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Review

해체 원전부지 내 방사성 핵종의 수리지질학적 거동: 방사성 핵종 이동 모델링 구축에 대한 연구 사례

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Hydrogeological fate of radionuclides at decommissioned nuclear power plant sites: Case studies for radionuclides transport model development

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요약: 이 검토 논문은 원자력 발전소 시설과 관련된 잠재적인 환경 및 공공 보건 위험을 이해하고 이를 완화할 필요성으로부터 작성되었으며, 원자력 발전소에서의 방사능 오염에 대한 연구 사례, 특히 방사성 핵종 이동 모델의 개발에 대해 다루었다. 광범위한 문헌 고찰을 통해 다양한 오염 유형, 범위, 효과 및 현장 조건을 제시하였다. 이러한 면밀한 사례 연구를 통해 얻어진 유용한 경험을 국내 다른 사례에 적용할 수 있을 것이다. 이 검토 논문은 모델링 연구에서 사용된 데이터에 중점을 두고 있으며, 기존 문헌과 현장 관측에서의 정보 수집 및 처리를 강조하였다. 수치 모델링에 중요한 품질 보증 및 품질 통제(quality assurance/quality control; QA/QC) 절차에 대해 설명하며, 입력값의 신뢰성과 정확성을 보장하기 위한 모델링 매개변수 평가에 대한 심층적인 논의를 포함하였다. 또한, 머신 러닝 입력을 위해 전략적으로 조직된 데이터베이스 시스템의 개발에 대해 살펴보았으며, 정교한 데이터 분석을 위한 기초를 마련하고자 하였다. 이 검토 논문은 특정 사이트 조건에 맞는 적절한 수치 모델의 선택, 철저한 데이터 수집 및 처리, 그리고 신뢰할 수 있는 데이터베이스 시스템의 개발이 해체 원자력 발전소의 성공적인 관리에 필수적임을 강조한다. 이 논문은 해체 원자력 발전소 부지에서 방사성 핵종 이동을 예측하기 위한 모델링 전략을 수립하는 데 기여할 수 있으며, 궁극적으로 이러한 시설의 효과적인 관리에 도움을 줄 수 있다.

주요어: 방사성 핵종, 오염, 모델링, 원자력 발전소, 해체

ABSTRACT: Motivated by the urgent need to understand and mitigate potential environmental and public health risks associated with decommissioned nuclear power plants, this review paper explores studies on radioactive contamination at these facilities, with a particular focus on the development of radionuclide transport models. It begins with a comprehensive literature review, examining various contaminant types, extents, effects, and site conditions. Through careful examination of case studies, the paper extracts valuable insights from historical contamination incidents to guide contemporary practices. The primary emphasis is on data utilized in modeling studies, highlighting the collection and processing of information from both existing literature and on-site observations. The paper discusses the quality assurance and quality control (QA/QC) procedures crucial for numerical modeling, including an in-depth assessment of modeling parameters to ensure the dependability and precision of inputs. Furthermore, it explores the development of a robust database system, strategically organized for machine learning inputs, laying the foundation for sophisticated data analysis. The review highlights that choosing the right numerical models for specific site conditions, conducting thorough data collection and processing, and developing reliable database systems are essential for the successful management of decommissioned nuclear power plants. This paper can contribute to developing a modeling strategy for predicting radionuclide transport in decommissioned nuclear power plant sites, ultimately supporting the effective management of these facilities.

Key words: radionuclide, contamination, modeling, nuclear power plant, decommissioning

1. Introduction

Since the operation of the first nuclear power plant, Kori-1, began in 1978, South Korea now has 28 nuclear power plants. Among them, 23 are pressurized water reactors, 3 are pressurized heavy-water reactors, and 2 have been permanently shut down, playing a crucial role in the country's industrial development and power supply (Korea Hydro and Nuclear Power Co., Ltd., 2024). With the increasing need for carbon neutrality and greenhouse gas reduction, the 10th Basic Plan for Long-Term Electricity Supply and Demand, announced in January 2023, aims to raise the proportion of nuclear energy from 23.4% in 2018 to 34.6% by 2036 (Ministry of Trade, Industry and Energy, 2023). This plan includes the construction of 4 additional nuclear power plants by 2036.

