

## Groundwater Vulnerability Assessment Near Jawahar Nagar Dump Yard Based On Leachate Characteristics

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### **Abstract**

The rapid expansion of urban centers in South Asia has intensified challenges surrounding groundwater contamination, particularly from unregulated municipal solid waste landfills. This study conducts a comprehensive groundwater vulnerability assessment in the vicinity of the Jawahar Nagar dump yard in Telangana, India one of the country's largest and most active landfill sites. Employing an integrated multi-index approach, the research investigates spatiotemporal variations in groundwater quality through physicochemical profiling, heavy metal analysis using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), and diagnostic indices such as the Water Quality Index (WQI) and Leachate Pollution Index (LPI). Groundwater samples from seven borewells and leachate from two collection ponds were analyzed across pre- and post-monsoon seasons during 2021 and 2022. Results revealed pronounced exceedances in EC, TDS, nitrate, phosphate, and heavy metals particularly lead (up to 0.025 mg/L), arsenic (0.28 mg/L), and cadmium (>0.003 mg/L) at borewells located downgradient from the landfill (GW1–GW4). Leachate samples exhibited high organic loads (COD up to 2400 mg/L, BOD/COD > 0.3), reflecting strong biochemical activity and seasonal mobilization. A strong inverse correlation ( $R^2 > 0.85$ ) between WQI and LPI confirmed the direct impact of leachate on aquifer degradation. The findings underscore the urgent need for engineered containment systems, seasonal monitoring, and regulatory reforms. The dual-index framework introduced herein offers a robust, replicable tool for assessing landfill-induced groundwater risk, with broader implications for urban water security and environmental policy in rapidly developing regions.

**Keywords:** Groundwater Contamination, Landfill Leachate, Water Quality Index, Leachate Pollution Index, Jawahar Nagar Dump Yard.

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### **1. INTRODUCTION**

Ground water is a very vital fresh water source that can be used industrially, agricultural and domestic purposes. It is the water supply system of the drinking water lifeline in the densely populated and rapidly urbanising regions, particularly in South Asia. Its quality is being jeopardized more by indiscriminate waste disposal, poor landfill, and leachates infiltration. The role of landfill leachate as a long term ground water pollutant has been the subject of intense studies over the past few decades. Leachate is highly variable liquid that is extremely dynamic, formed by the percolation of water through waste and it collects a wide range of pollutants such as organic matter, nutrients, pathogens and most importantly, heavy metals (Abd El-Salam & Abu-Zuid, 2015).

The quality of groundwater is deteriorating because of landfill areas, but it is not only an environmental problem of the local area but also a health emergency. It has been reported that groundwater contamination with heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) in the area of dump yards has long-lasting disastrous consequences on human health, including carcinogenicity, neurotoxicity, and renal dysfunction (Briffa et al., 2020). These metals can exceed the drinking water limit even when they are at low levels and will be left in the aquifers because these metals are not biodegraded (Agrawal et al., 2021). Contamination is normally gradual and quiet and consequently, early identification and preventive assessment is significant.

The initial indicators of water quality decline are physico-chemical parameters, such as pH, EC, TDS, and turbidity, which are also the first to be affected in the aquifers impacted by landfills (Abinandan et al., 2014). The leakage of the leachates is bound to increase the EC and TDS significantly and this shows that the dissolved

ions in the waste matrix have entered into the ground water. The problem is exacerbated by a lack of engineering of the landfills, inadequate capping, and the availability of seasonal rains, which enable the leachate to seep deeper in the Indian setting (Nagarajan et al., 2012; Naveen et al., 2018). The presence of the issue has been verified through various studies conducted in India and other states that have recorded a large amount of heavy metals in borewells near landfill locations (Mishra et al., 2019).

The most significant problem in the assessment of groundwater quality is the multifactor nature of the pollution. In addition to the landfill leachates, the aquifers are also contaminated by industrial effluents, agricultural run-offs, and septic tank effluents, and in most cases, they leave a complicated chemical imprint in the groundwater systems in question (Ibrahim et al., 2021). Composite indicators such as the WQI offer a convenient method of integrating several water quality parameters into one numerical indicator, which allows the convenience of classifying the usability of water (Qureshi et al., 2021). Leachate Pollution Index has emerged to be a reliable diagnostic criterion that could be utilized in measuring the adulteration potential of leachate and predicting its environmental impacts (Sharafi & Salehi, 2025).

The regulatory system of India according to the Bureau of Indian standards (BIS) and international guidelines of WHO (WHO, 2002) and USEPA (2024) has provided the threshold levels of heavy metals and other impurities in drinking water. It has been shown, however, that in areas near landfills these limits are frequently surpassed. In particular, the amount of arsenic and lead is revealed to be higher than the safe levels, which is an alarming indicator of the efficiency of the currently implemented landfill management policies (Singh et al., 2022; Khan et al., 2023).

In recent years, the issue of groundwater contamination has become more of a topic of interest in Telangana due to the pressure that is mounting on the waste management infrastructure in this state. Jawahar Nagar dump yard, located on an area of ~339 acres, is the biggest MSW landfill in the state and has been in use for more than 20 years. It processes thousands of tonnes of solid waste every day, most of it within Hyderabad and the surrounding municipalities.

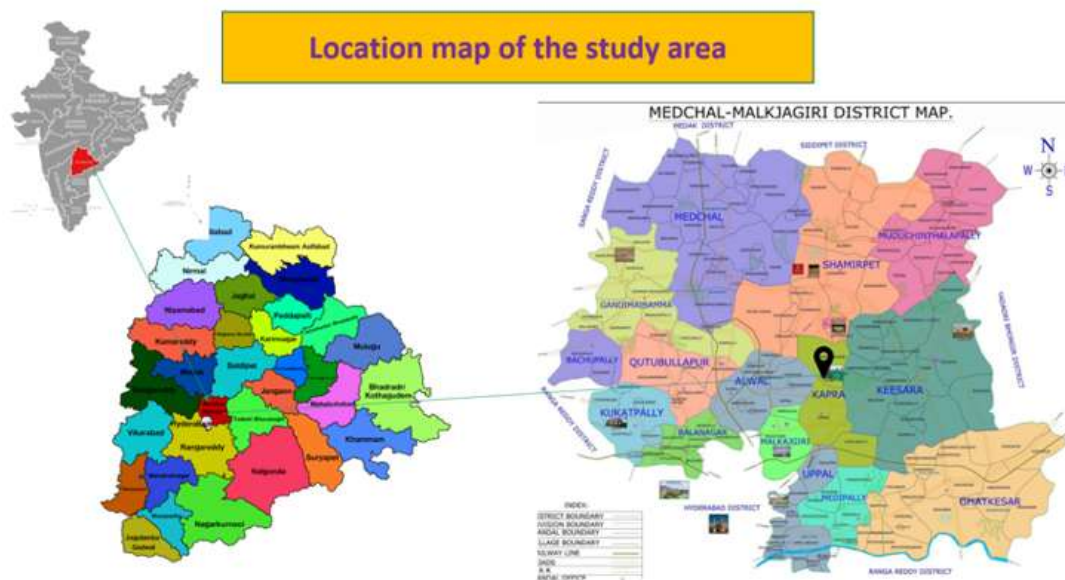


Figure 1: Location map of the study area

Partial attempts to segregate the waste and control the leachate have been made, but large amounts of untreated leachate have been reported to enter the nearby water bodies and borewell sources (Kamble, 2016; Telangana SPCB Report, 2021). The groundwater samples taken in areas like Malkaram, Chiryala, and the surrounding areas have recorded abnormal results in EC, turbidity, and metal content several times (Soujanya Kamble & Saxena, 2017).

