



Quantifying and trend analyzing dynamics of water quality variables of two Indus basin rivers of Indian Punjab

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Received: 13 January 2023 / Accepted: 6 June 2023 / Published online: 20 June 2023
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Abstract

Water scarcity is becoming a global problem especially in the arid and semi-arid climates. Besides shrinking in quantity, surface and ground waters are getting polluted due to anthropogenic activities. Management of water resources requires analysis of long-term water quality data. The present work is the first study that uses long-term data (2004–2020) of 30 water quality variables from 24 locations across rivers Satluj and Beas, the two main tributaries of river Indus flowing through India. Exploratory analysis revealed least variation in pH and dissolved oxygen (DO) and greatest variation in total coliform (T. Coli) and fecal coliform (F. Coli). Beas had 78% samples of designated best use category B (outdoor bathing), 18% of C (drinking after conventional treatment and disinfection) and 4% of A (drinking without conventional treatment but after disinfection). On the contrary, 31% samples of Satluj belonged to B, 32% to C and rest to D (wild life and fisheries) and E (other uses). Locations Mukerian (Beas) and D/S Buddha Nullah (Satluj) were identified as hot spots. Mann–Kendall analysis showed significant increasing trend for pH, chemical oxygen demand (COD), biological oxygen demand (BOD), potassium, DO, T. Coli, F. Coli and nitrite at majority of the locations. Significant decreasing trends were observed for electrical conductivity, calcium, phosphate, sulfate, total dissolved solids, chloride, nitrate and total hardness. Rising levels of BOD, COD, T. Coli and F. Coli had carryover impact on confluence waters. Therefore future remedial actions must focus on hot spots and variables showing significant increasing trends.

Keywords Designated best use · Hot spots · Long-term trends · River · Water quality

Introduction

Clean water is one of the basic requirements of life and assured availability of clean water is essential for sustainable human development. India has 18% of the world population while it has only 4% of global fresh water resources. The annual per capita freshwater availability in the country has declined from 5177 m³ in 1951 to about 1545 m³ in 2011 (DoWR 2019), close to the 1000 m³ mark identified to label a country or a region facing “water scarcity”. As per a report by United Nations (2022), 74% of the global population had access to safely managed drinking water by 2020 but 2 billion people could not access such services. Therefore, water scarcity is a rising concern among nations and declining per capita water availability in India is a triggering situation which calls for an urgent action to augment clean water supplies. Rivers or surface waters are an important source of clean water supply and are considered the key source to perform daily chores in life. However, mindless growth in

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industries, human population and changing human life style has deprioritized this natural resource. Though flowing water in the river has the capacity to self-purify yet anthropogenic activities such as construction of dams, diversion of river water for industries, domestic and agriculture use and disposal of untreated waste water and industrial effluents has over-shadowed this capacity. Most of the rivers in India are bearing the brunt of inhumane behavior due to the regular disposal of tremendous amounts of untreated wastes into them. In India, about 40 million liters of waste water is disposed off in rivers every year. About 70–80% of rivers in India are polluted and such situation has aggravated with unprecedented increase in urbanization, industrialization and human population (Khan et al. 2022; Sharma 2012).

Punjab, being India's agriculturally productive state has continued with good economic growth but problems such as land degradation, deterioration of surface as well as ground water quality are emerging (Singh et al. 2020). In Indian Punjab, rivers Beas and Satluj once the most pristine, are at the receiving end due to the continuous waste disposal from rural and urban areas and industries that are not letting the rivers reach their natural state. Not surface waters alone, studies are also suggestive of groundwater contamination with increasing deterioration of surface water quality (Edet and Worden 2009). Surface waters were the important source of irrigation during green revolution period (1966–1967) with canals contributing about 42% and tube-wells about 18.5% of the total net irrigated area of the country. However, post green revolution there was fourfold increase (73.91%) in dependency on ground waters (especially tube-wells) sources (Dutta 2018). Such shift in dependency from surface to groundwater besides putting burden on groundwater sources causes rise in the C footprint of food grain production (Benbi 2018). Thus relying on the surface waters will minimize the C footprint as well as address the 6th UN sustainable development goal targets of clean and safe water supply, improving water quality and protecting and restoration of water related ecosystems. The current state of Satluj and Beas rivers is highly degraded and has a direct negative impact on human health, aquatic life, and agriculture as well as groundwater resources. To protect the ecohydrological quality of river waters, to maintain the integrity of their functions and to escape the situation of water scarcity challenges, it becomes imperative to consistently monitor dynamics of water quality variables that can assimilate to destroy self-purification capacity of rivers. Long-term river water quality monitoring data can be thoroughly studied to find solutions and design different pollution management strategies. Studies have been conducted worldwide to explore long-term changes in the surface water quality (Duan et al. 2018; Pinto et al. 2017; Wan and Li 2018; Kumar et al. 2021). However, studies on

assessment of water quality of Satluj and Beas are based on findings of limited monitoring locations over one or few years (Jindal and Sharma 2011; Sharma et al. 2017; Chugh et al. 2009; Solanki and Khera 2019). No comprehensive study is yet available on the long-term analysis of river water quality of Satluj, Beas and their confluence waters. In the present study, statistical analysis techniques such as exploratory analysis and trend tests are employed which are promising tools to understand spatio-temporal changes in river water quality variables. Therefore, in the present study, long-term spatio-temporal data on different water quality variables, collected over a period of 16 years for Beas, Satluj and confluence waters, was used (1) to quantify the dynamics of different water quality variables for their impact assessment on Beas, Satluj and confluence waters, (2) to characterize locations as “near clean” or “hot spots” with respect to different water quality variables and (3) to identify the presence of any significant increasing or decreasing trends in variables. Thus, in depth investigation of monitoring data will provide a more comprehensive depiction of the water quality profiles of the Beas and Satluj rivers and confluence waters.

Methodology

Study area

Beas River originates near the Rohtang Pass of Himalayas at an altitude of about 4361 m above mean sea level. It enters Punjab plains through Hoshiarpur district near Talwara, passes through Kapurthala and Amritsar (Fig. 1). It covers a length of 214 km in Indian Punjab and joins Satluj near Harike at the border of districts Tarn Taran and Ferozepur of Punjab, further continuing southwest along the India-Pakistan border before entering Pakistan. Satluj, the longest tributaries of the Indus water system originate in the northern Himalayan slopes, at an altitude of 4570 m above the mean sea level. It enters Punjab at Nangal in Rupnagar district and leaves the state near Ferozepur covering a length of 440 km and finally drains into the river Indus in Pakistan.

Water quality variable data

Data on water quality variables (30) of rivers Satluj and Beas along with the geographical coordinates of 24 different sampling locations were acquired from Punjab Pollution Control Board (PPCB). Four additional variables namely, sodium adsorption ratio (SAR), percent sodium (Na%) relative to other cations, Kelly ratio (KR) and magnesium adsorption ratio (MAR) were computed using Eqs. 1–4, respectively.

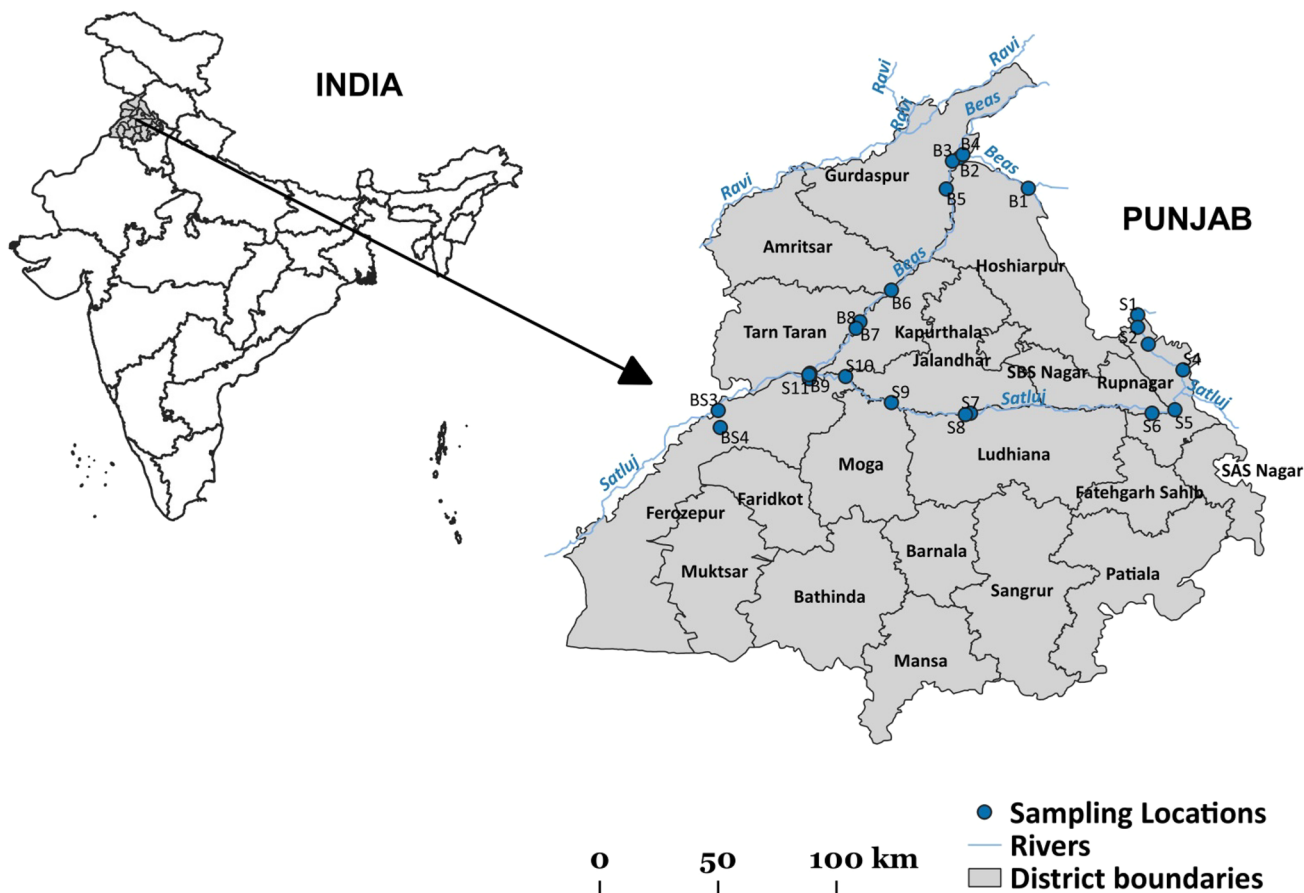


Fig. 1 Water quality sampling locations of rivers Beas and Satluj and confluence waters in the Indian state of Punjab. The sampling locations are marked B1–B9 for river Beas, S1–S11 for river Satluj and

BS1–BS4 for confluence waters. For a description of the sampling locations see Table 1

$$\text{Sodium adsorption ratio (SAR)} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} \tag{1}$$

$$\text{Percent sodium (\% Na)} = \frac{\text{Na}^+ + \text{K}^+}{\text{Na}^+ + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+} \times 100 \tag{2}$$

$$\text{Kelly ratio (KR)} = \frac{\text{Na}^+}{\text{Ca}^{2+} + \text{Mg}^{2+}} \tag{3}$$

$$\begin{aligned} \text{Magnesium adsorption ratio (MAR)} \\ = \frac{\text{Mg}^{2+}}{\text{Ca}^{2+} + \text{Mg}^{2+}} \times 100 \end{aligned} \tag{4}$$

Data timeline spanned from Jan, 2004 to Jan, 2020 for 9 sampling locations of Beas, 11 of Satluj and 4 of confluence of the two rivers. Sampling locations with their location codes are presented in Table 1. Sampling locations were mapped using QGIS software (Fig. 1). Data, on most of the water quality variables, were available on quarterly basis

(January, April, July and October) for each year till 2015 and on monthly basis from 2016 through 2019 except for unavailability for February and March in 2016. Water quality variables considered in the present study along with their methods of analysis are given in Table 2. Water quality analysis was mostly done for 10–13 water quality variables on the available data except for the month of April when quality analysis was conducted for 26–30 water quality variables for all sampling locations. The entire data record of water quality variables was compiled in MS Excel and subjected to further statistical analysis to quantify and understand the relationship among different water quality variables.

