Impact Assessment of Leachate Pollution Potential on Groundwater: An Indexing Method

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Abstract: The present study quantifies the pollution potential of the leachate and its effects on surrounding groundwater in the vicinity of four nonengineered dump sites in the study regions of Solan, Mandi, Sundernagar, and Baddi in Himachal Pradesh in India. The analysis primarily focused on the determination of leachate characteristics for determination of the leachate pollution index (LPI), groundwater characterization at different downstream distances using the water quality index (WQI), and heavy metal pollution index (HPI) to study the effects of leachate pollution on groundwater. Characterization of leachate samples revealed that most of the physicochemical parameters and heavy metals were in excess of the permissible limits for the study regions of Himachal Pradesh. The water quality improved with an increase in downstream distance from the dumpsite per the indexing method. Principal component analysis (PCA) was carried out to determine the components arising from natural and anthropogenic components while hierarchical cluster analysis (HCA) was used to determine and identify the regions of low, moderate, and high pollution zones in the groundwater. **DOI: 10.1061/(ASCE)EE.1943-7870.0001647.** *© 2019 American Society of Civil Engineers.*

Author keywords: Leachate pollution index; Water quality index; Groundwater contamination; Seasonal variation; Open dumpsites; Himachal Pradesh.

Introduction

The increased rate of migration of rural population to the urban cities has led to overwhelming demographic growth in many cities through the world (Dehghanifard and Dehghani 2018; Gupta et al. 2015). This is also true in Indian context, wherein the majority of the Indian population is rapidly migrating from an agricultural-based to a service- and industrial-based economy (Kumar and Kaushal 2015; Lydie et al. 2013). The increment in the production rate of municipal solid waste (MSW) is directly proportional to the economical enhancement of living beings (Rathod et al. 2013; Ashwani and Abhay 2014; Lydie et al. 2013). Urban areas in India generate about 48 million tons of household waste annually with per capita generation varying between 0.2 and 0.87 kg per capita per day (Rana et al. 2015, 2017; Gupta et al. 2015; Kawai and Tasaki 2016). The increased rate of waste generation in urban areas is troublesome for disposal of waste as it leads to poor aesthetic appearance and is a potential environmental and human health hazard particularly for developing countries (Lydie et al. 2013; Przydatak and Kanownik 2019).

This is primarily because municipal solid waste consists of a huge quantity of hazardous and toxic chemicals and in contact with moisture, leads to a generation of leachate which has the potential to contaminate the surrounding soil and groundwater conditions (Buerge et al. 2011; Talalaj 2014; Srigirisetty et al. 2017; Spoelstra et al. 2017). The problem is further compounded as open dumping of solid waste is the most common form of disposal due to minimum costs involved (Ali et al. 2014; Srigirisetty et al. 2017). The treatment and processing of waste in most of the cities in India is a problematic issue due to the generation of an immense quantity of municipal solid waste. Moreover, lack of effective and economical waste processing techniques for the proper handling and final abandoning of household waste is the matter of severe concern (Zahoori and Ghani 2017).

Increased dumping of such wastes in open landfills leads to severe environmental issues and pollution of the natural biosphere including air, water, and soil pollution (Unnisa and Bi 2017; Guo et al. 2018). As reported from earlier literature (Rana et al. 2018b; Sharma and Ganguly 2016), the major fraction of solid waste generated in India and in our study locations is primarily organic in nature. During the rainfall condition, these organic fractions have a tendency to get dissolved in rainwater leading to a generation of leachate which can affect the quality of the groundwater depending on the permeability conditions of the soil.

Leachate is a dark brown liquid released when rainfall comes in contact with the solid waste in landfill and pull out contaminants into the liquid phase (Mor et al 2006; Sharma and Ganguly 2016; Chonattu et al. 2016). Leachate primarily consists of carbon, nitrogen, manganese, and many more chemicals including solvents and organic and inorganic salts (Srigirisetty et al. 2017). Further, the leachate generated is a mixture of harmful chemicals consisting of organic, inorganics (presence of different cations and anions), heavy metals, such as cadmium, lead, nickel, chromium, and zinc, and other refractory chemicals (Subramani et al. 2017; Asuma and Aweto 2013; Nagarajan et al. 2012). These constituents vary in proportion depending on the waste characteristics at the dumpsite, site hydrology, and volume of rainfall experienced at the dumpsite (Kanmani and Gandhimathi 2013; Zhan et al. 2014). Leachate characteristics are also affected by the *age* of the landfill site

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Note. This manuscript was submitted on March 14, 2019; approved on July 12, 2019; published online on December 28, 2019. Discussion period open until May 28, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Environmental Engineering***, © ASCE, ISSN 0733-9372.

and also the proportion of stabilized waste present on the dumpsite (Singh et al. 2016; Talalaj 2014). In practice, those landfill sites which are in operation for less than five years have pH values of leachate varying from 4 to 6.5 and are acidic in nature due to the generation of carboxylic acid (Talalaj and Biedka 2016), whereas older or matured landfills have a pH varying between 8 to 8.5, are more alkaline in nature due to the generation of methane, and are indicative that the landfill is nearing the end of its lifespan.

In this perspective, leachate pollution index (LPI) is evaluated to categorize the toxicity potential of the leachate so that immediate corrective actions can be implemented at the dumping locations (Vathsalan et al. 2017; Bhalla et al. 2014a, b). The LPI is the weighted average of the important physicochemical and heavy metals constituents of the leachate being assigned a certain scale and is a single figure between 5 and 100 (De et al. 2016) like a score that exhibits the pollution potential of the leachate. The higher the value of the LPI, the greater is the toxicity potential of the leachate.

In the preceding context, the pollution of groundwater is a serious and potential environmental issue due to the percolation of leachate into the groundwater (Ikem et al. 2002; El-Salam and Abu-Zuid 2015; Sharma et al. 2016; Agbozu et al. 2015). The water quality index (WQI) and heavy metal pollution index (HPI) are vital tools to evaluate the parametric characterization of water which is easy and informative for the regulators and policy makers. It proves useful in identifying suitable remedial measures and provides efficient supervision of groundwater reserves (Badmus et al. 2015; Sharma et al. 2016; Rana et al. 2018a; Milivojevic et al. 2016). The water quality index provides a single value, which is obtained by integrating the different water quality parameters with relevant standards, depending on the parametric constituents and their concentration present in groundwater samples.

The quality of groundwater mainly depends upon the classification of the index values obtained. In principle, it is the reciprocal of LPI where in a higher value of LPI indicates poor quality of groundwater and vice-versa (Swamee et al. 2013; Agbozu et al. 2015).

The purpose of the present study was to assess the pollution potential of leachate generated from the dumpsites located in four different study locations by determining the LPI of the leachate. The WQI was assessed using three techniques to observe the existing contamination of the groundwater. Similarly, the HPI of the groundwater was also computed to determine the quality of the groundwater. Further, the Pearson's correlation coefficient, PCA, and HCA were also used to emphasize the correlation between the results obtained.

For the smooth functioning of a sanitary landfill system, it is imperative to have a proper leachate management system to prevent the contamination of groundwater. (Naminata et al. 2018; Krcmar et al. 2018). If the groundwater is polluted by leachate, its after effects last for a long time (even a few years after closure of landfill), thereby making the groundwater unsuitable for drinking or any other useful purposes (Ranjan et al. 2013; Brennan et al. 2016; Przydatak and Kanownik 2019). Hence, the present study is an initiative in identifying the potential contamination of the groundwater by the leachate generated from the dumpsites and its toxicity.

Site Location

Sundernagar lies within the coordinates of (679652.36 3490248.24). The municipal solid waste generation rate is 18–20 tons per day (TPD) with the per capita waste generation rate of 0.44 kg per day (Sharma et al. 2018). The solid waste is disposed of in an open landfill contributing to environment pollution.

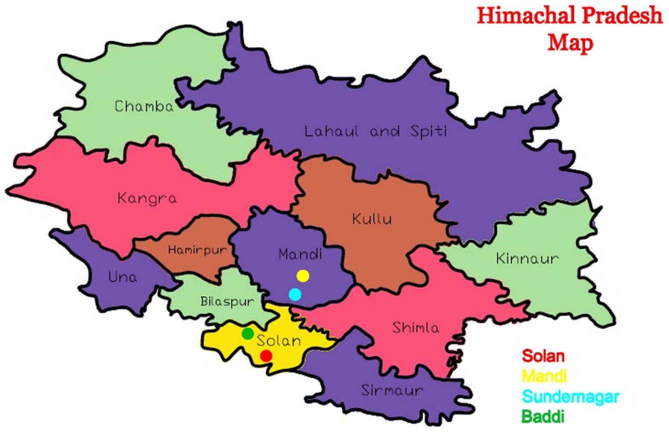


Fig. 1. Location of study regions.

Mandi lies in the coordinates of (682002.86, 3496499.36) with a waste generation rate of 21 TPD and per capita generation of 0.44 kg per day (Sharma et al. 2018).

Solan town lies in the coordinates of (700384.18, 3420901.86), and the estimated waste generation is in the ranges of 21–22 TPD with a per capita generation rate of 0.42 kg per day (Sharma et al. 2018).

Baddi lies within the coordinates of (671106.39, 3426301.39). The waste generation of the town is 18 TPD, and the per capita generation is 0.43 kg/day (Sharma et al. 2018).

For all the preceding study locations, the collected waste is disposed of in open landfills. The study locations are shown in Fig. 1, and the location of dumpsites and the groundwater sampling points of respective study regions have been shown in Fig. 2.

