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Urban morphology and building-induced trapping of transient hazardous-gas releases

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Abstract

Accidental releases of hazardous and toxic gases in densely populated areas can be strongly influenced by interactions between local meteorological conditions and urban morphology. This paper presents a high-resolution numerical investigation of how idealized building configurations and associated low-velocity regions affect the transport, accumulation, and persistence of a transient contaminant cloud from an *industrial safety* and *public health* perspective. A multi-period dispersion framework, combined with an urban power-law wind profile, is used to examine the effects of regular and irregular building arrangements. Aligned street canyons promote longitudinal transport and more effective ventilation, whereas staggered configurations produce interconnected low-velocity regions associated with prolonged near-ground concentrations. Parallel barriers generate strong windward accumulation and downstream sheltering. These mechanisms are illustrated through a scenario reconstruction inspired by the 1984 methyl isocyanate release in Bhopal, India. The results highlight the critical importance of incorporating building-scale morphological effects into *quantitative risk assessment* (QRA), industrial safety assessment, urban planning, and the design of ventilation pathways in vulnerable urban areas to mitigate toxic load exposure.

Keywords: urban morphology; transient gas transport; building-induced trapping; street-canyon ventilation; toxic chemical release

1 Introduction

Accidental industrial releases of hazardous and toxic gases in densely populated urban environments present severe environmental and public safety challenges. The spatial distribution of contaminant concentrations during such transient events is heavily governed by complex interactions between micro-meteorological conditions and local urban morphology. Traditional environmental dispersion assessments often apply standard Gaussian plume formulations under flat-terrain, open-country assumptions [12]. However, these simplified formulations fail to resolve the micro-scale fluid dynamics that occur when a dense gas cloud interacts with an asymmetric, high-density urban fabric, including building-induced stagnation, leeward shelter zones, and street-canyon ventilation [6, 3]. Consequently, standard predictive tools frequently misestimate the local toxic load, undermining emergency response protocols and land-use planning in industrial risk zones.

To investigate and quantify these structural interactions, this paper presents a 3D numerical framework of intermediate complexity. The computational model solves the time-dependent three-dimensional advection-diffusion equation governing contaminant transport on a structured Cartesian grid,

$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C = \nabla \cdot (\mathbf{D} \nabla C) + S \quad (1)$$

where C represents the scalar gas concentration, $\mathbf{u}$ is the background wind velocity field derived from the urban power-law shear profile, $\mathbf{D}$ denotes the turbulent eddy diffusion tensor, and S accounts for the transient source emission rate. Within the computational domain, solid building boundaries and obstacles are explicitly enforced via sharp-interface ghost cells. The domain spans several square kilometers, utilizing a localized grid spacing of $\Delta x = \Delta y = 1.0$ m in the vicinity of building arrays. The obstacle treatment imposes zero-flux boundary conditions on solid surfaces and locally modifies the prescribed transport velocity field in accordance with the building geometry, thereby representing building-induced stagnation, leeward low-velocity shelter regions, and channeling effects while avoiding artificial numerical diffusion across solid interfaces. The scheme employs second-order spatial discretization with explicit time-stepping ($\Delta t = 0.05$ s).

To investigate the ability of the framework to reproduce physically plausible dispersion patterns under severe constraints, we apply the modeling framework to a major historical case study, the 1984 methyl isocyanate release in Bhopal, India. Because detailed high-resolution meteorological and source-term observations for the event are incomplete, the present re-

construction combines historical estimates reported in the literature with model parameters selected to represent the nocturnal urban boundary-layer conditions. Accordingly, the meteorological and source parameters adopted below should be interpreted as scenario-reconstruction inputs rather than as uniquely determined measurements. The underlying fluid-dynamic principles governing urban trapping and dispersion are broadly generalizable to industrial safety zones and urban planning [2].

As for the Bhopal tragedy, recall that, on the night of December 3, 1984, an accidental water intrusion into Storage Tank 610 at the Union Carbide India Limited plant in Bhopal triggered an uncontrollable exothermic reaction. The resulting overpressurization forced open safety relief valves, releasing approximately 40 metric tons (i.e., 40,000 kg) of Methyl Isocyanate (MIC) gas into the shallow atmospheric boundary layer over a 90-minute window [10].