Regardless of the controversy surrounding the expansion or reduction of nuclear power in a given country, ensuring the safe transport and disposal of radioactive waste produced by nuclear power plants remains a significant global issue. Among the various components of radioactive waste, actinides have particularly long half-lives, spanning hundreds of thousands of years, and are highly hazardous to human health (Zhang and Brady, 2002). While the safe storage of nuclear waste is the ultimate responsibility of the nuclear industry, leaked radionuclides can enter the soil, dissolve in pore water, and be transported through advection or diffusion during operation or decommissioning of nuclear power plants (Schick, 2005). As illustrated in Fig. 1, radionuclides can infiltrate groundwater and surface water through advection, dispersion, and adsorption/

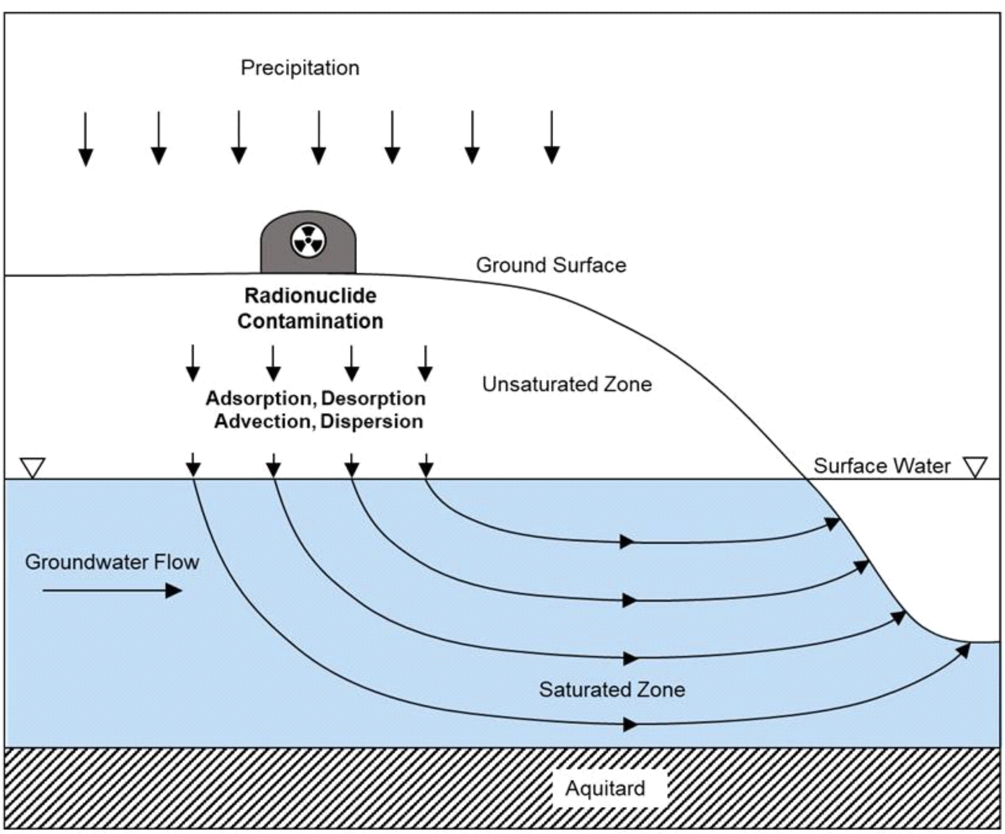

Fig. 1. A conceptual diagram for behaviors of radionuclides at decommissioned nuclear power plant sites.

desorption traveling through unsaturated and saturated zones. Understanding the behavior of radionuclides through various media significantly contributes to site remediation in the event of radionuclide releases (Onishi *et al*., 1981). Thus, an in-depth review of existing studies, contamination incidents, and assessment tools is crucial for gaining a complete understanding of radionuclide transport.

The prediction of radionuclide transport at a given site is typically conducted using a groundwater flow and transport model (Thiessen *et al*., 1999). Although lessons learned from case studies, particularly involving groundwater modeling, are important to adapt to new sites, such as decommissioning nuclear power plants in South Korea, there has been a lack of thorough review of such historical cases. Identifying appropriate numerical models, determining the required physical and chemical parameters for these models, and managing databases acquired from previous case studies are crucial for the future management of decommissioning nuclear power plants.

The main objective of this review paper is to present case studies related to radionuclide transport at decommissioned nuclear sites, with a particular focus on the development of radionuclide transport models. This paper aims to conduct an in-depth literature review to establish a foundational understanding of radioactive contamination at nuclear power plants, covering contaminant types, extents, effects, and varying site conditions. It offers a concise overview of the objectives of various previous studies and the context of contamination in nuclear power plants. This review paper highlights the collection and processing of data from both literature and field studies, emphasizing the importance of parameter evaluation through quality assurance and quality control (QA/QC). It focuses on the development of a robust database system for organizing field and modeling data, a crucial objective that lays the groundwork for effective machine learning inputs and subsequent analyses. Thus, the paper aspires to contribute to the enhancement of contamination management strategies in decommissioned or decommissioning nuclear power plants.

