Water quality of the Chhoti Gandak River using principal component analysis, Ganga Plain, India

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Chhoti Gandak is a meandering river which originates in the terai area of the Ganga Plain and serves as a lifeline for the people of Deoria district, Uttar Pradesh. It travels a distance of about 250 km and drains into Ghaghara near Gothani, Siwan district of Bihar. It has been observed that people of this region suffer from water-borne health problems; therefore water samples were collected to analyse its quality along the entire length of Chhoti Gandak River.

The principal components of water quality are controlled by lithology, gentle slope gradient, poor drainage, long residence of water, ion exchange, weathering of minerals, heavy use of fertilizers, and domestic wastes. At some stations water is hard with an excess alkalinity and is not suitable for drinking and irrigation purposes. The variation in the local and regional hydrogeochemical processes distinguished the geogenic sources from the anthropogenic one.

1. Introduction

Ganga Plain is one of the most densely populated regions of the world due to its availability of water, fertile soil, and suitable landscape. Density of the river is high in eastern Uttar Pradesh and Bihar. Rivers are considered as a lifeline but are now adversely affecting the population by fluvial hazards (Singh 2007). India is water-stressed and is likely to be water-scarce by 2050 due to the continuous and increasing demand for water (Gupta and Deshpande 2004). Water resources and water quality affect the economic, social, and political development of the society.

It has been observed in the field that people of the Deoria district are suffering from water-borne health problems mainly related to throat, skin, and stomach. The hydrogeochemistry of ground water and anthropogenic control over dolomatization reaction in the alluvial sediments of the Deoria district located within the Chhoti Gandak River Basin have been analysed (Bhardwaj *et al* 2009). However, no attempt has been made to analyse the water quality and water chemistry of this river. The hydrogeochemical process reveals the zones and quality of water. This process also helps us to understand the changes in water quality due to sediment–water interaction and anthropogenic influence. The impact of land use on the quality of water is an important aspect to develop a suitable policy and legislative or regulatory mechanisms. Lack of such efforts results in the deterioration of water quality which causes health problems and also damages the industrial sector. Therefore, it is essential to evaluate the relationship between chemical variables and to identify local and regional processes which influence quality of water, using principal component analysis for proper planning, water resource management, and sustainable development. Domestic and industrial wastewater constitutes a constant polluting source, whereas surface runoff is a seasonal phenomena mainly controlled by climate within the basin (Singh *et al* 2004). Weathering of primary
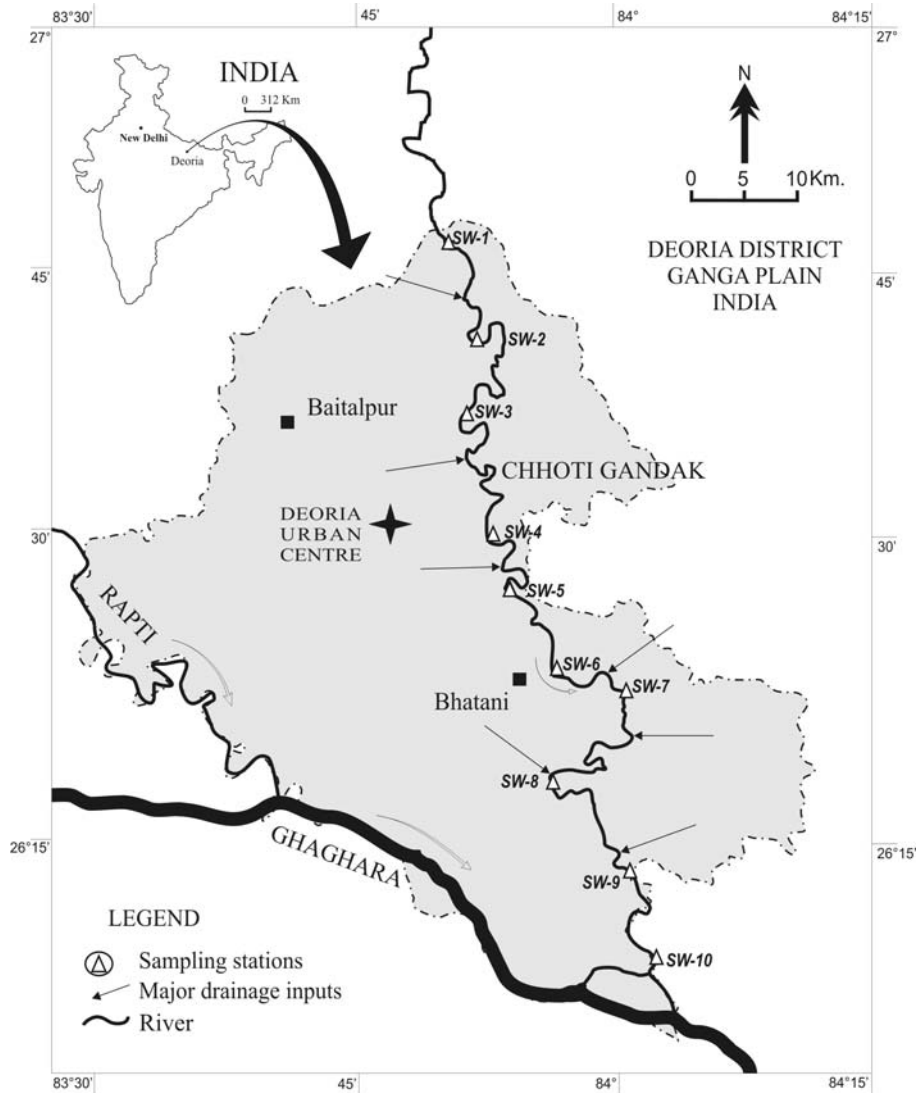
Figure 1.   Chhoti Gandak River, Ganga Plain, India.

