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Risk and Pollutant Protective Concentration Levels of Drilling Waste Used to Pave Oil and Gas Field Well Sites

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Abstract: Paving oil and gas field well sites of drilling waste allow us to reuse solid waste. However, to keep the risk within acceptable limits, some questions need to be answered: what is the dilution effect that soil and groundwater have on the transport of pollutants? What is the minimum concentration of pollutants leached from drill wastes? In this study, we focus on the paving of well sites using drilling wastes, and we analyze the pollutant migration pattern in the soil vadose zone and groundwater mixing zone after rainwater leaching. The drilling waste pollutant protective concentration level (PCL) and the corresponding dilution attenuation factor (DAF) were then proposed. In addition, the PCL's accessibility, uncertainty, and environmental significance were further analyzed. It was found that the pollutant dilution factor (DF) of the groundwater mixed zone was strongly influenced by the thickness of the mixed zone, the groundwater Darcy rate, the length of the contaminant source, and the permeability, and each contributed approximately 25%. The soil vadose zone attenuation factor (AF) was primarily influenced by the soil vadose zone (i.e., groundwater depth) thickness that contributed approximately 53%. The contaminant DAF values of the well site drilling waste paving (e.g., the soil vadose zone thickness ranged from 5 to 30 m) ranged from 12 to 84. Additionally, the PCL values of the contaminants ranged from 12 to 84 times of the acceptable concentration (e.g., the Class III permissible limits of the Groundwater Quality Standards GB/T 14848-2017) at the groundwater compliance point. The expression for the exponential relationship between the DAF or PLC and the depth of the soil vadose zone was also provided in this study. The study results provide a reference for the actual process of the use of drilling wastes to pave well sites and for solid waste treatment or soil remediation decision-making and the associated risk assessment procedures.

Keywords: drilling waste; well site; protective concentration levels; leachate; dilution attenuation factor

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Academic Editors: Javier Rodrigo-Ilarri and José-Esteban Capilla-Romá

Received: 4 November 2024
Revised: 11 December 2024
Accepted: 20 December 2024
Published: 26 December 2024

Citation: Yang, J.; Yang, Y.; Tian, L.; Zhou, J.; Wang, Y. Risk and Pollutant Protective Concentration Levels of Drilling Waste Used to Pave Oil and Gas Field Well Sites. *Water* **2025**, *17*, 30. https://doi.org/10.3390/w17010030

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1. Introduction

Drilling waste treatment and disposal have become difficult problems for the oil and gas industry with the rapid growth of global oil and gas exploration. Large amounts of drilling waste are being generated. For instance, Chinese crude oil production was 1.86×10^8 t and the natural gas production was 1.71×10^{11} m^3 in 2021, an increase of approximately 5% compared with the 2020 statistics [1]. The worldwide exploration and exploitation of oil and gas resources have increased to ensure the world's energy security. Drilling wastes are solid wastes produced during oil and gas extraction, and they include

drilling cuttings, dehydrated drilling mud (water-based or oil-based) [2], and oily waste degreasing residue. An approximate total of 375,000 m^3 (approximately 700,000 t) of oil-based drilling wastes was generated in China by the end of 2020 from typical gas wells. Approximately 250 m^3 of drilling wastes can be produced by a single gas well, and drilling wastes can reach up to 800–1000 m^3 for a single deep oil well [3]. The total drilling waste amount is predicted to remain stable at $>3 \times 10^7$ m^3 during the next 10 years [4]. There will be higher costs to dispose of drilling wastes when delegated to other companies. However, drilling wastes contain multiple contaminants such as soluble heavy metals, petroleum hydrocarbons (PHs), organic pollutants, and other additives. If drilling wastes are improperly disposed of or discharged directly to the environment, this will cause serious environmental pollution [4]. It is necessary to research resource utilization methods for drilling wastes that can accommodate high quantities and be environmentally friendly to meet the future strategic needs of the oil and gas industry.

Drilling wastes are currently utilized and disposed of by means of landfills, stockpiles, burned bricks/ceramics, prepared concrete, and paved well sites, or they are injected into salt mines [4]. Burned bricks and ceramic granules can effectively solidify the heavy metals found in drilling wastes, but it is difficult to process large quantities of drilling wastes due to the light consumption of bricks or ceramics. Paving oil and gas field drilling well sites are effective and lower cost methods to dispose of large quantities of drilling wastes. However, due to the presence of PHs and heavy metals in the drilling wastes, contaminants may migrate to the groundwater underneath the drilling wastes as they are leached by rainfall under a paved well site scenario. Hence, the environmental risk of the groundwater exposure pathway is a key risk under this scenario. Therefore, it is necessary to study the pollutant migration and transformation laws and propose protective pollutant concentration levels (PCLs) for drilling wastes that can accomplish acceptable health risks for drilling waste bedding well sites. In this study, we attempt to produce a data-based theoretical foundation for the large-scale, low-cost, and environmentally friendly disposal of drilling wastes.

