also present in the form of channel and point bars (Khan and Rawat 1992).

**Fig. 7** Spatial and temporal variations in material finer than 75  $\mu\text{m}$



**Table 3** Test results for the determination of clay lumps and friable particles

Sample	Weight (g)	Retained (g)	Result (%)
T 9	50	49.7	0.6
GB	25	25	0
MRG 8	50	49.9	0.2
MRG 10	50	50	0
MRG 15	25	24.9	0.4

**Sampling and methodology**

Bank sediments were collected from 16 locations across the stretch of Ramganga River, 10 of its major tributaries (Tables 1 and 2) before meeting the river and two samples of River Ganga (before and after confluence). This sampling was done over two seasons—pre-monsoon and monsoon.

Since Ramganga River covers a stretch of 642 km from its origin to its confluence with River Ganga and there are 28 samples in total, it is not possible to cover at one go. Therefore, the sampling for each season is divided into three phases—upstream (RG 1–RG 5), midstream (RG 6–RG 10), and downstream (RG 11–RG 16). Tables 1 and 2 show the list of locations across the stretch of Ramganga River and its tributaries and Ganga River before and after confluence, from where samples were collected for this study over two seasons.

**Table 4** Determination for lightweight particles test for all samples

Sample	Weight (g)	Retained (g)	Result
RG 6	100	99.7	0.3
RG 10	50	48.7	2.6
RG 11	100	97.7	2.3
GB	200	193	3.5
T4	50	48.6	2.8
T5	50	49.2	1.6
T9	200	195.1	2.45
MRG 6	50	48	4
MRG 8	200	198.2	0.9
MRG 10	100	99.8	0.2
MRG 11	50	48.7	2.6
MRG 12	100	98.3	1.7
MRG 14	200	197.4	1.3
MRG 15	200	199.8	0.1
MGA	200	198.3	0.85
MGB	200	197.5	1.25
MT4	200	199	0.5
MT5	100	99.7	0.3
MT9	200	198.1	0.95

**Table 5** Organic impurities test for all samples

Pre-monsoon			Monsoon		
Sample	Color	Result	Sample	Color	Result
RG 6	Lighter	Satisfactory	MRG 6	Lighter	Satisfactory
RG 8	Lighter	Satisfactory	MRG 8	Lighter	Satisfactory
RG 10	Lighter	Satisfactory	MRG 10	Lighter	Satisfactory
RG 11	Lighter	Satisfactory	MRG 11	Lighter	Satisfactory
RG 12	Lighter	Satisfactory	MRG 12	Lighter	Satisfactory
RG 13	Lighter	Satisfactory	MRG 13	Lighter	Satisfactory
RG 14	Lighter	Satisfactory	MRG 14	Lighter	Satisfactory
RG 15	Lighter	Satisfactory	MRG 15	Lighter	Satisfactory
RG 16	Lighter	Satisfactory	MRG 16	Lighter	Satisfactory
GA	Lighter	Satisfactory	MGA	Lighter	Satisfactory
GB	Lighter	Satisfactory	MGB	Lighter	Satisfactory
T4	Similar	Satisfactory	MT4	Lighter	Satisfactory
T5	Lighter	Satisfactory	MT5	Lighter	Satisfactory
T9	Lighter	Satisfactory	MT9	Lighter	Satisfactory

The Bureau of Indian Standards proposes a list of tests for fine aggregates to be used in concrete and mortar for construction purposes. IS 2386 (Part I) (1963) provides a list of tests, their significance, procedures, and interpretation of results. Similarly, the American Society for Testing and Materials (ASTM) specifies certain standard tests that apply to fine aggregate before their use in concrete.

