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Vulnerability assessment using hazard potency for regions generating industrial hazardous waste

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ABSTRACT

This study proposes a methodology that would measure the hazardous characteristics of industrial waste based on its physical and chemical properties. A composite hazardous waste index (HWI) is framed using a new aggregation operator proposed in this study. However, HWI alone cannot be used to compare the hazardous characteristics of different wastes. The concept of hazard potency (HP) is introduced in this study in order to address this problem. HP can be calculated not only for a single waste stream but also for multiple industrial processes in an industry. Thus the hazardous wastes generated from two industries can be directly compared using this methodology. The vulnerability arising out of an industrial unit has been evaluated using HP values of the unit and the population residing within its impact area. The industries in a region are prioritized based on the vulnerability of the adjoining population using the non-dominated sorting algorithm. Solutions are ordered into various levels of domination depending on their HP and population values. A case study of Kolkata Metropolitan Area is provided to substantiate the methodology.

1. Introduction

Urban areas in developing countries like India have immense pressure on its land resources. High population density in all the major cities is a common phenomenon. Sporadic and organic growth of these cities along with unplanned allocation of industries has worsened the situation. Occurrence of industrial facilities, warehousing and storage facilities are common in the core of these cities or their peripheral areas. These fixed facilities not only handle hazardous chemicals but also generate substantial amount of hazardous waste. The risk of spillage or fire in such facilities cannot be ruled out and their impact on the adjoining population may have catastrophic results. In this light, a mechanism to assess the hazardous potential of all such facilities in a region is necessary.

Researches on impact of hazardous chemicals and industrial solid waste from specific industrial sites have been conducted in the past, where emphasis was on waste characterization and identification of treatment methodologies. Yang [1] emphasized on research pertaining to waste characterization in the industrial processes in a region for an effective waste management. Pollutants found in wastewater of palm oil industry and semi-conductor industries were analyzed. Mbuligwe and Kaseva [2] have conducted a study on the type and quantity of industrial solid waste generated in the city of Dar-es-Salaam. The wastes generated were characterized according to the nature of generating industrial units. A SWOT analysis was carried out on the existing hazardous waste management of the city.

Similar studies were also conducted on specific industries. Mendez et al. [3] had worked on the characterization of waste from eight different paper mills. Abreu and Toffoli [4] had worked on the characterization of chromium waste from tanneries. Fiore et al. [5] had conducted waste characterization studies on waste generated from aluminium foundry. The composition of different type of waste generated e.g. Policast mud, furnace slag, etc. were studied and treatment methods were also suggested.

Khan and Abbasi [6] designed accident hazard index (AHI) to rate potential accidents in industries based on direct impact (heat load, overpressure load and toxic load) and indirect impact (on environment based on Delphi method). The attributes were aggregated using the root sum power addition operator (for exponent value equal to 2). Khan et al. [7], in continuation with the previous research, had proposed a safety weighted hazard index which accounted for the potential damage as well as the preparedness (in terms of safety measures) of the industries. Zabeo et al. [8] had designed a framework based on multi-criteria decision analysis

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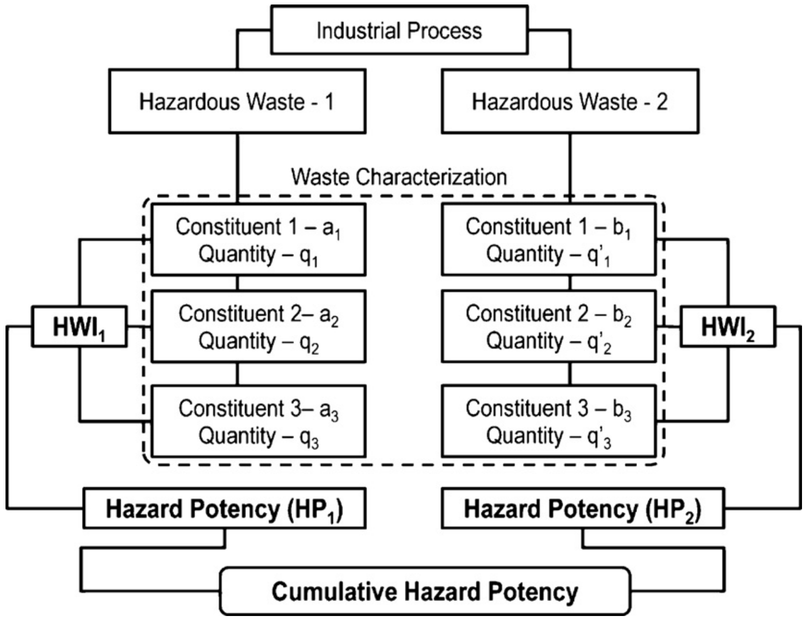

Fig. 1. Proposed methodology for computing cumulative hazard potency of an industrial waste generating unit.

(MCDA) to assess vulnerability of a region due to soil contamination from different sources. This involved four major attributes which consisted of several sub-attributes with a normalized score. The aggregation of attributes was done using the Choquet integral operator. Sebos et al. [9] had designed a methodology to guide landuse planning in a region having polluting industries. Vulnerability of the existing landuse was evaluated based on ten criteria (such as population sensitivity, population density, landuse classification and distribution, etc.). The proposed landuse was decided after overlapping the vulnerability data with the damage zoning.

The knowledge of waste characterization from individual industry has not been transferred to policy makers and implementing agencies and a gap exists between the acquired knowledge and various guidelines, schemes or policies for regional waste management.

This study attempts at meeting the gap between the existing research on waste characterization and vulnerability assessment. A methodology is proposed for measuring the hazard potency of various waste generating units in a region and determining their vulnerability for a better regional hazardous waste management.

The following section will explain the methodology of the proposed model and discuss the principal components of the model.

2. Methodology

The first step for determining the hazard potency of a region is to identify all the industrial processes in the region, the types of hazardous waste produced and their quantities. Next, the hazardous wastes generated by each industrial process have to be characterized. The characterization of waste depends upon its physical and chemical properties which can be attributed to either the raw materials that go into the industrial process or, the compounds that result from production. The methodology adopted in this study has been represented in Fig. 1.

In the present study, hazardous wastes generated by various industrial units in a region were taken into account. The waste characterization was done based on Hazardous Waste (Management and Handling) Amendment Rules, 2003. The waste from each unit was further characterized using secondary data from relevant literature studies and a unique composite index or the hazardous waste index (HWI) was calculated for each waste stream. This composite index was calculated based on an aggregation method. HWI values are independent of the quantity of hazardous waste and are dependent on its chemical composition. Therefore, to compare waste streams from two different industrial processes, the concept of hazard potency (HP) was introduced.

The hazard potency (HP_i) of any industrial process is calculated using Eqs. (1) and (2).

$$HP_i = HWI_i \times Q_i \tag{1}$$

$$HP_{Total} = \sum_i HWI_i \times Q_i \tag{2}$$

where Q_i is the amount of hazardous waste '*i*' generated in a given industrial unit, HWI_i is the hazardous waste index of *i*th waste stream and HP_{Total} is the cumulative hazard potency of an industrial unit.

