Response of groundwater contamination hazard rating systems to variations in subsoil conditions beneath municipal solid waste (MSW) dumps in developing countries

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Abstract

Groundwater hazard rating systems are generally based on source-pathway-receptor approach. This study determines the response of rating system to the variations in subsurface conditions (generally designated as pathway component). Besides, the study also investigates the ability of the rating systems to respond to the changes in other components too (i.e., source and receptor components). For the purpose, three groups of sites with various combinations of site conditions, that may be encountered in the field, are employed, e.g., a smaller site located in sandy soil with receptors all around it using groundwater or a larger site having a thick clay layer underneath it and the receptors in vicinity using groundwater for drinking. For the analysis, four sets of corresponding rating scores are determined in this study from the selected eleven rating systems (ten earlier rating systems and mGW-HARS, a recently developed system). The investigation shows that mGW-HARAS performs the best for the three sets; for the remaining one set, the performance of mGW-HARAS is marginally lower than its predecessor, GW-HARAS. The sensitivity analysis of the selected rating systems with respect to four critical pathway parameters depicts that mGW-HARAS is sensitive to all the four parameters and has the highest sensitivity to soil permeability, i.e., 83% amongst all the selected rating systems. When these rating systems are applied to ten waste dumps from Indian cities, only one system, i.e., mGW-HARAS, is able to categorize these waste dumps in four hazard categories and responds suitably to the subsurface conditions encountered at these waste dumps.

Keywords Rating systems · Waste dumps · Municipal waste · Groundwater contamination · Subsurface conditions

Introduction

Water pollution is the major environmental concern nowadays. Although a wide range of water treatment technologies ranging from biological treatment to membranes (Chen et al. 2019; Zhang and Jiang 2018; Mo et al. 1983) are available, prevention of water contamination is still considered a better approach. Amongst the water resources available, groundwater is considered critical from the perspective of providing drinking water to the masses.

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Contamination of groundwater from leachate generated in waste sites is an imminent threat to the environment in a near vicinity of a landfill (Christensen et al. 2011; Macfarlane et al. 1983; Tanse et al. 2007). The leachate quantity and quality get affected by the area of the waste site, depth of the waste pile on the site, amount of rainfall received, and type of cover installed, whereas the extent of groundwater contamination depends on the subsurface conditions, e.g., permeability of the soil between the waste and the groundwater table, depth to aquifer, aquifer thickness and permeability, and groundwater gradient in the aquifer (Sharma and Reddy 2004).

For hazard assessment from waste disposal sites, approaches fall generally into one of the three categories: deterministic water balance analyses, stochastic simulation models, or relative hazard methodologies (Nixon and Murphy 1998; Ubavin et al. 2017; Kumar et al. 2016). This study delves into relative hazard methodologies, popularly known as hazard rating systems. These hazard rating systems are generally based on source-pathway-receptor approach.

The role of the pathway component, i.e., subsurface conditions, is critical in keeping the subsurface aquifer pure and in pristine state. All the rating systems take into account the subsurface conditions for determining the hazard rating of a waste site (Singh et al. 2013). These rating systems have been evaluated for determining the groundwater hazard rating/subsurface contamination potential (Singh et al. 2009; Datta and Kumar 2017).

However, these studies do not focus on the most critical aspect for groundwater contamination, i.e., response of these rating systems to the change in subsurface conditions. Moreover, for assessment, these studies employ the conceptual sites with continuously varying site conditions, i.e., varying from a smaller site having thick clay layer beneath it with no receptors to a large site sitting on sandy soil with receptors all around it using groundwater, and do not assess these rating system when the site conditions are mixed and matched.

The objective of the study is to assess the existing rating systems for their response to changes in subsurface conditions (i.e., pathway component). The study also evaluates the effect on this response when site conditions in other compartments (i.e., source and pathway) change. The study employs data from million-plus cities of India and hence, the scope of the study is limited to waste dumps in larger cities of developing countries.

Characteristics of MSW dumps

Municipal solid waste dumps are generally bigger than hazardous waste sites. A study (Datta and Kumar 2016) recently conducted in cities having more than a million in India showed that the ranges of base area and waste heights in waste dumps are 2–53 ha and 2–29 m. The widest dump at Deonar,

Mumbai, has a base area of 120 ha, whereas the tallest dump at Okhla, New Delhi, has a height of 60 m.

The characteristics of waste disposed at a dump are very difficult to determine. But literature review shows that the biodegradable fraction varies from 35 to 65% (Kumar et al. 2009; CPCB 2006). The hazardous fraction of MSW is generally less than 1% (Sharma and Lewis 1994). Referring to site characteristics, overall, 44% of the sites having sand or silt in their vadose zone pose high hazard to the groundwater supplies (Datta and Kumar 2016). About 56% of the sites have impermeable strata (i.e., clay or rock) underneath them. The analysis of the depth to groundwater table at the dumpsites shows that more than 85% of the sites have the groundwater at low to moderate depth (5–25 m). The fraction of sites having depth to groundwater table at a minimal depth of less than 5 m constitutes 28% of the sites. Table 1 shows the range of values encountered for the parameters relevant for groundwater contamination.

Groundwater contamination hazard rating systems

A number of hazard rating systems exist in literature to assess groundwater contamination hazard rating system (Singh et al. 2010). For most of these rating systems, the parameters in pathway component represent the subsurface conditions and thus the subsurface conditions will be designated as pathway characteristics in the study. These existing rating systems use the following parameters (eleven in total) for pathway: depth to groundwater, geochemical properties of vadose zone media, thickness of silt/clay layer in vadose zone, thickness of lowest permeability layer of vadose zone, soil permeability, permeability of lowest permeability layer of vadose zone, aquifer media/soil type, aquifer permeability, aquifer thickness, groundwater gradient, and distance to groundwater well.