The contaminant transport patterns in porous media, soil, and groundwater have been well studied; however, no specific guidance had been provided on what leaching concentrations are allowed for drilling wastes used in paved well sites. This is not conducive to environmental management and oil and gas industry development. Various researchers [5–8] have analyzed the theory and model of solute transport in porous media, and this provides a theoretical basis for the transport of soil pollutants. The soil attenuation model was used to calculate the soil screening values to form a series of USA standards [9]. However, at the time, there were fewer applications of existing porous media models to study pollution control in solid waste paved well sites. The three types of media, namely, the surface solid waste, the soil envelope, and groundwater, had not yet been considered in an integrated manner to study the acceptable contamination level for solid waste when solid waste is used as bedding for a well site. These factors result in the high-cost over-treatment of solid waste pollutants and the over-regulation of solid waste pollutants.

Therefore, a steady-state continuous source model was used to study contaminant transport from solid wastes into soil and groundwater from drilling waste bedded well sites.

The model construction consisted of (1) the simulation of the process of pollutants entering the soil vadose zone and groundwater mixing zone with rainwater under the drilling waste bedded well site; (2) the adoption of a risk assessment of the drinking groundwater pathway to obtain the C_2 pollutant concentration at the groundwater exposure point (Figures 1 and 2); (3) the calculation of the pollutant dilution factor (DF) and C_1 concentration at the groundwater mixing zone; (4) the calculation of the attenuation factor (AF) and C_0 concentration at the soil vadose zone; (5) an analysis of the parameter sensitivity

and the relationship between the *DF*, *AF*, *PCL*, and soil vadose zone thickness; and (6) an analysis of the *PCL* accessibility, uncertainty, and environmental significance. This study provides recommendations for decision-making regarding the utilization and disposal of drilling wastes and a methodology for an environmental risk assessment of solid waste disposal on land.