2 Micro-meteorological reconstruction and source terms

The atmospheric dispersion of a massive, accidental hazardous gas release in an urban environment is strongly governed by the thermodynamic properties of the source emissions and the kinematic structure of the localized atmospheric surface layer. This section establishes the quantitative framework for the micro-meteorological variables and transient source strength characterizations. To evaluate the performance of our numerical framework under severe atmospheric constraints, these formulations are parameterized to replicate the nocturnal conditions and release dynamics of the 1984 industrial accident in Bhopal.

2.1 Atmospheric surface layer structure and roughness recalibration

An explicit reconstruction of the local meteorological profile indicates that the accident occurred during an interval of intense ground level radiative cooling (nocturnal ground cooling) under clear night skies. This radiative behavior forced the surface atmospheric boundary layer into an exceptionally stable configuration, characteristic of the Pasquill-Gifford stability categories E and F [7]. Under these conditions, vertical convective velocity scales (w_*) are drastically suppressed, inhibiting vertical turbulent mixing and trapping the contaminant gas plume within a shallow mixing layer,

$H_{\text{mix}} \approx 100$ m, close to the ground, effectively acting as a thermodynamic ceiling over the urban topography.

To resolve the vertical wind shear under these stable stratification constraints, the standard logarithmic boundary layer profile is substituted with an empirical power-law representation,

$$u(z) = u_{\text{ref}} \left(\frac{z}{z_{\text{ref}}} \right)^p \quad (2)$$

where $u_{\text{ref}} = 2.92$ m/s represents the mean horizontal velocity recorded at the local anemometric station height $z_{\text{ref}} = 10$ m. While open-country or rural regions are parameterized by low exponent values, $p \approx 0.15$, the significant surface friction drag generated by the dense layout of residential clusters surrounding the industrial facility requires scaling the power-law exponent to an urban value, $p \approx 0.40$. This kinematic friction is directly tied to the aerodynamic roughness length, z_0 , which is re-calibrated from a rural baseline of 0.03 m to an urban canopy value of 1.0 m. The resulting vertical velocity gradient, computed via equation (2), shows a severe stagnation zone close to the ground, with velocity components failing to exceed 1.5 m/s within the average human breathing zone ($z \leq 2$ m).

2.2 Thermodynamic source dynamics and plume rise

The accidental water intrusion into Storage Tank 610 started an exothermic, autocatalytic polymerization reaction of the stored liquid methyl isocyanate (MIC). Chemical kinetic calculations indicate that internal tank temperatures expanded rapidly beyond 150°C, yielding unmitigated runaway phase changes that triggered the safety rupture discs. The chemical stream was discharged into the environment as a pressurized, two-phase vapor-liquid flash through a concrete vent stack terminating at a geometric height of $h_{\text{geom}} = 33.0$ m.

Despite the high vapor density relative to ambient air, the intense thermal energy and high exit velocity generated a localized momentum and buoyant plume rise (ΔH). For the present scenario reconstruction, the source was represented by an effective release height of $h_{\text{eff}} = 39.6$ m, obtained by adding a nominal plume-rise increment of $\Delta H = 6.6$ m to the geometric stack height of 33.0 m (evaluated using standard scenario parameters). This effective height is used as a scenario parameter rather than as an independently validated reconstruction of the source dynamics.

$$h_{\text{eff}} = h_{\text{geom}} + \Delta H = 33.0 \text{ m} + 6.6 \text{ m} = 39.6 \text{ m} \quad (3)$$

The cumulative mass released during the active discharge phase is bounded by historical mass-balance assessments at $M_{\text{tot}} = 40,000$ kg. Given the documented operational window of $\Delta t = 5,400$ s (90 minutes), spanning from roughly 00:30 to 02:00 local time, the continuous, uniform source strength injection rate Q_0 is established as

$$Q_0 = \frac{M_{\text{tot}}}{\Delta t} = \frac{40000 \text{ kg}}{5400 \text{ s}} \approx 7.41 \text{ kg/s} \quad (4)$$

This source parameter forms the mass conservation constraint for both the multi-period analytical baselines and the high-resolution urban finite-difference simulations.