Subsurface parameters and their importance

To investigate the importance of various pathway parameters, their occurring frequencies in the existing eighteen rating systems were found out (Table 2). Three parameters, i.e., depth to groundwater, distance to groundwater well, and soil permeability, are the most frequently occurring (used by seventeen, sixteen, and fourteen rating systems respectively) parameters amongst all the pathway parameters. Groundwater gradient is another parameter, employed in six rating systems, out of the total eighteen.

On the other hand, the parameters being used by the least number of systems are thickness of silt/clay layer in vadose zone, thickness of lowest permeability layer of vadose zone, and permeability of lowest permeability layer of vadose zone. Assuming the occurring frequency as a measure of the

Table 1 Parameters for assessment of groundwater contamination hazard rating and their ranges (Datta and Kumar 2016)

Site parameter	Minimum value	Maximum value	Ration
Site area (ha)	2	53	27
Waste height (m)	2	29	15
Biodegradable waste (%)	40	75	2
Annual rainfall (mm)	500	2500	5
Soil permeability (m/s)	1.00E−10	1.00E−02	1.00E+07
Depth to groundwater (m)	5	25	5
Groundwater gradient (%)	0.5	5	10
Distance to communities (m)	500	2000	4

importance of the parameters, four parameters, i.e., depth to groundwater, distance to groundwater well, soil permeability, and groundwater gradient, have been taken as critical parameters for pathway in this study.

Application to sites with varying site characteristics

Out of the eighteen systems reviewed, ten "earlier" rating systems were selected for assessment, i.e., DRASTIC (Aller et al. 1985; Ghazavi and Ebrahimi 2015), Hazard Ranking System (HRS-1990) (USEPA 1990), Environmental Repair Program Hazard Ranking System (ERPHRS) (Department of Natural Resources 2001), Washington Ranking Method (WARM) (Science Applications International Corporation 1990), National Classification System (NCS) (CCME 2008), Risk Screening System (RSS) (Ministry for the Environment (NZ) 2002), Risk Assessment for Small Closed Landfills (RASCL) (Ministry for the Environment (NZ) 2004), National Productivity Council method (NPC) (National Productivity Council 2003), JENV (Joseph et al. 2005), and GW-HARAS (Singh et al. 2009). One more system, mGW-HARAS (Datta and Kumar 2017), a recent improvement on the earlier rating systems, was also assessed in detail. These systems were selected because (i) they represent all the methodologies being employed in the existing rating systems and (ii) these can evaluate hazard for groundwater route independent of other routes and produce a separate numerical score. As mGW-HARAS is an improved version of the earlier rating systems, the results from mGW-HARAS will be discussed separately throughout this study.

The selected rating systems were assessed by their response in terms of values obtained for the rating scores for the conceptual waste sites with varying site conditions. These rating systems were applied to three groups of waste sites in total. These three groups consist of waste sites having conditions varying with respect to characteristics in source, pathway, and receptor. Broadly, the characteristics of the groups of waste sites are as follows: (i) Group I: the worst source, pathway varying from best to worst and the worst receptor; (ii) Group

II: the best source, pathway varying from best to worst and the worst receptor; and (iii) Group III: the worst source, the worst pathway and receptor varying from best to worst. For the assessment of these rating systems, the main criteria are the rating scores obtained for the sites with the best and worst conditions, i.e., the first and last sites in each of the groups.

Application of the selected rating systems gives different values of the scores (normalized to the scale of 0–1000) for these sites. The waste sites can be classified into four hazard categories: sites with low hazard (hazard rating between 0 and 250), sites with medium hazard (hazard rating between 250 and 500); sites with severe hazard (hazard rating 251 between 500 and 750) and sites with very severe hazard (hazard rating between 750 and 1000).

Application to sites with the worst source, pathway varying from best to worst, and the worst receptor

At first, the selected eleven rating systems were applied to Group I waste sites namely HGW-1, HGW-2, HGW-3, HGW-4, and HGW-5 having varying characteristics for the pathway (Table 3). In general, groundwater contamination hazard of the sites would increase from HGW-1 to HGW-5. For these sites, the source parameters, i.e., area, waste heights, annual rainfall, and waste composition, are corresponding to the worst source, based on a country-wide survey of waste dumps from million-plus cities of India (Datta and Kumar 2016). The values for critical pathway parameters, i.e., depth to groundwater, soil permeability, groundwater gradient, and distance to groundwater well, vary from the best values for site HGW-1 to the worst values for site HGW-5. For the receptors, worst scenario has been taken as that of drinking water use by a population of 10,000 and having a sensitive environment in the vicinity.

This group, i.e., Group I, represents the hazard ratings for large waste sites with groundwater users in vicinity when pathway conditions are varied from best to worst. In case of groundwater contamination, the presence of clay soil layer plays a crucial part and hence pathway component becomes very important. Recalling the four classifications with respect to hazard posed, a site with worst conditions for source and

Table 2 Pathway parameters and their occurring frequency for various hazard rating systems (adapted from (Singh et al. 2010))

Parameters	LeGr and	S-WIMATRIX	DRASTIC	HRS-1990	ISM	ERPHRS	DPM	WARM	SRAP	NCS	NCAPS	HR-FCP	RSS	RASCL	NPC	JENV	GW-HARAS	m GW-HARAS	Frequency (out of 17)
Depth to groundwater	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	17
Geochemical properties of vadose zone media	✓	✓	✓			✓													3
Thickness of silt/clay layer in vadose zone					✓														1
Thickness of lowest permeability layer of vadose zone			✓																1
Soil permeability	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	14
Permeability of lowest permeability layer of vadose zone				✓															1
Aquifer media/soil type		✓	✓	✓															3
Aquifer permeability		✓	✓					✓	✓	✓									5
Aquifer thickness										✓	✓								2
Groundwater gradient	✓											✓		✓	✓	✓	✓		6
Distance to groundwater well	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	16

receptor, but having best pathway conditions (i.e., having thick layer of clayey soil), can be categorized as having low hazard, i.e., a rating in the range of 0–250. Similarly for the same site with worst pathway, conditions (i.e., having fractured rock or gravelly strata in the subsurface) can be categorized as posing very severe hazard, i.e., a rating in the range of 750–1000. Thus, ideally, the range of scores for Group I waste sites should be between less than 250 and more than 750. In other words, the larger the range of scores for HGW-1 and HGW-5 from a rating system, the better the response of the system.