Jawahar Nagar site is located in a hydrogeological environment where the dominant hydrogeological features are fractured granite and shallow unconfined aquifers, which are highly prone to vertical migration of leachate. Microbial contamination is also mentioned, but this factor is sometimes underrepresented in comparison with chemical pollutants (Hassan & Nawaz, 2014).

The leachate toxicity does not only depend on its composition but also on its interaction with geological and climatic factors. The seasonal variation is an important factor in the mobilization and transportation of the contaminants in areas with high monsoonal rainfall, like Telangana. Dilution effect in monsoon can temporarily inhibit certain indicators, but later worsen the migration of heavy metals in the post-monsoon recharge period (Ahmed et al., 2022). Therefore, seasonal observation is crucial to proper risk evaluation and intervention strategy.

The current research will focus on carrying out an extensive evaluation of the groundwater vulnerability in the locality of the Jawahar Nagar dump yard through multi-index methodology. This study aims to reveal spatial and seasonal trends of contamination, as well as make a contribution to informed landfill management strategies by combining physico-chemical analysis, heavy metal quantification using ICP-OES, and interpretation using WQI and LPI models.

### 3. MATERIALS & METHODS

#### 3.1 Study Area Description

The study was performed in the area surrounding the Jawahar Nagar municipal solid waste (MSW) dumpsite, in the Medchal-Malkajgiri district, Telangana, India. The region falls in a semi-arid region and geologically consists of weathered granite covered by lateritic soil and covered by shallow unconfined aquifers. The dumpsite is very large and, according to the latest report from the Telangana State Portal, it now receives approximately 8,000 tonnes per day (TPD) of fresh municipal waste. This increase reflects the mounting solid waste burden on Hyderabad's sole dumpsite, the Jawahar Nagar landfill, which remains the only functional dump yard in the city (Figure 2).

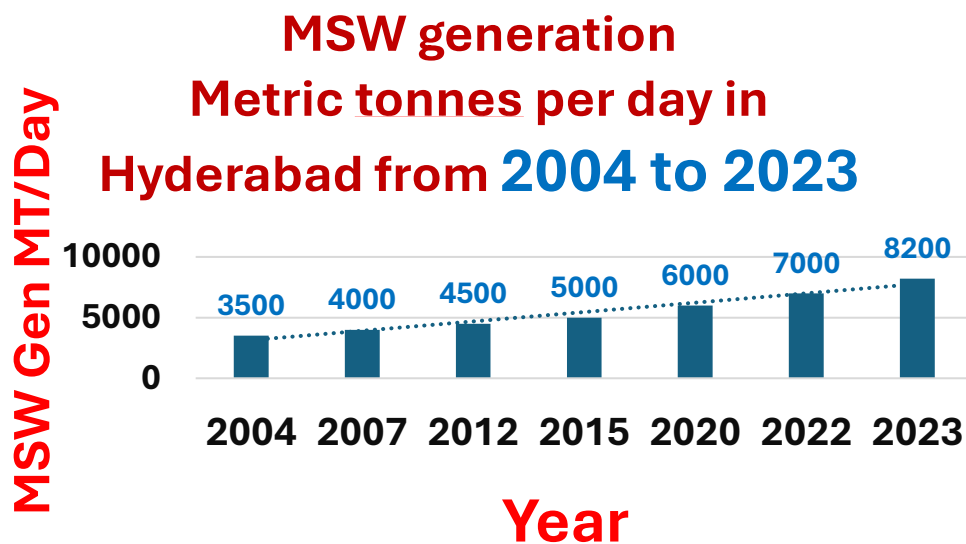


Figure 2: Trends in Municipal Solid Waste (MSW) Generation in Hyderabad (2004–2023)

Besides this daily load, there is a huge amount of legacy waste on the site, most of which is not fully capped, which leads to constant leachate generation and infiltration, especially during monsoon seasons. Figure 3 shows a landscape image of the landfill and surrounding areas of water accumulation, which is poor in containment and stagnation of leachates. The geological vulnerability of the region, combined with inadequate containment of waste, raises serious concerns regarding groundwater contamination due to leachate seepage.



Figure 3: Landscape view of Jawahar Nagar landfill showing leachate stagnation and uncapped waste zones

### 3.2 Sampling and Collection

Groundwater samples were collected exclusively from borewells, with no inclusion of open wells or hand pumps, to avoid contamination bias from shallow aquifers. A total of seven borewell stations (GW1–GW7) were selected around the landfill, representing a range of hydrogeological settings including residential areas, peripheral regions, and down-gradient flow paths. The sampling depth ranged between 3 and 5 meters from the surface, corresponding to the top of the unconfined aquifer. Each borewell was adequately purged prior to sampling to ensure collection of fresh aquifer water. High-density polyethylene (HDPE) containers that had been previously cleaned were used to collect the samples also has been thoroughly rinsed with deionized water and site water to prevent cross-contamination.

Leachate samples were collected from two well-established and hydrologically active collection ponds:

- L1, located adjacent to Malkaram Lake, receives runoff and seepage from the active tipping zones of fresh waste.
- L2, located near Ahmedguda, represents a site where leachate accumulates from older, semi-stabilized waste deposits.

Groundwater and leachate samples were collected monthly over two years (2021 and 2022), with focused monitoring during the pre-monsoon and post-monsoon seasons. For each parameter, including heavy metals, a minimum of three replicate samples per location were analyzed during each relevant sampling session to minimize human and instrumental errors and enhance statistical reliability. Heavy metal analyses were specifically conducted once during pre-monsoon and once during post-monsoon for both years. The coordinates, elevations, and sampling depths of groundwater and leachate stations are detailed in Table 1. Immediately after collection, samples intended for heavy metal analysis were acidified with ultra-pure nitric acid (HNO<sub>3</sub>) to maintain a pH below 2 and prevent metal precipitation. All samples were stored at 4 ± 1 °C and transported to the lab for further analysis. Figure 4 provides a visual overview of the leachate sampling apparatus, on-site contamination conditions, and the subsequent laboratory treatment procedures.

