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### Journal
ACS ES&T Water, 5(1)



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### Publication Date
2025-01-10

### DOI
10.1021/acsestwater.4c00891

Peer reviewed

ACS ES&T Water



pubs.acs.org/estwater Article

# Application of the DRASTIC Model to Assess the Vulnerability of Groundwater Contamination Near Zaporizhzhia Nuclear Power Plant, Ukraine

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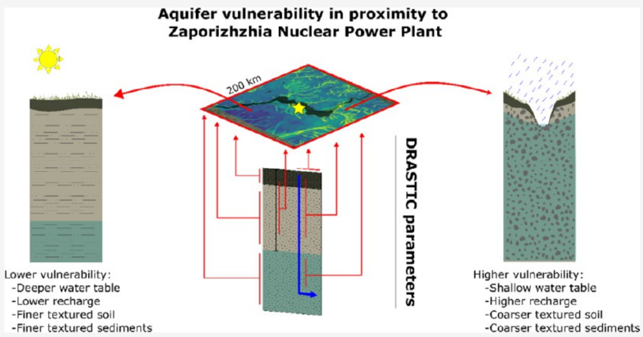
Cite This: ACS EST Water 2025, 5, 366−376






**ABSTRACT:** Russia's invasion of Ukraine continues to have a devastating effect on the well-being of Ukrainians and their environment. We evaluated a major environmental hazard caused by the war: the potential for groundwater contamination in proximity to the Zaporizhzhia Nuclear Power Plant (NPP). We quantified groundwater vulnerability with the DRASTIC index, which was originally developed by the United States Environmental Protection Agency and has been used at various locations worldwide to assess relative pollution potential. We found that there are two major gradients of groundwater vulnerability in the region: (1) broadly higher risk to the northeast of the NPP and lower risk to the southeast driven by a regional gradient in water availability and water table depth; and (2) higher risk in proximity to the channels and floodplains of the Dnipro River and tributaries, which host coarser-textured soils and sedimentary deposits. We also found that the DRASTIC vulnerability index can be used to identify and prioritize groundwater well-network monitoring. These and more detailed assessments will be necessary to prioritize monitoring and remediation strategies across Ukraine in the event of a nuclear accident, and more broadly demonstrate the utility of the DRASTIC approach for prognostic contamination risk assessment.

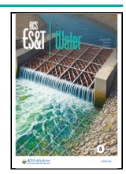
**KEYWORDS:** *radionuclide, groundwater, contaminant transport, vulnerability mapping, vadose zone, environmental hazards*

## 1. INTRODUCTION

Russia's invasion of Ukraine has negatively impacted human and environmental health,[1] with the potential to contaminate soil and water over the long-term. The potential for radioactive contamination of groundwater is of particular concern, especially in the areas surrounding nuclear power plants (NPPs). The dangers of radionuclide release and transport into the subsurface environment have been demonstrated by studies of groundwater vulnerability resulting from the Chernobyl NPP disaster in the Kyiv region of Ukraine.[2] There is clearly an urgent need to understand the current state of contamination and assess the risks associated with vulnerable nuclear facilities in Ukraine, particularly the largest nuclear power plant in Europe, the Zaporizhzhia NPP.[3] The overall objective of this work was to perform a proof-of-concept vulnerability assessment of groundwater using the DRASTIC model[4] applied to the area around the Zaporizhzhia NPP. The DRASTIC model was developed by the United States Environmental Protection Agency to assist with assessment of the pollution potential (DRASTIC vulnerability index) of any geologic or hydrogeologic setting, and has previously been applied to the region surrounding the Chernobyl NPP.[2] While our primary objective was to help inform emergency response in the event of an actual nuclear accident, we also aimed to demonstrate how the DRASTIC approach can be applied in general to gain insights about groundwater vulnerability in cases where on-the-ground data are scarce.

Ukraine is heavily reliant on nuclear energy. Before the Russian invasion of Ukraine in 2022, Ukraine operated four nuclear power plants with 15 reactors providing about 50−55% of the country's electricity needs (Figure 1).[5,6] The Zaporizhzhia NPP is the largest in Europe and is located on the southern bank of the former Kakhovka Reservoir on the Dnipro River, about 135 km southwest of Zaporizhzhia. It has six reactors and produced about half of the country's nuclear energy when it was operational. It currently stores both

Received: September 16, 2024
Revised: November 27, 2024
Accepted: December 2, 2024
Published: December 12, 2024







https://doi.org/10.1021/acsestwater.4c00891
ACS EST Water 2025, 5, 366−376


**Figure 1.** Map of Ukraine showing its nuclear power plants and the study area of 40,000 $km^2$ (shown by a dashed line) around the Zaporizhzhia NPP. Number of circles indicate the number of reactors. The acronym VVER denotes water−water energetic reactor type. Locations of NPPs were obtained from the World Nuclear Association.[6]

radioactive materials and spent nuclear fuel. The spent nuclear fuel is stored onsite in cooling pools and a dry cask storage facility. Russia's capture of the Zaporizhzhia NPP on March 4, 2022, and its current use as a military operations base has significantly raised the threat of a nuclear accident. As a result, it is vital to understand the environmental risks and impacts of contamination events here and across all of Ukraine's nuclear facilities.[3] It is important to note that the Kakhovka Reservoir water level has decreased substantially since June 2023, after its primary dam was compromised. Although the loss of the Kakhovka Dam has impacted the groundwater level depth in this area, we have no way of quantifying changes in groundwater given that the region of interest is an active war zone. The model described herein did not account for this change and assumed a stable reservoir and dam; however, we address the likely effects of a drop in the Kakhovka Reservoir water level after presenting our quantitative analysis (see Section 3).

Potential radioactive contamination of regional groundwater within the Zaporizhzhia region could result from the vertical transport of contaminants through the overlying soil and vadose zone to the water table. Different radionuclides have different mobilities; for instance, $^{137}Cs$ adsorbs strongly and is less likely to reach groundwater compared to tritium, $^{3}H$, or $^{90}Sr$. Here we avoid making specific predictions about potential radionuclide release and assume that the hypothetical risk-driving contaminant has the mobility of water. Proceeding from this assumption, we demonstrate that readily available digital information can be assembled to derive an initial assessment of groundwater vulnerability. We collected and analyzed hydrogeological, soil, and topographical data from the literature and several reports for the 40,000 $km^2$ region around the Zaporizhzhia NPP (Figure 1). These data were then used to parametrize the DRASTIC model, integrating the hydrologic and geologic features of the subsurface to identify groundwater vulnerability to contamination across this region.