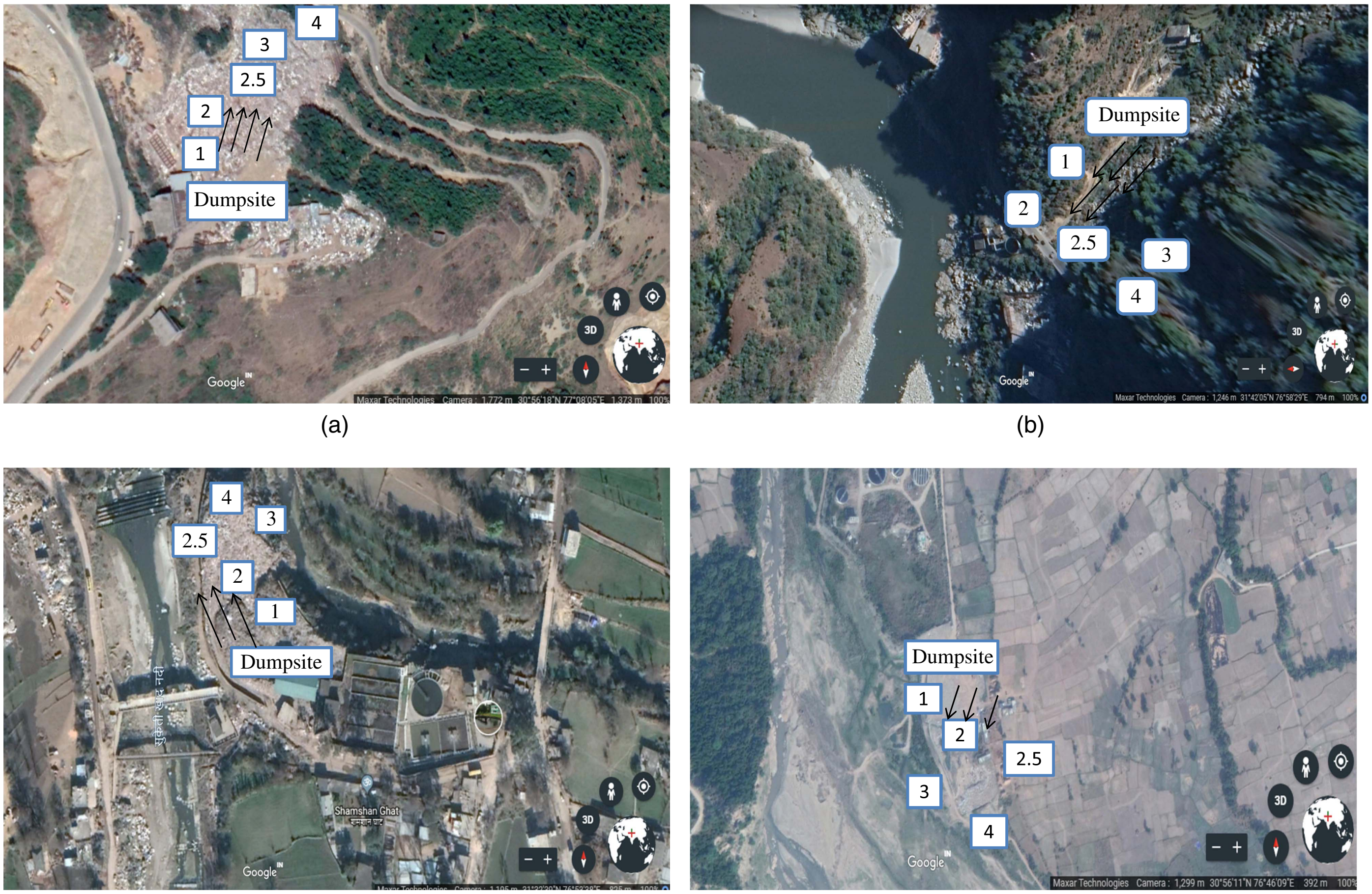
Material and Methods

Leachate Sampling and Analysis

The physical and chemical characterization of leachate produced in the dumpsites were evaluated to check its pollution potential based on the seasonal variation in the study areas including Solan, Mandi, Sundernagar, and Baddi of Himachal Pradesh. A monitoring campaign was conducted for collection of the leachate samples covering summer, rainy, and winter seasons. In this context, samples were collected during May–June 2017 (S1), July–August 2017 (S2), and December–January 2017 (S3) from the downward direction from the disposal site to characterize seasonal variations.

Further, from April 2018, about 8 TPD of municipal solid waste from the Solan dumpsite was being shifted to the dumpsite of Shimla city. The study was reconducted at this particular location to observe the effect of a reduced load on the dumpsite at this particular location. In this context, the leachate samples were again collected in the month of *April-May 2018* to determine the pollution potential due to reduced loading conditions at the dumpsite.

The samples were extracted from the three different points in the downstream direction and then mixed properly in such a way to obtain the representative mix of samples (Rana et al. 2018b; Hossain et al. 2014). The leachate samples were assembled in tight flexible elastic containers and immersed in 1 M nitric acid (HNO3) for a day (Brennan et al. 2016; Rana et al. 2018a; Hossain et al. 2014). Overall, 36 samples of leachate were gathered from four respective solid waste dumping locations covering different seasons. The collected samples were conveyed to the laboratory and stockpiled in a freezer at 4°C temperature and thereby assessed



(a) (b)

(c) (d)

Fig. 2. Location of dumpsite and groundwater sampling points for (a) Solan; (b) Mandi; (c) Sundernagar; and (d) Baddi. (Images © Google, Maxar Technologies.)

for different physical, chemical, and heavy metal analysis such as pH, total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammoniacal nitrogen (NH_4-N), chlorides, calcium, sulfate content, and heavy metal parameters including iron, copper, nickel, zinc, lead, mercury, arsenic, cyanide, and chromium. The method of determination of the aforementioned parameters has been analyzed according to the standard methods of the American Public Health Association (APHA 2012). The pH and TDS were determined by an electrometric method and gravimetric method, respectively. COD and BOD were determined by open reflux method and Winkler method, respectively (Godwin and Oghenkohwiroro 2016; Rana et al. 2018a). Heavy metals analysis was carried out by using an atomic absorption spectrophotometer (AAS make - GBC, Model - Avanta, Braeside, Victoria, Australia).

Groundwater Sampling and Analysis

The physicochemical characterization of groundwater was analyzed to determine its possible contamination level due to the percolation of leachate. The groundwater samples were collected from the submersible pumps and hand pumps lying in a downward direction at various distances of 1, 2, 2.5, 3, and 4 km from the dumpsites. A total number of 60 samples were analyzed in all the three seasons from the four sites in the year of 2017.

Further, similar to the preceding analysis for leachate, groundwater samples from the Solan region were also collected in the month of April 2018 and analyzed to check for variations in the physicochemical properties due to a reduction in waste load caused by possible lesser effects of leachate on the groundwater samples.

The parameters analyzed for physicochemical characterization of groundwater included, for example, pH, total solids, ammoniacal nitrogen, phosphate, turbidity, biochemical oxygen demand (BOD), sulfate, total hardness, calcium, magnesium, total alkalinity, nitrates, chlorides, fluorides, and electrical conductivity, and COD. The physicochemical parameters analysis including calcium, magnesium carbonate, bicarbonate, and chloride has been carried out by gravimetric analysis in the laboratory according to APHA 2012 (Wagh et al. 2016; Asuma and Aweto 2013). However, the sulfate, phosphate, and nitrate were examined by means of a spectrophotometer instrument (UV-VIS Spectrophotometer 108, GBC Scientific Equipment, Braeside, Victoria, Australia).

Leachate Pollution Index

Leachate pollution index (LPI) is the tool that is used to indicate the pollution potential of leachate generated from the open dumping of MSW. LPI is an increasing scale index in which the higher value denotes the increased environmental pollution levels and is determined by the Delphi technique (Bhalla et al. 2014a, b; Vathsalan et al. 2017). In all, about 18 parameters have been proposed for utilization to determine the LPI. The details of these mentioned parameters have been discussed earlier in previously reported literature (Rana et al. 2018a; Agbozu et al. 2015).

Table 1. Water quality rating per OWQI, BIS, and NSFWQI methods

Serial No.	OWQI	BIS	NSFWQI	Water quality rating
1	90–100	≤50	90–100	Excellent
2	85–89	50–100	70–90	Good
3	80–84	100–200	50–70	Fair
4	60–79	200–300	25–50	Poor
5	0–59	≥300	0–25	Very poor

Sources: Data from Rana et al. (2018a); Sayadi and Ghaleno (2016).
Note: NSFWQI = National Sanitation Foundation Water Quality Index.

To summarize, the parameters include pH, TDS, BOD, COD, TKN, ammonia nitrogen, total iron, copper, nickel, zinc, lead, chromium, mercury, arsenic, phenolic compounds, chlorides, cyanide, and total coliform bacteria. As observed, both physicochemical and biological parameters are considered for determination of LPI. In principle, each of these selected parameters are assigned a certain weightage depending on the importance of the parameter, and if all the 18 parameters are present in the tested samples, then the summation of the weights assigned for the individual parameter should be ***one*** (Agbozu et al. 2015).

Water Quality Index

WQI is a similar tool describing the quality of water using an aggregate index. It comprises of subindices for each parameter and the aggregations of subindices in a solitary index value providing the water quality index (Gibrilla et al. 2011; Swamee et al. 2013; Tirkey et al. 2013). Further, the selection criteria of the parameters for determination of WQI were adopted based on the significance of the considered parameters (Sharma et al. 2016). The index value thus obtained is the process of identifying the existing water quality in a single value which helps in identifying the best environmental management practices for utilizing the water (Tirkey et al. 2013; Ilaboya et al. 2014).

