



# Spatiotemporal Analysis of Leachate at the Metepec Landfill: Implications for Solid Waste Management



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**Received:** 06-24-2025

**Revised:** 09-23-2025

**Accepted:** 11-04-2025

**Citation:** A. C. Bernal, J. Garfias, H. J. Rendón, H. Ramírez, and S. Pedroza, "Spatiotemporal analysis of leachate at the Metepec landfill: Implications for solid waste management," *Int. J. Environ. Impacts.*, vol. 9, no. 1, pp. 318–325, 2026. <https://doi.org/10.56578/ije090123>.



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**Abstract:** Groundwater contamination, exacerbated by improper solid waste disposal, is a critical environmental problem, especially in regions such as the Toluca Valley, where water supply depends on aquifers. This study quantified leachate generation at the Metepec landfill in the State of Mexico using the Water Balance Model (WBM) and the Hydrologic Evaluation of Landfill Performance model (HELP 3). Three hydrological years (dry, average, and wet) were analyzed to represent contrasting scenarios. The results showed that leachate generation is directly related to precipitation. In dry months, infiltration represented less than 17% of annual rainfall, while in some months evapotranspiration was higher. The HELP 3 model estimated higher volumes due to the moisture generated by waste decomposition. Comparative analysis revealed that, in the absence of barriers, percolation exceeded 12% of annual precipitation. When a clay layer was implemented, infiltration was practically eliminated, and with a geomembrane it was reduced to approximately 1% of total precipitation. These results demonstrate the effectiveness of structural configurations in reducing leachate generation. The study concludes that the implementation of impermeable barriers and post-closure monitoring programs is essential to mitigate environmental impacts and protect groundwater resources.

**Keywords:** Groundwater; Percolatio; Leachate; Solid waste landfill; Water balance; Aquifer

## 1 Introduction

Environmental pollution has increased considerably in recent decades, mainly due to human activities and inadequate solid waste management. Despite scientific and technological advances, many ecosystem alterations remain irreversible or difficult to mitigate. A major concern for the scientific community is the contamination of water resources, including both surface water and groundwater [1, 2].

Groundwater is a fundamental source of water for domestic and agricultural use in many regions worldwide. Although it is generally less vulnerable to contamination than surface water, recovery after contamination is extremely difficult due to slow natural renewal processes [3].

While river water typically has a residence time of only a few days, groundwater in aquifers may remain for hundreds of years, which makes natural purification very slow [4]. Globally, the importance of groundwater is evident. In the United States, 59% of the population relies on groundwater, and in some European countries (e.g., France and Denmark) this share exceeds 70%, reaching 100% in certain areas [3]. In Mexico, annual groundwater extraction is approximately 28,000 Mm<sup>3</sup>: 71% for agriculture, 20% for urban public supply, 6% for industry, and 3% for domestic uses and drinking water [5].