The DRASTIC index has been used worldwide to evaluate the pollution potential of groundwater.[7] DRASTIC lacks the specificity of more detailed process-based or statistical modeling approaches (e.g., particle tracking models[8] or weights of evidence models[9]). However, index-based tools like DRASTIC are ideal for rapid risk assessment in situations where detailed ground measurements of hydrologic processes are scarce.[10,11] The DRASTIC index and derivative indices have been successfully validated with measured groundwater contaminant levels in groundwater; for instance, modified versions of the DRASTIC index were correlated with groundwater nitrate levels in agricultural settings in northeastern India and northeastern China.[12,13]

The DRASTIC mapping approach has three components: the designation of mappable hydrogeologic conditions (i.e., parameters), the superposition of a relative rating system associated with the characteristics of each parameter, and a weight associated with each parameter that reflects its relative importance for pollution potential. Parameters include factors that affect and control groundwater movement, including depth to the water table (D), net groundwater recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone media (I), and hydraulic conductivity of the aquifer (C). The product of each parameter rating and parameter weight is then combined to yield a numerical value called the DRASTIC vulnerability index. The DRASTIC vulnerability index combines hydrogeologic information to rank areas with respect to groundwater vulnerability. This coarse analysis of groundwater vulnerability can help plan for strategic deployment of resources to evaluate environmental protection strategies, prioritize monitoring, and initiate cleanup efforts. It may also provide the foundation for prioritizing more detailed investigations of groundwater vulnerability to contamination.

The application of the DRASTIC vulnerability index is based on the following assumptions:[4] (1) Contaminants are introduced at the ground surface; (2); Contaminants are flushed into the groundwater by precipitation; (3) Contaminants have the mobility of water, and; (4) The area of evaluation is 100 acres or greater. The DRASTIC model parameters can be adjusted to account for the retardation of contaminants by increasing or decreasing the ratings associated with some of the DRASTIC parameters (e.g., impact of the vadose zone (I) aquifer hydraulic conductivity (C)). In the environment, the mobility of different radionuclides is inherently complex, and varies due to their chemical properties and interactions with local groundwater and soil or rock. For example, under circumneutral pH, the radionuclide $^{137}Cs$ strongly adsorbs to clay and organic matter, significantly limiting its ability to migrate with groundwater. The opposite behavior is observed in environments with low concentrations of clays or organic matter, such as sandy soils, where $^{137}Cs$ can complex with aqueous ions in the groundwater and migrate. Uranium forms soluble aqueous complexes under oxidizing conditions and migrates with groundwater, but also remains fairly immobile under more reducing conditions, by adsorbing to minerals.[14] Plutonium has low mobility as it strongly adsorbs to minerals and organic matter, although it can migrate at low concentrations when it adsorbs to colloids, small naturally occurring particulates in groundwater.[15] Long-term studies at the Chernobyl Exclusion Zone suggest that mobility of long-lived radionuclides of concern follow the sequence $^{90}Sr > {}^{137}Cs > {}^{238,\,239,240}Pu \sim {}^{241}Am$.[16] This may suggest that $^{90}Sr$ would be of greatest concern for groundwater and $^{137}Cs$ for soil at the Zaporizhzhia NPP. However, the source, radiologic composition, and release patterns from a hypothetical accident



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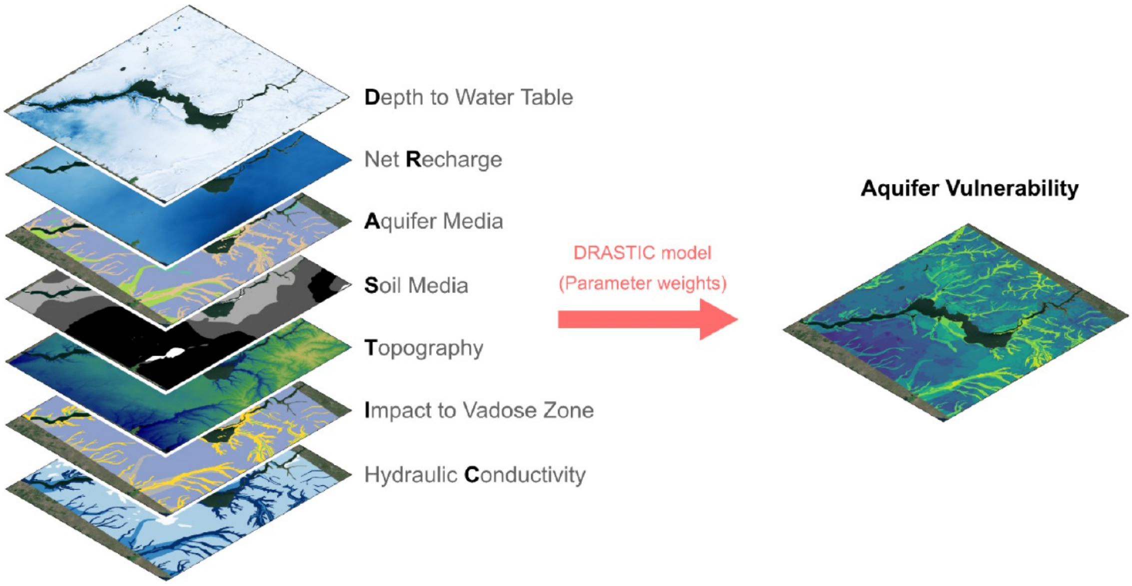


**Figure 2.** An illustration of calculations of GIS-based DRASTIC vulnerability index mapping process. Adapted from Ramakrishna et al. (2020).[17]

at the Zaporizhzhia NPP do not warrant speculation at this time. We do not attempt to address the radiologic source or mobility questions here; this level of detail is likely better suited to more comprehensive reactive transport modeling efforts. The DRASTIC approach applied in this study thus does not consider the soil, aquifer sediments, and contaminants' specific sorption−desorption characteristics and radionuclide decay.

The following equation is used to determine the DRASTIC vulnerability index:

$$D_R \times D_W + R_R \times R_W + A_R \times A_W + S_R \times S_W + T_R \times T_W + I_R \times I_W + C_R \times C_W = DRASTIC\ Index \quad (1)$$

where D, R, A, S, T, I, and C refer to the DRASTIC model parameters described above, the subscript $R$ refers to the rating associated with a particular hydrogeologic parameter, and the subscript $W$ refers to the parameter weight. The ratings for each DRASTIC parameter range from 1 to 10, with the higher ratings implying greater groundwater contamination vulnerability. Each DRASTIC parameter is assigned a relative weight that ranges from 1 to 5 (Table S1). The most significant parameters have a weight of five (e.g., depth to the water table) and the least significant are assigned a weight of one (e.g., topography). The details of the DRASTIC system of parameters, ratings, and weights are discussed in detail in the Supporting Information.