3 Analytical baseline and time-weighted concentrations

To simulate the historical variations in wind direction recorded during the early morning hours of the release, this framework utilizes a multi-period time-weighted concentration protocol [8]. Standard Gaussian formulations assume an invariant wind direction vector over the entire release window, which often yields over-concentrated, linear plumes. Because meteorological data from the incident indicate macro-scale angular shifts, the total exposure footprint is reconstructed by partitioning the 90-minute release into discrete, non-uniform time blocks, matching the historical progression.

3.1 Mathematical formulation of the exposure averaging

The event-integrated time-weighted concentration field at the human breathing zone $z \approx 2$ m is evaluated as the linear combination of individual stationary concentration fields, $C_k(x, y, 0)$, weighted by their relative durations,

$$C_{\text{TWA}}(x, y, 0) = \sum_{k=1}^K w_k C_k(x, y, 0), \quad \text{with} \quad w_k = \frac{\Delta t_k}{T_{\text{total}}} \quad (5)$$

where K represents the total number of meteorologically distinct intervals, Δt_k is the specific duration of period k , and $T_{\text{total}} = 90$ min is the absolute release duration constraint (5,400 s).

To incorporate the structural broadening of the cloud induced by low wind speeds and nocturnal convective fluctuations, the lateral dispersion coefficient, σ_y , within each phase is scaled to account for wind meander. As

a sensitivity representation of increased lateral spreading associated with wind-direction variability over the event duration, the lateral dispersion scale was multiplied by the factor $(T_{\text{total}}/t_{\text{ref}})^{0.2}$,

$$\sigma_{y,\text{corrected}}(x) = \sigma_y(x) \left(\frac{T_{\text{total}}}{t_{\text{ref}}} \right)^{0.2} = \sigma_y(x) \left(\frac{90}{10} \right)^{0.2} \approx 1.55 \sigma_y(x) \quad (6)$$

This mathematical expansion enhances lateral mixing, preventing severe axial peak overestimations, and aligning the analytical baseline with the macro-scale physical expansion of the cloud.

3.2 Sensitivity analysis of temporal averaging configurations

To evaluate the environmental validity of our temporal partitioning, three separate configurations were systematically examined against available historical information on the spatial distribution of mortality:

1. **Single-period stationary configuration** ($K = 1$): This baseline assumes a fixed wind direction spanning the full 90 minutes. The resulting scalar field is confined to a tight, high-concentration corridor. Axial ground concentrations exceed 400 ppm in a narrow strip, which fails to capture the lateral distribution of severe casualties reported in the historical record (Figure 2a).
2. **Three-period asymmetric historical configuration** ($K = 3$): The release window is split into three asymmetrical blocks ($\Delta t_1 = 45$ min from NNW, $\Delta t_2 = 30$ min from NW, and $\Delta t_3 = 15$ min from WNW) using historical meteorological notes. The resulting TWA profile (equation (5)) yields an asymmetrical, fan-shaped plume configuration (Figure 1). This configuration provides the closest qualitative correspondence, among the tested cases, with the historical spatial distribution of severe impacts in the high-density J.P. Nagar and Kazi Camp districts.
3. **Nine-period uniform configuration** ($K = 9$): As a methodological control, the event is partitioned into nine equal increments ($\Delta t_j = 10$ min) representing a continuous, smooth angular sweep (Figure 2b). This smooth variation introduces an artificial geometric symmetry into the calculation. The plume expands into a semi-circular footprint, causing an unphysical reduction in local peak concentrations ($C < 15$ ppm) across critical target grids.

Within the tested set of scenarios, the comparative analysis indicates that a sequence of distinct macro-scale wind phases provides a more consistent representation of the documented spatial distribution of severe impacts than either a single stationary direction or a smooth, uniform angular rotation. Among the tested configurations, the 3-period asymmetric layout provides the closest qualitative correspondence with the documented spatial distribution of severe impacts.