According to the range of the rating scores obtained, the earlier rating systems can be classified into three categories depending on the score for HGW-1 and HGW-5 (Fig. 1): systems showing high variation in the scores, i.e., high response (DRASTIC and GW-HARAS); systems with the medium response (HRS-1990, ERPHRS, RSS, NPC, and JENV); systems with the low response (WARM, NCS, and RASCL).

The scores from DRASTIC and GW-HARAS are in wider ranges of 500–955 and 642–1000 respectively (Fig. 1). Overall, both the systems perform as expected for the site HGW-5 (i.e., worst source, worst pathway, and worst receptor). However, for site HGW-1, the ideal scores would have been less than 250 and both the systems fail on this aspect. DRASTIC system takes into account complete range of soil permeability, i.e., ranging from clay to karst limestone, whereas, for depth to groundwater, it considers a reasonable range from 1.5 m to 30 m. The system accords ratings in the range of 1–10 to these two parameters. However, it does not have source and receptor components and hence all the changes in hazard rating are as a result of the changes in pathway components. Moreover, out of the four critical pathway parameters as discussed above, it does not employ groundwater gradient and distance to groundwater well. On the other hand, GW-HARAS uses six parameters in its pathway component. In addition to the aforementioned four parameters, it also employs aquifer thickness and aquifer permeability. The system considers relevant ranges of depth to groundwater, groundwater gradient, and distance to nearest groundwater well. However, the range of soil permeability is limited, i.e., 10^{-9} to 10^{-5} m/s only, and hence, the system accords the same rating to sandy soil and gravel/fractured rock substrata. Also, the system assigns combined rating to depth to groundwater and soil permeability in the relatively smaller range of 0.7–1.0. Moreover, it assigns combined rating to four parameters together, i.e., aquifer thickness, aquifer permeability, groundwater gradient, and distance to nearest groundwater well in the range of 0.8–1.0 only, which suppresses the response from change in an individual parameter.

All the other systems have low to medium variation in the scores of HGW-1 and HGW-5. Amongst these systems, HRS-1990, ERPHRS, RASCL, NCS, WARM, and RSS are mainly

intended for hazardous waste sites, and these systems would show wider variations in the scores of hazardous waste sites with similar site conditions. Two systems, NPC and JENV, have been developed for municipal waste sites.

The least variations in the scores of the sites HGW-1 and HGW-5 are in the case of three systems, i.e., RASCL, NCS, and WARM. RASCL, NCS, and WARM use three out of the four critical parameters and do not use groundwater gradient. For RASCL, while the range of the values of permeability is appropriate, the corresponding range of rating is limited to 0.7–1 only for a waste dump, i.e., having poor capping and storm water control; also the ranges of the values of the other two parameters, i.e., distance to groundwater well and the depth to aquifer, are very small and hence the system does not respond to the variation in the pathway parameters. For the NCS system, the ranges of soil permeability and depth to groundwater are relatively shorter. Although the range of distance to groundwater well was reasonable in NCS, it uses an ordinal ranking system for the parameter meaning that rating for a parameter within a defined range is constant. Also for the distance to groundwater well, the division of the full range into sub-divisions has not been done properly, e.g., the distance of 1–5 km gets the same rating. WARM uses a suitable range for depth to groundwater and distance to groundwater well; however, the range of soil permeability employed, i.e., 10^{-9} to 10^{-5} m/s only, needs improvement, as in the case of GW-HARAS.

Other systems, e.g., HRS-1990, ERPHRS, RSS, NPC, and JENV, have the ranges of scores in the middle. All of these systems employ three out of the four critical parameters except NPC which also uses groundwater gradient. Two systems, i.e., HRS-1990 and ERPHRS, employ appropriate range of distance to groundwater, where other three systems, i.e., RSS, NPC, and JENV, use the relative smaller ranges of the parameter. With regard to soil permeability, again two of these five systems, i.e., HRS-1990 and ERPHRS, employ the greater range from 10^{-9} to 10^{-5} m/s, similar to GW-HARAS. JENV and NPC systems use much shorter ranges of soil permeability. RSS system combines soil permeability with the depth to groundwater suppressing the effect of change in a single parameter. For the distance to groundwater well, all the systems employ a proper range except RSS.

Application to sites with the best source, pathway varying from the best to the worst, and the worst receptor

The second group of waste sites consists of HGW-6 to HGW-10. The site characteristics of HGW-6 to HGW-10 are similar to those for HGW-1 to HGW-5 respectively, except for the source parameters. For the source parameters, sites HGW-6 to HGW-10 employ the best values. A waste site having the best source parameters would result in source rating being

Table 3 Characteristics of sites with varying site conditions to evaluate the rating systems (Groups I–III; HGW-1 to HGW-15)

	Group I					Group II					Group III				
	HGW-1	HGW-2	HGW-3	HGW-4	HGW-5	HGW-6	HGW-7	HGW-8	HGW-9	HGW-10	HGW-11	HGW-12	HGW-13	HGW-14	HGW-15
Source															
Site area (ha)	25	25	25	25	25	5	5	5	5	5	25	25	25	25	25
Waste height (m)	15	15	15	15	15	5	5	5	5	5	15	15	15	15	15
Biodegradable fraction	65	65	65	65	65	40	40	40	40	40	65	65	65	65	65
Annual rain (mm)	1500	1500	1500	1500	1500	500	500	500	500	500	1500	1500	1500	1500	1500
Waste disposed/day	1000	1000	1000	1000	1000	300	300	300	300	300	1000	1000	1000	1000	1000
Evapotranspiration	400	400	400	400	400	300	300	300	300	300	400	400	400	400	400
Pathway															
Depth to groundwater (m)	50	25	15	10	5	50	25	15	10	5	5	5	5	5	5
Soil permeability (m/sec)	1×10^{-09}	1×10^{-07}	1×10^{-05}	1×10^{-04}	1×10^{-02}	1×10^{-09}	1×10^{-07}	1×10^{-05}	1×10^{-04}	1×10^{-02}	1×10^{-02}	1×10^{-02}	1×10^{-02}	1×10^{-02}	1×10^{-02}
Aquifer thickness (m)	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Aquifer permeability (m/sec)	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}	1×10^{-04}
Groundwater gradient (%)	0.5	1	3	4	5	0.5	1	3	4	5	5	5	5	5	5
Distance to groundwater well (m)	3000	2000	1000	750	500	3000	2000	1000	750	500	500	500	500	500	500
Receptor															
Population drinking water	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000	0	0	0	10000	100000
Crop area being irrigated (ha)	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	0	50	500	500	5000
Distance to sensitive environment (m)	500	500	500	500	500	500	500	500	500	500	3000	3000	500	3000	3000