Once all the DRASTIC parameter ratings are identified and weights applied, an overall DRASTIC vulnerability index can be determined (i.e., eq 1). The spatial variability in the vulnerability index can be determined if appropriate geospatial information is available. Figure 2 shows a schematic of how the data are integrated to quantify the spatially resolved DRASTIC vulnerability index. Below, we apply this workflow to determine groundwater vulnerability near the Zaporizhzhia NPP.

## 2. MATERIALS AND METHODS

In the following sections, we describe the sources of information used to assign ratings to the seven DRASTIC parameters spatially. Our study area is a 40,000 km$^2$ area centered around the Zaporizhzhia NPP (Figure 3). Like most of Ukraine, the Zaporizhzhia area is topographically flat with level plains averaging approximately 175 m above sea level. These plains are dissected by regional highlands and lowlands trending northwest-southeast dissected by river valleys, ravines, and gorges. Most of the study area surrounding the Zaporizhzhia NPP region is comprised of fertile Chernozem (black earth) soils rich in organic matter and heavily used for agriculture. Chernozems correspond to the Mollisol Order in the USDA Soil Taxonomy.


**Figure 3.** Map showing the 40,000 km$^2$ study area in Ukraine with a yellow star showing the location of the Zaporizhzhia NPP. The aerial map is from Google Satellite Imagery (Map data ©2024 Google).

### 2.1. Depth to Water Table (D).

Well data provide the most direct information for the first DRASTIC parameter: Depth to the water table. However, most of the well locations and mean water levels were identified from available historical

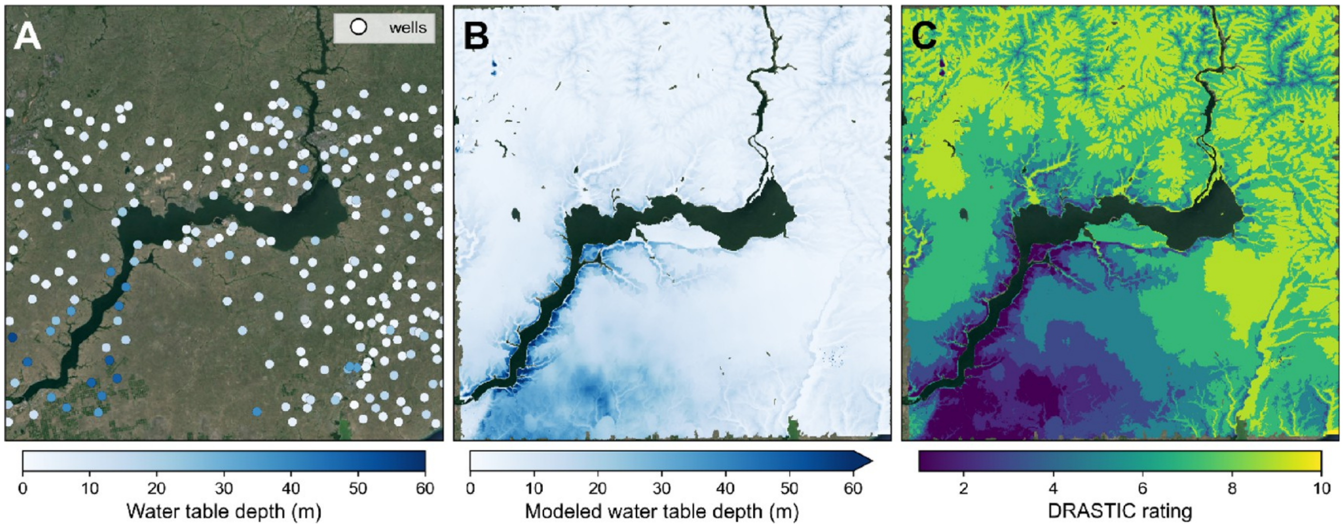


**Figure 4.** (A) Map of the study area showing groundwater monitoring wells from a series of historical hydrogeology maps,[18−23] (B) well data extrapolated to estimate regional water table depths, and (C) the water table depth converted to DRASTIC water table rating using Table S4.

hydrogeologic maps from the 1960s to the 1980s,[18−23] which likely do not represent all current operating well locations in the study area. Additionally, the water table data come from wells located in valleys with less coverage in areas of higher elevations. In the area where we have sufficient well data, the data indicate a relatively shallow water table (<10 m) with deeper water levels in upland areas farther from stream beds and in drier areas southwest of the Zhaporizhzhia NPP.

To extrapolate water table depth across the entire region of interest, we assumed that the water table depth is a function of (1) the elevation difference between a given location and the nearest stream channel, calculated using a 30-m resolution digital elevation model,[24,25] Section 2.5; (2) the absolute elevation of each well; and (3) the aridity index (the ratio of annual potential evapotranspiration to mean annual precipitation) calculated using gridded 30-year (1961−1990) climate averages from the *TerraClimate* data set.[26] Based on the *TerraClimate* data and topographic information, we calibrated a statistical model to the available well observation data (depth to groundwater) from readily available and digitized hydrogeologic maps (Figure 4A). The region includes an unconfined upper aquifer and multiple deeper confined aquifers; we only included water level data from wells screened in the uppermost unconfined aquifer ($n$ = 261 wells). The model trained on these wells was then used to populate a regional water table map at a 50-m resolution (Figure 4B).

We observed that relationships between water table depth, topography, and aridity were not necessarily linear, so we estimated water table depth from topographic and climate data using a generalized additive model (GAM). This approach allowed us to predict water table depth as a curvilinear smooth function of the predictor variables. The model took the form:

$$\log(WTD) = f(\text{height above streambed}) + f(\text{elevation}) + f(\text{aridity index}) \quad (2)$$

where log(WTD) is the base-10 logarithm of water table depth and the terms on the righthand side of the equation are thin plate penalized regression splines. The GAM was fit using the R package "mgcv"[27] using default settings for the spline parameters. The GAM explained 35.4% of the null deviance in the data. The estimated degrees of freedom and test statistics for each parameter are listed in Table S2.

We evaluated the impact of using model-extrapolated estimates of water table depth on the DRASTIC vulnerability index by comparing vulnerability indices based on our model at well locations to vulnerability indices calculated directly from available groundwater monitoring well data (Figure S2). The strong correlation between these vulnerability indices suggests that using statistically extrapolated estimates of water table depth is not likely to have a significantly impact the final DRASTIC vulnerability index.