Section 3 elaborates the calculation of HWI using aggregation method. The efficacy of the composite HWI lies in its computation simplicity. The computations are based on National Fire Protection Association (NFPA) ratings which can be procured from Material Safety Data Sheet (MSDS) of the industrial chemicals and wastes. A working solution based on the above stated methodology and its application is also provided in this study. The Kolkata Metropolitan Area was selected for the above mentioned purpose.

The methodology has introduced new concepts like HWI and HP_{Total} which would be further explained in the following sections.

3. Calculation of hazardous waste index (HWI)

Hazardous wastes are composite wastes consisting of more than one hazard prone constituent, which makes it difficult to measure the hazard potency for a given hazardous waste. The existing research on the framework for comparison of two hazardous waste samples is not very extensive.

The framework for designing environmental indices constitutes of three major steps as proposed by Ott [10]. The first step is to identify attributes for the composite index (e.g. inflammability, toxicity, etc.) and calculate their index values. The second step constitutes of calculating the sub-index values of individual attributes based on the distribution characteristics of the attributes (i.e. whether the distribution is linear, stepped linear, polynomial, etc.). The final step is to use an appropriate aggregation operator to compute the value of the composite index. Researches pertaining to HWI have been limited, and the significant contributors are Jones [11], Gupta and Babu [12], Musee et al. [13]. However, researches on other environmental composite indices have been abundant. A number of studies have been done in the areas of water quality [14–16], air quality [17,18], and environmental quality [19–21]. Composite indices have also been used for computing risk indices [22] and specific studies on leachate pollution [23].

In this context, a composite index based on aggregation methods could be designed to summarize the hazardous potential of a waste. This study makes a similar attempt to find a composite index based on four major characteristics, namely – inflammability, toxicity, reactivity, and corrosivity values of the waste. The following section would elaborate the method that has been undertaken to design a composite HWI.

3.1. Methodology for designing HWI

Four major attributes of a hazardous waste, e.g. flammability, toxicity, reactivity and corrosivity are used to compute the HWI values of a waste. These are based on the NFPA ratings of flammability, health (toxicity), reactivity respectively for the given chemical waste. The pH value of a waste is used as a corrosivity index [13]. The next step in designing a composite index is determining a suitable methodology to calculate the sub-index value for each of the identified attributes. The sub-index values depend on the type of distribution of the attributes. Flammability, toxicity and reactivity indices are linearly distributed, while the distribution of corrosivity index (based on pH values) is parabolic in nature. The sub-index values for the linearly distributed indices were calculated using Eq. (3) which was used by Neumayer [24].

$$I = \left(\frac{x - x_{\min}}{x_{\max} - x_{\min}}\right) \tag{3}$$

The sub-index values for corrosivity index (pH value) are based on the Walski and Parker's Index (1974) which is a decreasing scale index. As HWI proposed in this study is an increasing scale index, the Walski and Parker's Index has been modified using Eqs. (4)–(6) where the values are lowest for pH value of 7 and highest for pH values lesser than 2 and exceeding 12.

$$\text{For,} \quad 0 < x < 2; \quad I = 1 \tag{4}$$

Table 1
Index values of the selected hazardous waste (waste type 18.1, Schedule I).

Constituents	Share of total hazardous waste (%)	Flammability index (N_F)	Toxicity index (N_H)	Reactivity index (N_R)
NiO	25	0	0	1
CaO	2	0	2	3
Al_2O_3	73	0	0	2

$$2 < x < 12; \quad I = 1 - 0.04 \times \{25 - (x - 7)^2\} \tag{5}$$

$$x > 12; \quad I = 1 \tag{6}$$

where, I = sub-index value of pH, x = pH value.

For this study, the waste stream generated from an industrial unit located in Kolkata Metropolitan Area (KMA) has been considered. The industrial unit is a producer of industrial chemicals and fertilizer (Jayshree Chemicals and Fertilizers Limited located at Khardah in District 24 Parganas-North). The waste generated and its composition is shown in Table 1. The pH of the waste stream is 2 [25].

Sub-index values of different attributes are combined together using an aggregation operator. The operators used in this study have been selected from prevalent methods discussed by Ott [10], Swami and Tyagi [14], Kumar and Alappat [23] and Sadiq et al. [20]. Ten existing methods have been considered in this study, as shown in Table 2.

The weights assigned to the operators WLA, WRSSA and WM have been classified in three sets, namely w1, w2, and w3 (where each set consists of four weight functions, which add up to unity).

Weights assigned in set w1 have given more priority to attributes like flammability and toxicity. The set of weight function w2 has assigned more priority to corrosivity. The set w3 has assigned high priority to corrosivity (w33) and toxicity (w32) attributes. The values of the composite HWI calculated using different aggregation methods are presented in last column of Table 2.

A new operator for aggregation of composite index values has been proposed in this study. The general form is given by Eq. (7). The proposed aggregation method (PAM) is dependent on the number of sub-indices.

$$\text{C.I.} = \sum_{i=1}^{n} \left(\frac{I_i^n}{n}\right)^{1/n} \tag{7}$$

where, C.I. = composite index, I_i = sub-index value for attribute i, n = number of sub-indices.

Table 2
HWI values of the selected waste (waste type 18.1, Schedule I).

Sl. no.	Operator	Weight (if any)	HWI
1	Un-weighted additive method (UWA)	–	1.45
2	Weighted linear additive method (WLA)	w1[a]	0.26
		w2[b]	0.5
		w3[c]	0.43
3	Root sum power additive method (RSPA)	–	1
4	Root mean square additive method (RMSA)	–	0.77
5	Weighted root sum square additive method (WRSSA)	w1[a]	0.45
		w2[b]	0.69
		w3[c]	0.6
6	Square root harmonic mean method (SRHM)	–	0.55
7	Swamee and Tyagi method (ST)	–	0.003
8	Un-weighted multiplicative method (UWM)	–	0
9	Weighted multiplicative method (WM)	w1[a]	0
		w2[b]	0
		w3[c]	0
10	Maximum operator method (Max.O)	–	1
11	proposed aggregation method (PAM)	–	0.71

[a] Weight functions for w1 – {flammability:toxicity:corrosivity:reactivity = 0.5:0.25:0.15:0.1}.
[b] Weight functions for w2 – {flammability:toxicity:corrosivity:reactivity = 0.05:0.1:0.15:0.4}.
[c] Weight functions for w3 – {flammability:toxicity:corrosivity:reactivity = 0.2:0.3:0.3:0.2}.

Table 3
HWI values for the waste type identified in KMA.