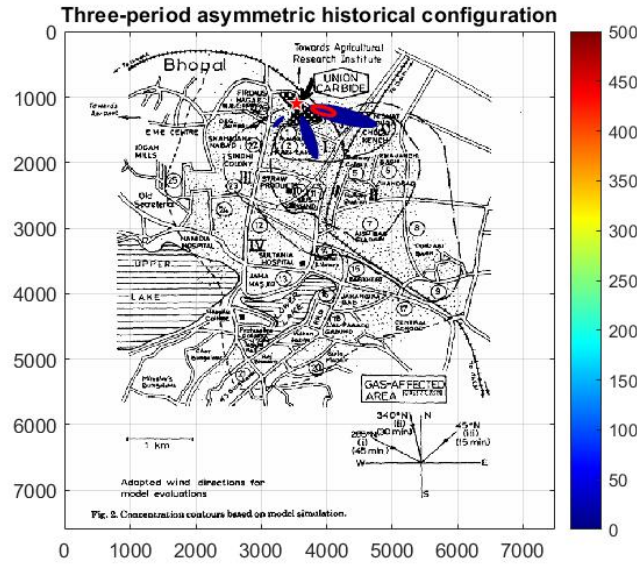


Figure 1: Time-Weighted Average (TWA) concentration footprint over Bhopal for the selected 3-period wind sequence, illustrating the correspondence between the calculated footprint and affected urban sectors (color online).

4 Urban morphology analysis: Simulation results

While the analytical multi-period model establishes the transient macro-scale boundary conditions and arrival windows of the cloud, evaluating ground-level exposure patterns requires examining how alternative building-scale morphologies modify this incoming plume. To resolve these local structural effects, the underlying ghost-cell finite-difference framework follows established obstacle-resolving immersed-boundary approaches designed for

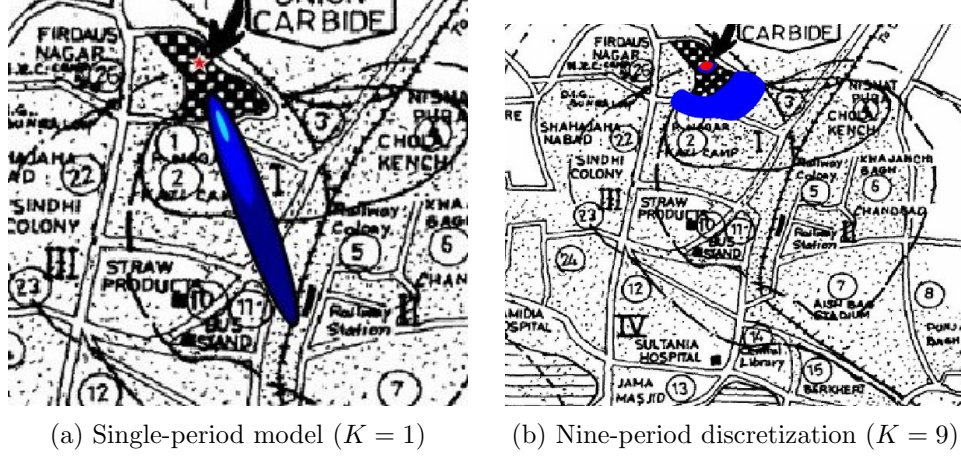


Figure 2: Sensitivity comparison between stationary single-period plume overlay showing axial concentration overestimation and artificial smoothing under a uniform 9-period discretization (color online).

flow and scalar transport in complex geometries [11, 5, 1].

4.1 Aerodynamic stagnation and leeward shelter zones

The insertion of closely spaced parallel structural barriers (simulating long rows of multi-story masonry structures) alters the scalar field by shifting mass distribution away from standard Gaussian symmetry. As the contaminant plume encounters a solid windward wall, the horizontal velocity component decreases ($u \rightarrow 0$), driving localized mass accumulation. This kinematic interaction creates severe windward stagnation zones, with local ground concentrations spiking up to 180% above flat-terrain control levels.