The modeled water table depth map is shown in Figure 4B. The water table depth in this region is relatively shallow to the north and southeast of the Zaporizhzhia NPP, ranging between 0 and 15 m, and deepens to the southwest to between 20 and 40 m with a maximum of approximately 60 m in the drier southwestern area. We also mapped the absolute water table elevation across the part of the study region where we had access to well data, using thin plate splines to interpolate elevation between wells (R package "fields".[28] This approach confirmed that groundwater elevation is lower in the southwestern quadrant of the study region (Figure S3). We converted the depth to the water table to a DRASTIC water table rating (Figure 4C). The higher indices observed in the northeastern region reflect the shallower water table leading to higher groundwater vulnerability to contamination.

**2.2. Net Recharge (R).** The net recharge, or volume of water that infiltrates into the ground and reaches the groundwater table is defined as the precipitation minus the estimated or measured evapotranspiration. The Ukrainian climate in the northern Zaporizhzhia area is characterized as continental with cold winters and hot summers (Köppen-Geiger climate zone Dfa). In contrast, the area to the south is classified as arid cold steppe with low annual precipitation (Köppen-Geiger climate zone Bfa).[29] In our study area, we used the *TerraClimate* soil water balance model outputs to determine net recharge, which we assume can be approximated by total runoff.[26] *TerraClimate* is a high-resolution global data set (1/24°, −4-km) that consists of monthly climate and climatic water balance data from 1958−2015. *TerraClimate* provides monthly surface water balance components by using a

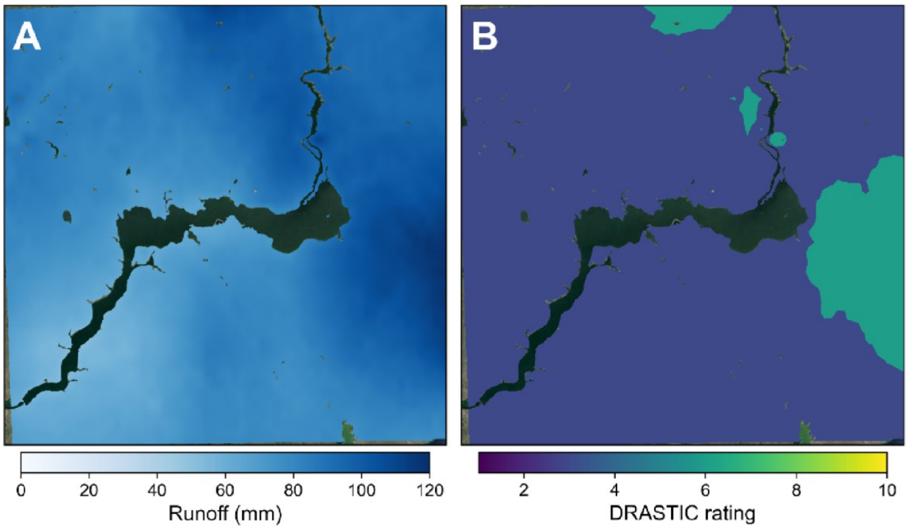


**Figure 5.** (A) TerraClimate water balance model runoff estimate for the Zaporizhzhia NPP region, which we assume approximates recharge and (B) the associated DRASTIC rating for the Recharge parameter following Table S5.

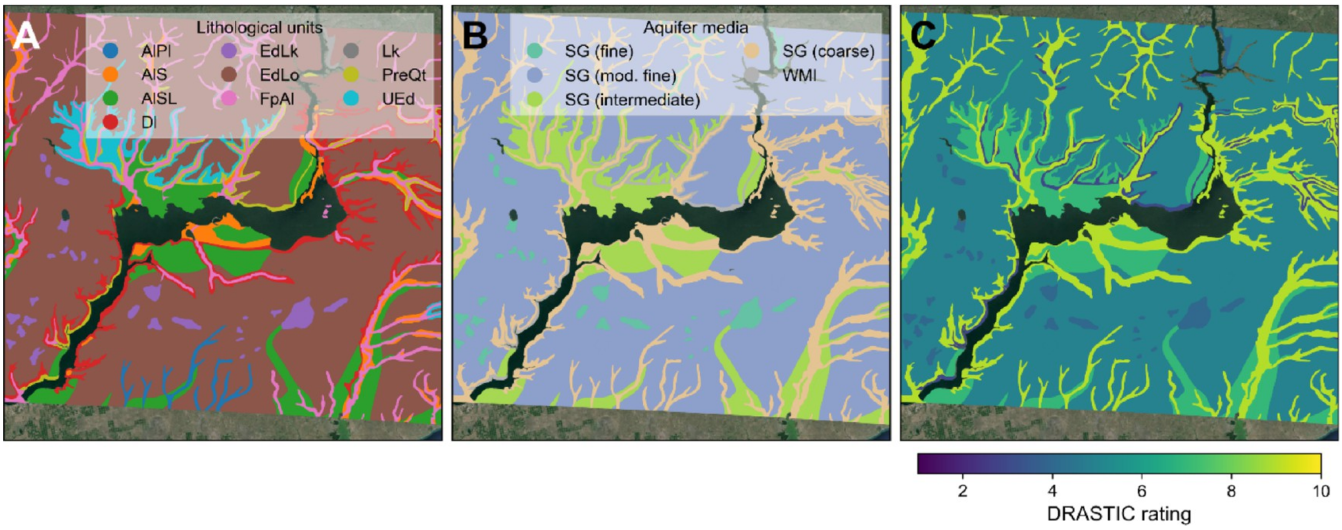


**Figure 6.** (A) Digitized lithological map of study area, (B) an aquifer media map derived from (A) denoting Sand and Gravel ("SG"; distinguished by grain size in parentheses) and Weathered Metamorphic/Igneous ("WMI") material, and (C) DRASTIC aquifer media ratings following Table S6.

simple water balance model that incorporates evapotranspiration, precipitation, temperature, and plant available soil water to estimate total runoff.[26]

Figure 5A shows the simulated runoff for our study area, which we use to approximate groundwater recharge under the assumption that overland flow is a minor component of the water balance. The maximum annual net recharge in the overall study area is approximately ∼110 mm/yr in an area that trends wettest northeast of the Zaporizhzhia NPP (ranging: ∼90−120+ mm/yr). Near the Zaporizhzhia NPP and to its northwest and southwest the net recharge is about half, 50−80 mm/yr. It should be noted that *TerraClimate* does not consider potential recharge from agricultural practices, which in the farming area surrounding Zaporizhzhia NPP is likely to be significant. Indeed, flooding of agricultural fields may dramatically increase groundwater recharge and warrants further study as it relates to groundwater vulnerability in this region. The estimated recharge is converted to a DRASTIC recharge rating using Table S5 (Figure 5B).