Sl. no.	Type of waste	Flammability (N_F)	Toxicity (N_H)	Reactivity (N_R)	Corrosivity (pH)	HWI
Schedule I						
1	1.9 [28–31]	1	0	1	7	0.21
2	3.3 [32–36]	2.89	1.08	0.01	6.04	0.51
3	4.5 [33,34,37–39]	0.49	1.71	0.09	12	0.71
4	4.6 [32]	1.2	0.4	0	7.5	0.21
5	5.1 [40]	1	1	0	5	0.21
6	6.2 [41]	1	2	1	8	0.42
7	6.3 [41]	1	2	1	8	0.36
8	9.1 [38,42,43]	0.84	0.86	0.17	9	0.19
9	12.9 [33–35,37–39,42]	1.14	1.9	0.89	5.1	0.35
10	15.1 [44]	0	2	0	7	0.35
11	16.3 [36]	0	0.0375	6	0	0.03
12	17.1 [36]	0	0.06	0	7	0.01
13	17.2 [35–37,39,42,45,46,47]	0.63	2.95	0.32	7.5	0.52
14	18.1 [48–50]	0	1.77	0.04	2	1.28
15	20.2 [51,52]	0.6	0.4	0	7	0.11
16	20.3 [51,53]	3	1.92	0	7	0.55
17	21.1 [38,51,54,55]	1.0985	2	0	7	0.36
18	26.2 [33–35,37–39,42]	0.99	1.02	0.01	6.7	0.21
19	28.2 [56]	0.04	0.02	0	7	0.01
20	28.5 [53,57]	3	1.11	0	7	0.53
21	30.2 [33,38,39,42,58–60]	1	2.36	1.7	7.26	0.45
22	34.3 [35,38,61]	1.96	2.92	0	8.1	0.54
23	36.2 [35,36,38]	0.056	1.995	0	5	0.35
24	36.4 [62]	1	0	1	7	0.21
Schedule II						
1	B1 [33]	0	1	0	7	0.18
2	B3 [37]	0	2	0	7	0.35
3	B4 [38]	0	2	0	7	0.35
4	C14 [39]	0	3	0	7	0.53

The structure of the proposed method is similar to the root mean square additive method (RMSA).

Using the above 10 aggregation operators and the PAM the value of HWI were computed as shown in Table 2.

The HWI computed for all the operators were checked for problems of aggregation like ambiguity and eclipsing and it was found that only seven operators, i.e. WLA (w2, w3), WRSSA (w1, w2, and w3), SRHM, RMSA, RSPA, Max.O, and PAM were free from these errors.

These seven operators were further analyzed for sensitivity to change in sub-index values; corrosivity and flammability were selected as they were the highest and lowest valued sub-index respectively. The sensitivity was conducted by iterating the sub-index value from 0 to 1 in eleven iterations (at an interval of 0.1) and checking for ambiguity and eclipsing problem in the HWI values for all iterations. The results were plotted and represented as Figs. 2 and 3.

The outputs from the iterations of sub-index values were also analyzed for ambiguity and eclipsing errors. Eight operators such as WLA (w3), WRSSA (w1, w2, and w3), RMSA, SRHM, Max.O, and PAM were found to be devoid of any aggregation errors. For these selected eight aggregation operators, first order sensitivity analyses (rate of change of HWI values versus the change in sub-index value) were carried out. The result of first order sensitivity analysis for corrosivity sub-index is shown in Fig. 4.

WRSSA (w2, w3) operator exhibit higher sensitivity for lower value iterations but are not much sensitive for higher value iterations. Max.O is insensitive for both the lower and higher valued iterations. PAM and RMSA are comparable, although PAM is more sensitive for higher value iterations. The first order sensitivity of the PAM operator reveals its similarity to a logistic curve – where the lower values of sub-indices will yield a smaller HWI value compared to multiplicative operators but relatively higher values for high value of sub-indices. Similarly, first order sensitivity of HWI for flammability sub-index has been analyzed and is shown in Fig. 5. It indicates that WRSSA (w1), SRHM and PAM as the most sensitive operators.

PAM is the only operator that has shown consistency in both the cases of first order sensitivity analyses. Henceforth, in this study the PAM operator is used for calculating HWI values.

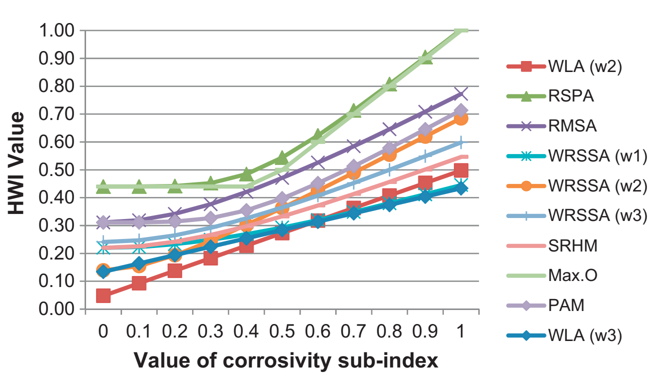

Fig. 2. Sensitivity of HWI value for corrosivity sub-index.

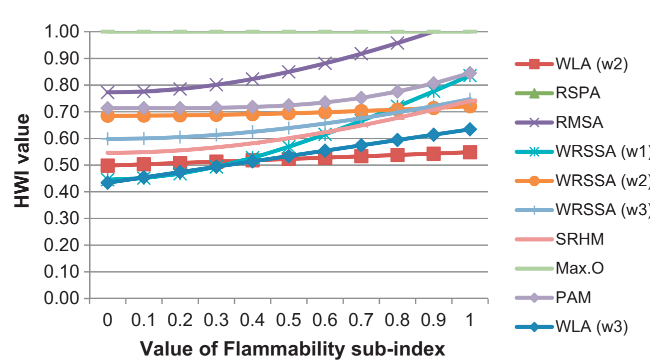

Fig. 3. Sensitivity of HWI value for flammability sub-index.

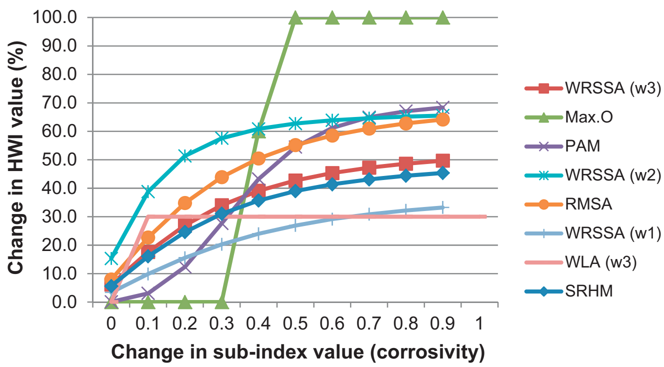

Fig. 4. First order sensitivity of HWIs for corrosivity sub-index.

4. Application of hazard potency values in regional waste management

The methodology presented in Section 2 shows that the HP of hazardous waste generated from an industrial process can be calculated by finding the product of the HWI value of the waste and its quantity. Industrial wastes usually consist of more than one waste. HP can be found by identifying all the wastes in the waste stream (i.e. waste characterization), calculating HWI and HP for all the wastes identified, and finally, adding HP of all the wastes identified in the waste stream. The HP values of wastes produced by different industrial units can be directly compared and decisions in regional waste management can be taken based on them. A case study has been presented in the next section to demonstrate the methodology proposed in this paper. The Kolkata Metropolitan Area has been selected for the above mentioned purpose.

