Hydraulic profiling tool for groundwater vulnerability assessment at an MSW landfill

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Abstract

Characterization of the unsaturated zone below an MSW landfill is critical to evaluate the groundwater pollution vulnerability assessment. The permeability of the soil in the unsaturated zone, the depth of the water table, and the quality of pore water in the soil can provide a reliable site-specific estimate of pollution vulnerability. To evaluate these factors, an attempt was made to use the hydraulic profiling tool (HPT) in the unsaturated zone below a non-engineered MSW landfill in Delhi. HPT was equipped with an injection logger capable of qualitatively measuring permeability at the cm scale and an electrical conductivity (EC) dipole that measures the bulk soil conductivity. HPT findings were compared with piezocone penetration tests (CPTu) and the electrical conductivity of extracted pore water from the soil cores. The results indicate that pressure from the injection logger works effectively for medium/fine sand and silt and has greater sensitivity to permeability changes for these soils than CPTu. Pore-water EC was found to have a good correlation with volumetric water content and EC from HPT. A groundwater vulnerability matrix was conceptualized using factors based on the time of leachate travel and maximum pore-water EC observed, both derived from HPT, and risk scores were assigned from 1-5, corresponding to the 9 zones of the matrix. The locations surveyed at the dumpsite received scores of 4 and 5, which depicts high vulnerability. The results indicate that HPT can be used for rapid site-specific groundwater vulnerability assessments.

Keywords: HPT, CPT, electrical conductivity, landfill, unsaturated, permeability, groundwater vulnerability.

1. Introduction

In developing countries like India, the most commonly used method of solid waste disposal is open dumping of waste (CPCB 2021). Although open dumps have been prohibited and mandated to be closed, around 3000 open dumpsites remain operational in India, which is significantly higher than the number of engineered landfills present (MoEFCC 2016). These sites for open dumping are often selected based on the availability of open land close to the city, and the level of protection against groundwater contamination by the subsurface is often overlooked. Therefore, conducting in-situ assessments at such sites is essential to measure the risk of groundwater contamination. Some well-known indexes for groundwater vulnerability assessment, such as DRASTIC, have been used extensively by several researchers but only provide a regional scale assessment and lack site-specific hydrogeological factors (Wang, He, and Chen 2012).

The in-situ assessment at a dumpsite needs to be rapid and at high resolution to ensure that even cm-scale changes in stratigraphy or plume behavior are captured. The three most important parameters contributing to groundwater contamination vulnerability are the depth of the unsaturated zone, the permeability of the unsaturated zone, and the contamination potential of the leachate. Considering these three parameters, the hydraulic profiling tool (HPT) can be used for rapid in-situ assessments. This tool was developed by Geoprobe Systems and contains two sensors – a pressure transducer and an electrical dipole. The schematic of the tool is shown in Figure 1. The pressure transducer is located above a stainless-steel screen from where water is pumped at a rate of 300-400 ml/min, and it measures the pressure required to maintain this constant flow rate. (McCall and Christy 2020). This flow rate is sufficient to generate enough pressure in soils that can be measured by the transducer while also ensuring that no soil fracturing occurs due to excessive high pressures (Fitzgerald 2009). The measured pressure indicates the saturated permeability of the soil in contact, and several correlations have been developed to calculate the same (Borden, Cha, and Liu 2021; McCall et al. 2009). The second sensor that measures bulk soil electrical conductivity (EC) is an electrical dipole located 15 cm above the probe tip. It measures the voltage difference between two conducting surfaces upon applying a constant current and the ratio of current and voltage multiplied by a geometric constant gives conductivity of the bulk soil in contact with the dipole (Christy, Christy, and Wittig 1994). The electrical conductivity is relevant for the in-situ contamination assessment of a dumpsite as it is indicative of the total dissolved salts (TDS) present in the pore water of the soil, and since the leachate from MSW has an abundance of TDS, it is a suitable parameter to assess leachate migration and extent of the contamination. HPT can also be used to evaluate the depth of the unsaturated zone, as it can measure the waste-soil transition depth and the depth of the water table. The prior can be measured by observing the pressure change with depth as there is a significant increase in pressure at the waste-soil interface due to permeability difference. The depth of the water table can be known by measuring the hydrostatic pressure by stopping the flow and probe penetration. This probe is advanced using hydraulic push assisted by percussing hammering at variable rates, generally around 2 cm/s.

Percussion hammering is only used when the desired penetration rate is not achieved with hydraulic push.