Exploratory statistical analysis

Descriptive statistics viz. mean, maximum, minimum, and coefficient of variation (CV) for different water quality variables was computed in MS Excel. Data screening was done and the values which were below detection limit (BDL) were not made part of the analysis (Ye and Kameyama 2020). Analysis of variance (ANOVA) was performed

Table 1 Sampling locations along rivers Beas, Satluj and confluence waters

Location code	Sampling location name
River Beas	
B1	Talwara
B2	U/S Pathankot
B3	D/S Pathankot
B4	Mirthal Bridge Gurdaspur
B5	1 km D/S effluent discharge point at Mukerian
B6	G.T. Road, under Bridge Near Kapurthala
B7	U/S Goindwal
B8	100 m D/S Industrial discharge point Goindwal
B9	Beas at Harike
River Satluj	
S1	100 m, U/S of H/W Nangal
S2	D/S NFL
S3	100 m, D/S Nangal
S4	Kiratpur Sahib
S5	U/S Head works, Ropar
S6	1 km D/S Rishab Paper Mill
S7	U/S BudhaNullah
S8	100 m D/S BudhaNullah confluence Ldh
S9	Boat Baridge, DharamkotNakodar Road
S10	D/S East Bein
S11	Bridge Harike, Amritsar
After confluence	
BS1	D/S Harike
BS2	Harike Lake D/S from canal
BS3	U/S Hussainiwala H/W Ferozepur
BS4	D/S Hussainiwala H/W Ferozepur

by employing Tukey post hoc test at 95% confidence level (Tukey 1977) using SAS software to compare means of different water quality variables of river Beas, Satluj and confluence waters. Overall percent change in the water quality variables after convergence of rivers, was determined as per Eq. (5)

$$\% \text{change in variables after confluence} = \frac{\text{Value of variable before confluence} - \text{value of variable after confluence}}{\text{Value of variable before confluence}} \times 100 \quad (5)$$

The samples for each site at a given time were classified into five Designated Best Use (DBU) categories on the basis of pH, T. Coli, DO and BOD (CPCB, IS 2296:1992; <https://cpcb.nic.in/water-quality-criteria/>). DBU categorizes water into five different classes as, A = Drinking water source without conventional treatment but after disinfection; B = Outdoor bathing; C = Drinking water source after conventional treatment and disinfection; D = Fisheries and wildlife and E = Irrigation, industrial cooling and controlled waste

disposal (Table 3). This information was used to find the number of samples that fell into different categories (A, B, C, D & E) across locations over the time span of ~ 16 years.

Calculation of Nemerow's pollution index (NPI)

This index is expressed as the relative value when the concentrations of the variables are related to their standard value (Nemerow and Sumitomo 1970). This method has been used in different studies for finding out the responsible parameter for polluting the water (Khan et al. 2022).

NPI of different variables was calculated using the Eq. (6)

$$\text{NPI} = \frac{C_i}{L_{ij}} \quad (6)$$

where, C_i the observed concentration of i th parameter, L_{ij} is permissible limit of i th parameter for j th water use. For $\text{NPI} \leq 1$ indicates that the variable is not present in amounts to cause or contribute to the pollution whereas for $\text{NPI} > 1$ indicates that the particular variable has the potential to contribute to the pollution of water.

Identifying hot spots and near clean locations

A site with highest frequency of maximum concentration is termed as “hot spot” and a site with highest frequency of minimum concentration is termed as “near clean” location. Hot spots were calculated based on the maximum value encountered in the range for a location over time. The hot spots and near clean locations indicate the number of times, during entire span of 16 years, a particular location had maximum or minimum value of the water quality variable, respectively. Minimum (Maximum) is the value of the variable reported as minimum (maximum) across stretch of Beas/Satluj/confluence during a specific year. These values were calculated for all the years using “IF” logic function with binary output (“0” and “1”) in excel and their further

summation calculates for how many times a location reports the “minimum” (“maximum”) value of the variable. In case of DO, minimum value is indicative of bad quality waters and maximum value indicates, more dissolved oxygen available for the aquatic life to use, thus suggests presence of non-stressed oxygen conditions. So, high frequency of minimum and maximum value of DO suggests lack of dissolved oxygen and presence of abundant dissolved oxygen, respectively.

Table 2 Water quality variables, acronyms, methods of determination and detection limits

S. no.	Water quality variable	Acronym	Units	DL	Method/instrument used	S. No	Water quality variable	Acronym	Units	DL	Method/instrument used
1	pH	–	Unitless	–	Glass electrode; pH meter	19	Nitrite nitrogen	NO ₂ ⁻	mg L ⁻¹	0.1	Colorimeter
2	Electrical conductivity	EC	µS/cm	–	Salt bridge; conductivity meter	20	Total Kjeldhal nitrogen	TKN	mg L ⁻¹	0.0	–
3	Turbidity	–	NTU	–	Turbidity meter	21	Free ammonia	Free NH ₃	mg L ⁻¹	–	–
4	Alkalinity	–	mg L ⁻¹	–	Titration method	22	Phosphate phosphorus	PO ₄ ³⁻	mg L ⁻¹	0.01	–
5	Total hardness	TH	mg L ⁻¹	–	Versenate method	23	Calcium	Ca ²⁺	mg L ⁻¹	–	Flame photometer
6	Chemical oxygen demand	COD	mg L ⁻¹	5	Open reflux method	24	Magnesium	Mg ²⁺	mg L ⁻¹	–	–
7	Biochemical oxygen demand	BOD	mg L ⁻¹	0.5	Winker method	25	Potassium	K ⁺	mg L ⁻¹	–	–
8	Dissolved oxygen	DO	mg L ⁻¹	–	–	26	Sodium	Na ⁺	mg L ⁻¹	–	–
9	Total fecal coliform	F. Coli	MPN/100 ml	1.8	Multiple tube fermentation	27	Sulfate sulfur	SO ₄ ²⁻	mg L ⁻¹	–	Turbidity method
10	Total coliform	T. Coli	MPN/100 ml	–	technique	28	Chlorides	Cl ⁻	mg L ⁻¹	–	Titration method
11	Fixed dissolved solids	FDS	mg L ⁻¹	10	Gravimetric method	29	Water temperature	–	°C	–	Mercury-filled Celsius thermometer
12	Total dissolved solids	TDS	mg L ⁻¹	–	–	30	Sodium adsorption ratio	SAR	Unitless	–	Equation 1
13	Total fixed solids	TFS	mg L ⁻¹	5	–	31	Sodium percent	Na%	–	–	Equation 2
14	Total soluble solids	TSS	mg L ⁻¹	–	–	32	Kelly ratio	KR	–	–	Equation 3
15	Fluorides	F ⁻	mg L ⁻¹	0.1	Ion selective electrode	33	Magnesium adsorption ratio	MAR	–	–	Equation 4
16	Boron	B	mg L ⁻¹	0.05	Atomic Absorption Spectrophotometer						
17	Ammonical nitrogen	NH ₄ ⁺	mg L ⁻¹	0.0	Colorimeter						
18	Nitrate nitrogen	NO ₃ ⁻	mg L ⁻¹	0.01	–						

DL detection limit

Table 3 Designated best use criteria of water quality (Source: <https://cpcb.nic.in/water-quality-criteria/>)

Designated best use	Class of water	Criteria
Drinking water source without conventional treatment but after disinfection	A	Total coliforms organism MPN/100 ml shall be 50 or less pH between 6.5 and 8.5 Dissolved oxygen 6 mg/L or more Biochemical oxygen demand 5 days 20 °C 2 mg/l or less
Outdoor bathing (organized)	B	Total coliforms organism MPN/100 ml shall be 500 or less pH between 6.5 and 8.5 Dissolved oxygen 5 mg/l or more Biochemical oxygen demand 5 days 20 °C 3 mg/l or less
Drinking water source after conventional treatment and disinfection	C	Total coliforms organism MPN/100 ml shall be 5000 or less pH between 6 to 9 Dissolved oxygen 4 mg/l or more Biochemical oxygen demand 5 days 20 °C 3 mg/l or less
Propagation of wild life and fisheries	D	pH between 6.5 and 8.5 Dissolved oxygen 4 mg/l or more Free ammonia (as N) 1.2 mg/l or less
Irrigation, industrial cooling, controlled waste disposal	E	pH between 6.0 and 8.5 Electrical conductivity at 25 °C micromhos/cm Max. 2250 Sodium adsorption ratio max. 26 Boron max. 2 mg/l
	Below-E	Not meeting A, B, C, D & E Criteria

Mann–Kendall time trend analysis and Sen’s slope statistics

The Mann–Kendall trend test was used to detect any existing significant trends in time series of months of January, April, July and October from 2004 to 2019 using “kendall-TrendTest” function in the “EnvStats” package in R (Millard 2014). It is a special case of testing for monotonic trend where observations are taken periodically and are equally spaced over time. This test produces Z_S statistic score which if > 0 suggests presence of increasing trend, < 0 suggests presence of decreasing trend and $= 0$ suggests no trend in the data at specific significance level ($\alpha = 0.01$ or $\alpha = 0.05$). Here, Z_S is computed as follows (Eq. 7) with condition of sample size > 10 ,

$$Z_S = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0 \end{cases} \quad (7)$$

Here, $\text{Var}(S)$ is the variance of Mann–Kendall test statistic (S) and are computed as follows (Eq. 8):

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (8)$$

here, n is the number of data points, m is the number of tied groups and t_i denotes the number of ties of extent i . A tied group is a set of sample data having the same value.

As far as S statistic (Mann 1945) is concerned, it represents (Eq. 9)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (9)$$

where n is the number of data points, x_i and x_j are the data values in time series i and j ($j > i$), respectively and $\text{sgn}(x_j - x_i)$ is the sign function (Eq. 10) as:

$$\text{sgn}(x_j - x_i) = \begin{cases} +1, & \text{if } (x_j - x_i) > 0 \\ 0, & \text{if } (x_j - x_i) = 0 \\ -1, & \text{if } (x_j - x_i) < 0 \end{cases} \quad (10)$$

Significant data trends with $p < 0.05$, detected for each variable, were mapped for all locations using QGIS software. Each location was color coded to represent spatial distribution of significant increasing (red), decreasing (blue) and no-significant trends (white). “kendallTrendTest” also yield Sen’s slope statistics that calculate slope for each pair of observations as follows -

$$\beta_1 = \text{Median} \left(\frac{Y_j - Y_i}{X_j - X_i} \right); \quad i < j \quad (11)$$

Sen (1968) generalized the slope estimator as proposed (Theil 1950) in Eq. 11–12,

$$\beta_1 = \text{Median} \left(\frac{Y_j - Y_i}{X_j - X_i} \right); \quad i < j, X_i \neq X_j \quad (12)$$

where the X 's are tied and the slope is computed based on the median of the remaining ' N ' two-point estimated slopes. To run Mann–Kendall test, prewhitening was not performed

because the data for each variable had large sample size and high magnitude of slope of trend especially for the variables which had high CV. Therefore, as per suggestions in literature the prewhitening procedure is not needed for large samples ($n \geq 50$) having high slopes of trend ($b \geq 0.01$), which if applied would cause significant power loss and would affect the rejection rate of the test in these cases (Bayazit and Önöz, 2007).