and secondary minerals contributes to cations and silica in the system (Jacks 1973 and Bartarya 1993).

In the present study, a detailed investigation has been made to identify the hydrogeochemical processes and their relation with water quality, hydrochemical evolution of water system through principal component analysis, and spatial variation in the water quality. Assessment of water quality is important to determine its suitability for consumption in the domestic, agricultural, and industrial sectors.

2. Study area

Chhoti Gandak River originates near Dhesopool in Mahrajganj district of Uttar Pradesh and after traveling a distance of about 250 km towards south, joins the Ghaghara near Gothani in Siwan district

of Bihar. Chhoti Gandak River with its tributaries along with Rapti and Ghaghara are the main drainage of the Deoria district. The drainage pattern is subdendritic to dendritic and the streams are perennial to ephemeral in nature. Deoria district is located between 26°06′–26°44′N latitude and 83°30′–84°12′E longitude in Uttar Pradesh (figure 1). Basic information of Chhoti Gandak River and Deoria district is given in table 1.

Geologically, the area is made up of Quaternary alluvium of different ages consisting of clay, silt, sand, and gravel mixed in different proportions. The valley and channel width, cliff pattern, point bars and discharge of the river are controlled by climate, the migration and tilting is controlled by tectonics, and river terraces are evolved under the control of both tectonics and climate (Singh *et al* 2009). Older alluvium (Bhangar) and newer alluvium (Khadar) are the two morphostratigraphic units as described in the classical literature of the

Table 1. *Basic information of Deoria district and Chhoti Gandak River.*

Basic data of Deoria district	
Geographical location	Ganga Plain
Latitude	26°06′N–26°44′N
Longitude	83°30′E–84°12′E
Climate	Sub-humid
Humidity	43%–84%
Temperature range	9.0°C–39.2°C
Average annual rainfall	1128.11 mm
Average annual evapotranspiration	1323.7 mm
Area	2489.41 km^2
Total population (2001)	27,30,376
Population density	1062
Population growth rate	23.85%
Forested area	2.61 km^2
Salt affected land	33.66 km^2
Cultivable land	2117.16 km^2
Rangeland	40.28 km^2
Flood affected land	10.75 km^2
Basic data of Chhoti Gandak River	
Slope gradient	21.00 cm/km
Sinuosity	2.05
Valley width	0.1–0.5 km
Channels widths	25–200 m
Relief (both the banks)	0.1 to 7.0 m

Ganga Plain (Pascoe 1917). Upland terrace surface, river valley terrace surface, and present day river channel made up of older alluvium and newer alluvium are the main geomorphic units which are depositional in nature (Singh 1996). Two main depositional areas, identified in the Ganga Plain are (a) channel areas and (b) interchannel areas. Sedimentation in the interchannel areas takes place mainly by sheet flow (Kumar *et al* 1995), and interfluve deposits (Singh *et al* 1999). Whereas river deposit sediments in the channel areas are in the form of channel-bar deposits (Singh and Singh 2005).

3. Methodology

Water samples were collected in two sets from different stations at regular intervals along the entire length of Chhoti Gandak River during summer (June), 2006. The collected samples were stored in acid-cleaned, high-density polyethylene (HDPE) bottles (1000 ml), which were carefully rinsed three times before use. The use of HDPE bottles minimizes container pollution and promotes the sample preservation (Hall 1998). Analyses of

water samples were carried out immediately after collection. Samples were stored in a refrigerator at 4°C prior to analysis. Temperature, pH, conductivity, total dissolved solids were determined in the field by Cyber Scan 510. Potassium and sodium by Systronics Flame photometer 128, nitrate by Perkin Elmer, UV/VIS spectrometer, Lambda 40. Other parameters were measured using standard water quality procedures (American Public Health Association 1992, 1998). The reproducibility of the analytical procedures was checked by carrying out duplicate analysis. The variation in result was less than 5% of the mean. Ability to replicate samples was determined by collecting two samples at every station.