Fig. 1 Range of GW contamination ratings from selected rating systems for sites in Group I: HGW-1 to HGW-5
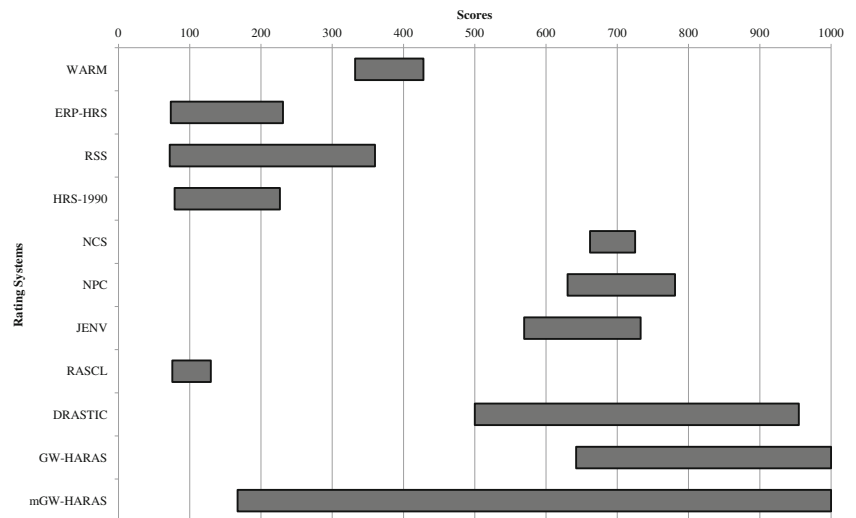
minimum, which would, in turn, bring the site hazard rating lower even with worst conditions for pathway and receptor. This group represents the hazard ratings of smaller waste sites with groundwater users in vicinity when pathway conditions are varied from best to worst. The ideal range for HGW-6 to HGW-10 can be postulated as less than 250 (for HGW-6) to just more than 500 (for HGW-10).

The results depict similar trend for scores from rating systems as in the case of HGW-1 to HGW-5 except some evident differences (Fig. 2). The most interesting observation is that GW-HARAS, which proved to be superior in case of HGW-1 to HGW-5, is the worst performer in the case of waste sites, i.e., HGW-6 to HGW-10. In GW-HARAS, a site having best conditions results in extremely low source rating, which, ultimately, brings the rating score of a site to below 100 even with the worst pathway and receptor conditions. Other systems perform similarly as in the case of HGW-1 to HGW-5 because of the reasons discussed above.

Application to sites with the source varying from best to worst, the worst pathway, and the worst receptor

When the results for the sites HGW-1 to HGW-5 and HGW-6 to HGW-10 are observed together, then the effect of source variation with the worst pathway and receptor becomes evident. Using the results of the sites HGW-1 and HGW-5 and HGW-6 and HGW-10, i.e., from Figs. 1 and 2, a range of rating scores can be inferred when the source is varied from best to worst, with worst conditions for pathway as well as receptor (Fig. 3). In this case, the criterion of judging the performance of various rating systems is also the variation in the scores when the source changes from best to worst. However, contrary to earlier, the ideal score variation in this case should be from 500 to 1000. The

reason lies in considering the pathway and receptor conditions as worst for this case.

None of the earlier rating system performs as expected (Fig. 3). GW-HARAS shows the widest variation in the scores, i.e., 79–1000; however, it does not match the ideal range of 500–1000. GW-HARAS places extraordinary importance on the source rating (Datta and Kumar 2017), varying from 37 to 1000 and hence brings out such a wider variation in the scores.

Other systems, i.e., HRS-1990, ERPHRS, RSS, NPC, JENV, WARM, NCS, RASCL, and DRASTIC, are not able to respond to the change in the source conditions as desired. For the six systems, i.e., HRS-1990, ERPHRS, RSS, WARM, NCS, and RASCL which have been developed to deal with both kind (municipal and hazardous waste) of sites, the source rating does not change much in case of municipal waste sites because of the two reasons mainly: (i) lower rating to municipal waste as compared with hazardous waste and (ii) employing limited range of waste quantity in the system. So with a low source rating, the hazard rating of the site gets dragged to the lower ranges in turn. DRASTIC does not have a source component in its algorithm, and hence it does not respond to the change in source components (Fig. 3). However, amongst these systems, NPC and JENV show some variation in the range of 674–781 and 639–733 respectively within the desired range of 500–1000. These two systems are mainly intended for municipal waste dumps and use a size range suitable for municipal waste dumps.

Application to sites with the worst source, the worst pathway, and receptor varying from best to worst

The third group of waste sites consists of HGW-11 to HGW-15. For these waste sites, the values for the parameters in source and pathways correspond to worst conditions, whereas

the site characteristics in receptor component vary from best to worst. This group represents the hazard ratings of a larger waste site sitting on sandy soil when the receptor condition varies from best (no groundwater use) to worst (groundwater use as main source of drinking water). Even in the case where groundwater is of no use, the impact in terms of subsurface contamination of soil and groundwater still occurs. As a result, for the worst source, worst pathway, and the best receptor conditions, the impact would be at least severe. So the ideal range in such a case can be assumed as between 500 and 1000.