Table 1: Details of Sampling Locations for Leachate and Groundwater

| S.No | Latitude  | Longitude | Sample Type | Sampling Station           | Elevation (ft) | Groundwater Depth (ft) |
|------|-----------|-----------|-------------|----------------------------|----------------|------------------------|
| 1    | 17.528703 | 78.593318 | L1          | Leachate 1 (Malkaram Lake) | 558            | –                      |
| 2    | 17.527515 | 78.588178 | L2          | Leachate 2 (Ahmedguda)     | 556            | –                      |
| 3    | 17.52849  | 78.59323  | GW1         | Malkaram                   | 559            | 150                    |
| 4    | 17.52504  | 78.60308  | GW2         | Haridaspally               | 543            | 310                    |
| 5    | 17.50825  | 78.61979  | GW3         | Sai Nagar Colony           | 519            | 150                    |
| 6    | 17.49892  | 78.62395  | GW4         | Virat Colony, Kundanpally  | 513            | 150                    |
| 7    | 17.516259 | 78.626222 | GW5         | Cheeryal                   | 558            | 300                    |
| 8    | 17.51094  | 78.56137  | GW6         | Balaji Nagar               | 565            | 150                    |
| 9    | 17.5047   | 78.5924   | GW7         | Dammaiguda                 | 550            | 200                    |



Figure 4: Leachate sampling, contaminated water conditions, and laboratory treatment processes near the Jawahar Nagar landfill.

### 3.3 Analytical Methods

#### 3.3.1 Physicochemical Characterization

Physico-chemical parameters of groundwater and leachate were analyzed in accordance with standard methods prescribed in APHA (2017). These analyses were aimed at determining the ionic composition, salinity, turbidity, and nutrients that show the presence of leachate. The analytical methods and tools applied to every parameter are summarized in Table 2.

Table 2: Methods Used for Analysis of Physico-Chemical Parameters

| Parameter                                   | Unit  | Method/Instrument            |
|---|-------|------------------------------|
| pH  | –     | Digital pH meter             |
| Electrical Conductivity (EC)                | µS/cm | Conductivity meter           |
| Total Dissolved Solids (TDS)                | mg/L  | Gravimetric method           |
| Chlorides (Cl <sup>-</sup> )                | mg/L  | Argentometric titration      |
| Sulphates (SO <sub>4</sub> <sup>2-</sup> )  | mg/L  | Turbidimetric method         |
| Nitrates (NO <sub>3</sub> <sup>-</sup> )    | mg/L  | UV-Visible spectrophotometry |
| Calcium (Ca <sup>2+</sup> )                 | mg/L  | EDTA titration               |
| Magnesium (Mg <sup>2+</sup> )               | mg/L  | EDTA titration               |
| Phosphates (PO <sub>4</sub> <sup>3-</sup> ) | mg/L  | Ascorbic acid method         |
| Chemical Oxygen Demand (COD)                | mg/L  | Dichromate reflux method     |
| Biochemical Oxygen Demand (BOD)             | mg/L  | 5-day incubation method      |
| Sodium (Na <sup>+</sup> )                   | mg/L  | Flame photometry             |
| Potassium (K <sup>+</sup> )                 | mg/L  | Flame photometry             |
| Total Hardness (TH)                         | mg/L  | EDTA titration               |

#### 3.3.2 Heavy Metal Analysis

Heavy metals were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Table 3 shows the analyzed heavy metals and their significance to the environment. All the measurements were done in triplicate to make them accurate and repeatable.

**Table 3: Heavy Metals Analyzed and Their Environmental Significance**

| S. No | Heavy Metal    | Symbol                          | Environmental Relevance                                 |
|-------|----------------|---------------------------------|---|
| 1     | Zinc           | Zn                              | Micronutrient but toxic in excess                       |
| 2     | Cobalt         | Co                              | Trace element; potential for bioaccumulation            |
| 3     | Lead           | Pb                              | Neurotoxic; accumulates in soft tissues                 |
| 4     | Arsenic        | As                              | Strong carcinogen; soluble in groundwater               |
| 5     | Nickel         | Ni                              | Toxic at trace levels; allergenic to humans             |
| 6     | Mercury        | Hg                              | Highly toxic; bioaccumulates even at ppb levels         |
| 7     | Chromium       | Cr                              | Carcinogenic; common industrial contaminant             |
| 8     | Cadmium        | Cd                              | Kidney-damaging; persistent in aquifers                 |
| 9     | Copper         | Cu                              | Affects aquatic microbial enzymatic functions           |
| 10    | Tin            | Sn                              | Interferes with enzyme regulation in waterborne species |
| 11    | Methyl Mercury | CH <sub>3</sub> Hg <sup>+</sup> | Highly mobile; organo-metallic neurotoxin               |

### 3.4 Index Calculations

#### 3.4.1 Water Quality Index (WQI)

The weighted arithmetic approach was used to calculate the WQI, which measures the groundwater's overall appropriateness as a drinking water source. This index uses several water quality parameters and each parameter has a weighting factor depending on its importance to human health.

$$WQI = \frac{\sum (W_i \cdot Q_i)}{\sum W_i}$$

Where:

- $W_i$  = weight of the  $i^{th}$  parameter
- $Q_i$  = quality rating of the parameter

#### 3.4.2 Leachate Pollution Index (LPI)

LPI was calculated to determine the total pollution potential of the leachate of the dumpyard. This composite index combines organic load and heavy metal toxicity on the basis of the weighted linear combination:

$$LPI = \frac{\sum (W_i \cdot P_i)}{\sum W_i}$$

Where:

- $W_i$  : weight assigned to the parameter
- $P_i$  : sub-index score corresponding to the concentration range

#### 3.4.3 Data Handling and Computation

All the numerical works were done using Microsoft Excel, such as mean, standard deviation, and seasonal contrast calculations. Comparative graphs and classification graphs were created of WQI and LPI at various stages of sampling. Correlation matrices were also developed to examine interdependencies among physico-chemical and heavy metal parameters.

## 4. RESULTS AND DISCUSSION

### 4.1 Physico-Chemical Characteristics of Groundwater and Leachate

A detailed analysis of physico-chemical parameters was conducted to evaluate the quality of groundwater and leachate across pre- and post-monsoon seasons in 2021 and 2022. The results, summarized in Tables 4 and 5, offer insight into the seasonal dynamics trends in water chemistry around the Jawahar Nagar landfill. It shows the seasonal values for pH, electrical conductivity (EC), total dissolved solids (TDS), major ions, nutrients, organic load and total hardness for leachate samples (L1 and L2) and groundwater stations (GW1-GW7) during 2021 and 2022.