There are multiple methods for assessment of WQI including the National Sanitation Foundation index (NSFI), Oregon water quality index (OWQI), Bureau of Indian Standard 10500, Arithmetic Weight index, and Canadian Council of Ministers of the Environment index method (Sharma et al. 2016; Ilaboya et al. 2014). In this study, we have utilized three: Oregon water quality index (OWQI), Bureau of Indian Standard (BIS 10500 standards) methods, and NSFI technique for the assessment of groundwater quality. The details pertaining to the determination of WQI using these methods have already been well reported in literature (Rana et al. 2018a; Sayadi and Ghaleno 2016), and the same methodology have been used for the classification of groundwater quality. The different categorizations of groundwater quality rating based on the preceding three methods have been summarized in Table 1.

Heavy Metal Indexing

Heavy metal pollution index (HPI) is an evaluation technique that provides the complex impact of individual heavy metal on the water quality (Milivojevic et al. 2016). The weightage assigned is between zero and one, reflecting the virtual importance of water quality, and inversely proportional to the standard (Si) for each parameter. In this context, water quality and its appropriateness for drinking purpose can be inspected by evaluating its HPI (Zakhem and Hafez 2015). The systematic data quality was guaranteed through the execution of laboratory quality assurance and quality control, utilization of standard procedures, and the calibration of the values with standards. The detailed description for calculation of HPI has already been discussed in reported literature (Zakhem and Hafez 2015), and the same methodology has been utilized for determining HPI of groundwater for our study locations.

Multivariate Statistical Analysis

Multivariate statistical analysis of the parameters reduces dimensionality and skewness and thereby highly useful in analyzing such large environmental data sets. Further, utilization of a multivariate analysis is a useful technique in analyzing parametric characteristics of the groundwater samples as it helps in making correlations between different chemical compositions and groundwater samples (Gibrilla et al. 2011; Manikandan et al. 2014; Rana et al. 2018a). The present study uses two multivariate statistical methods including principal component analysis (PCA) and hierarchical cluster analysis (HCA) using the software statistical packages for social science (SPSS) statistics version 22.0. Both these statistical techniques provide information regarding a different physicochemical analysis of the different measured parameters varying in composition and record their impact on the groundwater quality (Singh et al. 2016). The study reported a total of 16 parameters including pH, TDS, total suspended solids (TSS), COD, BOD, turbidity, phosphate, sulfate, calcium, magnesium, chlorides, electrical conductivity, ammoniacal nitrogen, nitrate, fluoride, and total alkalinity. The multivariate statistical analysis including Pearson's correlation coefficient analysis, PCA, and HCA are unbiased methods that may provide better correlations amongst the samples and variables (Singh et al. 2016).

Correlation Matrix Analysis

Pearson's correlation coefficient matrix is produced in order to categorize the rotations among the parameters and sources of groundwater pollution (Bhuiyan et al. 2016; Loganathan and Ahamed 2017). The correlation matrix shows the agreement of an interparameter relationship with the results that are produced from the principle component analysis (PCA). It also shows some new associations between the parameters that are not adequately represented. Pearson's correlation is an expressive method used to appraise the degree of interrelation and association between two different variables. A correlation with a positive sign specifies the perfect positive correlation between the two variables, whereas a correlation with a negative sign specifies that one variable can be altered inversely in relation to other variables (Loganathan and Ahamed 2017). However, the correlation of zero signifies there is no relationship between different variables.

Principal Components Analysis

The principal component analysis (PCA) is a technique that produces *principal components* to identify the particulars and details of the multivariate analysis in a reduced dimensional space and help to grant the comprehension regarding the amount of variance in the data set (Osei et al 2010; Jolliffe and Cadima 2016). Apart from this, PCA also analyzes the data set representing observations prescribed by various intercorrelated dependent variables.

Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) is one of the important multivariate statistical analysis methods that has a major role in data analysis in environmental engineering (Singh et al. 2016; Rana et al. 2018a; Tiri et al. 2017). Cluster analysis or data segmentation

Table 2. Average leachate characteristics of the monitoring campaign carried out at different dumpsites

Parameters	Solan	Mandi	Sundernagar	Baddi	Standards for disposal		
pH	8.36	8.77	8.17	9.44	Inland surface water	Public sewers	Land disposal
TDS	3,413.00	3,087.33	2,882.67	4,525.33	5.5–9.0	5.5–9.1	5.5–9.2
TSS	2,376.33	2,289.00	2,316.33	3,790.33	2,100	2,100	2,100
Cl-	932.67	808.00	718.67	1,426.67	—	—	—
SO_4^{2-}	393.56	472.10	372.70	712.17	1,000	1,000	600
PO_4^{3-}	1.47	1.29	1.33	2.92	—	—	—
TH	741.30	933.50	731.80	1,181.53	—	—	—
COD	1,091.00	1,222.00	828.33	1,682.67	—	—	—
Ca2+	536.73	695.80	446.53	811.33	250	—	—
Conductivity	5,962.67	5,283.00	5,387.67	6,276.33	—	—	—
NH_4-N	528.83	450.67	432.70	529.67	—	—	—
BOD	693.33	524.33	446.03	638.00	50	50	—
TKN	480.40	515.30	412.90	649.87	30	350	100
Cu	2.61	3.24	3.74	4.75	—	—	—
Ni	0.13	0.34	0.20	0.73	3	3	—
Zn	3.76	5.27	2.42	7.05	3	3	—
Pb	1.88	1.78	1.23	3.83	5	15	—
Cr	0.34	0.31	0.29	0.54	0.1	1	—
Fe	47.72	34.33	35.85	59.50	—	—	—
Cd	0.06	0.04	0.03	0.09	—	—	—
Arsenic	BDL	BDL	BDL	BDL	—	—	—
Mercury	BDL	BDL	BDL	BDL	—	—	—
Cyanide	0.03	0.05	0.023	0.138	—	—	—

Note: All units in mg/L except pH and conductivity. TH = total hardness.

is a unique method that is utilized for the related grouping of data and observations into clusters or subsets, wherein within each of the clusters, the data have correlations amongst themselves (Yim and Ramdeen 2015). As such, different clusters can represent different interpretations. This indicates the groupings of various data sets by developing a cluster or dendrogram.

Results and Discussions

Leachate Characterization

The physical and chemical characterization of the leachate samples collected and analyzed for the three monitoring campaigns have been summarized in Table S1, and the average concentrations of these parameters have been summarized in Table 2 for all of the study locations.

The *average* pH values over the three monitoring campaigns at the study locations were determined to be 8.36, 8.77, 8.17, and 9.44, respectively, for Solan, Mandi, Sundernagar, and Baddi. The pH value of the leachate sample at all the dumpsites showed higher values (average pH >8) indicating that the dumpsites were primarily in the methanogenic phase and were almost reaching the end of their lifespan. Similarly, pH results were reported for other similar studies carried out in the dumping site of Chandigarh and 6.8 to 8.3 in the dumping site of Chennai, respectively (Aziz et al. 2018; Rana et al. 2018a).

The *average* TDS concentrations over the three monitoring campaigns at the study locations were determined to be 3,413, 3,087, 2,883, and 4,525 mg/L, respectively, for Solan, Mandi, Sundernagar, and Baddi. The TDS concentrations at all the study locations exceeded the disposal standards (2,100 mg/L) for inland surface, public sewers, and land disposal conditions. High concentrations of TDS in leachate signify leaching of ions from the landfill site which leads to an increase in salinity, thereby increasing its toxicity which can severely affect the characteristics of the groundwater (Aziz et al. 2018; Rana et al. 2018a). This is also correlated by the high values of electrical conductivity observed for the leachate samples at all the study locations as it represents high ionic concentrations. The *average* electrical conductivity over the three monitoring campaigns at the study locations were determined to be 5,963, 5,283, 5,388 and 6,266 μS/cm for Solan, Mandi, Sundernagar, and Baddi, respectively. Similarly, the average chloride concentrations were determined to be 933, 808, 719, and 1,427 mg/L for Solan, Mandi, Sundernagar, and Baddi, respectively. This signifies that the chloride concentrations are within permissible limits for disposal in public sewers and inland surface waters (limit = 1,000 mg/L) but unsuitable for land disposal (limit = 600 mg/L) for leachate generated from Solan, Mandi, and Sundernagar study locations. For the Baddi study locations, the chloride concentrations exceed also disposal standards for all the three conditions. In general, chloride concentrations are conservative pollutants with negligible effects in long term considerations (Aziz et al. 2018; Ilaboya et al. 2014).

The COD concentrations of the leachate samples varied between 982 and 1,202 mg/L for Solan, 1,122–1,326 mg/L for Mandi, 768–893 mg/L for Sundernagar, and 1,487–1,822 mg/L for Baddi. The values all exceed the disposal standards and are toxic in nature. Similarly, in this context, the BOD concentrations of the leachate samples from the dumpsites vary from 673 to 716 mg/L for Solan, 512–533 mg/L for Mandi, 437–461 mg/L, and 627–649 mg/L for Sundernagar and Baddi region, respectively. The average BOD/COD were determined to be 0.64, 0.43, 0.54, and 0.38, respectively for Solan, Mandi, Sundernagar, and Baddi. This shows that the leachate generated from the Solan location has a high proportion of organics with it, and this primarily due to the dumping of rotten, unsold, or putrescible fruits and vegetables being disposed of directly in the Solan dumpsite (Sharma et al. 2018). The lowest ratio was observed for the Baddi dumpsite indicating a higher presence of inorganics in leachate composition which is due to the dumping of a large proportion of hazardous wastes generated from the industries at the dumpsite (Sharma et al. 2018). The results obtained for our study locations were in sharp contrast to similar reported earlier studies like in Chandigarh wherein the BOD/COD ratio were significantly low being less than 0.1 indicating a minimal concentration of organics in the leachate samples (Rana et al. 2018a). The NH_4-N concentrations for the study locations varied between 525 and 532 mg/L, 428–478 mg/L, 423–444 mg/L, and 521–542 mg/L for Solan, Mandi, Sundernagar, and Baddi, respectively, over the monitoring campaign. The NH_4-N concentrations are primarily generated due to degradation of organic fractions leading to the production of biogas and methane.