Chemical data were analyzed by the principal component analysis, which quantifies relationship between the variables by computing the matrix of correlations for the entire dataset. In the present study results of the first three principal components were selected following Kaiser (1958) to explain the hydro-geochemical processes that control the ion concentrations of water, which account for most of the total variance in the dataset.

4. Results and discussion

4.1 *Water quality of the river*

Analysis of the chemical constituents of the Chhoti Gandak River at different stations is shown in tables 2 and 3. The tables indicate that the concentration of pH ranges from 6.24 to 8.61 and total dissolved solid (TDS), which is a measure of the degree of quality, varies from 60–192.6 mg/L, with a mean of 103.56 mg/L. As per the classification of TDS (Fetter 1990), all the water samples come under fresh type (TDS <1000 mg/L). The total hardness (TH) in the water is in the range of 45–370 mg/L which indicates that the water of some sampling stations belongs to a very hard category (>300 mg/L; Twort *et al* 1974). Cation and anion analysis shows that the content of Ca^{2+} is between 6 and 36 mg/L; Mg^{2+} is between 4.8 and 42 mg/L, Na^+ is between 12 and 86 mg/L, K^+ is between 2.1 and 116 mg/L; HCO_3^- is between 98 and 451 mg/L; Cl^- is between 3.5 and 121 mg/L; SO_4^{2-} is between 88 and 186 mg/L; NO_3^- is between 14 and 38 mg/L; and F^- is between 0.4 and 0.59 mg/L, with mean values of 20.6, 18.2, 35.4, 21.2, 195.6, 38.1, 134.5, 24.5, and 0.45 mg/L, respectively. Water is characterized by $Na^+ > Ca^{2+} > Mg^{2+}$: $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ facies.

The pH and concentration of TH and Ca^{2+} in 40, 80 and 10% respectively of the water samples are more than the safe permissible limits proposed

Table 2. *Chemical constituent of the water at various stations.*

Parameters	Sampling stations									
	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-10
Temperature (°C)	29.2	31.3	32.2	36.6	34.4	31.4	32.8	38.7	29.7	34.2
pH	8.61	8.00	7.63	6.67	7.99	6.24	7.22	7.75	6.48	7.27
Conductivity (μs/cm at 25°C)	214.0	293.8	204.7	120.4	310.0	240.8	190.5	148.2	125.8	136.7
TDS	104.2	161.7	102.4	60.1	192.6	114.7	93.4	74.6	63.3	68.6
K^+	4.1	5.8	52	8.4	8.1	10	2.8	2.8	116	2.1
Na^+	27	14	59	12	14	42.5	15	54	86	31
Ca^{2+}	12	36	12	36	36	22.5	24	6	8	14
Mg^{2+}	19	4.8	42	8.4	6.0	25.3	7.3	7.3	41	21
Cl^-	3.5	17	121	14	21	60	25	7.1	85	28
F^-	0.54	0.46	0.40	0.43	0.44	0.59	0.42	0.44	0.42	0.44
NO_3^-	28	14	18	24	16	38	26	28	21	32
SO_4^{2-}	148	88	112	128	110	163	114	158	186	138
HCO_3^-	193	152	451	146	134	190	98	195	238	159
SiO_2	28	14	12	14	12	22	16	12	10	12
Total hardness (as $CaCO_3$)	110	110	370	125	115	160	90	45	190	120
SAR	1.59	0.60	2.54	0.66	1.06	2.15	0.97	4.94	3.84	1.73

Values of ions in mg/L (excluding physical data and ratios).

by Indian Standard Institute (1983) and World Health Organization (1984) (7–8.5 for pH, 100 mg/L for TH and 30 mg/L for Ca^{2+}) (table 4). So it can have an adverse affect on human health (Holden 1970; Maiti 1982). About 80% of the total water samples fall in the C1–S1 zone of salinity diagram (figure 2), and 20% in C1–S2 zones in the EC/SAR diagram (sodium adsorption ratio $= Na^+/\{[Ca^{2+} + Mg^{2+}]/2\}0.5$) (figure 2). This comes under the good water quality zone for irrigation (table 4). About 20% of the total water samples fall in the permissible to doubtful category and 70% of the samples come under excellent to good category and rest of the samples (10%) comes under good to permissible category in the EC/%Na^+ diagram [per cent $Na^+ = (Na^+ + K^+) \times 100/(Ca^{2+} + Mg^{2+} + Na^+ + K^+)$] (figure 3) (table 4).