4.1. Case study of Kolkata Metropolitan Area

The Kolkata Metropolitan Area (KMA) has an area of 1851.41 square km and a population of 14.72 millions, as per Census of India, 2001. It consists of 41 urban local bodies (municipalities and municipal corporations) and 24 panchayats (administrative units for rural areas). As per the Report on Inventory of Hazardous Waste Generation and the Hazardous Waste Generating units in West Bengal [26], KMA had 180 small and medium scale industries and 20 large scale industries. In this study the industrial units which generate more than 50 metric ton of hazardous waste have been selected for demonstration of the methodology. A list of industrial units in KMA adopted for the study, the types of production, along with the types and the quantities of wastes generated are provided in tab1 (supplementary material).

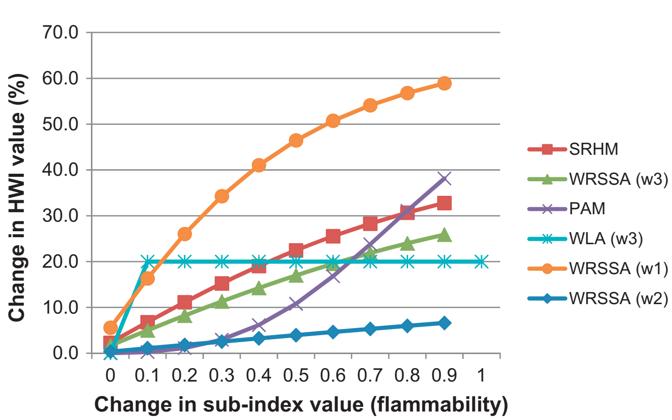

Fig. 5. First order sensitivity of HWIs for flammability sub-index.

The Report on Inventory of Hazardous Waste Generation and the Hazardous Waste Generating units in West Bengal [26], which is based on the Hazardous Waste (Management and Handling) Amendment Rules (HWMHR) [27], published under the notification of the Government of India was used for compiling tab1 (supplementary material). Schedule I of HWMHR identifies industrial processes which are hazardous in nature and generate waste which are extremely hazardous, irrespective of the concentration of the waste. Schedule II identifies chemical compounds which are deemed hazardous only when they exceed the prescribed limits mentioned in HWMHR. Following the HWMHR, 38 different types of hazardous wastes were identified from the waste stream generated by the selected industrial units in the study area.

Waste characterization was done by collecting the details of each of the waste identified in KMA using the HWMHR. The share of hazardous waste in the total waste stream generated was calculated and the composition of the waste stream for each waste type was obtained from different secondary sources. The waste characterization done for Schedule I hazardous wastes are shown in tab2 (supplementary material).

The waste type 5.2, 12.1, 33.2, 33.3 and 34.2 as per Schedule I have not been included in the study as reliable secondary data on waste characteristics were not available. However, the amount of these wastes generated in the study area is miniscule.

Hazardous waste generated in the KMA and belonging to Schedule II are B1 (chromium III and its compounds), B3 (copper and its compounds), B4 (lead and its compounds), C14 (zinc and its compounds), and D1 (total sulphur). The prescribed concentration of each of the above mentioned waste is given in HWMHR 2003.

With an idea of the waste that is being generated in KMA, the HWI for each waste type can be computed using the PAM operator, as shown in Section 3.

4.1.1. Calculation of HWI for each waste type generated in KMA

As mentioned in the methodology in Section 2 of this study, the HWI can be calculated using the flammability, reactivity, toxicity, and corrosivity index of a waste. The NFPA ratings have been used for all the above mentioned indices. The NFPA values of a given waste (chemical) are readily available from MSDS of the particular waste. The MSDS of all the wastes identified in the previous section were collected, and HWI of each waste type was computed using PAM operator. The outputs are presented in Table 3 and Table 4.

The MSDS of wastes like total sulphur, manganese are not prepared; hence contributions of these wastes in the HWI value of waste streams e.g. D1, 9.1 (containing total sulphur) and 4.5, 26.2 (containing manganese) have not been considered. The pH values of most of the wastes have been obtained from secondary sources (as provided in tab2, supplementary material). Waste streams from most of the industries have a pH value ranging from 5.5 to 7.5, as they pre-treat the waste before final disposal to treatment, storage and disposal facilities (TSDF). Thus, for waste streams categorized under 1.9, 15.1, 17.1, 20.2, 20.3, 21.1 and 36.4 of Schedule I, and waste streams under Schedule II, whose pH could not be obtained through secondary sources, a pH value of 7 has been assumed.

4.1.2. Calculation of HP of the waste streams generated in KMA

The HWI values calculated for the Schedule I and II hazardous wastes generated in KMA are absolute values. They are independent of the amount or concentration of waste. Thus, it would be erroneous to compare two wastes without knowledge of their hazardous waste content. To compare two waste streams directly the concept of HP has been introduced in this study. The method to calculate HP values of a given waste stream has been shown in Section 2. The HP values for all the waste streams generated from the 38 industrial units in KMA have been calculated and shown in Table 4.

Table 4
Calculation of HP of all the waste streams identified in KMA.