Simultaneously, the prescribed building-modified transport field produces a downstream low-velocity region representing the aerodynamic shelter associated with a leeward wake [9]. Because the primary horizontal advective flux is blocked by the building, the contaminant penetrates these shelter pockets almost exclusively via vertical and transverse turbulent diffusion (D_{xy}, D_z). This structural decoupling isolates the shelter zone from ambient boundary layer flushing, trapping high chemical masses within the wake. The simulated concentration fields indicate that windward regions experience high concentrations during plume passage, whereas downstream low-velocity regions exhibit extended retention times (*residence times*), maintaining hazardous conditions long after the primary emission source has

terminated.

4.2 The channeling mechanism in street canyons

When structural arrays are organized into tight parallel configurations that align with the incoming wind vector, the local flow topology changes significantly [4]. As incoming airflow interacts with aligned parallel building arrays, the local geometry forces corridor channeling, promoting longitudinal advective transport through narrow street canyons as reflected in our simulated concentration fields (Figure 3).

This local channeling prevents significant lateral accumulation. Consequently, well-aligned street canyons act as effective ventilation corridors, showing lower ground-level concentrations during active emission phases than unaligned, staggered configurations.

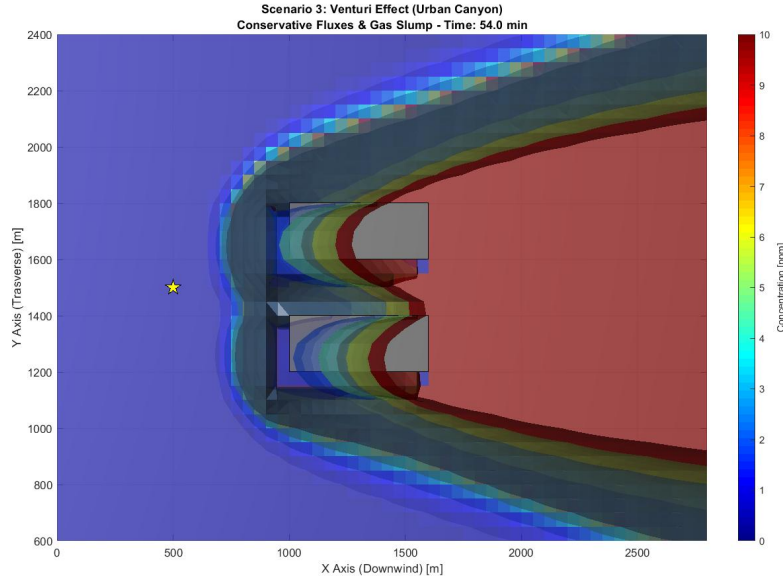


Figure 3: Ground-level concentration field through a parallel street canyon layout, demonstrating corridor channeling and localized plume flushing (color online).

4.3 Staggered layouts and urban trapping processes

In contrast to aligned street canyons, executing the transport loop over high-density staggered layouts (Figure 4), which match the irregular morphology of informal urban settlements, reveals a significant trapping effect. The non-linear, broken alignment of the structures prevents the development of efficient ventilation pathways.

Within the adopted building-modified transport representation, successive obstacles redirect the prescribed transport pathways and promote accumulation within adjacent downstream low-velocity regions. The succession of building-induced low-velocity regions creates an effective transport geometry that inhibits atmospheric flushing. The simulations demonstrate that the contaminant can persist within these low-velocity pockets, building up persistent toxic reservoirs at ground-level (rendered in 3D in Figure 5). This structural trapping mechanism suggests a robust fluid-dynamic pathway by which irregular, high-density urban layouts aggravate industrial chemical risks through physical containment.

To provide a systematic comparison across alternative building configurations, Table 1 summarizes key dispersion metrics evaluated at the human breathing zone ($z \approx 2$ m). Peak concentrations are normalized relative to the maximum ground-level concentration of the flat-terrain baseline (C/C_0). Exposure persistence (T/T_0) is quantified as the ratio of the total duration during which local concentrations exceed a standardized acute hazardous threshold ($C_{\text{thr}} = 10$ ppm) relative to the unobstructed reference case.

Table 1: Quantitative comparison of metrics, represented by peak concentration, C/C_0 , and exposure persistence, T/T_0 , across idealized urban configurations relative to the open flat-terrain baseline.