Even though HPT and other similar tools like direct push injection logger (DPIL), permeameter (DPP), slug test (DPST), and high-resolution K (HRK) have been developed recently in the past 10-15 years, there has already been significant research showing a good agreement with the traditional methods for computing saturated permeability (Vienken, Leven, and Dietrich 2012; Aguila et al. 2023; Slowiok et al. 2022). These include slug tests, pumping tests, cone penetration tests, empirical correlations from grain size distribution, and inverse modeling of field observation using numerical methods. HPT has also been used in many applications, such as the modeling of aquifer heterogeneity, validation of hydraulic tomography, identification of high permeability zones for groundwater sampling, and facies identification. The other parameter, electrical conductivity, was initially measured by an independent probe in the form of a resistivity cone penetrometer (RCPTu). The correlation of conductivity/resistivity with pore-water conductivity has been used to identify probably contaminated soils and find soil parameters such as porosity, dispersivity, degree of saturation, tortuosity, soil microstructure, clay surface conductivity, and distribution coefficient (Arnepalli et al. 2010; Campanella and Weemees 1990; Revil and Glover 1997; AbuHassanein, Benson, and Blotz 1996). Mondelli, Giacheti, and Howie (2010) used RCPTu at an MSW landfill and attempted to find a correlation of soil resistivity with fines content (%) and soil behavior index from cone penetration tests. The authors stated that low resistivity with low fine content may indicate contamination in the soil.

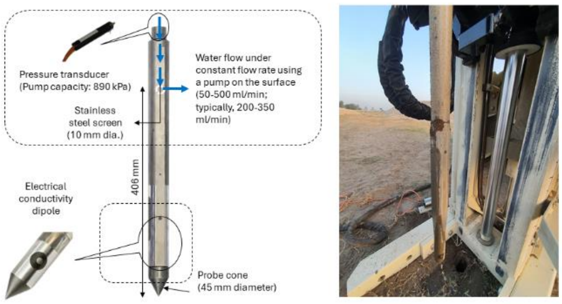


Figure 1. Schematic of hydraulic profiling tool (HPT)

Both EC and HPT pressure have never been used together at a MSW landfill. Based on the literature, the authors see high potential of using both parameters in a MSW dumpsite for groundwater vulnerability assessment. Therefore, the objective of this research is to conduct a groundwater vulnerability assessment using the EC and HPT profile at an existing old dumpsite.

2. Methodology

2.1. Site description

The site selected for this study was an old MSW dumpsite located in Bhalswa in the north district of Delhi, India. The plan view of the dumpsite is shown in Figure 2. This dumpsite started in 1992 and is still in operation even though its design capacity of waste was reached in 2005. The area of the dumpsite is 5 acres and the height of the landfill is approximately 50 meters. The dumpsite is lying on alluvium deposits of fine sands, known as ‘Yamuna sand’, named after the river Yamuna which flows 10 km east of the landfill. Clay layers are also found at many locations along with this alluvial sand. The depth of the bedrock at this location is about 80 m. The groundwater is roughly 2-3 m below the original ground level and the direction of flow is north-eastwards towards the river Yamuna (CGWB 2016). Local variation in flow direction can be observed in the vicinity of the landfill due to the local rise of water level. Several residential colonies have been developed in the vicinity of the dumpsite with some even having no access to tap water and rely partially on groundwater which may be highly contaminated by the dumpsite. This poses great risk to human health and a groundwater vulnerability assessment is essential to plan future corrective actions.