The heavy metal characterization of the leachate based on seasonal variation from the four study locations has been summarized in Table S1, and the representation of the physicochemical parameter and heavy metal result analysis have been shown graphically in the attached supplementary document representing Figs. S1–S21. The heavy metal analysis revealed that the average concentrations of nickel and zinc were within permissible limits at all of the study locations. The presence of zinc content in the leachate samples is primarily due to the presence of discarded batteries and lamps in the waste. Similarly, average concentrations of copper were well within permissible limits at Solan study locations and slightly exceeded the permissible levels in Sundernagar and Mandi. The highest concentrations of copper were reported for Baddi well exceeding the prescribed standards. This is primarily because the waste from the Baddi dumpsite has some components of industrial wastes. Concentrations of copper in leachate samples primarily arise from the dumping of scrap metals, discarded medicines, and batteries (Rana et al. 2018a). The average Pb concentrations exceeded the permissible limits at all the study locations. The Fe content has been found on the higher side due to the reason that the highest steel scraps are disposed in the dumping site and is maximum for the Baddi location. The oxidation of ferrous to ferric form and the formation of ferric hydroxide are the reason for the brown color of leachate (Dharmarathne and Gunatilake 2013).The arsenic and mercury content in the leachate samples in all study regions were below the detection level (BDL); however, the average cyanide concentration was on the higher side for the Baddi region (0.34 mg/L). In general, the heavy metals concentrations in dumpsite are usually higher in the acidogenesis phase due to the metal solubility and consequently lower pH value due to production of organic acids (Kolekar et al. 2016). The increment in pH value and decrease in heavy metal solubility ensue a subsequent decrease in the concentrations of heavy metals. High concentrations of heavy metals in the leachate sample can also be attributed to unsegregated wastes being dumped at the disposal sites (Kolekar et al. 2016). Further, the presence of such high concentrations of heavy metals in leachate are indicative of the inadequacy of the dumping of MSW in open dumpsites and are potential sources of environmental and health hazards and needs to be redressed.

Comparison with other reported literature revealed that the leachate produced from the waste disposal site in Gazipur also consists of zinc, lead, chromium, copper, and nickel content in a certain amount. However, the heavy metal concentrations for the study locations were comparatively less than reported for tricity locations of Chandigarh, Mohali, and Panchkula (Rana et al. 2018a).

The physicochemical and heavy metal characterization of the leachate samples that were again collected from the Solan study location (April 2018) to observe any variations due to reduced loading conditions on the dumpsite has been summarized in Table S2.

It was observed that there was significant reduction in the concentration of physicochemical and heavy metal parameters due to the reduced MSW load on the dumpsite. This suggests that some alternatives are needed for reducing the possible MSW loading at the dumpsites.

Table 3. Leachate pollution index of the leachate from study regions in Himachal Pradesh

Serial No.	Study regions	LPI (S1)	LPI (S2)	LPI (S3)	Average value
1	Solan	15	17	19	17
2	Solan[a] (after waste load reduction)	—	—	—	15
3	Mandi	15	16	19	17
4	Sundernagar	13	13	16	14
5	Baddi	16	24	26	22

[a] Monitoring carried out during April 2018.

Leachate Pollution Index

The average and seasonal variation of LPI calculated for different study locations has been summarized in Table 3. To summarize, the average LPI over the three seasons were determined to be 17, 17, 14, and 22 for Solan, Mandi, Sundernagar, and Baddi, respectively. It is observed from the results that samples exceed the permissible range of the leachate disposal standards of 7.38, thereby needing suitable treatment before its disposal. Seasonal variation showed an increased value of LPI over the three monitoring seasons and thereby increased the pollution potential of the leachate at all the study locations due to the continuous dumping of mixed municipal solid waste at the dumpsites.

For the Solan study location, a revised determination of LPI based on characterization of parameters for a single monitoring campaign in April 2018 showed a reduced LPI value of 15, and the result has been summarized in Table 2. This indicated a slight reduction in the pollution potential of the leachate due to reduced MSW loading conditions on the dumpsite.

Groundwater Characterization

The physicochemical characterization of the groundwater samples analyzed from the study locations have been summarized in Table S3, and again, after reduction of the waste load from Solan region, the physicochemical characterization of the groundwater samples has been reported in Table S4, respectively. The physicochemical parameters were compared with the standards as prescribed by the World Health Organization (WHO) and Bureau of Indian Standards (BIS) (Rana et al. 2018a). The average pH values for all the study locations at different downstream distances can be classified as *within near-neutral ranges* and were well within the limits specified by BIS (Rana et al. 2018a). The results obtained from the study locations were similar to the results conducted in nearby tricity locations of Chandigarh, Mohali, and Panchkula (Rana et al. 2018a). Increased pH concentrations in groundwater in the vicinity of the landfill sites are indicative of percolation of mature leachate contamination (Boateng et al. 2019). The average total alkalinity for all the study locations for all the downstream distances exceeded the permissible limits of BIS standards, and the parameter has the ability to affect the taste and odor of water making it unpalatable.

The highest TDS concentrations were observed for the dumpsite located in Baddi wherein the average concentrations were greater than 500 mg/L at all the downstream distances, and the least concentrations (about 275 mg/L) were observed for the dumpsite located in Sundernagar. The concentrations at the other two locations were within intermediate ranges lying between 350 and 500 mg/L.

In general, TDS concentrations are representative of salts filtering from soil and other environmental pollutants being contaminated by leachate (Wagh et al. 2016). The TDS concentrations at the study located were corroborated by electrical conductivity values which ranged between 479.22–523.44 μS/cm, 628.98–647.84 μS/cm, 458.83–473.64 μS/cm, and 710.9–745.12 μS/cm for dumpsites of Solan, Mandi, Sundernagar, and Baddi, respectively. Such high values of electrical conductivity are representative of large ionic concentrations in groundwater maybe due to contamination from leachate (Boateng et al. 2019; Manikandan et al. 2014). Comparison with reported literature carried out for nearby locations in Chandigarh, Mohali, and Panchkula revealed the value of electrical conductivity in the range of 954–1,850 μS/cm, 460–595 μS/cm, and 570–720 μS/cm, respectively (Rana et al. 2018a).

The total suspended solids (TSS) concentrations are representative of dissolved inorganics and a small fraction of organics in the groundwater [WHO 2004, 2008; BIS 10500 (BIS 2012)]. The parameter is also indicative of a generic nature of the water including its salinity. The TSS concentrations were well within the permissible limits for all the study locations at the different downstream distances. However, the turbidity values at all of the study locations at different downstream distances exceeded the permissible limit values prescribed by BIS [BIS 10500 (BIS 2012)]. In this context, parameters of chloride, nitrate, and fluoride concentrations were within the acceptable limits of BIS and WHO standards [WHO 2008; BIS 10500 (BIS 2012)]. The average sulphate concentrations varied from 27 to 108 mg/L, 27 to 40 mg/L, 27 to 33 mg/L, and 62 to 69 mg/L over the respective downstream distances for Solan, Mandi, Sundernagar, and Baddi, respectively. The concentrations were well within the prescribed standards of 200 mg/L by the BIS. A high sulphate concentration can lead to dysentery in children and also biological corrosion (Chidanand et al. 2013). Similarly, the average nitrate concentrations were well within the permissible limits for all the study locations for all of the considered downstream distances.

Table 4. Water quality index based on Oregon water quality index

Serial No.	Town	Summer	Rainy	Winter	Average	Classification (average)
1	Solan	66	64	64	65	Poor
2	Mandi	67	66	65	65	Poor
3	Sundernagar	69	68	67	68	Poor
4	Baddi	59	59	58	59	Very poor

The parameter BOD of the groundwater specifies the amount of organic material present in the groundwater sample (Zakhem and Hafez 2015). The BOD concentrations present in the groundwater samples varied within the ranges of 0.20–0.28 mg/L for Solan, 0.23–0.28 mg/L for the Mandi region, 0.14–0.20 mg/L for Sundernagar, and 0.52–0.63 mg/L for the Baddi region, respectively. The concentrations were well within the permissible limits and indicated fewer fractions of dissolved organics in the groundwater samples. Similarly, the COD value of the groundwater samples in the Solan region varied between the range of 3.52 to 4.77 mg/L, within 2.52 to 2.96 mg/L for the Mandi region, within ranges of 2.60 to 2.82 mg/L for Sundernagar, and between 6.44 and 8.01 mg/L for the Baddi region, respectively. The BOD/COD ratio was less than 0.2 which is representative of more nonbiodegradable fractions in the groundwater samples. Ammoniacal nitrogen concentrations were determined to exceed the permissible limits for all study locations at all the different downstream distances.