2. Case studies on contamination in nuclear power plants

There are several studies available in the literature that address various aspects of nuclear power and radiation risk assessment. This review paper examines a few recent examples of such studies. Aly *et al*. (2020) focused on a nuclear power program in Egypt, assessing radioactivity concentrations in groundwater following a hypothetical reactor accident. Sato *et al.* (2023) examined the impact of a cooling pond drawdown near the Chornobyl Nuclear Power Plant, observing increased ^{90}Sr concentrations in the Pripyat River floodplain. Kim *et al*. (2020) addressed the challenge of handling soil data in nuclear power plant decommissioning, emphasizing the significant influence of properly managing data at or below detection limits. Byon *et al.* (2020) evaluated soil contamination at the Kori Unit 1 nuclear power plant decommissioning site, providing a framework for assessing soil contamination and offering a guideline for similar projects based on Kori Unit 1 characterization. These studies collectively contribute to understanding and managing radiation risks in the context of nuclear power programs, accidents, and decommissioning.

2.1. Nuclear power reactor in El-Negila, Egypt

Aly *et al*. (2020) discuss Egypt's nuclear power program and the need to assess and control radiation risks associated with it. This research aims to project the concentration of radioactivity in groundwater over a 50-year period after a hypothetical accident at a planned Nuclear Power Reactor in El-Negila, located on the Northwestern Coast in Egypt. The scenario under consideration is a loss of coolant accident (LOCA) involving a 1000 MWe pressurized water reactor. The release pathway was identified as containment bypass. Radioactive emissions were defined by the severe accident source terms, which reflect the proportion of the reactor's inventory that was released. The duration of the release was prolonged to 48 hours, assuming a constant contaminant release rate and stable meteorological conditions throughout. The study estimates radioactive releases and models the dispersion of radioactive pollutants in the air, followed by their transport through groundwater around the reactor. The primary concern is long-term radiation contamination, particularly from ^{137}Cs and ^{90}Sr isotopes, which gain radiological significance over time.

To predict radioactive contamination in groundwater, the research uses data from the RASCAL code (Ramsdell *et al*., 2012) as input for the MODFLOW-MT3D model (Zheng and Wang, 1999) simulating a 50-year period. The RASCAL code calculates the "source term," which denotes the varying rates at which each radionuclide is discharged from the facility over time, as well as atmospheric dispersion and radionuclide concentration. The resulting ground-level radionuclide concentrations are employed as input parameters for the MODFLOW-MT3D model. The model incorporated existing data and was calibrated to reflect the steady-state conditions of 2010, showing reasonable agreement with observed water levels. It is important to note that in this study, the unsaturated zone was not considered, and it was assumed that infiltration directly reached the groundwater. Two groundwater dispersion scenarios were considered: one without pumping and the other with pumping wells stressing the system. The simulation results indicated that the initial concentrations of ^{137}Cs and ^{90}Sr at the release site exceeded the World Health Organization (WHO) limits for radionuclides in drinking water. However, over the 50-year simulation, these concentrations decreased in all directions, indicating the retention of radionuclides in the aquifer matrix. Notably, the retention of ^{90}Sr surpassed that of ^{137}Cs. In the second scenario with pumping wells, low levels of both isotopes still appeared in a well at the coast due to various factors influencing groundwater dispersion, such as half-life, dispersion, adsorption, and desorption processes. The pumping rate is about 40 m^3/h, and it was observed that the concentration of both radionuclides was higher in the southeastern direction compared to other directions.

The slow migration of the cesium isotope ^{137}Cs in most soils is a widely accepted fact. A previous hydro-geophysical study in the El-Negila region indicated the presence of five distinct layers, including wadi fill, clay, dry limestone, water-bearing limestone, and clay. Based on this study, cesium tends to adhere strongly and quickly to soil particles, particularly clay and organic material. This adherence primarily occurs through a chemical process involving ion exchange. A significant portion of the radionuclides can become irreversibly bound to the soil, particularly resulting from the trapping of radionuclides by organic matter in soil and their diffusion into clay between layers. Additionally, half-life, retardation, and ion-exchange mechanisms can influence the transport of radioactive ^{137}Cs and ^{90}Sr.

2.2. Chornobyl nuclear power plant (ChNPP)

Sato *et al.* (2023) examined the influence of the cooling pond drawdown at the Chornobyl Nuclear Power Plant (ChNPP) on the surface and subsurface system from 2010 to 2019. They examined the variations in ^{90}Sr and ^{137}Cs concentrations, as well as shifts in water table within the shallow aquifer near the ChNPP, both prior to and following the drawdown. Additionally, they examined the relationship between groundwater table and ^{90}Sr concentrations across various water bodies. The research revealed that ^{90}Sr concentrations rose significantly in the Pripyat River floodplain following the drawdown, surpassing the established drinking water guidelines. Groundwater levels decreased in many monitoring wells, and the increased ^{90}Sr concentrations were linked to reduced leakage from the cooling pond, affecting groundwater flow and velocity. The study suggests the need for ongoing monitoring to assess the long-term impact on groundwater and radionuclide transport.