Amongst the earlier rating systems, the rating scores from GW-HARAS were very close to the ideal range anticipated (Fig. 4). There were also some responses in the scores of five systems namely WARM, ERPHRS, RSS, HRS-1990, and RASCL, but not in the ideal range of 500–1000. For the other earlier rating systems, i.e., NCS, NPC, JENV, and DRASTIC, there was almost no response to the change in receptor conditions.

GW-HARAS uses a separate receptor component and because of the higher value of source rating in case of worst source conditions, the system is able to respond to change in receptor conditions. Five other systems, i.e., WARM, ERPHRS, RSS, HRS-1990, and RASCL, also employ receptor component. However, in the case of these systems, the source rating was so low that it leads to the scores being clustered to the lower side of the scale, i.e., less than 400.

Although NCS system employs a receptor component, it uses six parameters in the receptor component. The presence of six parameters leaves the system unresponsive to changes in one or two important parameters, e.g., water use type. Another reason of the non-responsiveness of NCS is the use of improper sub-divisions in case of parameters, e.g., the system assigns same rating to the

sensitive environment within a distance of 1–5 km. Three systems NPC, JENV, and DRASTIC do not have receptor component and hence do not respond to change in receptor conditions.

Application of mGW-HARAS

The performance of mGW-HARAS, the most recently developed rating system, will be discussed in this section (Figs. 1, 2, 3, and 4).

For sites HGW-1 to HGW-5, the ideal range of scores was postulated to be less than 250 to more than 750. The resulting scores from mGW-HARAS range from 167 to 1000 (Fig. 1), closely resembling the ideal range. For sites HGW-6 to HGW-10, the ideal variation in scores is less than 250 to just more than 500. The rating scores from mGW-HARAS again match the ideal range (Fig. 2). To observe the effect of variation in source conditions with the worst pathway and worst receptor conditions, the scores for waste sites HGW-1 to HGW-5 and HGW-6 to HGW-10 are observed together. The ideal range of scores in this case should be 500–1000. The scores from the system are in the range of 525–1000 (Fig. 3). For the sites HGW-11 to HGW-15 also, the scores should ideally be between 500 and 1000. The scores from mGW-HARAS are in the range of 600–1000 (Fig. 4). Only in the case of the sites HGW-11 to HGW-15, the performance of mGW-HARAS is marginally surpassed by one system, GW-HARAS giving the range of 542–1000.

Amongst the eleven rating systems, mGW-HARAS performs the best when applied to waste sites with continuously varying conditions. The system uses all the four critical parameters of the pathway. Moreover, the system employs the widest range of values (10^{-9} to 10^{-2} m/s) as well as the

Fig. 2 Range of GW contamination ratings from selected rating systems for sites in Group II: HGW-6 to HGW-10
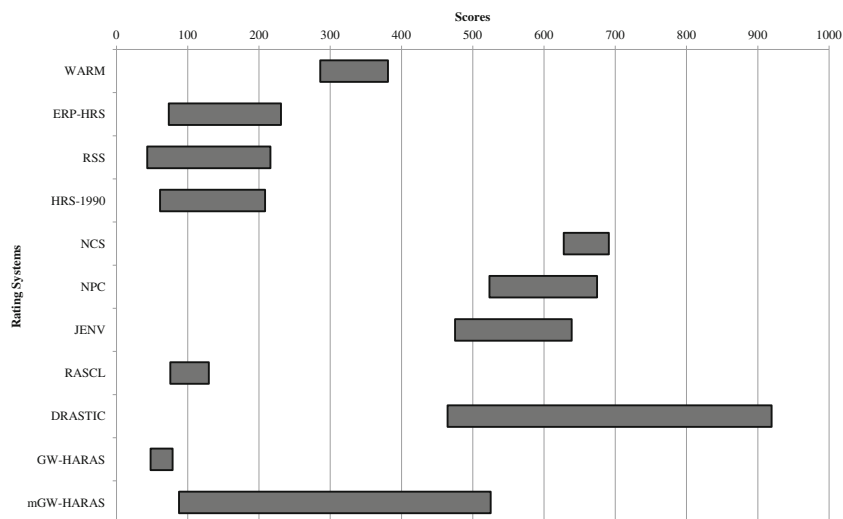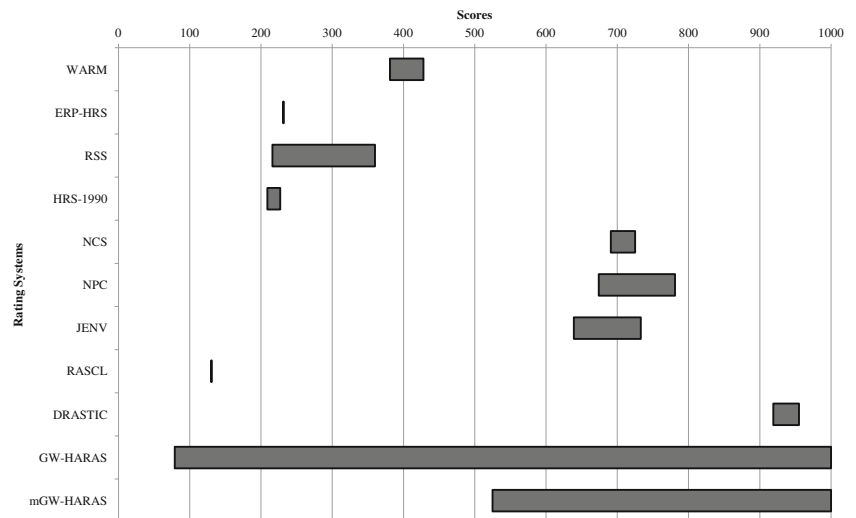
Fig. 3 Range of GW contamination ratings for the sites with source varying from best to worst, worst pathway and worst receptor (inferred from Figs. 1 and 2)

corresponding rating (0.2–1) for the most critical parameter, i.e., soil permeability. In addition to the pathway component, the system also has some modifications in the source component, from its parent rating system, i.e., GW-HARAS. The source rating in GW-HARAS varies from 37 to 1000 (Kumar et al. 2016), whereas for mGW-HARAS, the source rating only varies from 427 to 1000. For the modification in source component, changes were made to all the parameters in the source component, i.e., waste quantity, waste composition, and annual rainfall. Because of the changes in the source and pathway component, mGW-HARAS is suitably able to respond with the best and worst source as well.