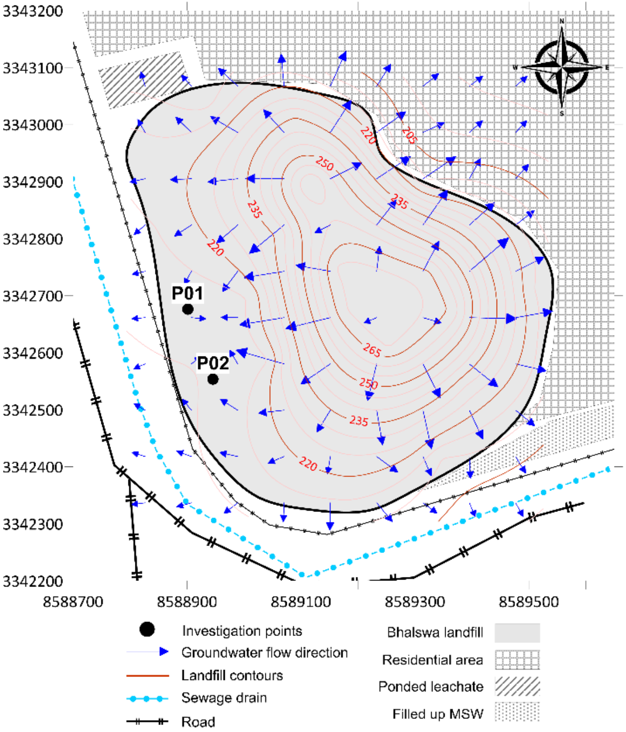


Figure 2. Plan of Bhalswa dumpsite and investigation locations (P01, P02) where CPTu, HPT and soil sampling were conducted

2.2. Site investigation

A site investigation program was carried to profile multiple locations using high resolution site characterization tools such as piezocone (CPTu), HPT, and continuous soil samplers. Two locations (P01 and P02) located on the west boundary of the dumpsite are discussed in this study and are shown in Figure 2. The depth of HPT and CPTu profiles was about 14-16 m below the waste surface whereas the soil sampling was carried up to 12 m. A 10 cm^2 piezocone was used for cone penetration tests and soil behavior type (SBT) was evaluated using Robertson (2016). Dilative and contractive soil types were merged as it was not relevant for this study. HPT was halted at multiple depths and flow was stopped to measure the hydrostatic pressure to estimate the groundwater level. This was verified further by using the groundwater sampler and a digital groundwater level meter. Calibration checks of HPT pressure transducer and EC sensor was carried before every test. Soil sampling was carried using a dual tube soil sampling system which ensures high integrity and representativeness of the sample with minimum cross contamination. The continuous soil cores obtained from the unsaturated zone below the landfill were cut into 15 cm sections and pore-water was extracted for analysis of pore-water conductivity. The pore-water extraction was carried out using drainage centrifugation method using customized centrifuge bottles. All tools were penetrated using a direct push rig. Anchoring using helical augers were carried wherever necessary generating a maximum pushing capacity of 16 tons. A pre-bore depth of 1.5-3 m was carried to avoid any debris at the surface.

3. Results and discussion

CPT, HPT and EC profiles of the two locations investigated at the Bhalswa landfill is shown in the Figure 3. At P01, the depth of waste was 7.6 m and the thickness of the unsaturated zone was 2.9 m. The top of the unsaturated zone represents the natural ground level (NGL). The unsaturated zone primarily consisted of silty sand (SM) overlying the low compressibility clay (CL). The CL layer extends to the saturated zone to a depth of almost 2 m below the water table which is at 10.6 m below the surface level. CL layer is followed by poorly graded sand (SP) of 1.5 m thickness. The properties of all soil types are shown in Table 1. A similar soil profile is also observed at P02, but with the thickness of wasteand unsaturated zone equal to 4.6 m and 4.3 m, respectively. The groundwater level is 8.9 m below the surface. The elevation difference between the P01 and P02 was 2.2 m with P01 at higher elevation.

Table 1. Properties of different soil types existing below the Bhalswa dumpsite, Delhi

Properties	SM	CL	SP
Gravel (%)	0	0	0.3
Coarse sand (%)	0.6	0	0.3
Medium sand (%)	1.1	0	27
Fine sand (%)	61.2	16.1	72.2
Silt (%)	30.4	56.3	0.3
Clay (%)	6.5	27.5	0
Liquid limit (%)	-	23.2	-
Plastic limit (%)	-	17.2	-
Plasticity index (%)	-	6	-
CEC (meq/100g)	-	20	-
Major minerals	Quartz (50%) Muscovite (20%) Albite (15%)	Muscovite (44%) Quartz (30%) Kaolinite (7%)	Quartz (62%) Muscovite (22%) Albite (9%)

3.1. Variation of HPT and EC with depth

3.1.1. Waste layer

The waste layer generally had very erratic CPT profiles at P01 as it showed all three types of soil behavior type – clay, sand and transitional. The presence of hard material such as brickbats, rock, concrete in the waste can result in sand like classification due to high qc. The presence of soft materials such as organic matter, paper, cardboard will give low qc values shifting more towards clay like behavior. Therefore, SBT classification should be used very carefully with MSW. u2 was non zero throughout the depth in MSW indicating high degree of saturation. Electrical conductivity varied from 0.82 to 11.8 mS/cm in the waste zone. For comparison the bulk soil conductivity of uncontaminated saturated coarse sands is about 0.2 mS/cm. These values indicate the possibility of a high degree of contamination as the actual electrical conductivity in the pore-water of the MSW would actually be much higher than the bulk value (Rhoades, Raats, and Prather 1976). The leachate extracted from this dumpsite has an EC of 31 mS/cm which shows the presence of high TDS.