Sl. no.	Name of generator	Type of waste	Total quantity of waste (metric ton p.a)	Share of hazardous waste (%)	HWI	Hazard potency (HP)
1	G D Electroplating	12.9	171.6	3.94	0.35	2.37
2	Hindustan Heavy Chemicals	17.1	1	0.02	0.01	22.71
		17.2	1.8	2.73	0.52	
		16.3	252	0.0125	0.03	
		5.1	108	100	0.21	
3	Jayshree Chemicals & Fertilizers	18.1	1.99	100	1.28	2.55
4	BSNL	6.2	84	100	0.42	55.19
		12.9	60	3.94	0.35	
		C14	36	100	0.53	
5	Bristol Petroleum	4.5	45	0.05	0.71	0.03
		36.2	26.55	0.144	0.35	
6	CETP, Central Leather Complex	30.2	24,000	16.8	0.45	1814.40
7	Alchrome	B1	96	100	0.18	17.28
8	Dabur India Ltd.	5.1	1.35	100	0.21	9.13
		28.2	2.205	2	0.01	
		28.5	216	0.036	0.53	
		34.3	31.8	51.27	0.54	
9	UIC Wires Ltd.	5.1	0.9	100	0.21	58.99
		6.2	124.8	100	0.42	
		12.9	56	3.94	0.35	
		B4	31.2	100	0.18	
10	DIC India Ltd.	20.2	27	20	0.11	94.34
		21.1	260.4	100	0.36	
11	Eternit Everest Ltd.	15.1	180	100	0.35	63.00
12	Hindustan Unilever Ltd.	3.3	12	1.27	0.51	54.96
		5.1	7.2	100	0.21	
		21.1	0.6	100	0.36	
		34.3	192	51.27	0.54	
13	HPCL Ramnagar Terminal	3.3	288	1.27	0.51	1.87
14	Bajaj Chemicals	B1	70	100	0.18	12.60
15	Diach Chemicals and Pigments Ltd.	9.1	175.2	74.8	0.19	24.90
16	Eastern Railway Depot.	3.3	24.345	1.27	0.51	1.29
		5.1	0.6	100	0.21	
		21.1	0.03	100	0.36	
		B4	2.845	100	0.35	
17	Hindalco Industries	4.6	39.23	40	0.21	152.75
		5.1	711.7	100	0.21	
18	Imperial Tubes Pvt. Ltd.	6.2	12	100	0.42	6.78
		12.9	27	3.94	0.35	
		C14	12	100	0.53	
19	Krishna Technochem Pvt. Ltd.	20.3	54	100	0.55	29.70
20	Lord's Chemicals	B1	960	100	0.18	172.80
21	Mahadev Fabrics	5.1	0.099	100	0.21	1.45
		26.2	120	5.67	0.21	
22	Mahavir Pumps	6.2	1.8	100	0.42	6.55
		12.9	420	3.94	0.35	
23	Rajnath Metals	9.1	75	74.8	0.19	10.66
24	Ranjan Industries	6.3	360	100	0.36	145.22
		9.1	36	74.8	0.19	
		B3	30	100	0.35	
25	Utkarsh Tubes Pvt. Ltd.	6.2	180	100	0.42	77.75
		12.9	156	3.94	0.35	
26	Bhusan Ltd.	5.1	2.7	100	0.21	28.56
		12.9	108	3.94	0.35	
		C14	50	100	0.53	
27	Dankuni Coal Complex	1.9	120	4.8	0.21	1.21
28	Hindustan Motors Ltd.	5.1	26	100	0.21	15.51
		12.9	50	3.94	0.35	
		21.1	26	100	0.36	
29	ITC Ltd., Tribeni Tissues Div.	5.1	6.77	100	0.21	49.72
		26.2	4056	5.67	0.21	
30	Indian Rayon and Industries Ltd.	5.1	0.15	100	0.21	3.60
		26.2	300	5.67	0.21	
31	Indotan Chemicals	B1	1440	100	0.18	259.20
32	Kesoram Rayon	5.1	4.446	100	0.21	80.34
		17.1	294.3	0.02	0.01	
		17.2	1.685	12.732	0.52	
		34.3	286.4	51.27	0.54	
33	Kundu Refinery Works	4.5	36	0.05	0.71	7.88
		4.6	93.6	40	0.21	
34	Mega energy Pvt. Ltd.	9.1	93.84	74.8	0.19	13.34
35	Nezone Strips Ltd.	12.9	54	3.94	0.35	0.74
36	Nezone Tubes Ltd.	6.2	180	100	0.42	127.22
		12.9	54	3.94	0.35	
		C14	96	100	0.53	

Table 4 (*Continued*)

Sl. no.	Name of generator	Type of waste	Total quantity of waste (metric ton p.a)	Share of hazardous waste (%)	HWI	Hazard potency (HP)
37	PMC Rubber Chemicals Pvt. Ltd.	5.1	0.5	100	0.21	46.69
		20.3	80	100	0.55	
		34.3	8	51.27	0.54	
		36.4	7	25	0.21	
38	Walzen Steel India Pvt. Ltd.	5.1	10.8	100	0.21	3.92
		12.9	120	3.94	0.35	

If the HP values of all the industrial units in KMA are plotted in ascending order, as shown in Fig. 6, it can be seen that CETP, Leather Complex has the highest HP followed by Indotan Chemicals, Hindalco Industries, Lord's Chemicals, etc. However, vulnerability assessment solely based on HP values is biased towards the characteristics of the generators (i.e. the industries); as it does not take into account the adjoining population, which might be affected in case of any hazardous event. Thus, the concept of HP needs to be supplemented by attributes of affected population for true representation of the vulnerability of a region arising out of industrial units.

4.1.3. Regional vulnerability assessment using hazard potency

In regional waste management, it is important not only to know the HP value of the industries in a region, but also the population residing in its vicinity. Here population refers to the number of people residing within a pre-determined impact area of a hazardous waste generating unit. Thus, the vulnerability (V) due to each hazardous waste generating unit can be represented by Eq. (8).

$$V = f\{\mathrm{HP}, \mathrm{Population}\} \tag{8}$$

Vulnerability increases with increase in HP values as well as with the size of adjoining population. As the trade-off between the HP values of an industrial unit and adjoining population is unknown, it can only be subjectively determined. Therefore, a non-weighted multi-objective optimization has been carried out in this study.

In the present case study, spatial location of all the industrial units was identified and a catchment radius of 1 km was earmarked with the industrial unit at its centre, as shown in Fig. 7. The 1 km impact radius was taken assuming that population within this catchment area would be the worst hit. The population within the catchment area was estimated using the Census of India, 2001 data.

A non-dominated sorting algorithm for the entire set of industrial units was used [63]. Using the concept of domination, Pareto optimal set consisting of the industrial units was sorted from the entire set of industrial units. After multiple iterations, the entire set of solutions was sorted into different levels of domination. This was achieved by simultaneously classifying the set of solution for a given iteration into a domination level (based on iteration number) and removing the classified set of solutions from the population for the next iteration. The same procedure was repeated till all units were classified into various domination levels.

The output of non-dominated sorting consisting of selected industrial units in KMA, in various levels of domination is shown in Table 5. Level 1 refers to highest level of vulnerability and Level 10 refers to lowest level.

The industrial units generating large amount of waste and located in less populous surroundings can be grouped in same non-dominated solution level with the ones located in thickly populated surroundings but generating waste with low HP values. For instance, both CETP of Leather Tanneries at Bhangore (generating

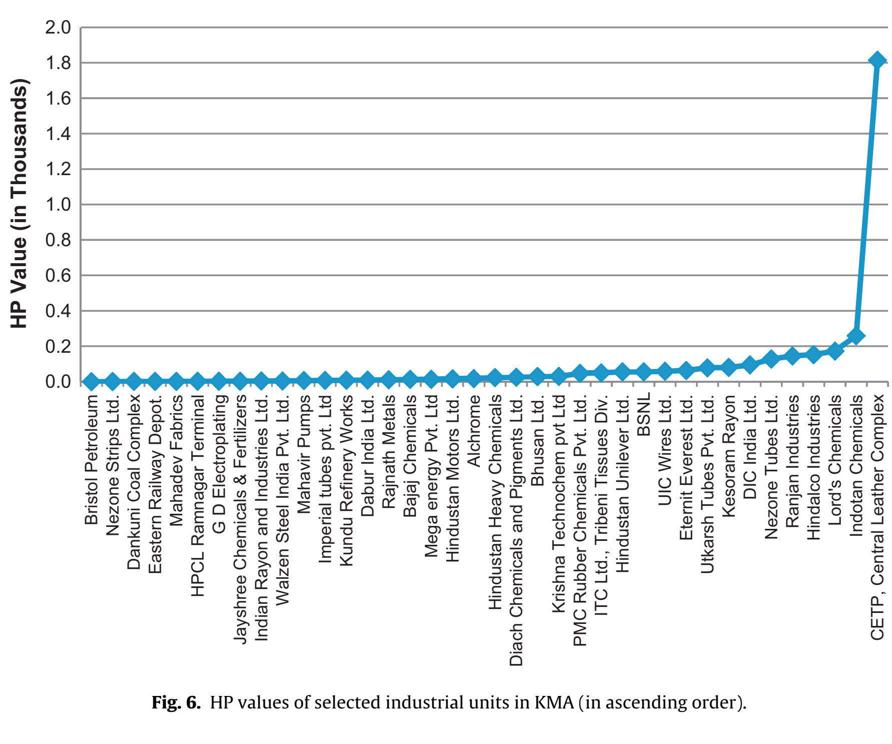

Fig. 6. HP values of selected industrial units in KMA (in ascending order).