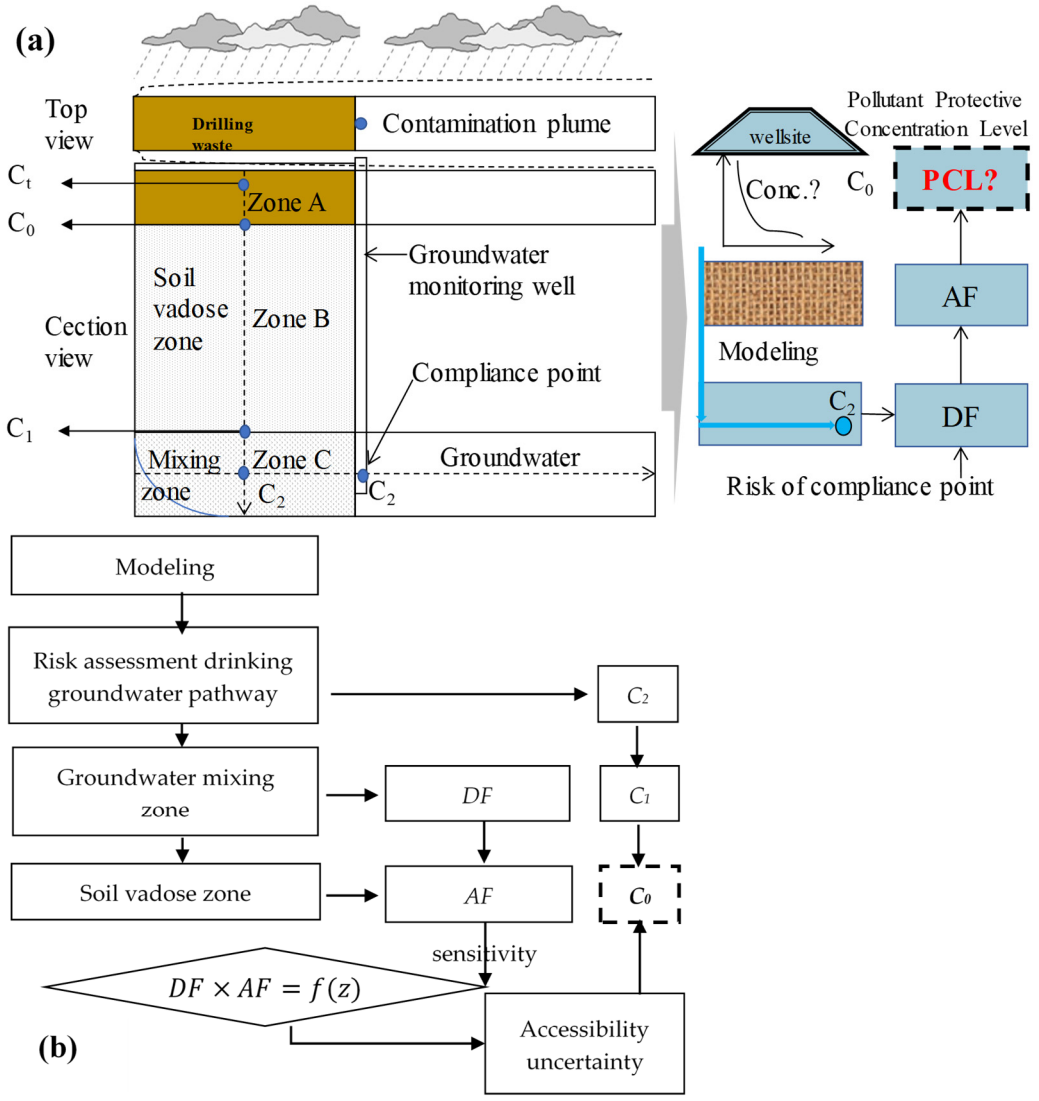

Figure 1. Pollutant protective concentration levels of pollutant based on migration pathway (**a**) and logic structure diagram (**b**). C_2 is defined as the heavy metal and petroleum hydrocarbon concentration of the groundwater mixing zone (Zone C in (**a**)); C_1 is defined as the heavy metal and petroleum hydrocarbon concentration of end of the soil vadose zone (end of Zone B in (**a**)); C_0 is defined as the heavy metal and petroleum hydrocarbon concentration of the end of drilling waste (end of Zone A in (**a**)); *PCL* is defined as protective pollutant concentration levels; *DF* is defined as the pollutant dilution factor; *AF* is defined as the attenuation factor.

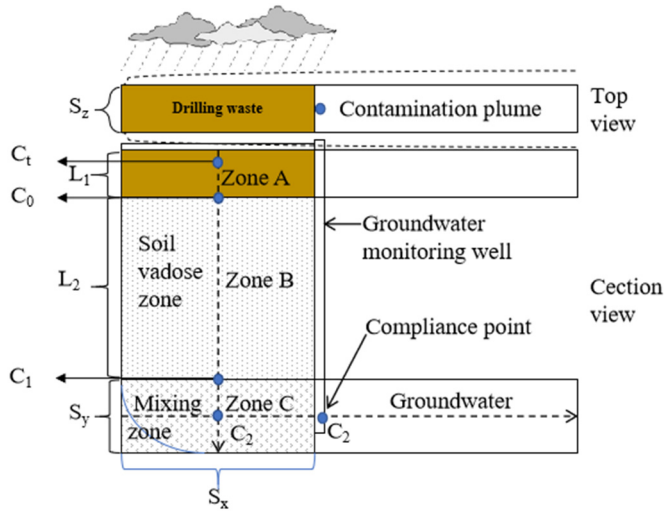

Figure 2. Conceptual model of the drilling waste paving well site.

2. Materials and Methods

2.1. Model

Drilling waste was used to pave the well site, and the upper layer was covered with natural soil to reduce the pollutant gas-phase migration pathway. Thus, the pollutant migration pathway of the drilling wastes was dominated by the leaching of precipitation into the groundwater through the soil. A schematic diagram of the drilling waste bedded well field is shown in Figures 1 and 2. The pollutants passed through three zones in sequence using rainwater as a carrier: the drilling waste (Zone A), the soil vadose zone (Zone B), and the groundwater mixing zone (Zone C). In this study, the pollutant migration processes in Zone B and Zone C were considered. Pollutants, such as heavy metals and PHs, were released in a continuous source, steady-state manner. There was a pollution dilution attenuation effect in zones B and C. The basic assumptions are presented below.

2.2. Exposure Concentration of the Compliance Point of Petroleum Hydrocarbons (PHs) in the Groundwater

Since the PH exposure concentration of the compliance point in groundwater is not yet available in the China Groundwater Quality Standards [10], it was calculated based on the non-carcinogenic risk of the drinking groundwater pathway, as follows [11,12]:

$$C_2 = AHQ \times RfD_o \times WAF \div CGWER_{nc} \quad (1)$$

$$CGWER_{nc} = \frac{GWCR_a \times ED_a \times EF_a}{BW_a \times AT_{nc}} \quad (2)$$

where C_2 is the contaminant concentration compliance point in the groundwater, mg/L; *AHQ* is the acceptable hazard quotient for the individual contaminant, dimensionless; *RfDo* is the reference dose for oral ingestion, mg/(kg·d); *WAF* is the groundwater allocation factor, dimensionless; *CGWERnc* is the exposure to contaminants that corresponds to the drinking of affected groundwater, L/(kg·d); *GWCRa* is the daily water consumption of an adult, L/d; *EDa* is the exposure period of an adult, a; *EFa* is the frequency of exposure of an adult, d/a; *BWa* is the body weight of an adult, kg; and *ATnc* is the average time of the non-carcinogenic effect, d.

2.3. Dilution Factor for Contaminants in the Groundwater Mixing Zone

The contaminant dilution effect in the groundwater mixing zone is described in Equation (3) [13,14]. The model is similar to the steady-state Additive Manufacturing

Technology standard model and is based on the following assumptions: (1) a uniform and constant concentration in the source; (2) an instantaneous linear equilibrium partitioning of the contaminant between the different phases; (3) a uniform dilution of the leachate with groundwater within a "mixing box" in the aquifer; and (4) an unconfined aquifer with homogeneous and isotropic hydrologic properties [13,14].

Consequently, the pollutant concentration threshold C_1 at entry into the mixing zone is represented as follows (the threshold for Zones B and C):

$$C_1 = C_2 \times \left(1 + \frac{k \times i \times S_y}{Inf \times S_x}\right) \tag{3}$$

where k is the hydraulic conductivity, m/d; i is the hydraulic gradient, dimensionless; S_y is the thickness of the mixing zone, m; S_x is the length of the contamination source along the direction of water flow, m; and inf is the infiltration rate, m/d.