Results and discussion

Exploratory statistical analysis

Certain sampling locations had values of the water quality variables close to zero or BDL while for others the values crossed their permissible and desirable limits (Table 4). For Beas, most of the water quality variables were well within the limits as per Bureau of Indian standard (BIS-10500 2012) guidelines except for Turbidity, BOD, T. Coli, F. Coli, TSS, Free NH_3 , PO_4^{3-} , Ca^{2+} and Mg^{2+} . On the contrary, most of the variables for Satluj exceeded their acceptable and permissible limit(s). However, after the confluence most of the variables were well within the limits except BOD, Na%, KR and MAR.

Overall, there was variation of 3.5–304.9%, 4.7–554.8% and 4–360.0% in the water quality variables for Beas, Satluj and confluence waters respectively, at different sampling locations over 16 years (Fig. 2). For Beas and confluence waters, only five variables had CV more than 100 whereas for Satluj 11 variables had CV greater than 100. The magnitude of variation associated with variables such as pH (3.5–4.7%) and DO (7.8–27.9%) was very small compared with T. Coli (103.2–304.9%), F. Coli (120–554.8%), Free NH_3 (130–154.6%) and TSS (206.9–256.9%) for both the rivers and confluence waters. Except for some locations of Satluj, the pH of rivers Beas, Satluj and confluence waters was well within the limit (6.5–8.5) and ranged from neutral to alkaline in reaction. Less variation in pH was expected because of its tendency to increase or decrease in response to the nature (basic or acidic) and rate of material being dumped into the river waters.

Less fluctuating levels of DO suggest that highly polluted locations of rivers did not have enough levels of DO prior to outfall of untreated wastes, which resulted in notable spikes in the levels of T. Coli and F. Coli and subsequent higher variation in these variables. However, such spikes could not drive huge drop in the DO as the level of DO was already near zero. This was the case at certain locations (Rishab Mill, D/S Buddha Nullah, Dharamkot and East Bein) along stretch of river Satluj where DO level was zero or BDL. The overall range of DO (BDL to 9.80 mg L^{-1}) was wider for Satluj compared to Beas ($4.8\text{--}9.8 \text{ mg L}^{-1}$) and confluence

waters ($4\text{--}9.5 \text{ mg L}^{-1}$). Drop in DO for Satluj caused the range to look wide as DO did not drop to zero or BDL for Beas and confluence waters. However, the upper limit of $\sim 9 \text{ mg L}^{-1}$ of DO pictured good quality waters but such scenario was mainly associated with the upstream locations at the entry of the rivers Beas and Satluj.

Great amount of variation was associated with some of the water quality variables (for instance, $\text{CV} = 304.9\%$ in T. Coli for Beas). T. Coli and F. Coli had wide variation and exceeded their acceptable limits at certain locations of Beas, Satluj and confluence waters. Significantly higher T. Coli and F. Coli were observed for Satluj compared to Beas and after confluence (Table 4). Higher values of T. Coli and F. Coli than their acceptable limits indicate the unsuitability of the Satluj water for drinking as well as irrigation purposes. The coliform bacteria may enter the river water by runoff from the open sewage system near the human habitation on the river banks and from untreated disposal from sewage, septic tank and uncontrolled dumping of organic waste (Alam et al. 2021) at different times of the year. High levels of T. Coli and F. Coli causes water borne diseases like jaundice, Typhoid, Cholera etc. in humans and their land application can have adverse effects on agriculture causing contamination of human food chain leading to several infectious diseases (Nieder et al. 2018).

Similar to T. Coli and F. Coli, BOD and COD also showed close interaction with DO. These variables showed variation up to 200% for river Satluj. For Beas, BOD went up to 10 mg L^{-1} just for Mirthal Bridge Gurdaspur (B4; April 2015) and Mukerian (B5; April 2005). Significantly higher BOD (upto 115 mg L^{-1}) for Satluj indicates presence of biodegradable organic matter that comes from industries such as dairy, paper, pulp and textiles. These industries release effluents with moderate to high BOD such as starch, vegetable oils, fats, waxes, organic acids (formic-, acetic and carboxylic acids) and reducing agents (sodium sulfide, sodium dithionite) (Chakraborty 2010). Degradation of these effluents provide nutrients for the growth of the bacteria and other microorganisms suggesting higher industrial and domestic pollution loads in Satluj due to rapid development of industries, agriculture and urbanization. In this region, Buddha Nullah and East Bein drains are known to be the major point source of pollution discharging untreated waste water into the Satluj. Buddha Nullah contributes about $16,672 \text{ kg/day}$ of BOD load, while East Bein adds approximately $20,900 \text{ kg/day}$ of BOD load (Verma 2021). Higher BOD indicates depletion of the DO in the water. Lower DO and higher BOD are attributed mainly to discharge of effluents, slower water flow rate of river due to water diversion and higher temperature that increases the organic decomposition of untreated sewage and agricultural runoff (Herojeet et al. 2017). Higher levels of BOD are suggestive of presence of pollutants detrimental to aquatic life. The COD

Table 4 Descriptive statistics (2004–2020) for river Beas, Satluj and confluence waters

Variable	Critical limit			Beas			Satluj			Confluence waters				
	Desirable	Permissible	No. of observations	Min	Max	Average	No. of observations	Min	Max	Average	No. of observations	Min	Max	Average
pH	6.5–8.5	–	844	6.5	8.3	7.5 ^b	1038	6.3	8.6	7.6 ^a	373	6.7	8.5	7.5 ^a
EC	2250	–	843	158	513.0	263.2 ^c	1038	168	1787	396.2 ^a	373	160	513	305.9 ^b
Turbidity	1	5	521	0.9	122.0	24.8 ^a	634	0.8	164	21.1 ^b	228	1.8	124	24.3 ^a
Alkalinity	200	600	512	44	172.0	95.5 ^a	636	28	372	100.5 ^a	229	35	156	96.8 ^a
TH	200	600	521	16	180.0	110.7 ^a	636	10.5	296	110.4 ^a	229	18	176	102.6 ^b
COD	250	–	828	1, BDL	32.0	8.76 ^b	917	1, < 5, BDL	416	26.4 ^a	363	1, < 5	24	9.6 ^b
BOD	2	–	771	0.1, < 1, BDL, ND	10.0	1.20 ^b	691	0.2, < 1, ND, BDL	115	8.7 ^a	293	0.2, BDL, ND	10	1.7 ^b
DO	> 7	–	844	4.8	9.8	7.44 ^a	1028	0, B	9.8	6.6 ^c	373	4	9.5	6.9 ^b
F. Coli	–	–	808	2, ND	5000	178.4 ^b	972	9, < 2, ND	1,700,000	14,835.4 ^a	355	20, ND	3500	374 ^b
T. Coli	< 50	–	844	23	50,000	716.1 ^b	1034	23	3,500,000	33,371.6 ^a	371	70	6300	1002 ^b
FDS	–	–	422	78	458	147.6 ^c	515	19	1109	241.4 ^a	185	78	360	175 ^b
TDS	500	2000	521	98	480	173.5 ^c	636	106	1180	268.8 ^a	229	120	378	197 ^b
TFS	–	–	99	98	170	132.8 ^c	121	116	890	222.4 ^a	44	120	224	165 ^b
TSS	–	–	500	4, ND, BDL	1208	95.8 ^a	589	0.8, ND, BDL	494	35.8 ^c	225	6, ND	1112	58.8 ^b
F ⁻	1	1.5	369	0.08, ND, BDL	1.0	0.2 ^c	499	0.1	2.6	0.5 ^a	183	0.10	1.0	0.3 ^b
B	0.5	1	213	0.04, BDL	0.96	0.2 ^a	292	0.02, BDL	4.8	0.2 ^a	100	0.05, BDL	0.72	0.2 ^a
NH ₄ ⁺	–	–	371	0.12, ND, BDL	2.4	0.7 ^c	613	0.2, BDL	30	2.4 ^a	224	0.14, BDL	9	1.5 ^b
NO ₃ ⁻	45	–	800	0, ND, BDL	4.4	1.2 ^c	1014	0.07	14	1.6 ^a	362	0.10	4.3	1.3 ^b
NO ₂ ⁻	–	–	367	0, ND	3.8	0.8 ^c	416	0.03, ND	10.4	1.4 ^a	152	0.04, ND	4	1.2 ^b
TKN	0.5	–	367	0.1, BDL	5.0	1.3 ^c	605	0.4, BDL	68	4.2 ^a	225	0.8, BDL	8.4	2.4 ^b
Free NH ₃	–	–	122	0.003, BDL	0.35	0.02	140	0.00005, BDL	0.6	0.07	57	0.001, BDL	0.5	0.05
PO ₄ ³⁻	–	–	435	0, BDL	3.8	0.5 ^c	607	0.04, BDL	6.4	1.1 ^a	225	0.05, BDL	3	0.9 ^b
Ca ²⁺	75	200	521	10.0	140	31.7 ^a	636	8.8	110	29.4 ^b	229	8	64	28.3 ^b
Mg ²⁺	30	100	521	2.0	81	8.1 ^b	636	2.4	100	10.1 ^a	229	2	90	8.6 ^b
K ⁺	–	–	476	0.6	6.8	2.6 ^c	590	0.7	54	5.9 ^a	213	0.8	50.4	3.9 ^b
Na ⁺	–	–	476	1.0	45	14.5 ^b	590	0.7	202	28.3 ^a	213	2.3	86.3	15.9 ^a
SO ₄ ²⁻	200	400	521	1.20	120	14.3 ^b	636	5.0	146	22.9 ^a	229	5	28	15.5 ^b
Cl ⁻	250	1000	521	6.0	138	18.2 ^c	636	5.0	220	34.1 ^a	229	6	128	23 ^b
Water temperature	–	–	610	1.0	39	19.3 ^b	758	5.0	35	20.8 ^a	269	10	34	21.2 ^a
SAR	10	–	476	0.04	1.8	0.6 ^b	579	0.03	7.6	1.1 ^a	209	0.1	4.3	0.7 ^b
Na%	60	–	476	5.2	68.1	36.3 ^c	590	6.7	91.2	48.1 ^a	213	12.9	86.7	41.6 ^b
KR	1	–	476	0.04	2.0	0.59 ^c	590	0.03	10.1	1.1 ^a	213	0.09	4.8	0.8 ^b
MAR	50	–	521	9.2	82.8	29.6 ^c	636	9.71	83.6	35.9 ^a	229	8.06	82.4	33.6 ^b