**2.3. Aquifer Medium (A).** The aquifer medium is an important parameter in the DRASTIC vulnerability index. Our description of the aquifer media material was derived from two legacy surficial quaternary deposit maps[30,31] that were digitized as shown in Figure 6A. We compared water table depths at groundwater well locations (Section 2.1) with geologic maps and accompanying cross sections and determined that the shallow unconfined aquifers in the Zaporizhzhia NPP study area lie primarily in surficial quaternary sediments. The major surficial lithologic units in our study area are (in order of prevalence): loess and loess-derived deposits; alluvial deposits in active stream channels, coarse-textured flood deposits and river terrace deposits associated with the Dnipro River, and exposed prequaternary deposits. Mapped lithological units correspond to labeled, colored polygons ("AlPl": Alluvial-prolluvial deposits; "AlS": Sandy alluvial deposits on floodplain terraces; "AlSL": Sandy alluvial deposits on floodplain terraces with loams and silty sands; "Dl": Deluvial deposits; "EdLk": Clayey eolian-deluvial and lacustrine deposits; "Lk": Lacustrine


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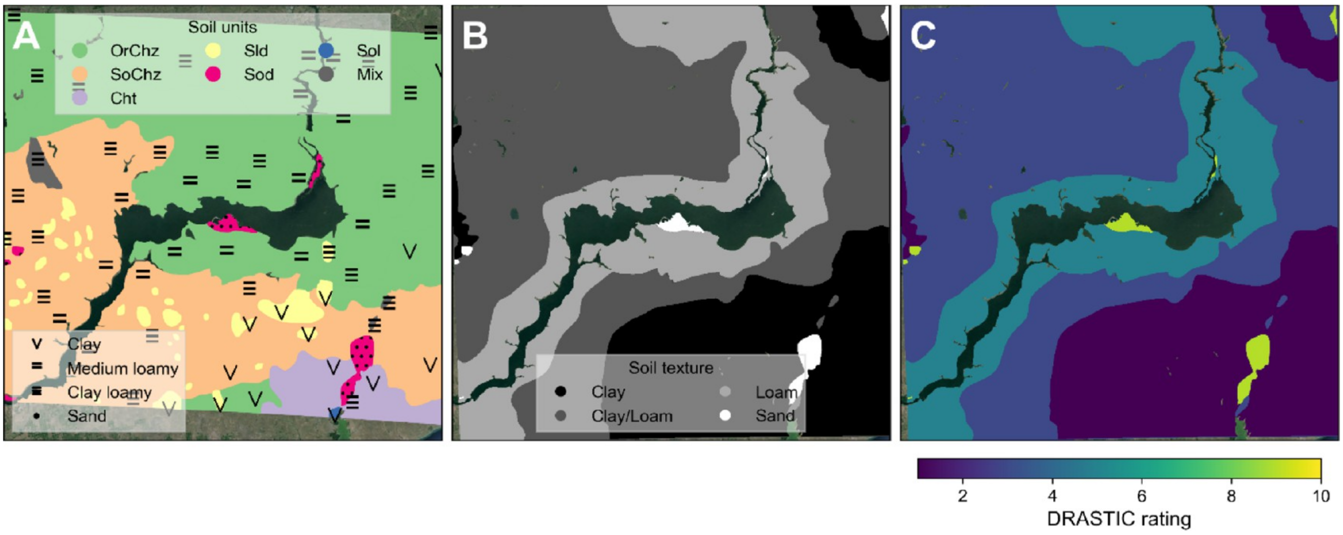


**Figure 7.** (A) Digitized soil map of study area for use in the DRASTIC model. Mapped taxonomy units correspond to labeled, colored polygons ("OrChz": Ordinary Chernozems on loess; "SoChz": Southern Chernozems on loess; "Cht": Chestnut soils on loess; "Sld": Solodized soils; "Sod": Soddy soils; "Sol": Solonetzs; "Mix": Mixture of meadow-Chernozemic soils on loess and meadow soils on deluvial and alluvial deposits). (B) Map of soil textures derived from symbols plotted in (A). (C) The soil texture map translated to DRASTIC soil media ratings following Table S7.

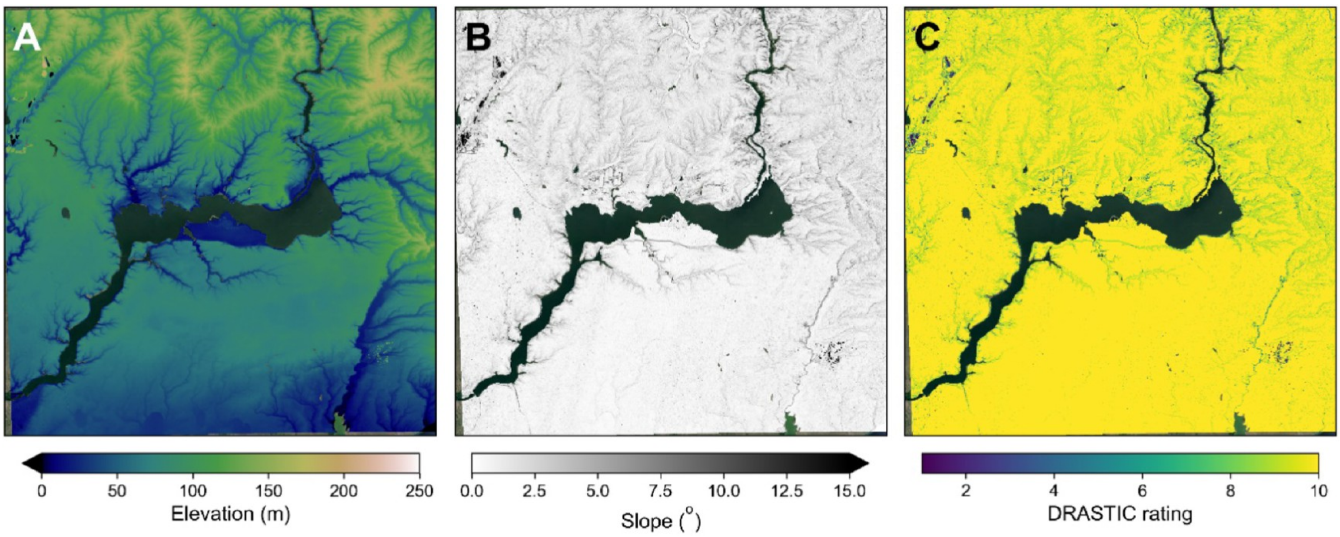


**Figure 8.** (A) An elevation map of the study area generated from JAXA ALOS (AW3D30),[25] (B) the Digital Elevation Map (DEM) data set translated to slope, and (C) DRASTIC topography rating following Table S8.

deposits; "EdLo": Eolian-deluvial, loess-like loam and loess; "FpAl": Floodplain alluvial; "UEd": Undivided eluvial and deluvial deposits; "PreQt": Pre-Quaternary metamorphic/igneous bedrock). The lithologic units from these digitized quaternary deposit maps were assigned a grain size based on our interpretation of each unit description and used to generate a map of aquifer media (Figure 6B). The associated aquifer ratings (Figure 6C) were generated using Table S6 which converts broad lithologic categories to DRASTIC aquifer media ratings.