Sensitivity analysis

After the application of rating systems to the waste sites with varying conditions, the sensitivity of the rating systems to the change in pathway parameters from best to worst values was investigated. To perform sensitivity analysis, a site having values of all the parameters at their mid-value was assumed as the base case except soil permeability. For soil permeability, geometric mean of the values was used. The parameters for source and receptor components were similar to that assumed for the worst conditions (i.e., same as for waste site HGW-5). The values of the pathway parameters were varied from their best to worst values and respective change in groundwater contamination rating was recorded. Again, performance of earlier rating systems (ten in numbers) will be discussed first and then that of mGW-HARS.

The results of sensitivity analysis have been provided in supplementary tables (Tables S.1 to S.3) and Table 4. Amongst earlier rating systems, GW-HARAS

is the only system which responds to variation in all the four critical parameters (Table 4). NPC also employs all the four parameters but the range of the groundwater gradient in the system is not pertinent so it does not show any sensitivity to the parameter. Seven of these systems, i.e., WARM, ERPHRS, RSS, HRS-1990, NCS, NPC, and JENV, exhibit sensitivity only to three parameters except groundwater gradient, whereas two systems, i.e., RASCL and DRASTIC, show sensitivity to two parameters only. Although RASCL uses the parameter distance to groundwater well but the range considered is not suitable and hence does not show any sensitivity to it. DRASTIC does not use this parameter in its algorithm.

The rating systems demonstrate different degrees of sensitivity to various parameters. The sensitivity of the rating systems to the change in soil permeability needs detailed analysis on account of the fact that it is the parameter having the largest possible range, i.e., 10^{-2} to 10^{-10} m/s, and also one of the most common parameters being employed by the rating systems. Amongst the earlier rating systems analyzed, HRS-1990, RSS, ERPHRS, and DRASTIC are the most sensitive to the changes in soil permeability with corresponding changes in hazard rating as 79%, 60%, 50%, and 50% respectively. The lowest changes in hazard ratings are exhibited by NCS, NPC, WARM, and JENV corresponding to changes in soil permeability. The changes in GW-HARAS and RASCL are in the middle, i.e., around 35%. For depth to groundwater, the highest sensitivity is demonstrated by ERPHRS, whereas GW-HARAS proves to be most sensitive to the change in groundwater gradient. For distance to groundwater well, RSS shows 100% sensitivity.

Fig. 4 Range of GW
contamination ratings from
selected rating systems for Group
III: HGW-11 to HGW-15
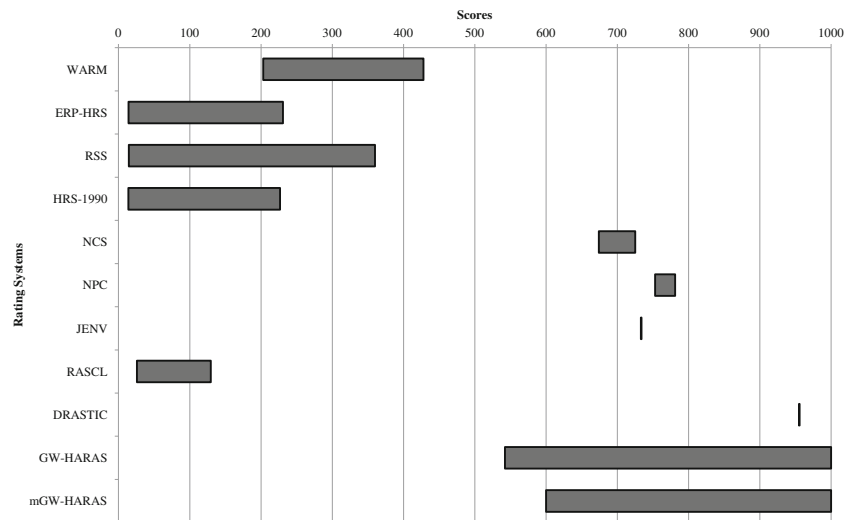
mGW-HARAS shows sensitivity to all the four parameters (Table 4). Amongst all the systems, it has the highest sensitivity to soil permeability, i.e., 83%. For groundwater gradient also, it demonstrates the highest sensitivity. For depth to groundwater, mGW-HARAS exhibits sensitivity in the middle, whereas for distance to groundwater well, its sensitivity is on the lower side.

Case studies

The new system was applied to ten MSW dumps situated in various cities of India (Table 5) so as to evaluate its performance. All the dump sites are uncontrolled, do not have any covers and liners, and are currently in operation except the one, i.e., dump A, which is no longer operational. The site areas vary from 8 to 120 ha. It is to be noted that the waste dumps being considered for the case studies have varied subsurface conditions underneath them (Table 5). While the waste dumps, e.g., dumps A, B, E, F, G, and H, have clayey soil underneath them, other waste dumps, e.g., dumps

C, I, and J, have silt to fine sand underneath them. Dump D is unique in the case that it has fractured rock underneath it. In addition to the mGW-HARAS, all the ten earlier rating systems were applied to these case studies and scores were normalized to the scale of 0–1000 (Table 6 and Fig. 5).

The individual scores and the range of scores from various rating systems differ a lot (Fig. 5). The scores from WARM, ERPHRS, RSS, HRS-1990, and RASCL are confined to the lower portion of the scale, i.e., less than 450, whereas the scores from NCS, JENV, and NPC are clustered in the middle of the scale, i.e., 430 to 770. DRASTIC is the only system confined to the upper region, with the range of 540–940. The scores from GW-HARAS and mGW-HARAS are spread on a wider range, i.e., 251–1000 and 188–908 respectively.