Therefore, the DF of the contaminants in the groundwater mixing Zone C is as follows:

$$DF = 1 + \frac{k \times i \times S_y}{Inf \times S_x} \tag{4}$$

2.4. Attenuation Factor for Contaminants in the Soil Vadose Zone

The pollutant transport in the soil vadose zone followed the following basic assumptions: (1) pollutants were transported in the soil vadose zone in a one-dimensional vertically downward direction; (2) pollutants underwent adsorption–resolution in the soil vadose zone with a retention factor of R_{d1}; and (3) the pollutant reactions in the liquid phase were consistent with a first-order kinetic process, with a reaction constant of λ. The chemical reactions of the pollutants adsorbed into the solid phase were not considered. The differential equations for the transport of pollutants in the soil vadose zone are as follows:

$$\frac{\partial C}{\partial t} = \frac{D_1}{R_{d1}} \frac{\partial^2 C}{\partial z^2} - \frac{u_1}{R_{d1}} \frac{\partial C}{\partial z} - \lambda C \tag{5}$$

where t is the migration time, d; D_1 is the hydrodynamic dispersion coefficient, m^2/d; z is the vertical migration distance (or thickness of soil vadose zone), m; μ_1 is the seepage velocity, m/d; and R_{d1} is the retardation factor, dimensionless.

The initial and boundary conditions were as follows:

$$C(z,t)\mathrm{I}_{t=0} = 0,\ 0 \le z \le +\infty \tag{6}$$

$$C(z,t)\mathrm{I}_{z=0} = C_0,\ t > 0 \tag{7}$$

$$C(z,t)\mathrm{I}_{z\to+\infty} = 0,\ t > 0 \tag{8}$$

Using the Laplace transform, the solution for a one-dimensional semi-infinite domain was obtained [15], as shown below:

$$\frac{1}{C_0} = \frac{1}{2C_1}\left[\begin{array}{l} \exp\left(\frac{(u_1-\mathrm{w})\cdot z}{2\cdot D_1}\right)\cdot \mathrm{erfc}\left(\frac{R_{d1}z-\mathrm{w}t}{2\sqrt{R_{d1}D_1 t}}\right)+ \\ \exp\left(\frac{(u_1+\mathrm{w})\cdot z}{2\cdot D_1}\right)\cdot \mathrm{erfc}\left(\frac{R_{d1}z+\mathrm{w}t}{2\sqrt{R_{d1}D_1 t}}\right) \end{array}\right] \tag{9}$$

where

$$R_{d1} = \left(1 + \frac{\rho_{b1} K_{d1}}{\theta}\right) \tag{10}$$

$$w = \sqrt{{u_1}^2 + 4\lambda D_1} \tag{11}$$

$$\mathrm{K_{d1}} = \mathrm{K_{oc}}\cdot \mathrm{f_{oc}} \tag{12}$$

$$f_{oc} = \frac{f_{om}}{1.7 \times 1000} \tag{13}$$

$$D_1 = \alpha_1 \cdot u_1 + D^* \tag{14}$$

$$\alpha_1 = 0.83(\log z)^{2.414} \tag{15}$$

Hence, the pollutant concentration when entering the soil (thresholds in Zones A and B) can be represented as follows:

$$C_0 = C_1 \times AF. \tag{16}$$

Thus, the AF of contaminants in the soil vadose zone is given by

$$\frac{1}{AF} = \frac{1}{2}\left[\begin{array}{l} \exp\left(\frac{(u_1 - w)\cdot z}{2\cdot D_1}\right) \cdot \operatorname{erfc}\left(\frac{R_{d1} z - wt}{2\sqrt{R_{d1} D_1 t}}\right) + \\ \exp\left(\frac{(u_1 + w)\cdot z}{2\cdot D_1}\right) \cdot \operatorname{erfc}\left(\frac{R_{d1} z + wt}{2\sqrt{R_{d1} D_1 t}}\right) \end{array} \right] \tag{17}$$

Thus, the *PCL* of contaminants in the drilling waste is given by the following equation:

$$PCL = C_2 \times DAF \tag{18}$$

where $DAF = DF \times AF$.

2.5. Samples and Test Methods

To analyze the accessibility of the PCL of pollutants in drilling wastes, 42 water-based drilling cuttings were obtained from the oil and gas fields in typical regions of China. Those samples were mixed with deionized water (liquid–solid ratio 10:1). The mixture was placed on a horizontal oscillating device with an oscillation frequency of 110 ± 10 times/min and an amplitude of 40 mm for 8 h, and then stood for 16 h. The leachate was filtered. This procedure was based on the "Toxicity Leaching Methods for Solid Waste Leaching Horizontal Oscillation Method" [16,17]. The heavy metal leaching concentrations in drilling wastes were determined by inductively coupled plasma mass spectrometry. The PH concentration in the leachate was detected by gas chromatography. In addition, data on other pollutant concentrations in drilling waste were analyzed using various references.

2.6. Analysis Method and the Monte Carlo Simulation

Origin 2021 was used to analyze the pollutant concentration of the drilling waste distribution. The Monte Carlo simulation (MCS) was used to determine uncertainty or sensitivity. The computations were conducted using 10,000 iterations [18]. Crystal Ball V11.1.2.4 software was used for the MCS [18].