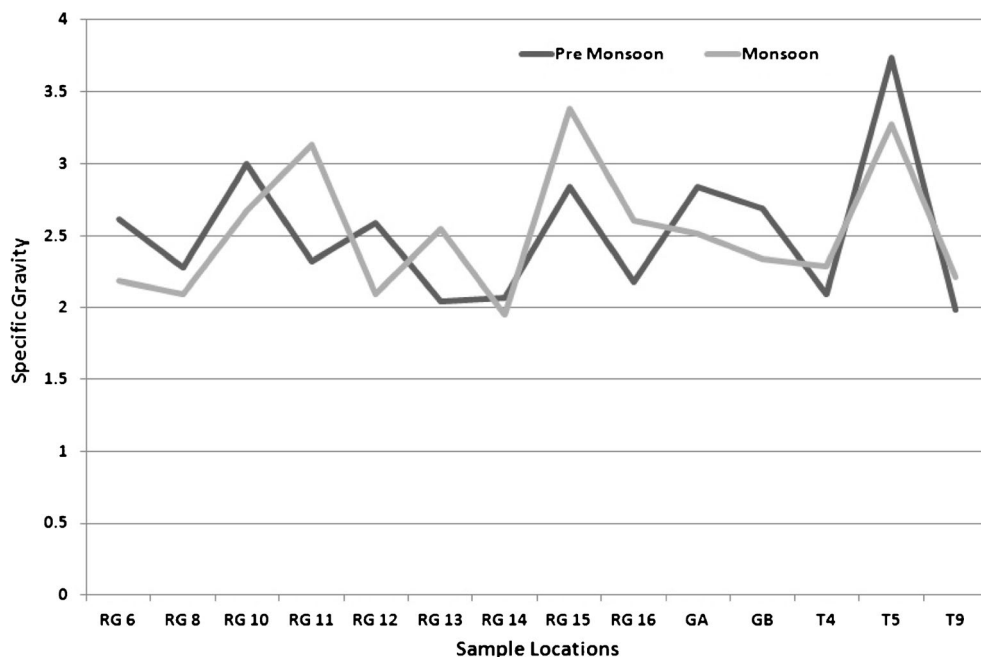
The tests that were performed are analysis of particle size and shape (IS 2386 (Part II) (1963)), determination of materials finer than 75 μm (IS 2386 (Part III) (1963)), determination of clay lumps and friable particles (ASTM C142/C142M-10 2010), determination of lightweight particles in aggregate (ASTM C123/C123M-14 2014), determination of organic impurities (ASTM C40/C40 M-11 2011), determination of specific gravity and water absorption (IS 2386 (Part IV and Part V) (1963)), determination of acid-soluble chloride in mortar and concrete (ASTM C1152/C1152M-04e2 2012), and determination of water-soluble sulfate in soil (ASTM C1580-09e1 2009).

**Results and discussion**

**Particle size distribution**

Figure 6 shows the variation in fineness modulus of fine aggregates over two seasons—pre-monsoon and monsoon. A general trend is seen that the pre-monsoon samples have a higher fineness modulus, which indicates coarser particles. This trend could be explained by the higher water discharge during the monsoon months of June to September (Fig. 3), which indicate a higher velocity of the water.

**Fig. 8** Spatial and temporal variations in specific gravity



According to the sixth power law, a higher velocity of water indicates the ability of a river to transport coarser sediments (Chen 1991). It is also observed that the fineness modulus for Mubarakpur (RG 6) is less than Shamli (RG8) in both seasons. This could be explained by the proximity of Mubarakpur to the 128-m-high Ramganga Dam at Kalagarh (RG 5) with a reservoir covering an area of 55 km<sup>2</sup>. The water that is trapped deposits most of the coarser sediments in the reservoir, and the water that is let go carries relatively fine-grained sediments at Mubarakpur. However, the sudden increase in fineness modulus at Shamli is seen because of the confluence of Kho River (T4) with Ramganga in between Mubarakpur (RG 6) and Shamli (RG 8). At the point of confluence, the water discharge of Ramganga is relatively less

than Kho because of the presence of the dam, which leads to a significant influence of the sediments of Kho River (T4) with a relatively higher fineness modulus. Another sudden increase in the fineness modulus is seen from Nagria Kalan (RG 14) to Zarinpur (RG 15), which could be attributed to the confluence of another major tributary of Ramganga River in between the two locations —River Baigul (T9).

