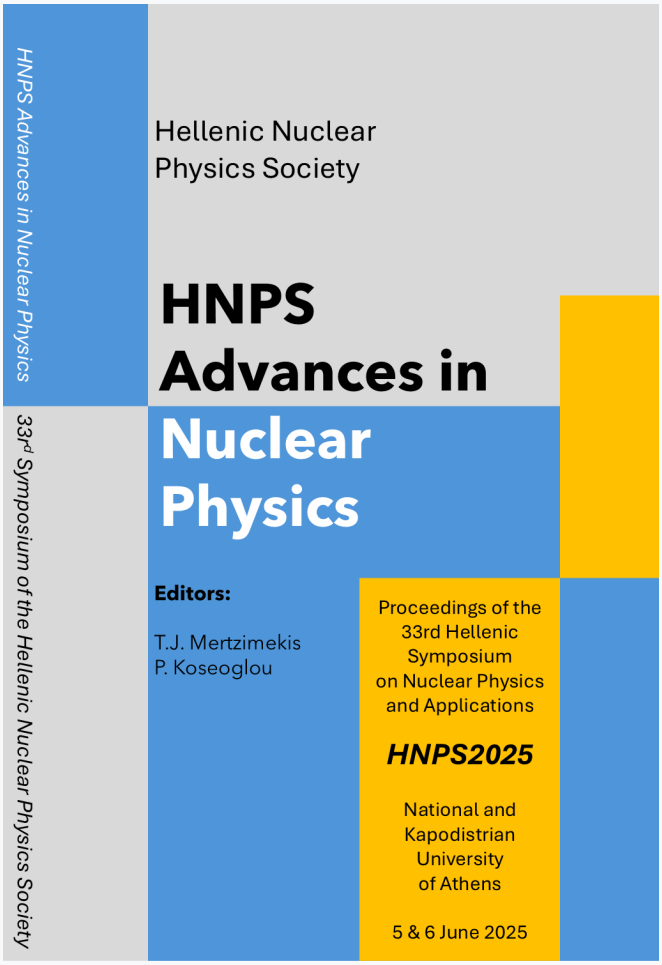
HNPS Advances in Nuclear Physics

Vol 32 (2026)

HNPS2025



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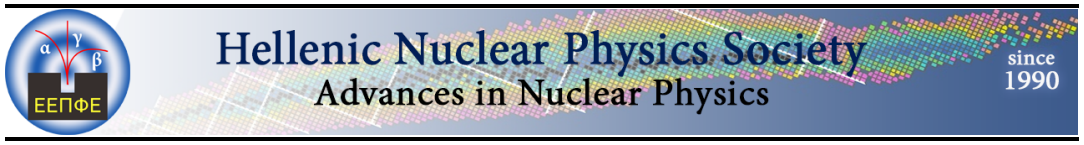
doi: 10.12681/hnpsanp.8683

To cite this article:

Karpouza, E., Gelatsoras, F. P., Siltzovalis, G., & Mertzimekis, T. J. (2026). Evaluation of Environmental Radioactivity in Thessaly after Storm Daniel: A Pilot Study. *HNPS Advances in Nuclear Physics*, *32*, 1–5. https://doi.org/10.12681/hnpsanp.8683

HNPS Advances in Nuclear Physics Vol. **32**, 1–5 (2026)
doi: 10.12681/hnpsanp.8683



ARTICLE

Evaluation of Environmental Radioactivity in Thessaly after Storm Daniel: A Pilot Study

E. Karpouza,* F.P. Gelatsoras, G. Siltzovalis, and T.J. Mertzimekis

Department of Physics, National and Kapodistrian University of Athens, GR-15784, Greece
*Corresponding author: evyenia-kar@hotmail.com

(Received: 17 Oct 2025; Accepted: 04 Nov 2025; Published: 06 Nov 2025)

Abstract
The level of radioactivity is examined in regions of Thessaly affected by disastrous floods after storm Daniel in September 2023. The purpose of this study is to map the specific radioactivity of natural isotopes (^{40}K, ^{232}Th and ^{238}U-series) and of the artificial isotope ^{137}Cs in the affected areas. Twenty surface soil samples were collected from undisturbed locations, free of agricultural or urban activity, approximately a year after the floods. Following standard sample preparation, measurements were conducted with high-resolution γ-ray spectroscopy using a High-Purity Germanium (HPGe) detector at the γSPEC laboratory of the National and Kapodistrian University of Athens (NKUA). The results are illustrated on maps, while values for the absorbed doses of ionizing radiation and the external hazard indices were calculated using UNSCEAR models.