Letters (a, b and c) superscript to averages indicate significant ($p < 0.05$) differences in the averages of Beas, Satluj and confluence waters with ANOVA
 BDL below detection limit, ND not detected

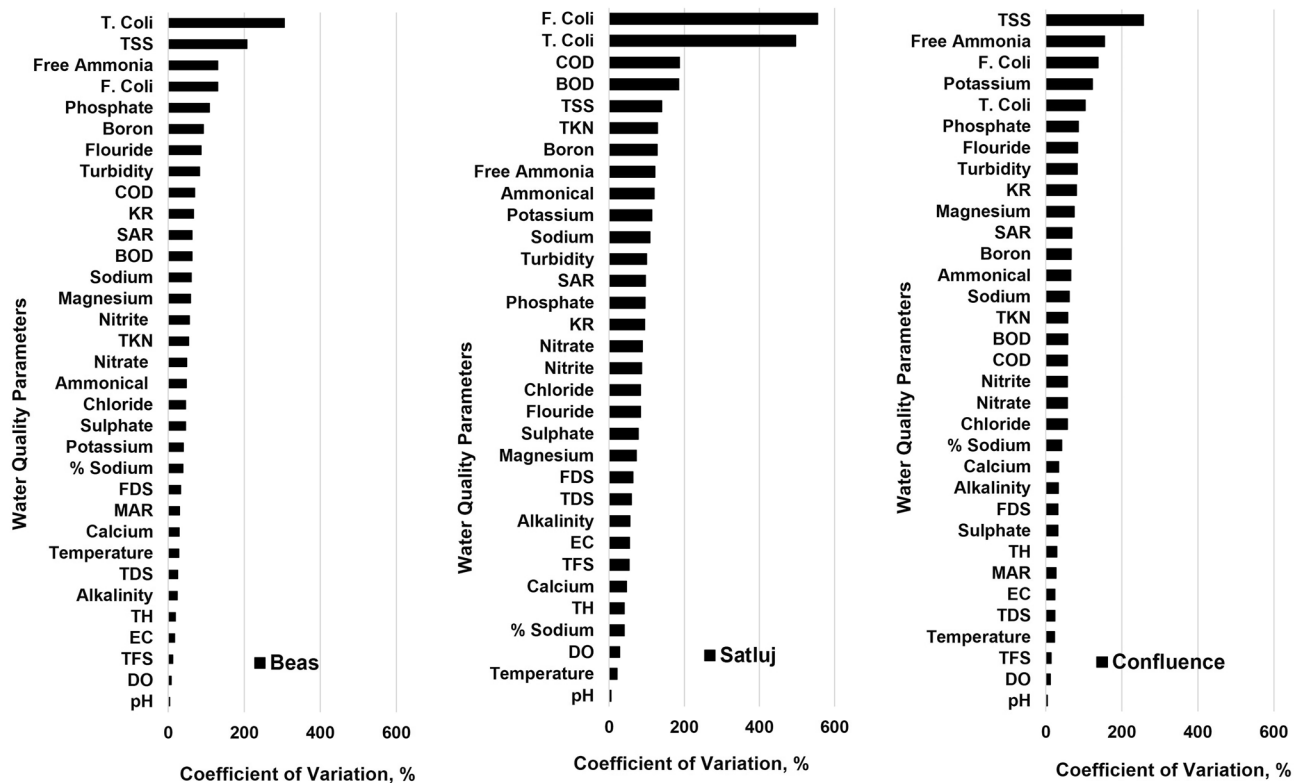


Fig. 2 Range of coefficient of variation (CV) of different water quality variables across rivers **a** Beas **b** Satluj and **c** confluence waters. *Temperature – water temperature

was within the permissible limit for Beas and confluence waters, however at Buddha Nullah and Dharamkot sites of Satluj COD levels were $> 250 \text{ mg L}^{-1}$. Earlier studies have also reported higher BOD, COD and lower DO in the downstream waters of Buddha Nullah in river Satluj (Kaur 2000). It is therefore important that effluents with elevated levels of BOD and COD must be properly treated (aerobic, anaerobic, filtration, coagulation and flocculation) before their release into the river to prevent the contamination of the aquatic ecosystems (Kumar and Saravanan 2017).

Turbidity is an indicator of suspended and colloidal matter that may be inorganic or organic in nature (Swanson and Baldwin 1965). It showed greater variation for Satluj (0.80–164.0 NTU) compared to Beas (0.9–122 NTU) and confluence waters (1.8–124 NTU). High turbidity in the river waters may be due to heavy flow events causing washing off of the soil particles from river banks, runoff from agricultural fields and discharge of domestic sewage and industrial effluents. Higher turbidity deteriorates water quality and impacts its use for domestic and industrial purposes as well as affects aquatic life.

TSS, a measure of concentration of suspended solids, was higher for Beas and confluence compared to Satluj (Table 4). High levels of TSS indicate presence of high silt and clay content, plankton, algae, and fine organic debris that may

serve as a carrier of toxins. TDS was more for Satluj compared to the Beas and confluence waters (Table 4). Higher TDS levels imply high amounts of dissolved salts, coming from dyeing and textile industries located mainly near Ludhiana and Jalandhar districts in the Satluj catchment. Effluents of these industries are heavily contaminated with pollutants such as suspended, dissolved solids and toxic metals (Kumar and Saravanan 2017). Use of common salt and glaubersalt, increases the level of TDS in the textile waste water and direct discharge of it to surface or ground waters can bring immediate hike in the TDS levels (Islam and Guha 2013). Satluj had some of the locations with TDS $> 1000 \text{ mg L}^{-1}$ indicating its unsuitability for irrigation. However, for Beas and confluence waters, the TDS levels were well below 1000 mg L^{-1} and their subsequent use for irrigation may not pose any long-term threat. TDS levels and concentration of major ions are also closely related with season and flow rate of rivers (Tsirkunov et al. 1992).

Significantly higher levels of ammonia were observed in the water samples of Satluj ($0.2\text{--}30 \text{ mg L}^{-1}$) compared to Beas ($0.1\text{--}2.4 \text{ mg L}^{-1}$) and confluence waters ($0.14\text{--}9 \text{ mg L}^{-1}$). Higher levels may be due to microbial decomposition of nitrogenous compounds in the organic matter, from aquatic faunal secretion and can also come from industrial effluents (Tsirkunov et al. 1992). Phosphates were higher in

Satluj reaching 6.4 mg L^{-1} for certain locations, strictly not acceptable for drinking and excess of it can lead to eutrophication in the aquatic systems. Higher levels of phosphate in Satluj may have its origin in the agricultural and farmyard manure runoff, as well as from municipal and industrial effluent discharge. Ca^{2+} and Mg^{2+} were more than their acceptable but less than their permissible limits at certain locations of rivers Beas (Mukerian and D/S Pathankot), Satluj (D/S Buddha Nullah) and confluence waters (D/S Harike canal and D/S Harike). Average values for Ca^{2+} , Mg^{2+} and TH were within the permissible limits indicating that the overall water quality was not hard.

Variables such as FDS, TFS, NO_3^- , TKN, K^+ , and Cl^- , were also found to be statistically different for both rivers and confluence waters (Table 4). High averages of variables for Satluj locations compared to Beas (except TSS) and confluence waters (except for TH) were again suggestive of presence of more pollutant load in Satluj. Such differences were dependent on the nature (anthropogenic/geological) and load of sources influencing the concentration of variables in both rivers and confluence waters. The variables which were not significantly different were either buffering themselves to a certain concentration with the help of some natural or anthropogenic force (dilution by rain water or any treatment plant) or they did not have any potential source to get affected.

The irrigation water quality indicators (EC, SAR, Na%, KR and MAR) were well within their limit except for KR and EC for Satluj. MAR exceeded its permissible limit for some locations of both rivers and confluence waters. EC had wide range ($168\text{--}1787 \mu\text{Scm}^{-1}$) for Satluj and its higher levels suggest conditions non-conducive for sensitive crops. Mixing of both rivers led to change in the water quality characteristics of both rivers. There was both an increase and decrease in the magnitude of the water quality variables. As shown in Fig. 3, mixing of both rivers' waters led to simultaneous increase and decrease in the magnitude of variables of river Beas as well as of Satluj. A significant drop occurred in the variables COD (-64%), BOD (-81%), T. Coli (-97%) and F. Coli (-97%) in the river Satluj whereas a significant rise occurred in Free Ammonia ($+150\%$), NH_4^+ ($+113\%$), F. Coli ($+110\%$), F^- ($+88\%$), TKN ($+80\%$), PO_4^{3-} ($+76\%$) and NO_2^- ($+54\%$) in Beas waters. It can be said that the overall water quality of Satluj after confluence with river Beas improved because of the dilution of Satluj water.

Designated best use of Beas, Satluj and confluence waters

Only 4% of the water samples of Beas fell in category A that occurred at first sampling location at Talwara (B1). About 78% of the water samples fell into category B and 18% in category C (Fig. 4a and d). As Beas moved down its

course from Talwara, DBU declined to category B and C. At Mirthal Bridge Gurdaspur (B4) and Harike (B9) locations, the water quality was mostly of B category with magnitude of 95.9% and 91.8% of water samples, respectively. Rest of the sampling locations (B5 to B9) viz. Mukerian, Kapurthala, U/S and D/S Goindwal witnessed category B and C quality waters.

At the first sampling site (Talwara, B1) of river Beas most of the water samples were within the permissible limits. But as the river moved down its course, the number of samples exceeding the permissible limit increased. For instance, approximately 68.9% of Beas water samples exceeded turbidity limit at Talwara and the percent rose to 98.3% at Mukerian (B5) and at D/S industrial point Goindwal (B8). Approximately, 13% of water samples had DO less than the permissible limit at effluent discharge point at Mukerian, while for other locations DO level in waters was good and more than the required value. Similarly, for BOD the number of samples exceeding the permissible limit was highest at the effluent discharge point in Mukerian (31.97%). The water of Beas was not fit for drinking and bathing because of the presence of high loads of T. Coli., mainly contributed by human and animal excreta. Overall, 78.7% of the samples exceeded their permissible limit for T. Coli and were off category A, thus not fit for drinking. Percent samples exceeding the permissible limit for T. Coli increased to 100% at Mirthal bridge Gurdaspur and for locations onward. About 68.1% samples were not fit for outdoor bathing at the effluent discharge point, Mukerian.

For river Satluj, most of the water samples were categorized as B and C (Fig. 4b and e). Only 3% of the water samples were fit for drinking at the first sampling location at U/S Nangal. As the river moved down its course, the DBU category changed from A to B (31%), C (32%), D (25%) and E (10%). Water quality status remained of category B up to sampling location Kiratpur (S4) and thereafter it changed to C and D as the river moved down through locations near Roper (S5), Rishab mill (S6) and Buddha Nullah (S7). The water quality status further degraded and fell to category D and E as the river reached D/S Buddha Nullah (S8), moved through Dharmkot (S9) and East Bein (S10).