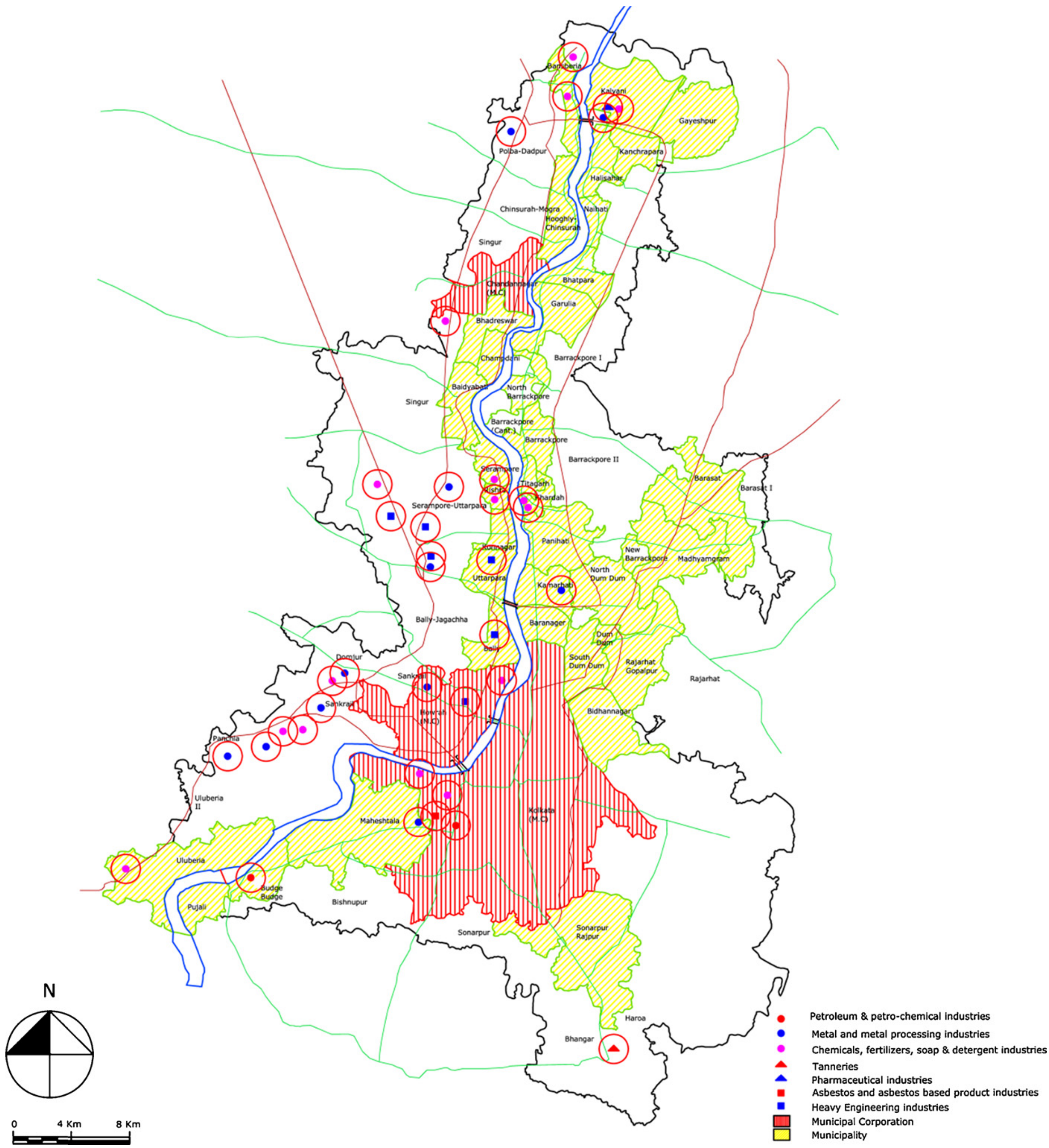

Fig. 7. Location and catchment area of selected industrial units in KMA.

the highest quantity of waste in the region but located in sparsely populated area) and GD Electroplating at Belgharia (generating the smallest quantity of waste in the region and having the highest population within the 1 km catchment radius) exist in the Level 1 non-dominated solution set.

The results of non-dominated sorting for first 7 iterations are shown graphically in Fig. 8. Each level representing a Pareto frontier lies at a distance from the origin depending on the level of its vulnerability – Level 1 with highest level of vulnerability lies farthest from origin.

The inclusion of catchment population attribute with the HP value of an industrial unit has provided a framework for assessing and ranking vulnerability arising out of spatial allocation of industrial units within a region.

Table 5
Levels of vulnerability of selected industrial units in KMA.

Name of industrial unit	HP values	Population within 1 km catchment area
Non-dominated solutions: Level 1 (highest vulnerability)		
G D Electroplating	2.37	81,425
CETP, Central Leather Complex	1814.40	4179
DIC India Ltd.	94.34	76,756
Hindalco Industries	152.75	59,496
Indotan Chemicals	259.20	8177
Non-dominated solutions: Level 2		
Eternit Everest Ltd.	63.00	72,943
Hindustan Unilever Ltd.	54.96	76,756
Lord's Chemicals	172.80	18,836
Non-dominated solutions: Level 3		
Hindustan Heavy Chemicals	22.71	48,119
BSNL	55.19	39,415
HPCL Ramnagar Terminal	1.87	76,756
Bajaj Chemicals	12.60	61,184
Ranjan Industries	145.22	9461
Utkarsh Tubes Pvt. Ltd.	77.75	15,349
Kesoram Rayon	80.34	11,281
PMC Rubber Chemicals Pvt. Ltd.	46.69	46,697
Non-dominated solutions: Level 4		
Jayshree Chemicals & Fertilizers	2.55	44,663
UIC Wires Ltd.	58.99	11,779
Eastern Railway Depot.	1.29	61,184
Hindustan Motors Ltd.	15.51	30,808
ITC Ltd., Tribeni Tissues Div.	49.72	23,345
Indian Rayon and Industries Ltd.	3.60	43,888
Nezone Tubes Ltd.	127.22	8864
Non-dominated solutions: Level 5		
Bristol Petroleum	0.03	26,195
Krishna Technochem Pvt. Ltd.	29.70	15,349
Non-dominated solutions: Level 6		
Diach Chemicals and Pigments Ltd.	24.90	11,603
Alchrome	17.28	11,779
Rajnath Metals	10.66	15,349
Bhusan Ltd.	28.56	6795
Non-dominated solutions: Level 7		
Dabur India Ltd.	9.13	11,779
Mahavir Pumps	6.55	15,349
Mega energy Pvt. Ltd.	13.34	2633
Non-dominated solutions: Level 8		
Kundu Refinery Works	7.88	8864
Mahadev Fabrics	1.45	15,349
Imperial Tubes Pvt. Ltd.	6.78	10,659
Non-dominated solutions: Level 9		
Walzen Steel India Pvt. Ltd.	4.40	8864
Dankuni Coal Complex	1.21	9536
Non-dominated solutions: Level 10 (lowest vulnerability)		
Nezone Strips Ltd.	0.77	8864