The corrected HPT pressure varied from 37 to 160 kPa with a mean of 78 kPa which generally indicates a permeability lower than coarse sand but higher than clays. The HPT profile is not so erratic in the waste as the CPT profile and marks a clear increase in pressure at the interface with soil indicating that HPT is a better tool for demarcating waste-soil interface than CPT.

3.1.2. Unsaturated zone

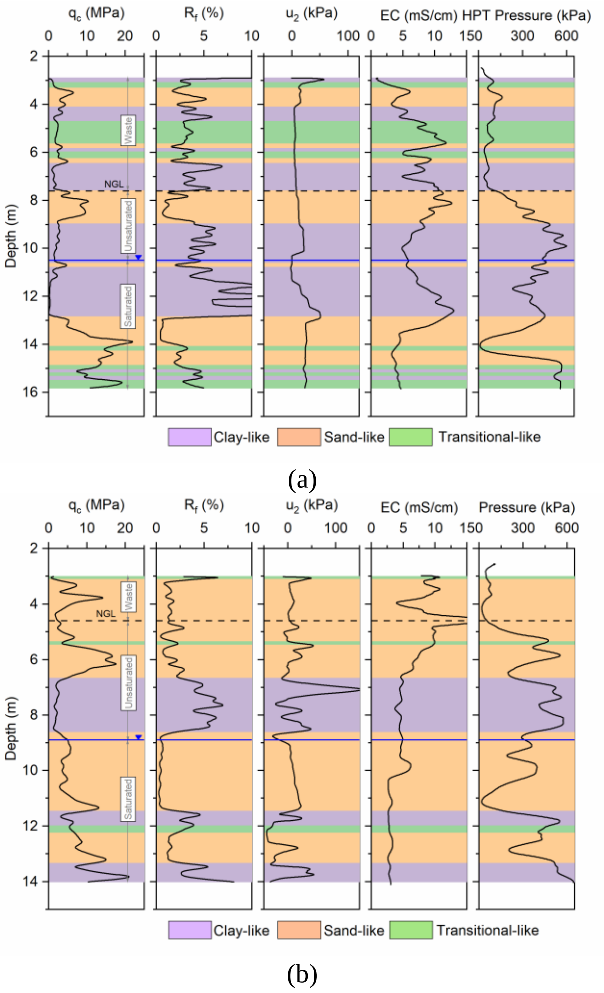
The silty sand layer (SM) in the upper part of unsaturated zone is characterized by the CPT as sand-like. A linear increase in the u2 indicates that water content might be increasing with depth leading to higher excess pore pressure. A steady decrease in electrical conductivity from 10 to 7.7 mS/cm is observed in this layer indicating the decrease in TDS with depth. This could be due to some form of attenuation by the soil by the phenomenon of sorption, precipitation or redox reactions. In the clay layer (CL) which occupied the lower part of the unsaturated zone, the decrease is more significant from 7.7 mS/cm to 4.8 mS/cm in 1.5 m, i.e., 50% decrease. Clays generally have higher cation exchange capacity than silts and sands which can lead to more attenuation of TDS due to higher sorption potential of positively charged free cations. The presence of higher organic matter in clays also increases its sorption capacity.

The HPT pressure is observed to be increasing with depth in the silty sand layer from 135 to 450 kPa indicating the increase in fines with depth. This insight is missing in the qc or Rf profiles where constant values are observed for the entire SM layer. This suggests that HPT is more sensitive to permeability changes than CPTu. In the clay (CL) layers the pressure is above 450 kPa at all depth in the unsaturated zone indicating a lower permeability than the above SM layer. This clay layer was categorized by CPT as clay like with low qc and high Rf values. A very good agreement was observed between HPT pressure and SBT classification.

3.1.3. Saturated zone

The u2 profile with depth increases more than the hydrostatic pressure possibly due to excess pore water pressure generated during cone advancement. The HPT pressure reduced to 300-400 kPa in the saturated clay layer indicating higher permeability than the unsaturated part of the same layer. The clay layer that extends below the water table showed an increase in EC from 4.8 mS/cm to 13 mS/cm in 2 m. This increase could be due to lateral migration of contaminants from another location such as either from the center of the landfill or from the nearby drain. The increased EC or TDS does not appear to be from contributed by the top waste as then it would have decreased steadily from the top. The electrical conductivity decreases with depth after the clay layer from 13 mS/cm to 4 mS/cm. This could be due to higher dilution due to the greater velocity in the high permeability sand layer. Below this sand lies the transitional soil zone as identified by the CPT and generally has high pressure in the range of 500 kPa indicating a low permeability stratum.