4.2 *Compositional relations*

Compositional relations in water show that conductivity has a strong correlation with TDS, and moderate correlations with Ca^{2+} and pH. TDS has correlation with Ca^{2+} and pH. K^+ has strong correlation with Na^+, Mg^{2+} and moderate correlation with Cl^-, SO_4^{2-}, HCO_3^- and total hardness. Na^+ has a good correlation with Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^- and total hardness. Mg^{2+} has high correlation with Cl^-, total hardness, HCO_3^- and moderate correlation with SO_4^{2-} ions. Cl^- has a good correlation with HCO_3^- and SiO_2. NO_3^- has correlation with SO_4^{2-} and HCO_3^-. Total hardness has strong correlation with HCO_3^-.

4.3 *Principal component analysis*

The principal component analyses for the water of Chhoti Gandak River are shown in table 5. It includes loading for the rotated component matrix, eigenvalues for each component, per cent and cumulative per cent of variance explained by each component, and communality indicating the proportion of variance of each variable controlled by the set of components.

It indicates that the first three principal components together account for 77.966% of the total variance in the dataset, in which the first principal component is 34.139%, second principal component is 25.671%, and the third principal component is 18.156% of the total variance. The high (0.7–0.98) values of communality for all chemical variables (15) and the eigenvalues of the first three principal components (more than one) can be used to assess the dominant hydrogeochemical processes. The concentrations of Cl^-, Mg^{2+}, TH, HCO_3^-, K^+, and Na^+ show high positive loadings (0.728–0.941) whereas concentrations of SO_4^{2-} have

Table 3. *Descriptive statistics of the analyzed chemical components (at 10 sampling stations).*

Parameter	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation
Temperature	29.2	38.7	33.05	2.98673	8.9206
pH	6.24	8.61	7.386	0.75424	0.5689
Conductivity	120.7	310	198.52	67.76903	4292.6418
TDS	60.1	192.6	103.56	43.59916	1900.8871
K^+	2.1	116	21.21	36.46622	1329.7854
Na^+	12	86	35.45	24.68293	604.2472
Ca^{2+}	6	36	20.65	11.97231	143.3361
Mg^{2+}	4.8	42	18.205	14.16773	200.7247
Cl^-	3.5	121	38.16	38.44448	1477.9782
F^-	0.4	0.59	0.458	0.05978	0.03573
NO_3^-	14	38	24.5	7.47217	55.8333
SO_4^{2-}	88	186	134.5	29.7069	882.5000
HCO_3^-	98	451	195.6	97.80161	9565.1556
SiO_2	10	28	15.2	5.59365	31.2889
Total hardness	45	370	143.5	88.35063	7805.8333

Table 4. *Compliance of river water quality of water samples (%) to drinking and irrigation standards.*

Distribution of water samples			
Drinking purpose			
Chemical constituents	WHO (1984)	ISI (1983)	Samples (%) exceed the safety limits
pH	7–8.5	7–8.5	40
TDS	500	500	Within the range
TH	100	300	80
Ca^{2+}	75	75	Within the range
Mg^{2+}	30	30	10
Na^+	200	–	Within the range
HCO_3^-	–	300	Within the range
Cl^-	200	250	Within the range
SO_4^{2-}	200	150	Within the range
NO_3^-	45	45	Within the range
F^-	1.5	0.6–1.2	Within the range
Irrigation purpose			
Diagram	Zone	Samples (%)	Water quality type
EC versus SAR	C1–S1	80	Good
	C1–S2	20	Good
EC versus % Na	Permissible to doubtful	20	Good
	Excellent to good	70	Good
	Good to permissible	10	Good

low positive loadings (0.205) for the first principal component. In the second principal component TDS, conductivity, and Ca^{2+} concentrations have high positive loadings (0.785–0.890) and the concentration of pH, TH, F^-, and SiO_2 shows low positive loading (0.016–0.324). For the third principal component, the concentrations of F^-, and SiO_2 show high positive loadings (0.904–0.951), the concentrations of NO_3^- show moderate positive loadings (0.584) and the concentrations of SO_4^{2-},
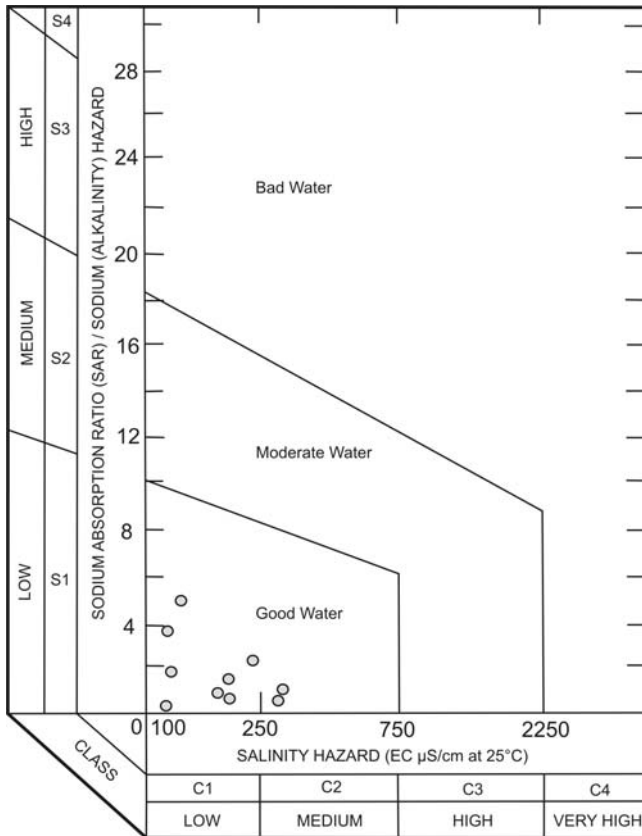
Figure 2. Classification of water for irrigation. Circles denote the chemical data of the water sampling stations.