3. Results and Discussion

3.1. Pollutant Exposure Concentrations at the Groundwater Compliance Point

The exposure concentration at the groundwater compliance point in groundwater C_2 was calculated based on Section 2. When the acceptable hazard quotient of the human health risk of the groundwater drinking pathway was 1, the C_2 of *PH* was calculated, as shown in the Table S1. Parameters such as *GWCRa*, *Eda*, and *Bwa* followed the recommended parameters by the Chinese Population Exposure Parameters Manual and Technical Guidelines for Risk Assessment of Soil Contamination of Land for Construction [19]. The heavy metal exposure concentration compliance point in the groundwater adhered to the Class III permissible limits of the Groundwater Quality Standards, as shown to Table S2.

3.2. Dilution Attenuation (DF) of Contaminants in the Groundwater and Soil in a Region

The DF of the contaminants in the groundwater mixing zone was calculated based on the conceptual diagram and equations for the drilling waste bedding well site, as shown in Table 1. The key parameters of the DF equation referred to the Technical Guidelines for Risk Assessments of Soil Contamination of Land for Construction [11].

Table 1. Dilution attenuation (DF) of contaminants in the mixing zone of groundwater in a region.

Parameter Symbol	Parameter Description	Unit	Value	Source
Ugw	Darcy rate	m/d	0.8	
Sy	Thickness of mixing zone	m	2	[11]
inf	Infiltration rate	m/d	0.0008	
Sx	Length of contaminated source	m	200	Assumed
DF	Dilution factor of mixing zone	Dimensionless	11	Equation (4)

The AF for contaminants in the soil vadose zone was calculated based on the conceptual diagram and equations for the drilling waste bedding well site, as shown Table 2. The AF of the contaminants with the current parameters is shown in Table 2.

Table 2. AF of contaminants in the soil vadose zone in a region.

Parameter Symbol	Parameter Description	Unit	Value	Source
μ_1	Seepage velocity in soil vadose zone	m/d	0.07	Assumed
ρ_{b1}	Bulk density	kg/L	1.67	[11]
k_{oc}-PH	Organic-water partition coefficient	L/kg	796	EPA
f_{om}	Organic matter content in soils	g/kg	17.4	[11]
f_{oc}	Organic carbon content	Dimensionless	0.01	Equation (13)
K_{d1}	Soil–water distribution Coefficient	L/kg	8.15	Equation (12)
θ	Porosity water filled	Dimensionless	0.54	[11]
R_{d1}	Retardation factor	Dimensionless	26.2	Equation (10)
λ	Decay constant	1/d	0.0019	Assumed
z	Thickness of soil vadose zone	m	10	Assumed
α_1	Dispersivity (longitudinal)	m	0.83	Equation (15)
D*	Molecular diffusion coefficient	m^2/d	0.0002	Assumed
D_1	Hydrodynamic dispersion coefficient	m^2/d	0.02	Equation (14)
t	Time	d	25,550	Assumed
AF-PH	Attenuation factor	Dimensionless	1.32	Equation (17)
AF-As			1.32	
AF-Ba			1.26	
AF-Cr^{6+}			1.27	
AF-Co			1.46	
AF-Cu			1.42	
AF-Pb			1.26	
AF-Mn			1.50	
AF-Hg			1.52	
AF-Mo			1.29	
AF-Ni			1.27	
AF-Se			1.25	
AF-Zn			1.27	

Therefore, the PH combined dilution attenuation factor ($DAF = DF \times AF$) of the drilling waste was 14.52 when the drilling waste was used to pave a well site under conditions such as a 10 m soil vadose zone thickness, as shown in Tables 1 and 2. In addition, the heavy metal DAF values ranged from 13.75 to 16.72. The disposal of drilling wastes in regions with similar parameters as those shown in Tables 1 and 2 refers to these DAF values.

3.3. DAF Parameter Sensitivity Analysis

A sensitivity analysis [19] was performed based on the MCS [20–23] to evaluate the effect of parameters on the DAF. Figure 3 shows that four parameters, namely, the mixing zone thickness (S_y), the Darcy rate (U_{gw}), the length of the contaminated source (S_x), and the infiltration rate (inf), affected the DF value. The soil vadose zone thickness had a greater influence on the AF value. For all parameters, the soil vadose zone thickness was more easily screened or controlled during the actual paving well site scenarios. Therefore, it was necessary to describe the relationship between the different soil vadose zone thicknesses and the dilution attenuation coefficients.

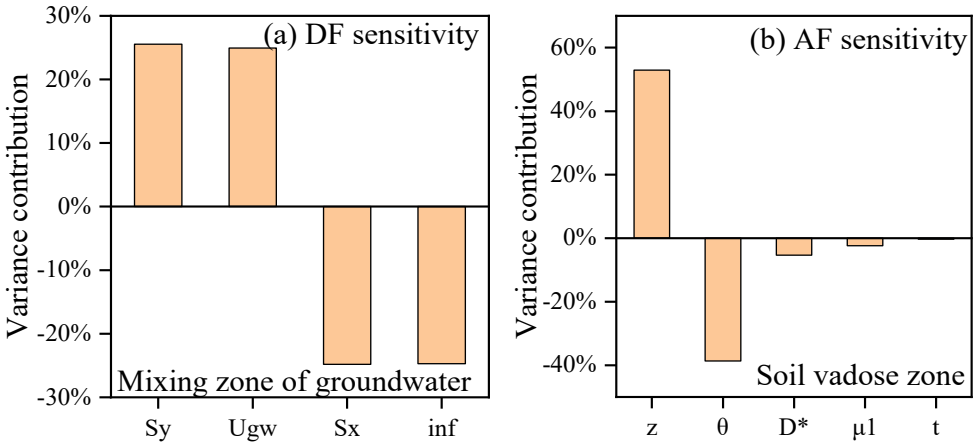

Figure 3. Sensitivity analyses of DA and AF.