When these waste dumps are categorized according to the hazard posed (i.e., low, medium, severe, and very severe), then the performance of rating system becomes more clear in general (Table 6). While four systems, i.e., WARM, ERPHRS, HRS-1990, and NPC, put all the ten dumps in one category only, five systems

Table 4 Summary of sensitivity analysis

Base case scenario	Resultant hazard score (% change)										
Site parameters	WARM	ERPHRS	RSS	HRS-1990	NCS	NPC	JENV	RASCL	DRASTIC	GW-HARAS	mGW-HARAS
Depth to groundwater(m)	16	33	30	5	2	4	1	20	32	6	22
Soil permeability(m/s)	10	50	60	79	4	10	15	38	50	32	83
GW Gradient (%)	0	0	0	0	0	0	0	0	0	4	13
Distance to GW well (m)	1	90	100	4	3	12	8	0	0	16	9

Table 5 Site characteristics of the MSW dumps from Indian cities

Site name	Dump A	Dump B	Dump C	Dump D	Dump E	Dump F	Dump G	Dump H	Dump I	Dump J
Region	Central India	Central India	Western India	Western India	South India	South India	Eastern India	Western India	North India	North India
Base area (ha)	8	21.5	28	22.5	81	81	21.4	120	13	29.8
Landfill height (m)	16	5	24	20	8	6.4	24	15	48	32
Biodegradable fraction	43	48	43	55	41	41	51	43	45	61
Hazardous waste	5	5	5	5	5	5	5	5	5	5
C&D waste	20	20	20	20	20	20	30	20	20	16
Annual rain (mm)	950	1050	803	885	1200	1200	1650	2400	721	721
Depth to groundwater (m)	20	3	20	6	6	5	10	10	12	5
Soil permeability (m/sec)	1.00E-09	1.00E-08	5.00E-07	1.00E-02	8.00E-09	1.00E-09	1.00E-09	1.00E-09	7.00E-06	7.00E-06
Aquifer thickness (m)	25	11	40	35.0	25	15	50	30	35	35
Aquifer k (m/sec)	1.00E-05	1.00E-05	1.33E-03	1.00E-05	1.00E-05	1.00E-05	1.00E-06	1.00E-06	9.00E-05	9.00E-05
GW gradient (%)	1	3	1	5	2	2	1	1	1	1
Distance to GW well (m)	1500	500	500	750	1000	1000	2000	1500	500	500
GW use	DW (SS), Livestock	DW (MS), Livestock	DW (MS), Livestock	DW (MS), Livestock	DW (MS), SE, Livestock	DW (MS), SE, Livestock	DW (SS)	DW (SS)	DW (MS), Livestock	DW (MS), Livestock

DW(MS), main source for drinking water; *DW(SS)*, supplementary source for drinking water; *Livestock*, water being used for livestock; *SE*, sensitive environment

namely RSS, NCS, JENV, RASCL, and DRASTIC classified the ten sites in two hazard categories. The scores from GW-HARAS categorize the dumps in three categories only. mGW-HARAS is the only system allocating these dumps into four hazard categories (Table 6). The scores from GW-HARAS and mGW-HARAS have been discussed in detail, as given below.

Two sites, i.e., dumps D and J, are categorized as posing very severe hazard by GW-HARAS as well as mGW-HARAS. Both the sites have the large quantity of waste at the site, medium rainfall at the site, and lower depth to the groundwater table. Both the systems give a rating of more than 900 to dump D. However, the rating scores for dump J are 1000 and 823 from GW-HARAS and mGW-HARAS respectively. The stark difference between the two sites is the soil permeability; while dump J has silty sand underneath it, dump D sits on a fractured rock. So for a particular system, the rating score for dump D should be higher, which is not the case with GW-HARAS. mGW-HARAS performs ideally and gives higher hazard rating to dump D as compared with dump J.

However, the noticeable difference between the performances of two systems is evident in the case of dump H. Dump H is the site with the largest area in India, located in high rainfall region and in near vicinity of communities. However, this site has clayey soil underneath it and soil permeability is very low. mGW-HARAS suitably places dump H in medium hazard category. On the contrary, GW-HARAS assigns the very severe category to dump H as the system is mainly governed by source rating.

GW-HARAS does not put any site in low hazard category. The site with low hazard, as indicated by mGW-HARAS, is dump A. This waste dump does not accept the waste anymore, is smaller in size and has a thick clay layer below the waste. On the contrary, GW-HARAS assigns medium hazard category to the dump.

Hence, mGW-HARAS is able to suitably respond to the site conditions of waste dumps in Indian cities and categorize them in four different categories.

Conclusions

The study examines the response of the groundwater contamination hazard rating systems to variations in subsurface conditions beneath MSW dumps. The following can be summarized from the study:

- Out of the eighteen rating systems examined in the study, depth to groundwater, soil permeability, and distance to nearest groundwater well and groundwater gradient are

Table 6 Hazard rating scores (hazard categories) for waste dumps in Indian cities from various rating systems