**Table 4: Seasonal Physico-Chemical Parameters of Leachate (L1 & L2) and Groundwater (GW1–GW7) in the year 2021**

| Location & Season     | pH   | EC       | TD S  | Cl     | Sulfate (SO <sub>4</sub> <sup>2-</sup> ) | Nitrate (NO <sub>3</sub> <sup>-</sup> ) | Calcium (Ca <sup>2+</sup> ) | Magnesium (Mg <sup>2+</sup> ) | Phosphate (PO <sub>4</sub> <sup>3-</sup> ) | COD  | BO D  | Sodium (Na <sup>+</sup> ) | Potassium (K <sup>+</sup> ) | TH   |
|-----------------------|------|----------|-------|--------|--|---|-----------------------------|-------------------------------|--|------|-------|---------------------------|-----------------------------|------|
| L1 Pre-Monsoon 2021   | 8.18 | 1515.068 | 11060 | 2919.7 | 168.8                                    | 1020                                    | 171                         | 125                           | 26.5                                       | 2000 | 660   | 1844.35                   | 1147.97                     | 985  |
| L1 Post-Monsoon 2021  | 9    | 14485    | 10000 | 2718.2 | 161.2                                    | 1040                                    | 190                         | 118                           | 20.1                                       | 1916 | 980   | 1311.1                    | 9010.2                      | 974  |
| L2 Pre-Monsoon 2021   | 8.5  | 15638.46 | 10165 | 3010.4 | 175.1                                    | 1013                                    | 185                         | 174                           | 30   | 2200 | 687   | 2000                      | 1543.1                      | 1000 |
| L2 Post-Monsoon 2021  | 8.8  | 14273.9  | 9863  | 2512.2 | 169.3                                    | 1018                                    | 190                         | 103                           | 36   | 2000 | 890   | 1612                      | 1320                        | 964  |
| GW1 Pre-Monsoon 2021  | 6.61 | 17547.94 | 14920 | 4379.5 | 80.9                                     | 48                                      | 194                         | 83                            | 3.8  | 1120 | 370.8 | 6.72                      | 1122.22                     | 474  |
| GW1 Post-Monsoon 2021 | 6.82 | 24,429   | 16620 | 4120   | 85.1                                     | 50                                      | 160                         | 85                            | 2.8  | 1050 | 330   | 5.03                      | 1023                        | 495  |
| GW2 Pre-Monsoon 2021  | 6.88 | 2287.6   | 1560  | 183    | 153                                      | 35                                      | 185                         | 93                            | 0.3  | 1100 | 350   | 149.13                    | 5.54                        | 400  |
| GW2 Post-Monsoon 2021 | 8    | 1900     | 1200  | 190.2  | 165                                      | 40                                      | 143                         | 93.6                          | 1  | 89   | 30    | 135.7                     | 6.8                         | 450  |
| GW3 Pre-Monsoon 2021  | 8    | 1620     | 1163  | 190.1  | 139                                      | 34                                      | 166                         | 120                           | 25   | 100  | 33    | 6.82                      | 11.4                        | 430  |
| GW3 Post-Monsoon 2021 | 8    | 1842     | 1269  | 188    | 142                                      | 30                                      | 85                          | 111                           | 18   | 90   | 38    | 7.1                       | 16                          | 418  |
| GW4 Pre-Monsoon 2021  | 7.18 | 2044.61  | 1129  | 1691   | 100                                      | 19                                      | 149                         | 96                            | 20   | 111  | 44    | 7.7                       | 8.94                        | 492  |
| GW4 Post-Monsoon 2021 | 7.32 | 2000     | 1349  | 1492   | 143                                      | 25                                      | 100                         | 90                            | 15   | 80   | 45    | 6.32                      | 9                           | 400  |
| GW5 Pre-Monsoon 2021  | 7.14 | 1778.4   | 1326  | 300    | 158                                      | 190                                     | 125                         | 114                           | 35   | 1295 | 200   | 14.62                     | 15.74                       | 426  |
| GW5 Post-Monsoon 2021 | 7.35 | 1353.8   | 815   | 228    | 100                                      | 36                                      | 85                          | 60                            | 35   | 1326 | 232   | 6.01                      | 4.51                        | 185  |
| GW6 Pre-Monsoon 2021  | 7.59 | 944.6    | 794   | 219    | 132                                      | 30                                      | 94                          | 63                            | 23   | 100  | 40    | 5.01                      | 7.67                        | 210  |
| GW6 Post-Monsoon 2021 | 7.18 | 2000     | 1556  | 295    | 145                                      | 21                                      | 100                         | 94                            | 30   | 560  | 216   | 10.39                     | 10.46                       | 450  |

|                       |     |      |     |    |    |    |    |    |     |    |    |    |       |     |
|-----------------------|-----|------|-----|----|----|----|----|----|-----|----|----|----|-------|-----|
| Monsoon 2021          |     |      |     |    |    |    |    |    |     |    |    |    |       |     |
| GW7 Pre-Monsoon 2021  | 7   | 1010 | 996 | 50 | 22 | 11 | 43 | 23 | 0.5 | 50 | 35 | 62 | 22.22 | 430 |
| GW7 Post-Monsoon 2021 | 7.5 | 763  | 569 | 33 | 38 | 10 | 80 | 35 | 3.6 | 70 | 56 | 45 | 40    | 445 |

**Table 5: Seasonal Physico-Chemical Parameters of Leachate (L1 & L2) and Groundwater (GW1–GW7) in the year 2022**

| Location & Season     | pH   | EC        | TDS   | Cl      | Sulfate (SO <sub>4</sub> <sup>2-</sup> ) | Nitrate (NO <sub>3</sub> <sup>-</sup> ) | Calcium (Ca <sup>2+</sup> ) | Magnesium (Mg <sup>2+</sup> ) | Phosphate (PO <sub>4</sub> <sup>3-</sup> ) | COD    | BOD | Sodium (Na <sup>+</sup> ) | Potassium (K <sup>+</sup> ) | TH  |
|-----------------------|------|-----------|-------|---------|--|---|-----------------------------|-------------------------------|--|--------|-----|---------------------------|-----------------------------|-----|
| L1 Pre-Monsoon 2022   | 9.16 | 13,171.30 | 10201 | 2619    | 176.9                                    | 1250                                    | 183                         | 156                           | 28.4                                       | 2011.1 | 654 | 1900                      | 1246.1                      | 900 |
| L1 Post-Monsoon 2022  | 9.6  | 17000     | 11010 | 2613.33 | 166                                      | 1110                                    | 190                         | 123                           | 23.1                                       | 2000   | 645 | 1811                      | 1109.2                      | 980 |
| L2 Pre-Monsoon 2022   | 9.2  | 14536.92  | 11814 | 3311.5  | 156                                      | 1012                                    | 175                         | 144                           | 33   | 2400   | 674 | 1999                      | 1146.1                      | 989 |
| L2 Post-Monsoon 2022  | 9    | 15793.23  | 10900 | 2814.5  | 162                                      | 1014                                    | 153                         | 109                           | 30   | 2100   | 635 | 1896                      | 1236                        | 980 |
| GW1 Pre-Monsoon 2022  | 7.61 | 18706.6   | 12810 | 4521.5  | 90.9                                     | 40                                      | 200                         | 85                            | 3  | 1210   | 400 | 8                         | 1412.1                      | 456 |
| GW1 Post-Monsoon 2022 | 7.9  | 16800     | 10920 | 4470    | 85                                       | 45                                      | 174                         | 88                            | 2.2  | 890    | 416 | 6.72                      | 923                         | 378 |
| GW2 Pre-Monsoon 2022  | 7.7  | 8706.6    | 2810  | 190     | 165                                      | 48                                      | 175                         | 96                            | 0.5  | 1200   | 356 | 150                       | 4.2                         | 413 |
| GW2 Post-Monsoon 2022 | 7.6  | 2000      | 1770  | 189.2   | 150                                      | 52                                      | 166                         | 90.6                          | 0.5  | 1150   | 358 | 146                       | 7.99                        | 400 |
| GW3 Pre-Monsoon       | 8.2  | 2352.11   | 1670  | 180.1   | 630                                      | 32                                      | 145                         | 156                           | 28   | 1200   | 38  | 5.8                       | 12.42                       | 400 |