The cooling pond (CP) near the ChNPP, built in 1976 and expanded in 1981, covers 22.9 km^2 with 151 million m^3 of water. Initially, water came from the Pripyat River, but post-2016, the CP was divided into three areas due to dropping water levels, affecting seepage and drainage flows. Currently, precipitation is the only inflow, with evapotranspiration and subsurface leakage as outflows. From 2011-2013 to 2017-2019, In the Pripyat River floodplain, including Azbuchin Lake north of the ChNPP, ^{90}Sr concentrations were elevated due to reduced leakage, shifts in groundwater flow direction, and slower groundwater movement as the water levels in the cooling pond reduced by 6 m. Groundwater modeling using MODFLOW showed groundwater travel times from the CP to the drainage ditch range from 2 to 3 months, and direct seepage to the Pripyat River takes 1.5-3 years, extending to 3–5 years in some locations due to lower velocities. This highlights the need for ongoing monitoring to assess potential contamination sources.

Moreover, the regional groundwater model for the Chernobyl exclusion zone (ChEZ), designed by the Institute of Geological Sciences (IGS), was used to predict the drawdown of water levels in the cooling pond. The groundwater flow model was constructed using the MODFLOW finite-difference numerical code with the Visual MODFLOW for pre- and post-processing the simulation results.

To calibrate the groundwater model, data from water level observations in monitoring wells within ChEZ were utilized. The calibration process involved adjusting parameters such as hydraulic conductivity and precipitation and infiltration recharge rates. The results of the model calibration showed a strong correlation between the simulation results and the observed data regarding the discharge flux rates near the cooling pond. However, the model predicted total seepage from the pond that were about 20% lower than the observed values. The hydraulic conductivity (K_f) values obtained from this model were: K_f = 10 m/day and K_f = 5 m/day for the unconfined aquifer layer (Quaternary deposits) and the confined aquifer layer (Eocene deposits), respectively.

This regional groundwater flow model was employed in various tasks related to the analyses of the cooling pond related to decommissioning and remediation. Specifically, it was used to assess the temporal changes in water level drawdown within the pond, predict the eventual hydrogeological conditions, and estimate the impact of groundwater drawdown in the pond on the hydrogeological features surrounding hazardous regions. Seepage losses, which were greater than evaporation losses, primarily influenced early drawdown stages. These losses decreased over time as water levels lowered, reducing the hydraulic head difference, and the shoreline retreated, increasing the flow path length to the Pripyat River.

2.3. Colorado School of Mines Research Institute

Kim *et al.* (2020) investigated a challenge in nuclear power plant decommissioning, particularly regarding the handling of soil data, where most samples were near the detection limit (BDL). Traditional methods of managing BDL data, like ignoring it or replacing it with zero or the detection limit, are statistically biased and not very useful. Drawing from statistical techniques in environmental science, such as the Kaplan-Meier (KM) approach, Robust Regression on Order Statistics (ROS), and maximum likelihood (MLE), they explored ways to handle BDL data in the context of nuclear decommissioning. The results emphasized that properly using BDL data can significantly influence dose/risk, waste volume, and disposal costs in decommissioning nuclear power plant projects.

This study was based on soil data from the decommissioning project of the Colorado School of Mines Research Institute (CSMRI). The institute site, located in Jefferson County, Colorado, was used for various mining-related research activities from 1912 to 1985. These activities involved establishing extraction processes for natural resources, causing contamination of nearby buildings and soils with natural radioactive elements (e.g., uranium, thorium, and radium). The S.M. Stoller Corporation conducted a soil survey at the site, collecting data on various radionuclide concentration levels (^{226}Ra, ^{228}Ra, ^{228}Th, ^{230}Th, ^{232}Th, ^{234}U, ^{235}U, and ^{238}U). The data consisted of 30 data points with a 30% censoring percentage, and different detection limits (DLs) were used for different radionuclides.

For the radionuclides modeling, the key information used for analysis included contaminated zones, soil concentrations, saturated and unsaturated zones, and values related to occupancy and ingestion. Initially, the study estimated residual radioactive concentrations using various methods, such as ignoring BDL data, using the DL in place of BDL data, and employing statistical approaches. The study used the Environmental Protection Agency's ProUCL statistical software for analyzing BDL data. The RESRAD code (Ramsdell *et al.*, 2012) was utilized to calculate the overall dose value and the associated uncertainty, considering individual input parameters. To determine the input parameter value for RESRAD, they used both site-specific and default values. Specifically, radionuclide concentrations and the characteristics of the contaminated zone were among the site-specific parameters.