Water Quality Index

The WQI is an efficient tool to inform the policy makers using a single index value (Tirkey et al. 2013; Rana et al. 2018a) denoting the quality of water. The WQI in the present study was determined using three methodologies—namely, the Oregon Water Quality Index (OWQI), BIS 10500, and the National Sanitation Foundation Water Quality Index (NSFWQI) water quality index which has already been discussed in the methodology section. The WQI values determined using the three methods have been summarized in Tables 4–7, respectively. The OWQI for the Solan region was determined to be 66 in the summer season, 64 in the rainy season, and 64 in the winter season. Similarly, the WQI for the Mandi region was reported to be 67 in the summer season, 66 in the rainy season, 65 in the winter season, and for Sundernagar, was reported as 69 in the summer season, 68 in the rainy season, and 67 in the winter season. Finally, the WQI for the Baddi region was reported as 59 in the summer season, 59 in the rainy season, and 58 in the winter

Table 5. Water quality index based on BIS 10500

Distances (km)	S1				S2				S3			
	Solan	Mandi	Sundernagar	Baddi	Solan	Mandi	Sundernagar	Baddi	Solan	Mandi	Sundernagar	Baddi
1	107 (FQ)	123 (FQ)	101 (FQ)	165 (FQ)	117 (FQ)	131 (FQ)	105 (FQ)	176 (FQ)	129 (FQ)	139 (FQ)	111 (FQ)	200 (PQ)
2	101 (FQ)	114 (FQ)	55 (GQ)	128 (FQ)	106 (FQ)	120 (FQ)	59 (GQ)	139 (FQ)	120 (FQ)	126 (FQ)	65 (GQ)	145 (FQ)
2.5	92 (GQ)	105 (FQ)	51 (GQ)	112 (FQ)	76 (GQ)	111 (FQ)	53 (GQ)	117 (FQ)	112 (FQ)	113 (FQ)	60 (GQ)	144 (FQ)
3	83 (GQ)	94 (GQ)	45 (EQ)	85 (GQ)	90 (GQ)	102 (FQ)	49 (EQ)	94 (FQ)	80 (GQ)	103 (FQ)	54 (GQ)	119 (FQ)
4	76 (GQ)	80 (GQ)	44 (EQ)	79 (GQ)	80 (GQ)	86 (GQ)	47 (EQ)	83 (GQ)	87 (GQ)	89 (GQ)	50 (GQ)	88 (FQ)

Note: FQ = fair quality; GQ = good quality; and EQ = excellent quality.

Table 6. Average water quality index based on NSFWQI

Distances (km)	Average WQI (NSF method)				Average (classification)			
	Solan	Mandi	Sundernagar	Baddi	Solan	Mandi	Sundernagar	Baddi
1	79	84	90	70	Good quality	Good quality	Good quality	Fair quality
2	81	87	92	74	Good quality	Good quality	Excellent quality	Good quality
2.5	84	87	92	75	Good quality	Good quality	Excellent quality	Good quality
3	88	89	94	77	Good quality	Good quality	Excellent quality	Good quality
4	89	90	94	78	Good quality	Good quality	Excellent quality	Good quality

Table 7. Water quality index of Solan (April 2018) based on BIS 10500, OWQI, and NSFWQI

Serial No.	Distances (km)	BIS (WQI)	NSFWQI	OWQI
1	1	102	90	67
2	2	84	91	
3	2.5	78	91	
4	3	72	93	
5	4	62	94	

season, respectively. From the results obtained in Table 4, it can be observed that the water quality index varied in the range of 60–70 according to the OWQI for three study regions of Solan, Mandi, and Sundernagar and was categorized as *poor quality*. However, per OWQI, the groundwater samples from Baddi region was classified as *very poor* with the WQI value being less than 60, and this can be attributed to the pharmaceutical and industrial activities in the town. Further, it is important to mention that the WQI value of 59 is a borderline value to be classified as *very poor* in accordance with the OWQI standards as the range varies between 0–59 for this category.

Apart from this, the relative weight of the groundwater parameters for evaluation of WQI based on BIS has been summarized in Table S5, and the calculated WQI and its categorization as poor, fair, good, and excellent per BIS 10500 standards for all the three monitoring seasons and for all the downstream distances have been presented in Table 5. It is observed that there is a significant reduction in WQI (i.e., improvement in water quality) with an increase in the downstream distance due to dilution. The highest WQI values obtained using this methodology was observed in the monitoring campaign of S3. The *average WQI* considering the seasonal variations at different downstream distances utilizing this method and its categorization has been summarized in Table S6.

It is observed from the aforementioned tables that per the WQI methodology using the BIS 10500 standards of water quality assessment methods, the study areas of Solan, Mandi, Sundernagar, and Baddi are of fair category within the vicinity of a 1-km distance from the dumpsite in the summer and rainy season, but it is in the winter season wherein Baddi town exhibits the most adverse quality of water. It is perceived that at a 2.5-km distance and thereafter, the water quality of Solan, Sundernagar, and Mandi shows good quality, but the Baddi town shows adverse quality of water. However, up to the distance of 4 km from the domain of the dumpsites, Solan, Mandi, and Baddi dumpsites exhibit good quality of water, whereas Sundernagar town shows excellent water quality. Apart from this, it is critically observed that the water quality improved with the increase in downstream distances from the dumpsites, but continuous dumping of MSW at all the study locations without proper supervision can lead to further deterioration of the existing groundwater quality.

The water quality index based on the WQI was developed by the National Sanitation Foundation (NSF) which provides a standard method for comparing the relative quality of various parameters of groundwater samples (Sayadi and Ghaleno 2016). It is observed from Table 6 that per the National Sanitation Foundation method for water quality assessment, the study areas including Solan, Mandi, and Sundernagar lies under a good category range, whereas the Baddi region lies under a fair category within the domain of a 1-km distance from the dumpsite due to the involvement of industrial and pharmaceutical activities in the town. The *average WQI* considering the seasonal variations at different downstream distances utilizing this method and its categorization has been summarized in Table S7. It is noticed that with an increment in the distance from the dumping site, the water quality of Solan, Sundernagar, Mandi, and Baddi have shown significant improvement in the quality of groundwater.

Table 8. Average concentration of heavy metal analysis of groundwater in study regions (mg/L)

Parameters	Solan	Mandi	Sundernagar	Baddi
Fe	0.26	0.24	0.02	0.89
Zn	0.19	0.12	0.13	0.75
Cu	0.05	0.02	0.04	0.08
Cr	0.34	0.00	0.07	0.07
Ni	0.01	0.00	0.00	0.04
Pb	0.03	0.01	0.00	0.09
Cd	0.02	0.01	0.02	0.03

Further, the effect of reduced the loading condition of 8 tons at the Solan dumpsite was also investigated, and the WQI was determined using three aforementioned techniques. The WQI obtained from the OWQI was determined to be 67, a slight increase from the overall average value of 65 showing slight improvement in water quality due to reduced MSW loading effects. The WQI index values using all three methods for the revised loading conditions have been summarized in Table 7. It is observed from the table that there is significant reduction in concentrations of physicochemical parameters and improvement in water quality due to the reduced MSW loading condition at the Solan dumpsite. The WQI analysis results show that the quality of the groundwater is severely affected by the leaching of ions primarily for those locations which are in closer proximity to the dumpsite (<2–2.5 km).

Heavy Metal Pollution Indexing

The heavy metal concentrations for the groundwater sources have been summarized in Table S8 as mentioned earlier, and the average concentration of heavy metal have been reported in Table 8. Over the entire monitoring campaign carried out for different seasons, the average concentrations of zinc were well below the permissible limits (5 mg/L) per the BIS standards. In contrast, all the study locations exceeded the cadmium concentrations (0.003 mg/L) per BIS standards. Iron and copper concentrations exceeded the standards (0.3 mg/L for Fe; 0.05 mg/L for Cu) at the Baddi open landfill site, whereas chromium was exceeded at all the study locations except Mandi where it was not detected.

Heavy metal pollution indexing (HPI) of groundwater was evaluated for all the four study regions seasonally as discussed earlier in the methodology section. The heavy metal indexing of groundwater samples was assessed and was compared to two sets of standards—namely, BIS: 10500 standards and WHO standards. The HPI values determined have been summarized in Table 9. The HPI is a standard parameter for comparing the groundwater characteristics in the context of heavy metal contamination (Zakhem and Hafez 2015). The average range of heavy metal pollution indexing by using BIS:10500 standards of the four study regions including Solan, Mandi, Sundernagar ,and Baddi exhibits the value (i.e., 193, 76, 125, and 213), and heavy metal pollution indexing by using WHO standards exhibits the values (i.e., 218, 91, 157, and 249), respectively. The results obtained from the analysis were clearly indicated that HPI of the groundwater samples from Solan, Sundernagar, and Baddi was above the critical index value of 100 by using both the standards, whereas the HPI of the Mandi region showed comparatively a lesser value of pollution index in heavy metals (i.e., below critical value 100). However, with the increase in time and seasons, a significant increment has been observed in

Table 9. Heavy metal pollution index of the groundwater in study regions of Himachal Pradesh

Serial No.	Study regions	HPI (S1-IS:10500)	HPI (S1-WHO)	HPI (S2-IS:10500)	HPI (S2-WHO)	HPI (S3- IS:10500)	HPI (S3-WHO)	Average HPI value (IS:10500)	Average HPI value (WHO)
1	Solan	164	184	193	217	224	255	193	218
2	Mandi	57	62	79	96	94	117	76	91
3	Sundernagar	94	115	127	150	156	208	125	157
4	Baddi	188	214	221	259	232	275	213	249

the HPI value for all three seasons including summer, rainy, and winter season. The higher HPI values were due to the migration of the landfill leachate generated from the municipal solid waste dumpsite into the deep aquifers (Milivojevic et al. 2016).