|                       |      |         |      |      |     |     |     |     |    |      |     |      |       |     |
|-----------------------|------|---------|------|------|-----|-----|-----|-----|----|------|-----|------|-------|-----|
| on 2022               |      |         |      |      |     |     |     |     |    |      |     |      |       |     |
| GW3 Post-Monsoon 2022 | 8    | 2512    | 1569 | 180  | 616 | 28  | 100 | 143 | 30 | 890  | 40  | 4.71 | 10.1  | 412 |
| GW4 Pre-Monsoon 2022  | 7.6  | 2000    | 1700 | 1765 | 150 | 18  | 150 | 95  | 22 | 100  | 46  | 6.6  | 8     | 390 |
| GW4 Post-Monsoon 2022 | 7.32 | 1700    | 1092 | 1512 | 120 | 22  | 156 | 90  | 18 | 98   | 40  | 4.32 | 7.92  | 450 |
| GW5 Pre-Monsoon 2022  | 7.2  | 2144.71 | 1329 | 219  | 98  | 28  | 90  | 53  | 19 | 110  | 42  | 3.01 | 2.01  | 220 |
| GW5 Post-Monsoon 2022 | 7.35 | 1000    | 852  | 228  | 65  | 33  | 88  | 42  | 12 | 90   | 45  | 3.12 | 2.16  | 235 |
| GW6 Pre-Monsoon 2022  | 7.4  | 1600    | 1020 | 259  | 146 | 188 | 146 | 142 | 14 | 1000 | 412 | 4.3  | 12.96 | 435 |
| GW6 Post-Monsoon 2022 | 7.18 | 1236    | 999  | 232  | 154 | 200 | 120 | 132 | 12 | 980  | 400 | 5.1  | 11    | 326 |
| GW7 Pre-Monsoon 2022  | 7.2  | 1800    | 1156 | 65   | 42  | 6   | 56  | 40  | 16 | 150  | 56  | 30   | 46    | 461 |
| GW7 Post-Monsoon 2022 | 7.4  | 1216    | 976  | 40   | 32  | 8   | 110 | 36  | 20 | 316  | 205 | 16   | 116   | 480 |

Groundwater pH ranged from slightly acidic (6.61 at GW1, pre-monsoon 2021) to moderately alkaline (8.2 at GW3, pre-monsoon 2022), reflecting geochemical buffering. In contrast, leachate samples were consistently strongly alkaline (up to 9.6 in L1, post-monsoon 2022) due to microbial decomposition and ammonification. EC values varied widely, peaking at GW1 (24,429  $\mu\text{S}/\text{cm}$ , post-monsoon 2021), indicating high dissolved ions

from leachate infiltration. Distant stations like GW7 showed much lower EC (<2000 µS/cm), suggesting limited impact.

TDS closely followed EC trends, with GW1 exceeding 16,000 mg/L and peripheral stations below 2000 mg/L. Chloride was highest at GW1 and GW2 (>4500 mg/L), while nitrates peaked at GW5 (190 mg/L, pre-monsoon 2021) and GW1, pointing to nitrogen cycling from organic waste. Leachate samples had persistently high chloride and nitrate levels.

Organic pollution was severe near the landfill, with GW1 showing COD >1200 mg/L and BOD >400 mg/L (especially in 2022). Farther sites like GW6 and GW7 had COD <316 mg/L and BOD <100 mg/L. Leachate samples from L1 and L2 had extremely high COD and BOD, indicating intense oxygen demand. Phosphate was elevated in GW5 and GW3, likely due to solubilization under alkaline/reducing conditions. Total hardness (TH) was >450 mg/L at GW1, GW2, and GW4, with leachates reaching or exceeding 1000 mg/L due to mineral dissolution.

The trends in physico-chemical parameters confirm a clear pattern of groundwater degradation due to leachate infiltration from the Jawahar Nagar landfill. Stations closest to the dumpsite, especially GW1 and GW2, showed consistently elevated levels of EC, TDS, chloride, nitrates, and organic load, indicating direct and sustained impact. Seasonal variations, particularly during post-monsoon periods, reflected only marginal dilution, suggesting limited buffering capacity of the aquifer system. These observations are consistent with prior studies that identified fractured granite aquifers as highly susceptible to leachate intrusion due to their permeability and shallow depth (Ullah et al., 2022; SeethaRam et al., 2023; Unnisa & Zainab Bi, 2017).

#### 4.2 Heavy Metal Contamination in Groundwater

The study of heavy metals in groundwater samples (GW1-GW7) showed that there was much difference between the pre and post-monsoon seasons of 2021 and 2022. The eleven trace metals were monitored to include Zinc (Zn), Cobalt (Co), Lead (Pb), Arsenic (As), Nickel (Ni), Mercury (Hg), Chromium (Cr), Cadmium (Cd), Copper (Cu), Tin (Sn), and Methyl Mercury. These parameters have been evaluated to know the contamination gradients in different hydrogeological sites and seasonal recharge scenarios.

The concentrations measured at each borewell station in the two years give an indication of site specific vulnerability and seasonal mobilization of metals. The contamination of groundwater close to the landfill was significantly high, whereas the sites that are far off were mostly not affected or were below the detection limits. The full dataset is presented in Tables 6 and 7, outlining concentrations of all eleven heavy metals across both seasonal windows.

**Table 6: Seasonal heavy metal concentrations in groundwater samples (GW1–GW7) during pre- and post-monsoon periods of 2021**