Additionally, the study analyzed the uncertainty of the model using Latin hypercube sampling (LHS) with 1000 samples. LHS divided the sample distribution into equally likely intervals, and one random sample was chosen from each interval to represent the whole range of the distribution, as noted in Table 1 of Kim *et al*. (2020). Subsequently, they employed a regression approach to determine the correlation between resultant dose and parameter values applied to the model, assessing their relative importance in affecting the dose. They also used partial rank correlation coefficients to calculate the correlation between input and output parameters and to estimate the contributions of individual parameters to uncertainties in the dose results.

The study compared residual radioactivity concentrations using statistical methods such as KM, ROS, and MLE, against traditional approaches like disregarding BDL data or replacing it with DL. The findings suggest that ignor-

Table 1. Commonly used modeling tools.

Modeling Tool	Description	Reference
RESRAD	The RESRAD (Residual Radioactive Materials) family of codes is used for assessing the potential human health and ecological risks from exposure to radioactive materials. RESRAD typically addresses soil, water, and air pathways and is widely used in environmental remediation and decommissioning projects.	Byon *et al*. (2020); Kwon *et al*. (2022)
MODFLOW	MODFLOW is a widely-used groundwater flow modeling software. It is often used to simulate the movement of water and solutes, including radionuclides, in subsurface environments.	Sohn *et al*. (2011); Sohn and Lee (2013); Chanhoi and Yee (2014); Aly *et al*. (2020); Sato (2022)
GOLDSIM	GoldSim is a simulation tool that utilizes probabilistic modeling to address various challenges in environmental management and risk analysis across diverse applications. It is used to model the transport of radionuclides and other contaminants in complex systems.	Bang *et al*. (2014); Lee and Choi (2015); Poškas *et al*. (2019)
HYDRUS	HYDRUS is a simulation platform designed to model the flow of water, heat, and various solutes within two- and three-dimensional unsaturated porous media. It is used to study water and solute transport in soils and can be applied to radionuclide transport.	Nair *et al*. (1996); Jakimavičiūtė-Maselienė *et al*. (2016); Antonov (2017); Zhang *et al*. (2021)
EPRI-DOSE	Developed by the Electric Power Research Institute (EPRI), EPRI-DOSE is used for radiological dose assessments in the nuclear industry, including the evaluation of radiological impacts from nuclear facilities.	Wall and Johnson (2019); Floyd *et al*. (2021); Segarra *et al*. (2021)
HYSPLIT	The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model is utilized to evaluate the atmospheric movement and spread of radionuclides. It is often applied to atmospheric release scenarios.	An *et al*. (2015); Zali *et al*. (2017); Pirouzmand *et al*. (2018)
PHREEQC	PHREEQC (PHysicochemical REactive geochemical transport code) is used for modeling the geochemical reactions that influence radionuclide transport, particularly in surface water and groundwater systems.	Marin *et al*. (2010); Neveux *et al*. (2016); Chen *et al*. (2023); Rozov *et al*. (2023)
MCNP	The Monte Carlo N-Particle (MCNP) code is a general-purpose radiation transport code used for simulating the behavior of particles, including photons, electrons, and neutrons, in various materials and scenarios.	Brice (1998); Gul *et al*. (2016); Shaat *et al*. (2020)
TOUGH	The TOUGH (Transport of Unsaturated Groundwater and Heat) suite of codes is used to simulate coupled thermal-hydrological-mechanical-chemical (THMC) processes, including radionuclide transport in the subsurface.	Mori *et al*. (2015); Wen *et al*. (2015); Lee *et al*. (2023)
HydroGeoSphere	HydroGeoSphere (HGS), developed by Aquanty Inc., is an integrated simulator designed for surface and subsurface flow, as well as solute and thermal transport. It has found extensive application in various nuclear-related studies and projects, offering features for radionuclide transport, including scenarios with and without discrete fractured networks in bedrock.	Blessent (2009); Levison (2009); Blessent *et al*. (2011); McKelvie *et al*. (2011); Hoppe (2013); Sudicky *et al*. (2013); Park *et al*. (2020); Aquanty Inc. (2023); Musy *et al*. (2023)

ing BDL data leads to narrow distributions with high peak values for residual concentrations of various radionuclides. However, incorporating BDL leads to increased variability while reducing peak values. Furthermore, they suggested that the MLE method generally provides the highest average concentration estimates and the lowest standard deviations for the majority of radionuclides (^{226}Ra, ^{228}Ra, ^{228}Th, ^{230}Th, and ^{232}Th). This may be because it forces the data into parametric distributions. The KM method, a nonparametric approach, results in the lowest means and the largest standard deviations for these radionuclides, including ^{234}U. In contrast, the ROS method yields estimates falling between the KM and MLE methods regarding both mean and standard deviation. The results from traditional methods can occasionally resemble those obtained from statistically robust methods (KM, ROS, and MLE).

