

A Lightweight Configurable Brownout Susceptibility Model for VTOL Operations

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Abstract

Brownout—dust plume raised by rotor downwash during landing and hover—can rapidly reduce visibility and increase vehicle take-off and landing (VTOL) operational risk. We present a lightweight, configuration-driven workflow that maps brownout susceptibility from Earth observation (EO) products and a digital elevation model (DEM) using a threshold concept. The risk increases when the rotor-induced shear stress surpasses the local entrainment threshold specific to each location. Spatial variability is driven by soil moisture, vegetation (NDVI), and DEM-derived roughness, while uncertainty is propagated per pixel via Monte Carlo sampling ($N=200$) to produce probability raster $P(\text{brownout})$ and margin diagnostics. In an approximately 400 km² study area in Czechia, the reference scenario ($\alpha = 0.05$) yields a mean brownout probability of 0.31, with 28 % of the area exceeding the probability of 0.5. Monte Carlo method poses approach where increasing alpha (from 0.04 to 0.06) expands the area of hazardous zones which enable rapid scenario comparison and prioritization of possible landing zones.

Keywords: brownout, remote sensing, risk mapping, Monte Carlo method

Introduction

Brownout is an operationally critical phenomenon observed during landing, take-off, or hover over dusty terrain, when rotor downwash and recirculating flow in ground effect entrain surface particles and generate an obscuring dust cloud. A North Atlantic Treaty Organization (NATO) technical report documents the associated safety impacts (loss of visual references, degraded decision-making), reviews mitigation measures, and emphasizes the role of human factors (NATO, 2012). From a physical perspective, brownout can be viewed as a cascade of coupled processes:

- rotor-induced flow near the ground (ground effect),
- particle entrainment and transport, and
- visual obscuration.

Experimental and numerical investigations of rotor downwash indicate that the spatial distribution of velocities and vortex structures in ground effect is a key driver of entrainment (Wadcock et al., 2008).

High-fidelity brownout modelling commonly relies on Eulerian frameworks or Computational Fluid Dynamics / Discrete Element Method (CFD–DEM) model approaches, which are well suited for mechanistic understanding, validation, and design studies; however, they are less practical for rapid, large-area screening and are often computationally and financially demanding (Phillips C. & Brown R. E., 2009; Cao Y et al., 2021). Therefore, a susceptibility-mapping approach based on a threshold formulation of entrainment can be employed, where spatial variability is captured through remotely sensed surface parameters.

Data and study area

We propose a configuration-driven workflow for operational brownout susceptibility mapping. Its viability is demonstrated in a 400 km² area in Czechia surrounding the Dukovany Nuclear Power Plant, situated on the boundary between the Vysočina and South Moravian regions and centred at UTM Zone 33 coordinates $E = 590,700$ m and $N = 5,437,100$ m.

Input layers were chosen to capture three surface properties controlling dust entrainment—surface moisture, vegetation cover, and microrelief—which represent primary, EO-mappable controls on entrainment. **Moisture** increases inter-particle cohesion and raises the entrainment threshold (Fécan, F. et al., 1999). **Vegetation** provides surface shielding and stabilization, reducing the availability of erodible material (Engelstaedter, S. et al., 2003). **Microrelief (mainly roughness)** redistributes near-surface shear stress through sheltering and drag partitioning, lowering effective stress on exposed particles (Engelstaedter, S. et al., 2003). Other candidate predictors (e.g., soil texture/erodibility or land-cover classes) were considered but omitted to keep the workflow lightweight and transferable with consistently available gridded inputs (Xi, X. & Sokolik, I. N., 2015). Surface moisture is adopted from the Copernicus Surface Soil Moisture (SSM) product, which provides daily topsoil relative water content as percent saturation (0–100 %) at 1 km resolution (October 2014–present) (EEA, 2026). SSM is converted to a dimensionless index $\theta \in \langle 0,1 \rangle$ by $\theta = \text{SSM}/100$. Given its 1 km resolution, SSM is interpreted as a background moisture constraint. Resampling SSM to the 10 m target grid ensures raster alignment but does not introduce sub-kilometre moisture detail.