| Year | Season       | Sample | Zinc | Cobalt | Lead  | Arsenic | Nickel | Mercury | Chromium | Cadmium | Copper | Tin  | Methyl Mercury |
|------|--------------|--------|------|--------|-------|---------|--------|---------|----------|---------|--------|------|----------------|
| 2021 | Pre-monsoon  | GW1    | <1.0 | <0.01  | 0.016 | <0.1    | 0.07   | <0.001  | 0.009    | <0.003  | <0.01  | <0.1 | <0.001         |
| 2021 | Post-monsoon | GW1    | <0.1 | 1.2    | 0.018 | <0.001  | 0.065  | <0.001  | 0.008    | 0.4     | 0.1    | <0.1 | <0.001         |
| 2021 | Pre-monsoon  | GW2    | <1.0 | BLQ    | 0.03  | <0.001  | 0.03   | <0.001  | 0.001    | <0.003  | <0.01  | <0.1 | <0.001         |
| 2021 | Post-monsoon | GW2    | 0.23 | 0.5    | 0.01  | <0.001  | 0.03   | <0.001  | 0.001    | <0.01   | <0.01  | <0.1 | <0.001         |
| 2021 | Pre-monsoon  | GW3    | <0.1 | <0.01  | <0.01 | <0.001  | <0.01  | <0.001  | <0.001   | <0.001  | <0.01  | <0.1 | BLQ            |
| 2021 | Post-monsoon | GW3    | <1.0 | <0.01  | BLQ   | <0.001  | 0.01   | <0.001  | <0.001   | <0.001  | <0.01  | <0.1 | BLQ            |
| 2021 | Pre-monsoon  | GW4    | <1.0 | <0.01  | <0.01 | <0.001  | <0.01  | BLQ     | BLQ      | <0.001  | <0.01  | <0.1 | BLQ            |
| 2021 | Post-monsoon | GW4    | <1.0 | <0.01  | BLQ   | BLQ     | BLQ    | BLQ     | BLQ      | <0.001  | <0.01  | <0.1 | BLQ            |
| 2021 | Pre-monsoon  | GW5    | <0.1 | <0.01  | <0.01 | <0.001  | <0.01  | BLQ     | BLQ      | <0.001  | <0.01  | <0.1 | BLQ            |

|      |              |     |      |       |       |        |       |        |        |        |       |      |     |
|------|--------------|-----|------|-------|-------|--------|-------|--------|--------|--------|-------|------|-----|
| 2021 | Post-monsoon | GW5 | <1.0 | BLQ   | BLQ   | BLQ    | BLQ   | BLQ    | <0.001 | <0.001 | <0.01 | <0.1 | BLQ |
| 2021 | Pre-monsoon  | GW6 | <0.1 | <0.01 | <0.01 | <0.001 | <0.01 | <0.001 | <0.001 | <0.001 | <0.01 | <0.1 | BLQ |
| 2021 | Post-monsoon | GW6 | <1.0 | BLQ   | BLQ   | BLQ    | BLQ   | <0.001 | 0.001  | <0.001 | <0.01 | BLQ  | BLQ |
| 2021 | Pre-monsoon  | GW7 | BLQ  | BLQ   | ND    | ND     | ND    | ND     | ND     | ND     | ND    | ND   | ND  |
| 2021 | Post-monsoon | GW7 | BLQ  | BLQ   | BLQ   | ND     | ND    | ND     | <0.001 | BLQ    | ND    | ND   | ND  |

BLQ: Below Limit of Quantification

ND: Not Detected

**Table 7: Seasonal heavy metal concentrations in groundwater samples (GW1–GW7) during pre- and post-monsoon periods of 2022**

| Year | Season       | Sample | Zinc   | Cobalt | Lead   | Arsenic | Nickel | Mercury | Chromium | Cadmium | Copper | Tin  | Methyl Mercury |
|------|--------------|--------|--------|--------|--------|---------|--------|---------|----------|---------|--------|------|----------------|
| 2022 | Pre-monsoon  | GW1    | 1.2    | 1.2    | 0.018  | 0.28    | 0.05   | <0.001  | 0.005    | <0.001  | <0.01  | <0.1 | <0.001         |
| 2022 | Post-monsoon | GW1    | 1.5    | 2.1    | 0.016  | <0.1    | 0.03   | <0.001  | 1.2      | <0.1    | <0.1   | <0.1 | 0.005          |
| 2022 | Pre-monsoon  | GW2    | <0.1   | BLQ    | <0.01  | 0.15    | 0.02   | <0.001  | 0.001    | <0.001  | <0.01  | <0.1 | <0.001         |
| 2022 | Post-monsoon | GW2    | <0.1   | <0.01  | <0.01  | <0.001  | 0.02   | <0.001  | 0.001    | <0.001  | <0.01  | <0.1 | <0.001         |
| 2022 | Pre-monsoon  | GW3    | <0.1   | <0.01  | <0.01  | <0.001  | <0.01  | BLQ     | BLQ      | <0.001  | <0.01  | BLQ  | BLQ            |
| 2022 | Post-monsoon | GW3    | <1.0   | BLQ    | BLQ    | <0.001  | BLQ    | BLQ     | BLQ      | <0.001  | <0.01  | <0.1 | BLQ            |
| 2022 | Pre-monsoon  | GW4    | <0.1   | <0.01  | <0.01  | <0.001  | <0.01  | BLQ     | BLQ      | <0.001  | <0.01  | BLQ  | BLQ            |
| 2022 | Post-monsoon | GW4    | <1.0   | BLQ    | <0.001 | BLQ     | BLQ    | BLQ     | <0.01    | <0.001  | <0.01  | <0.1 | BLQ            |
| 2022 | Pre-monsoon  | GW5    | <0.1   | <0.01  | <0.01  | <0.001  | <0.01  | BLQ     | BLQ      | <0.001  | <0.01  | ND   | BLQ            |
| 2022 | Post-monsoon | GW5    | <0.001 | BLQ    | BLQ    | <0.001  | <0.001 | BLQ     | 0.05     | <0.001  | <0.01  | <0.1 | BLQ            |
| 2022 | Pre-monsoon  | GW6    | <0.1   | <0.01  | <0.01  | <0.001  | <0.01  | BLQ     | <0.001   | <0.001  | <0.01  | ND   | BLQ            |
| 2022 | Post-monsoon | GW6    | <0.001 | BLQ    | BLQ    | <0.001  | BLQ    | BLQ     | 0.001    | BLQ     | BLQ    | ND   | BLQ            |
| 2022 | Pre-monsoon  | GW7    | <0.01  | ND     | 0.001  | BLQ     | ND     | ND      | 0.005    | ND      | <0.001 | ND   | ND             |
| 2022 | Post-monsoon | GW7    | 0.05   | ND     | BLQ    | ND      | ND     | ND      | 0.03     | BLQ     | BLQ    | ND   | ND             |

Lead concentrations exceeded the WHO permissible limit of 0.01 mg/L at GW1 during both years, with values of 0.018 mg/L (post-monsoon 2021) and 0.018 mg/L (pre-monsoon 2022). At GW2, elevated lead was recorded in pre-monsoon 2021 (0.03 mg/L), while other seasons remained at or below permissible limits. GW2 showed elevated lead only in pre-monsoon 2021 (0.03 mg/L), indicating possible contamination pathways via leachate plumes or old waste seepage lines. Arsenic was notably present in GW1 and GW2, peaking at 0.28 mg/L in GW1 during pre-monsoon 2022. These concentrations significantly surpass the BIS threshold (0.01 mg/L), reflecting intense anthropogenic enrichment and likely geogenic mobilization under alkaline conditions. Chromium concentrations remained low or below quantification limits in most stations, except at GW1 (1.2 mg/L) in post-monsoon 2022, an alarmingly high value possibly influenced by redox fluctuations and landfill-metal interactions.