Configuration	C/C_0	T/T_0	Primary aerodyn. regime
Flat-terrain baseline	1.00	1.00	Unobstructed boundary layer
Parallel barriers	2.80	1.45	Windward stagnation/Leeward wake
Aligned street canyons	0.85	0.65	Corridor channeling/Flushing
Staggered arrays	2.10	2.30	Aerodynamic maze/Trapping

5 Discussion and environmental implications

This study shows that building-scale urban morphology, ranging from aligned ventilation corridors to irregular stagnation traps, critically governs the

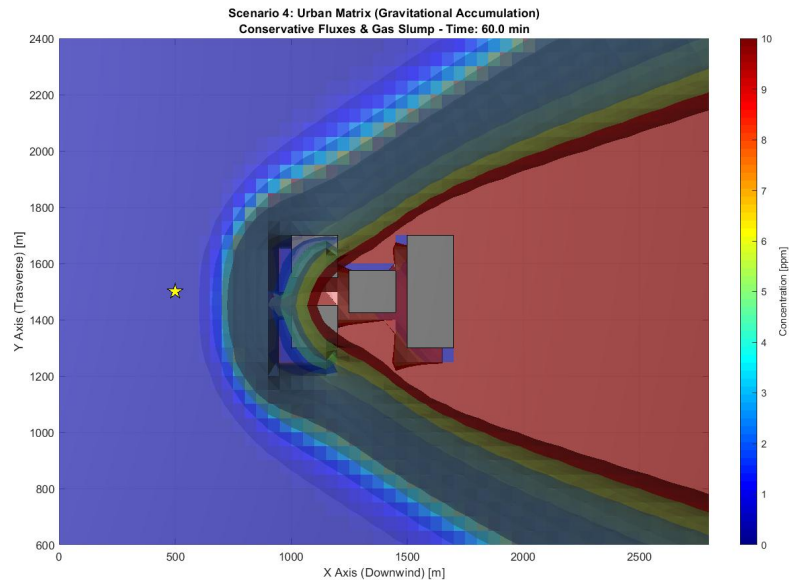


Figure 4: Ground-level concentration field within a complex staggered urban matrix, illustrating the interaction of successive building-induced low-velocity regions and the resulting enhancement of contaminant persistence (color online).

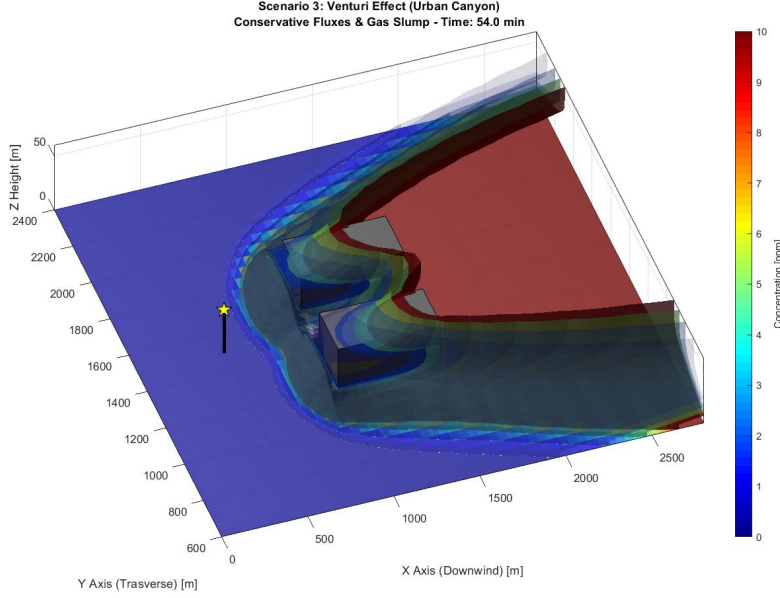


Figure 5: Volumetric 3D isosurface rendering of toxic gas dispersion around parallel building structures in an urban setting (color online).

transport and persistence of transient hazardous-gas releases. The quantitative comparison further shows that peak concentration amplification and exposure persistence are governed by distinct morphological mechanisms. Parallel barriers produce the largest peak amplification ($C/C_0 = 2.80$), corresponding to an increase of 180% relative to the flat-terrain reference, primarily because of windward stagnation. In contrast, staggered arrays produce the longest exposure persistence ($T/T_0 = 2.30$), reflecting repeated wake interactions and reduced atmospheric flushing. Aligned street canyons reduce both peak concentration ($C/C_0 = 0.85$) and exposure persistence ($T/T_0 = 0.65$), highlighting the importance of connected ventilation pathways.