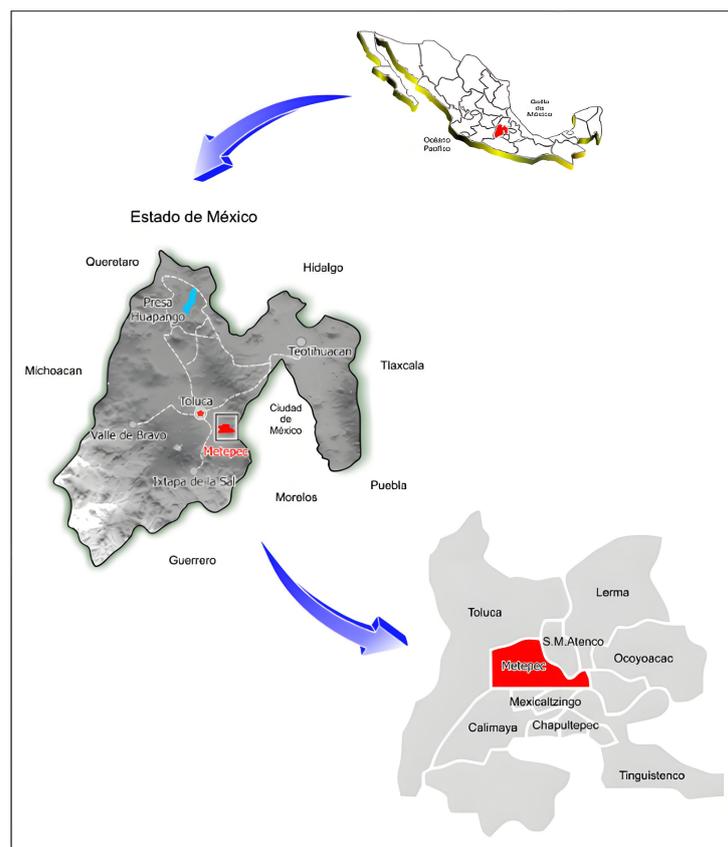
Despite its importance, aquifer contamination is a recurring problem in many parts of the world. Several studies have documented cases of point-source contamination derived from industrial activity, as well as the presence of nitrites and saline intrusion in coastal aquifers due to high concentrations of chlorides and sulfates [6]. Likewise, solid waste landfills represent a significant source of contamination, since they generate leachates from the decomposition of waste, in addition to the infiltration of precipitation or melting water [7]. These leachates, when infiltrating the

soil, can move horizontally, affecting the quality of the soil and vegetation, or vertically, reaching the aquifers and compromising the water resource [8]. The main transport mechanism for these contaminants is infiltration through the unsaturated zone, eventually reaching the aquifers [9].

Various international studies have shown that the efficiency of impermeable barriers varies according to climatic conditions and local regulations. Berger [7] evaluated the performance of the Hydrologic Evaluation of Landfill Performance model (HELP) model in multi-layer sealing systems in Europe, demonstrating leachate reductions of over 95%. Similarly, Podlasek et al. [8] documented that the implementation of hydrogeological monitoring systems in Poland and the Czech Republic allows for anticipating leaks and mitigating risks to aquifers. In contrast, in Mexico, limited application of these measures persists, highlighting the need to strengthen the regulatory framework and technical planning. This comparison highlights the gap between international and national practices and represents the importance of this study as a contribution to applied knowledge in the Mexican context.

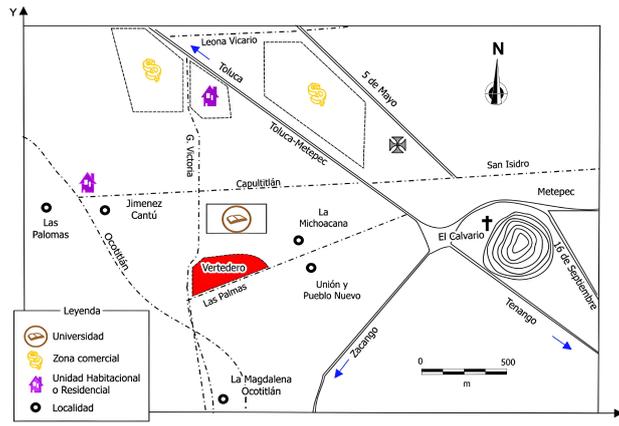
Municipal solid waste may contain hazardous constituents such as heavy metals and biological contaminants, and many landfill sites have reached or are approaching their capacity limits [10]. Since the 1970s, sanitary landfills have been implemented as a more controlled waste-disposal option [11]. Nevertheless, landfills remain a major pollution source, affecting soils, surface water, and groundwater, and contributing to gas emissions such as methane [12]. Landfill operation involves chemical and biological degradation processes, effectively turning the site into a biochemical reactor that requires adequate design to minimize leachate infiltration and reduce environmental impacts [13]. Leachate flow dynamics are influenced by factors such as waste field capacity and the distribution of underlying silt and clay lenses [14]. Therefore, reducing long-term infiltration and minimizing aquifer-contamination risks require control measures, including impermeable cover materials that enhance water retention and limit percolation [15].

In this context, this research aims to quantitatively estimate the leachate flow generated at the Metepec landfill in the State of Mexico. Figure 1 spatially locates the study area. The national and state contexts, as well as the neighboring municipalities, are also included.