conductivity, TDS, Mg^{2+}, and pH show low positive loadings (0.025–0.327).

The high positive loadings of Cl^-, Mg^{2+}, TH, HCO_3^-, K^+, and Na^+ ions on the first principal component suggest that the first principal component is associated with a combination of various hydrogeochemical processes and augment more mineralized water (TDS). For instance, a high positive loading of Na^+ ion suggests ion exchange on the clay materials. The process of dissolution of Na^+ and Cl^- ions indicates a higher rate of weathering in the area. Low slope gradient causes longer residence time for water and higher water-rock interactions which result in the enrichment of Na^+ and Cl^- ions, apart from their higher solubility character. The concentration of HCO_3^- in water is the result of the reaction of soil CO_2 with the dissolution of silicate minerals. Generally, mineral dissolution during water–soil and water–rock interactions depends on the amount of CO_2, originated from H_2CO_3. Thus, mineral saturation in water depends on the amount of pCO_2, Ca^{2+}, CO_2, HCO_3^-, and H_2CO_3. Decrease in pCO_2 and H_2CO_3 values during out gassing of CO_2 results in increase of HCO_3^- and pH levels (Ozler 2003). The concentration of TH and HCO_3^- suggests that most of the hardness in the water is temporary. The high

positive loadings of K^+ and Mg^{2+} ions, for the first principal component indicate the weathering of feldspar and ferro-magnesium minerals together with anthropogenic sources (Hem 1991; Zhang *et al* 1995 and Satyanarayana and Periakali 2003). The higher concentrations of TDS observed on the first principal component is related to Ca^{2+} and conductivity which is an indication of man-made pollution due to domestic wastes (Chettri and Smith 1995; Fisher and Mullican 1997 and Scheytt 1997). The concentration of NO_3^- in the water is also anthropogenic (irrigation return flow, fertilizers, and domestic wastes). The combination of HCO_3^- and NO_3^- ions is an indication of the hydrogeochemical effect of runoff leakage on the water (Wang and Luo 2001). The association of F^- and SiO_2 in water is due to ion exchange of F^- and OH^- in the clay minerals, low slope gradient, longer residence of water in the aquifer zone, intensive and long-term irrigational practices, and heavy use of fertilizers (Subba Rao and Devadas 2003).

The function of geogenic and anthropogenic activities on the water chemistry can be assessed with the help of scatter diagrams, ionic signatures, and mechanisms controlling the water chemistry diagrams to explain the processes responsible for controlling the water quality. The chemical data of water for half of the sampling stations with respect to Ca^{2+} and Mg^{2+} ions (called alkaline-earth elements)/HCO_3^- in this area (figure 4A) fall below the equiline. This suggests that excess of alkalinity (HCO_3^-) in the water is balanced by alkalis (Na^+ plus K^+). The plotting of chemical data related to the alkaline-earth elements/total cations (TC) in the water shows that the chemical data lie far below the equiline (figure 4B). This indicates an increasing contribution of the alkalis on TC. Significantly, the decrease in the alkalis corresponds to a simultaneous increase in the Cl^- plus SO_4^{2-} ions (figure 4D), suggesting a different source for these ions. A plot of $Na^+ + K^+/Cl^-$ is illustrated in figure 4E. Excess of Na^+ over Cl^- in the water reflects silicate weathering (Stallard and Edmond 1983). The water in the area has a high ratio of Na^+ plus K^+/TC (figure 4G) depicting the contribution of cations through silicate weathering and/or soils (Sarin *et al* 1989). At a majority of sampling stations, Cl^- plus SO_4^{2-} is greater than HCO_3^- (figure 4H). The relative abundance of Cl^- plus SO_4^{2-} compared to HCO_3^- (figure 4H) is due to the enriched water particularly in SO_4^{2-}. Except one sampling station for which $SO_4^{2-} > Cl^-$ (figure 4F).