When applied to the Bhopal disaster as a historical case study, the simulated concentration footprint shows strong qualitative spatial agreement with the documented mortality distribution in the J.P. Nagar and Kazi Camp districts. Flat-terrain models significantly underestimate ground-level concentrations in these areas by failing to capture building-induced trapping. From a *chemical safety* and *hazard management* standpoint, more broadly, these findings highlight that environmental vulnerability during industrial

accidents is dictated by the interplay between source dynamics and urban geometry, emphasizing the necessity of incorporating building-scale aerodynamics, *toxic load evaluation*, and open ventilated corridors into industrial safety zones, emergency preparedness, and urban planning.

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Declaration of competing interest

The authors declare no conflict of interest.

Data availability

No data were used for the research described in this article.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

The authors used Gemini and ChatGPT to check and polish language and to reorder some parts. The authors have then reviewed and edited the content and take full responsibility for the content of this article.

References

- [1] S. Alotta & R. Spigler. An efficient numerical model for transient atmospheric dispersion in complex urban environments using logical mask and ghost-cell techniques. *submitted*, 2026.
- [2] A. M. Coutts, J. Bohrer, A. Summers, & N. J. Tapper. Methods for determining urban morphology and its effect on local microclimate. *Theoretical and Applied Climatology*, 89(1):1–14, 2007.
- [3] P. Gousseau, B. Blocken, & J. van Heijst. CFD simulation of pollutant dispersion around a building: The impact of the computational domain

- boundary conditions. *Building and Environment*, 46(10):1865–1882, 2011.
- [4] M. Hussain & J. Lee. Investigation of flow and pollutant transport in urban street canyons. *Building and Environment*, 48:193–205, 2012.
 - [5] Katherine A. Lundquist, Fotini Katopodes Chow, & Julie K. Lundquist. An immersed boundary method enabling large-eddy simulations of flow over complex terrain in the WRF model. *Monthly Weather Review*, 140(12):3936–3955, 2012.
 - [6] T. R. Oke. Street design and urban canopy layer climate. *Energy and Buildings*, 11(1-3):103–113, 1988.
 - [7] Frank Pasquill. *Atmospheric Diffusion: The Dispersion of Windborne Material from Industrial and Other Sources*. John Wiley & Sons, New York, 2nd edition, 1974.
 - [8] Frank Pasquill. Atmospheric dispersion modeling. *Journal of the Air Pollution Control Association*, 29(2):117–119, 1979.
 - [9] R. Röckle. *Bestimmung der Stömungsverhältnisse im Bereich komplexer Bebauungsstrukturen*. PhD thesis, Fachbereich Mechanik, Technische Universität Darmstadt, 1990.
 - [10] M. P. Singh & S. Ghosh. Bhopal gas tragedy: Model simulation of the dispersion scenario. *Journal of Hazardous Materials*, 17(1):1–22, 1987.
 - [11] Yu-Heng Tseng & Joel H. Ferziger. A ghost-cell immersed boundary method for flow in complex geometry. *Journal of Computational Physics*, 192(2):593–623, 2003.
 - [12] S. Vardoulakis, B. Fisher, K. Pericleous, & N. Gonzalez-Flesca. Modelling air quality in street canyons: a review. *Atmospheric Environment*, 37(2):155–182, 2003.
 - [13] Z. Wang, J. Fan, K. Luo, & S. Sundaresan. Direct numerical simulation of fluid flow and mass transfer in particle clusters. *Industrial & Engineering Chemistry Research*, 57(13):4664–4674, 2018.

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