3.4. Relationship of the PCLs and the Soil Vadose Zone Thickness

According to the above-mentioned results, the PCL and DAF values were affected by the soil vadose zone. The DAF variation patterns of different pollutants after passing through the soil vadose zone and the groundwater mixing zone with the soil vadose zone thicknesses are shown in Figure 4. The DAF values were exponentially related to the soil vadose zone thickness according to Equations (4), (17) and (18). The DAF presented the dilution and attenuation effect of soil and groundwater on pollutants. As shown in Figure 4, the dilution and attenuation effect of soil and groundwater on pollutants was positively correlated with the thickness of the vadose zone. The thicker the vadose zone, the stronger the dilution and attenuation effect on pollutants. On another hand, the DAF of different pollutants varied greatly, which was mainly related to the adsorption of pollutants by the soil.

The pollutant PCL values of the drilling wastes corresponding to the different depths of the groundwater were calculated on the basis of the pollutant DAF to determine the applicability of the use of drilling wastes to pave well sites under different geologic conditions (different soil vadose zone thicknesses). In the case of an acceptable pollutant concentration risk at the groundwater compliance point (i.e., the heavy metal concentration was not higher than the standard value of the groundwater category III and the PH concentration was not higher than 0.3 mg/L), the inverse calculation of the PCLs of the drilling waste pollutant is as shown in Figure 5. Among them, the PCL values of the heavy metals Se, Pb, Ni, As, Hg, Cr^{6+}, and Mo were low. However, the PCL values of Zn, Mn, and Cu were

higher, which may have been related to their low toxicity or stronger adsorption by the soil. Therefore, heavy metals such as Se, Pb, Ni, As, Hg, Cr^{6+}, and Mo are more of a concern.

