

Implications of Low-Wind Directional Variability on Sector-Based Emergency Preparedness and Response at the Proposed Uyombo Nuclear Power Plant Site, Kenya

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1. Introduction

Kenya's proposed nuclear power program requires the development of an emergency preparedness and response (EPR) framework appropriate to its national and site-specific conditions. Following the Fukushima accident, the International Atomic Energy Agency (IAEA) strengthened emergency preparedness and response (EPR) framework with greater emphasis on site-specific, hazard-informed preparedness [1]. This approach requires consideration of facility characteristics, site conditions, and factors that may influence the implementation of protective actions. In the Precautionary Action Zone (PAZ), the actions are initiated promptly because of the potential for severe consequences close to the facility and without dependence on plume direction, whereas within the Urgent Protective Action Planning Zone (UPZ), protective actions may be directed toward areas projected to be affected by the radioactive plume [1], [2].

This site-specific requirement is especially relevant to Kenya's proposed nuclear power plant on the equatorial East African coast of the western Indian Ocean, a region without operating nuclear power plants from which established site-specific EPR experience can be directly drawn. The coastal meteorological environment reflects the interaction of equatorial and western Indian Ocean circulation with the alternating Kaskazi (northeast) and Kusi (southeast) monsoons, inter-monsoon transitions, and overlapped with land-sea breeze circulation. These interacting processes produce notably different seasonal weather regimes, ranging from persistent monsoon flow to periods of weak and directionally variable winds. Because sector-based UPZ implementation depends on the projected direction of radioactive plume transport, characterization of this distinctive meteorological environment is particularly important for developing site-specific EPR arrangements for Kenya's emerging nuclear power program.

This study therefore evaluates the implications of low-wind directional variability on sector-based EPR at the proposed Uyombo nuclear power plant site in coastal Kenya. Ten years of ERA5 reanalysis data (2016–2025) [3] were screened for wind speeds below 2 m s^{-1} accompanied by wind-direction changes exceeding 90° within one hour. A representative variable-wind event was subsequently evaluated using the Radiological Assessment System for Consequence Analysis

(RASCAL) and compared with a persistent-wind case under the same source-term assumptions. The analysis examines whether severe directional variability can redistribute PAG-significant consequences across a wider angular portion of the UPZ and thereby affect the practical implementation of sector-based protective actions.

2. Methods and Results

The emergency planning zones and planning distances adopted for the analysis are summarized in Table I. The study focuses primarily on the **5–30 km UPZ**, where protective actions may be implemented according to the projected affected direction [1], [2].

Zone	Planning distance
EAB	Site-specific
PAZ	3–5 km
UPZ	5–30 km
EPd (plume)	>30 km-100k

Table I. Emergency planning zones and planning distances

2.1 Meteorological Data and Event Identification

Hourly ERA5 reanalysis data for 2016–2025 were used to characterize wind conditions at the proposed Uyombo site [3]. A low-wind, directional variability

An event was defined as an hour in which the wind speed was less than 2 m/s and the mean wind direction differed from that of the preceding hour by more than 90° . The 90° criterion was used to identify substantial directional changes capable of shifting the projected plume pathway toward different UPZ sectors.

The ten-year analysis identified 111 qualifying events, approximately 11 per year. Their occurrence showed a clear seasonal pattern, with the highest frequencies in February and March during the Kaskazi (northeast monsoon) season and in April and November during the inter-monsoon periods, as shown in Fig. 1. In contrast, no qualifying events were identified during the Kusi (southeast monsoon) season. This seasonal contrast indicates that substantial low-wind directional variability is a recurring but season-dependent meteorological feature at the site and should therefore be considered in site-specific emergency planning.