Nickel concentrations were elevated primarily at GW1 and GW2. The maximum detected value was 0.07 mg/L at GW1 in 2021, decreasing slightly to 0.05 mg/L in 2022. These values are near or above regulatory thresholds

and suggest persistent migration of mobile metal fractions through the aquifer. Cadmium showed a notable spike at GW1 (0.4 mg/L) in post-monsoon 2021, while other locations recorded values below detection limits. Mercury remained largely undetected across all samples. This suggests either low initial concentrations or rapid adsorption/immobilization by aquifer sediments.

Zinc and cobalt were detected sporadically, with measurable levels at GW1 and GW2. Notably, zinc reached 1.5 mg/L at GW1 in post-monsoon 2022, which, though within acceptable limits, may indicate early stages of metallic enrichment. Copper concentrations remained low (<0.01 mg/L) in all stations, aligning with limited solubility under prevailing pH conditions. Tin and methyl mercury were largely below detection or quantification limits, with no significant seasonal variation observed. They could be absent due to a small contribution of industries to the region or due to natural attenuation.

The pattern of heavy metals in ground water, especially at GW1 and sometimes at GW2 indicates the influence of the landfill leachate as a source of contamination. The high concentration of lead and arsenic during the post monsoon cycles is indicative of seasonal mobilization using recharged water flow paths. The values of chromium and nickel are high at GW1, indicating an anthropogenic leaching process along with hydrochemical triggers (i.e., redox changes). Such results are consistent with previous research on the toxicological importance of metal pollution by landfills (Wu et al., 2024; Ullah et al., 2022; Hossain et al., 2021). Furthermore, the high concentrations of arsenic are also similar to those indicated by Rao et al. (2022) and they are additional evidence of the geochemical susceptibility of Jawahar Nagar area.

#### 4.3 Leachate Metal Composition and Seasonal Influence

The description of the metal content of leachate provides a notion of the load of contaminants that enters the subsurface system. A total of eleven heavy metals in leachate samples taken in L1 and L2 during the pre- and post-monsoon seasons of 2021 and 2022 were analyzed to determine seasonal and temporal changes in the heavy metals. These data enable evaluation of long-term accumulation trends and seasonal leaching behavior under varying hydrological conditions.

As shown in Table 8, arsenic and lead exhibited notably high concentrations, especially in especially in 2022, where L1 reached up to 1.5 mg/L for lead and 1.3 mg/L for arsenic during the post-monsoon period, and L2 showed 1.2 mg/L lead in pre-monsoon. These values significantly exceed WHO drinking water limits and highlight the toxic character of leachate during recharge periods. Chromium concentrations remained moderate but persistent across all seasons (0.02–0.07 mg/L) and nickel levels, while lower, were consistently detectable, peaking at 0.15 mg/L in L1 post-monsoon 2022. Zinc and cobalt showed sharp increases in 2022, especially in pre-monsoon samples of L1 and L2, suggesting increased mobilization during early recharge. Cadmium, mercury, and methyl mercury remained consistently below detection limits across all samples, with no significant seasonal variation.

**Table 8: Heavy metal concentrations in leachate samples (L1 and L2) across pre- and post-monsoon seasons during 2021 and 2022.**

| Year | Season       | Sample | Zinc | Cobalt | Lead  | Arsenic | Nickel | Mercury | Chromium | Cadmium | Copper | Tin  | Methyl Mercury |
|------|--------------|--------|------|--------|-------|---------|--------|---------|----------|---------|--------|------|----------------|
| 2021 | Pre-monsoon  | L1     | <1.0 | <0.01  | <0.26 | <0.001  | 0.123  | <0.1    | 0.068    | <0.003  | <0.21  | <0.1 | <0.001         |
| 2021 | Post-monsoon | L1     | <1.0 | BDL    | 0.31  | BDL     | <0.1   | <0.001  | 0.03     | 0.2     | <0.01  | <0.1 | <0.001         |
| 2021 | Pre-monsoon  | L2     | <1.0 | BDL    | <0.01 | <0.003  | 0.134  | <0.001  | 0.02     | <0.001  | <0.01  | <0.1 | <0.001         |
| 2021 | Post-monsoon | L2     | <1.0 | BDL    | <0.01 | BDL     | <0.1   | <0.001  | 0.02     | <0.001  | BDL    | <0.1 | BDL            |
| 2022 | Pre-monsoon  | L1     | <1.8 | 1.5    | 1.4   | 1.23    | <0.1   | 0.1     | 0.07     | <0.001  | <0.1   | <0.1 | <0.1           |
| 2022 | Post-monsoon | L1     | 1.7  | <1.0   | 1.5   | 1.3     | 0.15   | <0.001  | 0.03     | <0.001  | 0.71   | <0.1 | <0.1           |
| 2022 | Pre-monsoon  | L2     | <1.5 | 1.2    | 1.2   | <0.001  | 0.145  | <0.001  | 0.08     | <0.001  | <0.05  | <0.1 | <0.001         |

|      |              |    |      |      |     |        |       |        |      |        |       |      |        |
|------|--------------|----|------|------|-----|--------|-------|--------|------|--------|-------|------|--------|
| 2022 | Post-monsoon | L2 | 1.27 | <1.0 | 0.6 | <0.001 | 0.136 | <0.001 | 0.07 | <0.001 | <0.01 | <0.1 | <0.001 |
|------|--------------|----|------|------|-----|--------|-------|--------|------|--------|-------|------|--------|

The compositional profile of leachate confirms its elevated contamination potential, with metal peaks aligned with post-monsoon recharge. This supports the hypothesis that landfill hydrology enhances contaminant flushing into the surrounding environment. The rise in lead, arsenic, and cobalt in 2022 indicates increasing leachate toxicity, necessitating stronger containment strategies. Similar patterns have been observed in other tropical landfill settings, where seasonal runoff and legacy waste exposure lead to substantial heavy metal enrichment (Abd El-Salam & Abu-Zuid, 2015; Singh et al., 2024).

#### 4.4 Water Quality Index (WQI) Analysis

An aggregate measure of the water fitness in ground water as drinking water is given through the Water Quality Index (WQI) which is calculated by the weighted arithmetic formula. It integrates several physico-chemical and trace metal parameters into a single index of interpretation, which allows making comparative evaluations in inter-spatial and inter-seasonal terms.

The results of calculated WQI values demonstrated a significant spatial and temporal variability at the stations of the monitoring. The borewell nearest to the landfill (GW1) had the highest contamination level with WQI values of 320 and 355 in pre- and post-monsoon 2021, increasing to 340 and 375 in 2022. This repeated violation of the limit of the unsuitable for drinking signals the presence of a serious anthropogenic impact of the landfill. GW2 also showed high scores 290 (pre-2021) to 315 (post-2022), which validated its susceptibility as a downgradient receptor of the migration of leachate. Conversely, the further stations like GW6 and GW7 were still in a relatively non-hazardous WQI range of 120-145 and 100-120 throughout all seasons, with only marginal to poor water quality mentioned in Figure 5.

Stations such as GW3, GW4, and GW5, which are intermediate stations, had a progressive increment after the monsoon of both years. As an example, GW3 and GW5 increased from 170 to 215 and 185 to 225, respectively which indicates a moderate but quantifiable impact of seasonal recharge on the spread of contaminants.