**Figure 1.** Metepec, State of Mexico

Figure 2 shows the location of the Metepec landfill relative to urban areas, roads, universities, shopping centers, and residential developments. This proximity highlights the potential risk of environmental contamination. Inadequate urban planning at the time many landfills were sited has led to social and environmental problems over time. In Metepec, urban growth has expanded toward the landfill area, which conflicts with environmental regulations established by the Government of the State of Mexico through the Ministry of Ecology.



**Figure 2.** Location of the Metepec landfill, State of Mexico

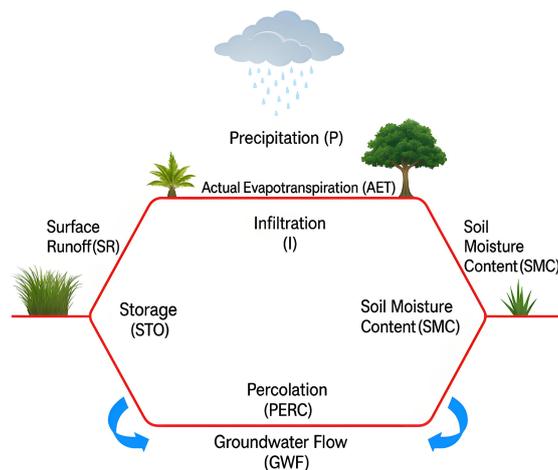
Accordingly, this study analyzes waste density, leachate accumulation, and their relationship with storage and leaching processes. Climatological, hydrological, and hydrogeological data for the region are compiled, together with a characterization of geological, geomorphological, and hydrochemical conditions [10]. Leachate infiltration is evaluated using a water-balance approach, and leachate flow is estimated using the HELP 3 model. These analyses support the development of a conceptual model of groundwater movement in the landfill area and provide a basis for management strategies that minimize environmental impacts and reduce aquifer-contamination risks [16].

## 2 Methodology and Materials

In this study, a water-balance approach and the HELP 3 model were used to estimate leachate generation at the Metepec landfill in the State of Mexico. Climatological, hydrological, and hydrogeological data were compiled, including precipitation, temperature, evaporation, and soil-sample information.

The soil samples obtained were analyzed in the laboratory to determine their physical and chemical properties. The HELP 3 model allowed for the evaluation of different leachate infiltration scenarios, taking into account climatic variability and soil conditions. Three landfill configurations were compared: untreated, with a silty clay layer, and with a geomembrane at the base.

The Water Balance Model (WBM) is based on the main moisture inputs and outputs of a system (e.g., a basin or a study area). Figure 3 summarizes the interactions among the variables considered in the WBM. The process begins with precipitation (P) over the landfill: part becomes surface runoff (ESC), part infiltrates (I), and part is lost through evaporation (E) and/or transpiration (T). A fraction is stored (S), and when the porous medium becomes saturated, gravity-driven flow produces percolation (PERC), which is interpreted as leachate. Groundwater inputs (G) may also be considered when applicable.



**Figure 3.** Water balance

The Water Balance method is represented algebraically with the following Eq. (1).

$$\text{PERC} = P - \text{AET} - \text{SR} \pm \Delta S \quad (1)$$

Percolation was analyzed for three hydrological years representing contrasting conditions: a dry year (2004–2005), a wet year (2002–2003), and an average year (1998–1999).

The HELP 3 model was used as a comparative tool because it simulates landfill hydrologic behavior by integrating climatic, soil, and design variables. Endorsed by the United States Environmental Protection Agency (USEPA), this model complements the traditional water-balance approach and improves the estimation of leachate flow under different scenarios.

Historical climate data were used as inputs, including precipitation, temperature, solar radiation, and vegetation cover. Physical properties of the landfill layers were also defined, such as material type, thickness, porosity, and permeability. The model divides the landfill profile into vertical layers (waste, cover soil, and barrier layers such as clay or geomembranes) and simulates runoff, storage, evaporation, and percolation processes.