An anomaly in the variation of fineness modulus is an abnormally low value at Moradabad (RG 10). It is interesting to know that the fineness modulus is governed by the size of particles up to 150 μm only. The particle size distribution shows that over 93% of the sediments are smaller than 150 μm, but the Material Finer than 75 μm test (Fig. 7) shows that just 11.5% particles are finer than 150 μm. This



**Fig. 9** Satellite images from Google Earth showing the meandering of Ramganga River at Surjanpur (RG 7)





**Fig. 10** Satellite images from Google Earth showing the meandering of Ramganga River at Malakpur Shamli (RG 8)

effectively puts over 80% of the particles in the range of 75 to 150  $\mu\text{m}$ . The grain size distribution of the sample at Moradabad (RG 10) is very similar to the properties of Malakpur Shamli (RG 8) with a fineness aggregate of 0.904. This shows that the fineness modulus does not give us a good idea of the particle size distribution for fine to very fine sand, with particles of nearly the size of the smaller-sized sieves that are used in this test.

**Determination of materials finer than 75  $\mu\text{m}$**

The test for materials finer than 75  $\mu\text{m}$  gives us an idea about the part of the fine aggregate that is easily dispersed by wash water. Most of the samples in this study show less than 5% of such materials present, with recommendations at less than 3% and up to 1% for the construction of dams.

As evident from Fig. 7, a general trend shows a higher amount of such material present in the monsoon samples, barring two exceptions Moradabad (RG 10) and Saifni (RG

11). This could be due to the higher range of particle size in the sediments transported by the river during the monsoon months.

The effect of the dam constructed at Kalagarh (RG 5) is also evident in the materials finer than 75  $\mu\text{m}$ . The difference of materials finer than 75  $\mu\text{m}$  during monsoon and pre-monsoon is very low at Mubarakpur (RG 6), which is close to the dam. The reason is that even during monsoons, the discharge at the dam is controlled leading to a lower velocity of water and settling of sediments in the reservoir. As we move downstream, the difference in materials finer than 75  $\mu\text{m}$  between the pre-monsoon and monsoon months becomes more prominent, the highest difference being shown at Zarinpur (RG 15).

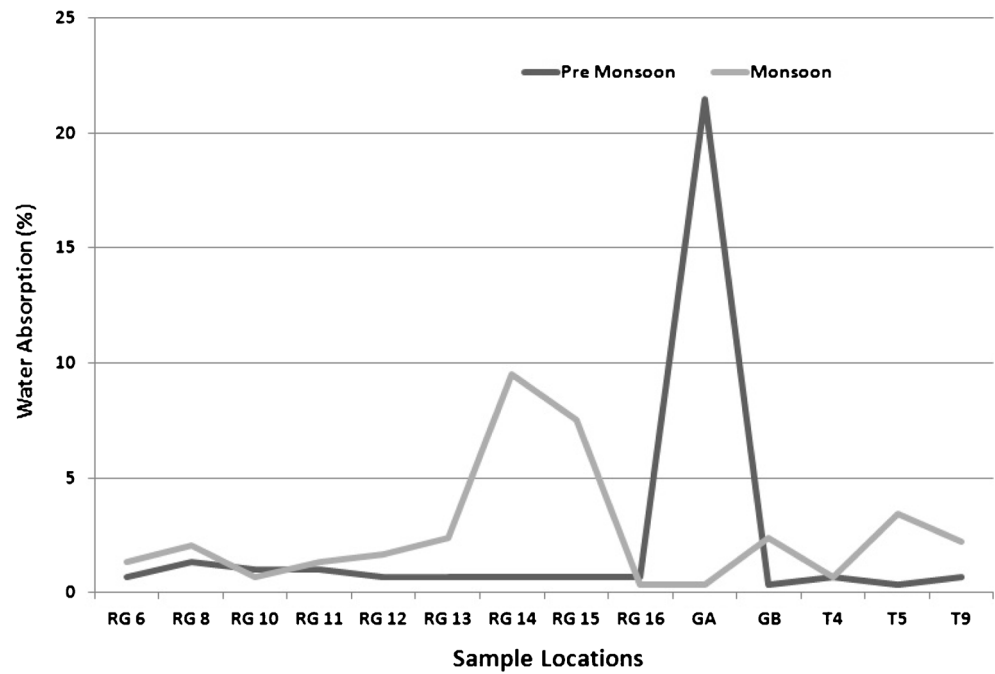
**Determination of clay lumps and friable particles**