Keywords: Storm Daniel; Environmental Radioactivity; ^{137}Cs Dispersion; Radiological Mapping

1. Introduction

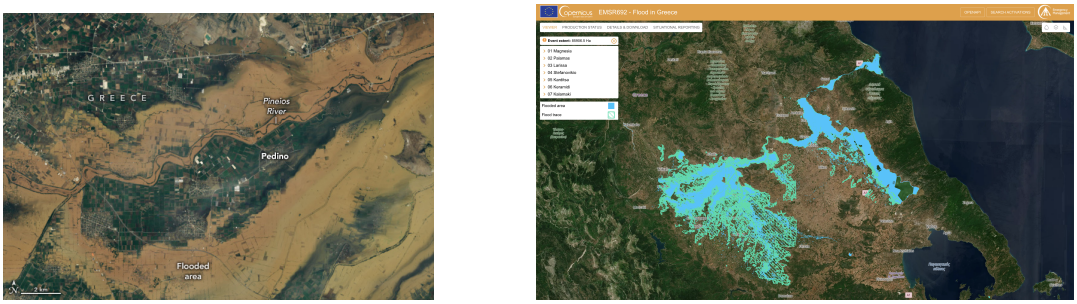
In September 2023, Storm Daniel severely affected large parts of Greece, causing extensive damages to agriculture and civic infrastructure via massive flooding [1]. The Thessaly plain in central Greece experienced exceptionally high rainfall totals, with particularly intense precipitation recorded in Larissa, Trikala, Karditsa, and the surrounding agricultural areas. The accumulated water exceeded the drainage capacity of the basin, resulting in the overflow of the Pinios River and the inundation of vast cultivated lands (Fig. 1a,1b).

The main focus of the present study is on the areas surrounding Larissa. Following the Chernobyl accident in 1986, radioactive fallout led to the deposition of various radionuclides - including the long-lived ^{137}Cs. Surveys conducted in the following years reported some of the highest residual contamination levels in regions near Kalambaka, Grevena, and adjacent uplands [2–7].

Although recent data on site-specific radioactivity levels in the region prior to Storm Daniel are limited, it is well established that ^{137}Cs can be remobilized by surface runoff [8]. Therefore, it is

 ISBN 2654-007X (print), 2654-0088 (online).

interesting to investigate the role of floodwaters contributing to the wash-off and redistribution of ^{137}Cs across the Thessaly plain by means of soil samples studied using γ-ray spectroscopy.



(a) September 8, 2023, Thessaly, Greece [9]

(b) Flooded areas after storm Daniel, Thessaly, Greece [10, 11]

Figure 1. Maps of Thessaly areas affected by Storm Daniel.

2. Materials and Methods

We collected twenty (20) surface soil samples from flood-affected sites, free of prior agricultural and urban activities (see Fig. 2a), eight (8) months after the event. Sampling was carried out during a dry period. Soil was collected from the upper 10 cm level of surface ground, where ^{137}Cs is known to be trapped [12]. Each sample weighed about 1 kg.