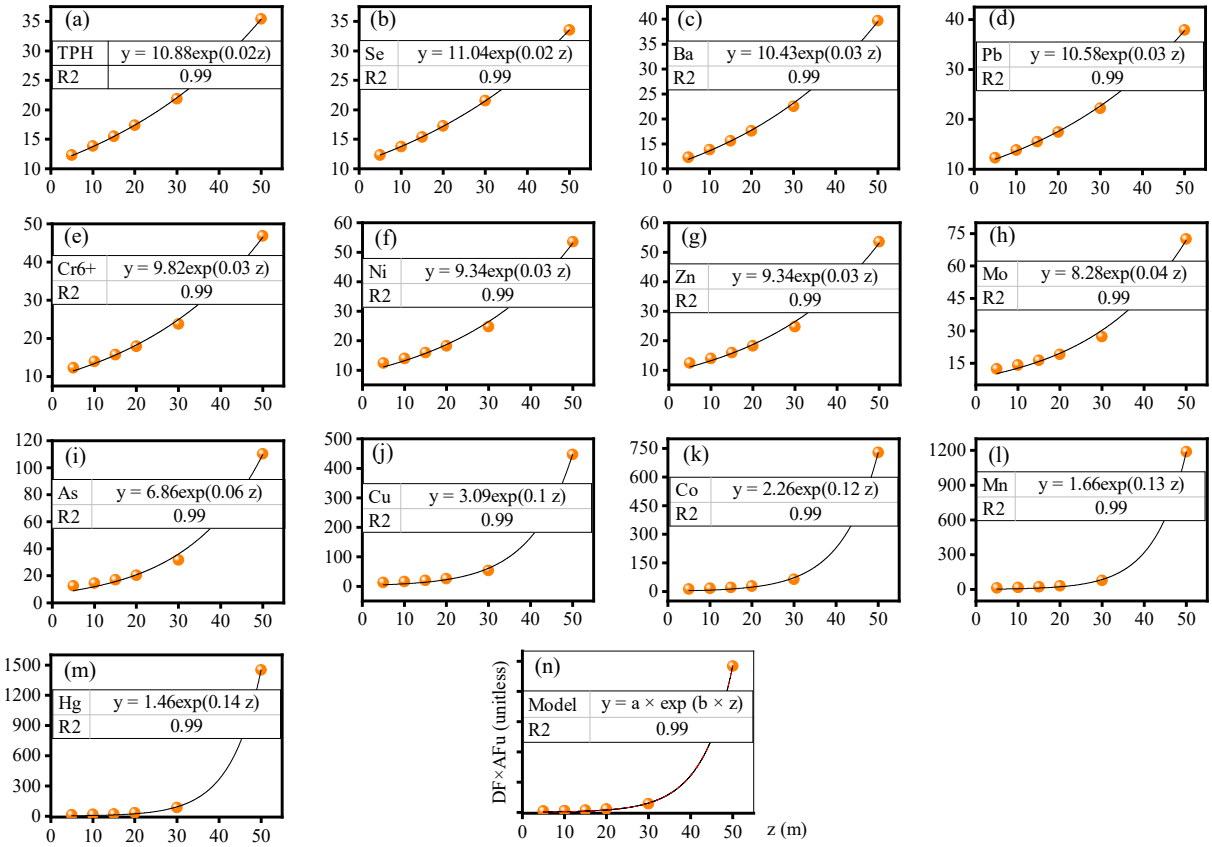

Figure 4. Relationship between DAF and soil vadose zone thickness (z): (**a**) DAF of TPH and z; (**b**) DAF of Se and z; (**c**) DAF of Ba and z; (**d**) DAF of Pb and z; (**e**) DAF of Cr^{6+} and z; (**f**) DAF of Ni and z; (**g**) DAF of Zn and z; (**h**) DAF of Mo and z; (**i**) DAF of As and z; (**j**) DAF of Cu and z; (**k**) DAF of Co and z; (**l**) DAF of Mn and z; (**m**) DAF of Hg and z; (**n**) DAF model general formula.

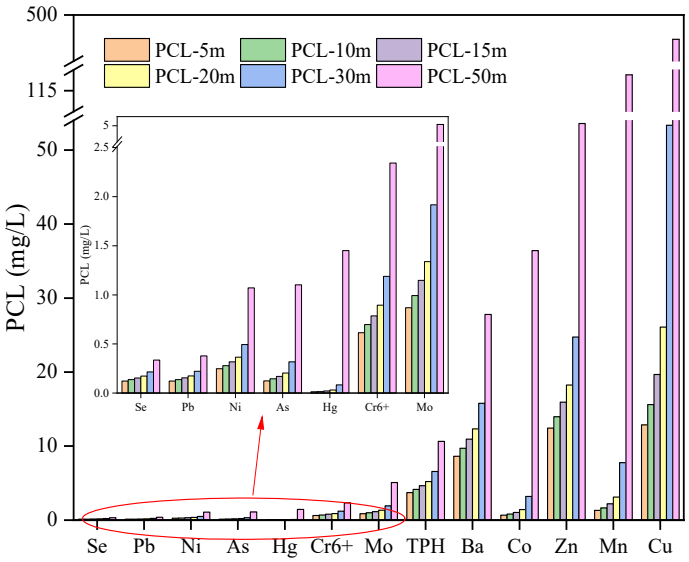

Figure 5. PCLs of pollutants in the drilling wastes for different soil vadose zone thicknesses.

3.5. PCL Reachability of Pollutants in the Drilling Wastes

To investigate the accessibility or reachability of the pollutant PCLs proposed in this study for the use of drilling waste to pave well sites with different soil vadose zone

thicknesses, we investigated the current pollutant leaching concentrations of drilling wastes and analyzed the accessibility or reachability.

First, 42 treated drilling waste samples were collected from Northwest China and analyzed for the PH and heavy metal leaching concentrations. It was found that the Cr, Ni, Cu, Pb, and As leaching concentrations were low, and the leaching concentrations of other heavy metals were below the detection limit. The heavy metal and PH leaching concentrations are shown in Figure 6. The sampling and analysis results showed that the heavy metal leaching concentrations from drilling wastes met the PCL requirements. The upper 95% confidence limit of the PH leaching concentration (2.85 mg/L) is shown in Figure 6a, and the mean value was 1.62 mg/L. The distribution of the PCL of PH under different groundwater depths (5–50 m) ranged from 3.7 to 10.6 mg/L, as shown in Figure 5. Thus, the current PH leaching concentration of the drilling wastes met the PCL requirement.

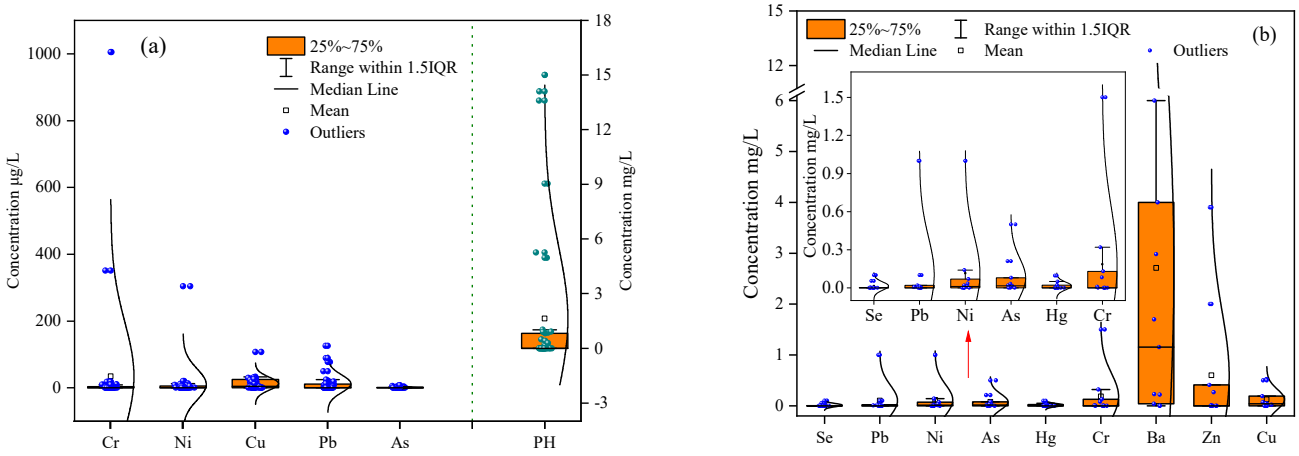

Figure 6. Contaminant concentrations in the drilling wastes ((**a**) this work and (**b**) literature).