In summary, the choice of method has a significant impact on the estimated residual concentrations, with MLE generally providing higher mean estimates, KM lower means with higher variability, and ROS falling in between. The findings showed that substituting BDL data with DL yields the highest mean concentrations of soil radioactivity for the majority of the radionuclides examined. Ignoring BDL values gives the next highest concentrations for these radionuclides, which implies that treating BDL data by either ignoring it or substituting it with DL data represents a conservative approach in analyzing dose values, though the differences in the resulting mean concentrations were relatively insignificant.

2.4. Kori Unit 1 nuclear power plant decommissioning site

Byon *et al*. (2020) focused on evaluating soil contamination at the Kori Unit 1 nuclear power plant decommissioning site, both on the surface and subsurface. It employed the RESRAD-OFFSITE code (Gnanapragasam and Yu, 2015) for realistic dose modeling, taking into account factors covering contaminant movement in air and groundwater systems and secondary pollution. The study established a guideline known as the Derived Concentration Guideline Level (DCGL), which is important for determining the maximum concentration of each radionuclide in groundwater. To analyze the primary exposure pathways, site-specific parameters were applied both at the Kori site and offsite in 'Area 1', where residents are situated 0.7−1.5 km from the reactor. A preliminary dose estimation for 'Area 1' was also performed. This research offers a framework for assessing soil contamination at decommissioning nuclear power plant sites, covering surface and groundwater contamination and providing a model for basement fill. It serves as a guideline for evaluating similar sites, relying on the characterization of Kori Unit 1.

Byon *et al*. (2020) considered two methods for evaluating soil contamination at Kori Unit 1: one based on a simplified conceptual site model, and another following the methodology used at Rancho Seco Nuclear Power Plant, which utilized four unsaturated zones. In contrast, the Zion Nuclear Power Plant approach involved separate evaluations for surface and subsurface soils. The Zion NPP method was more comprehensive, incorporating a structured and current assessment that considered media-specific characterization, including groundwater results. To calculate doses and DCGLs for surface and groundwater contamination, the RESRAD-OFFSITE code was applied both on-site and in the offsite 'Area 1'. In decommissioning nuclear power plants, the comprehensive soil evaluation process includes deriving DCGLs for both surface and subsurface soil materials for individual radionuclides, using site release criteria, and calculating the factors influencing groundwater exposure through the Basement Fill Model (BFM) for assessing groundwater contamination and determining the concentration of mixtures of multiple radionuclides using surrogate ratios and the unity rule. Additionally, the procedures include conducting dose assessments and demonstrating compliance with release criteria. It is important to note that the study excluded considerations of the area factor and $DCGL_{EMC}$ (Derived Concentration Guideline Level for Elevated Residual Radioactivity).

3. Contaminant investigation tools and result analysis

General modeling tools for radionuclide transport encompass various software and codes used to simulate the movement of radioactive materials in the environment. These tools are crucial for assessing the dispersion, fate, and potential risks associated with radionuclides. Some commonly used modeling tools are included in Table 1.

These tools are essential for assessing and estimating how radionuclides behave in different environmental settings, including soil, groundwater, surface water, or the atmosphere. The selection of a specific tool depends on the modeling objectives, the characteristics of the system under study, and the level of detail required for the analysis.

4. Data collection and processing

Radionuclide transport modeling involves a variety of parameters that describe the behavior of radioactive materials in the environment. These parameters can be specific to the particular radionuclides being modeled and the characteristics of the site. The advection-dispersion governing equation incorporating multi-species reactions can be written as (Hwang *et al*., 2019; Aquant Inc., 2023):

Table 2. Parameter values used in literature for radionuclide modeling.

Radionuclide	Location	Data type	Groundwater velocity (m/d)	R	K_d	Reference
^{90}Sr	Chernobyl NPP	Field observation	0.47-0.56	3.8	0.8	Bugai *et al*. (2019)
^{137}Cs	El-Negila, Egypt	NPP risk assessment modeling (RASCAL, MODFLOW2000, MT3DMS)	0.000585			Aly *et al*. (2020)
^{90}Sr	El-Negila, Egypt	NPP risk assessment modeling (RASCAL, MODFLOW2000, MT3DMS)	0.000585	5.5	0.8	Aly *et al*. (2020)

$$\nabla \cdot (\phi S_w D \nabla C_i - qC_i) + [\phi S_w R \lambda_i C_i]_{par} \pm \Omega_c = \frac{\partial(\phi S_w R C_i)}{\partial t} + \phi S_w R \lambda_i C_i \quad (1)$$

where C_i (M L^{-3}) represents a species concentration, denotes time (T), D (L^2 T^{-1}) indicates the hydrodynamic dispersion, Ω_c (M L^{-2} T^{-1}) represents the source/sink term, λ_i (T^{-1}) is the first-order decay rate, and is water flux in the variably-saturated zone (L T^{-1}). In the scenario of a straightforward decay chain, there is a single parent species, similar to what occurs in radioactive decay. However, for organic compounds undergoing degradation, a specific species may originate from multiple parent sources due to the complexity of the degradation pathways. The retardation factor, R, is given by:

$$R = 1 + \frac{\rho_b}{\phi S_w} k_d \quad (2)$$

where ρ_b represents the bulk density (M L^{-3}) and K_d indicates the equilibrium partition coefficient that characterizes a linear Freundlich adsorption isotherm refers to the relationship between the concentration of a substance adsorbed onto a surface and its concentration in the surrounding medium, where the adsorption process follows a linear form of the Freundlich model (M^{-1} L^3). It is important to note that under variably-saturated conditions, the water saturation level is included in the definition of the retardation factor (R). The parameters required for modeling radionuclide transport are collected using the variables specified in the corresponding equation.

Table 2 lists the simulation conditions applied to nuclear power plant sites and their corresponding radionuclide species. Bugai *et al*. (2019) performed ^{90}Sr simulations in groundwater system with a velocity ranging from 0.47 to 0.56 m/d. The distribution coefficient and retardation factor applied are 0.8 and 3.8 d^{-1}, respectively. Aly *et al.* (2020) also simulated ^{137}Cs and ^{90}Sr to perform a risk assessment of a nuclear power plant site in El-Negila, Egypt. The retardation and distribution parameters applied for the ^{90}Sr simulations were 5.5 and 0.8, respectively.

Table 3 provides an overview of several radionuclides commonly discharged from nuclear power plants, outlining key characteristics that influence their environmental behavior and potential impacts. ^{131}I, with a short half-life of 8 days, is soluble in water and can be absorbed by vegetation, posing concerns about thyroid exposure in humans. ^{137}Cs, a fission byproduct with a half-life of 30 years, is soluble and binds to soil particles, making it persistent in the environment and capable of uptake by plants. ^{90}Sr, another fission byproduct with a half-life of 28.8 years, behaves chemically like calcium and is known for bioaccumulation in the food chain, particularly in dairy products. ^{239}Pu, a product of nuclear reactors and certain weapons, is an alpha emitter and poses hazards if inhaled or ingested. ^{99}Tc, with a half-life of 211,000 years, is highly soluble and mobile in the environment, raising concerns about its long-term impact. Understanding these characteristics is crucial for assessing the environmental fate and potential risks associated with radionuclide discharge from nuclear facilities.

Table 4 lists the field estimation values for total activity of key radiologically significant radionuclides (^{137}Cs, ^{90}Sr, $^{238\text{-}241}Pu$, and ^{241}Am) at different sites in the Chernobyl exclusion zone (CEZ). According to Bugai *et al*. (2022), The cooling pond represents another important 'point source,' contaminated as a result of the contaminated water discharged from the ChNPP Unit 4 emergency cooling system and radioactive fallout on the surface of the water. Key contamination sources and their inventories are out-

Table 3. Characteristics of selected radionuclides discharged from nuclear power plants (IAEA, 2019).

Radionuclide	Half-life	Decay	Source	Behavior	Environmental concerns
^{131}I	8 days	Beta decay	Nuclear fission (reactors)	Highly soluble in water, can be absorbed by vegetation	Short-lived, concerns about thyroid exposure in humans
^{137}Cs	30 years	Beta decay	Nuclear fission (reactors, weapons testing)	Soluble in water, binds to soil particles	Persistent in the environment, potential uptake by plants
^{90}Sr	28.8 years	Beta decay	Nuclear weapons testing, fission byproduct	Behaves chemically like calcium	Bioaccumulation in the food chain, especially in dairy products
^{241}Am	432 years	Alpha decay	Nuclear reactors (spent fuel)	Resembles plutonium and europium chemically	Concern if released into the environment, alpha radiation hazard
^{239}Pu	24,110 years	Alpha decay	Nuclear reactors, certain nuclear weapons	Behaves chemically like other actinides	Hazardous if inhaled or ingested due to alpha radiation
^{99}Tc	211,000 years	Beta decay	Nuclear reactors (fission product)	Highly soluble in water, mobile in the environment	Long-lived, concerns about its potential environmental impact

Table 4. Characteristics of radionuclides contaminated in Chernobyl nuclear power plant (unit: Bq) (Bugai *et al*., 2022).

Species	Radionuclide half-life, years	Activity inventory	Radioactive waste dump sites	Cooling pond (bottom sediments)
^{137}Cs	30.2	2×10^{15}	1.6×10^{14}	1.2×10^{14}
^{90}Sr	28.8	5.4×10^{14}	1.3×10^{14}	1.7×10^{13}
^{238}Pu	87.7	6.2×10^{12}	1.2×10^{12}	2.1×10^{11}
$^{239+240}Pu$	2.4×10^{4} (^{239}Pu) 6.5×10^{3} (^{240}Pu)	1.5×10^{13}	2.9×10^{12}	5.2×10^{11}
^{241}Am	432.2	2.7×10^{13}	5.3×10^{12}	9.5×10^{11}
Reference		Kashparov *et al.* (2004)	Molitor *et al.* (2017)	Buckley *et al.* (2002)

lined in Table 4. ChNPP Unit 4 'Sarcophagus' is a well-known 'hot spot' for groundwater contamination, with potential contamination sources including a buried soil layer related to the accident, containing nuclear fuel materials.

