



Human health risk assessment: Models for predicting the effective exposure duration of on-site receptors exposed to contaminated groundwater

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ABSTRACT

Clean-up of contaminated sites is usually based on a risk-based approach for the definition of the remediation goals, which relies on the well known ASTM-RBCA standard procedure. In this procedure, migration of contaminants is described through simple analytical models and the source contaminants' concentration is supposed to be constant throughout the entire exposure period, i.e. 25–30 years. The latter assumption may often result over-protective of human health, leading to unrealistically low remediation goals. The aim of this work is to propose an alternative model taking in account the source depletion, while keeping the original simplicity and analytical form of the ASTM-RBCA approach. The results obtained by the application of this model are compared with those provided by the traditional ASTM-RBCA approach, by a model based on the source depletion algorithm of the RBCA ToolKit software and by a numerical model, allowing to assess its feasibility for inclusion in risk analysis procedures. The results discussed in this work are limited to on-site exposure to contaminated water by ingestion, but the approach proposed can be extended to other exposure pathways.

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1. Introduction

The management of contaminated sites is often based on a risk-based approach, where the actual pollution of the site is evaluated depending on the effective risk posed to the human health of exposed receptors. This approach is based on the information collected during the contaminated site investigation, which are used to evaluate the potential effects on the health of exposed receptors, allowing to assess whether a particular site requires remedial action and eventually the specific risk-based remediation goal [1,2].

The most acknowledged technical and scientific references for this approach are the ASTM Risk Based Corrective Action (RBCA) standards for evaluating petroleum sites (E 1739-95) and chemical release sites (E 2081-00) [3,4]. The procedure outlined in these documents is based on a tiered approach for the management of contaminated sites, with increasing complexity in the definition of the site conceptual model and in the description of the physical and chemical phenomena underlying the fate and transport of contaminants. In Tier 1, aimed to the definition of the contamination screening values, only on-site receptors are considered, transport of contaminants is described through simple analytical

models and conservative default values are used for all hydrogeological, geometrical and exposure data, without requiring any site characterization. In Tier 2, aimed to evaluate site-specific target levels, off-site receptors are included in the conceptual model, all input data should possibly be site-specific, whereas models used to describe contaminants' transport are still analytical. Usually, the risk analysis procedure is performed using the Tier 2 conditions, that represent a reasonable compromise between the need for a detailed site assessment and the advantage of handling a rather simple and easy-to-use management tool. Therefore, only in very specific situations, where a more detailed description of the contaminant transport through numerical models is required, risk analysis is performed following the Tier 3 approach.

Among the different simplifying assumption of Tier 2 models, a key one consists in considering a constant concentration value for the contamination source throughout the entire exposure period of a generic receptor. This approach is somehow mitigated in the case of vapor volatilization from soil, by introducing a limit on the maximum amount of contaminant that can be generated by the contamination source, whereas no mention to this issue is given in the ASTM-RBCA guidelines for contamination source in groundwater, neither for volatilization, nor for migration in the saturated zone. This assumption may lead, for some types of constituents and soils, to extremely conservative results in terms of risk as the source reduction due to the various attenuation processes may occur and have a significant influence on contaminant

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Nomenclature

C_0	initial concentration (mg/L)
C_{poe}	concentration at point of exposure (mg/L)
C_w	concentration in liquid phase (g/m ³)
E	daily chronic contaminant exposure rate (mg/(kg × day))
ED	exposure duration (years)
ED _{eff}	average exposure duration (years)
f_{oc}	mass fraction of organic carbon (g/g)
HQ	hazard quotient (–)
i	groundwater gradient (m/m)
K_d	soil/water partition coefficient (L/kg)
K_d^*	limit soil/water partition coefficient (L/kg)
K_{oc}	organic carbon/water partition coefficient (mL/g)
K_s	saturated hydraulic conductivity (cm/s)
M_s	mass in soil sorbed phase (kg)
M_{tot}	total mass initially present (kg)
M_{transp}	mass transported (kg)
M_w	mass in dissolved phase (kg)
Q	groundwater flow (m ³ /s)
R	lifetime cancer risk (–)
RfD	reference dose (mg/(kg × day))
S_d	thickness of source-zone area (cm)
SF	slope factor (1/[mg/(kg × day)])
SSTL	site-specific target level (mg/kg or mg/L)
S_w	length of source-zone area parallel to groundwater flow (cm)
t	time (years)
U_{gw}	ground water Darcy velocity (cm/day)
V	source volume (m ³)
W_{gw}	width of source-zone area (cm)
θ_e	soil porosity (cm ³ /cm ³)
ρ_s	dry soil bulk density (g/cm ³)