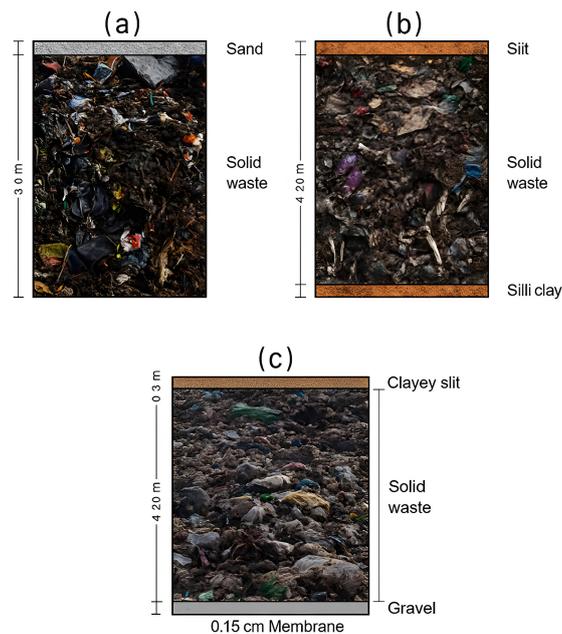
HELP 3 model parameters were defined based on prior applications and USEPA technical recommendations for sanitary landfills. For example, the geomembrane thickness (1.5 mm) was selected as a common design value that provides low permeability and adequate mechanical resistance [17]. The clay layer thickness (0.60 m) was used as a secondary barrier, consistent with literature reporting the effectiveness of composite geomembrane-clay systems in reducing leachate infiltration risks [18].

These parameters were selected based on their common application in sanitary landfills and their proven effectiveness in reducing leachate infiltration under similar hydrogeological conditions.

However, the HELP 3 model has inherent limitations, such as the assumption of homogeneous landfill layers, which may not fully represent site variability [19]. This model was selected over alternatives such as HYDRUS or MODFLOW because it has been validated in international landfill-management studies, integrates climatic, structural, and soil variables efficiently, and enables comparative simulations with relatively low computational requirements [20].

The three hydrological years analyzed (1998–1999, 2002–2003, and 2004–2005) were selected based on historical precipitation records from the National Meteorological Service (SMN). The year 1998–1999 represents average climatic conditions, 2002–2003 corresponds to a wet year with above-average precipitation, and 2004–2005 represents a dry year with significantly lower rainfall. These years were selected to represent contrasting climatic scenarios and evaluate landfill behavior under different hydrological conditions.

In this research work, different landfill design scenarios were evaluated: without a bottom barrier, with a silty clay layer, and another with a geomembrane. The model allowed comparing how these adjustments affect leachate generation and volume, providing a technical basis for improving site management and reducing the risk of contamination of the underlying aquifer. Figure 4 presents the schematic profiles of the three scenarios used to estimate percolation rates at the Metepec landfill.



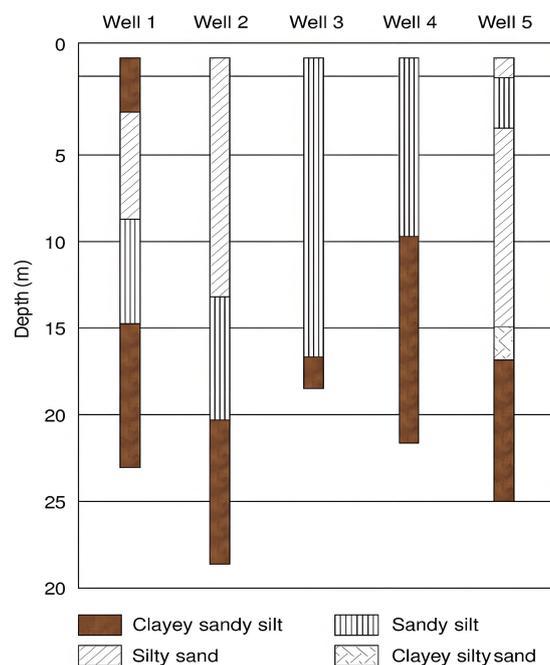
**Figure 4.** Schematic profiles: (a) status quo; (b) landfill with silty clay cover; (c) landfill with a geomembrane

Regarding the analysis of land uses, a lithology was identified on the periphery of the landfill, it is composed mainly of altered volcanic materials, silt and clay, which directly influences the water retention and infiltration capacity on the site. Figure 5 shows a soil sample taken when drilling the wells.