At U/S Nangal only 2.1% of the samples exceeded the permissible limit for BOD set for DBU class A, which drastically increased to 96.8% at D/S Buddha Nullah and 97.9% at East Bein. Almost 73.7% of the samples exceeded the permissible limit for T. Coli at U/S Nangal that further increased to 100% at D/S NFL and for rest of the locations. None of the samples had DO less than the permissible limit for all the locations prior to Buddha Nullah but afterwards, the number of samples (below permissible limit) rose to 96.8%. Higher levels of DO in Satluj waters before reaching Buddha Nullah, suggests that river was able to maintain its self-purifying capacity. The condition of Satluj was worse

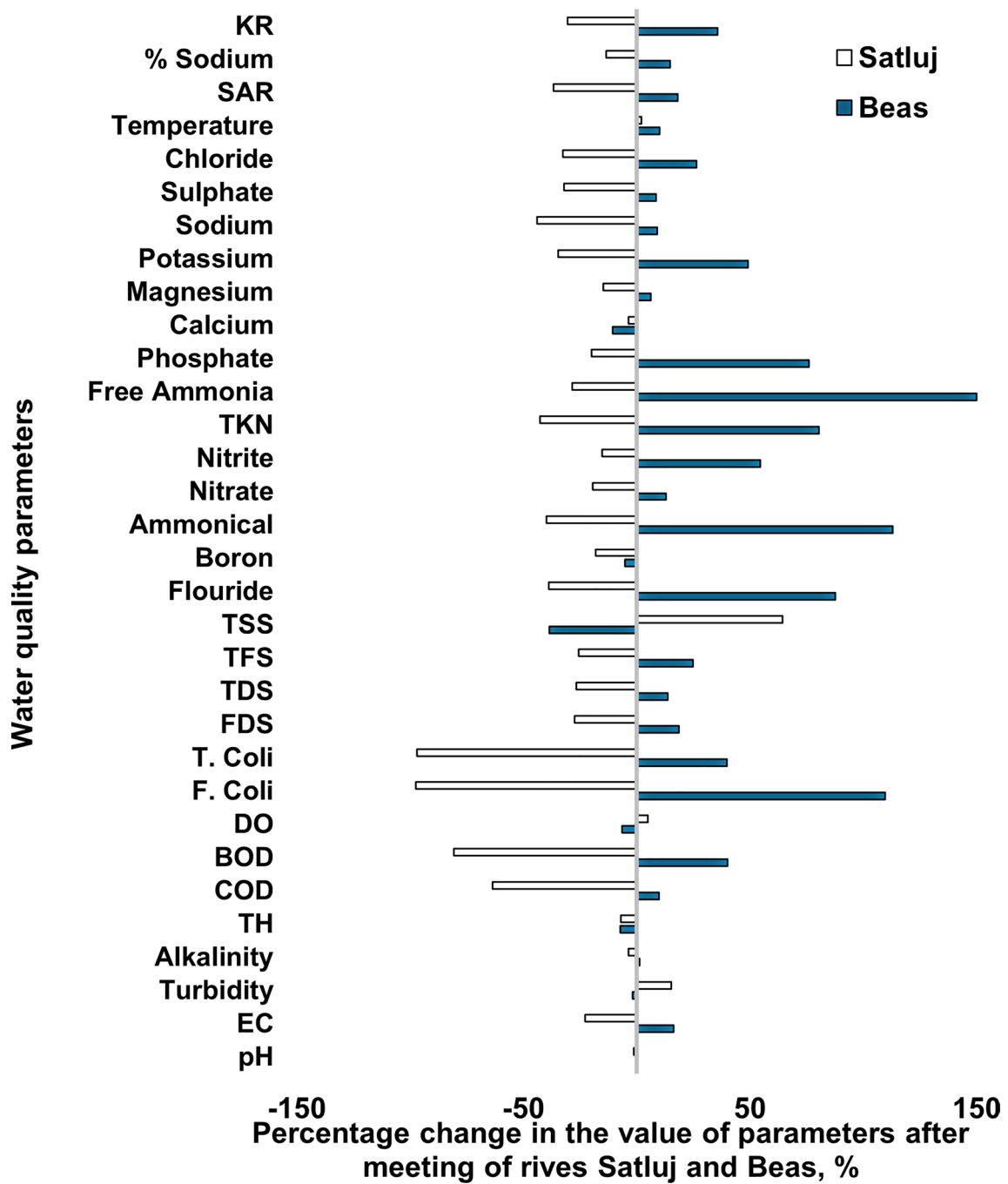


Fig. 3 Percent increase or decrease in the water quality characteristics of river Satluj and Beas after confluence

with regard to turbidity and NH_4^+ as most locations had samples not meeting the requirements for DBU category A. The number of samples exceeding permissible limit for T. Coli, stayed higher throughout the river course and for F. Coli, the number of samples rose from Rishab Mill and stayed higher thereafter. Water samples exceeding permissible limits for K^+ , NO_3^- , Mg^{2+} , Ca^{2+} , Na^+ , Alkalinity, TDS, TH, COD, B, pH, and F^- were mainly confined to the locations U/S Buddah Nullah and D/S Buddha Nullah across

stretch of river Satluj. The water quality status of river Satluj started to improve on confluence with Beas and reached to a quality level of B and C. Confluence waters had 48% of their samples categorized as B, 51% as C and 1% as D (Fig. 4c and f). The percent of samples rose in category C as the water moved down its course from D/S Harikae to D/S Hussainiwala.

Falling off of the drinking water quality criteria category of A suggests contamination of river water during its course

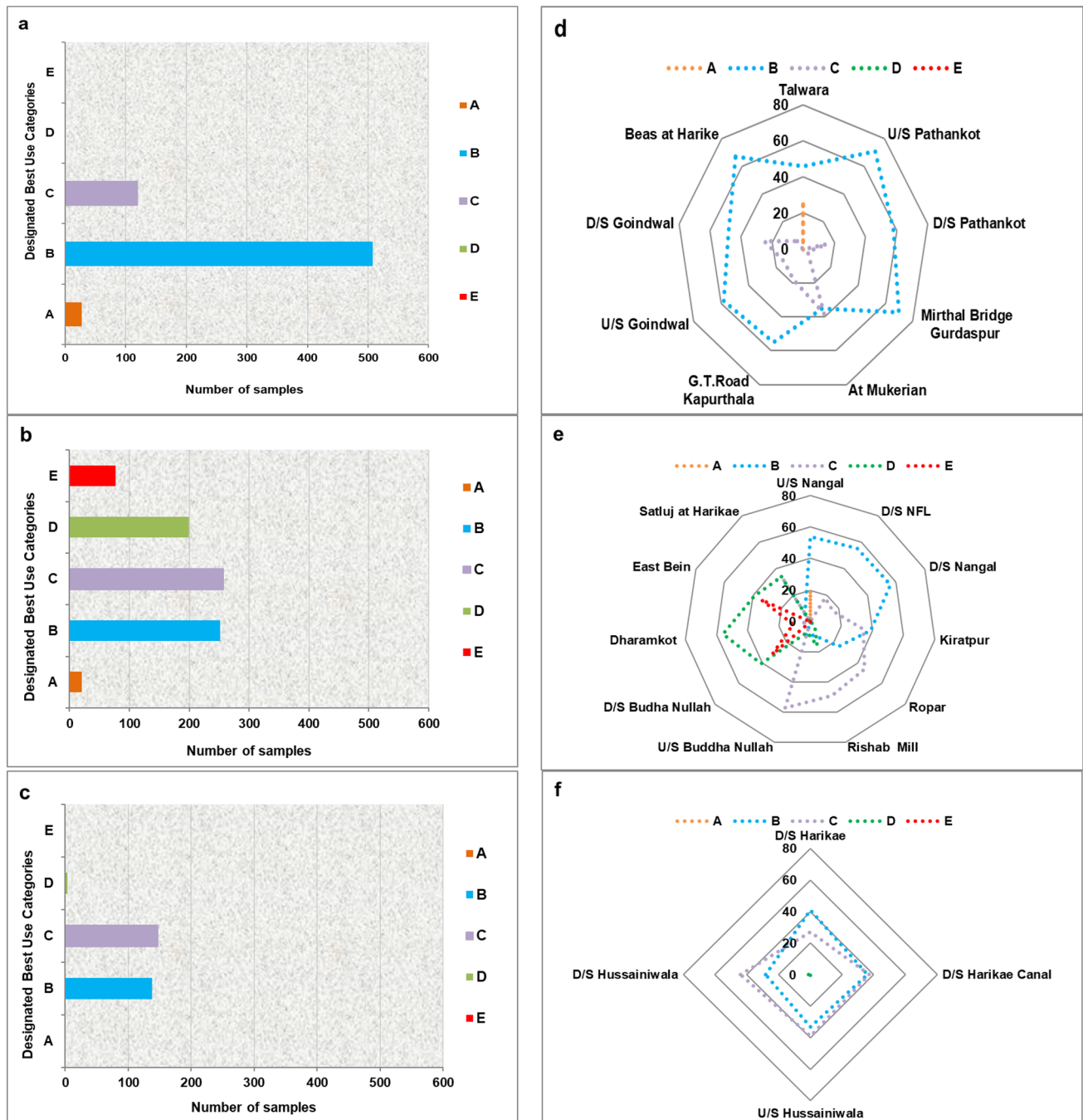


Fig. 4 Total (pooled across locations) and location-wise number of samples falling under different designated best use (DBU) categories from 2004 to 2020 for river Beas (a and d), Satluj (b and e) and After confluence (c and f)

with various other sources that have outfall in the Beas-Satluj river network. Studies based on 1 or 2 years data (Jindal and Sharma 2011; Sharma et al. 2017) also reported contamination of Satluj river down its course from U/S Nangal to Harikae and deterioration of drinking water quality from category A to B/C/D/E.

Hot spot vs near clean locations across stretch of river Beas and Satluj

For river Beas, most of the samples drawn at Talwara (B1) exhibited minimum values for majority of the water quality variables except for PO_4^{3-} and Na^+ (Supp Table 1). This suggested good water quality at Talwara location. The

main hot spots identified across stretch of river Beas were Mukerian, D/S Goindwal, D/S Pathankot and Mirthal Bridge Gurdaspur. Mukerian was identified to have the highest frequency of occurrence of maximum value for almost all the variables suggesting that it was the most polluted and degraded location on course of river Beas. The river Beas on its western and eastern banks is subjected to 13 different drains that directly or indirectly discharge urban and rural wastewater into it. Most of the sources that outfall into the drains does not have sewage treatment facilities installed at their end. Twenty-one industries mainly of sugar, distillery, gluten, brewery, paper mill and board mill are located in the Beas catchment and 12 of them are in Gurdaspur, Mukerian, Dasuya areas. Nine of these industries are located at Goindwal Sahib, Beas city and Kapurthala areas and mainly are of thermal power plant, food processing, pharmaceutical and coach factory. Though all of them have the treatment facilities installed but regular monitoring as well as performance evaluation of sewage treatment plants (STPs) or effluent treatment plants (ETPs) of the industries which are established near the bank of Goindwal Sahib drain, Beas River and Kali Bein is required (Govt. of Punjab 2019a). In addition to these effluents, runoff of fertilizers and pesticides that are extensively used in Punjab (Jadhav 2021) also add pollution to Beas.

Similarly, for Satluj, majority of the samples drawn at the first location -U/S Nangal exhibited minimum value for most variables except for TSS and thus suggestive of presence of near clean water conditions because of least human interference (Supp Table 1). The main hot spot on the stretch of river Satluj was D/S Buddha Nullah, except for Alkalinity and TKN. For Alkalinity and TKN, the frequency of occurrence of maximum value was highest at East Bein. Hence, D/S of Buddha Nullah was identified to be the most polluted location of Satluj. Thirty main drains have outfall into Satluj, and these carry untreated wastes from urban and rural areas and industries. Of these about 16 outlets within the limit of Ludhiana does not have any sewage treatment facility and directly discharge untreated industrial effluents and domestic sewage to Buddha Nullah (Govt. of Punjab 2019b). Further, more than 2000 industrial units out of 2423 in Ludhiana are discharging industrial waste directly or indirectly into the river.