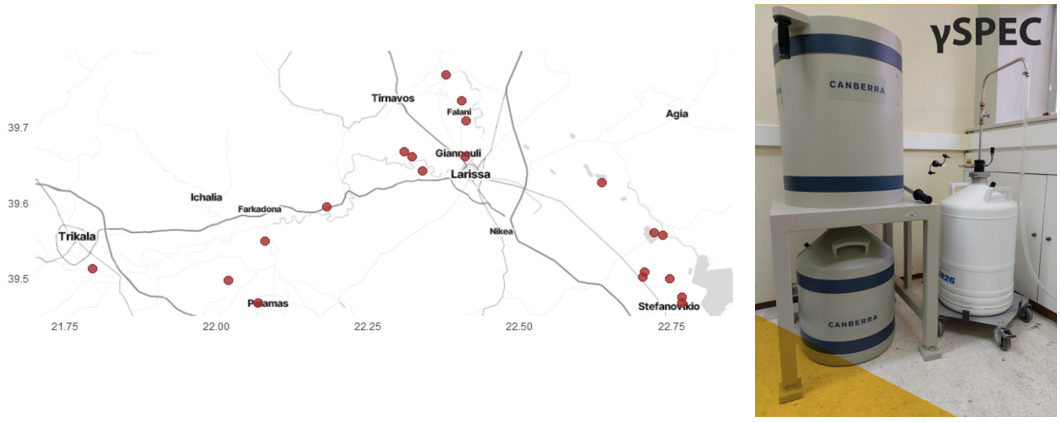


Figure 2. (a) Sampling locations (red dots) and (b) The γ-SPEC@NKUA spectrometry station.

The samples were first air-dried at ambient temperature for 24 h, then oven-dried at 60° for an additional 24 h, and cleaned of organic matter and foreign objects. They were subsequently sieved through a 2-mm mesh to obtain homogeneous soil powder, sealed in 200 ml PVC cylindrical containers, and weighed on a precision balance. Each sample had a dry mass of approximately 170-220 g. The sealed samples were left to sit for at least 3 weeks to reach radioactive equilibrium [13].

High-resolution γ-ray spectroscopy was performed with a shielded 40% High-Purity Germanium (HPGe) detector at the γSPEC Laboratory of the National and Kapodistrian University of Athens (NKUA) [14]. A picture of the station can be seen in Fig. 2b. Each sample was measured for at least

80'000 s. Spectra analysis was carried out with the SPECTRW software [15, 16]. Energy calibration and activity determination were performed using IAEA reference bulk samples prepared in the same counting geometry. The specific activity was calculated by dividing the measured activity by the corresponding sample dry mass.

3. Results

Specific activity Analysis of the photopeaks in the spectra yielded specific activities ($\mathrm{Bq\,kg^{-1}}$) for the anthropogenic isotope ^{137}Cs and the naturally occurring ^{40}K, ^{232}Th-series, and ^{238}U-series, as presented in Table 1. For ^{232}Th, the activity was derived from its daughter radionuclide ^{228}Ac at 911.2 keV, and for ^{238}U, from its daughter ^{214}Pb at 351.9 keV, respectively [13, 17].

Table 1. Specific Activities in $\mathrm{Bq\,kg^{-1}}$

Isotopes	Minimum	Maximum	Median	Std. Dev.
^{137}Cs	2.0 ± 0.2	66.0 ± 0.8	12.3	13.4
^{40}K	246 ± 5	534 ± 8	349	77
^{232}Th-series	8.7 ± 0.3	19.8 ± 0.6	12.9	3.1
^{238}U-series	6.9 ± 0.3	16.8 ± 0.4	9.0	3.0

Dosage and External Hazard Index The absorbed dose rate and the external hazard index H_{ex} for both natural (^{40}K, ^{238}U-series, ^{232}Th-series) and anthropogenic (^{137}Cs) radioactivity levels, estimated according to the UNSCEAR methodology [18], are reported. These metrics help assess whether the sampling sites meet safety criteria in terms of ambient radioactivity. Typical values for the external hazard index range between 0.1-1.

Table 2. Dose rate and external hazard index

	Minimum	Maximum	Median	Std. Dev.
Natural Dose Rate ($\mathrm{nGyh^{-1}}$)	24.1 ± 0.7	50.0 ± 1.1	33.4	6.5
Natural H_{ex}	0.19 ± 0.01	0.40 ± 0.01	0.27	0.06
Anthropogenic Dose Rate ($\mathrm{nGyh^{-1}}$)	0.25 ± 0.02	8.21 ± 0.10	1.78	1.67
Anthropogenic H_{ex}	0.0022 ± 0.0002	0.0720 ± 0.0009	0.0156	0.0147

4. Discussion and Conclusion

For the first time in Larissa, measurements of specific radioactivity levels were conducted following an extreme weather event that transformed the region. High-resolution spectroscopy results were visualized in bubble maps generated with the R programming language. Naturally occurring isotopes, including ^{40}K as shown in Fig. 4, are found within the expected range for Greek soils, as reported in previous studies [19–21]. In addition, the overall distribution is rather homogeneous. The specific activity of the manmade ^{137}Cs is elevated near Megala Kalivia (Trikala) - at 66 Bq/kg - compared to the other locations, as shown in Fig. 3, exceeding by approximately 3 times the levels measured in nearby locations 10 years ago [12].