A very similar profile of HPT and CPTu was also observed at P02. In the upper silty sand layer, intermediate pressure ranging from 60-400 kPa was followed by greater than 400 kPa pressure in the clay layer. Electrical conductivity also constantly decreased from 14 mS/cm to 4 mS/cm in the unsaturated zone. The EC significantly reduces 1 m below the water table to only 2.8 mS/cm similar to what was observed in P01 indicating that bulk soil EC can be used to identify the contamination zones in an aquifer. The sand layer (SP) below the clay layer in P01 was also identified by the low HPT pressure at P02. This shows that HPT can be used to identify the lateral extent of horizontal soil layers.



(a)

(b)

Figure 3. CPTu and HPT profile at locations (a) P01 and (b) P02. The color depicts the soil behavior type (SBT) calculated based on Roberston (2016)

3.2. Variation of HPT pressure with CPT

The variation of HPT pressure is examined with parameters from CPT such as qc, Rf, Δu and Ic, as shown in Figure 4. Ic generally increases in coarse to fine soils with 2.5 generally considered as the transitional value from sand-like towards clay-like behavior. qc and Δu values are randomly distributed and do not appear to have any correlation with HPT pressure. Rf and Ic, however, are observed to have high values at high pressure, which is generally observed in lower permeability soil. However, in sand like soils high values of HPT pressure are also observed indicating that HPT pressure can show high pressure values even in sands where possibly fine sand or silty sands are present. This hypothesis is also backed by the work of Borden, Cha, and Liu (2021) who derived a relation between saturated permeability and pressure by using numerical simulations of Liu, Borden and Butler (2019). The suggested correlation is given by

$$k_{sat}\ (m/s) = E \times 7.13 \times 10^{-6} \times \frac{0.12vd^2+0.12Q}{(0.15P_{corr})^{0.12}} \qquad (1)$$

E is the empirical derived hydraulic efficiency factor, v is the penetration rate in mm/s, d is the diameter of the cone in cm, Q is the flow in ml/min and P_{corr} is the corrected HPT pressure in kPa. The variation of HPT pressure with the permeability based on the average values from this investigation (v = 2.16, d = 45, Q = 330) is shown in the Figure 4. The E value varies from 0.5-2.0. It can be observed HPT pressure works in the range sand, medium to sand, silty. It is an effective tool in classifying medium, fine, silty sand and silts which will generally be classified as a single type by the CPTu. Similarly, this concept can also be applied to unsaturated soils as the soil near the influence zone of the screen becomes saturated due to the flow and the pressure measured corresponds to the saturated permeability only.

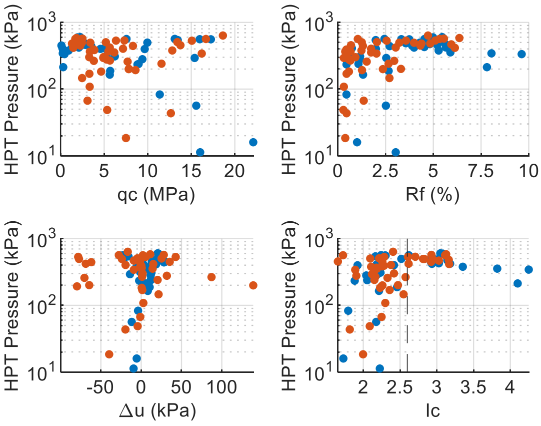


Figure 4. Variation of average HPT pressure with average CPTu-based parameters

3.3. Electrical conductivity with pore-water conductivity

For the validation of electrical conductivity measured in the field, the pore-water was extracted from the soil cores and the electrical conductivity was measured. The bulk soil electrical conductivity is dependent on the volumetric water content and its conductivity (Glover 2010). The effect of clay mineral conductivity also influences the bulk soil conductivity, but its contribution is insignificant in cases where EC of the pore-water is very high (Choo et al. 2016). The range of pore water electrical conductivity observed in this study ranged from 5 to 20 mS/cm which is higher than mineral conductivity and for this reason, the contribution of clay minerals to electrical conductivity may be ignored in this study. The effect of volumetric water content and its conductivity on bulk soil conductivity can be assumed by the simple equation, given by