To summarize, the context of groundwater pollution in the dumpsites of the study location pertains to contamination by leachate which percolate through the soil. However, as reported in literature, the rate of percolation is dependent on multifarious factors including the pollution potential of leachate, precipitation, zone of influence to cause pollution, and downstream distances considered from the actual polluted site location (El-Salam and Abu-Zuid 2015).Further, it has been observed that the samples analyzed for representing downstream distances closer to the dumpsite are more contaminated in general than those further away from them (i.e., more than the distance of 2.5 km). This is also due to loss of viscosity by the leachate encountering surrounding soil, thereby reducing its downstream velocity (Ali et al. 2014; El-Salam and Abu-Zuid 2015).

Multivariate Statistical Analysis

Correlation Matrix Analysis

Pearson's correlation matrix is the measure of the linear association between the two variables, and the values of the correlation coefficients always lies between -1 and $+1$ (Bhuiyan et al. 2016). The correlation between the different physicochemical characterization of groundwater samples of all four study regions including Solan, Mandi, Sundernagar, and Baddi has been shown in Tables S9–S12. The results obtained from the Pearson's correlation matrix of the Solan region indicated that the parameters including TDS, TSS, and pH are having a significant correlation with almost all the parameters such as BOD, turbidity, electrical conductivity (EC), calcium, magnesium, and phosphate. TDS showed the positive significant correlation with TSS ($r = 0.80$), BOD ($r = 0.81$), turbidity ($r = 0.81$), EC ($r = 0.82$), pH ($r = 0.85$), and calcium ($r = 0.80$), whereas in the Sundernagar region, the parameters including TDS, TSS, BOD, EC, TA, and nitrate are having a maximum positive correlation among different parameters explained earlier.

Principal Component Analysis

Two principal component analyses were obtained for the *Mandi* region with an Eigen value greater than unity and revealed 90.091% of total variance in the groundwater samples data sets. *Three* components were obtained for the *Sundernagar* and *Solan* region having an Eigen value greater than one, and the total variance revealed 90.382% and 87.806%, respectively. However, *only* one component was extracted for the *Baddi* region having an Eigen value greater than unity, and the total variance of the groundwater samples data set revealed 90.076% of the total component matrix. The component matrix and the total variance of the different parameters in the matrix have been presented in Tables S13–S24, and the plots for the rotated component matrix with variance for the respective study regions have been presented in Figs. 3–5.

Component 1

The first component in the groundwater samples data set of study regions including Solan, Mandi, and Sundernagar is influenced by the high positive loading in phosphate, pH, electrical conductivity, turbidity, chloride, ammoniacal nitrogen, BOD, and magnesium. The moderate positive loading is exhibited by total solids and COD, whereas poor positive loading is exhibited by calcium and alkalinity. The negative loading of the calcium is influenced by phosphorus ions. The calcium and phosphorus have a negative correlation with each other, whereas alkalinity and pH are positively correlated. As the alkalinity of water increases, the pH value of water samples also tends to increase. These parameters are indicative of the presence of hardness (due to calcium and magnesium ions), high electrical conductivity, and TDS.

However, in the Baddi region, the high positive loading has been illustrated by pH, total solids, BOD, COD, turbidity, sulphate, calcium, magnesium, chlorides, electrical conductivity, ammoniacal nitrogen, nitrate, fluoride, and total alkalinity. In this context, the principal component analysis revealed the results that the Baddi region had only one component matrix, and hence, no rotated component matrix can be extracted.

The high positive influence of phosphate in water is due to the urban and agricultural settings, and excess of it may cause eutrophication in water. The sulfate content is basically due to the agricultural activities and sewage practices, whereas electrical conductivity is

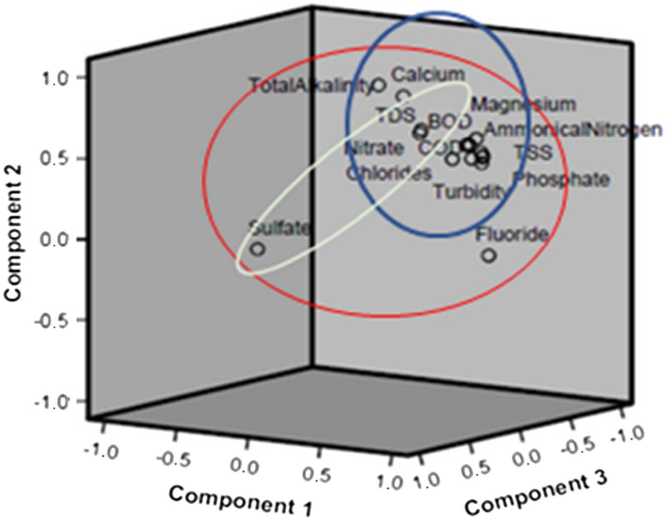


Fig. 3. Rotated component matrix with varimax normalized for Solan region.

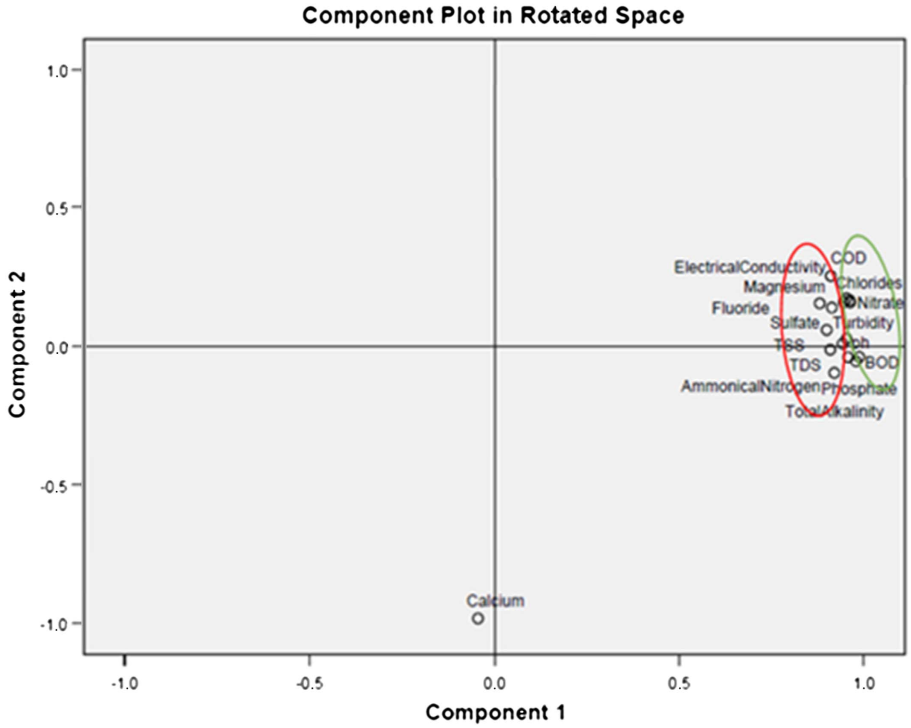


Fig. 4. Rotated component matrix with varimax normalized for Mandi region.

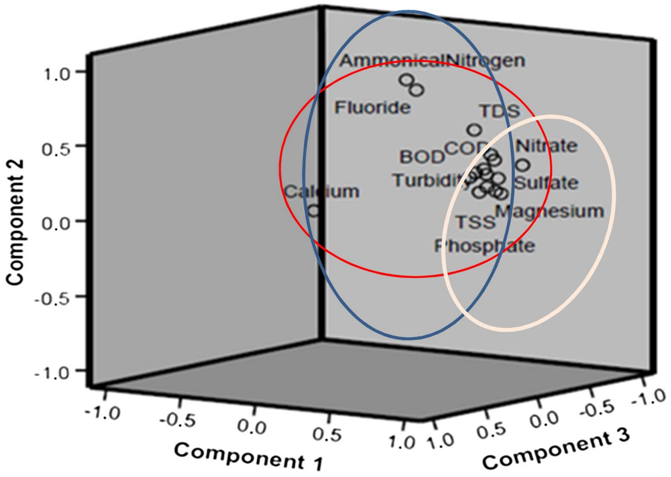


Fig. 5. Rotated component matrix with varimax normalized for Sundernagar region.

due to the concentration of salts in water. Alkalinity is due to the leaching of minerals in the groundwater aquifers.

Component 2

The second component in the groundwater data sets of Solan, Mandi, and Sundernagar has been illustrated by the high positive loading in the variables including total alkalinity, calcium, ammoniacal nitrogen, and fluorides, whereas variables including electrical conductivity, pH, turbidity, magnesium, chlorides, ammoniacal nitrogen, and fluorides exhibits moderate positive loading in the component matrix. For example, a higher pH tends to produce fluoride concentration in groundwater.

Component 3

The third component in the groundwater data sets of Solan and Sundernagar has been influenced by the high positive loading in the variables including calcium and sulfate.

Hierarchical Cluster Analysis

The principle of HCA is applied to four study regions of Himachal Pradesh. The groundwater samples data set is divided into different clusters, and the visual observation of the cluster is defined by the dendrogram illustrated in Figs. 6–9 for Solan, Mandi, Sundernagar, and the Baddi region of Himachal Pradesh, respectively. A dendrogram is commonly employed to represent the arrangement of clusters acquired by the hierarchical clustering technique. However, the agglomeration schedule in ward linkage for four study regions has been summarized in Figs. S22–S25. HCA utilizes the Ward method of statistics that prescribed the agglomerative hierarchical clustering procedure where the criteria for the set of clusters to integrate each step is based on the favorable value of an objective function. Ward's method of linkage employed the variance procedure to dictate the distances between clusters and helps to minimize the sum of squares of clusters that can be formed at each step (Rana et al. 2018a).

Solan

In the case of the Solan region, three cluster are formed (Cluster 1, 2, and 3) exhibiting low, medium, and high pollution regions. Cluster 1 exhibits different variables numbered as 6, 14, 4, 12, 13, 3, 5, 2, 16, and 10, and Cluster 2 exhibits variables numbered as 7, 9, and 8. Cluster 3 represents the variables numbered as 1, 11, and 15. The preceding represented variables of the individual cluster exhibits the pollution-based classification of the pollutant variables of various groundwater samples for different dumping sites.