The ionic signature Na^+: Ca^{2+}, is lower than unit except for three sampling stations (SW-3, SW-8 and SW-9) (table 6) and indicates a

Table 5. *Rotated component matrix of chemical data.*

Parameter	Principal components			Communality
	I	II	III	
K^+	0.796	−0.233	−0.208	0.79
Na^+	0.728	−0.569	−0.052	0.86
Mg^{2+}	0.922	−0.318	0.114	0.97
Cl^-	0.941	−0.031	−0.109	0.94
HCO_3^-	0.859	−0.104	−0.119	0.85
Total hardness	0.901	0.128	−0.109	0.84
TDS	−0.060	0.890	0.146	0.85
NO_3^-	−0.248	−0.613	0.584	0.84
SO_4^{2-}	0.205	−0.791	0.327	0.84
Ca^{2+}	−0.423	0.785	−0.109	0.94
Conductivity	−0.017	0.875	0.301	0.89
Temperature	−0.556	−0.246	−0.577	0.70
SiO_2	−0.164	0.016	0.904	0.87
F^-	−0.140	0.019	0.951	0.93
pH	−0.175	0.324	0.025	0.98
Eigenvalues	5.995	3.345	2.575	
% age of variance explained by component	34.139	25.671	18.156	
Cumulative % age of variance	34.139	59.890	77.966	

moderate concentration of Ca^{2+}. The moderate concentration of Ca^{2+} in the water is due to the ion exchange, which indicates an excess of alkalis over alkaline earth elements (figure 4C). The negative values (−0.006 to −2.12) of the Index of Base Exchange (IBE), i.e., IBE I ($Cl^- - Na^+ + K^+: Cl^-$) and IBE II ($Cl^- - Na^+ + K^+: HCO_3^-$) further support the enrichment of Na^+ in the water because of the clay horizons. The excess of Na^+ over K^+ in the water is due to the greater resistance of K^+ to the weathering and its absorption on the clay minerals.

Chemical data of water samples point towards a rock-dominance zone, according to the variations in the ratios of $Na^+: (Na^+ + Ca^{2+})$ and $Cl^-: (Cl^- + HCO_3^-)$ as a function of TDS in the water chemistry diagrams (figure 5). These diagrams assess the functional sources of dissolved ions as precipitation dominance, rock dominance, and evaporation dominance, which control the water chemistry (Gibbs 1970). The climatic conditions (sub-humid) also affect the evaporation and increase the concentrations of ions and thus TDS.

The area has mostly cultivable land with gentle slope gradient (21 cm/km) which is in partial equilibrium with the materials of the basins in a sub-humid climate. Chemical data's position within the rock dominance group depends on the
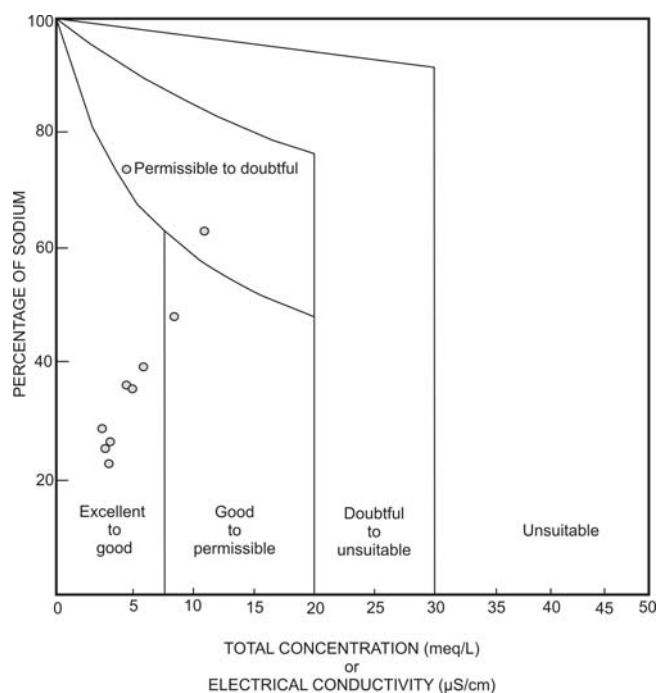

Figure 3. Suitability of water for irrigation. Circles denote the chemical data of the water sampling stations.