Vegetation cover is represented by Normalized Difference Vegetation Index (NDVI) as a proxy for surface shielding and stabilization, where higher NDVI generally implies fewer erodible particles. NDVI, with a resolution of 10 m, is derived from the Near-Infrared (NIR) and red bands (ESA, 2015), where bare soil values near zero and water evaluates negatives. Microrelief is derived from the Czech DMR 4G Digital Elevation Model (DEM) (5 m), produced by airborne laser scanning, with a declared vertical RMSE of ~ 0.3 m in open terrain and ~ 1.0 m in forest (ČÚZK, 2026). The higher-resolution DEM dataset (DMR 5G) was also considered, however its employment was not required given the lower resolution of the SSM (1 km) and NDVI (10 m) inputs.

Due to differences in Coordinate Reference System (CRS), resolution and extent of the input data, all layers were reprojected and resampled to a common 10 m grid (WGS 84 / UTM Zone 33N) and snapped to a reference raster to ensure pixel alignment and automation. The model is evaluated only where all inputs overlap (masked elsewhere). The time-varying layers (NDVI, SSM) are referenced to 08 Dec 2025.

Methods

The model is implemented as a configuration-driven raster workflow (Fig. 1) designed for rapid, repeatable screening rather than high-fidelity flow or particle simulation. The approach follows a threshold entrainment concept: at a given pixel x , brownout susceptibility increases when the effective rotor-induced near-surface shear is higher than the local entrainment threshold required to mobilize particles (Gillies, J. A. et al., 2010; Raffaele, L. et al., 2016). This formulation retains the core of physical logic (“rotor forcing must exceed what the surface can resist”) while remaining computationally light and transparent for sensitivity and uncertainty analysis.

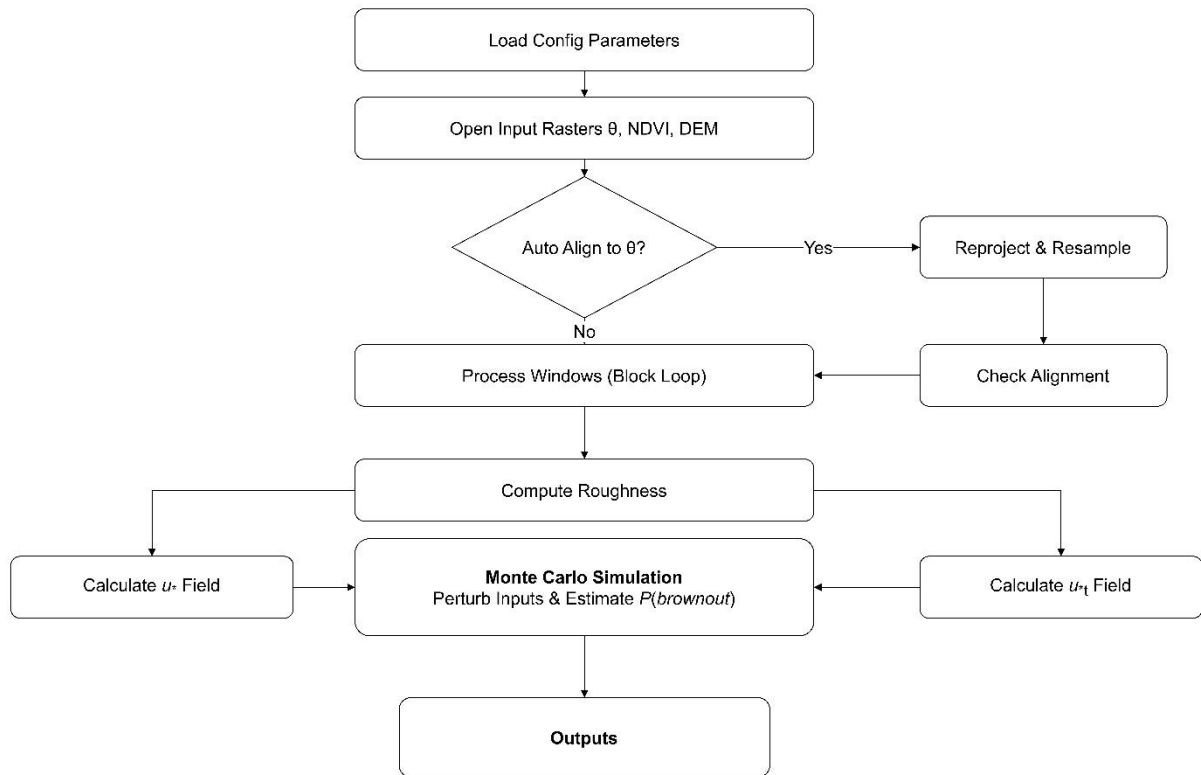


Fig. 1. Workflow of the proposed model (flowchart).