Due to the fineness of the particles, the test for the determination of clay lumps and friable particles was done only on five samples across the two seasons. This test required at least 25–



**Fig. 11** Satellite images from Google Earth showing the meandering of Ramganga River at Karanpur (RG 9)

**Fig. 12** Spatial and temporal variations in water absorption



30 g of aggregate that is retained by the 1.18-mm sieve. A suitable amount of material was obtained from only the said five samples.

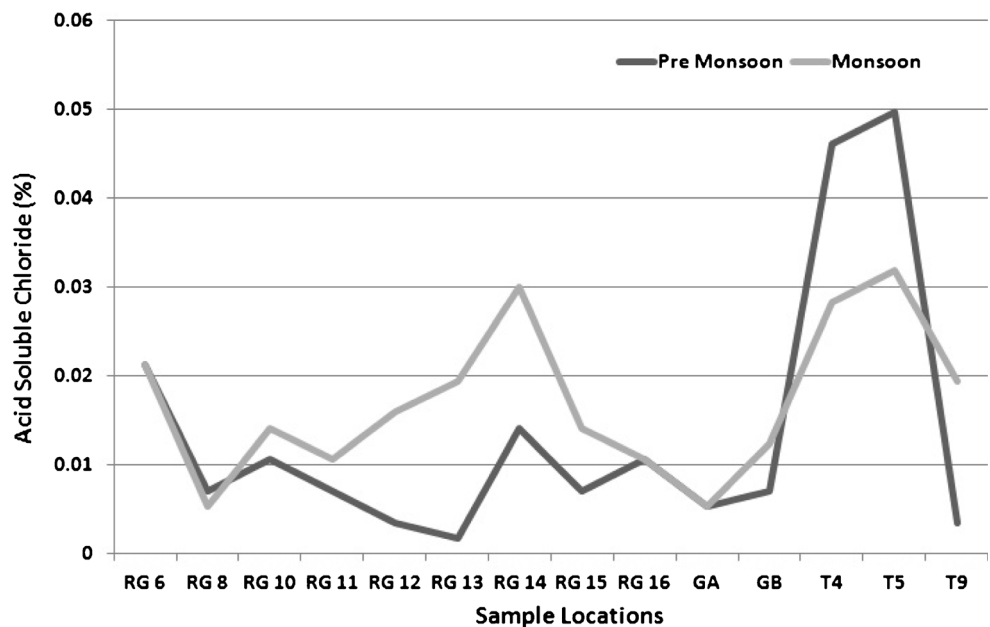
Table 3 shows that all the samples showed a very small result for the presence of clay lumps and friable particles, which are all well below the 3% limit set by ASTM C142/C142M-10 (2010). Two samples showed the absence of such particles completely, which is a good sign. These results indicate that the sediments are composed of hard minerals, but there is no pattern that is evident from the results.