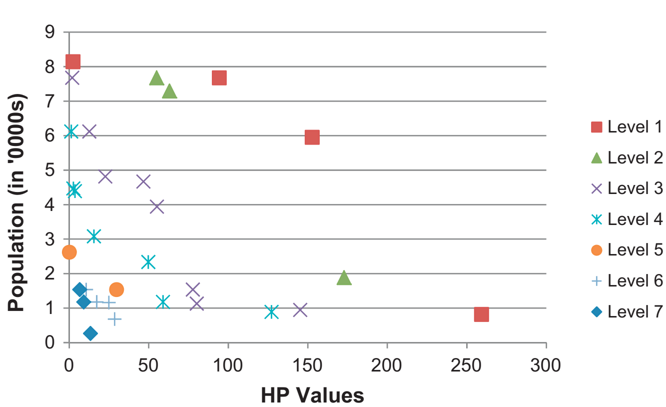

Fig. 8. Vulnerability levels of selected industrial units in KMA.

5. Conclusion

The study carries forward the research on waste characterization by suggesting a methodology and its application in regional hazardous waste management. As most of the hazardous wastes are composite in nature, the proposed concept of HWI relies deeply on waste characterization. The HWI is a composite index based on four parameters. This study has proposed a new aggregation operator to compute the value of HWI. The HWI can help in comparing two different types of waste directly. However, as the HWI values do not incorporate waste concentration attributes, no substantial conclusions can be drawn based on HWI values alone. The methodology of HP was proposed to address this issue. The value of HP depends on the concentration of waste and the HWI value of the waste. The concept of HP can be used to assess not only individual waste but also, the hazardous nature of industrial processes. Finally, the framework for vulnerability assessment of a region based on two attributes, i.e. HP values and the adjoining population was presented. The concept of non-dominated sorting was used for this purpose to classify solution sets in various levels of domination based on two variables i.e. HP value and adjoining population. The above mentioned framework was substantiated with the help of a case study of selected large and medium scale industrial units in KMA.

This study can find application in regional hazardous waste management which includes location allocation of new industrial units, TSDF, transportation, of hazardous waste, and preparation of crisis management plans.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2012.01.025.

References

[1] B.S. Yang, Industrial processes and waste characterization, Resour. Conserv. Recycl. 16 (1996) 93–112.
[2] S.E. Mbuligwe, M.E. Kaseva, Assessment of industrial solid waste management and resource recovery practices in Tanzania, Resour. Conserv. Recycl. 47 (2006) 260–276.
[3] A. Mendez, J.M. Fidalgo, F. Guerrero, G. Gasco, Characterization and pyrolysis behaviour of different paper mill waste materials, J. Anal. Appl. Pyrol. 86 (2009) 66–73.
[4] M.A. Abreu, S.M. Toffoli, Characterization of chromium rich tannery waste and its potential use in ceramics, Ceram. Int. 35 (2009) 2225–2234.
[5] S. Fiore, M.C. Zanetti, B. Ruffino, Waste characterization and recycle in an aluminium foundry, Resour. Conserv. Recycl. 45 (2005) 48–59.
[6] F.I. Khan, S.A. Abbasi, Accident hazard index: a multi-attribute method for process industry hazard rating, Process Saf. Environ. Prot. 75 (1997) 217–224.
[7] F.I. Khan, T. Husain, S.A. Abbasi, Safety Weighted Hazard Index (SWeHI) a new, user-friendly tool for swift yet comprehensive hazard identification and safety evaluation in chemical process industries, Process Saf. Environ. Prot. 79 (2) (2001) 65–80.
[8] A. Zabeo, L. Pizzol, P. Agostini, A. Critto, S. Giove, A. Marcomini, Regional risk assessment for contaminated sites part I: vulnerability assessment by multi-criteria decision analysis, Environ. Int. 37 (2010) 1295–1306.
[9] I. Sebos, A. Progiou, P. Symeonidis, I. Ziomas, Land-use planning in the vicinity of major accident hazard installations in Greece, J. Hazard. Mater. 179 (2010) 901–910.
[10] W.R. Ott, Environmental Indices: Theory and Practice, Ann Arbor Science Publishers, Ann Arbor, 1979.
[11] C.J. Jones, The ranking of hazardous materials by means of hazard indices, J. Hazard. Mater. 2 (1977) 363–389.
[12] J.P. Gupta, B.S. Babu, A new hazardous waste index, J. Hazard. Mater. A 67 (1999) 1–7.
[13] N. Musee, L. Lorenzen, C. Aldrich, An aggregate fuzzy hazardous index for composite wastes, J. Hazard. Mater. A 137 (2006) 723–733.
[14] P.K. Swamee, A. Tyagi, Describing water quality with aggregate index, J. Environ. Eng. 126 (5) (2000) 451–455.
[15] P.K. Swamee, A. Tyagi, Improved method for aggregation of water quality subindices, J. Environ. Eng. 133 (2) (2007) 220–225.
[16] A.K. Gupta, S.K. Gupta, R.S. Patil, A comparison of Water Quality Index for coastal water, J. Environ. Sci. Health A A38 (11) (2003) 2711–2725.