The workflow starts by loading the input raster layers (θ , NDVI, DEM) and aligning them to a common target grid. Alignment is critical because the model relies on pixel-wise operations; without strict co-registration, the estimated threshold and probability fields would be spatially inconsistent. We use the moisture layer θ as a practical alignment anchor (it is the coarsest input and defines the effective spatial scale and domain constraint). All other layers are reprojected and resampled and snapped to the reference grid; computations are performed in processing windows (block loop) to handle large areas efficiently and to keep memory usage stable.

To keep the rotor component lightweight and transferable, rotor forcing is represented by a scenario-level shear proxy rather than a spatially varying CFD field. The proxy is derived from a hover (actuator-disk) approximation. Hover thrust is approximated by the aircraft weight (Bell Helicopter Textron Inc., 2004), an induced velocity through the rotor disk (NASA, 2022) is computed from thrust, air density, and rotor disk area, and near-surface outwash (Tanner P. E. et al., 2015) is represented as a scaled induced velocity that decays with height (NASA, 2022). The height dependence is captured using a simple monotonic decay function (Tanner P. E. et al., 2015) because it reproduces the expected reduction of outwash with height while avoiding geometry- and terrain-specific flow modelling that would compromise speed and configurability. To account for unresolved near-surface turbulence and rotor-ground interaction within a lightweight screening framework, we introduce a single proportionality factor α . The outwash proxy is then mapped to an entrainment-relevant friction velocity u_* using α (Jasion & Shrimpton, 2012). Within each scenario, u_* is treated as spatially constant, reflecting the intent of a fast screening tool. Rotor forcing is controlled via scenario settings, while spatial variability is introduced through the surface-dependent threshold.

The factor α aggregates unresolved effects (rotor-ground interaction, near-surface turbulence, surface material response) into one tuneable sensitivity parameter. Because α is inherently uncertain and platform- and surface-dependent, we evaluate three values $\alpha = 0.04, 0.05, 0.06$ as

a compact sensitivity bracket around a nominal mid-case ($\alpha = 0.05$). The lower value represents a more conservative mapping (weaker effective shear and smaller hazardous extent), while the higher value represents a more permissive mapping (stronger effective shear and larger hazardous extent). The $\pm 20\%$ bracket is intentionally small enough to remain plausible for scenario testing, yet large enough to produce a clearly interpretable monotonic response in both mean probability and hazardous-area fraction without collapsing the map into all-safe or all-hazardous outcomes.

The entrainment threshold $u_{*u}(\mathbf{x})$ is modelled as a spatially varying function of three EO/DEM-derived surface-state factors: moisture ($\theta(\mathbf{x})$), vegetation cover (NDVI), and micro-relief/roughness $r(\mathbf{x})$. We adopt a multiplicative structure in which each factor acts as a monotonic scaling term that increases the threshold: moisture increases inter-particle cohesion, vegetation provides shielding and stabilization, and roughness redistributes near-surface shear through sheltering/drag effects (Marticorena, B. & Bergametti, G., 1995). The multiplicative form is used because it is simple, interpretable, and well-suited for sensitivity analysis: each term can be adjusted independently in the configuration without changing the implementation.

Microrelief is represented by terrain roughness computed as the local standard deviation of elevations in a moving window (Nield, J. N. et al., 2013). Two configuration parameters are used: the window size k sets the spatial support of the roughness metric, and γ defines a quality-control threshold for valid-data coverage. With a 10 m target grid and $k=9$, the roughness summarizes variability over an approximately 90×90 m neighbourhood, which captures meaningful terrain heterogeneity without amplifying pixel-scale noise. The computation is NaN-aware: only valid cells contribute, and outputs are suppressed where the fraction of valid cells falls below a threshold γ (JCGM, 2008) to reduce edge artifacts and maintain stable estimates in partially masked areas.

Uncertainty in selected inputs (e.g., θ , NDVI) and parameters (e.g., α , reference threshold terms) is propagated per pixel using Monte Carlo simulation with 200 realizations. In each realization, perturbed inputs or parameters are used to compute the margin between rotor-induced shear u_* and the local threshold $u_{*t}(\mathbf{x})$ (JCGM, 2008). Exceedance is recorded when the margin is positive. The brownout probability $P(\text{brownout})$ is then estimated as the exceedance frequency across the N realizations (JCGM, 2008). In addition to the probability map, diagnostic raster layers of the mean margin and its dispersion are also generated, enabling to separate consistently hazardous locations from near-threshold transition zones where the result is most sensitive to changing surface conditions or parameter assumptions (JCGM, 2008).