Near the Zaporizhzhia NPP, we assigned the highest aquifer ratings in the stream channels, which feature coarse-textured alluvial deposits and exposures of underlying prequaternary deposits. We assigned intermediate ratings in mixed grain size river terraces and flood deposits along the Dnipro River and larger tributary streams, including Quaternary terrace deposits immediately to the south of the NPP. We assumed that loess deposits and lacustrine deposits in upland areas are predominately composed of silt- and clay-size particles, and hence these units were assigned low ratings.

**2.4. Soil Media (S).** Ukraine is well-known for organic-rich soils, known as black soils or Chernozems. These soils are agriculturally fertile due to their high concentration of organic matter, phosphorus, nitrogen, and high base saturation.[32] We obtained a map of the soil taxonomy and types in the Zaporizhzhia area.[33] The digitized soil map is shown in Figure 7A and shows both the soil taxonomy (colors) and the soil texture classes (symbols). The green area in the northern portion of the study area is characterized by Chernozems derived from loess. The area shown in orange in the southern portion of our field area is comprised mainly of Chernozems lower in organic matter and a minor amount of solodized (clay-rich, sodic) soil shown in yellow. The purple area in the southern-most section of our field area is comprised mainly of


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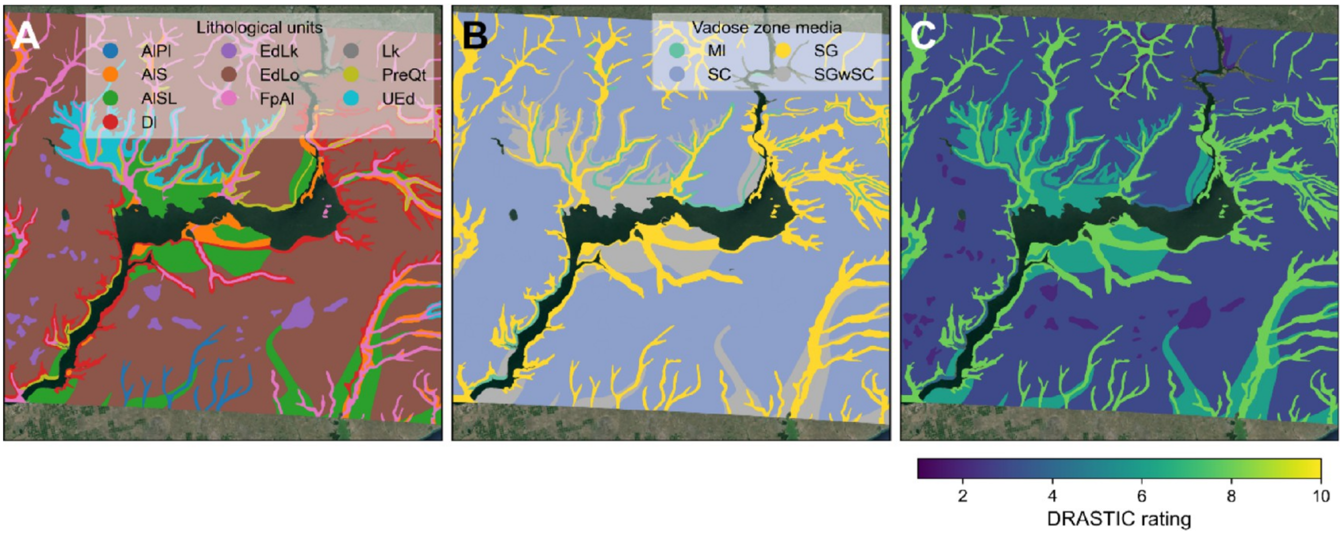


**Figure 9.** (A) Digitized lithological map of the study area for use in the DRASTIC model (mapped lithological units defined in Section 2.3), (B) vadose zone media map derived from this map (A) denoting Silt/Clay ("SC"), Sand and Gravel ("SG"), Sand and Gravel with significant Silt/Clay ("SGwSC") and Metamorphic/Igneous ("WMI") material, and (C) DRASTIC vadose zone rating following Table S9.

chestnut soils (Kastanozems) derived from loess. The bright pink areas refer to podzolic soils derived from the sandy parent material. Figure 7B shows the range of four soil texture classes taken from the symbols in the soil map (Figure 7A). Based on Table S7, these four soil texture classes: sand, loam, clay/loam and clay correspond to DRASTIC soil media ratings of 9, 5, 3, and 1, respectively (Figure 7C).

The Dnipro River strongly influences the soil texture classes that determine the DRASTIC rating: coarser textured sands and loams areas occur in proximity to the river, whereas clay/loam and clay soils are more prevalent farther from the Dnipro. The coarser textured soils near the Dnipro have a high DRASTIC rating (greater than 5), reflecting a high potential for infiltration of potential contamination compared to the clay/loam and clay soil areas to the northwest and southeast. This pattern suggests groundwater vulnerability is increased within a ∼ 10−20 km area on either side of the Dnipro River. Notably, the relatively young river terrace soils directly underlying the Zaporizhzhia NPP are classified as sands, indicating a high potential for contaminant infiltration near the NPP.

**2.5. Topography (T).** We derived topographic indices required for the DRASTIC model parametrization using a satellite-derived digital elevation model (DEM). One of the most currently accurate global DEMs is the Japanese Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) that uses Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) to generate high-resolution topographic maps at approximately 5-m (0.15-arcsecond) resolution.[25] We used JAXA's 30-m resolution ALOS DEM data product to create maps of slope (Figure 8) for use in the DRASTIC model and to obtain elevation and height above stream channel parameters used for extrapolating water table depth (Section 2.1). Height above the stream channel and slope were calculated using Whitebox Geospatial software (https://www.whiteboxgeo.com/) and the front-end interface from the "whitebox" R package.[34,35] The slopes across the site area are shallow, with most of the area having slopes between 0 and 5 degrees (Figure 8B). Shallow slopes between 0 and 5° correspond to a DRASTIC rating of 9−10. However, stream channels that feed into the Dnipro River are steeper and hence receive a lower rating. The DRASTIC topography rating was determined following Table S8 and is shown in Figure 8C.