Confluence of Satluj and Beas exhibited near clean condition at U/S Hussainiwala and at D/S Harikae with respect to almost all water quality variables (Supp Table 1). While locations D/S Hussainiwala and D/S Harikae canal were the main hot spots after confluence. The upstream locations of Beas (Talwara) and Satluj (U/S Nangal) and confluence waters (U/S Hussainiwala) had good amount of DO in them.

Nemerow's pollution index (NPI) calculated for first locations of Beas (B1), Satluj (S1) and confluence point (BS1) as well as the highly degraded locations of Beas (B5) and Satluj

(S8) (Table 6) also showed that the BOD and COD were consistently low for first locations over years. NPI for COD remained below 1 at B5 and S8 locations while it was higher than 1 for BOD except for some years (2007–2013) at B5. F. Coli levels were low at sites B1 and S1 while T. Coli levels were above 1. NPI values of B5 and S8 also suggest that S8 is more degraded compared to B5 as levels of BOD, T. Coli and F. Coli were excessively high at S8 location. While at BS1 where waters from Beas and Satluj merge therefore the levels of BOD, T. Coli and F. Coli dropped markedly. The interpretation of NPI was reverse for DO. With NPI > 1 for DO, suggest better DO conditions in the water compared to values < 1 which was highly prominent in S8. Based on the NPI values, T. Coli emerged as the key water pollutant that needs treatment facilities to be installed even for locations B1 and S1.

Mann–Kendall trend analysis of water quality variables

All variables had certain percent of locations with non-significant (4.2–100%), significant increasing- (0–79.2%) and significant decreasing- trends (0–95.8%). Fourteen variables (SAR > Mg²⁺ > Na⁺ > TSS > Alkalinity > Ca²⁺ > NO₂⁻ > Turbidity > pH > SO₄²⁻ > Water Temp > TH > TKN > NH₄⁺) had more than 50% of the locations showing non-significant trend (Table 5). The range of non-significant trend varied from 50 (NH₄⁺) to 100% (SAR). Except SAR, rest of the variables had some percentage of locations with significant increasing as well as decreasing- trends. Five variables (COD > K⁺ > DO > BOD > F. Coli) had > 50% of the locations that showed increasing trend with maximum locations for COD (79.2%) and least for F. Coli (54.2%). For variables such as PO₄³⁻ > FDS > TDS > Cl⁻ > F⁻ > NO₃⁻ > EC where > 50% of the locations showed decreasing trends and was minimum for EC (58.3%) and maximum for PO₄³⁻ (95.8%). Overall, there was a significant rise in COD across 79.2% locations and significant drop in levels of PO₄³⁻ for 95.8% of locations. Rising levels of variables such BOD, COD and F. Coli suggested increase in organic pollutant load in the river water. Variables that showed purely increasing trend (no-significant decreasing trend) along with non-significant trends at certain locations were pH, COD, K⁺, Na⁺, NO₂⁻ with percent locations varied from 4.2 to 79.2%. However, Ca²⁺, FDS, Mg²⁺, PO₄³⁻, SO₄²⁻-S, TDS, Cl⁻, NO₃⁻ showed purely decreasing trend (no-significant increasing trend) with non-significant trends at certain locations with percent locations ranged from 4.2 to 95.8.

On the other hand, the percentage of variables exhibiting non-significant trends was similar for Beas (42.5%) and confluence waters (41.1%) while the percentage rose

Table 5 Variables with percent of locations showing significant increasing, significant decreasing and no-significant trends

Variables	%, locations with		
	No trend	Increasing	Decreasing
pH	58.3	41.7	0.0
COD	20.8	79.2	0.0
BOD	37.5	58.3	4.2
EC	29.2	12.5	58.3
Ca ²⁺	66.7	0.0	33.3
F ⁻	16.7	8.3	75.0
FDS	12.5	0.0	87.5
K ⁺	29.2	70.8	0.0
Mg ²⁺	95.8	0.0	4.2
Na ⁺	95.8	4.2	0.0
NH ₄ -N	50.0	8.3	41.7
PO ₄ -P	4.2	0.0	95.8
SO ₄ -S	58.3	0.0	41.7
TDS	12.5	0.0	87.5
Alkalinity	75.0	8.3	16.7
Cl ⁻	16.7	0.0	83.3
DO	29.2	66.7	4.2
F. Coli	41.7	54.2	4.2
T. Coli	25.0	41.7	33.3
NO ₂ -N	66.7	33.3	0.0
NO ₃ -N	33.3	0.0	66.7
SAR	100.0	0.0	0.0
TH	54.2	4.2	41.7
TKN	54.2	8.3	37.5
TSS	79.2	8.3	12.5
Turbidity	66.7	12.5	20.8

to 57.1% in Satluj. The percentage of variables showing increasing trends remained same throughout the river network (Beas = 20.2%, Satluj = 20.5% and confluence waters = 22.3%) and small percentage of variables showed decreasing trends in Satluj (22.4%) compared to Beas (37.3%), and confluence waters (36.6%). So, the percentage of variables with no-significant trends was higher (57.1%) and with decreasing trends was lower (22.4%) in Satluj compared to Beas and confluence waters. Shift in percentage can be attributed to the variables such as EC, TH and nitrogen species (NH₄⁺, NO₂⁻, NO₃⁻, TKN) for exhibiting decreasing trends in Beas and confluence waters and no-significant trend in Satluj. Long-term trends indicate less variables showing “decreasing” and more showing “non-significant” trends in Satluj in comparison to Beas and after confluence waters (Fig. 5). However, on average basis, number of variables with increasing trends remained same (6) throughout the river network. The spatio-temporal changes in the concentration of the river water quality variables in long term are mainly attributed to anthropogenic and natural causes (Kumar et al. 2021). Presence of long-term increase, decrease or insignificant trends depend on the self-purifying capacity of the river, nature of the waste being disposed, its rate of disposal into the river system and on the efficiency of the waste treatment facilities installed to process the wastes.

For the sake of brevity, Mann–Kendall Z statistic and Sen’s slope statistic were presented only for extreme cases (first location Vs worst location) of Beas and Satluj as well as for the confluence point. The DO trends were significant and levels were rising at rate of 0.005 and 0.017 for locations for S1 and BS1. The slope statistic was maximum for

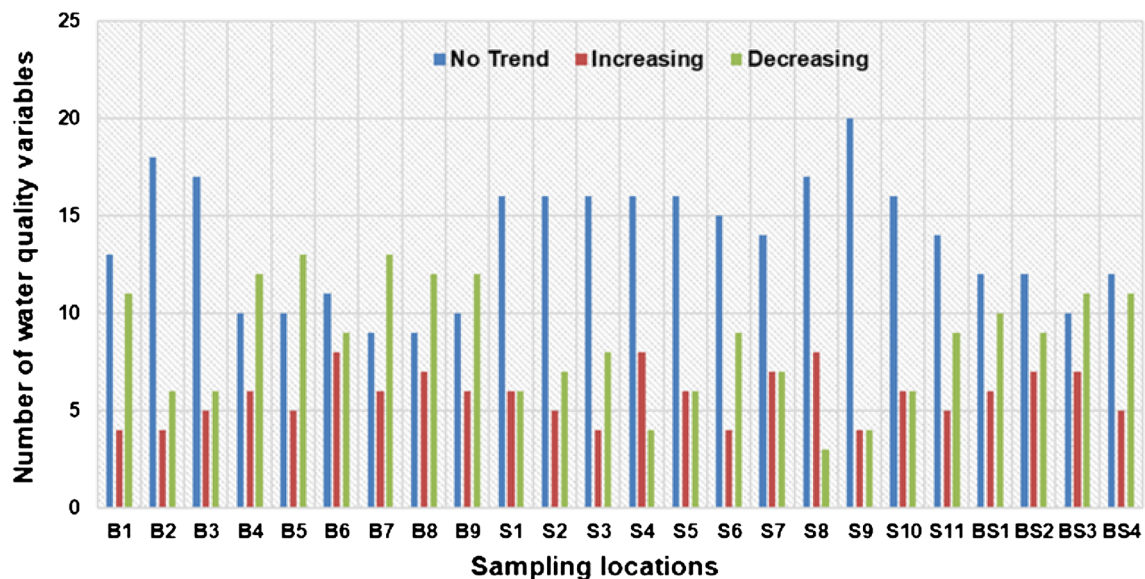


Fig. 5 Number of variables showing significant increasing, significant decreasing and no-significant trend for locations of Beas, Satluj and confluence waters

Table 6 Nemerow's pollution index (NPI) for dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total Coliform (T. Coli) and fecal Coliform (F. Coli) at Tal-

wara (B1), Mukerian (B5), U/S Nangal (S1), D/S Buddha Nullah (S8) and D/S Harikae (BS1) from 2004 to 2019

		2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
B1	DO	1.15	1.12	1.09	1.13	1.09	1.14	1.14	1.09	1.09	1.09	1.13	1.16	1.10	1.11	1.11	1.13
	COD	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.04	0.03
	BOD	0.26	0.29	0.15	0.10	0.17	0.19	0.20	0.18	0.23	0.18	0.28	0.25	0.34	0.35	0.43	0.41
	T.Coli	4.75	1.08	1.83	0.64	0.75	0.89	5.80	1.00	4.30	3.06	2.64	0.86	3.72	1.79	1.82	1.52
	F.Coli	0.09	0.03	0.01	0.01	0.01	0.02	0.24	0.02	0.23	0.20	0.23	0.12	0.56	0.29	0.27	0.18
B5	DO	1.05	0.99	1.00	1.04	1.02	1.07	1.06	1.00	1.00	1.04	0.92	0.82	0.81	0.88	1.01	1.12
	COD	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.09	0.08	0.08	0.06
	BOD	1.58	1.95	1.08	0.60	0.58	0.68	0.53	0.60	0.59	0.79	1.09	1.24	1.42	1.02	0.95	0.74
	T.Coli	79.50	157.50	196.75	11.05	11.33	14.00	17.00	19.00	22.00	15.45	18.60	9.60	11.66	9.02	12.88	12.35
	F.Coli	2.00	3.19	2.14	0.26	0.45	0.78	1.28	2.01	3.00	2.14	2.83	1.34	1.18	1.00	1.92	1.66
S1	DO	1.15	1.16	1.14	1.18	1.25	1.16	1.14	1.10	1.13	1.09	1.21	1.19	1.16	1.14	1.18	1.31
	COD	0.01	0.01	0.01	0.01	0.00	0.01	0.02	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.01
	BOD	0.30	0.36	0.23	0.35	0.35	0.31	0.59	0.71	0.42	0.41	0.35	0.35	0.35	0.35	0.35	0.35
	T.Coli	2.80	1.50	1.60	0.82	0.70	0.70	2.48	4.40	6.75	5.00	1.78	1.13	6.48	7.38	4.45	3.20
	F.Coli	0.10	0.01	0.01	0.01	0.01	0.01	0.17	0.23	0.22	0.17	0.18	0.14	0.74	0.87	0.30	0.18
S8	DO	0.62	0.56	0.50	0.83	0.29	0.34	0.61	0.60	0.60	0.54	0.51	0.60	0.58	0.43	0.42	0.50
	COD	0.23	0.20	0.25	0.23	0.65	0.54	0.37	0.23	0.24	0.12	0.19	0.22	0.28	1.00	0.87	0.47
	BOD	12.00	12.25	10.25	8.93	18.50	20.13	16.13	9.20	9.00	2.96	5.15	8.63	10.40	37.42	27.08	15.92
	T.Coli	3450.00	4475.00	2475.00	1400.00	1366.67	2350.00	1550.00	1280.00	1800.00	160.00	1100.00	1120.00	822.00	2461.67	11183.33	18436.67
	F.Coli	250.00	157.00	295.00	5.61	21.00	155.00	177.50	145.00	275.00	18.50	160.00	191.25	85.70	355.83	1245.83	2135.42
BS1	DO	1.06	0.92	0.94	0.89	0.80	0.81	0.87	0.96	0.80	0.98	0.94	0.90	0.97	0.97	1.02	1.11
	COD	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.07	0.08	0.07	0.06
	BOD	0.50	0.98	0.71	0.68	0.78	0.66	0.78	0.74	0.96	0.71	0.71	0.79	0.77	0.97	1.02	0.79
	T.Coli	30.55	17.50	13.00	8.50	8.67	10.00	10.00	13.00	12.00	11.75	11.70	8.95	6.22	8.18	54.27	58.50
	F.Coli	4.74	1.81	0.93	0.27	0.35	0.41	0.68	0.54	1.00	0.85	1.16	0.85	0.98	0.98	6.92	6.50