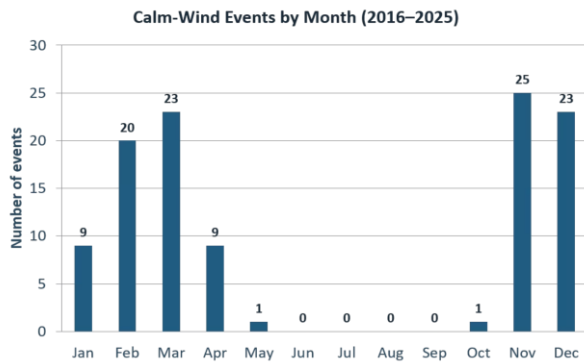


Fig. 1. Monthly distribution of low-wind directional-variability events identified from ERA5 data (2016–2025)

2.2 Atmospheric Dispersion Modeling and Results

Atmospheric dispersion was evaluated using the U.S. Nuclear Regulatory Commission's Radiological Assessment System for Consequence Analysis (RASCAL) [4]. An APR1400 reference-facility context and the RASCAL SOARCA long-term station blackout option of a generic large PWR severe-accident source term were adopted, with the source term held constant to isolate the effect of meteorological conditions. The source term was held constant to isolate meteorological effects. Low-wind directional variability was compared with a persistent-wind control at 10 m and 60 m release heights, with doses accumulated over 24 h. A 90° downwind reference sector was used for sector-based comparison[5].

Under low-wind directional variability, changes in wind direction produced successive plume pathways and PAG-relevant consequences across five UPZ sectors (N, P, Q, R, and A), as shown in Fig. 2. The accumulated angular extent was 112.5°, with secondary dose hotspots occurring along earlier plume pathways. Since RASCAL reports accumulated dose over the simulation period, this footprint represents the combined consequences of successive plume pathways rather than simultaneous plume occupation of all five sectors.

Although PAG-relevant doses in the persistent-wind case extended over substantial radial distances, their directional distribution remained confined. The main contrast between the two cases is therefore the angular distribution of the consequences, persistent wind maintained a stable transport pathway, while low-wind directional variability distributed PAG-relevant consequences across several UPZ sectors.

Release height affected dose magnitude and radial extent, but the principal difference in plume geometry remained associated with the meteorological condition

TEDE and Child Thyroid CED were used to evaluate PAG-relevant consequences. TEDE informs sheltering and evacuation, while Child Thyroid CED informs KI administration. The criteria applied were TEDE ≥ 10 mSv for sheltering, TEDE ≥ 50 mSv for evacuation, and Child Thyroid CED ≥ 50 mSv for KI administration

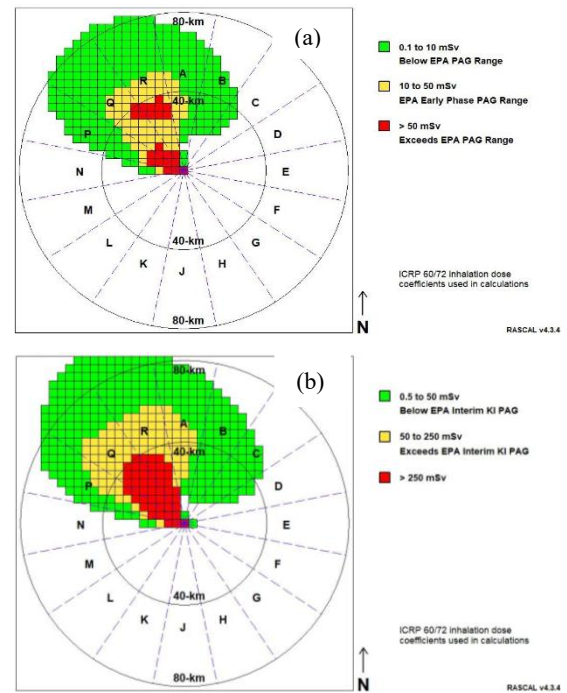


Fig. 2. RASCAL-predicted TEDE (a) and Child Thyroid CED (b) distributions under low-wind directional variability at 10 m release height.

In contrast, the persistent-wind control produced a narrower and continuous footprint along a stable downwind direction, as shown in Fig. 3.