**Determination of lightweight particles**

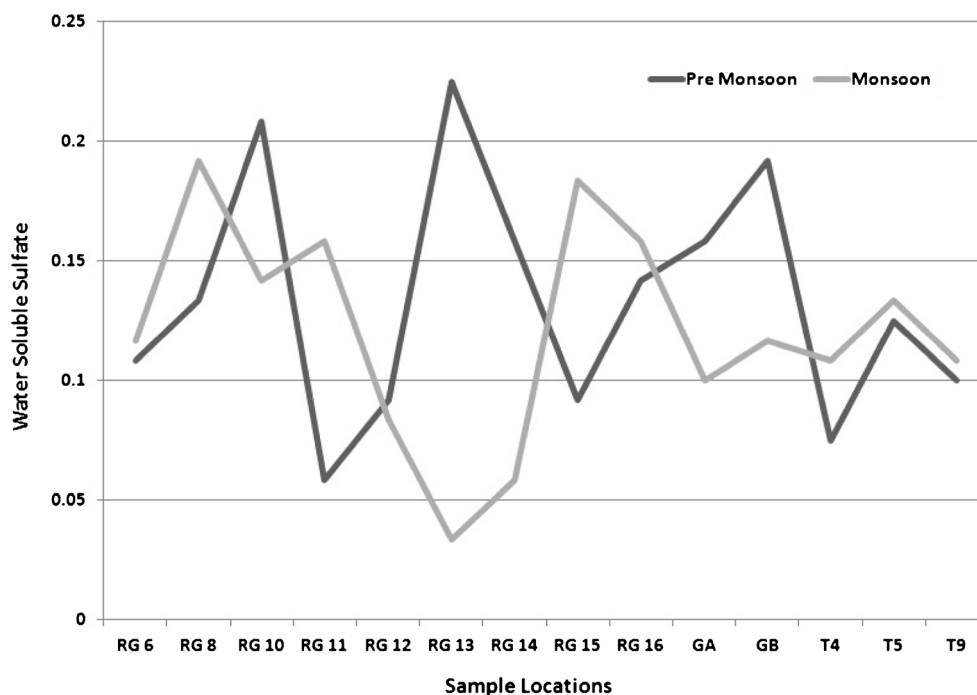
Similar to the test for the determination of clay lumps and friable particles, the test for the determination of lightweight particles requires at least 50 g of the sample retained by the 300- $\mu$ m sieve. Owing to this requirement, only 19 of the total samples were tested for the presence of lightweight particles by this procedure.

ASTM suggests that the lightweight particles present in the aggregates must be less than 3% to be accepted as fine

**Fig. 13** Variation in acid-soluble chlorides for both seasons



**Fig. 14** Variation in water-soluble sulfates for both seasons



aggregates. Table 4 shows that all the samples showed the presence of acceptable amounts of such lightweight particles.

These results go hand in hand with the results of the test for clay lumps and friable particles. These two tests together indicate that the sediments are formed of hard minerals. However, there is no regular pattern that is seen from the results. The sample from Moradabad (RG 10) shows the highest amount of lightweight particles among the rest. This could be because of the low fineness modulus of the sample as compared to the other samples, indicating the presence of finer particles in the Moradabad (RG 10) sample.

#### Determination of organic impurities

Preliminary results for the organic impurity test (Table 5) show that all the samples indicate insignificant amounts of organic impurities within them. All samples produced a lighter color than the threshold color after completing the test. These results eliminate the need to go for further tests to determine the exact amount of deleterious organic impurities in the samples.

The results of this test show the absence of organic impurities, which is an indication of low amounts of organic carbon in Ramganga River. However, the catchment area of Ramganga River in the Kumaon Himalayas has a lot of limestone, which gets eroded by the river. This leads to a high amount of inorganic carbon in the form of dissolved carbonates and bicarbonates in the river water.

Also, as organic carbon is absent in the sediments, most of the organic carbon is transported in dissolved state through the

river water. Similar findings of a higher proportion of the organic carbon being transported in solution have been reported earlier in the Himalayas (France-Lanord and Derry 1997), the Amazon River system (Amon and Benner 1996), and small, mountainous rivers in New Zealand (Carey et al. 2005).

#### Determination of specific gravity and water absorption

Figure 8 shows the spatial and temporal variation in the specific gravity of the Ramganga River sediments. Most of the values of specific gravity range between 2.0 and 3.5, with a significant amount of samples with specific gravity near about 2.5–2.6. This could indicate the presence of quartz, which has a specific gravity of 2.65. ASTM and IS require that the minimum value of specific gravity of the sediments should be 2.6.

It is also observed that there is very little difference between the specific gravities of the sediments at the same location over the two seasons. This is explained by the fact that the source rocks remain the same over the two seasons. Therefore, even if there is a difference in water discharge, rate of erosion, and consequently particle size distribution, the nature of the particles that constitute the sediments remains the same, leading to similar specific gravities.