relief, climate, and the composition of the material in the basin. It supports the view of scatter diagrams, ionic signatures, and mechanisms controlling the water chemistry diagrams, which explain
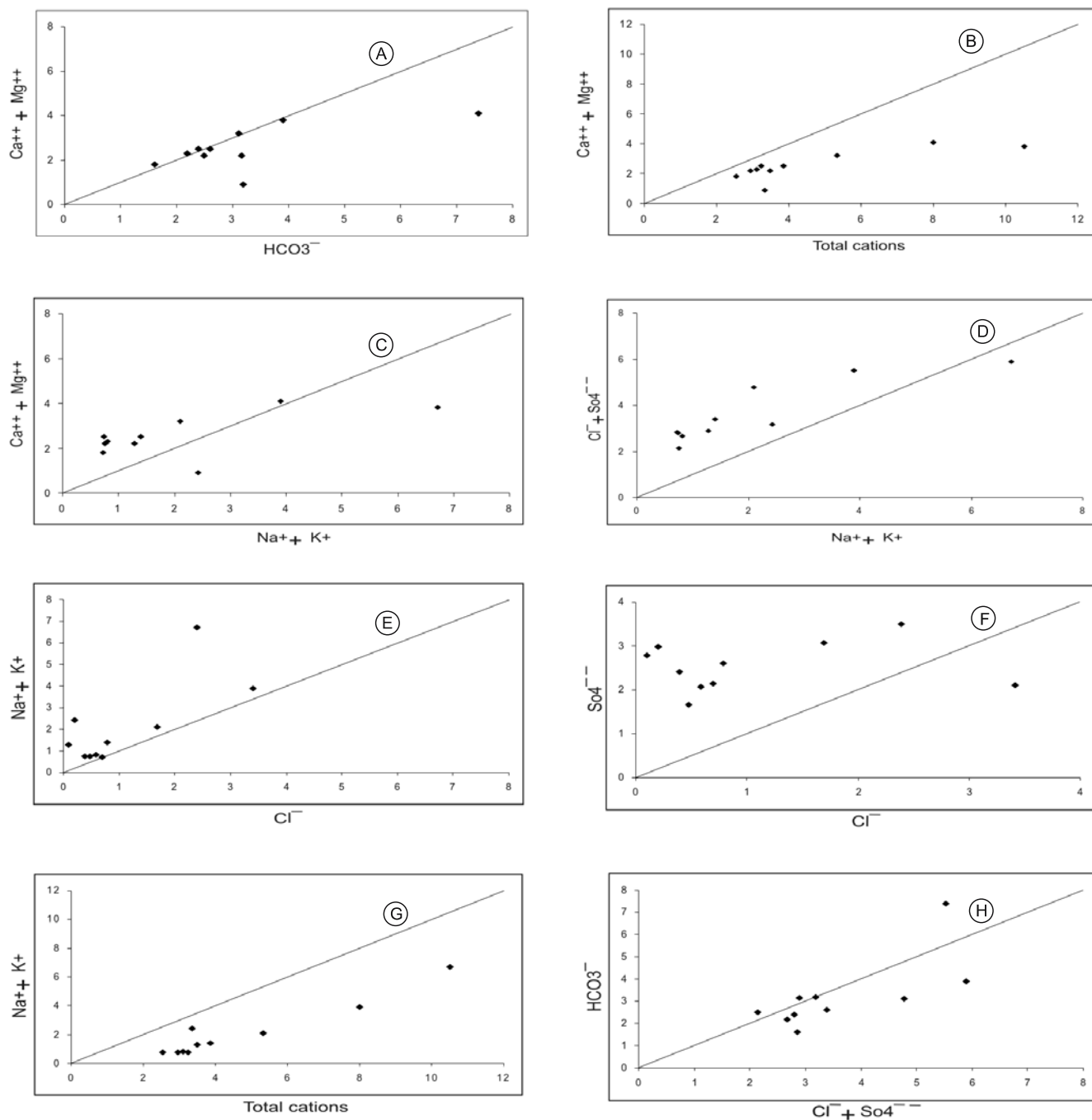
Figure 4. Scatter plots: A to H.

Table 6. *Particulars of ionic signatures.*

Signatures	Sampling stations									
	SW-1	SW-2	SW-3	SW-4	SW-5	SW-6	SW-7	SW-8	SW-9	SW-10
$Na^+ : Ca^{2+}$ (mmol/L)	0.98	0.17	2.14	0.15	0.17	0.83	0.27	3.92	4.68	0.96
IBE-1 (meq/L)	−0.006	0.183	1.23	0.42	0.332	−0.007	0.16	−1.75	−0.11	−0.486
IBE-2 (meq/L)	−1.046	−0.067	1.02	−0.04	−0.09	−0.77	0.1	−2.12	−0.59	−0.536