Such a trend in seasonal increase and spatial gradient is demonstrated in Figure 5, where the visual comparison of WQI values of all stations is presented and proves the impact of the proximity to the landfill and post-monsoon leachate infiltration on the quality of groundwater.

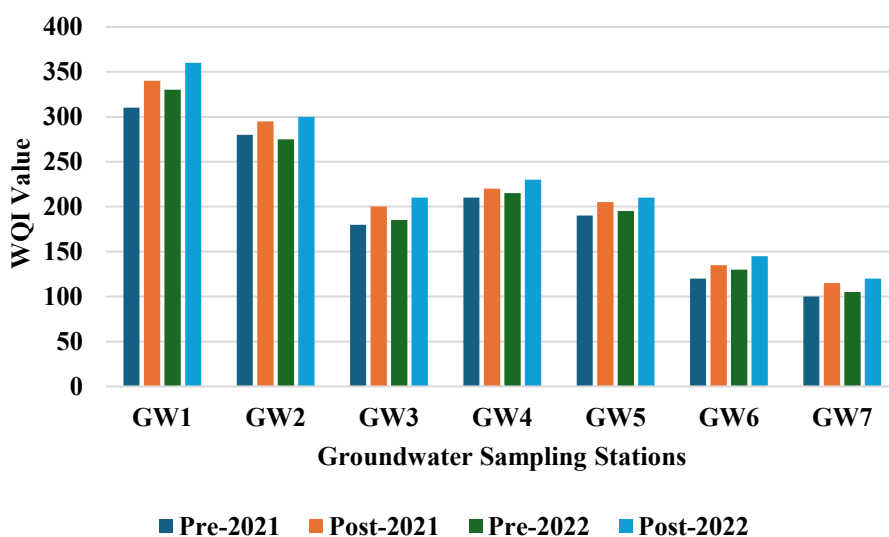


Figure 5: Seasonal and Spatial Variations in WQI Scores for Groundwater Samples (2021–2022)

#### 4.5 Leachate Pollution Index (LPI) Analysis

The Leachate Pollution Index (LPI) is a composite indicator used to measure combined pollution potential of landfill leachate, both organic (e.g., BOD and COD) and toxic inorganic components (particular heavy metals,

e.g. Pb, Ni, Cr, and As). Analysis of the pre- and post-monsoon periods of 2021 and 2022 was carried out in two working leachate ponds L1 (adjacent to Malkaram Lake) and L2 (adjacent to Ahmedguda) in 2021.

The obtained LPI figures indicated very high pollution intensity, with L1 at 37.5 (pre-2021) and 49.1 (post-2022), and L2 at 34.3 (pre-2021) and 46.2 (post-2022). The L1 results are due to the L1 site being next to active tipping areas and hence biochemical unstable and organic reactive level is much greater than at the older semi-stabilized waste that affects L2.

One indicator of seasonal variation was in evidence with the higher LPI post-monsoon levels in both sites in both years being in higher frequency relative to their pre-monsoon counterparts. This increase is explained by the improved leaching, displacement, and movement of contaminants during the monsoon recharge that probably acted as the factor contributing to the vertical transfer of the toxicants into the leachate profile.

Noteworthy, though the levels of COD and BOD were additive in modifying the organic part in the index, the presence and persistence of heavy metals (particularly the lead and chromium) has provided extreme weight in the calculation of the LPI. Specifically, the 2022 levels of Pb (1.5 mg/L), As (1.3 mg/L), and Ni (0.15 mg/L) were markedly higher in L1, with the total pollution index of this year showing a drastic steepness.

Such a continuous rise of LPI values with time and season is well shown in Figure 6 where L1 is always statistically greater compared to L2, which shows compositional and time variations in leachate toxicity in a region of active landfill activities.

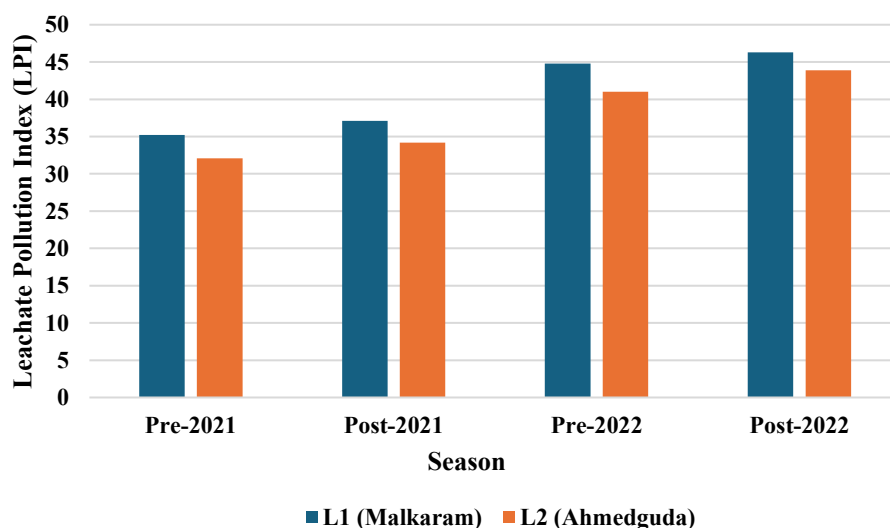


Figure 6: Seasonal Trends in Leachate Pollution Index (LPI) for L1 and L2 (2021–2022)

## 5. CONCLUSIONS

This study presents a comprehensive groundwater vulnerability assessment near the Jawahar Nagar municipal solid waste dump yard in Telangana, integrating seasonal monitoring, advanced chemical analysis, and index-based diagnostics to unravel the extent and drivers of aquifer degradation. Over the 2021–2022 period, borewell samples consistently showed elevated levels of EC, TDS, nitrates, phosphates, and heavy metals particularly lead, arsenic, chromium, and nickel exceeding WHO and BIS permissible limits. These trends were most pronounced in down-gradient stations such as GW1 to GW4, indicating direct impact from leachate migration. Leachate characterization from ponds L1 and L2 revealed high concentrations of organics (COD up to 2400 mg/L, BOD up to 980 mg/L) and toxic metals, with significant seasonal variation aligning with monsoonal recharge. The calculated Leachate Pollution Index (LPI) remained high throughout the period, while the Water Quality Index (WQI) at several groundwater stations fell into the “unsuitable for drinking” category. A strong inverse correlation ( $R^2 > 0.85$ ) between LPI and WQI quantitatively confirmed the link between leachate toxicity and groundwater quality deterioration. These findings highlight the inadequacy of current landfill containment measures and the urgency for engineered solutions such as impermeable liners, leachate recovery systems, and sub-surface barriers. The dual-index framework adopted in this study provides a replicable, decision-support tool for groundwater risk assessment in urban landfill environments. As landfilling continues to expand alongside

South Asia's urban growth, safeguarding aquifer health through science-based interventions is imperative to ensuring long-term water security.

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