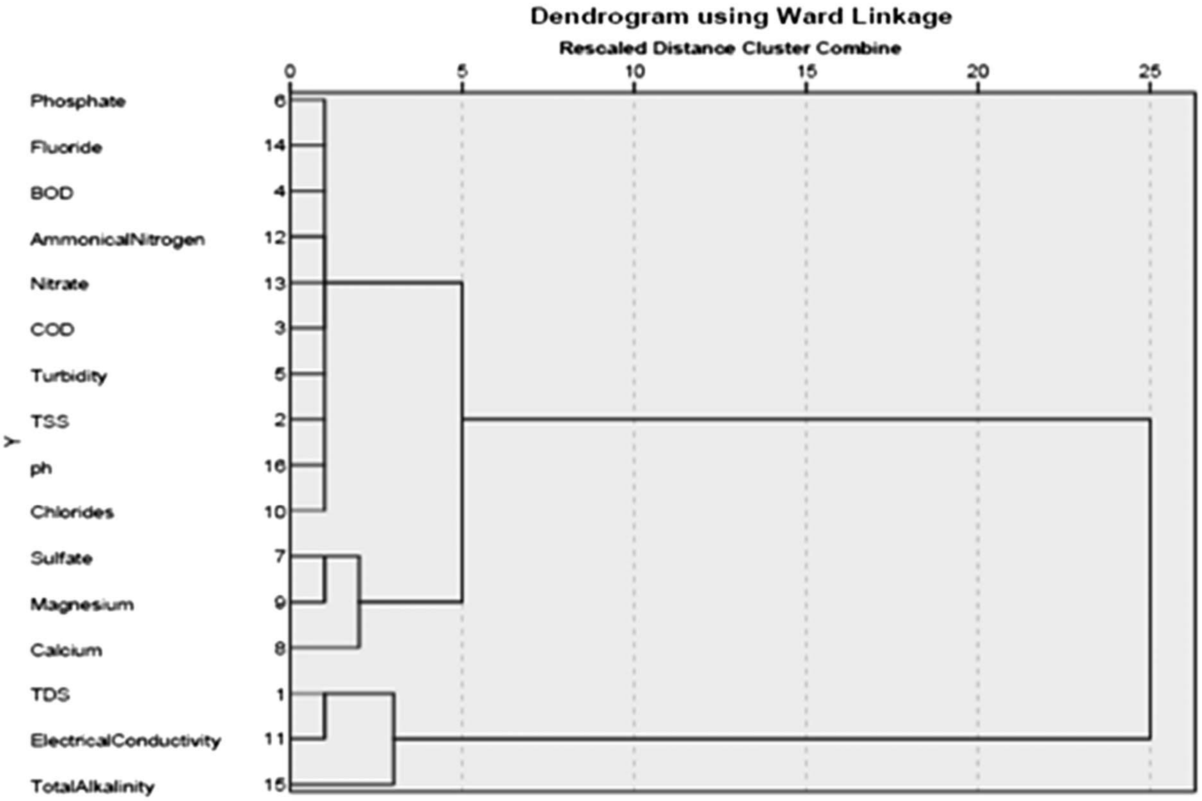


Fig. 6. Hierarchical dendrogram for groundwater samples in Solan region.

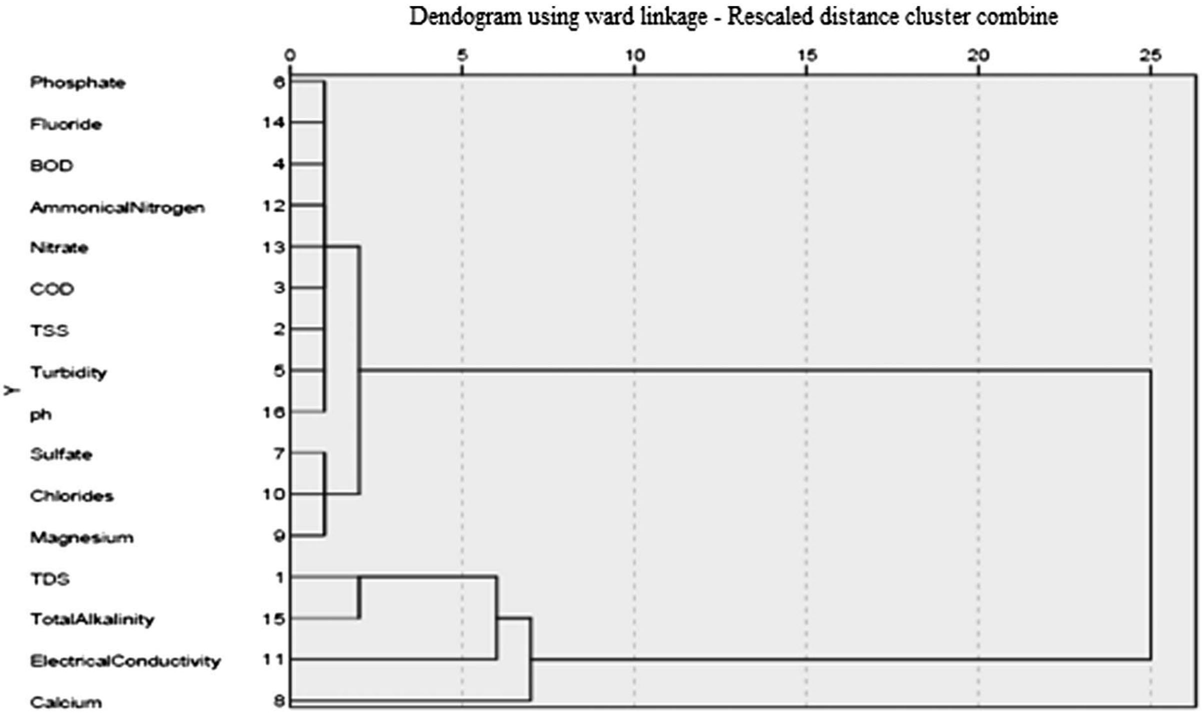


Fig. 7. Hierarchical dendrogram for groundwater samples in Mandi region.

For the dumpsite in Solan, Cluster 1 included the variables named as phosphate, fluoride, BOD, ammoniacal nitrogen, nitrate, COD, turbidity, total suspended solids, pH, and chlorides. The water samples revealed the less pollution in Cluster 1 due to the aforementioned variables present in the groundwater samples data set.

Cluster 2, exhibiting three variables including sulfate, magnesium, and calcium, revealed a moderate pollution region. The total

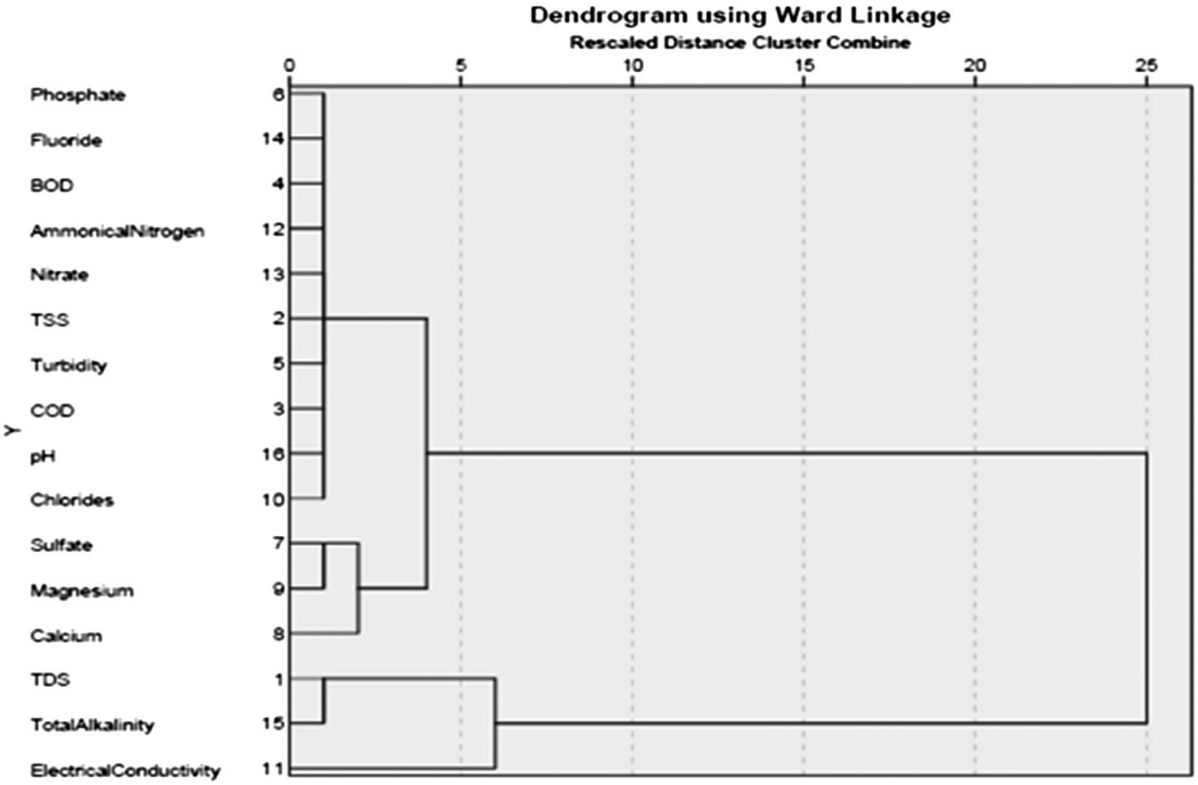


Fig. 8. Hierarchical dendrogram for groundwater samples in Sundernagar region.