IBE = index of base exchange; IBE-1 = $(Cl^- - Na^+ + K^+ : Cl^-)$; IBE-2 = $(Cl^- - Na^+ + K^+ : HCO_3^-)$.
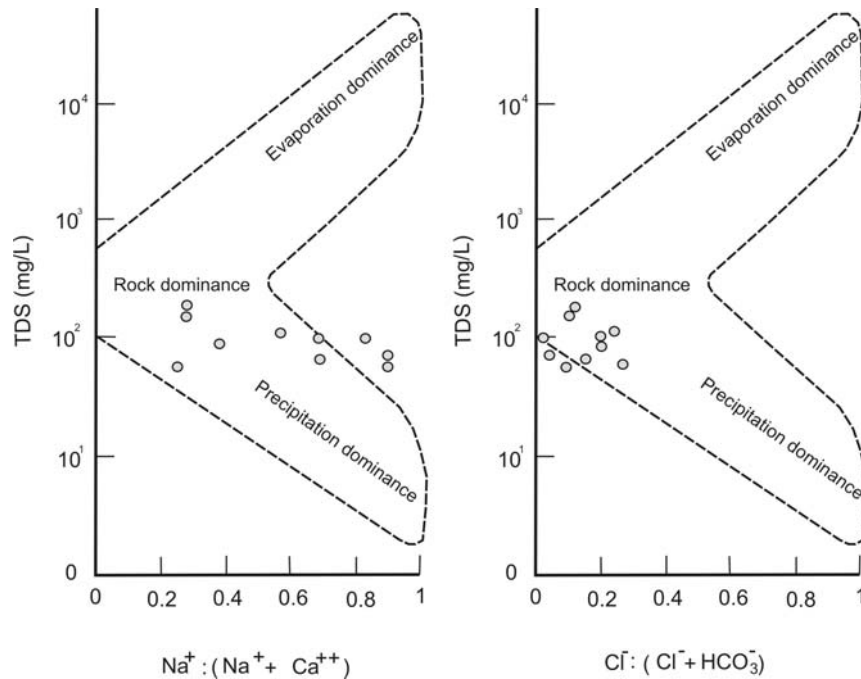
Figure 5. Mechanisms controlling the water chemistry Na^+: $(Na^+ + Ca^{2+})$ versus TDS and Cl^-: $(Cl^- + HCO_3^-)$ versus TDS. Circles denote the chemical data of the water sampling stations.

Table 7. *Distribution of groups.*

Groups	Chemical variables	First principal component		Second principal component		Third principal component	
		Positive	Negative	Positive	Negative	Positive	Negative
A	TH, Mg^{2+}	High	–	Low	Low (Mg^{2+})	Low	Low (TH)
B	Cl^-, HCO_3^-, K^+	High	–	–	Low	–	Low
C	Na^+	Moderate	–	–	Moderate	–	Low
D	SO_4^{2-}	Low	–	–	High	Low	–
E	TDS, conductivity, Ca^{2+}	–	Low	High	–	Low	Low (Ca^{2+})
F	pH	–	Low	Low	–	Low	–
G	F^-, SiO_2	–	Low	Low	–	High	–
H	NO_3^-	–	Low	–	Moderate	Moderate	–

Groups: low = less than ($\pm$) 0.500; moderate = ($\pm$)0.500 – 0.750; high = grater than ($\pm$) 0.750.

the variations in the chemical composition of water, as also observed in the first, second, and third principal component loadings.

The first, second, and third principal components loading plots illustrated in table 5, are divided into eight groups (table 7), namely, A–H, on the basis of their relative positions. Various groups of water identified clearly indicate the variables which broadly distinguish the geogenic sources (groups A, B and C) from the anthropogenic ones (groups D and E). It also infers that the variables in groups A, B, and C have high variability in the data set, in groups D and E variables have the second most influential function, and in

groups F, G, and H variables have some influence on the variability in the dataset.

5. Conclusions

Water of the Chhoti Gandak River is hard at most places. The concentrations of TH, Mg^{2+} exceed the safety limit prescribed for drinking at some of the stations and may cause physical disorders. At most of the stations however, water is of good quality for irrigation, and can be used for agricultural production. The scatter diagrams, ionic signatures, and mechanisms controlling the water

chemistry diagrams indicate that the first principal components are controlled by gentle slope gradient, poor drainage conditions, long residence of water, high rate of weathering, ion exchange, heavy use of fertilizers, and domestic wastes. Variables in groups A, B, and C have high variability in the dataset, in groups D, and E variables have the second most influential function, and in groups F, G, and H variables have some influence on the variability in the dataset. The groups broadly distinguished geogenic sources from the anthropogenic ones.

The present study suggests that the principal component analysis determines the assemblages of water quality, which are an indication of genetic processes and the origin of pollutants with respect to domestic and agricultural sectors. Analysis is useful for sustainable development through planning and for implementing remedial measures within time to mitigate the adverse effects of the poor quality of water on human health as well as on plant growth.

Acknowledgements

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