There is a significant difference between the specific gravities observed at Saifni (RG 11), Thiria Buzurg (RG 12), and Bareilly (RG 13) between the samples from monsoon and pre-monsoon seasons. This is attributed to the high degree of meandering of the river just upstream of Saifni (RG 11) at Surjanpur (RG 7), Malakhpur Shamli (RG 8), and Karanpur (RG 9) which changes the nature of the sediments eroded and



deposited over the two seasons. The degree of meandering of the Ramganga River at Surjanpur (RG 7), Malakhpur Shamli (RG 8), and Karanpur (RG 9) are shown in Figs. 9, 10, and 11.

Similar changes in the sediment characteristics due to substantial meandering of the river have been observed in the river South Esk, Glen Clova, Scotland (Bridge and Jarvis 1976).

Figure 12 shows the variation in water absorption over two seasons, pre-monsoon and monsoon, for the different samples across the river. A general trend shows higher water absorption values during the monsoon season. This could be due to the fact that the fineness moduli of monsoon samples were higher, indicating coarser particles, leading to a higher volume of pores. These pores get filled with water and increase the water absorption of the samples.

Quite interestingly, the monsoon samples show a zigzag pattern, probably because of a greater influence of tributaries in the monsoon season, leading to an erratic particle size distribution. A high value of water absorption is seen at Zarinpur (RG 15) during monsoon. This could be due to the high percentage of materials finer than 75  $\mu\text{m}$ , which get dissolved with water during the test. ASTM recommends that the surface dry water absorption must be less than 2.3%, and over 80% of the samples tested fall under that limit.

#### Determination of acid-soluble chloride

Figure 13 shows the results of the test for acid-soluble chloride for the pre-monsoon and monsoon samples of Ramganga River and its tributaries. The ASTM recommends that the value of acid-soluble chlorides must be less than 0.06% for reinforced and mass concretes, but less than 0.01% for structural concrete.

All the values fall under the ASTM recommendations of 0.06%, with the lowest value of 0.004% on Baigul tributary at Bilpur (T9) and the highest value of 0.050% on Phika tributary at Kishanpur (T5), both during the pre-monsoon. From the values that are observed in the tables, there is no pattern that emerges out of the data. However, the graphical representation shows that the property remains roughly the same over the two seasons, indicating the temporal stability of this property.

#### Determination of water-soluble sulfate

Figure 14 shows the results of the test for the determination of water-soluble sulfate in the aggregates. The ASTM recommends that the presence of water-soluble sulfates should be no more than 0.4% by mass.

The results across the two seasons show that the results are well within the limits specified by ASTM for this test. The maximum value of 0.225% is seen during pre-monsoon at Bareilly (RG 13) and the minimum value of 0.033% at the same location (RG 13) during monsoon.

A general trend shows lower values in monsoon than in pre-monsoon, perhaps because the soluble sulfate is washed away by the river water, which has a higher velocity and discharge during monsoons. However, no one trend emerges from the results of this test. Figure 14 shows the variation of the same data graphically.

#### Conclusions

In general, a greater variation in the physical properties of sediments like the distribution of particle sizes is observed as compared to the chemical properties such as water-soluble sulfate and acid-soluble chloride.

The spatial variations in the physical properties can be explained by the presence of the Ramganga Dam at Kalagarh; the contribution of sediments from major tributaries like Kosi, Bakhra, and Baigul; and the meandering of the river in the plains. The variations of these properties over the two seasons can be explained by the high water discharge and sediment flux during the monsoon months. The study also showed the shortcomings of the fineness modulus as a measure of the fineness of fine aggregates that have a considerable fraction of particles towards the lower sieve limits of the test.

The chemical properties across the seasons are found to be stable. Most of the samples conform to the guidelines of ASTM and IS, with no regular pattern emerging across the locations.

In particular, samples from River Ramganga from Zarinpur (RG 15) and Dabri (RG 16) during pre-monsoon and Saifni (RG 11) for both seasons are suitable for use as fine aggregates for concrete. Among the tributaries of the river, Phika at Kishanpur (T5) and Baigul at Bilpur (T9), both during monsoon season, show good results to be used as fine aggregates in concrete and mortar.

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