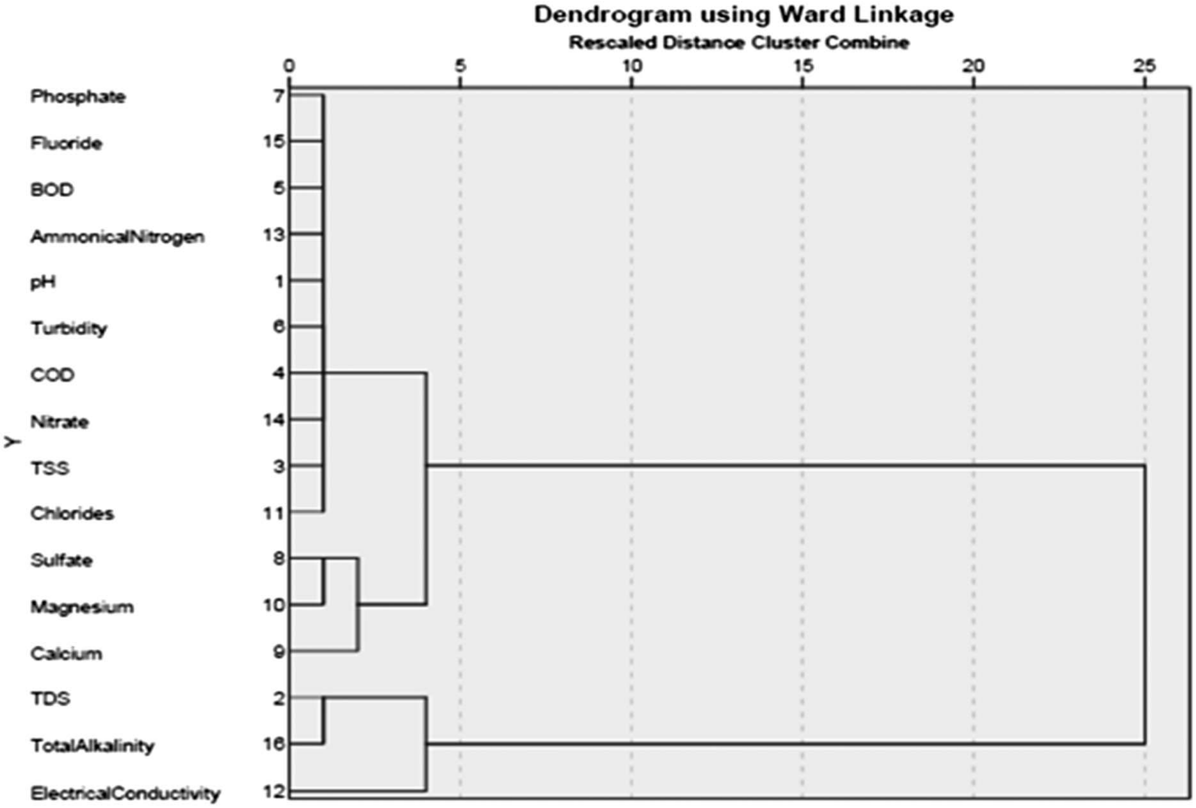


Fig. 9. Hierarchical dendrogram for groundwater samples in Baddi region.

hardness is due to the leaching of minerals in the groundwater and the presence of calcium and magnesium ions. Cluster 3 of the groundwater samples in the Solan region exhibits three more variables named as total dissolved solids, electrical conductivity, and total alkalinity, and due to the presence of these ions, it exhibited the high pollution region in the groundwater data set. Total dissolved solids are the salts, heavy metals, and traces of organics dissolved in water which become the cause of sediments and turbidity in the water and other anthropogenic sources.

Mandi

The groundwater samples data set of Mandi region revealed the formation of three clusters (Cluster 1, 2 and 3) exhibiting low, medium, and high pollution regions. Cluster 1 exhibits the variables numbered as 6, 14, 4, 12, 13, 3, 2, 5, and 16 while Cluster 2 exhibits variables numbered as 7, 10, and 9, Cluster 3 represents the variables numbered as 1, 15, 11, and 8. However, in the case of the Mandi region, Cluster 1 included the variables named as phosphate, fluoride, BOD, ammoniacal nitrogen, nitrate, COD, total suspended solids, turbidity, and pH. The water samples revealed the less pollution in Cluster 1 due to the aforementioned different variables present in less proportion in the groundwater samples data set. Cluster 2 exhibits three variables including sulfate, chloride, and magnesium and revealed a moderate pollution region, whereas Cluster 3 of the groundwater samples data set in the Mandi region exhibits four different parameters named as total dissolved solids, total alkalinity, electrical conductivity, and calcium and cause high pollution in the region. The high pollution region indicates the calcium content due to the agricultural activities basically by the application of excessive amount of lime to the soil.

Sundernagar

The groundwater samples data set of the Sundernagar region revealed three clusters formations (Cluster 1, 2, and 3) and exhibits low pollution region, medium pollution region, and high pollution region. Cluster 1 exhibits the variables numbered as 6, 14, 4, 12, 13, 2, 5, 3, 16, and 10, whereas Cluster 2 exhibits variables numbered as 7, 9, and 8. Cluster 3 represents the variables numbered as 1, 11, and 15. However, Cluster 1 represents the variables named as phosphate, fluoride, BOD, ammoniacal nitrogen, nitrate, total suspended solids, turbidity, COD, pH, and chlorides. The water samples revealed the less pollution in Cluster 1 due to the preceding present variables in the groundwater data set. Cluster 2 exhibits three variables including sulfate, magnesium, and calcium which revealed a moderate pollution, whereas Cluster3 of the groundwater samples data set in the Sundernagar region exhibits three parameters named as total dissolved solids, total alkalinity, and electrical conductivity that becomes the cause of high pollution in the region.

Baddi

The groundwater samples data set of Baddi region revealed three clusters formations (Cluster 1, 2 and 3) and exhibits low pollution region, medium pollution region, and high pollution region. Cluster 1 exhibits the variables numbered as 7, 15, 5, 13, 1, 6, 4, 14, 3, and 11 (phosphate, fluoride, BOD, ammoniacal nitrogen, pH, turbidity, COD, nitrate, total suspended solids, and chlorides) and revealed a less pollution region, whereas Cluster 2 exhibits variables numbered as 8, 9, and 10 (sulfate, magnesium, and calcium) and revealed a moderate pollution region. Cluster 3 represents the variables numbered as 2, 16, and 12 (total dissolved solids, total alkalinity, and electrical conductivity) and exhibits a high pollution region due to the saline water and moreover the leaching of minerals in the groundwater. Electrical conductivity of water is its ability to conduct an electric current, and electrical conductivity is directly related to the concentration of dissolved ionized solids in the water.

Conclusion

The present study shows that the open dumping of municipal solid waste is a big threat to the degradation of the quality of groundwater. The current study compiles the physicochemical characterization of leachate and groundwater, heavy metal analysis, leachate pollution index, water quality index, and heavy metal pollution index for the samples collected from four study regions of Himachal Pradesh. The physical, chemical, and heavy metal characterization of leachate samples extracted from the study areas in Himachal Pradesh exceeded the permissible values. The LPI of the samples of the dumpsites from Solan, Mandi, Sundernagar, and Baddi were determined to be 17, 17, 14, and 22, respectively, which exceeded the permissible values and indicated high toxicity levels. The groundwater quality of the study regions in Himachal Pradesh exhibited moderate to poor quality of water as determined using OWQI. The water quality assessment by means of BIS 10500 standards and NSFWQI analyses showed that groundwater samples extracted from sources closer to the immediate proximity of dumpsites were of moderate and fair quality, but the quality of groundwater improved with increasing distances from the dumpsites. In general, the contamination levels reduced with increasing downstream distances, and after a 4-km distance from the dumpsites, the water quality of Solan, Sundernagar, and Baddi were categorized as good quality, whereas for Sundernagar it was excellent quality. However, based on the seasonal variation analysis, the results revealed that the concentrations of different parameters of groundwater increase with time period. Out of four study regions, the water quality of the Baddi region degraded quickly due to the industrial activities running in the town. Similar results were obtained using the HPI analysis wherein the highest value of HPI were observed for the Baddi location and the lowest for the Mandi study area. It is critically recommended that waste should be initially segregated on the household basis prior to dumping into the waste disposal sites to preserve future contamination of groundwater sources. Multivariate statistical analysis including PCA and HCA revealed the total variance in the component matrix of PCA illustrated 87.805%, 90.091%, 90.382%, and 90.076%, respectively, in the data set of groundwater samples for Solan, Mandi, Sundernagar, and Baddi regions of Himachal Pradesh.The components in the groundwater samples data set of study regions including Solan, Mandi, Sundernagar, and Baddi is represented by the high positive loading in phosphate, pH, electrical conductivity, turbidity, chloride, ammoniacal nitrogen, and magnesium, whereas poor positive loading is exhibited by calcium and alkalinity. Apart from this, hierarchical cluster analysis (HCA) is utilized for grouping of the 16 variables of groundwater into three clusters for four study regions and revealed the pollution potential of different variables. It is recommended that the open dumping should be restricted, and proper engineered landfill along with the liner system, leachate collection and transfer mechanism, and energy monitoring system and final cover mechanism should be made to prevent the environmental pollution and to preserve the groundwater reserves.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Supplemental Data

Tables S1–S23 and Figs. S1–S25 are available online in the ASCE Library (www.ascelibrary.org).

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