$$EC_{pw} = \mathrm{M} \times \frac{EC_{bulk}}{\theta} \tag{2}$$

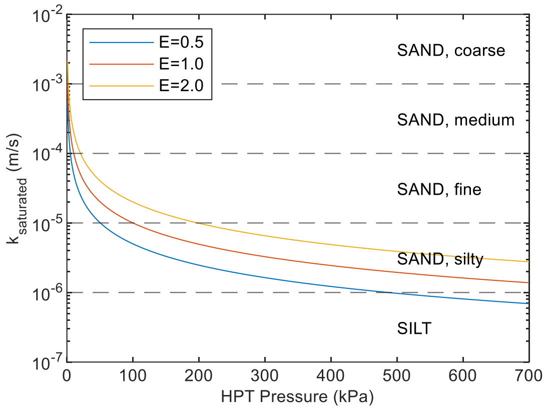


Figure 5. Correlation of HPT pressure and saturated permeability based on (Borden, Cha, and Liu 2021) using average values of flow and penetration rate

θ is the volumetric water content which was calculated by the water content measured from the soil cores multiplied by the soil bulk density. The EC_{pw} and water content is calculated for every 15 cm soil subsample and EC_{bulk} from HPT is averaged for this interval. The linear regression performed for Equation (2) resulted in M = 2.38 and is plotted in Figure 6. Most points appear to roughly follow this equation. However, water content lower than 15 % is not included in this analysis. At lower water contents, continuous water films are not formed in the pore-spaces and pore water contribution is minimal. Therefore, theoretically, there might be a threshold water content below which this equation is not applicable and hence, a more complex model might be able to fit this data. Nevertheless, the shows that EC_{pw} can be predicted from $EC_{bulk,}$ if volumetric water content is known.

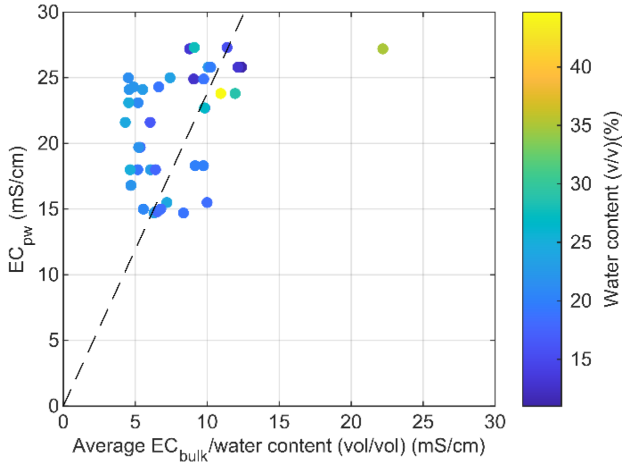


Figure 6. Correlation between bulk soil and pore-water electrical conductivity using volumetric water content

3.4. Groundwater vulnerability score

After calculating the capabilities of HPT and EC, groundwater vulnerability index is evaluated using both values. The risk of groundwater contamination is dependent on the depth of the unsaturated zone, the permeability and the electrical conductivity of the pore-water. To evaluate this index, two parameters are defined as

$$Time\ factor,\ T_f\ \ (\text{years}) = \frac{d_{unsat}^2}{\Sigma k_{sat}.\Delta h} \tag{3}$$

$$EC\ factor,\ EC_f\ (\text{mS/cm}) = \max\left(\frac{EC_{bulk}}{\theta}\right) \tag{4}$$

d_{unsat} is the depth of the unsaturated zone in m, k_{sat} is the saturated permeability in m/year and Δh is the depth interval in m corresponding to k_{sat}. The first parameter, T_f is indicative of the time required for the contaminants to reach the groundwater assuming a hydraulic gradient of 1 which generally takes place during gravity flow in the unsaturated zone if the water content is constant with depth. Saturated permeability is used as an approximation as no information can be derived about the soil water characteristic curve (SWCC) from HPT which is required to calculate the unsaturated permeability. A lower saturated permeability would result in higher T_f, which decreases groundwater vulnerability. The second parameter, EC_f, is indicative of the maximum pore-water electrical conductivity observed in the unsaturated zone. A higher EC_f indicates more risk to groundwater contamination. A groundwater vulnerability matrix is conceptualized with 9 zones using these two parameters and risk score is assigned to each zone from 1 to 5 with 1 being the safest and 5 being the most critical, as shown in Figure 7. These 9 zones are formed by 3 intervals of T_f and EC_f, each. T_f is divided into 3 intervals: T_f<0.1; 0.1< T_f <1; 1< T_f <10. T_f equal to 0.1 would mean it would roughly take 0.1 years for leachate to reach the groundwater. Similarly, for EC_f, it is characterized into same 3 intervals with transitional values of 5, 10 and 15 mS/cm. The parameter T_f and EC_f are calculated for both points P01 and P02 and are shown in Figure 7. P01 had a risk score of 4 and P02 had a risk score of 5. This indicates that Bhalswa dumpsite has high vulnerability of groundwater contamination.