Site name	Dump A	Dump B	Dump C	Dump D	Dump E	Dump F	Dump G	Dump H	Dump I	Dump J	Score range (category range)
WARM	334 (III)	383 (III)	348 (III)	406 (III)	381 (III)	370 (III)	284 (III)	297 (III)	360 (III)	383 (III)	284-406 (III-III)
ERPHRS	77 (IV)	139 (IV)	208 (IV)	207 (IV)	166 (IV)	83 (IV)	136 (IV)	155 (IV)	208 (IV)	208 (IV)	77-208 (IV-IV)
RSS	72 (IV)	252 (III)	420 (III)	270 (III)	126 (IV)	126 (IV)	99 (IV)	99 (IV)	360 (III)	360 (III)	72-420 (III-IV)
HRS-1990	116 (IV)	128 (IV)	162 (IV)	213 (IV)	124 (IV)	124 (IV)	115 (IV)	116 (IV)	145 (IV)	153 (IV)	115-213 (IV-IV)
NCS	617 (II)	744 (II)	715 (II)	766 (I)	682 (II)	716 (II)	699 (II)	699 (II)	701 (II)	715 (II)	617-766 (I-II)
NPC	587 (II)	708 (II)	700 (II)	733 (II)	725 (II)	733 (II)	614 (II)	678 (II)	679 (II)	747 (II)	587-747 (II-II)
JENV	436 (III)	531 (II)	581 (II)	649 (II)	512 (II)	496 (III)	521 (II)	502 (II)	622 (II)	674 (II)	436-674 (II-III)
RASCL	189 (IV)	302 (III)	216 (IV)	324 (III)	227 (IV)	227 (IV)	227 (IV)	252 (III)	216 (IV)	259 (III)	189-324 (III-IV)
DRASTIC	540 (II)	673 (II)	686 (II)	929 (I)	624 (II)	624 (II)	584 (II)	584 (II)	730 (II)	774 (III)	540-929 (I-II)
GW-HARAS	251 (III)	321 (III)	700 (II)	953 (I)	708 (II)	602 (II)	725 (II)	1000 (I)	692 (II)	1000 (I)	251-1000 (I-III)
mGW-HARAS	188 (IV)	361 (III)	561 (II)	908 (I)	390 (III)	313 (III)	255 (III)	261 (III)	731 (II)	823 (I)	188-908 (I-IV)

I, low hazard; II, medium hazard; III, severe hazard; IV, very severe hazard

the most frequently occurring parameters for the pathway component.

- Amongst the four critical pathway parameters selected in the study, the range of soil permeability encountered in the field is the largest, i.e., 10^{-10} to 10^{-2} m/s.
- When eleven rating systems (ten earlier systems and one, most recent one) were applied to the three groups of waste sites with varying characteristics, interesting finds came out about the rating systems.

  – Amongst the earlier rating systems, two systems GW-HARAS and DRASTIC performed best and worst alternatively, whereas other systems showed performance in the middle.
  – For larger waste sites, GW-HARAS and DRASTIC gave the better ranges of scores in response to changes in pathway conditions.

  – On the other hand, for smaller waste sites, GW-HARAS was the worst performing system in response to changes in pathway conditions. DRASTIC still gave the widest range of the scores.
  – When the source characteristics (i.e., size and annual rainfall mainly) were varied from best (smaller site) to worst (bigger site), GW-HARAS responded emphatically, but did not match the ideal range as the system places undue importance on the source. The performance of DRASTIC was the poorest as the system does not have a source component.
  – mGW-HARAS, the most recently developed rating system, showed the best performance to the changes in pathway component, source component, and receptor component when applied to the waste sites HGW-1 to HGW-15. The system is able to respond to the variation in site conditions because of (i) the widest range of the value

Fig. 5 Range of rating scores for waste dumps in Indian cities from various rating systems
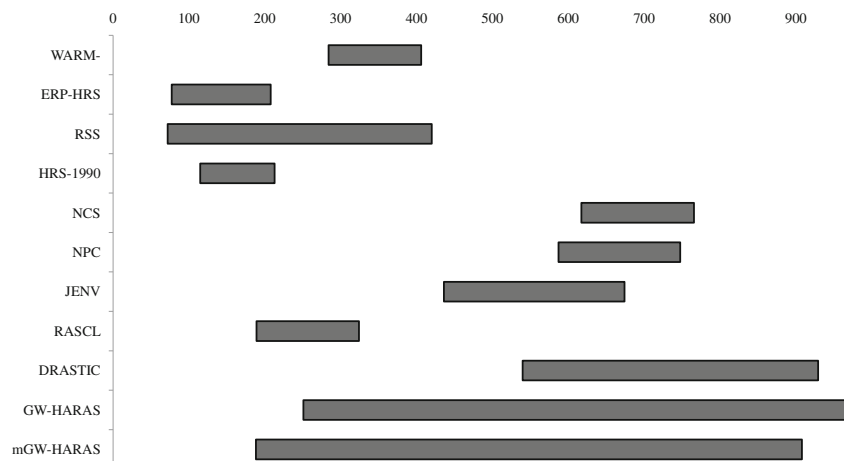
and rating of soil permeability being employed in the system and (ii) modification in the source component.

- The existing rating systems display varying sensitivity for the four parameters. Amongst the earlier rating systems, GW-HARAS is the only system which is sensitive to all the four parameters and HRS-1990 shows the highest sensitivity for soil permeability.

- mGW-HARAS shows sensitivity to all the four parameters. Amongst all the systems, it has the highest sensitivity to soil permeability, i.e., 83%. For groundwater gradient also, it demonstrates the highest sensitivity. For depth to groundwater, mGW-HARAS exhibits sensitivity in the middle, whereas for distance to groundwater well, its sensitivity is on the lower side.

- When all the eleven rating systems were applied to ten waste dumps from Indian cities, mGW-HARAS is able to suitably respond to the site conditions of waste dumps in Indian cities and categorize them in four different categories:

- Nine of the ten earlier rating systems classified the ten sites in one to two hazard categories. The scores from GW-HARAS categorize the dumps in three categories only. mGW-HARAS is the only system allocating these dumps into four hazard categories.
- mGW-HARAS performs ideally in assigning higher hazard rating to dump D (having fractured rock underneath it) as compared with dump J (having silty sand in substrata). On the contrary, GW-HARAS gives higher rating to dump J.
- The noticeable difference between the performances of GW-HARAS and mGW-HARAS is also evident in the case of dump H. Dump H is the site with the largest area in India, located in high rainfall region and in near vicinity of communities. However, this site has clayey soil underneath it and soil permeability is very low. mGW-HARAS suitably places dump H in medium hazard category. On the contrary, GW-HARAS assigns the very severe category to dump H as the system is mainly governed by source rating.

Compliance with ethical standards

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