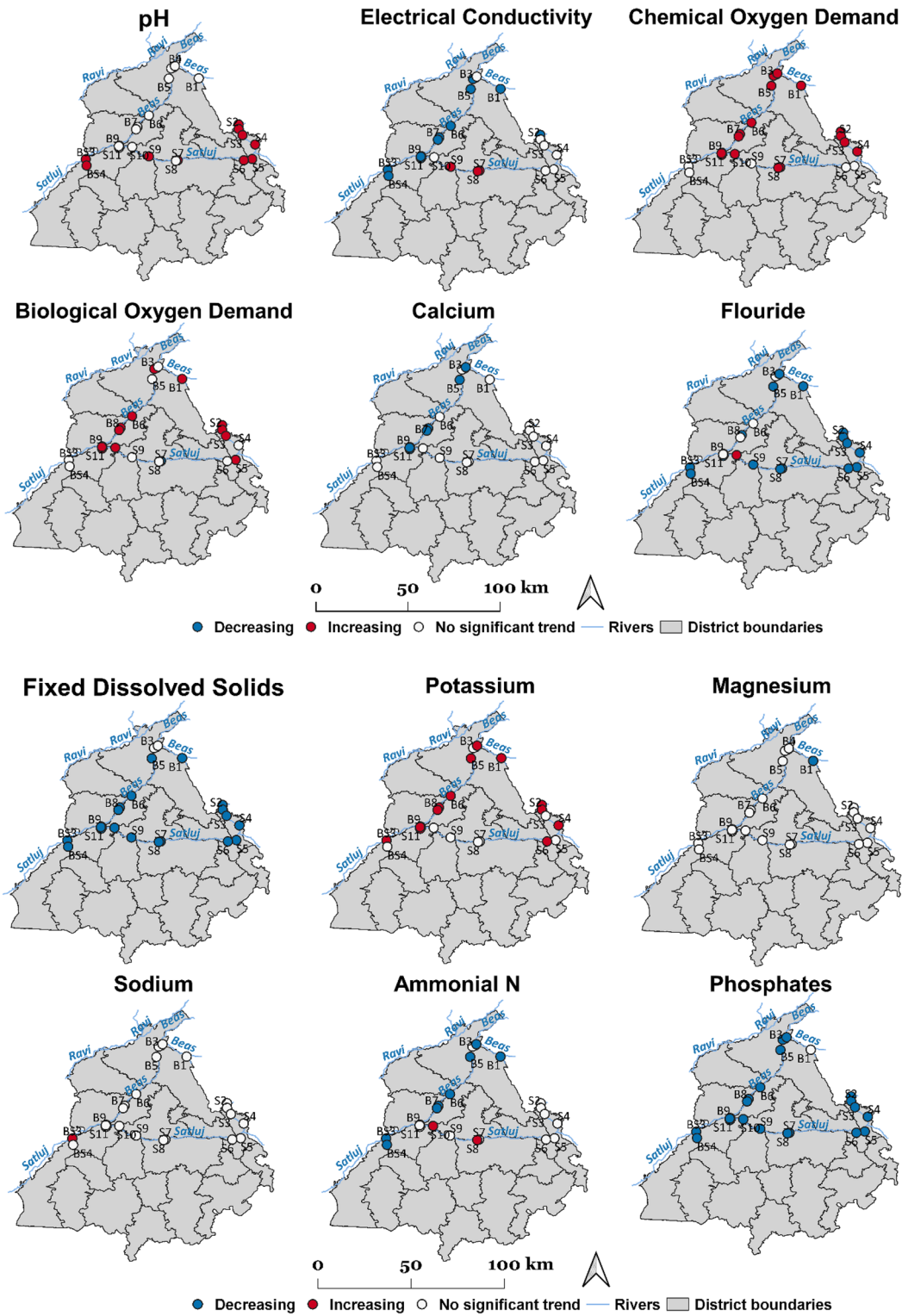
$NPI \leq 1$ – pollution-free, $NPI > 1$ – the variable has the potential to contribute pollution to water, while it is vice-versa in case of DO. Bold values represent variables responsible for pollution. Desirable limits presented in Table 4 were used to calculate the NPI for DO, COD, BOD, T. Coli and F. Coli

F. Coli and T. Coli at S8. Comparison of Mann–Kendall analysis to Nemerow's index reveals that though NPI values for COD were < 1 (Table 6) but the levels of COD were significantly increasing at rates higher for B5, S8 and BS1 compared to B1 and S1 locations. The analysis also revealed slow increase in the trend of BOD at locations B1 and S1. Such significant rise in the long-term trends of COD and BOD especially at near clean locations (B1 and S1) demand urgent action.

Spatial distribution of water quality variables

Mapping of trends helped highlight variables showing significant increasing, decreasing and non-significant trends at different locations. Non-significant trend was observed in pH for all locations of Beas while pH exhibited increasing trends for several Satluj locations (Fig. 6a) except a few (S8, S10 and S11) with non-significant trends. Confluence locations BS1 and BS2 exhibited no-significant trends in pH but increasing at BS3 and BS4. The B6 and S4 were the only locations of Beas and Satluj where alkalinity increased over time (Fig. 6b) while showed decreasing trends towards downstream locations of Satluj (S10, S11) and confluence points (BS1, BS2). Such increasing trends of pH and alkalinity can be attributed to the pollution coming from livestock, urban wastewater, agriculture land and especially related to the increasing urbanization and lack of wastewater treatment facilities (Luo et al. 2011) (Table 7).

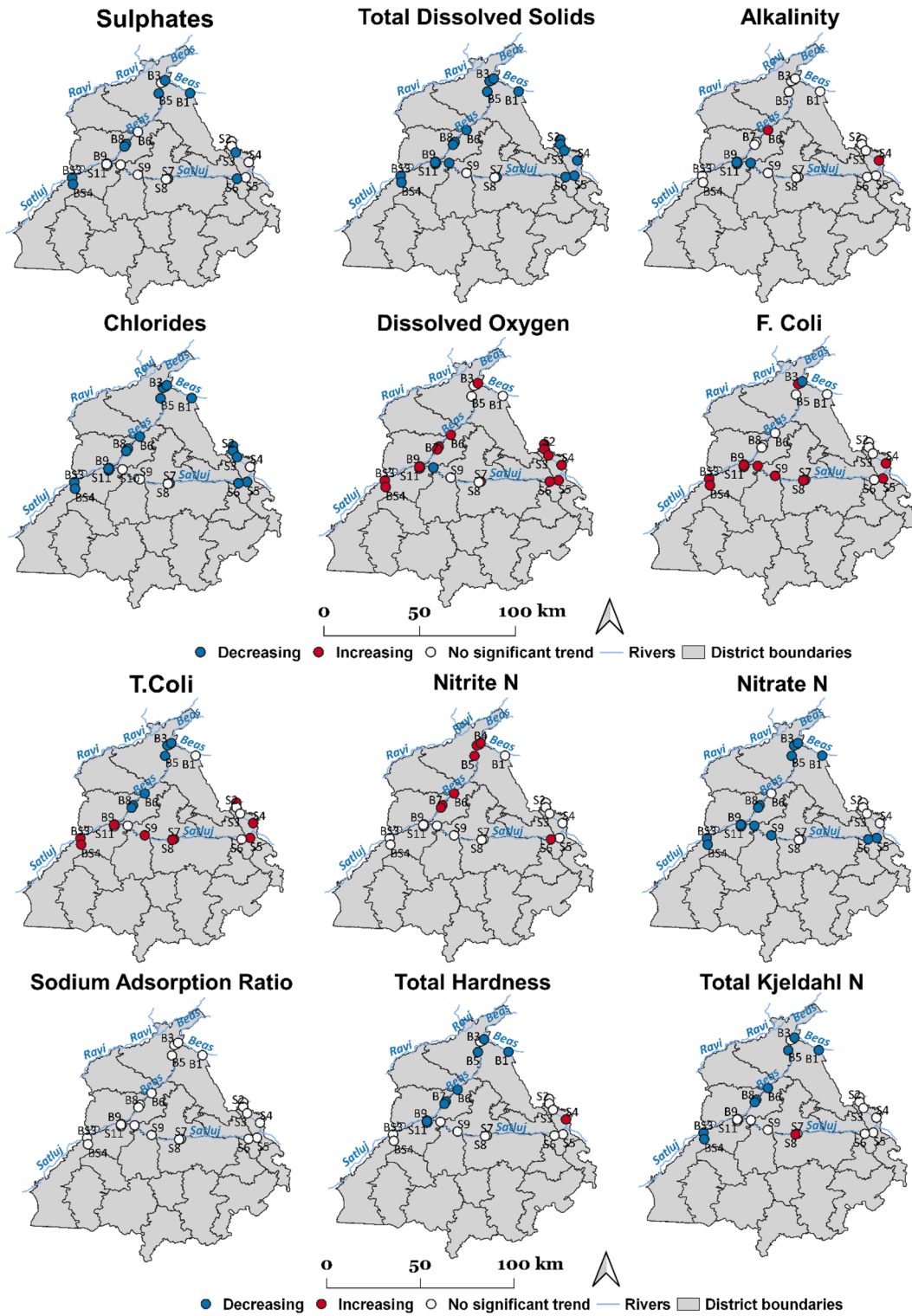
COD exhibited increasing trends for all locations of Beas, increasing trends for Satluj and confluence waters except few locations (S5, S6, S9 and BS3 and BS4) with no-significant trends. BOD showed increasing trends for Beas except (B4, B5), increasing for Satluj except a few with no-significant trends (S4, S6, S8, S9) and decreasing trend at S7 (Fig. 6a). DO increased at all locations, except a few of Beas (B1, B3, and B5) and Satluj (S8 and S9) with no-significant trends and decreased at S10. F. Coli exhibited increasing trend for all locations except B4 where it decreased and no-significant trends at locations B1, B2, B5 to B8, S1 to S3 and S6. T. Coli showed decreasing trend for Beas, increasing at B9 and no-significant trends at B1, S2, S3, S6 and S10 and after confluence locations (Fig. 6b). BOD, COD and F. Coli exhibited long-term increasing trends for maximum locations of Beas and Satluj while impact of T. Coli was mainly confined to Satluj with its subsequent impact on confluence waters. Long-term increase in BOD, COD, F. Coli and T. Coli can be attributed to the increasing population, urbanization and subsequent increase in the domestic waste generated from rural and urban areas over time (Fashae et al. 2019). Lack of treatment facilities, no upgradation of the treatment facilities and mixing of domestic sewage with industrial effluents further enhance the levels of such variables in river waters for instance, outfall of wastes from Buddha nullah and East Bein to Satluj (Sharma et al. 2017). S10 showed decreasing trends in DO with increasing BOD and COD while rest of the locations did not exhibit negative correlation of DO with BOD and COD. Results of similar nature have also been reported



a. Spatial distribution of significant trends in water quality variables for Beas, Satluj and confluence over period of ~16 years