Figure 5 shows a soil sample obtained from monitoring wells installed in 2005 on the northern border of the Metepec landfill, where silt and clay lenses were identified in the stratigraphic profile. The lithological structure of these monitoring wells is presented in Figure 6, illustrating the stratigraphic arrangement of the materials and their influence on leachate movement. These strata directly influence moisture retention and reduce infiltration capacity, which explains the localized accumulation of leachate even in the absence of artificial barriers and represents a potential risk to the quality of the underlying aquifer. Thus, the geological evidence complements the results of the WBM and HELP 3 models by showing how the stratigraphic basis determines the percolation dynamics observed in the evaluated scenarios. This condition underscores the need to implement post-operational monitoring and control measures at the site to preserve water resource quality and mitigate negative environmental impacts.



**Figure 5.** Photo of the soil sample obtained



**Figure 6.** Lithological profile of the wells

The study’s findings underscore the need to optimize landfill cover and sealing systems, as well as to implement comprehensive models that consider local hydrogeological characteristics to reduce the risk of impacts on groundwater resources.

### 3 Results and Discussion

The results showed that leachate generation is directly related to precipitation, and that in dry months, infiltration accounted for less than 17% of annual precipitation. Furthermore, actual evapotranspiration occasionally exceeded infiltration, suggesting that part of the percolated water corresponds to leachate from waste. Table 1 presents a summary of the results estimated by the WBM for the three hydrological years studied.

**Table 1.** Annual mean parameters

Period	Precipitation (mm)	Runoff (mm)	Infiltration (mm)	Actual Evapotranspiration (mm)	Percolation (mm)
1998–1999	861	146	715	508	187
2002–2003	1058	180	878	551	301
2004–2005	740	125	615	511	84

The WBM showed percolation in the three hydrological years analyzed, although in the dry year it represented less than 12% of the annual precipitation.

The HELP 3 model produced higher values due to the additional moisture generated by organic waste decomposition. Table 2 summarizes the annual hydrological values obtained for the dry year under the three landfill scenarios evaluated with the HELP 3 model. Three scenarios were evaluated: (1) landfill without bottom treatment and a sand cover, (2) landfill with a silty clay layer, and (3) landfill with a geomembrane barrier.

**Table 2.** Annual values obtained for the dry year in the three scenarios with the Hydrologic Evaluation of Landfill Performance (HELP 3) model in an untreated landfill

Parameters	Status Quo (mm)	Status Quo (%)	Silt-Covered Landfill (mm)	Silt-Covered Landfill (%)	Membrane Landfill (mm)	Membrane Landfill (%)
Precipitation	740	100	740	100	740	100
Runoff	7.4	1	26	4	348	47
Evapotranspiration	644	87	714	97	392	53
Lateral Drainage	–	–	–	–	0	0
Percolation	89	12	0	0	0	0
Storage	0	0.03	0	0	0	0

The results indicate that protective barriers significantly reduce leachate percolation and therefore decrease the potential risk of groundwater contamination. The most favorable scenario was the geomembrane configuration, which reduced leachate percolation to approximately 1% of total precipitation.

This information is consistent with international studies. Al-Hashimi et al. [15] reported that the implementation of geomembranes in European landfills reduced leachate percolation by between 1% and 3% of total precipitation, while Sinnathamby et al. [12] documented similar efficiencies in cover systems under climate change scenarios in the United Kingdom. Similarly, Podlasek et al. [8] noted that the combination of geomembranes with hydrogeological monitoring programs in Poland and the Czech Republic has effectively controlled infiltration into aquifers. These results reaffirm that the behavior observed in Metepec aligns with international experiences and validates the relevance of using impermeable barriers as a mitigation strategy. Table 3 presents the comparative results obtained from the WBM and HELP 3 models for the three hydrological years analyzed.