**2.6. Impact of the Vadose Zone (I).** The vadose zone is the area from the land surface to the aquifer water table, representing the main route for contaminants to travel from the ground surface to the underlying aquifer. The characteristics of the vadose zone strongly influence the attenuation of contaminants. As a result this parameter is assigned the highest weight of 5 when computing the DRASTIC index. Given the relatively shallow water table depths throughout the study area (from 0 to 15 m), the characteristics of the vadose zone could be estimated using the same digitized surficial geologic maps used for characterizing the aquifer medium (Figure 9A). The lithologic units identified in the geologic map were then classified into different categories of vadose zone media (Figure 9B). These categories were translated to DRASTIC vadose zone ratings following Table S9 (Figure 9C). The vadose-zone properties that determine susceptibility to contaminant transport are broadly similar to the properties that impact the aquifer medium; hence DRASTIC ratings for the vadose zone show similar spatial patterns to the aquifer medium ratings (Figure 6C), with the highest vulnerability ratings in coarse-textured stream deposits and river terraces, and low ratings in upland loess and lacustrine deposits (Figure 9C).

**2.7. Hydraulic Conductivity (C).** The hydraulic conductivity of the shallow aquifer materials was based on identification of the composition of the aquifer material using the quaternary geologic map of the area,[36] applying a hydraulic conductivity to rock types based on published estimates[36] (Table S10) and converting those hydraulic conductivities to DRASTIC ratings using Table S11. For example, unconsolidated sand is estimated to have a hydraulic conductivity of $10^3$ gal/day/ft$^2$ which leads to a DRASTIC rating of 10 given the high conductivity of the medium. However, finer textured deposits will tend toward much lower hydraulic conductivities, which lead to a DRASTIC rating of 1. The predominance of fine-textured loess deposits in the vicinity of the Zaporizhzhia

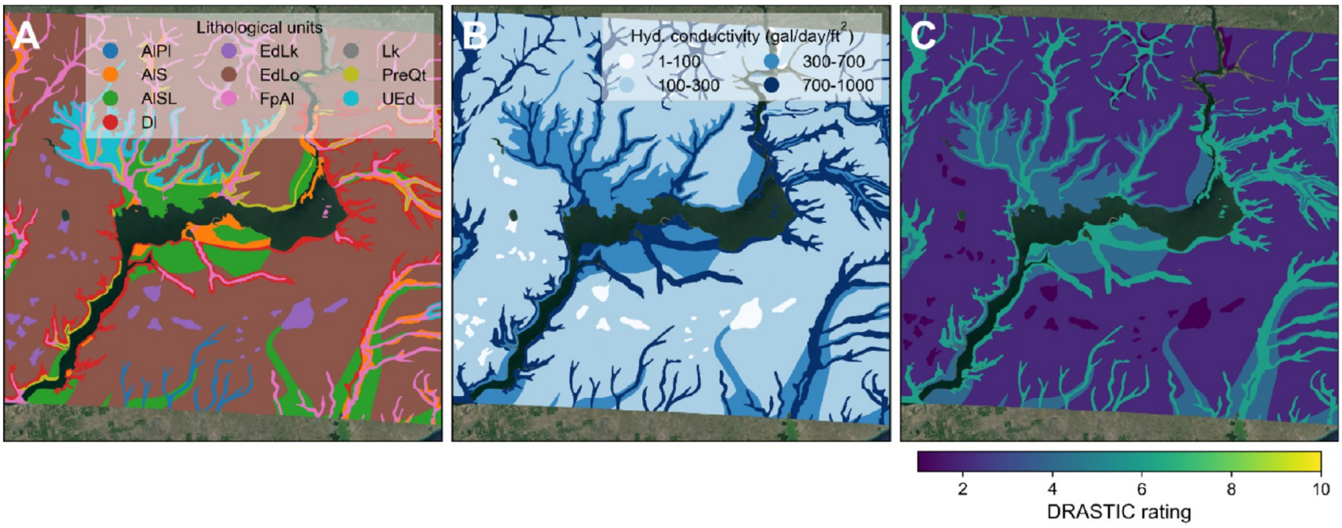


**Figure 10.** (A) Digitized lithological map of study area produced from Perelstein (1974) and Storchak (1983) for use in the DRASTIC model (mapped lithological units defined in Section 2.3),[30,31] (B) hydraulic conductivity ranges are estimated from this map based on aquifer material and the relationships presented in Table S10 and originally contained in Freeze and Cherry (1979, their Table 2.2),[36] and (C) DRASTIC hydraulic conductivity ratings following Table S11.

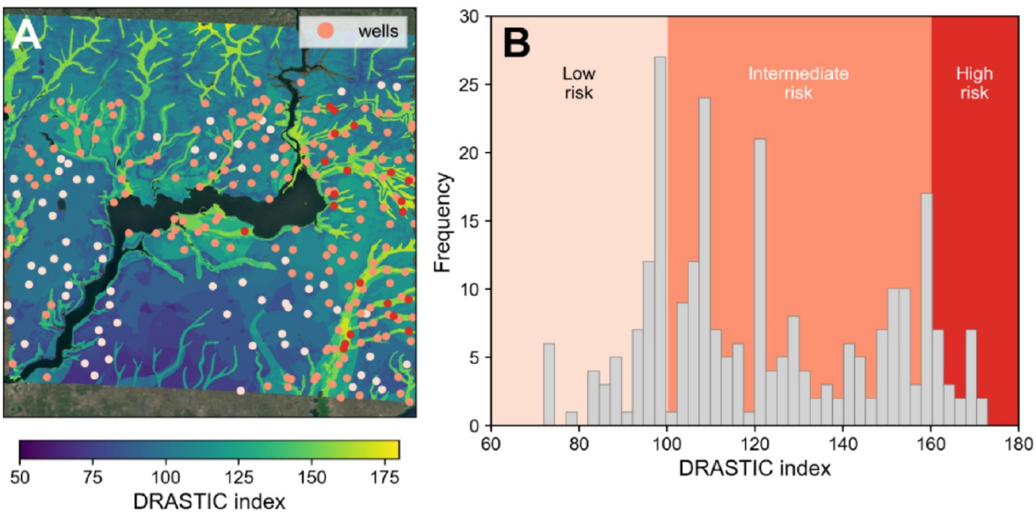


**Figure 11.** (A) DRASTIC vulnerability index for the 40,000 km$^2$ region centered on the Zaporizhzhia NPP. The vulnerability index is calculated from multiple hydrogeologic factors and conditions (eq 1) and the network of groundwater wells spatially encompassed by the analysis. (B) A histogram summarizing the relative extent to which these wells are vulnerable to contamination, which is determined by binning the range of DRASTIC indices into "Low risk" (<100), "Intermediate risk" (101−160), and "High risk" (>160) classes following Liggett and Gilchrist (2010).[37]