Results and Discussion

The model was evaluated on a common target grid after harmonizing the input layers θ , NDVI, and DEM. Computations were restricted to pixels with full data overlap and valid values; out of all evaluated pixels, only 24.7 % were included. Brownout probability $P(\text{brownout})$ (Fig. 2) was estimated per pixel using Monte Carlo simulation (200 realizations), producing a continuous probability map complemented by margin diagnostics.

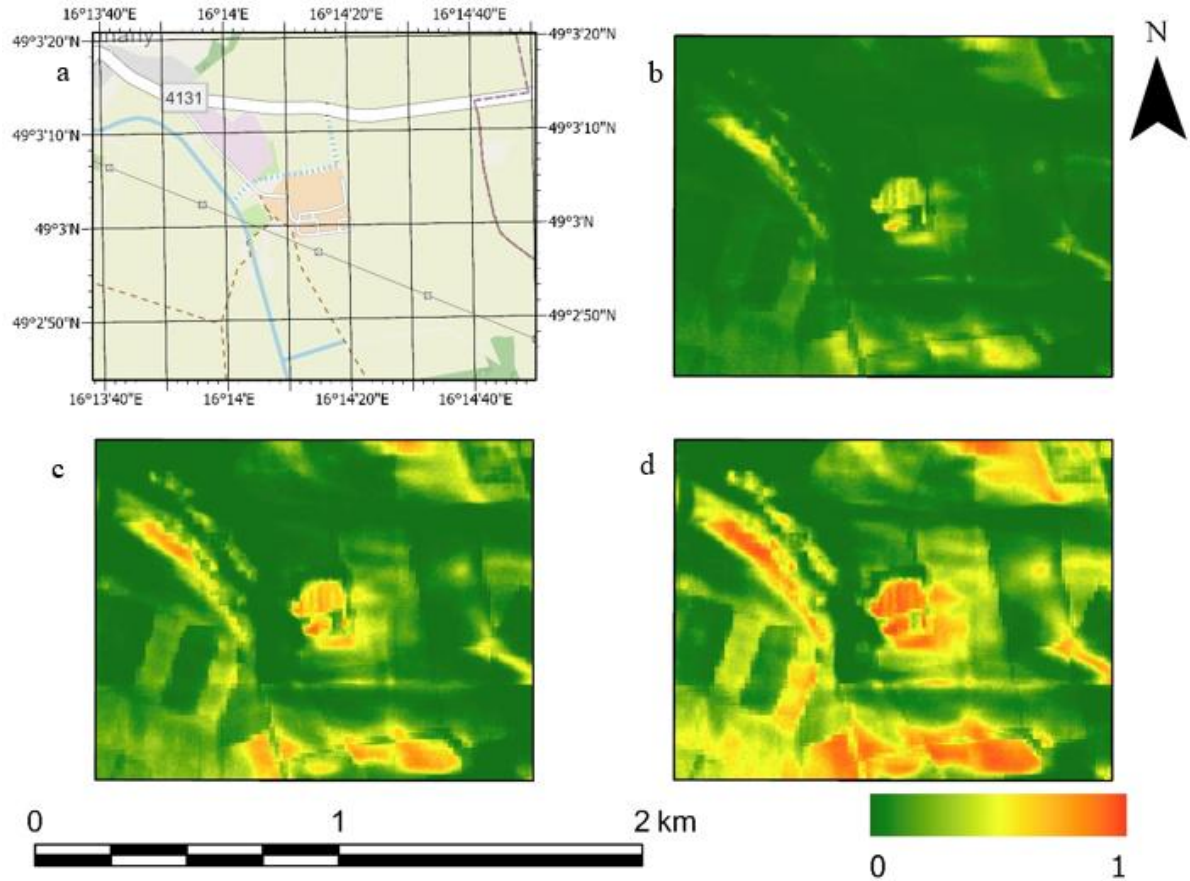


Fig. 2. Brownout hazard map for operational planning. (a) OpenStreetMap (OSM) basemap. (b–d) $P(\text{brownout})$ for $\alpha = 0.04, 0.05, 0.06$.