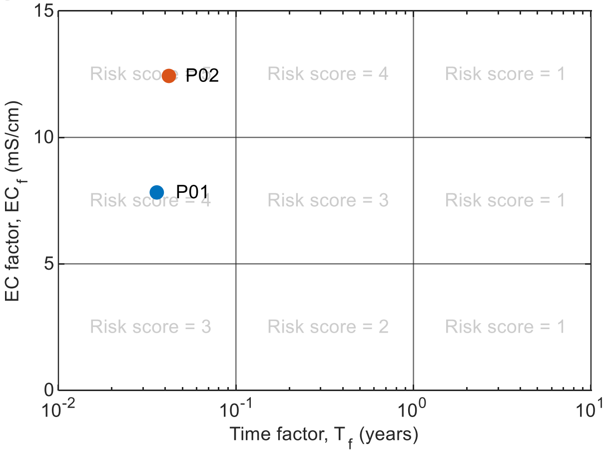


Figure 7. Groundwater vulnerability matrix with 9 zones having risk scores from 1 to 5 with 1 being the safest and 5 being the most unsafe. Risk scores of P01 and P02 are evaluated by calculating T_f and EC_f for each location

4. Conclusion

The potential of HPT for evaluating the groundwater vulnerability was examined using two tests conducted at an un-engineered MSW landfill located in Delhi. The parameters included for this score were the permeability of the vadose zone, depth of vadose zone and the electrical conductivity of the pore-water in the vadose zone. An attempt was made to calculate all parameters using a single HPT profile of pressure and electrical conductivity. Before that, the profile of HPT was examined and was compared with CPTu tests conducted at the same locations and it revealed that HPT pressure is more sensitive to permeability changes than CPTu as it could identify the fines variation with depth in silty sand and clays whereas CPT profile was constant in these layers. The standard HPT pressure range of 0-600 kPa was found to be applicable to medium sands to silts. For the electrical conductivity of the pore-water, an attempt was made to find its correlation with bulk soil electrical conductivity measured by HPT and volumetric water content. A simple linear correlation was found to provide satisfactory results but at some depths the pore-water electrical conductivity was underpredicted. The need for a more complex correlation was highlighted, which may be more representative. A groundwater vulnerability score was calculated using a matrix based on two factors which represent the time of leachate migration to groundwater and the maximum pore-water electrical conductivity. The 9 zones of the matrix were divided into a risk score of 1-5 with 5 being the most unsafe case and 1 being the safest. These parameters were calculated for the two locations and a risk score of 4 and 5 was obtained indicating high risk to groundwater contamination at the current site. Site-specific assessments of groundwater vulnerability can be performed using this framework as it only requires few HPT profiles at a contaminated dumpsite, which may take less than a week. However, several assumptions regarding saturated permeability and no retardation and consideration of only inorganic dissolved contaminants makes this method highly qualitative and more detailed site investigation program may lead to better estimates.

References

AbuHassanein, Z. S., C. H. Benson, and L. R. Blotz. 1996. "Electrical resistivity of compacted clays." *Journal of Geotechnical Engineering* 122 (5): 397-406. https://doi.org/10.1061/(asce)0733-9410(1996)122:5(397).

Aguila, J. F., M. C. McDonnell, R. Flynn, A. P. Butler, G. A. Hamill, G. Etsias, E. M. Benner, and S. Donohue. 2023. "Comparison of saturated hydraulic conductivity estimated by empirical, hydraulic and numerical modeling methods at different scales in a coastal sand aquifer in Northern Ireland." *Environmental Earth Sciences* 82 (13). https://doi.org/10.1007/s12665-023-11019-6.

Arnepalli, D. N., B. H. Rao, S. Shanthakumar, and D. N. Singh. 2010. "Determination of distribution coefficient of geomaterials and immobilizing agents." *Canadian Geotechnical Journal* 47 (10): 1139-1148. https://doi.org/10.1139/t10-014.