Second, the leaching concentrations of major contaminants in drilling cuttings in the literature [3,24,25] were investigated, as shown in Figure 6b. It was found that the leaching concentrations of heavy metals were low and similar to the sampling and analyzing results found in this study. The literature reported PH leaching concentrations of 0.58–1.7 mg/L. Therefore, the contaminant leaching results in the literature also indicated that the PCLs of drilling wastes were within the limits [25].

3.6. Uncertainty

The PCL values of contaminants when drilling wastes were used to pave well sites were analyzed in this study based on the existing theoretical model. The pollutant PCL values were greatly influenced by the model and parameters. To conduct a quick and simple preliminary analysis of environmental risks, we made assumptions regarding the values of some parameters. In addition, some factors not in the model, such as soil lithology, were not considered.

First, the uncertainty of the model was evaluated. We adopted a steady state and constant source as the basic assumptions of the model; however, there may be non-steady states and transient releases of pollutants under actual conditions. Second, the uncertainty of model parameter selection was evaluated. There was regional variability in the model parameters; hence, there was uncertainty in the model parameters in the same region. For example, the pollutant adsorption constants may have been affected by environmental factors such as the pH value. Thus, the uncertainty in the above-mentioned factors caused the uncertainty in the PLC values.

The aim of this study was to provide a methodological basis and reference for the environmental risks of drilling waste road/well site utilization. When the PLC values in specific areas are applied, the actual situation must be considered.

3.7. Environmental Significance

The pollutant PCL values of drilling wastes, the DAF values of pollutants in different situations, and a pollutant migration model were proposed under the conditions of the use of drilling wastes to pave well sites in this study. The results of this study provided a basis for solid waste land use, disposal, or soil remediation decision-making. First, based on the relationship between the PCL and the thickness of the soil vadose zone, preliminary screening for the solid waste paving of a well site should be conducted. Second, under the constraints of specific geological conditions and pollutant properties (such as the soil vadose zone thickness and pollutant types), the degree of solid waste treatment should be such that the pollutant concentration does not exceed the PCL value, which will reduce the cost of non-necessary over-treatment of solid waste. Third, for historical land disposal scenarios, such as solid waste stockpiling and storage, based on the solid waste pollutant release patterns and transport modeling, the environmental risk of solid waste to groundwater and potential remediation targets were preliminarily determined.

4. Conclusions

Drilling wastes are difficult to utilize and dispose, and in this study, we simulated and analyzed the migration law of pollutants in the soil inclusion zone and groundwater mixing zone after dissolving with rainwater in the scenario of drilling waste near a bedding of a well site.

(1) The pollutant PCLs of drilling wastes and their corresponding DAFs were proposed in which the DF for the groundwater mixing zone was greatly influenced by the mixing zone thickness, the Darcy rate of the groundwater, the length of the pollutant source, and the permeability, with a contribution rate of 25% from each. The AF for the soil vadose zone was primarily influenced by the soil vadose zone thickness, with a contribution rate of approximately 53%.

(2) When the geological parameters were similar to those herein (e.g., the soil vadose zone thickness was approximately 10 m), the pollutants' DAF values in the drilling waste paving well site ranged from 13.75 to 16.72. In addition, the pollutant PCL values were 13.75–16.72 times the Class III permissible limits of the Groundwater Quality Standards GB/T 14848-2017 [10].

(3) The DAF or PCL was exponentially related to the groundwater depth, and this provides a reference for the actual process of the use of drilling wastes to pave well sites and for solid waste treatment or soil remediation decisions. In addition, due to modeling and parameter uncertainties, there were uncertainties in the DAF and PCL values that should be determined based on a combination of multiple actual factors.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w17010030/s1: Table S1: Exposure concentration at compliance point in groundwater C_2 mg/L; Table S2: Exposure concentration of heavy metals at compliance point in groundwater C_2 mg/L.

Author Contributions: All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by L.T. The research method was discussed with J.Z. The first draft of the manuscript was written by L.T. and J.Z. and all authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thank the Technique Research & Demonstration of Coprocessing Secondary Waste Dross in Typical Industrial Kiln (No. 20212ZDYF020047) and the Key Technologies for Environmental Risk Prevention and Control of Key Solid Waste Risk Sources in the Yellow River Basin (2022-YRUC-01–0303) for their support.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Acknowledgments: The author greatly appreciate the valuable comments and constructive suggestions from the anonymous reviewers.

Conflicts of Interest: Author Jinliang Zhou was employed by the company Yuyuan Ninghai Environmental Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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