[17] A.K. Gupta, R.S. Patil, S.K. Gupta, Air pollution potential indices in a coastal region in India, Int. J. Environ. Pollut. 19 (5) (2003) 430–441.
[18] A.K. Gupta, R.S. Patil, S.K. Gupta, A comparison of air quality indices for a port and harbor region in India, Int. J. Environ. Pollut. 26 (4) (2006) 313–326.
[19] N.S. Arunraj, J. Maiti, Development of environmental consequence index (ECI) using fuzzy composite programming, J. Hazard. Mater. 162 (1) (2009) 29–43.
[20] R. Sadiq, A.H. Sikandar, J. Cool, M.J. Manuel, Using penalty function to evaluate aggregation models for environmental indices, J. Environ. Manage. 91 (2010) 706–716.
[21] E. Boriani, A. Mariani, D. Baderna, C. Moretti, M. Lodi, E. Benfenati, ERICA: a multiparametric toxicological risk index for the assessment of environmental healthiness, Environ. Int. 36 (2010) 665–674.
[22] R.K. Rao, S.V. Rao, V. Chary, Estimation of risk indices of chemicals during transportation, Process Saf. Prog. 23 (2) (2004) 149–154.
[23] D. Kumar, B.J. Alappat, Selection of the appropriate aggregation function for calculating Leachate Pollution Index, Pract. Period. Hazard. Toxic Radioact. Waste Manage. 8 (4) (2004) 253–264.
[24] E. Neumayer, The human development index and sustainability – a constructive proposal, Ecol. Econ. 39 (2001) 101–114.
[25] S. Goel, K.K. Pant, K.D.P. Nigam, Extraction of nickel from spent catalyst using fresh and recovered EDTA, J. Hazard. Mater. 171 (2009) 253–261.
[26] West Bengal Pollution Control Board (WBPCB), Report on Inventory of Hazardous Waste Generation and the Hazardous Waste Generating units in West Bengal, Kolkata, 2009. http://www.wbpcb.gov.in/html/downloads/haz_inventory.pdf (accessed on 26.02.09).
[27] Hazardous Waste (Management and Handling) Amendment Rules (HWMHR), Ministry of Environment and Forest, Government of India, New Delhi, 2003. http://envfor.nic.in/legis/hsm/so593e.htm (accessed on 26.02.09).
[28] Asphaltene, MSDS No. 81451, Martex Inc., Minnetonka, Minnesota, March, 2009. http://www.martrexinc.com/msds/MSDS_Asphaltene_Pitch.pdf (accessed on 05.07.11).
[29] Petroleum Resin, MSDS No. 81451, Ziegler Chemical & Mineral Corp., Jericho, NY, March, 2003. http://www.cdtechno.com/msds/asset/petroleum_resin.pdf (accessed on 23.07.11).
[30] Wax, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010 http://www.sciencelab.com/msds.php?msdsId=9925433 (accessed on 06.07.11).
[31] Heavy Oil (Mineral Oil), MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010 http://www.sciencelab.com/msds.php?msdsId=9927364 (accessed on 05.07.11).
[32] Crude Oil, MSDS No. A0017.msd, El Paso Corporation, Houston, Texas, June, 2007. http://www.elpaso.com/msds/A0017-Crude%20Oil.pdf (accessed on 05.07.11).
[33] Chromium, NFPA Label of the elements. http://periodictable.com/Elements/024/data.html (accessed on 05.07.11).
[34] Nickel, NFPA Label of the elements. http://periodictable.com/Elements/028/data.html (accessed on 05.07.11).
[35] Cadmium, NFPA Label of the elements. http://periodictable.com/Elements/048/data.html (accessed on 05.07.11).
[36] Mercury, NFPA Label of the elements. http://periodictable.com/Elements/080/data.html (accessed on 05.07.11).
[37] Copper, NFPA Label of the elements. http://periodictable.com/Elements/029/data.html (accessed on 05.07.11).
[38] Lead, NFPA Label of the elements. http://periodictable.com/Elements/082/data.html (accessed on 05.07.11).
[39] Zinc, NFPA Label of the elements. http://periodictable.com/Elements/030/data.html (accessed on 05.07.11).
[40] Used Oil, MSDS No. 81451, Safety Kleen Systems, Inc., Plano, Texas, September 20, 2007. http://www.safety-kleen.com/msds/81451rev9-20-07.pdf (accessed on 05.07.11).
[41] Zinc fine ashes, MSDS, Numinor Chemical Industries Limited, Maalot, Israel, February 2010. http://www.numinor.com/files/MSDSZincFineAshes2010.pdf (accessed on 05.07.11).
[42] Iron, NFPA Label of the elements. http://periodictable.com/Elements/026/data.html (accessed on 05.07.11).
[43] Sodium, NFPA Label of the elements. http://periodictable.com/Elements/011/data.html (accessed on 05.07.11).
[44] Asbestos, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010 http://www.sciencelab.com/msds.php?msdsId=9926600 (accessed on 06.07.11).
[45] Vanadium oxide, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010 http://www.sciencelab.com/msds.php?msdsId=9927639 (accessed on 26.07.11).
[46] Phosphorous, NFPA Label of the elements. http://periodictable.com/Elements/015/data.html (accessed on 05.07.11).
[47] Tin, NFPA Label of the elements. http://periodictable.com/Elements/050/data.html (accessed on 05.07.11).
[48] Nickel Oxide, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010. http://www.sciencelab.com/msds.php?msdsId=9926217 (accessed on 21.07.11).
[49] Calcium Oxide, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010. http://www.sciencelab.com/msds.php?msdsId=9927480 (accessed on 21.07.11).
[50] Aluminum Oxide, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010. http://www.sciencelab.com/msds.php?msdsId=9922858 (accessed on 21.07.11).
[51] Toluene, MSDS No. M1003, Vee Gee Scientific, Inc., Kirland, WA, 2004. http://www.ee.iitb.ac.in/~nanoe/msds/toluene.pdf (accessed on 21.07.11).
[52] Methyl Ethyl Ketone, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010. http://www.sciencelab.com/msds.php?msdsId=9927358 (accessed on 21.07.11).
[53] Methanol, MSDS, Methanex Corporation, Vancouver, BC, October, 2005. http://www.ee.iitb.ac.in/~nanoe/msds/methanol.pdf (accessed on 19.07.11).
[54] 1,1,1-Trichloroethane, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010. http://www.sciencelab.com/msds.php?msdsId=9927305 (accessed on 21.07.11).
[55] 1,2,4-Tricholorbenzene, MSDS, Sciencelab.com, Inc., Houston, Texas, January, 2010. http://www.sciencelab.com/msds.php?msdsId=9927304 (accessed on 21.07.11).
[56] Platinum, NFPA Label of the elements. http://periodictable.com/Elements/078/data.html (accessed on 05.07.11).
[57] Ethylene dichloride, MSDS, Occidental Chemical Corporation, Dallas, Texas, December, 2005. http://msds.oxy.com/DWFiles%5CM5855_NA_EN%231.pdf (accessed on 19.07.11).
[58] Calcium, NFPA Label of the elements. http://periodictable.com/Elements/020/data.html (accessed on 05.07.11).
[59] Aluminum, NFPA Label of the elements. http://periodictable.com/Elements/013/data.html (accessed on 05.07.11).
[60] Magnesium, NFPA Label of the elements. http://periodictable.com/Elements/012/data.html (accessed on 05.07.11).
[61] Arsenic, NFPA Label of the elements. http://periodictable.com/Elements/033/data.html (accessed on 05.07.11).
[62] Activated thiazole (ACCICURE F), MSDS#PMC/RC/027/06, PMC Rubber Chemicals India Pvt. Ltd., Hooghly, West Bengal, January, 2006. http://www.pmc-rc.com/PMC-MSDS/PMC%20MSDS%20ACCICURE%20F_06.pdf (accessed on 07.07.11).
[63] K. Deb, Multi-objective Using Evolutionary Algorithms, Wiley, Chichester, UK, 2001.