A key parameter is α , representing the effective conversion of rotor outwash into entrainment-relevant shear. Sensitivity analysis showed the expected monotonic response: increasing α raises both mean $P(\text{brownout})$ and the spatial extent of hazardous areas. Practically, α controls the “conservativeness” of the estimate, from stricter (smaller risk extent) to more permissive (higher shear) scenarios. Since the probability $P(\text{brownout})$ and the coefficient α are dimensionless quantities, in following text, the character $[-]$ is omitted. Summary statistics indicates strong contrast between persistently low-risk and high-risk locations without overall saturation (Table 1).

Table 1. Summary statistics of $P(\text{brownout})$ for the α sensitivity study.

α	Evaluated pixels	P_{mean}	P_{min}	P_{max}	Fraction with $P > 0.5$
0.04	3,695,095	0.18395	0.000	0.935	0.156
0.05	3,695,095	0.31224	0.000	0.985	0.280
0.06	3,695,095	0.43182	0.000	1.000	0.442

The scenario-level shear/threshold balance and the resulting margin behaviour across the three α settings shows following (Table 2):

- In the conservative scenario ($\alpha = 0.04$), the imposed rotor-forcing level is lowest, so the margin distribution remains predominantly below zero and exceedance is confined to a limited set of localized hotspots; the map is dominated by “mostly safe” conditions with only scattered areas where the threshold is robustly exceeded.

- In the reference scenario ($\alpha = 0.05$), the margin field shifts upward, producing a clearer separation between persistently non-hazardous areas and recurrent hotspots, while also expanding near-threshold transition zones where small changes in EO inputs or scenario assumptions can flip exceedance and generate intermediate probabilities.
- In the higher-forcing scenario ($\alpha = 0.06$), the upward shift is strongest: exceedance becomes more frequent and more spatially extensive, hotspots intensify, and transition zones broaden, reflecting a more permissive (less conservative) operating assumption. Across all three scenarios, the entrainment threshold field remains governed by the EO-derived surface state, so α primarily acts as a transparent scenario knob that controls overall conservativeness, while the EO inputs determine where hotspots and decision-sensitive transition zones emerge (Table 2).

Table 2. Scenario-level shear/threshold and margin diagnostics.

α	u_* (scenario shear) [m/s]	u_{*t} mean [m/s]	Margin mean [m/s]	Margin median [m/s]	Margin max [m/s]	Margin P95 [m/s]	Margin STD mean [m/s]	Margin STD median [m/s]	Margin STD P95 [m/s]
0.04	0.800	1.525	-0.715	-0.524	0.244	0.176	0.361	0.314	0.658
0.05	0.999	1.525	-0.515	-0.325	0.443	0.377	0.381	0.334	0.667
0.06	1.199	1.525	-0.315	-0.125	0.643	0.576	0.398	0.386	0.691

From a usability perspective, the output is not a site-specific, single-use map, but a configuration-driven workflow. The model can be rerun for other areas or dates by substituting input raster datasets and adjusting parameters in the configuration file, without modifying the implementation. This supports repeated assessments (e.g., “dry” vs. “wet” conditions) and rapid scenario comparisons of α for approach planning and landing-zone selection.

In operational use, $P(\text{brownout})$ provides a fast, spatially explicit screening of known or pre-selected landing sites (Kovářík, V. et al., 2025) for a given shear scenario α . It supports landing zones comparison and route or approach planning by flagging near-threshold areas where small changes in surface state can trigger dust entrainment, therefore mitigating the risk of visual reference degradation and associated accidents. The output may also inform signature considerations by indicating where dust plumes are likely, but it does not assess soil bearing capacity or sinkage.

Conclusion

We developed and demonstrated a computationally efficient probabilistic brownout susceptibility mapping model for the AH-1Z Viper based on the threshold condition $u_* > u_{*t}$ parameterized by surface moisture θ , NDVI, and DEM-derived roughness. The workflow is intended for rapid screening rather than site certification; dedicated field calibration or validation and platform-specific re-parameterization (e.g., for small UAV multirotor) remain future work. The Monte Carlo framework yields not only $P(\text{brownout})$ but also margin diagnostics and uncertainty, enabling separation of persistently hazardous locations from near-threshold transition zones. Sensitivity analysis confirms a monotonic response to α , allowing transparent scenario-based evaluation of rotor-induced shear. The main practical outcome is a fast, transferable, configuration-driven workflow applicable across areas and conditions.

Importantly, the model is intended as decision support rather than an authority. The final decision making process in the terminal landing phase remains with the aircraft commander, who must account for tactical context, crew proficiency, and real-time observations.

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