**Table 3.** Comparative data of the two models in the three years of study and without treatment

Period	Precipitation (mm)	Actual Evapotranspiration (mm)	Actual Evapotranspiration (%)	HELP 3		WBM	
				Percolation (mm)	Percolation (%)	Percolation (mm)	Percolation (%)
1998–1999	861	525	62	336	38	201	23
2002–2003	1058	649	61	400	39	308	29
2004–2005	740	644	87	89	12	103	14

However, long-term implications must be considered. While the geomembrane scenario showed the greatest leachate reduction, its performance could be affected under extreme rainfall conditions, climate change-related phenomena, or the progressive deterioration of the material. The literature has indicated that, in the event of structural failures or extraordinary events, percolation rates can increase significantly [13, 15]. Therefore, it is essential to complement the technical design with post-operational monitoring plans and maintenance strategies that ensure the durability of the barriers and guarantee the long-term protection of the underlying aquifer.

In terms of practical feasibility, the implementation of impermeable barriers such as compacted clays or geomembranes entails costs that can be high for municipalities with limited resources. However, evidence of a significant reduction in leachate percolation justifies the investment in terms of protecting public health and water

resources. In Mexico, where many final disposal sites operate without adequate infrastructure, the main challenge lies in the lack of funding and mandatory technical guidelines for all municipalities.

Therefore, it is essential that public policies consider not only the mandatory use of impermeable barriers in new landfills, but also the integration of post-operational hydrogeological monitoring programs into national regulations, as a complement to NOM-083-SEMARNAT-2003. These actions would allow for the timely detection of potential leaks and ensure the sustainability of final disposal sites. Likewise, it is recommended that financing and inter-municipal cooperation schemes be designed to facilitate the implementation of these measures in regions with limited economic capacity.

#### 4 Conclusions

The study highlights the importance of quantifying and controlling leachate generation in solid waste landfills, particularly in contexts such as the municipality of Metepec, State of Mexico, where the landfill operated without adequate infrastructure. The research found that leachate production is strongly influenced by precipitation and the physical characteristics of the soil and solid waste. The use of WBM and the HELP 3 model allowed for a more accurate estimate of the volumes generated under different climatic and structural scenarios. The results indicated that improving landfill conditions with impermeable layers, such as clay or geomembranes, significantly reduces percolation and thus the risk of contamination of the underlying aquifer. It is concluded that proper site selection, adequate technical design, and post-closure monitoring are essential for environmentally responsible management. Likewise, it is recommended to continue with hydrogeological monitoring and promote public policies that strengthen the planning and control of final disposal sites, guaranteeing the protection of water resources and public health.

#### Author Contributions

Conceptualization, A.C.B. and H.J.R., methodology, A.C.B. and J.G., software, A.C.B. and J.G., validation, A.C.B., H.J.R., and J.G., formal analysis, A.C.B., investigation, A.C.B., resources, A.C.B. and J.G., data curation, A.C.B., writing—original draft preparation, A.C.B., writing—review and editing, A.C.B., H.R., S.P., and J.G., visualization, A.C.B., supervision, J.G., H.J.R., H.R., and S.P., project administration, A.C.B. All authors have read and agreed to the published version of the manuscript.

#### Acknowledgement

Special thanks to the Inter-American Institute of Water Sciences and Technology for the academic, technical, and logistical support provided throughout the research.

Special thanks to the University of Guadalajara for its technical and infrastructural support. The authors also acknowledge the valuable collaboration of the students and professors of the Master's programs in Water Sciences and in Cities, Climate Change, and Resilience for their valuable ideas and contributions.

Finally, the authors extend their gratitude to the students and professors of the Master's programs in Water Sciences for their valuable ideas and contributions.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## Nomenclature

P	Precipitation
PERC	Percolation
ESC	Runoff
ETR	Actual evapotranspiration
$\Delta S$	Change in storage