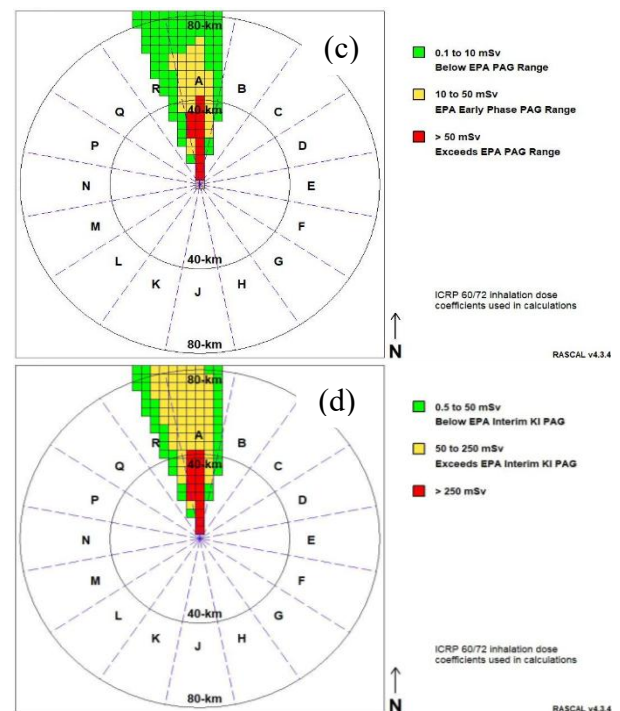


Fig. 3. RASCAL-predicted (a) TEDE and (b) Child Thyroid CED distributions under persistent-wind conditions at 10 m release height.

2.3 Implications for Sector-Based EPR

The results show that the applicability of sector-based protective actions within the UPZ depends on the prevailing meteorological condition. Under low-wind directional variability, the transport direction may not persist, and PAG-relevant consequences can extend into sectors outside the initially projected plume direction.

The operational concern is therefore not simply the width of the selected 90° protective-action sector, but whether sectors outside the initially selected area can be excluded while the plume direction is changing. A sector selected from the initial wind direction may adequately represent the plume at one stage of the release but may not cover areas affected after subsequent directional changes. This is particularly important for evacuation, which requires preparation and population movement [2].

Earlier plume pathways may leave dose hotspots while the plume shifts toward other sectors, potentially reducing the time available to prepare and implement evacuation in newly affected areas. Thus, under substantial low-wind directional variability, the principal concern is not necessarily the adequacy of the 90° sector itself, but the timely implementation of evacuation as the affected sector changes.

3. Conclusions

Ten years of ERA5 analysis identified 111 low-wind events with wind-direction changes exceeding 90° within an hour at the proposed Uyombo site, predominantly during Kaskazi and antimonsoon conditions, with none during Kusi. RASCAL showed a directionally confined plume under persistent wind but successive PAG-relevant pathways across multiple UPZ sectors under low-wind directional variability.

Under such variability, the key EPR implication is the sequencing of protective actions rather than abandonment of the 90° sector approach. Where plume migration could affect safe population movement, sheltering and KI administration may need to be prioritized before evacuation.

Importantly, even where PAG-relevant consequences affect only a small portion of an additional UPZ sector, protective action must still be considered for the population within that area. The significance of the affected area is determined by PAG exceedance, not by the proportion of the sector contaminated.

For the proposed Uyombo site, conventional sector-based implementation can therefore be maintained under persistent transport, while low-wind directional variability may require a more adaptive response as the affected sectors change with plume direction. or Kenya, these findings provide site-specific technical evidence to inform the development of EPR arrangements for the proposed nuclear power program, particularly the implementation of sector-based protective actions under

the country's equatorial coastal meteorological conditions.

These findings strengthen the importance of incorporating Kenya's site-specific equatorial coastal meteorology into EPR planning, while high-resolution on-site meteorological data will be needed to support operational implementation.

Acknowledgement

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