Borden, R. C., K. Y. Cha, and G. S. Liu. 2021. "A Physically Based Approach for Estimating Hydraulic Conductivity fromHPTPressure and Flowrate." *Groundwater* 59 (2): 266-272. https://doi.org/10.1111/gwat.13039.

Campanella, R. G., and I. Weemees. 1990. "Development and use of an electrical-resistivity cone for groundwater contamination studies." *Canadian Geotechnical Journal* 27 (5): 557-567. https://doi.org/10.1139/t90-071.

CGWB. 2016. *Aquifer mapping and ground water management plan of NCT Delhi.* (New Delhi).

Choo, H., J. Song, W. Lee, and C. Lee. 2016. "Effects of clay fraction and pore water conductivity on electrical conductivity of sand-kaolinite mixed soils." *Journal of Petroleum Science and Engineering* 147: 735-745. https://doi.org/10.1016/j.petrol.2016.10.009.

Christy, Colin D, Thomas M Christy, and Volker Wittig. 1994. "A percussion probing tool for the direct sensing of soil conductivity." Proceedings of the 8th National Outdoor Action Conference.

CPCB. 2021. *Annual Report 2020-21 on Implementation of Solid Waste Management Rules, 2016.* (New Delhi).

Fitzgerald, Michael R. 2009. *Influence of drainage state on direct-push permeability profiling methods*. The Pennsylvania State University.

Glover, P. W. J. 2010. "A generalized Archie's law for two conducting phases." *Geophysics* 75 (6): E247-E265. https://doi.org/10.1190/1.3509781.

Liu, G. S., R. C. Borden, and J. J. Butler. 2019. "Simulation Assessment of Direct Push Injection Logging for High-Resolution Aquifer Characterization." *Groundwater* 57 (4): 562-574. https://doi.org/10.1111/gwat.12826.

McCall, W., and T. M. Christy. 2020. "The Hydraulic Profiling Tool for Hydrogeologic Investigation of Unconsolidated Formations." *Ground Water Monitoring and Remediation* 40 (3): 89-103. https://doi.org/10.1111/gwmr.12399.

McCall, W., T. M. Christy, T. Christopherson, and H. Issacs. 2009. "Application of Direct Push Methods to Investigate Uranium Distribution in an Alluvial Aquifer." *Ground Water Monitoring and Remediation* 29 (4): 65-76. https://doi.org/10.1111/j.1745-6592.2009.01258.x.

MoEFCC. 2016. Solid Waste Management Rules, 2016.

Mondelli, G., H. L. Giacheti, and J. A. Howie. 2010. "Interpretation of Resistivity Piezocone Tests in a Contaminated Municipal Solid Waste Disposal Site." *Geotechnical Testing Journal* 33 (2): 123-136.

Revil, A., and P. W. J. Glover. 1997. "Theory of ionic-surface electrical conduction in porous media." *Physical Review B* 55 (3): 1757-1773. https://doi.org/10.1103/PhysRevB.55.1757.

Rhoades, J. D., P. A. C. Raats, and R. J. Prather. 1976. "Effects of liquid-phase electrical-conductivity, water-content, and surface conductivity on bulk soil electrical-conductivity." *Soil Science Society of America Journal* 40 (5): 651-655. https://doi.org/10.2136/sssaj1976.03615995004000050017x.

Robertson, P. K. 2016. "Cone penetration test (CPT)-based soil behaviour type (SBT) classification system - an update." *Canadian Geotechnical Journal* 53 (12): 1910-1927. https://doi.org/10.1139/cgj-2016-0044.

Slowiok, Max, Simon Oberhollenzer, Roman Marte, and Thomas Freudenthaler. 2022. "Determination of hydraulic conductivity using HPT & CPTu." In *Cone Penetration Testing 2022*, 697-702. CRC Press.

Vienken, T., C. Leven, and P. Dietrich. 2012. "Use of CPT and other direct push methods for (hydro-) stratigraphic aquifer characterization - a field study." *Canadian Geotechnical Journal* 49 (2): 197-206. https://doi.org/10.1139/t11-094.

Wang, J. J., J. T. He, and H. H. Chen. 2012. "Assessment of groundwater contamination risk using hazard quantification, a modified DRASTIC model and groundwater value, Beijing Plain, China." *Science of the Total Environment* 432: 216-226. https://doi.org/10.1016/j.scitotenv.2012.06.005.