concentrations. As a matter of fact, several studies have shown that natural attenuation (NA) can be particularly effective in reducing the mass, toxicity, mobility, volume and concentrations of contaminants [5–9]. NA refers to naturally occurring processes in soil and groundwater environments that act without human intervention [10]. These natural processes include biological degradation, volatilization, dispersion, dilution, and sorption of the contaminant onto the organic matter and clay minerals in the soil [11]. Recent studies have demonstrated the occurrence of natural attenuation by studying the evolution of the plume length [12–14], the mass reduction [15], the geochemical processes [16] and the vertical profile of vapors [17–19]. Various commercial packages are available for simulating these processes. The analytical models BIOSCREEN [20] and BIOCHLOR [21] allow to simulate the NA for petroleum fuel and chlorinated solvents, respectively. The Domenico analytical transport model [22] is the basis for these models and includes the assumption that the source concentration does not change with time. On the other hand, the RBCA ToolKit [23] and the RISC₄ [24] packages account for the decrease in exposure concentration due to volatilization, biodegradation and leaching for contaminated soil and due to dissolution and biodegradation in the case of groundwater source. In addition numerical models such as BIOPLUME III 2-D [25], MODFLOW [26] coupled with RT3D [27] and FEFLOW [28] allow to simulate this process.

It is worth noting that all these models simulate a transient condition and thus the risk is not calculated using the usual equations of a Tier 2 framework but rather as the sum of the incremental risk values associated to each exposure interval.

Hence in this paper a model to overcome the limitation of the ASTM-RBCA one, but keeping its original simplicity (Tier 2 framework), was developed. This model accounts for source attenuation, through a simple material balance, identifying the time required for depletion and consequently the effective exposure duration. The only source attenuation mechanism included in this work relies on run-off by groundwater flow, which is assumed to be dominant with respect to volatilization. Although biodegradation may some times contribute significantly to source depletion, it is not considered here, since it would require a level of characterization, that is usually not available when performing a Tier 2 risk analysis. The results provided by the proposed model are then compared with those obtained through the traditional ASTM-RBCA approach, a model based on the source depletion algorithm of the RBCA ToolKit software and a commercial numerical model (FEFLOW), allowing to assess its feasibility for inclusion in risk analysis procedures.

2. Modelling

The risk for human health correlated to the exposure to a given contaminant, may be calculated applying the following general equation:

$$R = E \cdot T \quad (1)$$

where T is the contaminant toxicity. The individual risk is defined as the risk for human health associated to a specific exposure route and to a single contaminant. Its determination is performed in a different way, depending on the type of contaminant's effects (carcinogenic or toxic), that the given compound may have on the human health receptor [29]. Namely, in the case of carcinogenic compounds:

$$R = E \cdot SF \quad (2)$$

where R is the life-long probability of incremental cancer case occurrence, caused by exposure to the contaminant, SF (slope factor) is the probability of incremental cancer case occurrence per unit dose, E is the exposure, averaged to a lifetime exposure duration (AT = 70 years).

For toxic, non-carcinogenic effects:

$$HQ = \frac{E}{RfD} \quad (3)$$

where HQ is the so-called "Hazard Quotient", defined as the ratio between the actual exposure to a given contaminant and the corresponding maximum allowable or reference dose, RfD (Reference Dose), i.e. the daily exposure rate that does not induce adverse effects on humans during the entire life-time; and E is the daily chronic contaminant exposure rate. The latter one is the product of the contaminant's concentration at the point of exposure, C_{poe} , with the effective exposure rate, EM, that may correspond to the daily ingested soil amount, inhaled air volume or ingested water volume, per unit body weight, depending on the exposure pathway considered:

$$E = EM \cdot C_{poe} \quad (4)$$

The estimation of the effective exposure rate requires evaluating the daily dose of the contaminated matrix that is assumed by the human receptors identified in the conceptual model [30].

The effective exposure rate, EM, depends on the ingestion or inhalation rate, CR, the exposure frequency, EF, the exposure duration, ED, the body weight, BW, and the averaging time, AT. The general form of the equation used to estimate this parameter is as follows:

$$EM = \frac{CR \cdot EF \cdot ED}{BW \cdot AT} \quad (5)$$

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