The case studies revealed that accurate prediction of radionuclide transport heavily depends on the uncertainties associated with the physical and chemical parameters used in the numerical models. In the context of radionuclide transport modeling, the evaluation of parameter values, commonly known as QA/QC for model inputs, is vital in guaranteeing the reliability and precision of simulation results. This phase involves a thorough examination and validation of the input parameters used in the transport models, aiming to assess their quality, consistency, and appropriateness. Parameter values such as initial concentrations, dispersion coefficients, decay constants, and other relevant factors are scrutinized to meet established quality standards. Rigorous QA/QC procedures are implemented to verify the accuracy of the input data, drawing on calibration exercises, field measurements, and laboratory analyses. The evaluation of parameter values is an integral step in the modeling process, contributing to the overall robustness and credibility of the simulations, and providing a foundation for making informed decisions regarding radionuclide transport in the studied environments. This ensures that the modeling outcomes align with real-world conditions, enhancing the reliability of predictions and supporting the effective management of radiological risks.

5. Database system development

The case studies revealed that investigating a particular site requires extensive data collection, and managing a reliable database system is crucial for achieving successful model outcomes and, consequently, effective site management. The development of a robust database system is essential for efficiently managing and organizing large volumes of

Table 5. Essential considerations of developing a database system for radionuclide transport modeling.

Consideration	Implementation
Database architecture and design	Define data structure, entity relationships, and ensure data integrity. Accommodate radionuclide transport data integration and scalability. Design database architecture to accommodate radionuclide transport data, ensuring scalability and flexibility.
Data quality Assurance and quality control	Implement robust QA/QC measures for data accuracy and consistency. Validate input parameters and address data inconsistencies. Conduct thorough validation of input parameters, periodic checks, and adhere to standardized protocols for data quality.
User interface and accessibility	Develop an intuitive interface for easy data input, retrieval, and analysis. Consider user permissions and data-sharing functionalities. Prioritize intuitive interface development and incorporate user permissions and data-sharing features for accessibility.
Integration with modeling software	Ensure seamless integration with modeling software for efficient data transfer. Enhance workflow efficiency and compatibility with industry standards. Integrate database system with modeling software for streamlined data transfer and compatibility with industry standards.
Security and ethical considerations	Enforce strong security measures, including encryption and access controls. Address ethical considerations including data privacy and consent. Adopt encryption, enforce access control measures, and carry out frequent security audits. Address ethical considerations to align with regulations.

data in diverse applications. In the context of radionuclide transport modeling, a comprehensive database system serves as the backbone for storing, retrieving, and managing various parameters, observational data, and simulation results. Table 5 explores the key aspects of developing a database system necessary for general radionuclide transport modeling.

In summary, the development of a database system for radionuclide transport modeling requires meticulous attention to architecture, data quality, user interface, integration capabilities, security, and ethical considerations. This is essential to create a reliable and user-friendly tool that advances scientific understanding and facilitates informed decision-making in radiological environmental assessments. A well-organized dataset serves as the foundation for constructing machine learning models that can effectively decipher complex relationships within radionuclide transport systems, contributing to more accurate predictions and informed decision-making in radiological environmental assessments.

6. Conclusions

As the need for decommissioning aging nuclear power plants increases, the technology for efficient site remediation has become crucial. For effective remediation, a systematic assessment of subsurface contamination and prediction of its spread are necessary. Additionally, an integrated system that evaluates and predicts contamination and selects optimal remediation technologies is required.

To establish a fundamental understanding of radioactive contamination at nuclear power plants, a literature review was conducted on the status of radioactive contamination and radionuclide transport modeling at these sites. This review expanded into case studies that analyze the types, extents, effects, and site conditions of contamination. Additionally, the review covered essential aspects for developing a data system for radionuclide transport modeling, including database architecture, data quality, user interface, integration capabilities, security, and ethical considerations. The review suggests that the appropriate selection of numerical models for specific site conditions, thorough data collection and processing, and the development of reliable database systems are key factors for the effective management of decommissioned nuclear power plants.

Through this comprehensive review, a foundation for modeling contaminant transport in heterogeneous unsaturated zones, which has not been adequately addressed previously, can be established. Furthermore, by providing detailed literature information on the distribution and transport of contaminants at contaminated sites, this review paper lays the groundwork for more accurate assessments and efficient site remediation.

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