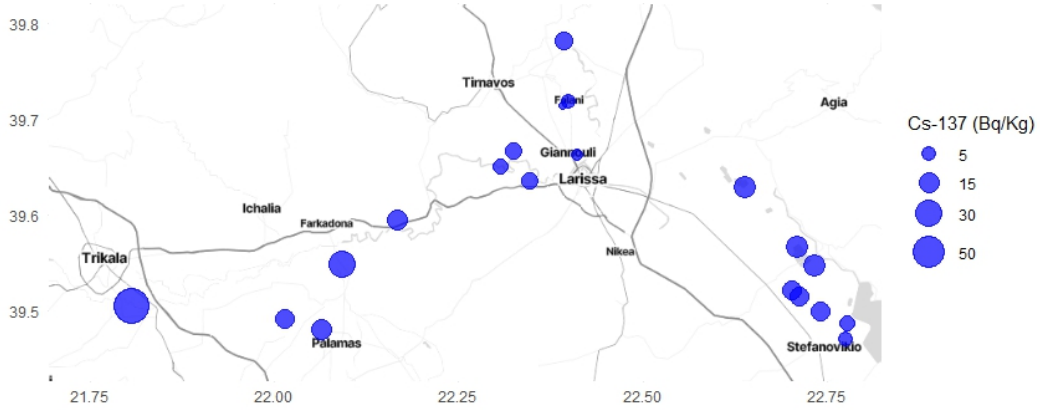


Figure 3. Specific activity levels of ^{137}Cs

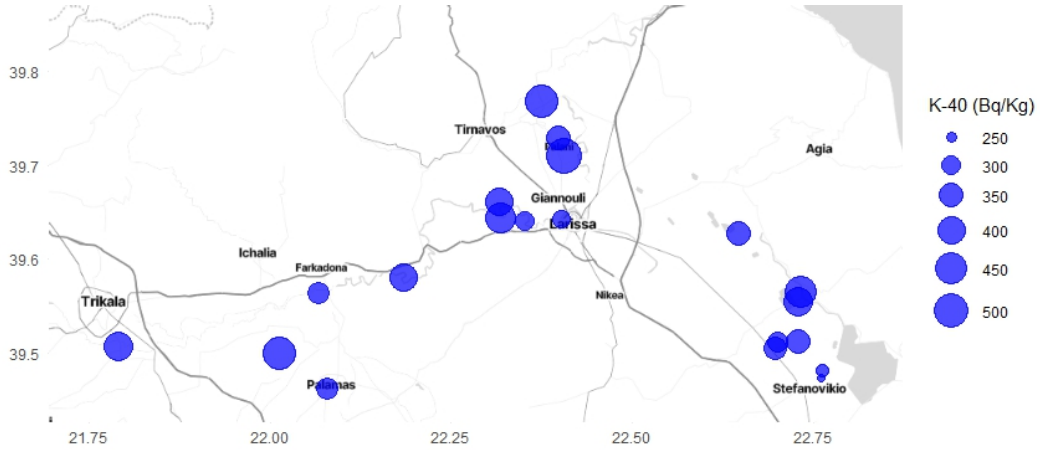


Figure 4. Specific activity levels of ^{40}K

The summary of the derived dose rates and external hazard values is presented in Table 2. The median value of dosage is slightly lower than the world average, 59nGyh^{-1} [18]. The external hazard indices, H_{ex}, are found less than 1, suggesting they remain under the recommended safety levels [22, 23].

In the near future, it is of particular interest to map the specific activities of radionuclides in the remaining flooded areas, around Karditsa and mount Pilion, where the precipitation was high [24], in order to assess the environmental impact of the extreme weather event conditions on local radioactivity levels.

Acknowledgements

We thank Prof. A. Argyraki for allowing full access to the Geochemistry Laboratory facilities at the Dept. of Geology & Geoenvironment for sample preparation.

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