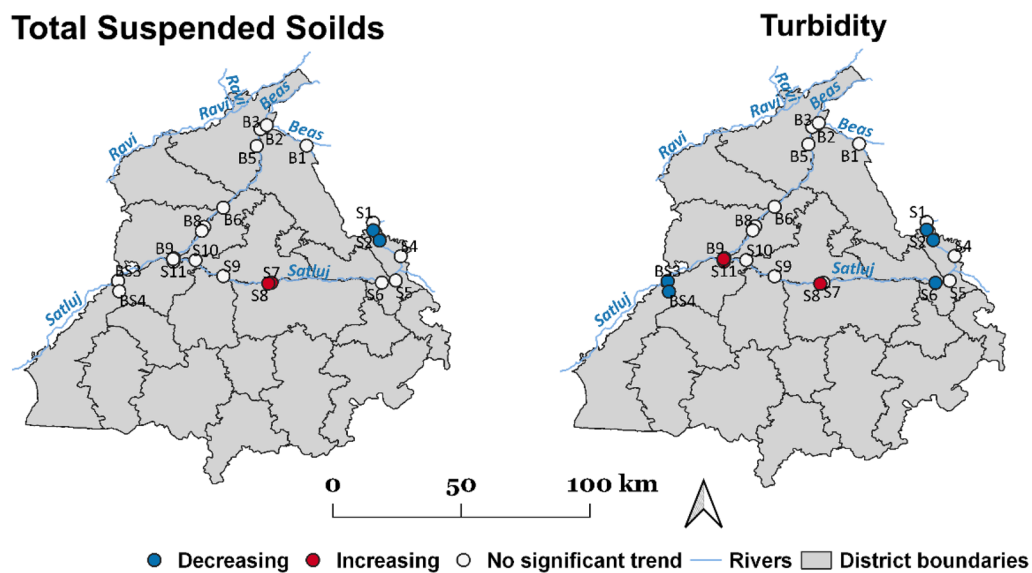
Fig. 6 a Spatial distribution of significant trends in water quality variables for Beas, Satluj and confluence over period of ~16 years. **b** Spatial distribution of significant trends in water quality variables for

Beas, Satluj and confluence over period of ~16 years. **c** Spatial distribution of significant trends in water quality variables for Beas, Satluj and confluence over period of ~16 years



b. Spatial distribution of significant trends in water quality variables for Beas, Satluj and confluence over period of ~16 years

Fig. 6 (continued)



c. Spatial distribution of significant trends in water quality variables for Beas, Satluj and confluence over period of ~16 years

Fig. 6 (continued)

by Ye and Kameyama (2020) where sites with decreasing trend of DO did not show increasing trends in BOD. Another reason for huge concern is long-term increasing trends of BOD and COD at monitoring locations present at the entry points of river Beas and Satluj in Punjab that demand further investigation.

Major cations (Ca^{2+} and Mg^{2+}), anions (Cl^- and SO_4^{2-}) as well as TH showed either decreasing or no-significant trends at locations of Beas, Satluj and confluence waters (Fig. 6a and b). Decline in concentrations of ions can be related to the influx of water from the melting of glaciers, runoff, and voluminous release of water from dams and from freshwater mixing due to precipitation.

Decline in nitrogenous species was observed (except for NO_2^- for Beas) for different locations of Satluj and Beas (Fig. 6a and b). Presence of long-term increasing trends of NH_4^+ and TKN for Satluj locations S8 (D/S Buddha nullah) and of NH_4^+ for S10 (D/S East Bein) were indicative of high pollution loads that can help proliferate microbial growth causing subsequent rise in BOD and fecal coliform count (Jannasch 1968). Rise in NO_2^- concentrations at most of the Beas locations is unclear and such pattern should be thoroughly investigated.

TDS had decreasing trends for all locations except S8 and S9. FDS showed decreasing trend except B2–B4 while TSS exhibited decreasing trend at S2 and S3, increasing at S7 and S8 with no-significant trend for rest of the locations. EC decreased at all locations of Beas and Satluj except B2, B4, S2–S6 and S10 with no-significant trend and increased for S7–S9 (Fig. 6a). F increased for S10

while showing decreasing trends for all Beas, Satluj and after confluence locations and except a few of Beas (B3, B6, B8 and B9). TSS, EC and F showed increasing trends for the most polluted stretch of river Satluj (S7–S10).

Sodium showed no-significant trend at all locations except BS3 where it exhibited increasing trend. Potassium, except for B3, S2, S5, S7–S10 and BS4, showed increasing trends for rest of the locations that can be attributed to runoff from the adjoining agricultural fields. Phosphates had decreasing trend for all the locations except B1 (no-significant trend) (Fig. 6a). The current trends indicate that future studies are required to be focused on study sites which are showing increasing/decreasing trends in Na^+ , K^+ and $(\text{PO}_4)^{3-}$ to further understand the underlying mechanisms whether arising due to point or non-point sources. SAR had insignificant trend at all locations. Turbidity showed no-significant trends for locations of Beas except B9 where it increased, with no-significant (S1, S4, S5, S9, S10), increasing (S8, S11) and decreasing (S2, S3, S6) trends for Satluj, and increasing for BS1 and BS2 and decreasing for BS3 and BS4 (Fig. 6c). Turbidity is expected to rise at the confluence locations where sudden increase in the volume of water at confluence can stir up the sediments at the bottom of the river.

Impact of changing trends of river Beas and Satluj on confluence waters

Level of variables at one sampling location can impact their level at the next sampling locations. For instance, water was

Table 7 Estimated values of Mann–Kendall trend and Sen's slope for dissolved oxygen (DO), Fecal Coliform (F. Coli), Total Coliform (T. Coli), chemical oxygen demand (COD) and biochemical oxygen demand (BOD) at Talwara (B1), Mukerian (B5), U/S Nangal (S1), D/S Buddha Nullah (S8) and D/S Harikae (BS1) from 2004 to 2019

	DO			F. Coli			T. Coli			COD			BOD		
	Z	Slope	Trend	Z	Slope	Trend	Z	Slope	Trend	Z	Slope	Trend	Z	Slope	Trend
B1	-0.989	0.000	Insignificant	0.497	0.000	Insignificant	1.182	0.196	Insignificant	7.107	0.076	Significant	4.479	0.007	Significant
B5	0.023	0.000	Insignificant	-0.101	0.000	Insignificant	-4.368	-5.714	Significant	5.557	0.153	Significant	0.220	0.000	Insignificant
S1	3.598	0.005	Significant	-1.346	-0.207	Insignificant	3.153	1.214	Significant	2.655	0.021	Significant	2.857	0.015	Significant
S8	-1.833	-0.009	Insignificant	6.467	1394.583	Significant	4.561	2058.824	Significant	2.925	0.750	Significant	1.661	0.130	Insignificant
BS1	5.615	0.017	Significant	7.230	3.333	Significant	1.802	2.037	Insignificant	4.605	0.121	Significant	2.435	0.005	Significant

Bold values were significant at *p* value < 0.05

expected to become turbid for BS1 due to convergence of Beas and Satluj, especially when waters of relatively less polluted Beas converge with relatively more polluted Satluj. Sudden mixing of river waters causes the settled material to become suspended in the river stream and converging waters themselves can also be the source of suspended materials. Convergence of Beas and Satluj also caused significant shift in the chemistry of confluence waters. Firstly, with merging waters impact of variables such as BOD, COD, T. Coli and F. Coli was carried forward in the confluence waters. Though converge of rivers did improve the water quality but could not lower the levels of variables (BOD, COD, T. Coli and F. Coli) to their acceptable limit. So, it is appropriate to say here that convergence of waters help carryover the residual impact of variables to confluence waters. Secondly, significant decreasing trends of variables such as calcium, chlorides, EC, TH, TDS, FDS, NO₃⁻ and PO₄³⁻ implied decrease in the dissolved salt concentrations per unit volume due to dilution brought by convergence of Beas and Satluj. Another important after effect of convergence of river waters was increase in DO in the confluence waters. Such increase occurred mainly due to dilution and was persistent due to lack of discharge of industrial effluents on its way thus, caused self-purification process to happen at its pace and furthered the DO in confluence waters. Overall decrease in the nitrogen species (NH₄⁺, NO₂⁻, NO₃⁻, TKN) was also observed in the confluence waters. Hence, confluence waters mainly exhibited residual influence of rivers Satluj and Beas.

Conclusions

Present scenario of increasing population, urbanization and industries force us to state that river water quality variables are susceptible to anthropogenic influences. Exploratory analysis indicates that most of the variables are beyond their permissible limits for Satluj compared to Beas and confluence waters. Designated best use analysis indicates that very few samples from entry locations serve the DBU for drinking and the water from rest of the locations is unfit for drinking. Though Talwara and U/S Nangal are identified as the least polluted but increasing trends of BOD and COD are a huge concern for such locations. Identified hot spots are Mukerian, Mirthal bridge Gurdaspur and D/S Goindwal on Beas and D/S Buddha Nullah and East Bein on Satluj which emanate due to tremendous disposal of untreated domestic and industrial wastes from villages and urban spaces having no treatment facilities. Significant increasing trends are observed in BOD, COD and F. Coli for majority of locations of Beas, Satluj and confluence waters. Though merging waters do improve the water quality due to dilution but the residual influence of variables (BOD, COD, T. Coli and F. Coli) is carried over to confluence waters. Locations

identified as hot spots and with significant worsening trends for different variables should be monitored regularly using advanced technologies, for instance real time monitoring, for tracking of the sources of wastes and for the performance evaluation of the treatment facilities installed to curb the menace of river water pollution. Such measures will help in achieving the 6th UN Sustainable Development Goal of ensuring availability and sustainable management of water and sanitation for all and improving water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, and halving the proportion of untreated waste water by 2030.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40899-023-00893-4>.

Acknowledgements The authors acknowledge the funding received from Punjab Pollution Control Board, India under the project Misc-179 (PC-4964) “Water quality status of Beas: Past and Present trend analysis for future prediction” and Department of Soil Science, Punjab Agricultural University, Ludhiana for providing the facilities for smooth conduct of the research work.

Data availability statements All data are reported within the paper.

Declarations

Conflict of interest The authors declare no competing interests.

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