NPP generally leads to low DRASTIC ratings for hydraulic conductivity except along stream channels where the finely textured deposits have eroded and the underlying aquifer materials have higher conductivities, resulting in higher DRASTIC ratings. Notably, the data source for estimating hydraulic conductivity—the quaternary geologic map—was identical to the data source used for mapping the aquifer and vadose zone medium. Consequently, the hydraulic conductivity vulnerability ratings show spatial patterns (Figure 10C) that resemble those calculated for the two related parameters (Figures 6C and 9C).

## 3. RESULTS AND DISCUSSION

We calculated the DRASTIC groundwater vulnerability index for the region surrounding the Zaporizhzhia NPP based on the assigned ratings and weights for each of the seven DRASTIC parameters (Figure 11). The DRASTIC rating map reveals two critical trends in groundwater vulnerability in this area. First, patterns in groundwater depth (Figure 4) and groundwater recharge (Figure 5) lead to a broad trend of increased groundwater vulnerability toward the northeast of Zaporizhzhia NPP and decreased vulnerability toward the southwest. This pattern is overlain by locally increased vulnerabilities that coincide with the presence of stream channels that lead to shallower depth to the water table (Figure 4) and more vulnerable aquifer medium (Figure 6), vadose zone medium (Figure 9), and aquifer hydraulic conductivity (Figure 10). The increased precipitation in the northeast region also coincides with a greater density of stream channels that exacerbate this pattern. Notably, ratings for aquifer medium, vadose zone medium, and aquifer hydraulic conductivity were all estimated from the same data source, quaternary geologic maps of the study region. The DRASTIC ratings for these parameters are highly correlated, whereas other parameters—


https://doi.org/10.1021/acsestwater.4c00891
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recharge, slope, soil medium, and water table depth—are not strongly correlated with any other parameter (Table S3). Consequently, ratings for aquifer medium, vadose zone medium, and aquifer hydraulic conductivity reinforce each other, emphasizing the high vulnerability of relatively coarse-textured stream and terrace deposits associated with the Dnipro River.

While the limited number of wells identified using historical geological maps[18−23] very likely do not represent the present-day distribution of active well sites across this region, they are sufficient to provide an example of how the DRASTIC vulnerability index may be applied to known well locations to assess their vulnerability to contamination. This type of evaluation may be used to prioritize well sampling programs to monitor contamination. For example, Figure 11 includes the location and vulnerability index associated with each historical well location. Based on this analysis, important patterns emerge in these data. First, well vulnerability is increased in the northeast region of our study area (Figure 11A). This pattern is consistent with the geospatial patterns that were discussed earlier. Second, well vulnerability appears to be exaggerated when compared to the overall patterns in groundwater vulnerability across this region. This likely reflects the fact that most wells are positioned in areas with a shallow water table to reduce groundwater pumping costs and well engineering (i.e., closer to stream channels). Finally, of the 261 wells identified in the historical maps in our region of interest, it appears that 8% fall into the high vulnerability category[37] as defined by the DRASTIC model (Figure 11B). This methodology appears to be a good first step in identifying wells that would require focused monitoring of radiological contamination if such an event were to occur.

We emphasize here that this analysis is primarily a proof-of-concept based on the limited readily available data. This analysis would benefit greatly from updated water table depth information, trends in agricultural irrigation patterns, groundwater monitoring well location information, and higher fidelity geologic maps. In particular, water table depth has a large influence on the DRASTIC index and our estimate of groundwater depth is highly approximate. We could not obtain contemporary groundwater data from the region for two reasons: (1) recent well records were not publicly available and; (2) collecting new measurements in an active war zone is infeasible. These limitations forced us to use legacy groundwater level maps from the 1980s. We believe these maps likely capture large scale relative patterns in groundwater levels, which appear related to local topography and the regional climate gradient. On the other hand, the effects of climate change on groundwater recharge and trends in groundwater pumping are unknown, and these factors have likely affected water levels since the 1980s. More recently, damage to the Kakhovka Dam may have caused a drop in groundwater levels close to the reservoir and the NPP. We have no reliable way of evaluating these possibilities remotely. Given these uncertainties, assessing present-day groundwater depth in the region seems like an important priority as soon as on-the-ground data collection is feasible.

In addition to uncertainty related to groundwater depth, our analysis of the subsurface geologic deposits is coarse. Given the information we had, we assumed that the uppermost aquifer is confined to quaternary loess, alluvium, and lacustrine deposits. However, our source maps indicated that prequaternary rocks are exposed along stream valleys throughout the region, and we have no information regarding the permeability of this geologic unit. Future data collection related to groundwater levels could include assessments of the hydraulic properties of the uppermost aquifer unit and would likely reveal much complexity missed by our analysis. Keeping in mind these important caveats, we believe that initial assessments like the one presented here are necessary to prioritize both monitoring and remediation strategies across Ukraine both in the event of a nuclear accident and in response to broader non-nuclear environmental hazards imposed by the war.

## 4. CONCLUSIONS

Our application of the DRASTIC index to the region surrounding the Zaporizhzhia nuclear power plant identified several regional gradients in groundwater vulnerability. Specifically, we found that stream channels are potential entry points for contaminants. At a larger spatial scale, a groundwater contamination risk is likely lower to the southwest of the NPP, where drier climate leads to lower groundwater recharge rates and a deeper water table. Our analysis can serve as the foundation for the more focused environmental modeling and remediation needs that may emerge in the coming years, and also demonstrates the power of the DRASTIC approach for evaluating contamination risk in situations where recent on-the-ground data are unavailable.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.4c00891.

Figures supporting groundwater analysis, table of correlation coefficients for DRASTIC parameters, and full description of DRASTIC parameters (PDF)

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## Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

Contributions of Slessarev, Golla, Alvarez, Kersting, and Zavarin at LLNL were performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The work at LLNL was supported by Laboratory Directed Research and Development funds (22-ERD-019). Contributions of Lawrence Berkeley National Laboratory coauthors were supported by LBNL's Laboratory Directed Research and Development Program. LBNL is operated under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy.

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